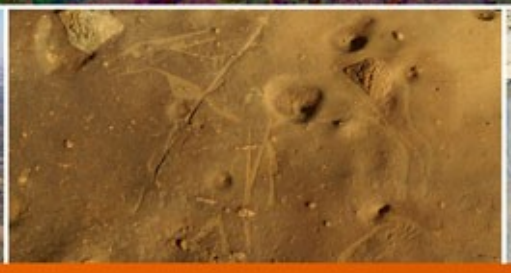
GEOPARKS OF THE WORLD



W. U. Reimold · R. L. Gibson

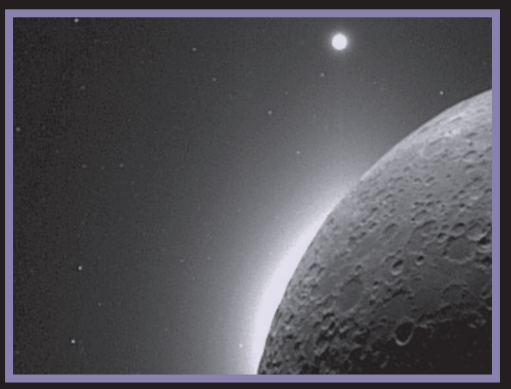
Meteorite Impact!

The Danger from Space and South Africa's Mega-Impact

The Vredefort Structure

Springer

Council for Geoscience



Knowledge is little
To know the right context is much
To know the right spot is everything

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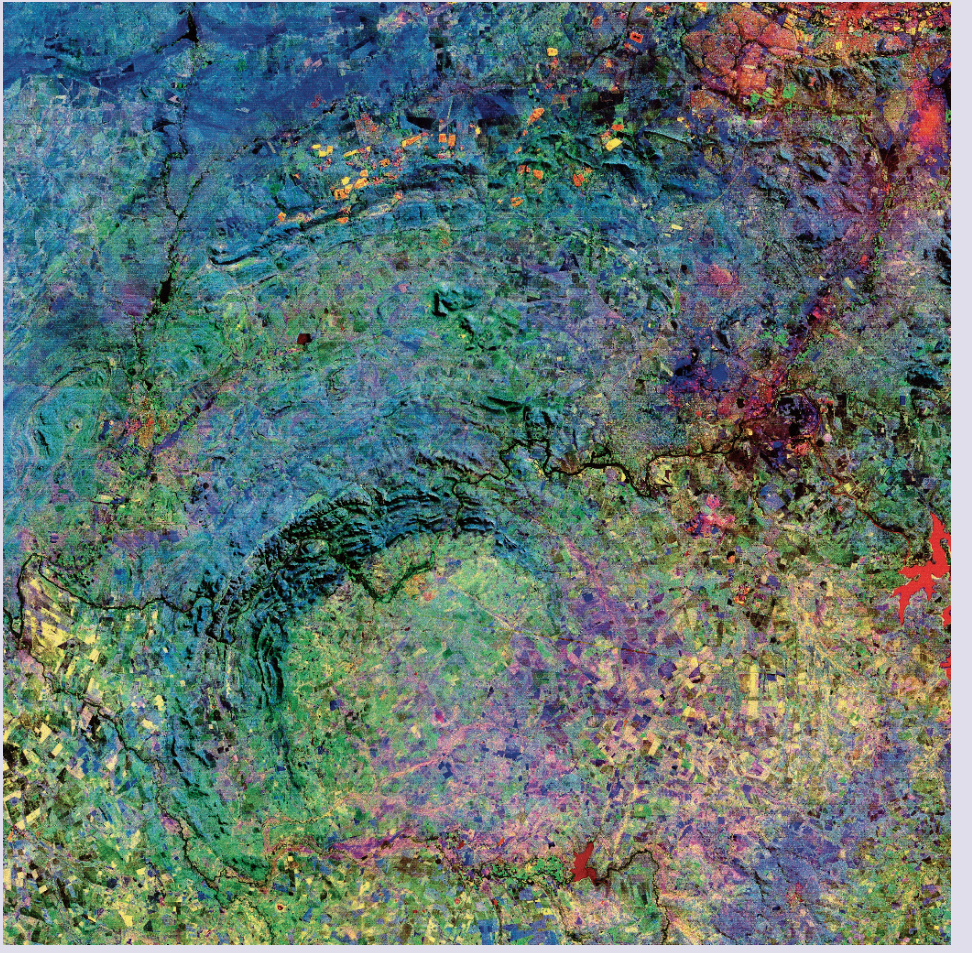

↑ **Figure 1:** False-colour Landsat Thematic Mapper satellite image of the Vredefort Dome and the surrounding Witwatersrand basin. Image courtesy of Michael Phillips, formerly of the University of Greenwich, United Kingdom. Image processed by M.E. Phillips, with input from Drs M.A. Bussell and I. McDonald at the University of Greenwich.

Aims & Scope of the *Geoparks of the World* Series

The Geopark initiative is booming! Spectacular geo-morphological landscapes and regions with special geological features or mining sites, notably promoted as "Geoparks", have proven to be excellent tools to educate the public about "Earth Sciences". Moreover, Geoparks can also be shown to be areas for recreation and significant sustainable economic development through geotourism. More and more national and international stakeholders are engaged in projects related to "Geo-conservation", "Geoparks" and "Geotourism" and have thus positively influenced the general perception of modern Earth sciences, remarkably.

The series provides a place for in-depth presentations of Geoparks and the developmental and management issues that surround them. It is not limited to existing Geoparks but can include the presentation of potential Geoparks and other areas of recognized geoscientific importance. While it is foreseen that the majority of the books will deal with the presentation of individual Geoparks or regions, the series may also include general books on Geopark development/management and also the proceedings from scientific meetings focusing on Geo-park/tourism/conservation issues.

METEORITE IMPACT!

The Danger from Space and South Africa's Mega-impact

the Vredefort Structure

BY

Wolf Uwe Reimold and Roger L. Gibson

WITH A CHAPTER BY

Anton Pelser, Mauritz Naudé and Kevin Balkwill

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Frontispiece:
Earthshine on the Moon.
Clementine spacecraft image of part of the Lunar surface solely illuminated by light reflected from Earth. The glow on the Lunar horizon is light from the Sun, which is just behind the Lunar limb. Planet Venus is visible at the top of the image.
Image courtesy of NASA, http://www.nasa.gov/multimedia/imagegallery/

Landscape of the Vredefort Dome.

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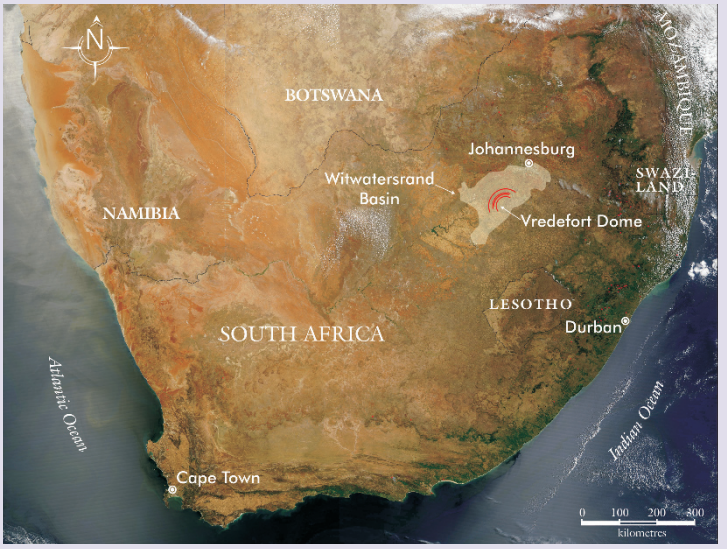


→ **Figure 2:** Location of the Vredefort Dome and surrounding Witwatersrand basin in north-central South Africa.

Foreword

There are few countries in the world that can compete with the superlative geological resources of South Africa. Whilst it is widely acknowledged that South Africa contains several of the world's greatest ore deposits, which have underpinned the national economy for more than a century, the tourism benefits provided by the geology are less well-known. In some of the country's premier tourist attractions — such as the uKhahlamba-Drakensberg Mountains, Table Mountain and the Cape Peninsula, the Cape Garden Route, and the Mpumalanga Escarpment and Blyde River Canyon, which are the product of the interaction of agents of erosion with the underlying geology — the focus has previously been restricted mainly to the landscape and scenery, with little mention of the even older history recorded in the rocks. Yet, with rocks whose ages range from a few million years to more than 3 500 million years, South Africa contains arguably the greatest record of the geological evolution of our planet of any country on Earth. Making up parts of this record are rock formations that can lay strong claims to being world-class and 'household names' in the international geosciences community, such as the ancient Barberton Greenstone Belt, the gold-bearing Witwatersrand basin, the Transvaal Supergroup with its record of primitive early life and huge iron and manganese deposits, the giant Bushveld Igneous Complex and its ore deposits, the Karoo Basin with its unparalleled fossil record of the ancestors of dinosaurs and mammals, diamondiferous kimberlite pipes and the world's richest homonin fossil sites around Sterkfontein. It is little wonder, then, that since the early 1990s South Africa has seen a dramatic rise in specialist geotourism, with overseas geoscience students and professionals visiting the country with the primary purpose of seeing these geological wonders for themselves. The raising of awareness of the tourism potential of this geological heritage amongst the broader public both locally and internationally has been a more recent phenomenon, but is proceeding apace on several fronts, with the creation of guidebooks for non-specialists describing the geology of individual cities, provinces, national parks and major national routes, the opening of geological and mining heritage exhibitions in museums, the training of geotourism guides and last, but not least, the declaration of several World Heritage Sites in South Africa which involve a significant, or even dominant, geological component. A seminal moment was the release in 2005 of the bestselling *The Story of Earth and Life – A southern African perspective on a 4.6-billion-year journey*, by Terence McCarthy and Bruce Rubidge that has, for the first time, presented the geological heritage of South Africa in a manner accessible to non-specialists.

In many ways, the story of the development of the Vredefort Dome and this book parallels the broader South African context. The Vredefort Dome, located in the heart of the Witwatersrand basin and close to Johannesburg, was a popular geotourism site for visiting geoscientists even whilst its origin was disputed (up until the mid-1990s). It was a popular recreational tourism venue even before this, with some of the most spectacular scenery in central South Africa, convenient access and the presence of the Vaal River the main attractions. A turning point arrived in July 1999 when the Department of Geology at the University of the Witwatersrand hosted the 62nd Annual Meeting of the Meteoritical Society. This event marked only the second time that this prestigious international conference had been held outside of Europe and North America and it provided an unprecedented opportunity for local scientists to showcase the breathtaking geological heritage of southern Africa via a series of pre- and post-conference

excursions. Amongst these, by far the most popular was to the Vredefort Dome. Given the fact that most of the conference delegates had never previously visited South Africa, an effort was made to include archaeological, historical, cultural and social commentary interspersed with the fascinating geological outcrops. Feedback from the excursion participants was unanimously enthusiastic and a joint request was made that the excursion guidebook should be published to reach a wider audience. This was realised in 2001, with the publication of Memoir 92 by the Council for Geoscience. By 2003, as the momentum built towards the listing of part of the Vredefort Dome as a World Heritage Site, public interest in the geological events that formed the Dome blossomed, and the Council began to receive numerous calls for copies of the Memoir from people wanting to visit the Dome as tourists. This was not an ideal situation, as the Memoir had been designed for a specialist geological readership. A decision was then taken to write a book that would be directed at a more general audience.

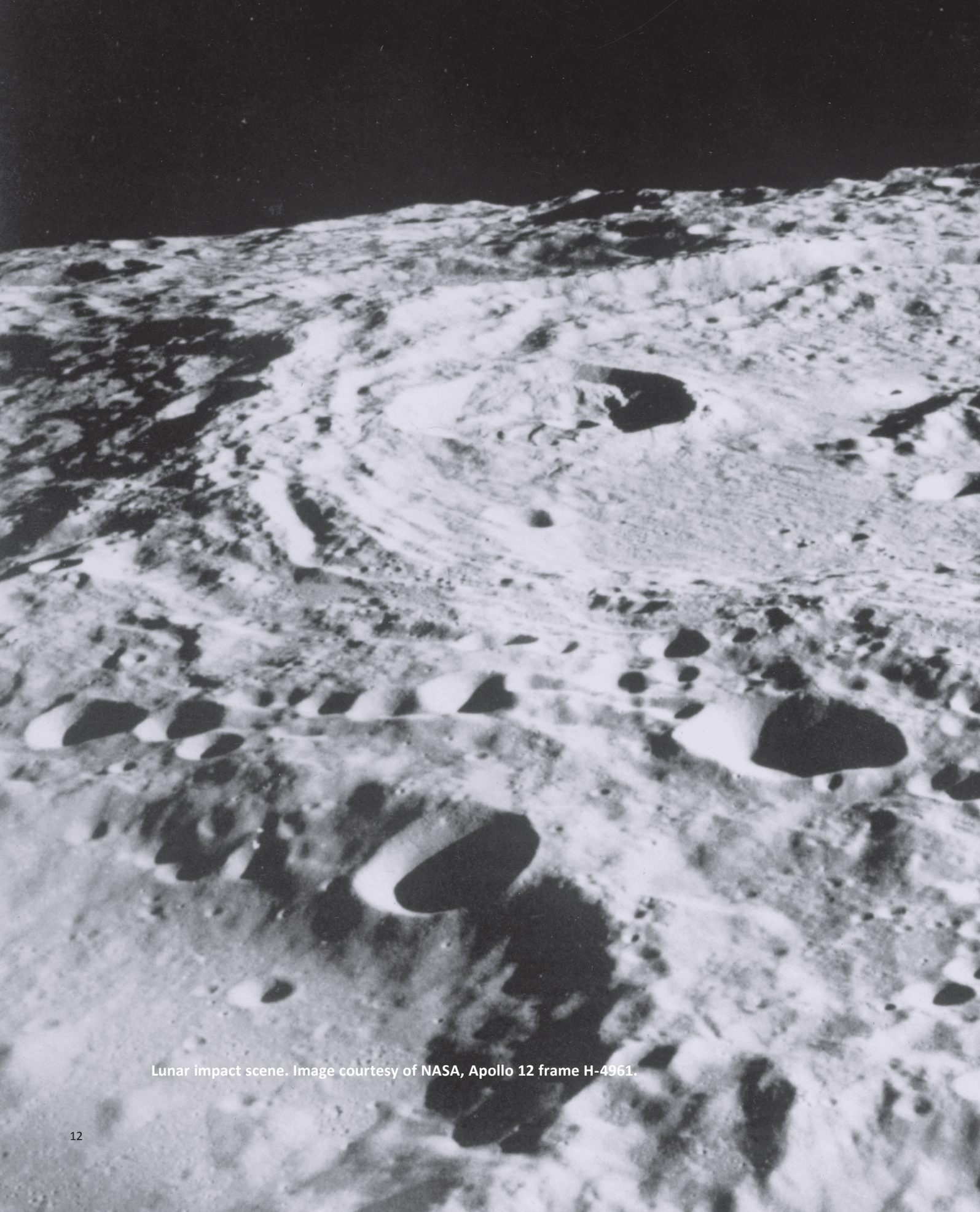
The first edition of *Meteorite Impact!* was published in July 2005 and coincided with the announcement in Durban by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) that the Vredefort Dome was to be listed as South Africa's seventh World Heritage Site. The UNESCO motivation highlighted the remarkable confluence of an exceptional geological situation with an area of striking natural beauty and biodiversity endowed with an archaeological and cultural-historical heritage stretching back to Stone Age and Iron Age times. In addition to listing the principal geosites and discussing the history of geological research on the Dome, the book provided a broad introduction of geological concepts, the geological history of South Africa and southern Africa's other impact structures, as well as a glossary to explain geological terms. A separate chapter on the archaeological, historical and botanical attractions of the Dome by subject experts was commissioned. The first edition, published by Chris van Rensburg Publications, was rapidly sold out and a second edition was released in December 2005, with the Council for Geoscience as a co-publisher. By the end of 2008 stocks of the second edition were almost sold out and Springer Publishers was approached about publishing a third edition with a view of furthering particularly overseas interest in this unique geological site.

Foreword to the Third Edition

The burgeoning public interest in the Vredefort Dome has both expanded the tourism infrastructure in the area and increased awareness amongst local landowners of the potential benefits of harnessing the geological heritage for tourism and educational purposes. To this end, the Tour Guide in Part II of the book has been substantially modified, with several new sites added to replace sites in the earlier editions that are less accessible from the major routes. Other additions to the text include updates on the more recent natural disasters between 2005 and 2008 that emphasise the ever-present danger to humanity posed by geological processes on our planet. The third edition has also benefitted from a slew of new Space missions to our neighbouring planets, and to asteroids and comets themselves, that have delivered both new insights into the nature of these bodies and a spectacular database of high-quality satellite images, some of which have been incorporated into this edition. With a new generation of planetary research currently underway, it is appropriate that the Vredefort Dome, acknowledged as a World Heritage Site, also remains an area of active research by the international scientific community. It is encouraging to note that the geoscientific research is now being joined by research into the archaeological, cultural-historical and natural history of the area. Together, the results of this research not only provide valuable additions to global scientific knowledge; they also have the potential to contribute to the expansion of the tourism capacity of the Dome, thereby providing economic benefits to the region. We hope that this book serves to illustrate to a wider audience the amazing treasures of this incomparable geological wonderland.

The origin of the Vredefort Dome and its unusual rock deformations have occupied the minds of some of the greatest exponents of South African and world geology over the past century. Writing this book has been a humbling experience and a timely reminder that science is a search after truth and meaning, and that it is never ending. With local and international colleagues and students, we have been fortunate to have been given the opportunity to work on this remarkable geological feature and to know that each new result is eagerly awaited by an international scientific community that recognises the wealth of information that the Vredefort Dome has to offer. As part of a broader initiative to develop awareness of the Dome, we hope that this book repays in some measure the warm hospitality and assistance of the people of the Vredefort Dome who have made us welcome in their homes and provided us with access to their land. This book is dedicated to our families — Yvonne, Carly, Elsbeth, Emma, James and Matthew — who have stoically borne our absences, working holidays and our obsessive need to continue exploring every facet of the Dome over the past two decades.

Wolf Uwe Reimold
Roger Gibson



Lunar impact scene. Image courtesy of NASA, Apollo 12 frame H-4961.

Part I

The early history of Earth

CHAPTER 1

The early history of Earth —
Impact, volcanoes, and early life

The Blue Planet.
Satellite image courtesy of Tokai University, Japan.

Introduction

Two thousand million years (Ma) ago a mountain-sized bolide from Space, travelling at tens of thousands of kilometres per hour, slammed into the Earth at a position approximately 120 km southwest of the present-day city of Johannesburg, in the vicinity of the present towns of Vredefort and Parys. Within moments, it had blown a hole tens of kilometres deep and more than 100 km wide into the crust of the Earth. The force of the impact hurled countless millions of tonnes of rock, some of it heated to temperatures of thousands of degrees centigrade (°C), around the crater over an area extending for hundreds of kilometres from the impact site (Fig. 3a). Fine dust particles and toxic chemicals from the vaporisation of the rock were thrown into the upper atmosphere where they spread around the Earth, blotting out the rays of the Sun for years, causing an unnatural global winter and widespread pollution. Fallout from this massive dust cloud settled through the atmosphere and was deposited all around the world. The blast wave from the explosion travelled through rock, air and water, triggering secondary catastrophes, such as earthquakes, landslides and tsunamis (giant flood waves in oceans) across the planet. At the point of impact itself, the initial crater lasted no more than a couple of minutes before its walls started to collapse and its floor started to rebound as the tremendous compression by the shock wave passed downwards and outwards. Within 10 minutes of the projectile having entered the atmosphere of the Earth, a circular crater 1–2 km deep and up to 250–300 km wide, filled with broken rock and superheated melt, scarred the landscape of the then existing continent. A huge impact crater, such as those still visible on the surface of the Moon (Fig. 3c), had formed. The greatest single geological catastrophe yet recorded on the face of our planet was largely, but not completely, over.

Today, the features of the landscape between Vredefort and Johannesburg look very different from what they were moments after the impact. There is no crater and the melt rocks are largely gone, victims of the far more gradual, but nonetheless relentless, forces of weathering and erosion that continue even today. However, a person looking down from a jetliner, or even a spacecraft, would note a crescent of hills and valleys, some 90 km in diameter, lying north and west of the towns of Vredefort and Parys (see Fig. 1). Closer to the ground, one sees that these hills have formed by the upturning and subsequent erosion of layers of rock that are part of an immense dome structure, caused by the rocks in the centre being pushed upwards relative to those around the margins (Fig. 3b). Since geologists first examined these rocks more than a century ago, they have been speculating that a violent event was responsible for the formation of the Vredefort Dome. It has taken nearly 100 years to recognise that the features found in the rocks of these hills and valleys have an unusual origin — a geological process that is, quite literally, *out of this world!*

The chapters in Part I of this book describe a voyage of discovery, tracing the scientific evidence that culminated in the recognition of the true origin of the Vredefort Dome, and show how geoscientists were able to assemble the pieces of the puzzle to obtain an understanding of the full scale of what happened in the area 2 020 Ma ago.

The impact event at Vredefort affected rocks that had formed at various stages during the earliest phase of Earth's evolution. Some knowledge of this early history of Earth is therefore required to fully comprehend the phenomenon that is the Vredefort event. This chapter describes the period from the Big Bang, the earliest event of the Universe, to the time just prior to impact.

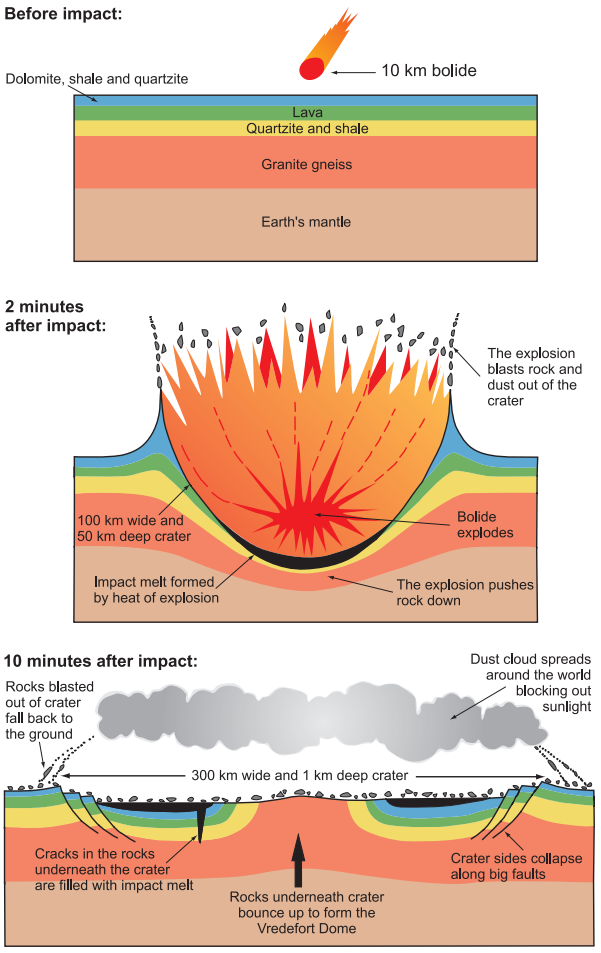
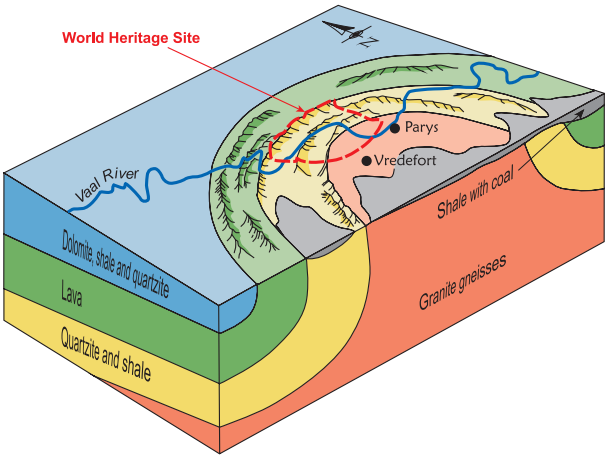


Figure 3a–c: A giant impact event 2 020 million years ago formed the Vredefort Dome.
← **a.** Cross-sections through the Earth's crust, showing how the Vredefort impact crater, with the Vredefort Dome at its centre, formed.
↓ **b.** Cutaway diagram of the Vredefort Dome today, showing how erosion of the upturned layers has produced the crescent of ridges and valleys seen in Figure 1.



↓ **c.** Oblique photograph of the 169 km wide impact crater Keeler, on the Lunar far side, showing what the Vredefort impact structure may have looked like 2 020 million years ago. The hills in the middle mark the position of the collapsed central uplift. Image courtesy of NASA, Apollo 12 frame H-4961.

Geological change — the answers within, and without

From its very beginnings in the early 19th Century, the science of geology, the study of the Earth, has been dominated by two apparently opposing fundamental points of view. On the one side has been the view that geological change is a gradual process and that rates of geological change remain relatively constant. This *uniformitarianist* approach was first proposed by Charles Lyell (1797–1875), whom many regard as the Father of Geology. Lyell suggested that slow change over incredibly long periods of time was capable of wearing down mountains and filling in seas with the sediments eroded from these mountains. Lyell challenged the prevailing orthodox view of his day, which held that change was catastrophic — events, such as volcanic eruptions, earthquakes, floods and tsunamis were regarded as random acts of Divine punishment that struck without warning. The *catastrophist* view did not require a very old Earth. Indeed, as late as 1650, James Usher, Archbishop of Armagh, postulated, after having added up the ages given in the Old Testament, that the world had begun at 10 o'clock on the morning of 26 October 4 004 BC! In his time, Lyell's uniformitarianist view could not, however, explain why catastrophic events occurred.

Nearly 150 years later, geoscientists managed to reconcile the two views by showing that slow movement of quasi-rigid pieces, so-called 'plates', of the rocky outer crust of the Earth, in response to flow within the interior of the Earth, drives almost all geological change. This Theory of Plate Tectonics has dominated geological thinking only since the 1960s. It recognises that individual catastrophic geological events, such as volcanic eruptions or earthquakes, although devastating to humans and other life forms in the short term, have been repeated hundreds or even thousands of times. These catastrophes are, from the perspective of geological time, simply short-lived 'blips' in a long, continuous history. Thus, it was our limited perspective of time, rather than a fundamental conflict in the mechanisms of geological change, that underpinned the uniformitarianist-catastrophist debate.

It has also become clear that long-term climatic change is a natural phenomenon. The Earth as a whole was significantly warmer during the Cretaceous period than it is today, and the planet has experienced quite a number of Ice Ages in the last couple of million years alone. By the latter part of the 20th Century, geoscientists had begun to appreciate that it is also the sheer scale of the cycles of nature on our planet that prevents us from fully understanding the continuous nature of geological change.

Today, many of the specialist fields of study within the geosciences are being recombined as geoscientists recognise that change in one aspect of the 'Earth System' affects other aspects. If we are to understand, for instance, climatic change, we need to understand ocean currents, the position of the continents at various times in the past and, ultimately, plate tectonics. However, just as the idea came to be accepted that the Earth needs to be viewed as a whole — holistically — and that what happens at the surface essentially reflects what happens within its interior, scientists made a discovery that requires our perspective to be on an even larger scale than that of our own planet.

The Structure of Earth

The interior of the Earth can be divided into three segments (Fig. 4a): the core, the mantle, and the outer shell that combines the lithosphere and the crust of the Earth. This internal structure is the result of differentiation, the separation of materials of different densities. The core of the Earth is subdivided into inner and outer core. The inner core comprises 1.7 % of the mass of the Earth and is thought to consist of solid iron and nickel. Despite the enormous temperature in the core, this zone remains solid because of the huge pressure exerted on it. This solid inner core is surrounded by a liquid outer core (30.8 % of the total mass of the Earth). The temperature in the outer core is some 4 000 °C and, as the pressure decreases with distance from the centre of the Earth, the outer core is liquid. The Earth's mantle, which surrounds the core, constitutes 67 % of the mass of the Earth. This is the volume between 2 890 km depth and ca 70 km depth. Much of the mantle is solid, but the upper mantle is at least partially molten (as is known from seismic-wave studies) in a region that is called the asthenosphere, between 70 and 40 km depth. Most of the mantle is composed of the minerals pyroxene, olivine and garnet. Partial melting of the upper mantle produces a magma of basalt composition, the rock that forms the crust of the Earth under the ocean floor and volcanic islands, such as the Hawaiian island chain.

The lithosphere and crust form the outer shell of our planet (Fig. 4b), to a depth of some 70 km, amounting to no more than 0.4 % of the mass of the Earth. The mantle lithosphere is relatively cool and rigid, and forms the transition zone between the hot mantle and the relatively cold crust. The crust can be compared to the thin skin of an apple in comparison with its entire volume. The lithosphere does not represent a single zone, but a giant puzzle of more or less tightly fitting segments, the continental and oceanic plates. There are eight large and several dozen small plates.

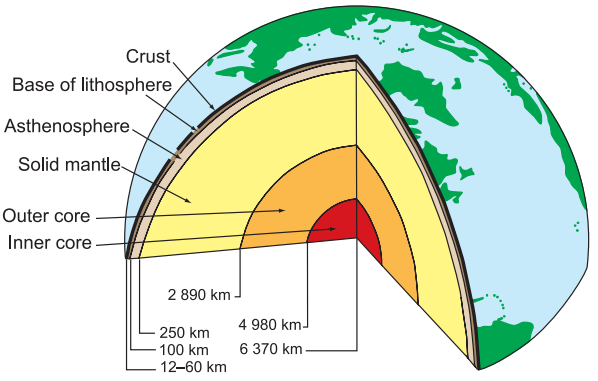


Figure 4a: Cross-section through the Earth's interior, showing the crust, mantle and core. The lithosphere represents the crust and the upper part of the Earth's mantle — that section which constitutes the plates. Below is the partially molten asthenosphere from where magma originates. After an illustration in McGuire (1999).

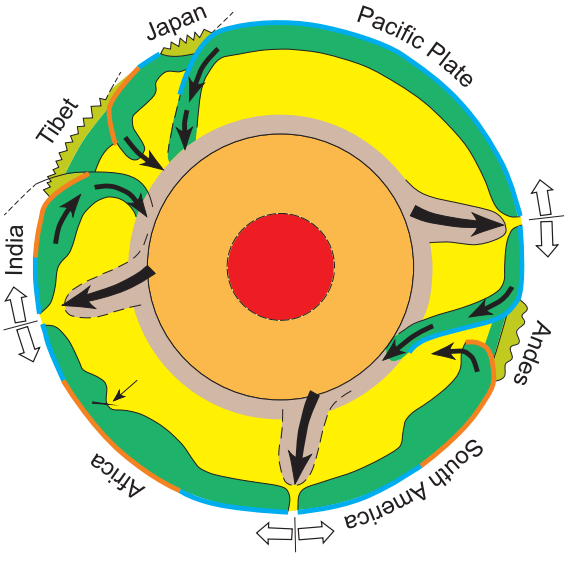


Figure 4b: A cut through the Earth roughly along the equator. Note the positions of mid-oceanic ridges, along which the crust spreads apart (marked by opposing arrows) and magma rises towards the surface, and the subduction zones, along which plates are dragged into the mantle. Different types of mountain ranges are formed, as typified by the Andes at subduction of oceanic crust, and the Himalayas where continental plates collide. Modified after an image in Spektrum der Wissenschaft, Compact 2/2002.

Plate tectonics — Earth's dynamo

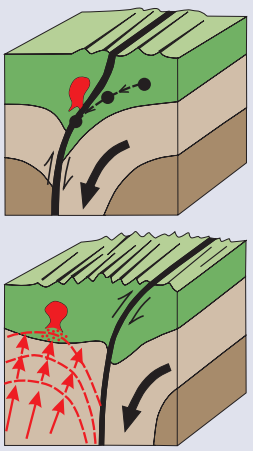
Individual plates are constantly 'on the move'. This slow movement of plates is a result of convection within the mantle of the Earth, driven by heat loss. As new crust is formed at some plate boundaries, crust is colliding at other plate boundaries, with some sinking back into the mantle to maintain the constant surface area of the Earth. This latter process is known as *subduction*.

New lithosphere is continuously formed at the so-called mid-ocean ridges. These features are ridges, thousands of kilometres long, that reach elevations of approximately 1.6 km above the surrounding ocean floor. Magma produced by partial melting of mantle material in the asthenosphere erupts at these ridges and forms new sea floor (oceanic crust). More and more magma erupts and the old oceanic crust is pushed apart; the sea floor spreads away from the ridge. This process is known as sea-floor spreading. With time, the new oceanic crust moves farther away from the mid-ocean ridges, cools and becomes denser. This cold, dense crust begins to sink into the mantle under gravity. It does this obliquely because the new crust forming at the mid-ocean ridges is actually pushing the oceanic crust sideways. These sites of sinking crust are called subduction zones. They are marked by kilometre-deep trenches in the sea floor and are commonly found around the edges of continents. The entire process of plate tectonics is illustrated in Figure 5a.

The surface of the Earth has been largely shaped through plate tectonics; the balance between sea-floor spreading and subduction maintains the constant surface area, and collisions of continents result in massive mountain ranges. A prime example is provided by the Himalayas between India and China, where the Indian plate collides with the Eurasian plate. Where continents break apart, along so-called rift zones, deep rift valleys form — as in northeast Africa, where the Rift Valley of Ethiopia and Kenya (Fig. 30, page 45) is the result of a part of northeast Africa splitting off the main continent.

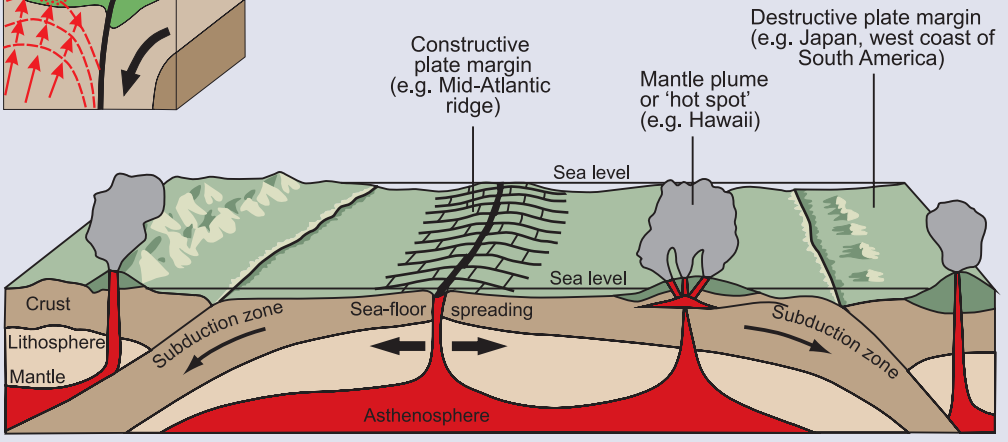
Plates are also shuffled obliquely past one another. These transverse movements lead to build-up of enormous stress in the lithosphere causing ruptures and earthquakes. An example of such grinding action between two plates is the well-known San Andreas Fault Zone in California (Fig. 37, page 55), a zone of continuous earthquake activity.

Continental collision is a continuous, but slow, process. Annual movements of plates



→ **Figure 5b:** Two possibilities of how granite can be produced through partial melting of material in the crust or the mantle. **Top:** Continental crust is subducted and thus subjected to ever-increasing temperature until, finally, at the lowest black dot, partial melting is achieved. The less-dense hot magma rises. **Bottom:** Hot material (illustrated by red arrows) rises through the asthenosphere and heats the bottom of the crust until it melts.

↓ **Figure 5a:** The effect of plate tectonics is that earthquakes and volcanism occur mainly in those regions where the plates interact with one another. Modified after a diagram by McGuire (1999).



usually are no more than 5–10 centimetres (cm). It takes many millions of years to build a mountain range or to destroy, by subduction, a vast area of oceanic crust. To destroy the crust underneath the entire expanse of the Atlantic Ocean would take some 130 million years. However, this is a mere blink of the eye against the 4 600 million years since the formation of our planet. The formidable Himalayas have been in existence for 'only' 35 Ma! Because it is made up of less-dense rocks than oceanic crust, continental crust is more buoyant and, thus, is not dragged into the mantle and reprocessed. As a consequence, continental crust is both much older (the oldest rocks on Earth are nearly 4 000 million years old) and thicker (ca 35–40 km thick) than oceanic crust, which is less than 10 km thick.

When the plates interact, stress is generated. Rock can only support so much stress before it ruptures. Thus, stored energy in the massive rock volume of the lithosphere is released in the form of powerful earthquakes. Such shallow-sourced earthquakes can be particularly catastrophic. A second type of earthquake originates from subduction of crust. By investigating the seismic waves released from these events, it has been established that such earthquakes can have their foci at depths exceeding 600 km.

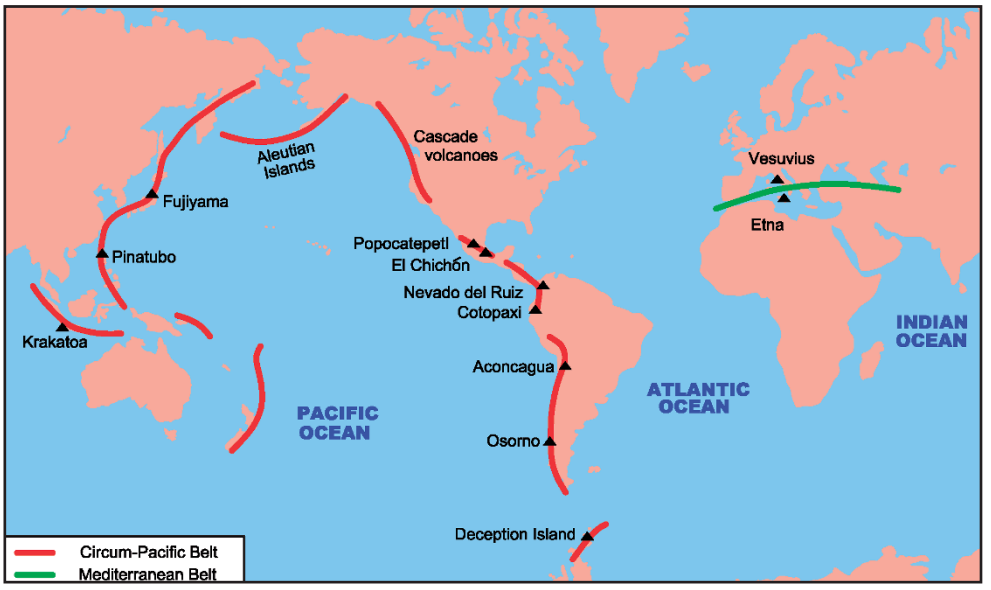
The second, often catastrophic, effect caused by plate tectonics is volcanism. This process allows heat to be lost from the interior of our planet. Volcanism occurs at mid-oceanic ridges, or at zones where plates converge on each other, when the subducting plate starts to heat up as it plunges to greater depths (Fig. 5b). When continents rupture along rifts, intraplate volcanism may occur — which in the past has produced some of the world's largest volcanic eruptions. These eruptions produced giant flood-basalt provinces, including those that formed the spectacular Drakensberg mountain range (Fig. 6). One of these eruptions, the great Karoo volcanic event at ca 180 Ma ago, flooded much of the southern part of the continent with lava.

The distribution of most of the hundreds of volcanoes on Earth is not random, but closely linked to plate boundaries. Thus, the border zone around the Pacific plate, involving parts of East Asia (easternmost Siberia, Japan, Indonesia, the Phillipines) and of the Americas (along the west coast of North and South America, right up into Alaska), is known appropriately as the Ring of Fire (Fig. 7).

That plate tectonics has been a phenomenon for thousands of millions of years can be gleaned from the rock record. For example, some of the earliest evidence for sea-floor spreading was discovered in the early part of the 20th Century — significantly through the insight of visionary workers, such as Alfred Wegener in Germany and Alex du Toit, the famous South African geologist (Reimold, 2007) — when it was established that rock records, fossils and evidence for past climates on the African and South American continents, as well as in Antarctica, could be closely matched. The rock record also shows that dramatic changes in climate have affected many continents, forcing the conclusion that individual plates at certain times in their past resided in equatorial regions or close to the polar regions. In the early 1960s, detailed measurements of magnetic minerals in rocks from the basaltic oceanic crust showed that they record the regular switching of the Earth's magnetic field and that these reversals can be matched in bands lying on either side of a mid-ocean ridge. Once it became possible to date the individual bands of magnetised rock, geologists were able to show that they must have formed symmetrically about the mid-ocean ridge before being split apart by the formation of new crust making up the next band. Undeniable proof of how sea-floor spreading occurs had finally been found!

→ **Figure 6:** The spectacular peaks of the Drakensberg are underlain by flood basalts that erupted during Gondwana breakup. Photo courtesy of Grant Bybee.

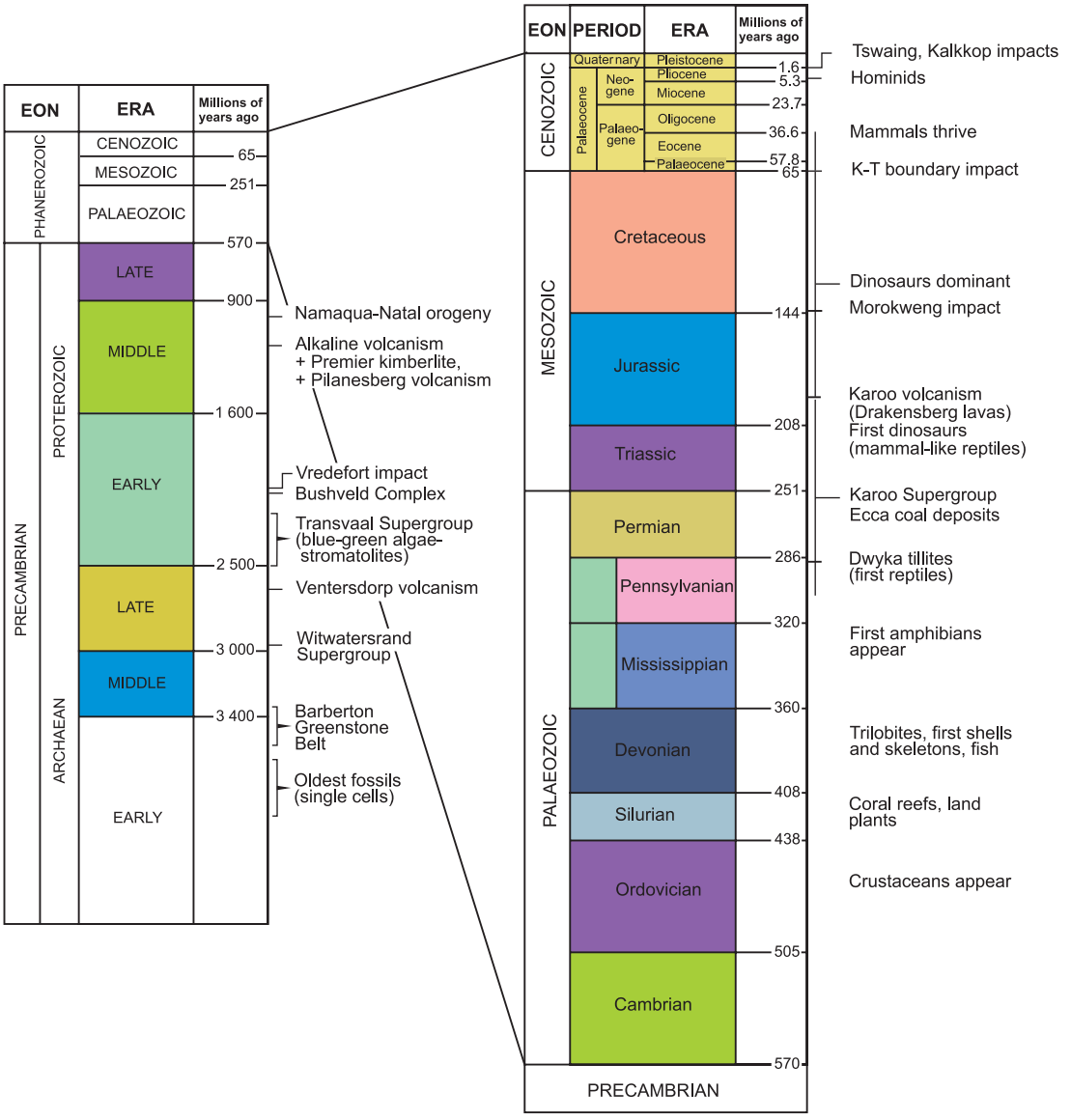
↓ **Figure 7:** The volcanic and earthquake regions of the World — the so-called 'Ring of Fire'. Active volcanoes and earthquake 'hot spots' are concentrated in a belt around the Pacific Ocean. A second belt that is frequently hit by volcanic and earthquake catastrophes is the Mediterranean belt, from Morocco to northern Iran. After a diagram in Plummer and Geary (1996).



Catastrophes

The geological theory of gradual change greatly influenced thinking in other areas of science. Charles Darwin (1809–1882), in the 19th Century, for instance, favoured gradual change as the driving force for evolution of life. However, studies of the fossil record in the last 50 years have made it clear that evolution has been punctuated by a series of catastrophes, known as mass-extinction events. These events caused the extinction of vast numbers of species over relatively short periods of geological time, only to be followed by rapid development (speciation) amongst the surviving species. The most famous of these mass extinctions, which occurred some 65 Ma ago at the so-called Cretaceous–Tertiary boundary (the boundary between these two periods — compare the Geological Timescale, Fig. 8) wiped out not only the dinosaurs that had dominated life on Earth for 130 million years, but altogether some 70 % of all species living at that time. Despite its enormous scale, this event is still overshadowed by a vastly larger extinction event, some 186 million years earlier, that wiped out not less than 90 % of all species: this 'Mother of All Mass Extinctions' took place at the boundary between the Permian and Triassic periods 251 Ma ago. In 1980, Nobel Prize winner Louis Alvarez and his team proposed a likely connection between the Cretaceous–Tertiary mass extinction and the impact of a large extraterrestrial bolide. Ever since, the question that has puzzled and stirred up geologists and palaeontologists has been whether a link existed between other mass-extinction events and specific geological catastrophes such as impacts or volcanic eruptions. As technology has improved and geological investigations have covered ever-larger areas of the Earth in greater detail, the global nature of many geological events has become clearer. For instance, while earthquakes and volcanoes may directly devastate a relatively restricted area (maybe tens or perhaps as much as hundreds of square kilometres), both processes are capable of generating tsunamis that can travel for thousands of kilometres from their source (Fig. 40, page 57), and volcanic eruptions have the added ability to cause regional, or even global atmospheric pollution (Fig. 38, page 56).

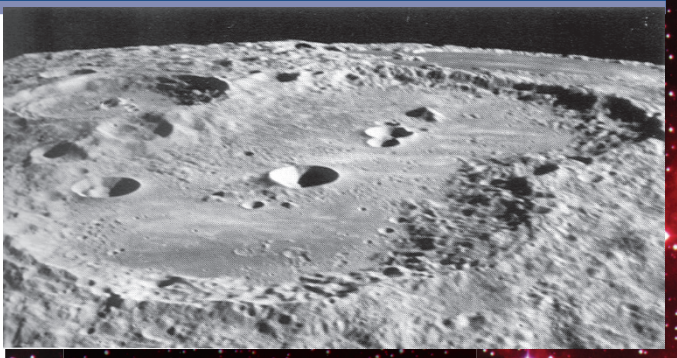
Figure 8: Geological time scale, marking the most important geological time divisions and some important events in the geological history of southern Africa. The Tertiary period has been renamed the Palaeogene; however, the term 'K–T boundary' persists.



Man on the Moon

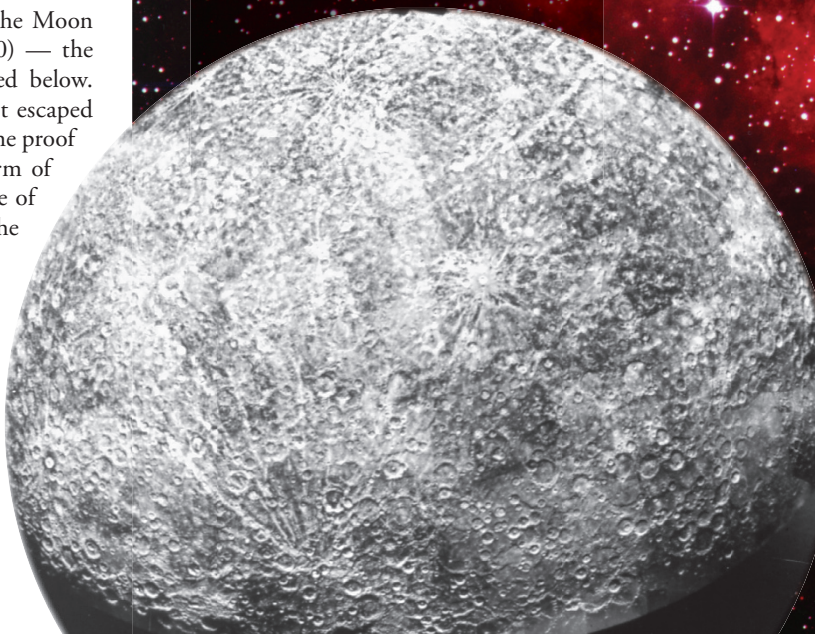
In the late 1960s, just as plate tectonics became firmly established in geological theory, humankind reached out beyond our planet, to the Moon. Craters on the Moon had been known since the first telescopes had been developed in the 16th Century. Galileo Galilei built his first telescope in 1609, and proceeded to make detailed observations on the craters of the Moon in that same year. Much speculation ensued, and for a long time the obvious interpretation was that these features represented volcanoes. Indeed, this is quite understandable, as volcanoes were the only crater phenomenon known to those early natural scientists. However, since the Space Race of the mid-20th Century between the former USSR and the USA, and especially since the Apollo landings on the surface of the Moon and then the Solar System-wide travels of the Pioneer and Voyager Space Probes of the 1970s, it has become clear that not only the Moon, but also every other solid body in the Solar System is peppered with crater structures, and that they are the result of bombardment by other planetary bodies — meteorites, asteroids and comets. This 'War of the Worlds' will be discussed in much more detail later, but the main question to be dealt with at this stage is: what happened to Earth? We now know, and can state with the utmost confidence, that Earth has experienced the same onslaught by bolides from Space as the Moon and the other planets (Figs 9 and 10) — the reasons for this certainty are outlined below. Indeed, the giant gas planets have not escaped this barrage of projectiles either, and the proof for this came in July 1994 in the form of the multiple blows dealt to the surface of the planet Jupiter (Figs 12 and 13) by the fragmented comet Shoemaker-Levy 9.

Impact cratering is now known as one of the fundamental processes taking place in the Solar System. Forty years of research have indicated that it has, without doubt,



↑ **Figure 9:** Van de Graaff Lunar impact crater (230 km long axis, 27°N, 172°E). A younger complex crater is superposed at upper left. Image courtesy of NASA, Apollo 17 frame H-22959.

↓ **Figure 10:** Photo mosaic of Mariner 10 imagery of the southern hemisphere of planet Mercury, showing the intense impact cratering that the closest planet to the Sun has had to endure. Courtesy NASA and Jet Propulsion Laboratory, Pasadena.



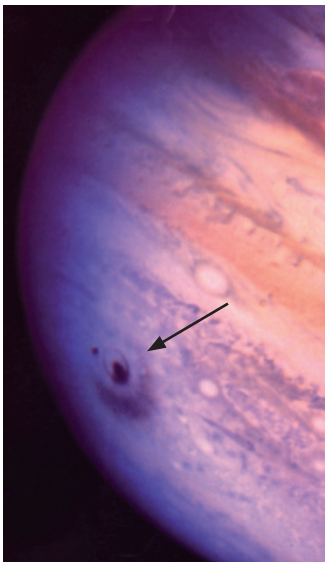
→ **Figure 11a:** NASA's Hubble space-telescope image (STScI-PR-28, October 1998) of Galaxy NGC 7742 — a spiral galaxy. It is thought that the 'lumpy, thick' ring around the core of the galaxy is an area of active star birth. The distance between the ring and the bright core is about 3 000 light years. Credit: Hubble Heritage Team (AURA, STScI, and NASA).

← **Figure 11b:** The Rosette Nebula in our Milky Way Galaxy, photographed from the European Southern Observatory in Chile. Photograph courtesy of David L. Block, University of the Witwatersrand, Johannesburg.

↓ **Figure 11c:** The spiral galaxy NGC 2997 photographed from the European Southern Observatory in Chile, showing carbon-based cosmic dust spanning 100 000 light years. Photograph courtesy of David L. Block, University of the Witwatersrand, Johannesburg.

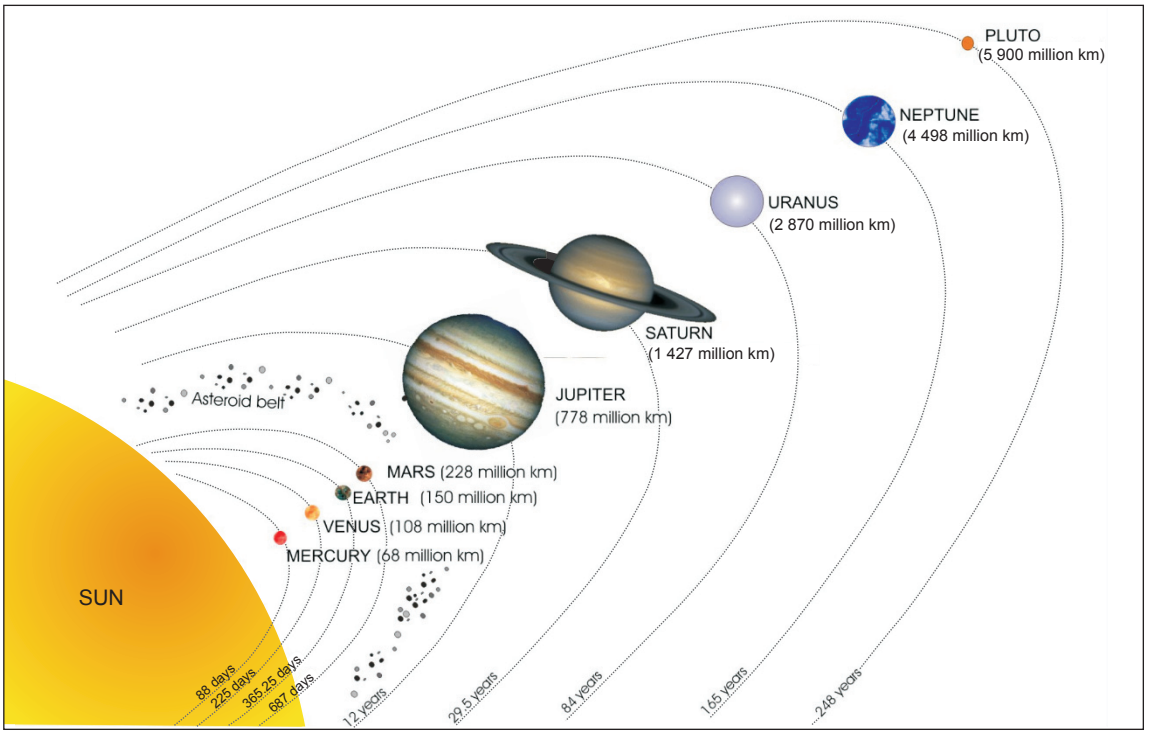
played a major role in the evolution of planet Earth and life on it. One can only speculate on what our species would be like if not for some major impacts that caused massive extinctions and terminated periods dominated by certain species, initiating proliferation of new ones. It is now clear that uniformitarianism does have its place — plate-tectonic processes have continuously modified Earth's surface and interior. However, catastrophism, in the form of massive blows by what Arthur C. Clarke, in his famous book of the same title, called the 'Hammer of God', has had its own role in the genesis of the world that we know. And it will continue to do so.

↑ **Figure 12:** The 'string of pearls' — a false-colour image of fragments of the comet Shoemaker-Levy 9 that broke up under the gravitational pull of Jupiter. The largest fragments are believed to have been not larger than perhaps 150 m. Image courtesy of NASA's Hubble space telescope.



→ **Figure 13:** July 1994 impact site (arrow) of a fragment of Shoemaker-Levy 9 in the atmosphere of Jupiter. Image courtesy of NASA's Hubble space telescope.

↓ **Figure 14:** Schematic presentation of our Solar System, illustrating the planets and their orbits (with regard to both their lengths, in kilometres, and time, in years), from the Sun outward. The relative sizes of the planets are also shown. Pluto was downgraded in 2006 to a planetesimal in the Edgeworth-Kuiper Belt.



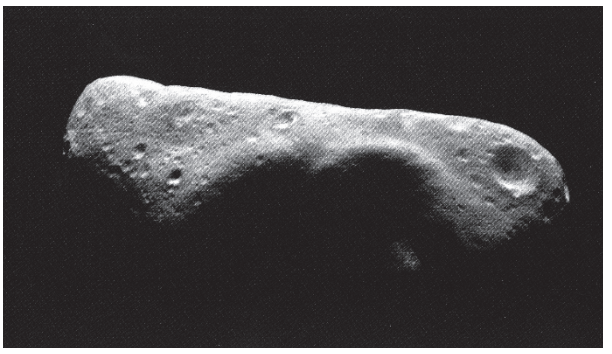
Our Solar System

The arrangement of the Sun and the planets in our Solar System (Fig. 14) is similar to a giant rotating disk, with the Sun situated in the centre. All the planets move in the same direction around the Sun, and they lie in approximately the same plane. Most planets also spin on their own axes. There are two types of planets: the Inner Planets, also known as the Terrestrial Planets, those closest to the Sun, are Mercury, Venus, Earth and Mars. These planets are relatively small and have high density. The Outer Planets, known as the Gas Giants, are Jupiter, Saturn, Uranus and Neptune and, as their name implies, are much larger and have densities of less than a quarter of those of the Terrestrial Planets. The outermost body in our Solar System, Pluto, is small and composed of rock and ice, and is not considered an actual planet; its orbit is distinctly inclined to the orbits of all the other planets, and it occasionally swings between the orbits of its closest neighbours, Uranus and Neptune. The smaller, denser Inner Planets are mostly composed of rock and metal, whereas the low densities of the Gas Giants are the result of their composition of mostly hydrogen and helium, besides ices of water, methane and ammonia. Our Sun is about one thousand times heavier than all the planets of our Solar System together. Moons (satellites) are bodies larger than five miles (about 8 km) across that orbit around a planet in fixed trajectories. Earth has one moon (the Moon), Mars two (Phobos and Deimos), Jupiter 16, Saturn 18, Uranus 15, Neptune 8, and Pluto one (Charon).

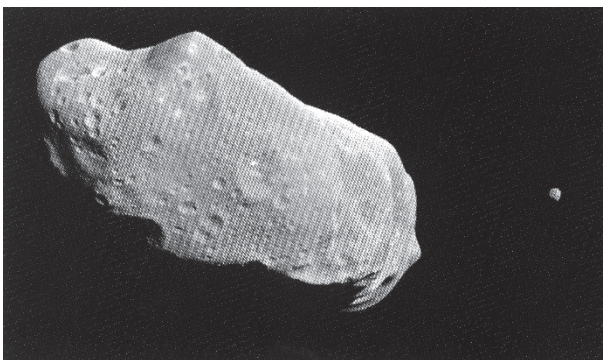
In addition to the planets and Pluto, there are countless so-called asteroids (Fig. 15) in the Solar System. The largest known asteroid is 1 Ceres, of 933 km diameter. Four thousand asteroids have been named to date, but it is estimated that tens of thousands of them exist, with most much smaller than 1 km in diameter, besides countless other smaller fragments. If the masses of all these bodies were combined, all the asteroids would amount to an object of no more than a twentieth of the size of the Moon.

Astronomers distinguish three main types of asteroids: (1) Near-Earth Asteroids (NEAs) include the Apollo, Aten and Amor asteroids. The Atens have orbits inside that of the Earth, the Amors cross the orbit of Mars and approach the orbit of Earth, and the orbits of the Apollos cross that of Earth. (2) The Main Belt Asteroids generally have stable circular orbits between Mars and Jupiter. (3) The third group, the Trojans, travel ahead and behind the orbit of Jupiter.

In addition, the Solar System is traversed by comets (Figs 17 and 18), comprising masses of loosely bound frozen water, ammonia, methane, carbon dioxide, and rock fragments and dust. Cores of comets may be up to 40 km in size. These bodies originate from beyond the orbit of Pluto, a vast region known as the Oort Cloud. There is also a closer source of comets, the Kuiper-Edgeworth Belt beyond the orbit of Neptune some 5 000 to 15 000 million kilometres from the Sun. Pluto is considered a large member of the objects in this belt.



↓ **Figure 15a:** The 35 km long and 13 km wide asteroid Eros, as imaged in February 2002 by the NEAR-Shoemaker space probe, giving a good example of how even asteroids have been hit again and again by bolides. Image courtesy of NASA.



↑ **Figure 15b:** At 58 by 23 km, asteroid Ida is somewhat larger than Eros. Visible at right is Dactyl, Ida's own little moon, which is thought to represent a fragment that was blown out of Ida in an impact event, but failed to escape Ida's weak gravitational field. Image courtesy of NASA.

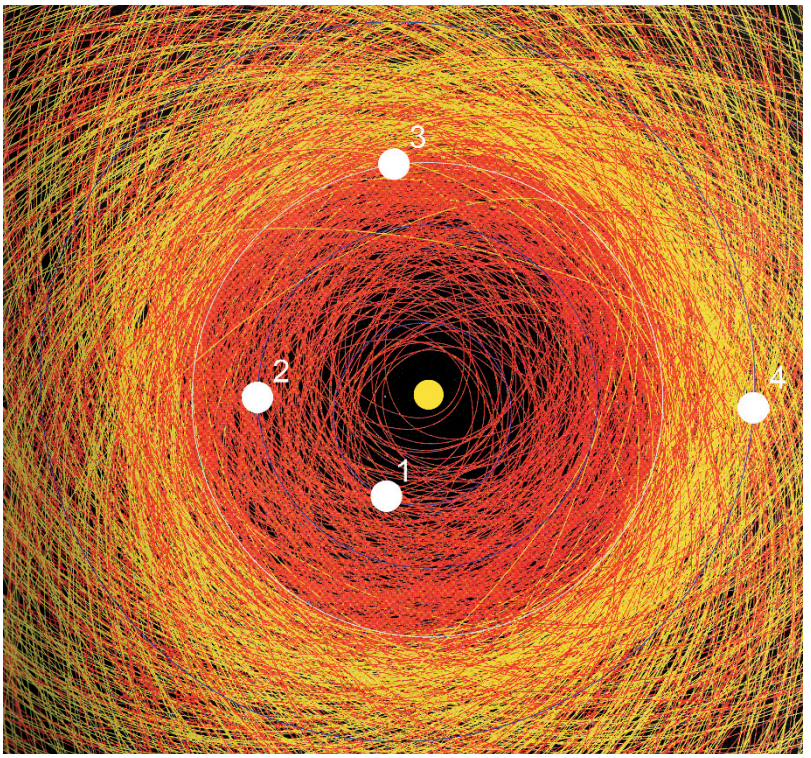


Figure 16: The orbits of the known (in early 2000) Near-Earth Asteroids, superimposed onto the orbits of the Inner (Terrestrial) Planets (1 Mercury, 2 Venus, 3 Earth and 4 Mars; the yellow dot is the Sun). The traffic density in the Solar System is quite obvious! Orbits shown with yellow lines are asteroid orbits that come closer to Earth than to Mars, but do not seem to be a threat to us at this time. However, the asteroids with orbits shown in red cross the orbit of Earth. Original image from the book 'Target Earth' by Duncan Steel, used here with the author's permission.

Figure 18: Comet Hale-Bopp, as photographed in 1997, showing its bluish tail of ionised material and white tail of dust. Image courtesy of Jet Propulsion Laboratory (Pasadena), Table Mountain Observatory.

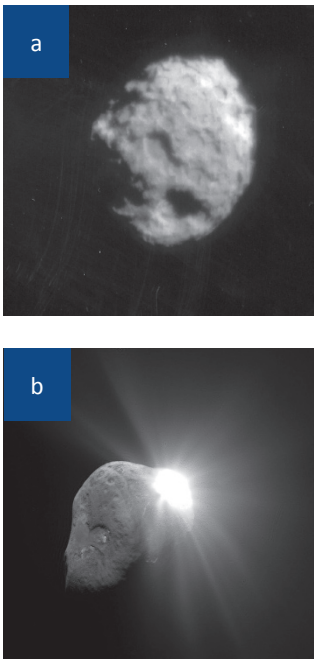


Figure 17: NASA missions exploring comets.

a. The highly irregular surface of the ca 5 km wide nucleus (core) of comet Wild 2, as imaged by NASA's Stardust mission in January 2004, may indicate a history of impact. The mission also analysed the coma of the comet and even sampled dust particles that were returned to Earth. Courtesy NASA and Jet Propulsion Laboratory (Pasadena).

b. Image taken 67 seconds after impact of a 370 kg copper sphere with the ca 6 km diameter nucleus of comet Tempel-1. The sphere was released from NASA's Deep Impact probe to investigate the composition and internal structure of a comet nucleus and the response of an ice-rich comet nucleus to an impact. The image was taken by the high-resolution camera on the mission's flyby spacecraft. Scattered light from the collision saturated the camera's detector, creating the bright splash seen here. Linear spokes of light radiate away from the impact site, while reflected sunlight illuminates most of the comet surface. The image shows topographic features, such as ridges, scalloped edges, and even possible impact craters. Image courtesy of NASA/JPL-Caltech/UMD.

Back to the beginning — from the Big Bang to early Earth

A book about the Vredefort Dome is not only about a two billion year old meteorite impact event. The catastrophic forces that ripped open the crust of the Earth have also provided a rare opportunity to examine rocks that record the preceding nearly 1 500 million years of Earth history (between 3 500 and 2 000 Ma ago). This geological information, when combined with that from elsewhere in southern Africa, provides insight into the origin and development of one of the earliest continents on planet Earth. In this evolution we see many similarities, and some differences, with the geological processes that occur today. The immense span of time also gives us a grasp of the great cycles of geology.

The oldest period of Earth history for which a geological record exists is called the Archaean ('very old'). It extends back to approximately 4 billion years; however, the planet called Earth is believed to be considerably older, about 4.6 billion years. Even this is not the beginning, because the Universe is believed to have formed with the so-called Big Bang perhaps as much as 13.8 billion years ago. The Big Bang is thought to have happened when an incredibly dense mass of matter exploded. It not only created all the matter in the Universe, but also time. Today, all matter is still expanding away from the place at which this 'explosion' occurred. With time, that matter has changed — initially only subatomic particles existed, but these soon began to combine to form protons and electrons, then simple atoms like hydrogen and helium, from which the first stars were formed. Matter is not evenly distributed through the Universe; in places, it became concentrated into galactic nebulae (for example, Figs 11a–c), which themselves contain denser concentrations of matter that evolved into stars and planets. It is estimated that the nebulae from which our own galaxy, the Milky Way, formed, began to coalesce some 10 billion years ago.

A star is created when matter accumulates and, in the core of this mass, temperature and pressure rise. Eventually a nuclear explosion may take place that causes fusion of hydrogen atoms to form helium. This nuclear reaction may go on for a long time, producing light and heat energy similar to the Sun.

However, very massive stars may evolve into a stage where they explode to form a phenomenon called a supernova. Supernova explosions can generate elements heavier than helium (oxygen, silicon, carbon, nitrogen, aluminium, iron) and produce elements even heavier than iron. The explosions spread these elements throughout a galaxy.

There are a number of theories on how our Solar System would have formed, but it is generally accepted that it formed from a gigantic, hot cloud of gas and dust, a nebula. Somehow triggered, perhaps through the explosion of a supernova, this nebula began to collapse. Matter started to rotate around a centre of gravity. Eventually the mass reached a value twice that of today's Jupiter, and the pressure in its interior made it so hot and dense that a so-called protostar formed — the weakly shining precursor of our Sun. Although the formation of the Sun took up 90 % of the original gas and dust of the nebula, much material remained and began to form a rotating disk around this newborn star. The flattened disk of leftovers became the precursor of our Solar System. As the disk rotated, the nebular dust evolved: particles began to adhere to one another — the process of accretion had begun. Larger dust particles formed, continuously increasing in size, until large bodies had been accreted. It is thought that once the protostar had reached a critical mass, the nuclear fusion process was initiated. The resulting shock wave cleansed the region of the galaxy from remaining nebular gas and dust. The larger bodies collided (impacted) and

grew further by accretion of debris, until only a small number of very large bodies remained — the planets.

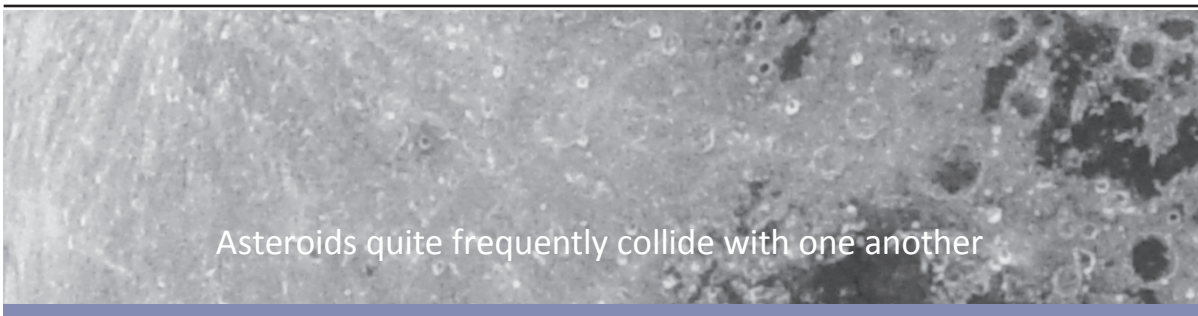
After some 100 million years, just about all the remains from the formation of the Sun had come together to form the planets of our Solar System. The rest was collected in satellites (moons) around some of the planets, and accreted to asteroids and comets.

This theory also explains why the planets of the Solar System have different compositions. With distance from the Sun, temperature decreased. The composition of the Inner Planets comprises silicate and metal, phases that form by condensation at very high temperatures. Comparatively lower condensation temperatures are required for the gases that form the bulk of the Outer (gaseous) Planets.

There is some leftover 'debris' from the formation of the Solar System in orbit around the Sun. Much of this material orbits in the so-called asteroid belt, between the paths of Mars and Jupiter. This material, in the form of particles or small planetesimals (the largest is 1 Ceres, with a diameter of 933 km), constitutes the asteroids, also called minor planets. Were it not for the gravitational pull of the huge planet Jupiter, this material might have combined to form an additional planet. Asteroids quite frequently collide with one another, and, in the early stages of the Solar System, when the number of possible projectiles was much higher than today, such collisions happened frequently. Any picture ever taken of the surface of an asteroid (Figs 15a and b) is testimony to this bombardment. Fragments of asteroids that are ejected after such impacts are known as meteoroids. Many of these have crossed the orbit of Earth and have entered the atmosphere of our planet. If they made it, in pieces, through the atmosphere to hit the ground, these chunks are known as meteorites. The study of meteorites has provided us with much immensely valuable information on the evolution of the Solar System — right back to its very beginning, and has even revealed tiny particles that predate the Solar System entirely (so-called presolar material).

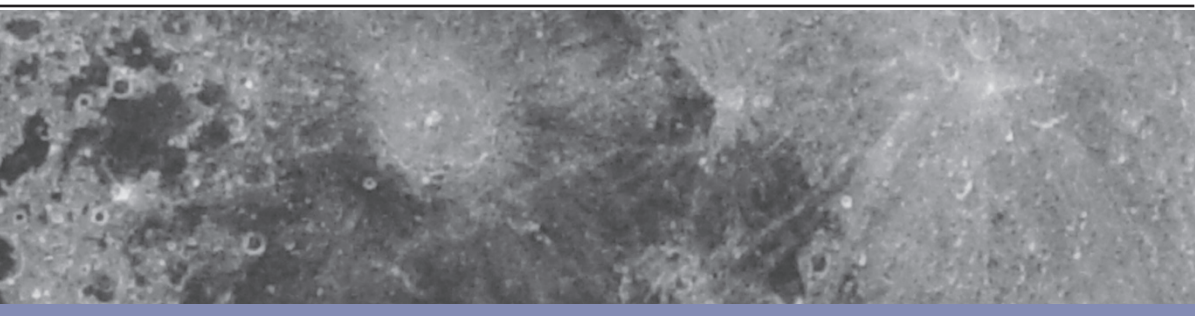
Some asteroids are large enough to internally differentiate, to form different zones in their interior. Causes for this could have been heating through radioactive decay or because of heat conduction in intense early magnetic fields. Thus, our meteorite collection represents a wide variety of materials, including samples of cores, mantles and crusts of planetesimals, as well as materials generated by impacts or by magmatic activity on the larger bodies.

It is highly likely that other planetesimals were entirely destroyed in massive collisions. Our Earth, too, may have had a narrow escape. One theory about the origin of our unusually large Moon (for a planet the size of Earth) is that Earth received a glancing blow from a Mars-sized asteroid that was sufficiently slowed by the impact to be unable to escape the gravitational field of Earth. Much of the interior of the impactor combined with some Earth debris to form the Moon, whereas a small fraction was incorporated into Earth. This explains why the two bodies have distinctly different bulk chemical compositions.


Asteroids quite frequently collide with one another

Impact –
the ubiquitous process

During the earliest phase of accretion of planetary material — first only atomic matter, then dust particles, and eventually larger and larger bodies — impact processes played a major role. Any collision between two or more entities (atoms, dust grains, planetesimals, planets) represents an impact event, and such collisions may result in accretion of matter from both affected bodies. During the first several hundred million years of the existence of early Earth, i.e. from just about 4.6 to about 4.0 billion years ago, Earth was subjected to an intense bombardment by various types of interplanetary matter — including rocky fragments, such as meteorites and the larger asteroids, as well as gas-rich comets. Many scientists have debated whether the rain of cometary bodies, whose mass is largely made up of enormous quantities of ice, including water ice, could have contributed to the formation of the early oceans on Earth. In addition, these repeated impact events transferred gigantic quantities of kinetic energy onto Earth, further contributing to the heat budget of the early Earth that comprised heat from the decay of radioactive elements (including potassium, uranium and thorium), which still today drives the internal dynamo of our planet.



The surface of the early Earth was a very hostile environment. A rain of lethal bolides from Space, volcanic eruptions caused by the overheated interior of the planet, massive electrical discharge on the surface, and noxious gases being ejected from volcanic eruptions might suggest it would not have been capable of supporting life. However, in the 1950s, Harold Urey and colleagues were able to demonstrate via a series of experiments that certain amino acids — the basic building blocks of life — could have been created under these conditions. As Alex Bevan and John De Laeter (2002) wrote: "Since the fabrication of complex carbon compounds, including amino acids, in laboratory experiments during the early 1950s, the image of a warm pool of murky liquid rich in carbon, hydrogen and nitrogen, occasionally struck by lightning and bathed in intense ultraviolet light, is inextricably linked with the possible origin of life".

The possibility that organic life may be able to develop in such exotic environments, including in warm and moist nooks of impact craters, is the driving force behind much of the current astrobiology and life-in-exotic-places programme. This programme searches for evidence of life in such diverse places as in deep gold mines, in lakes below the ice of the Antarctic continent, in meteorites, in impact crater deposits, and on Mars.

The oldest rocks

The formation of Earth and the other planets was probably relatively rapid, occurring within a hundred million years of the formation of the Solar System. At the time, the heat generated by gravity-driven collapse, the decay of radioactive elements in the Earth, and large bolide impacts, would have ensured a largely molten planet. However, by the end of this period, the planet would have strongly differentiated into a dense nickel-iron core and surrounding mantle, with a thin crust of less-dense rock. Over the next 500 million years, differentiation and cooling continued, producing a progressively thicker crust. This period of Earth's history is justifiably called the Hadean (after the ancient Greek mythological Hades, the fiery hell of that culture), in reference to the ferocious temperatures that prevailed. Tiny crystals of the mineral zircon ($ZrSiO_4$), from a very early granitic rock from western Australia that was eroded and then deposited into a younger sedimentary rock, have been radiometrically dated at 4 300 Ma. They represent the oldest evidence of Hadean crust on Earth. Actual rocks this old, however, have not yet been recovered and appear to be lacking, suggesting that the violence of internal convection within the Earth and continued meteorite bombardment of the planet conspired to destroy the early crust that was largely assimilated back into the mantle. Very little old crust (older than about 3 600 Ma) has been found on Earth: only a few isolated crustal fragments in Australia, Canada and Greenland are known to date, and only one exposure in the Slave Province of Canada has been dated at 4 100 Ma.

← **Figure 19:** The familiar face of the Moon, as photographed by the Apollo 11 crew on their way home, after having achieved the goal to land men on the Moon on 20 July 1969. The dark maria and lighter highlands are clearly distinguished, and relatively young impact craters with well-preserved rays of ejecta are visible in various sectors of the image. Image courtesy of NASA.

However, ongoing research will likely push back the age of the oldest rocks on Earth.

In contrast, the smaller Moon cooled more rapidly, and the suite of Lunar samples brought back to Earth by the astronauts of the Apollo Space Programme contains quite a number of samples from this earliest period. The sample suites returned from the Lunar Highlands contain a large number of rock fragments that formed from their precursor rocks by meteorite impact and that have been dated between 3 800 and 4 100 Ma; some even older igneous rock fragments, formed by magmatic processes, have been dated as well.

An idea can be formed of the intensity of the meteorite bombardment suffered by the early surface of the Earth if one looks at the Moon. The surface of the Moon is largely unchanged; the Moon is not a dynamic body, and still bears the scars of impacts that are billions of years old. The oldest crust, the Lunar Highlands, displays a much higher proportion of craters than the Lunar mare areas, where the crust is younger than 4 000 Ma (Fig. 19). However, by 4 000 Ma ago, the number of remaining asteroids and comets that had not collided with a planet (or that had not been trapped by one yet) started to decline and impacts became far less frequent. At the same time, it appears that Earth had cooled sufficiently to allow at least a little crust to survive.

The recent close flyby of NASA's Messenger probe past Mercury has demonstrated that, like the Moon, the crust of this planet is very old, as is evidenced by the extreme density of impact structures on the lunar surface (Fig. 53, page 69).

Contrary to Earth's earliest rock record, most ages obtained by the dating of meteorites show that they are nearly as old as the Solar System — 4.56 billion years. This indicates that the planetary bodies, on which these meteorites originated (the so-called parent bodies), were in existence and had already differentiated within a few million years of the formation of the Solar System.

In contrast to those few areas in other parts of the world where 'oldest rocks' have been detected, the oldest known rocks in southern Africa are 'only' approximately 3 500 Ma old. They are, however, far more extensive, and better preserved, than the small fragments of old crust elsewhere. Collectively, this assemblage of Archaean rocks in South Africa is referred to as the Kaapvaal craton (craton is the word for a stable, consolidated continental mass), and the Kaapvaal craton is widely believed to represent one of the first continents on Earth. Much of the craton is now buried beneath younger rock formations (Figs 21 and 23); however, the Archaean rocks are well exposed in the eastern and northeastern parts of South Africa (especially in the Mpumalanga and Limpopo provinces). Together with somewhat younger (only 3 200–2 900 Ma old) Archaean formations that mostly occur in the Gauteng and North West provinces, and that include the Vredefort Dome, these rocks provide the most comprehensive record of geological events of the early Earth.

Figure 20: The sequence of rock layers ('strata') that formed on the Kaapvaal craton between about 3 000 and 2 100 Ma ago, in order of age, with the principal stratigraphic names indicated.

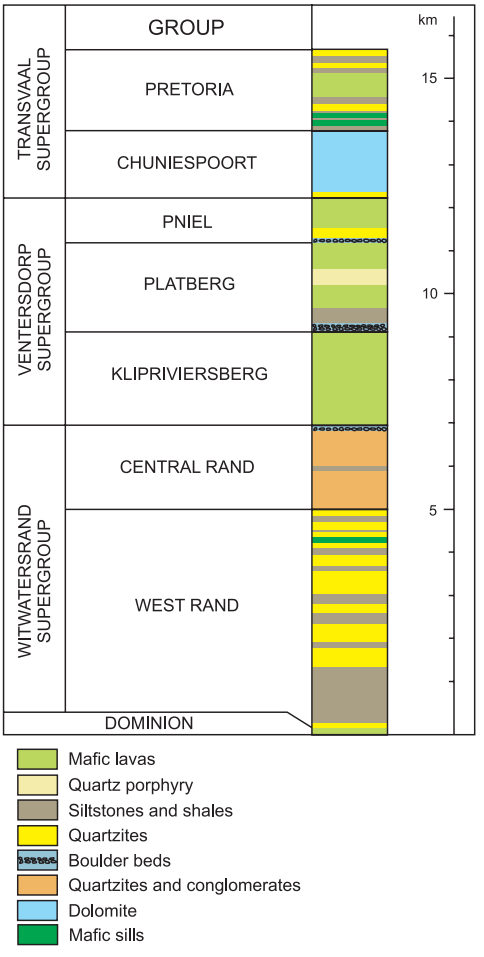
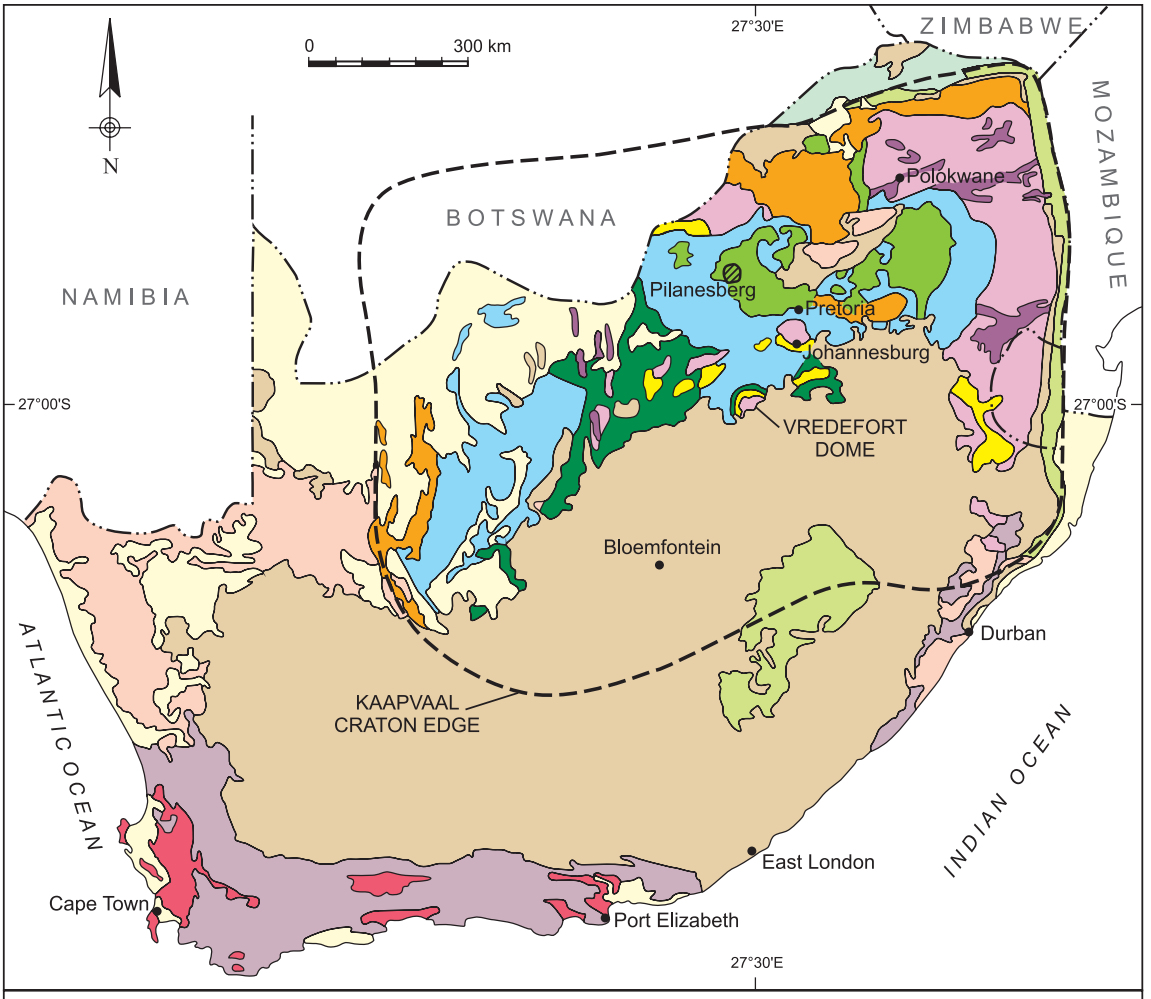


Figure 21: Simplified geological map of the southern African subcontinent, showing the distribution of the major stratigraphic classifications. The thick dashed line indicates the approximate outline of the Kaapvaal craton, one of the earliest continents on this planet.



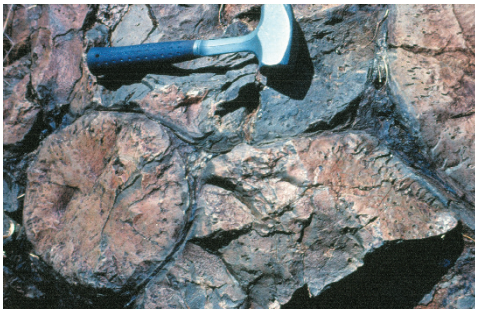
Time to cool —
birth of the Kaapvaal continent

As the temperature of the interior of the Earth was lowered in the Hadean period, the rate of upwards heat convection slowed. This, in turn, reduced the rate of destruction of the thin, initial volcanic crust. Remnants of lavas dating from this time, with distinctive bulbous pillow-like shapes (appropriately called pillow lavas) that indicate eruption underwater, can still be found in the Komati River valley near Barberton (Fig. 22). Estimates of the eruption temperature of these lavas, which are called *komatiites* after the Komati River valley where they were first discovered, range from 1 400 to 1 650 °C. This is significantly hotter than modern-day basaltic lavas erupting on the sea floor (~1 100–1 200 °C), which indicates that the temperatures in the interior of the Earth were much hotter in Archaean times than they are today.

In places, collisions occurred between pieces of this thin early crust; they were rammed together as a result of flow in the underlying mantle. Some geologists believe that as water-rich crust was subducted, it started to melt at temperatures of about 750–800 °C, producing silica-rich partial melts, which, because of their lower density compared with the komatiitic crust, could rise upwards (Fig. 5b). Others suggest that collision thickened the crust, which nonetheless remained buoyant (there is much debate among geoscientists why such crust might have remained buoyant; suggestions range from the presence of large amounts of water in the rocks, to the preponderance of lighter magnesium over heavier iron, to the temperature of the crust — hotter rock is less dense than colder rock). As the volcanic crust thickened, two important things would have happened: (1) For the first time, rocks were exposed above sea level, providing an environment that could allow weathering and erosion, and, thus, the formation of the first sediments; and (2) the most deeply buried levels of this crust were forced to greater depths, where the average temperature was higher than closer to the surface. Consequently, this crust heated up and started to melt, producing relatively less-dense, silica-rich rocks that rose upwards towards the surface, where they encountered cooler ambient temperatures, and solidified. Once such buoyant material existed, it became physically almost impossible to drag this crust back into the mantle for recycling — *the first continent had been born*.

Given the fact that the Earth's mantle was hotter in the Archaean because of the higher heat flow at the time, it is highly probable that heat convection and associated flow of magma in the mantle were very vigorous. Thus, these early, buoyant continental nuclei were repeatedly rammed by other pieces of crust. In the process, they would have been thickened, and their deep root zones melted. Not only the lavas melted — the early-formed sediments and the silica-rich rocks (typical rock types are tonalites and trondhjemites, compare Glossary) themselves experienced renewed melting during these younger events, which led to the formation of the first granites.

In this way, through tectonic processes and partial melting producing new volumes of buoyant crustal material, our continent, the Kaapvaal craton, grew both in size (laterally) and thickness (vertically), with slivers of oceanic crust and sedimentary rocks, collectively referred to as greenstone belts (the now altered lavas have a distinctly greenish colour), trapped between

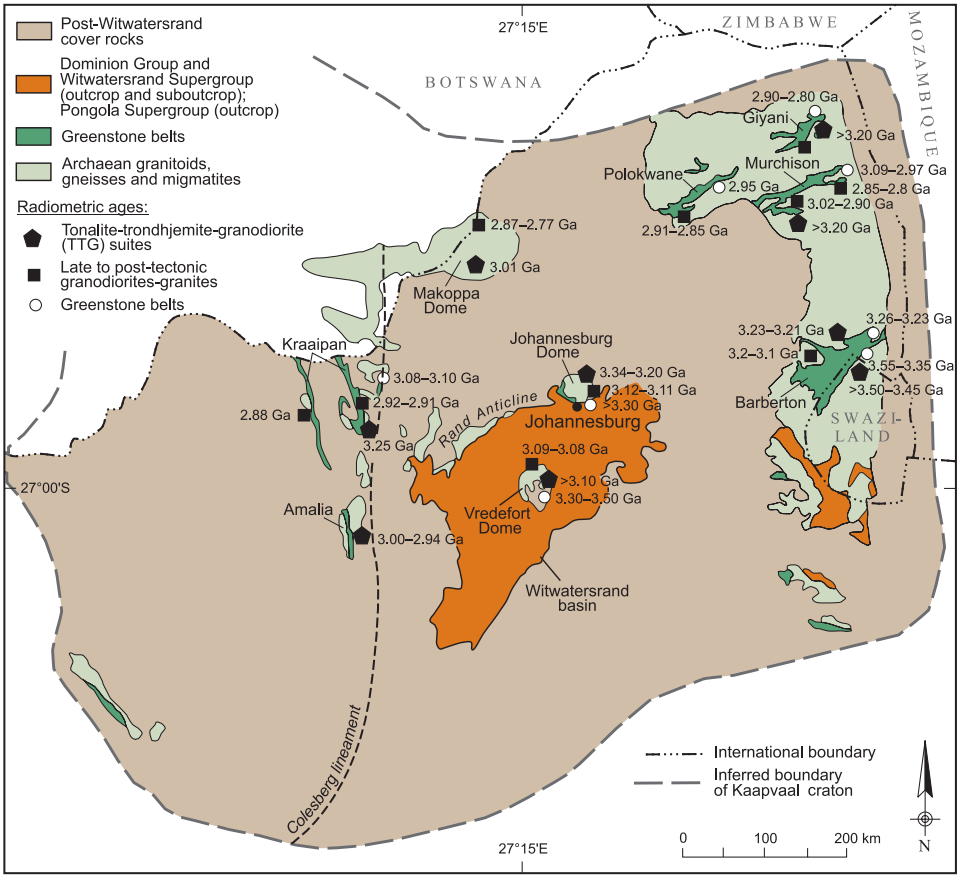


← **Figure 22:** A fine example of pillow lava from the Barberton Mountain Land (ca 3 500 Ma old). Photograph courtesy of Carl Anhaeusser, University of the Witwatersrand.

plutons (large, magmatic intrusive bodies) of crystallised silica-rich melts.

By measuring the amounts of radiogenic isotopes (radiometric dating) in rocks and minerals, it has been possible to calculate the ages of the rocks in the different parts of the craton. The oldest rocks of the Kaapvaal craton (Fig. 23), which are ~3.5 billion years old, are found in the vicinity of Barberton (Mpumalanga Province). In contrast, the rocks in the vicinity of Johannesburg and Vredefort are ~3.3–3.1 billion years old, whereas near Schweizer-Reneke, in North West Province, they are 3.1–3.0 billion years old; those around Polokwane (Pietersburg) and Murchison in Limpopo Province are 2.9–2.7 billion years old. This variation may indicate that the initial continental nucleus of the craton was formed from the rocks in the Barberton region and that, over a few hundred million years, younger rocks were added along the margins of this first continental nucleus. It has taken geoscientists a long time to unravel this history of a billion-and-a-half years, and which involved many successive stages of tectonism and magmatism. Such old rocks on Earth also have been subjected to one or more stage(s) of metamorphism, in which burial or uplift and heating or cooling of the rock cause it to form different minerals that are stable under the new conditions. In a craton as old as the Kaapvaal craton, it would be very unusual to find any such old rock that has not undergone at least one stage of metamorphism — a real challenge for the geologist trying to unravel Earth's early history.

Figure 23: Simplified geological map of the Kaapvaal craton, showing exposed greenstone belts and radiometric age data (from Eglington and Armstrong, 2004).



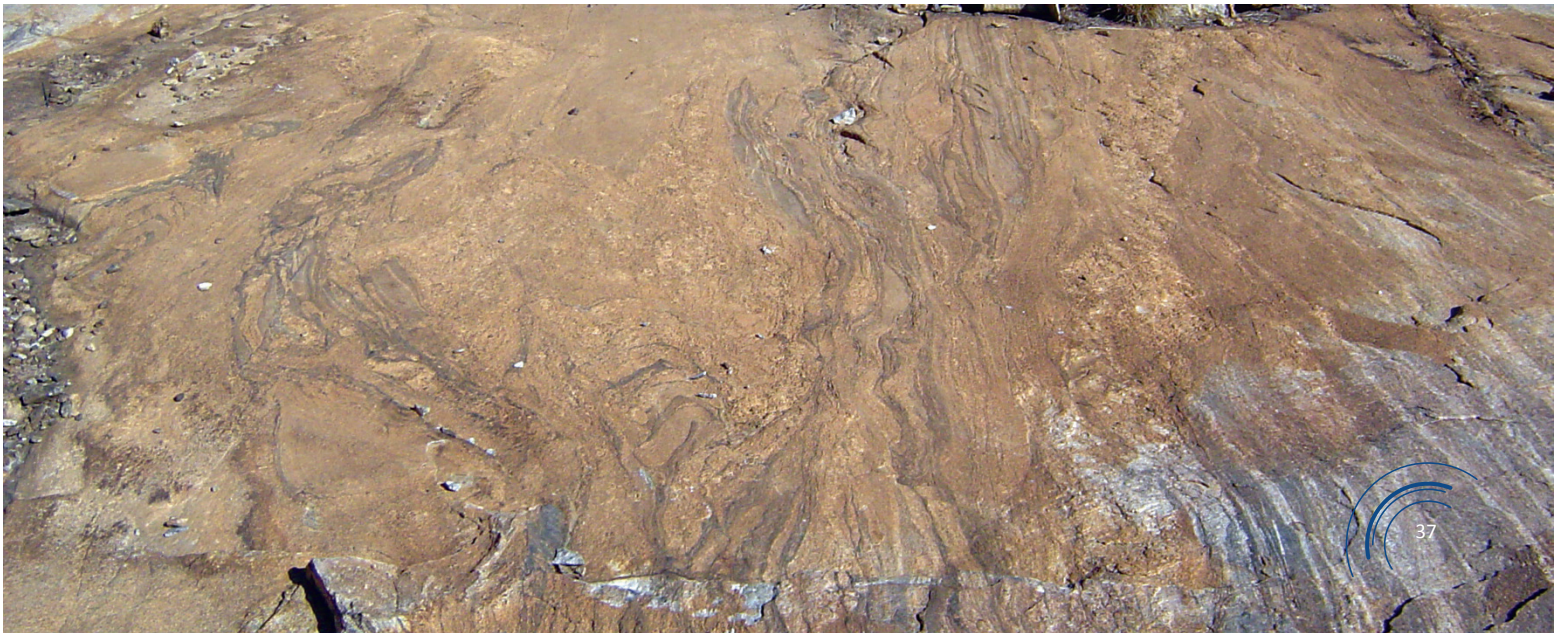
Old crust in the Vredefort Dome

The rocks in the Vredefort Dome (Fig. 86, page 131) show many aspects of the early history of the Kaapvaal craton. Metamorphosed komatiitic lavas, locally still showing pillow structures (Fig. 175, page 249) that could be as old as 3.5 billion years, are preserved in the southeast of the dome, in an area near the Greenlands railway siding, east of the town of Koppies in Free State Province. Elsewhere in the dome, old greenstone material has survived only as scattered remnants of metamorphosed sedimentary rocks and metamorphosed lavas in the area just south of the towns of Parys and Vredefort. The entire succession of Archaean lava and sediments, and tonalitic, trondhjemitic and granitic formations can be observed in the excellent exposures of crust in the dome. Tonalitic and granitic melts show chemical evidence of having been derived from the older trondhjemitic rocks that dominate the area.

Collectively, the rocks that underlie the core of the Vredefort Dome are referred to as the Archaean Basement Complex. These Archaean rocks in the central parts of the dome provide ample evidence for melting and very high-temperature metamorphism (up to ~875 °C). These rocks also preserve evidence of repeated deformation by tectonic forces that probably led to thickening of the crust and formation of mountain belts (orogens) when continents collided.

The last major period of melting and deformation in the Archaean Basement Complex of the Vredefort Dome occurred ~3.1 billion years ago, at which point a major mountain belt or chain of volcanoes must have existed in the region. Evidence of diamonds of this age that have been found in some of the kimberlite pipes in South Africa indicates that, by this time, the Kaapvaal continent was underlain by a thick keel ('rocky root') of more-dense rocks (so-called eclogite and harzburgite) that extended down to a depth of at least 120 km. At such depth, pressures are sufficiently high for carbon in the structure of the mineral graphite to convert to the diamond crystal structure. After this event at 3.1 billion years ago, it appears that the tectonic forces acting on the craton changed from compression to extension (i.e. the crust was no longer compressed, but was pulled apart). This had the consequence that the craton started to stretch and become thinner. Together with erosion, this had the effect of dramatically lowering the land surface within a few tens of millions of years.

Typical migmatitic gneisses of the Archaean Basement Complex in the Vredefort Dome.

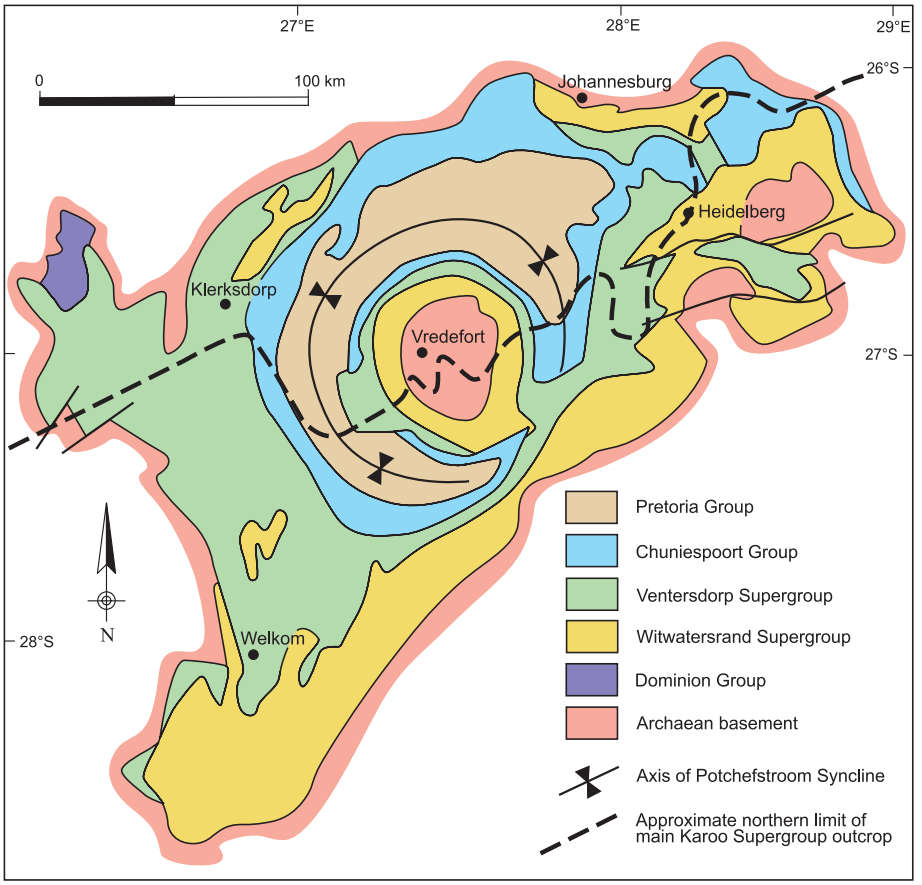


Rifting, oceans, volcanism

The stretching of the Kaapvaal craton crust caused it to break apart along large faults, which displaced some parts of the crust downwards relative to others, creating rift valleys similar to the East African Rift today (Fig. 30, page 45). Large volumes of basaltic and granitic magma rose upwards along these faults and erupted at the surface, forming volcanoes, while rivers deposited gravels and sandy sediment from the high-lying areas into the rift valleys. Collectively, these lavas and sediments are known as the Dominion Group. In the Vredefort Dome they are represented by a thin layer of lavas, only locally up to 250 m thick in the northwestern part of the dome, but dwindling to nothing in the southern and eastern parts. However, near Klerksdorp, to the northwest of the dome, they form a sequence exceeding 2.5 km in thickness (Fig. 24), indicating that a deeper rift basin existed here. The lavas in the dome still contain volcanic features, such as the so-called amygdales, which formed when small bubbles of water became trapped in the crystallising lava flows. Although no evidence exists of new oceanic crust having formed as a result of this rifting event, it is possible that parts of the Kaapvaal continent were split off in other places and that a new ocean formed between the rifted (separated) fragments. The Dominion Group rocks are 3 070 Ma old.

Over the following 350 million years (ca 3.07–2.71 billion years ago), the central parts of the Kaapvaal continent around Johannesburg and Vredefort appear to have been dominated by a shallow sea. One theory about the origin of this sea is that cooling of the craton, following the heating of the crust and underlying mantle during the Dominion event, caused the rocks to, quite literally, shrink. This, in turn, caused the surface to subside below sea level over a much wider area than the extent of the original rifts. An alternative view is that collision of the continent with another continental mass could have warped the crust downwards to form a basin adjacent to the zone of thickened crust at the margin where the collision occurred. Evidence that such collisions were taking place at this time exists along the northern and western margins of the craton, where the Pietersburg, Murchison, and Amalia–Kraaipan greenstone fragments, and related tonalites, trondhjemites and granites, were forming (Fig. 23). The collisions thickened the crust in these areas, forming mountains which, in turn, would have been eroded, releasing large amounts of sediment into rivers that, ultimately, would have been deposited into the nearest sea.

The initial sediment deposited about 2.97 billion years ago into this Witwatersrand Sea shows clear evidence of having entered the sea from the west and northwest, suggesting that the high ground lay in that direction at the time. The rocks of the Witwatersrand Supergroup (the entire sequence of rock deposited into this basin; Fig. 24) preserve tell-tale signs of having been laid down underwater or along beaches. Several cycles of shale (rock formed from silt and clay) and quartzite (the rock formed from deposition and consolidation of sand-sized particles of the mineral quartz) can be identified in the sedimentary sequence (Fig. 20). They testify to changes within the basin over long periods of time: the muds that ultimately solidified into shales probably formed farther from the coast in deeper water, where currents were weak or non-existent (as extremely fine-grained clay will not settle out if the water is too agitated). In contrast, the very pure quartzites would have formed along shorelines where waves and strong currents were able to winnow out the finer clay and silt, leaving a pure quartz sand. Today, nearly 3 billion years later, it is still possible to see the single grains of sand that lay along this ancient sea shore, and to determine the directions in which currents were flowing at the time from preserved sand ripples (see Fig. 190a).



← **Figure 24:** Simplified geology of the Witwatersrand basin around the Vredefort Dome, showing regions of Archaean crystalline basement (older than 3 070 Ma) as well as the main groups and supergroups deposited on top of it between ca 3 070 and 2 100 Ma. Note the northern limit of the Karoo Supergroup cover, with geological information to the south of it only known from drilling and geophysical analysis.

The cycles of sand and mud reflect movement of the ancient shoreline back and forth, over millions of years, either in response to changes in global sea level or to rise or fall of the land surface caused by geologic forces, or to different rates of sediment influx into the basin. By approximately 2.9 billion years ago, an up to 4 km thick pile of sediment had accumulated in this sea, forming what we now call the West Rand Group, the lower portion of the Witwatersrand Supergroup (Fig. 20). The thickness of sediment does not mean that the sea was originally 4 km deep; most likely the forces unleashed by collision along the continental margin triggered slow downwards warping of the surface of the continent over a large area, through this time interval. Alternatively, the weight of a thick layer of sediment deposited onto the crust may have caused it to flex downwards, forming a basin, which subsequently allowed more sediment to be deposited on top of the earliest layers.

Included among these sediments are banded ironstones, a rock type composed of alternating layers of quartz-rich (so-called chert) and iron-rich sediment. The iron and silica precipitated (settled out) from the seawater. There are also several layers of so-called diamictite, a rock formed from sediment dumped by glaciers or icebergs into oceans. Although they are now mostly overlain by younger rocks, the West Rand Group rocks are responsible for much of the spectacular and scenic terrain in the Vredefort Dome and elsewhere in the surrounding region, such as along the Witwatersrand Ridge between Germiston and Krugersdorp. The name of the entire region (Witwatersrand) is derived from the name of this ridge.

At ~2 900 Ma ago, however, the pattern of sedimentation in the Witwatersrand Sea changed. Mud layers largely disappeared and were replaced by coarse quartz sands and thin layers of even coarser gravels. What makes these gravels (now solidified, they are called conglomerate — Fig. 195, page 269; Fig. 197, page 271) so special is that, in addition to the large quartz pebbles which may be several centimetres in size, they contain minute grains of gold on such a scale that an estimated 45 % of all the gold ever found on Earth lies in them. In addition to the gold, they contain large quantities of the iron mineral pyrite (also known as 'fool's gold'; composition: FeS_2) and an uranium-bearing mineral called uraninite (composition: UO_2 to UO_5). The significance of both these minerals is that they react readily with oxygen, becoming weathered, and, hence, are not commonly preserved in modern sediments. Their abundance in the ancient Witwatersrand conglomerates is, thus, a key indicator that oxygen levels in the atmosphere of that time were still insignificant compared with today. In all probability, the atmosphere was a toxic mix of chemicals capable of dissolving rock at unprecedented rates when combined with water, which would have contributed strongly to the production of these vast amounts of sediment.

The sedimentary features in the quartzites and conglomerates indicate that the sediments were deposited along the shoreline of the Witwatersrand Sea, and in rivers flowing from nearby mountains to the northwest and west of the shore. The large size of the pebbles indicates that these rivers must have been strong flowing in order to be able to move these large, rather heavy components. This, in turn, suggests that the mountains were very close. The source of the gold must have lain in these mountains. The closest modern analogue to such a geological setting appears to be the New Zealand Alps, where fast-moving rivers flow from steep ravines onto a narrow coastal plain. Here, a combination of extreme weather, strong currents and wave action removes the finer sediment, leaving behind the coarser, and denser, gravel. Detailed reconstructions of large fan-shaped sediment piles, spreading out from very narrow sources, confirm that the Witwatersrand rivers must have been locked into steep-sided valleys that emptied quite suddenly onto a coastal plain.

At times, the buckling and thrusting that was responsible for creating the mountains along the northwestern and western margin of the Witwatersrand Sea actually affected the sedimentary rocks already deposited in the basin. Evidence from the gold mines indicates that these layers were repeatedly tilted upwards along the western and northern margins of the basin, exposing them to renewed erosion. In the process, the gold from older conglomerate layers was incorporated into the younger sediments, enriching them even further. In this way, with repeated movement of the shoreline back and forth, some 2 km of sediment was deposited. These rocks are now known as the Central Rand Group, the upper portion of the Witwatersrand Supergroup (see Fig. 20).

Deposition of the Witwatersrand gold reefs continued until about 2.7 billion years ago. Right at the top of the Witwatersrand Supergroup is the position of one of the most important ore horizons, the Ventersdorp Contact Reef. At the time, the geological forces that had compressed the Kaapvaal continent were reversed and another period of extension (stretching) followed. This split the craton apart along a series of major fractures. Huge quantities of magma flowed up these fractures to the surface, ultimately flooding across large parts of the continent as fissure eruptions. The so-called Ventersdorp lavas thickly covered vast areas of the continent. As for the Dominion event some 350 million years earlier, a series of rifts formed. However, both the extent and the volume of lava deposited within the Ventersdorp rifts dwarf the earlier Dominion event. This Ventersdorp extrusive event appears to have lasted for no more than a few million years, but, by the end, an average of 2 km of basaltic lava covered an area of more than 100 000 km^2, and the rifts contained an additional up to 3 km thick sequence of slightly younger, relatively more silica-rich lavas (of the type known as rhyolite) and sediments.

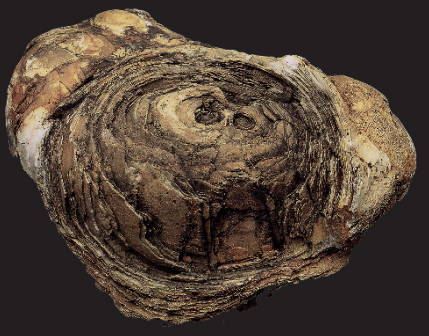
The Ventersdorp lavas cover large areas to the west of Potchefstroom, towards Kimberley. They represent one of the great flood-basalt events in the history of Earth, rivalling the equally famous Drakensberg event that occurred ~180 Ma ago.

At that time, Africa, Antarctica, South America, Australia and India had combined on their plate wanderings to form a huge supercontinent known as Gondwana ('Land of the Gond'). But, at 180 Ma ago, this continent started to split apart, and at the rift zones vast outpourings of magma occurred (Fig. 6, page 21 and Fig. 44, page 61). As with the Dominion event, there is no evidence whether the Ventersdorp event triggered the formation of new oceanic crust. By the time the Ventersdorp event was over, the source of the gold had disappeared and the unique conditions that had created the Witwatersrand gold reefs were gone forever.

There is some debate about whether, as with the smaller Dominion rifting and volcanic event, the cooling of the continent, after the extrusion of the Ventersdorp magmas, led to shrinking of the crust, thereby creating a broad basin below sea level; or whether the huge basin that developed after the Ventersdorp event was related to a younger subsidence event. The problem lies with the inability of geologists to date sedimentary rocks in the same way as they are able to do with igneous rocks: the problem with sediments is that they contain mineral grains derived from older rock — and often from many different older rocks. Thus, sediments could be mixtures of material from a number of sources of different ages. In contrast, all grains in an igneous rock crystallise at the same time, which, in favourable circumstances, allows geologists to date them. We, therefore, do not know whether sedimentation started immediately after the volcanic Ventersdorp event, or perhaps some 100 million years later.

By approximately 2 650 Ma ago, however, it appears that much of the Kaapvaal continent, from today's Northern Cape region to Limpopo Province and eastward to Mpumalanga, was relatively flat. This land surface was drowned as the sea encroached and, ultimately, was covered by a thin, but very extensive, sand and mud sequence now known as the Black Reef Formation. Within these sands are thin gravel units that contain traces of gold that have been mined in places. The sea of this time is known as the Transvaal Sea, and the sediments deposited into this basin as the Transvaal Supergroup (Fig. 20, page 33).

→ **Figure 25:** An example of stromatolites (algal colonies) growing now in shallow ocean water at some places along the western Australian coast (here, at Hamelin Pool). Image courtesy of Grant Cawthorn, University of the Witwatersrand.



→ **Figure 26:** A 30 cm wide stromatolite (dome-shaped algal growth feature) from the Malmani dolomite at a location west of the Vredefort Dome. Image courtesy of Dr Gero Kurat, Naturhistorisches Museum, Vienna (Austria).

→ **Figure 27:** A typical example of stromatolitic growth in dolomite of the Malmani Group of the Transvaal Supergroup, on the farm Dewetshof in the western outer collar of the Vredefort Dome. Hammer length, for scale, 35 cm.

Slow subsidence of the sea floor over the following 150 to 200 million years created ideal conditions for the growth of cyanobacteria in the shallow waters. These primitive organisms extracted carbon dioxide from the seawater as part of their photosynthesis process, releasing oxygen as a waste product. This changed the seawater chemistry and caused the depo-

sition of dissolved calcium from the water as calcium carbonate; while, in deeper water, soluble iron and manganese were dumped in immense quantities from the water when the oxygen reacted with them to form oxides. These huge iron and manganese formations of the Transvaal Supergroup are particularly well preserved around Thabazimbi in Limpopo Province, in the Northern Cape Province in the area of Sishen, and in the so-called Kalahari Manganese Field around Hotazel. The iron and manganese resources of South Africa are world class, but the manganese deposits are of particular importance: the total ore reserve in this country is estimated at approximately 50 % of that of the entire world. Similar, smaller deposits are found elsewhere around the world. All seem to have been formed prior to 2 100 Ma ago. This important observation is interpreted as the time when the supply of soluble iron and manganese in the oceans of the world was exhausted and oxygen levels in the atmosphere were able to increase. Increased oxygen levels allowed the development of more advanced life forms within the oceans that were able to use oxygen to generate energy, and signaled the beginning of the end of the cyanobacteria as the dominant life form on this planet, a position that they had held unchallenged for nearly two billion years.

Traces of the cyanobacteria in the Transvaal Sea are preserved as distinctive features called stromatolites, which display a range of shapes and sizes in accordance with their location relative to sea level (Figs 25–27). In the intertidal zone of coastlines, the organisms formed continuous flat mats. Below sea level, the size of the bacterial colonies, often forming distinct dome shapes, increased with increasing water depth. The shapes of these colonies varied, depending on current strength and direction. These algal growth forms were continually covered by the chemical sediment that was precipitated from the seawater, which required the bacterial colonies to grow upwards, explaining the strongly layered structure of these growths. Over time, the sedimentary ooze solidified and reacted with magnesium to form dolomite, a mineral of the composition $MgCa(CO_3)_2$, while silica was deposited along cracks and in layers to form ultrafine-grained chert. This process caused the fossilisation of the colonies into what we now call stromatolites (Figs 25–27).

Around 2 400 Ma ago, the continent was compressed again and its land surface was pushed upwards, thereby exposing the dolomites and cherts at the surface. As a result, weathering of the dolomites commenced. Rainwater combined with carbon dioxide in the atmosphere, forming a mild acid that reacted with dolomite. This acid dissolved the dolomite but left the insoluble chert behind as a rubbly breccia ('chert breccia') that can be found in rock layers in many places on the Kaapvaal craton. The entire stack of largely chemical sediments (carbonate rock, and iron and manganese stone) collectively forms the Chuniespoort Group of the Transvaal Supergroup.

The Transvaal dolomites contain a large number of caves that were formed quite recently in geological time, owing to the dissolution of carbonate by groundwater. Some of these caves acted as death-traps for early hominins and other species. They include such important palaeo-anthropological sites as Sterkfontein, Kromdraai, Swartkrans, Makapansgat and Taung, which have made South Africa world famous as the 'Cradle of Humankind'.

Some time after the deposition of the chemical sediments, by about 2 350 Ma ago, large parts of the Kaapvaal craton were once again below sea level, and other parts were rising rapidly to form

ideal preservation of early hominins and other species

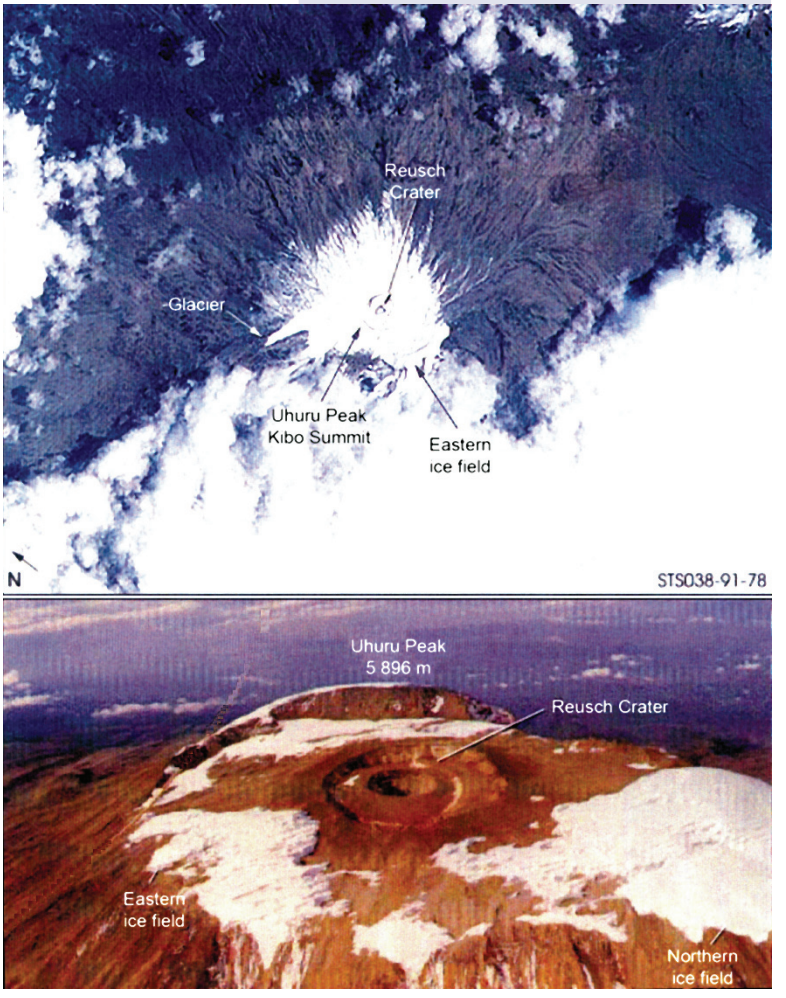
new mountains to the north, possibly as a result of collision of the Kaapvaal continent with other continents in its environs. The large amount of sediment eroded from these mountains was deposited into the sea as sand and mud layers, which today form the quartzites and shales of the Pretoria Group of the Transvaal Supergroup, best seen in the Magaliesberg mountain range between Pretoria and Rustenburg and, to a lesser extent, along the Old Potchefstroom road west of Johannesburg, where the Timeball Hill rocks form a prominent ridge.

Summary of the stratigraphy (the rock record) of South Africa

Time [million years]	Event	Important areas
3 600–2 900	Formation of Archaean Kaapvaal craton	Barberton Mountain Land, Murchison and Pietersburg greenstone belts, basement in the Vredefort Dome
3 074	Dominion rifting	Vredefort, Klerksdorp area
3 000–2 700	Witwatersrand sedimentation and Witwatersrand gold deposition	Witwatersrand basin, Pongola region of KwaZulu-Natal
2 700	Ventersdorp rifting	Northern Cape to Gauteng
2 650–2 150	Transvaal sedimentation: major iron and manganese ore deposits, oxygen increase in atmosphere	Northern Cape, Limpopo Province, Mpumalanga
2 060	Bushveld magmatism: platinum-group metals, chromium, vanadium	Bushveld Complex of Limpopo and Mpumalanga provinces
2 020	Vredefort impact event	Witwatersrand basin region
ca 1 800	Waterberg/Soutpansberg sedimentation	Limpopo Province
1 000	Collision between Kaapvaal craton and Antarctic continent	KwaZulu-Natal, Namaqualand magmatism along southern and western margin of the continent
500–300	Major mountain building (orogeny) along southern margin of the craton	Cape Fold Belt in Western and Eastern Cape provinces
300–180	Karoo basin development, ending with Drakensberg rifting	Dolerite sills and diamictites, other sediments with widespread fossil heritage throughout central part of South Africa
since 70	Namib and Kalahari deserts	

Mountains, fire and ice

↓ Figure 28: Space Shuttle views of the summit area of Africa's foremost volcano — Kilimanjaro. The top photograph was taken in 1990 by the crew of Space Shuttle flight STS 038 (image STS038-91-78) showing that much of the summit area was still covered by glaciers. The bottom image by STS-97 of December 2000 provides a stark contrast, with glaciers having receded dramatically — illustrating a significant shift in global climate over only ten years. Courtesy NASA's Earth Observatory.



It is obvious from this brief discussion of the Archaean and early Proterozoic history of the Kaapvaal continent that geology, as with much of nature, has worked in cycles. In its simplest form, the geological cycle involves:

- periods of splitting apart of crust along relatively narrow rift zones, which raises hotter rocks closer to the surface and invariably triggers volcanic and other magmatic activity
- cooling of the crust, causing the land surface to subside, thus opening the way for the formation of broad sedimentary basins
- periods of compression, triggered by collision between continental fragments, which thicken the crust, thus raising the land surface and forming mountain belts close to the site of collision and deep sedimentary basins farther away.

Of course, the exact geological products of each of these phases depend on a multiplicity of other factors. We have already seen that the development of life and the development of the atmosphere have influenced the geology in different ways at different times, but variations within the larger geological cycles also play an important role: for example, the relative amount of extension achieved, or the depth of subsidence. And through it all, it is important to remember that only a fraction of the original picture is preserved in the rocks, like small pieces of a puzzle.

Today we see evidence of rifting in East Africa — a zone of active volcanoes (Figs 28 and 29) and high surface elevations, which, nonetheless, contains large and quite deep rift valleys (Fig. 30) into which sediment is being deposited. The Alps in Central Europe and the Himalayas are large mountain chains in regions where continents are colliding, and from which large volumes of sediment are being eroded and fed into adjacent seas via some of the greatest rivers of the world (for example, the Ganges River of the Indian subcontinent). Both these chains are less than 35 Ma old, which, given

→ **Figure 29:** On 17 January 2002, the Nyiragongo volcano in eastern Democratic Republic of Congo erupted and sent massive lava flows into the city of Goma. Some hundred people were killed, hundreds of thousands of residents had to flee for their lives and more than 12 000 homes were destroyed. This computer-generated image combines a Landsat image and an elevation model based on data from the Shuttle Radar Topography Mission (SRTM). It gives a three-dimensional view of the volcano and the city of Goma at the edge of Lake Kivu (in the foreground). The recent lava flows are shown in bright red. Image courtesy of NASA's Earth Observatory.

the huge time spans already covered in this chapter, indicates how complex unravelling the geological history of a region is.

In South Africa, we have to go a little further back in time to find our own Alps and Himalayas — the Cape Fold Belt mountains along South Africa's southern coast. In their youth, 500 to 300 Ma ago, these mountains probably rivalled those other, much younger mountain belts. The Cape Fold Belt mountains were formed when southern Africa collided with a continent to the south, parts of which are today preserved in South America and Antarctica. Erosion from these mountains filled one of the greatest sedimentary basins on Earth — the Karoo basin. Karoo sediments still cover almost half of South Africa (see Fig. 21). By 180 Ma ago, this collision was over and the great continent of Gondwana started to split apart, producing, at the same time, the immense Drakensberg–Lebombo flood basalts. Several other cycles of collision and mountain building, and rifting, have been identified in the southern African geological record. The interested reader is referred to the book by McCarthy and Rubidge (2005) for more detail.

The driving force for this splitting and colliding of different parts of the crust of the Earth is convection in the Earth's mantle that is driven by loss of heat from the interior of the planet. Geoscientists remain undecided on how far back in time the process of plate tectonics can be extended — some believe that the processes in the Archaean were no different from those today, with perhaps some modifications caused by the higher interior temperatures and heat flow, and the presence of smaller plates and more vigorous convection rates; others believe that the Archaean processes were significantly different.

↓ **Figure 30:** The African continent from Space. A compilation of NOAA satellite images for the entire continent (Copyright Tokai University Research and Information Centre/EDC, 2004; reproduced with permission). The great deserts of north and southwest Africa are shown in brown. Topography (different elevation) is recognisable, including the great East African Rift, from the Horn of Africa down to its offshoots into southern Africa.

The unique Bushveld magmatic event

The deposition of the Transvaal Supergroup over a major part of the Kaapvaal craton was followed by another remarkable geological event at 2 060 Ma ago. This event created what is regarded as one of the geological wonders of the world: the Bushveld Complex (see Fig. 21) in north-central South Africa. Its origins remain a subject of intense debate among geoscientists. What is known, however, is that by about 2 100 Ma ago, the influx of sediment into the Transvaal basin was dwindling and the basin was filled; it may even have undergone erosion in places.

At 2 060 Ma, the crust in the regions of the North West and Limpopo provinces and south-eastern Botswana fractured and large volumes of basaltic lava poured out onto the surface of the continent. Some of it flowed into water, as indicated by locally occurring pillow structures. This was rapidly followed by the formation of a series of immense volcanoes, from which erupted huge amounts of silicic lava, so-called rhyolite, and explosive ash deposits. These rocks, which are best seen east of Pretoria, around Dullstroom and the Loskop Dam, but also in some excellent road-cuts along the freeway near Witbank, are grouped together as the Rooiberg Group.

← **Figure 31:** The National Monument site in the Dwars River gorge, eastern Bushveld Complex. Layering and bifurcation of UG1 chromitite layers within light-coloured anorthosite. This world-famous site was declared a National Monument in the early 1980s. Courtesy of Morris Viljoen, University of the Witwatersrand.

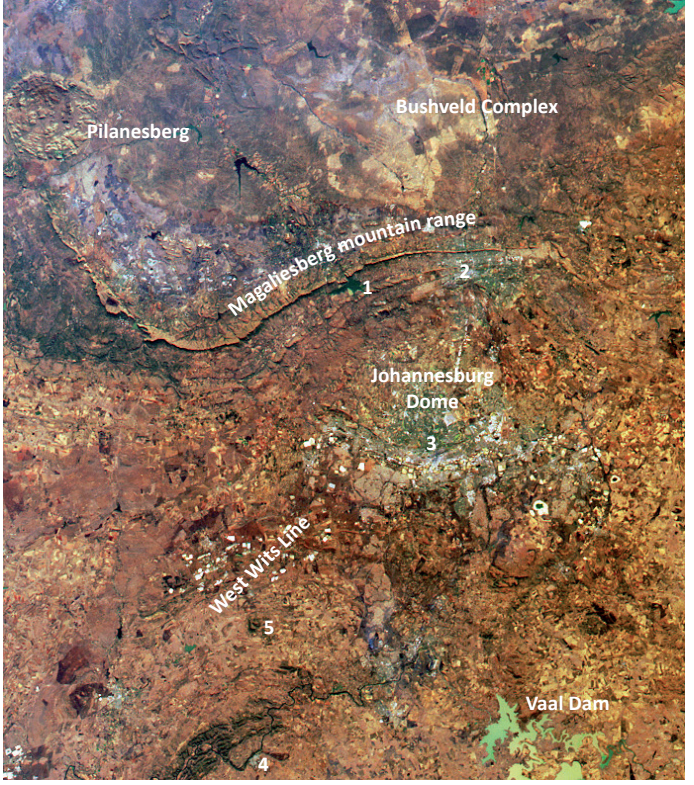
Immediately below these volcanic deposits, large volumes of basaltic magma intruded as horizontal sills between the sedimentary layers of the Transvaal Supergroup rocks. One of these sills expanded considerably more than the rest, as repeated pulses of magma were injected into the magma chamber. Slow cooling of this large volume of magma allowed crystals to grow to significantly larger sizes than in the underlying sills and overlying lavas, and gave sufficient time for these crystals to settle to the bottom of the magma chamber, creating remarkable layering that can be followed continuously for hundreds of kilometres (Fig. 31). Within less than one million years, more than 1.5 million cubic kilometres of magma had crystallised and cooled, forming a horizontal intrusion more than 300 km long, 200 km wide, and up to 7 km thick. These rocks, collectively called the Rustenburg Layered Suite (RLS), dwarf similar layered intrusions around the world, not only in terms of size, but also in the phenomenal deposits of platinum and the other platinum-group elements, vanadium and chromium that occur in some of these layers. This mineral wealth makes the Bushveld Complex the 'Treasury' of South Africa.

The intrusion of the Rustenburg Layered Suite was shortly followed by intrusion of large volumes of granite which ponded in a 2 km thick horizontal sheet above the Rustenburg Layered Suite, but beneath the volcanic carapace. On its own, this intrusion, called the Lebowa Granite Suite, is of gigantic size. In former times, tin and, locally, silver were mined from these granites. Together, the three phases of magmatism that form the Rooiberg Group, RLS and Lebowa Granite Suite are called the Bushveld Complex. Modelling of this Bushveld event suggests that the preserved volumes of rock represent only a fraction of the original volume of magmatic rock, and that the complex originally extended across much wider areas of the Kaapvaal craton. Proof of this is found in

the form of a large number of seemingly related intrusive bodies in other parts of the craton. One of these is the Losberg Complex, located between Johannesburg and Parys, the rocks of which bear a striking similarity to those of the Rustenburg Layered Suite. The Transvaal Supergroup rocks around the Vredefort Dome also contain many sills of intrusive rock, many of which are probably related to this event. In addition, several small granite and somewhat less silica-rich diorite bodies exposed in the Vredefort Dome (Fig. 86, page 131) have radiometric ages that overlap with the 2 060 Ma age of the Bushveld Complex. These rocks are associated with metamorphism of the rocks of the Witwatersrand Supergroup that indicates heating of the continental crust on a regional scale during the Bushveld event.

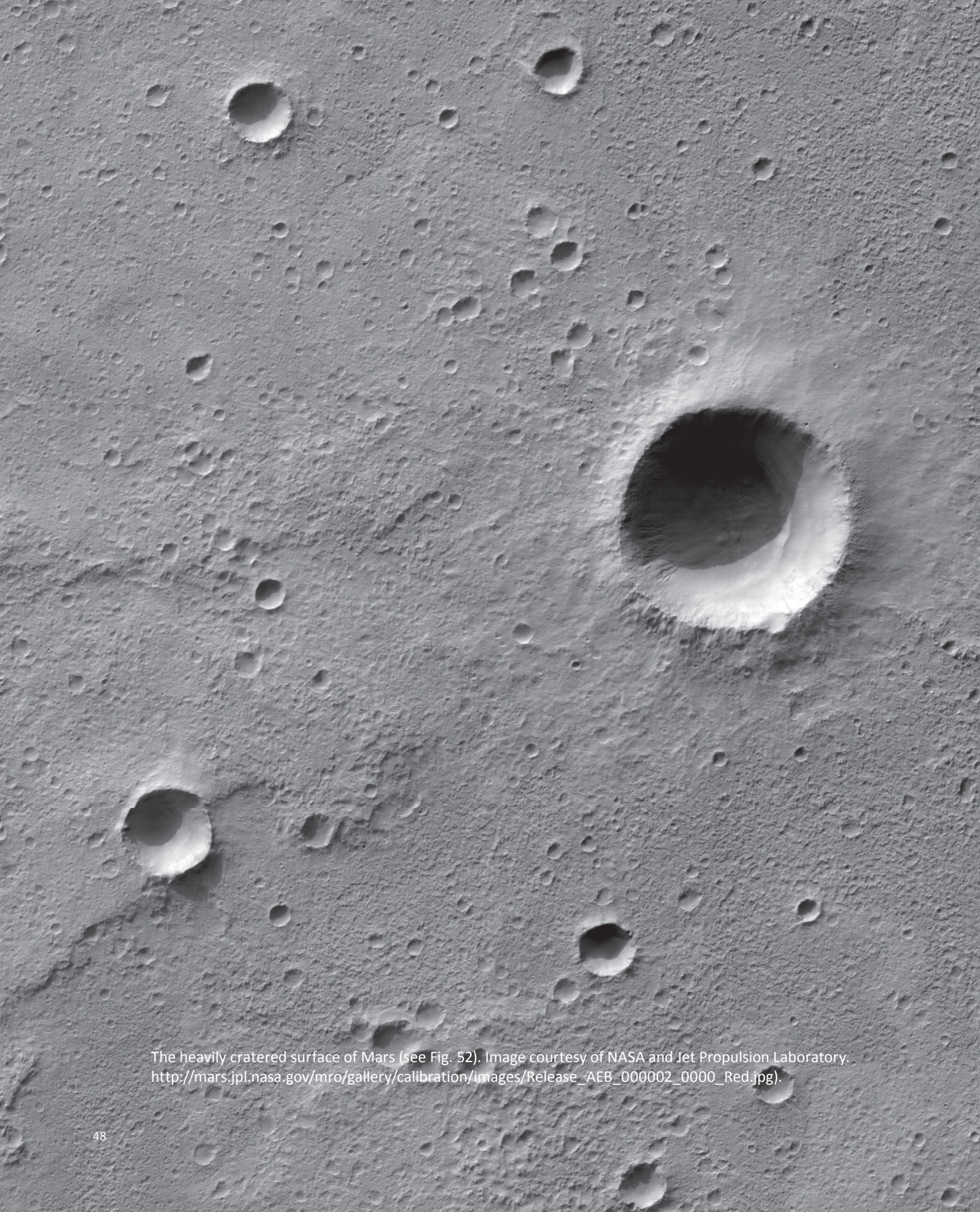
Whether this heating indicates that the Bushveld event was a larger and more intense rifting event than the Dominion and Ventersdorp events, and was, thus, part of another compression-extension cycle, remains unknown. However, within 40 million years, this cycle was interrupted by an event that had no relation to such internally driven cycles — the Vredefort impact event.

Unfortunately, the rock record has not provided us with a picture of the exact nature of the surface of the Kaapvaal craton in the region between the Bushveld Complex and the Vredefort Dome (the region shown in Fig. 32) at that time. The only facts available are: (1) The last-known sedimentary rocks deposited in the region, prior to the impact event, belong to the 2 600 to 2 100 Ma old Transvaal Supergroup and represent shales and quartzites. The only evidence for life at that time in the area around the Vredefort Dome comes in the form of stromatolites, proving that, at that time, the region was covered by a shallow sea. Whether this shallow ocean still covered the area around Vredefort at the time of impact, or whether the continental surface was raised above sea level, is not known. (2) The Bushveld magmatic phase had occurred some 40 million years earlier than the impact. Thus, magmatic rocks could have covered the surface. Immediately south of Potchefstroom is the Roodekraal Complex, consisting of diorite of presumed Bushveld age. Roodekraal represents the root zone of a now strongly eroded, wide volcano. But whether there was still active magmatism in the region at impact time remains uncertain. (3) It is also not known with certainty whether the surface in the impact area was flat, or whether it was topographically complex. Interpretation of structural geological data recently obtained could suggest that there were kilometre-scale areas that had been moved against one another, perhaps having given rise to a complex geological terrain. This could have been similar to the faulted terrain in present-day Johannesburg, where valleys, ridges and small plateaux alternate with one another (Fig. 33). However, whatever the surface appearance at the time of impact, it had no influence on the bolide!

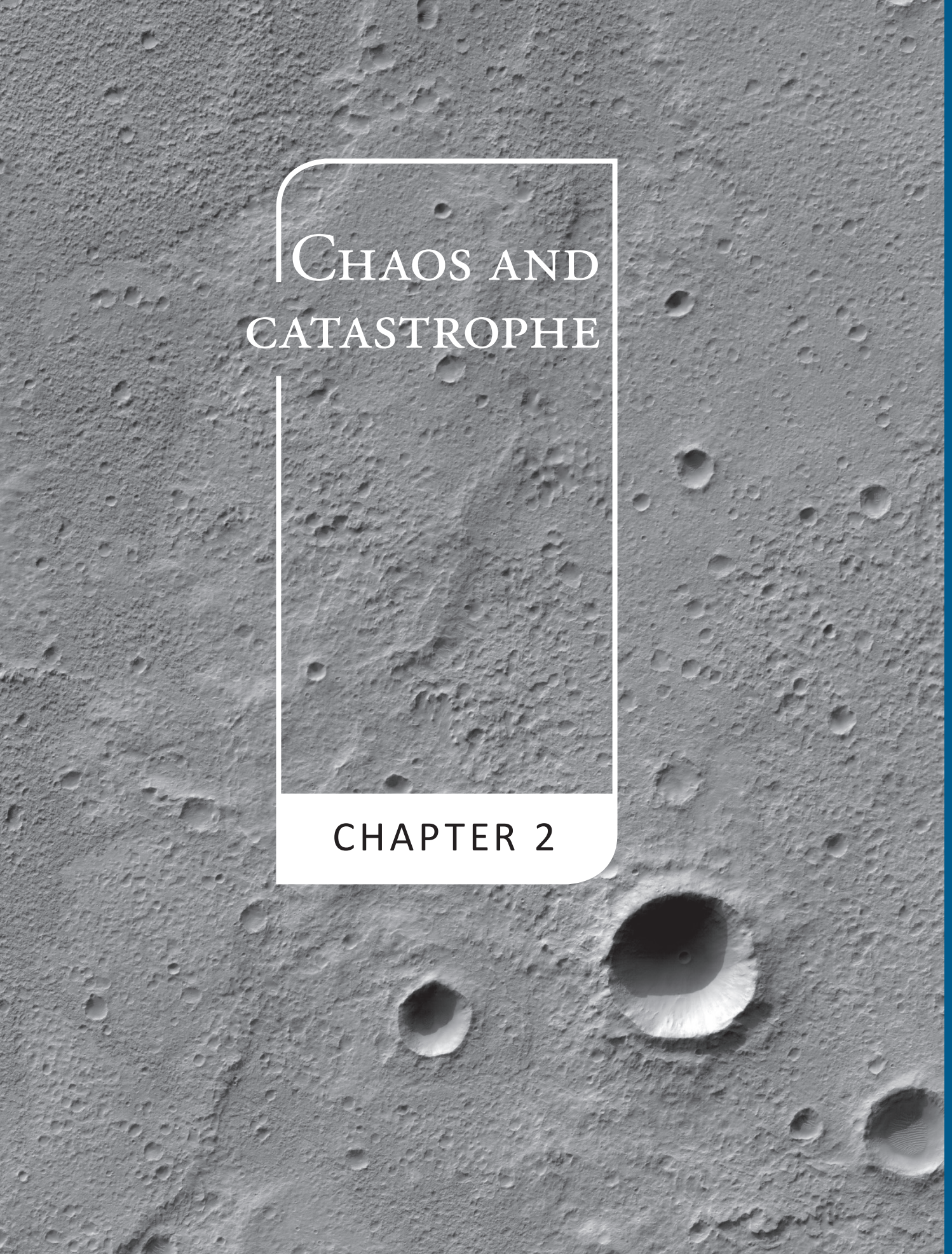


↑ **Figure 32:** Multi-angle Imaging SpectroRadiometer (MISR) image of the region between the Bushveld Complex in the north and the Vredefort Dome in the south. The Pilanesberg volcano in the northwest, the prominent range of the Magaliesberg, the Johannesburg Dome basement high, the northern edge of the Vredefort Dome, and the Vaal Dam make obvious landmarks. 1 Hartebeespoort Dam, 2 Pretoria, 3 Johannesburg CBD, 4 Parys, 5 Losberg Complex. Image courtesy of NASA's Earth Observatory.

← **Figure 33:** Witwatersrand Supergroup rocks at the Walter Sisulu Botanical Garden in Roodepoort (western Johannesburg) are upturned and faulted, possibly as a result of the Vredefort impact event. The garden includes a geological rock garden that presents all the major rock types in South Africa's 3 500 million year history.



The heavily cratered surface of Mars (see Fig. 52). Image courtesy of NASA and Jet Propulsion Laboratory. http://mars.jpl.nasa.gov/mro/gallery/calibration/images/Release_AEB_000002_0000_Red.jpg).



Chaos and catastrophe

CHAPTER 2

Introduction

Imagine that some 2 020 Ma (million years) ago an enormous block of rock (an asteroid), or of ice and some rocky material (a comet) slammed into the crust of the Earth. The actual impact site was several kilometres higher than the present-day land surface, above the area centred today on the small town of Vredefort in the Free State Province, some 120 km south-west of Johannesburg. This projectile was no slouch! It approached its target at a velocity of at least 40 000 km per hour, about 400 times faster than you should travel on the highways of South Africa, or 20 times faster than the speed of a rifle bullet! It is estimated that this block of rock or ice was at least 5–8 km and perhaps even as much as 15 km across, depending on its composition and, thus, mass. Its estimated velocity is uncertain, and the speed value of 40 000 km per hour is only a minimum guess. In fact, this bolide could even have been travelling as fast as 72 km per second, which translates into some 260 000 km per hour!

On impact, a gigantic amount of energy was instantaneously released: the mass and velocity of the bolide combined to release energy equivalent to the force of almost 100 million megatonnes of TNT explosive. By comparison, the atomic bombs that all but destroyed the cities of Hiroshima and Nagasaki in 1945 only contained the force of 20 000 tonnes of TNT, that is only one five-billionth (5 000 millionth) of the power of the Vredefort explosion! The momentum of the bolide was sufficient to drive it at least 10 km into the Earth, at which point it had become so strongly compressed that it exploded. An enormous compression wave, the shock wave, resulting from this blast caused a huge amount of rock from the immediate environs of the explosion site to vaporise completely, and several thousand cubic kilometres of rock were melted in the surrounding zone. The shock wave travelled rapidly radially away from the explosion centre, causing destruction of the rock along its path. As it spread outwards, it weakened, until some 200 km from the explosion site, it was completely dissipated. Nevertheless, some 150 km from the impact site (that would be the area of Johannesburg and its environs today) there was still enough energy left to fracture and fault (Fig. 33) massive volumes of rock. Huge amounts of debris were blasted out of the crater, which initially had a diameter of about 100 km and was at least 30–40 km deep.

As the crater was excavated, its surroundings became covered by a kilometre-thick layer of ejected blocks and finer debris, with ejected material forming a thick blanket for hundreds of kilometres around the impact site. With distance, the thickness of this ejecta blanket would have decreased, but it is estimated that at some 500 km away a metre-thick layer of ejected material would have accumulated. The ejecta thrown into the atmosphere darkened the sky all around the planet, blocking out the sunlight for many months or even years. This must have led to a dramatic, though probably short-term, change of the global climate.

Immediately after the 100 km wide transient crater had been excavated, it began to collapse. The enormously compressed crater floor below the point of impact rebounded after the shock wave had passed, and a central uplift rose above the original land surface — and then collapsed back into the crater. At the same time, the crater wall collapsed, with wide terraces of rock breaking off the rim and sliding into the crater interior. This widened the crater structure and flattened it to a degree until, finally, a 300 km wide, rather flat-floored crater, with a mountainous central uplift and terraced rim, had formed (compare Fig. 3). The width of the central uplift measured about 80 to 100 km and, after its collapse, it was still elevated above the crater floor by several kilometres. It is likely that, for millions of years thereafter, violent earthquakes, of magnitudes far beyond the currently used

Richter Scale (page 54), continued to shake the Earth as the grossly disturbed crust readjusted after the impact catastrophe.

More than 2 000 million years have passed since this catastrophe, and several kilometres of rock have been eroded from the continent since. Yet, the remnants of the crater structure, the root zone of the collapsed central uplift, remain, and some portions of it, the Vredefort Mountain Land, are highly visible. The origin of this strongly deformed mountainous terrain in the central part of the Witwatersrand basin remained questionable for much of the last century. Only after some 50 years of debate by, and disagreement amongst, geologists was irrefutable proof finally unearthed for the ancient

Vredefort Fact File

A large impact event of the magnitude of Vredefort would have had some amazing results. These are some pertinent facts about the Vredefort impact structure:

AGE: 2 020 ± 5 million years
(this makes Vredefort the oldest known impact structure in the world)

ORIGINAL CRATER SIZE: Diameter between 250 and 300 km
(exact size unknown because of deep levels of erosion; one of the three largest impact structures known on Earth)
The excavated transient crater would have been up to 40 km deep, but it quickly collapsed

DEPTH OF THE FINAL CRATER: Between 1 and 2 km

EXCAVATED VOLUME: Approximately 70 000 km^3

ENERGY RELEASED UPON PROJECTILE EXPLOSION: 100 million megatonnes of TNT
(1 megatonne is 1 million tonnes!)

TOTAL DURATION OF TRANSIENT CRATER GROWTH: Between 2 and 4 minutes

TOTAL DURATION OF FINAL CRATER GROWTH: Between 4 and 15 minutes

SIZE OF THE PROJECTILE: Between 5 and 15 km
(depending on its density, velocity and impact angle)

SEISMIC EVENTS CAUSED BY THE IMPACT: Approximately magnitude 14 on the Richter Scale
(this means that these events would have been millions of times more powerful than the worst earthquake recorded in recent times, which struck China in 1976, when an estimated 255 000 people perished)

DISTRIBUTION OF THE EJECTA: Hundreds of kilometres, with a very thick blanket near the crater decreasing in thickness to just a metre some 350–500 km from the crater

ENVIRONMENTAL EFFECTS:

- Blasting off of some atmosphere and, if the impact was into a shallow ocean, large volumes of oceanic water
- Large post-impact earthquakes related to the recovery of the crust from this gigantic disturbance
- Landslides and, though strongly debated, perhaps volcanism in other parts of the world
- If the impact was into an ocean of substantial depth, possibly tsunamis
- Rain of hot and molten ejecta
- Dust injection into the upper atmosphere and even higher resulted in global cooling (impact winter) for months to years
- Acid rain
- Global atmospheric greenhouse effect for decades to centuries caused by release of greenhouse gases

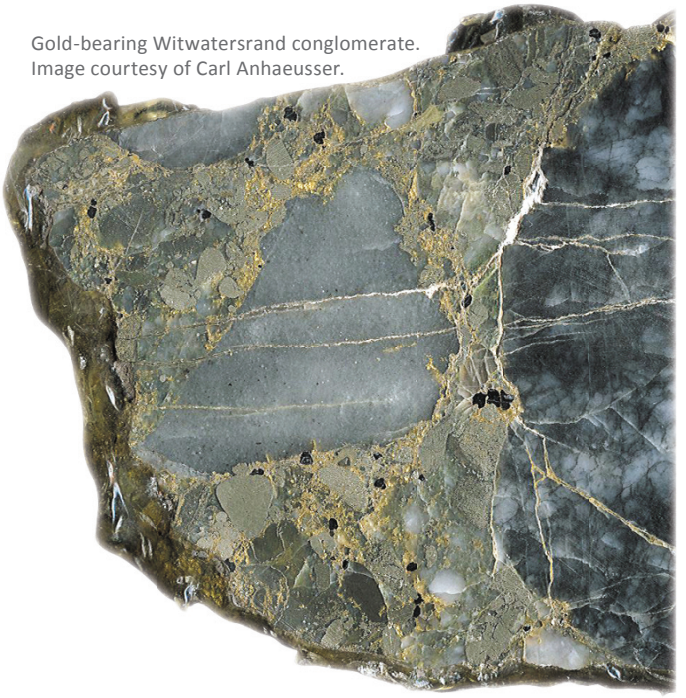
meteorite-impact event. In the following pages the story of the initial controversy amongst the experts concerning the origin of the Vredefort Dome, and of the detective work that was required to solve the riddle, is told.

The impact catastrophe is not the only reason why the Vredefort Dome is important. The dome lies in the centre of the so-called Witwatersrand basin, home to an estimated 15 million people — a major part of the population of South Africa. The Witwatersrand basin extends from the city of Johannesburg in the northeast and Heidelberg in the east to the Free State goldfields centred on the town of Welkom in the southwest, and beyond Klerksdorp in the west (Fig. 24). The Witwatersrand basin is internationally renowned as the largest gold deposit on Earth, from which some 45 % of all the gold ever mined, totalling more than 45 000 tonnes, has been won. Today, we know for certain that the gold was laid down, together with the ancient rocks of the Witwatersrand Supergroup, some 700–900 million years before the Vredefort impact. However, the impact did influence these gold-bearing rocks and is the reason why this ore deposit is still accessible but also deformed, making mining sometimes very difficult. The reason for this is that when the initial impact crater had been excavated to its maximum depth, it collapsed. A complex crater form with a central uplift surrounded by a deep ring basin resulted, and all of this was covered by thick layers of rock melt and ejected debris. If not for this thick cover and for the fact that blocks of the gold-bearing Witwatersrand rocks sagged and became down-faulted into the ring basin around the central uplift, much of the Witwatersrand gold would have been eroded over the past 2 000 Ma. If this had happened, no gold-mining industry would have evolved in this region, and the political and economic development of South Africa would surely have been vastly different.

Witwatersrand basin — the world's most important gold deposit

The special interest in the Vredefort Dome also stems from the fact that it is situated in the most scenic landscape between the Magaliesberg mountain range in the northeast and the mountains of Lesotho and the Cape region to the south. For geologists, the Vredefort region provides a window into the deep crust of the Earth, below all the cover rocks of the Transvaal, Ventersdorp, Witwatersrand and Dominion formations, right down into the crystalline basement. Vredefort, thus, shows us what happened within the Earth over the past 3 200 million years.

What is more, there are indications of a rich cultural history in the area: evidence was found of possible Middle Stone Age (about 200 000 years ago) human habitation and, more importantly, the remnants of extensive Iron Age settlements can be found throughout the Vredefort Mountain Land. In the late 19th Century fierce battles were fought in this region during the Anglo-Boer War, a gold rush took place along the ridges above the little hamlet of Venterskroon, and diamond diggings occurred along the Vaal River bed in the northern parts of the Vredefort Dome. In more recent times, the region has been a microcosm of the sometimes turbulent history of South Africa. Thus, the story of the Vredefort Dome is not restricted to one of the darkest moments in Earth history 2 020 Ma ago, but extends both further back in time towards the beginnings of our planet and forward via our ancient human ancestors to the modern era.

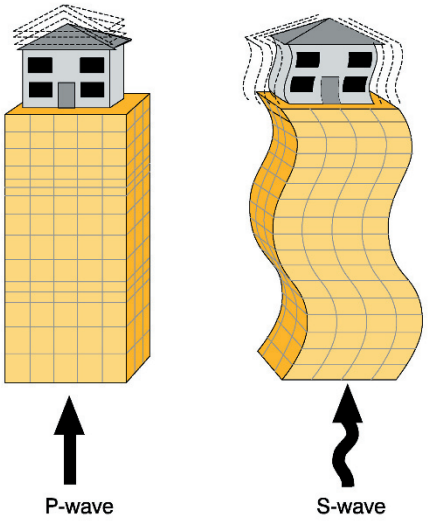


Gold-bearing Witwatersrand conglomerate. Image courtesy of Carl Anhaeusser.

Extinction or survival
— Our restless Earth

Our planet has had a long and intriguing history, some of which has been discussed in some detail in the preceding chapter. But, did this history proceed continuously, as numerous apparently continuous rock records (i.e. layered deposits of sedimentary rock) may suggest? We have discussed how the early concept of uniformitarianism had to be revised because of the realisation that catastrophic events have had decisive influences on Earth's and life's evolution. Today, many scientists have recognised the need to combine the concept of catastrophism with the uniformitarian, gradualistic view. Processes such as volcanism and earthquakes, floods or droughts have, again and again, caused havoc throughout the ages. What needs to be discussed are the different types of catastrophes, caused by Earth's own processes, and their consequences.

Natural catastrophes have been, and still are, part of everyday life. All regimes of this planet (geosphere, hydrosphere, and atmosphere) are prone to sudden upheaval. Significant earthquakes occur as frequently as 10 000 times every year, mostly in those parts of the world where plate collisions and subduction are involved (compare Box, page 19, and Fig. 5, page 20). Parts of the circum-Pacific belt (e.g. Japan, Indonesia, the Phillipines, and the countries along the west coast of North and South America), which is justifiably called the Ring of Fire (Fig. 7, page 22), and the active margins of plates in the region of the eastern Mediterranean are particularly threatened by this form of disaster. Not a year goes by that the Balkan region of Europe, Turkey or Iran is not afflicted by such a catastrophe.



↑ **Figure 34:** Sketch showing how the P- and S-waves caused by an earthquake affect buildings: the first wave to arrive at a target is the so-called P-wave, which stretches and squeezes the material through which it travels. P-waves are soon followed by S-waves that result in ground being shaken from side to side. The surface waves add a side-to-side or up-and-down rolling movement (like the waves in an ocean). Modified after an image by McGuire (1999).

↓ **Figure 35:** The 7.2 magnitude earthquake that struck western Japan on 17 January 1995 caused death and massive destruction. In Kobe, a town with 1.5 million inhabitants, seven thousand homes were razed by fires that were triggered by ruptured gas pipes. This image shows a stretch of highway (the Hanshin expressway) that collapsed in this event.

← **Figure 36a:** A strong, mining-induced earthquake in 1976 caused extensive damage (for example, the collapse of this six-storey high block of flats, known as the 'Tempest Hof' flats) in the town of Welkom, southwest Witwatersrand basin.

Earthquake damage in South Africa

→ **Figure 36b:** On 29 September 1969, a substantial earthquake (magnitude 6.3 on the Richter Scale) rocked the areas of Ceres and Tulbagh in the Western Cape Province, causing extensive damage to buildings (such as the one shown here) and several deaths. Images courtesy of the Council for Geoscience, Pretoria.

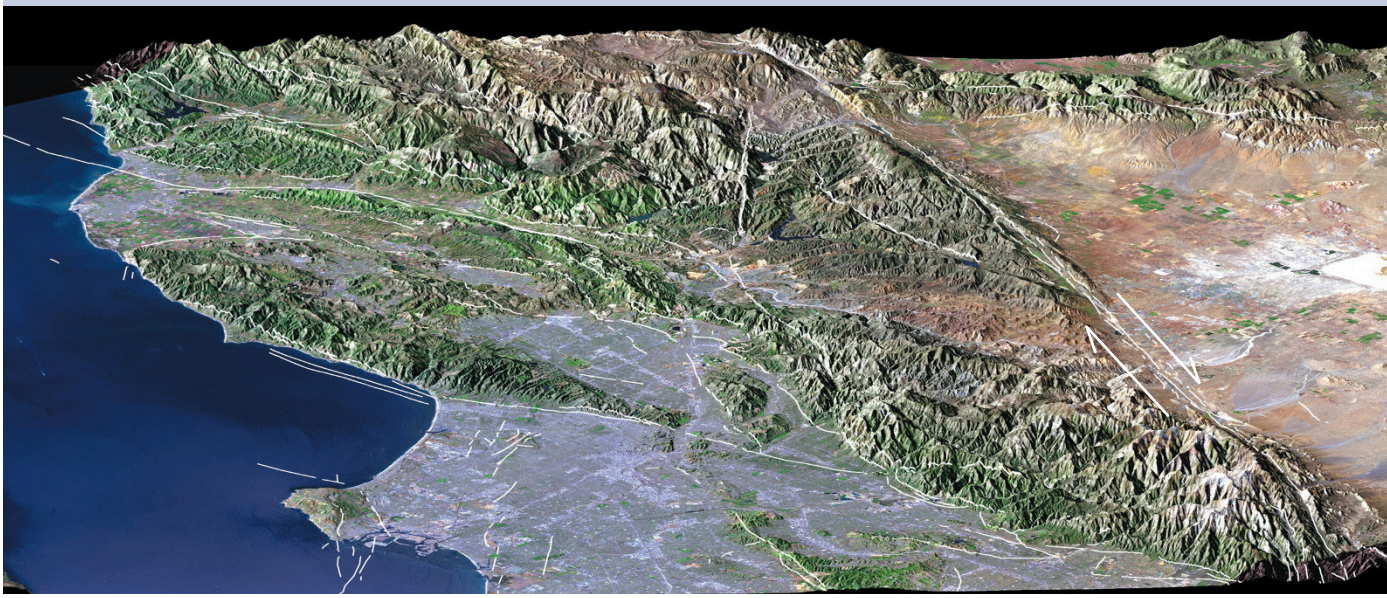
The Richter Scale: magnitude of earthquakes

Intensity	Characteristic Effects
<3.5	Only detected instrumentally; around upper levels, noticed by sensitive people
3.5–4.2	Slight vibrations similar to the passing of a truck; felt by people especially in upper floors of buildings
4.3–4.8	*Moderate to rather strong:* felt by people while walking to generally felt; sleepers awakened and bells ring
4.9–5.4	*Strong:* trees and suspended objects sway; damage because of overturning and falling of loose objects
5.5–6.1	*Very strong:* walls crack, plaster falls
6.2–6.9	*Destructive:* car drivers disturbed, houses crack, chimneys fall, poorly constructed buildings destroyed *Ruinous:* houses collapse, ground breaks open, pipes burst
7–7.3	*Disastrous:* ground cracks badly, many buildings destroyed, railway lines bent, landslides on steep slopes
7.4–8.1	*Very disastrous:* few buildings not destroyed, bridges destroyed; all infrastructure destroyed, great landslides, floods
> 8.1	*Catastrophic:* total destruction; objects thrown into the air, ground rises and falls in waves

In South Africa, the earthquake threat is not strong and is largely limited to mining-induced tremors in the region of the Witwatersrand basin. Most such earth tremors are very weak, measuring only 1–2 on the Richter Scale (see Box, page 54); dangerous earthquakes rank above about magnitude 5, and disastrous events generally register above 7. Welkom, a town in the northern Free State Province, was struck by a mining-induced earthquake in 1976, causing the total collapse of some buildings (Fig. 36a). The worst earthquake in South Africa in recent years also occurred near this town. At a magnitude of 5.3, this earthquake on 23 April 1999 caused extensive damage to buildings but, fortunately, not much loss of life. Another earthquake, on September 29 1969, affected the towns of Ceres and Tulbagh in the Western Cape (Fig. 36b).

The most disastrous earthquake of modern times occurred on 28 July 1976 in northeast China. It is estimated that some 255 000 people died and 164 000 were severely injured by this natural disaster, which registered 8.3 on the Richter Scale, and its hundreds of aftershocks. China's Sichuan Province suffered a major earthquake catastrophe on 12 May 2008. The main earthquake measured about magnitude 7.8 according to the Richter Scale, and numerous aftershocks of up to magnitude 6 followed thereafter. Several major cities were completely destroyed; an estimated 70 000 people lost their lives, about 300 000 people were injured and between five and six million people were made homeless. A 7.2 magnitude earthquake on 17 January 1995 all but destroyed the large Japanese city of Kobe (Fig. 35). The event triggered 140 fires that destroyed some 180 000 buildings. More than 6 000 people died and 43 000 more were injured. Earthquakes in past geological time can be recognised as they have left traces in the rock record, such as the presence of so-called turbidites, massive jumbles of rock that may have formed because of the sliding of huge rock masses, for example off the continental shelf, triggered by the violent ground motion generated by an earthquake. McGuire (2002) reports that the 20th Century had five earthquakes that alone caused the death of nearly one million people and resulted in an economic loss of more than 10 billion US dollars.

↓ **Figure 37:** The metropolitan area of Los Angeles is one of the most densely populated regions in the USA. A series of seismically active fault zones runs through this area and potentially could result in catastrophic earthquakes. The famous San Andreas Fault is also shown in this image, forming a topographic boundary between the San Gabriel Mountains in the central part of this image and the low-lying, mostly featureless, Mojave Desert in the eastern part that is moving to the right relative to the San Gabriel Mountains. Image courtesy of NASA's Earth Observatory.

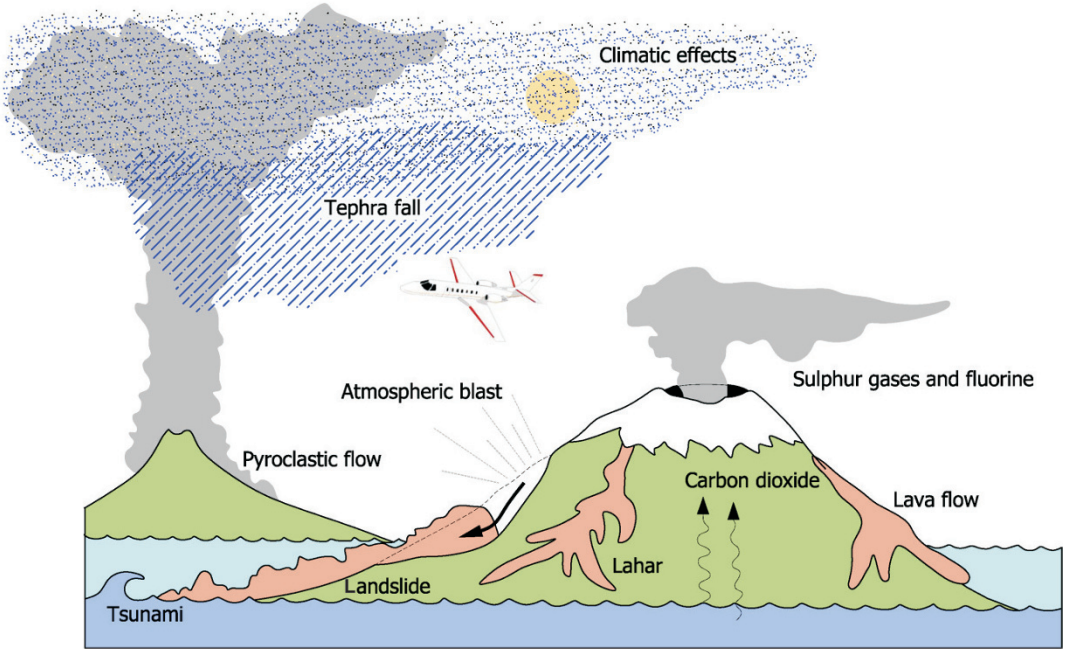


In the USA, California is a densely populated and economically vital region that is exposed to a severe earthquake threat. Tens of millions of people live along powerful tectonic structures, such as the San Andreas and San Gabriel faults, a fault zone hundreds of kilometres long that marks the contact between the North American and Pacific plates (Fig. 37). The large cities of San Francisco and Los Angeles, home to millions of people, straddle this long fracture zone in the crust of the Earth. In 1989, a powerful earthquake, causing damage of many billions of US dollars, was centred on the little town of Loma Prieta, south of San Francisco.

Volcanic eruptions also occur regularly around the globe (Fig. 38). In 2002 Mount Etna on the Italian island of Sicily, again began to disgorge massive volumes of hot liquid lava, threatening a number of villages on its slopes. The entire history of the cultures developed around the Mediterranean is interspersed with reports of violent volcanic eruptions. The Greek, Roman and other circum-Mediterranean cultures were severely influenced, and the Bronze Age Minoan culture was actually destroyed around 1 630 BC, when the Greek island Thera (now known as Santorini) was destroyed in a volcanic catastrophe. The Minoan civilisation was centred on Crete, but also involved Thera. Some 20 m of ash fell onto the remaining parts of Thera after the volcano exploded, and Crete, just one day by ferry from Thera, was deeply covered as well. It is likely that huge flood waves (tsunamis) lashed the populated shoreline of Crete. This event is the likely source for the myth about the lost civilisation of Atlantis. Thinner than normal tree-ring growth in Europe and North America at the time indicates an exceptionally cold period, reflecting the devastating environmental effects of such violent eruptions on a continental scale and beyond.

As has been shown in Fig. 7 (page 22), volcanoes are not scattered at random; the vast majority are aligned with major tectonic features, the so-called mid-ocean ridges and along oceanic–continental plate collision zones. As discussed in the previous chapter, mid-ocean ridges are exactly what the term means: ridges that extend for thousands of kilometres in the middle of the oceans, for example in the Atlantic Ocean,

Figure 38: Sketch diagram illustrating the principal hazards that can be caused by volcanic eruptions or explosions. They include lava flows, pyroclastic flows and ash clouds, gas explosions, volcanic gas eruptions, tsunamis, mudflows (lahars), and climatic effects. Modified after a figure in McGuire (1999).

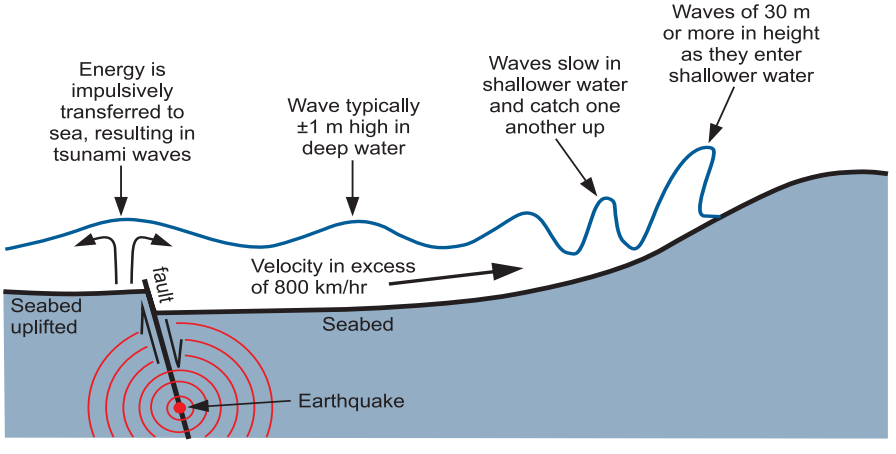


where the volcanic island of Iceland straddles this ridge feature. At these mid-oceanic ridges, new crust is produced as a result of volcanism. In contrast, at converging plate boundaries where subduction of oceanic crust underneath continents takes place, volcanism occurs because of the melting of subducted material and its subsequent rise to the surface. As with earthquakes, the plate margins around the Pacific Ocean typify this situation. An estimated 1 500 volcanoes occur along these particularly active zones.

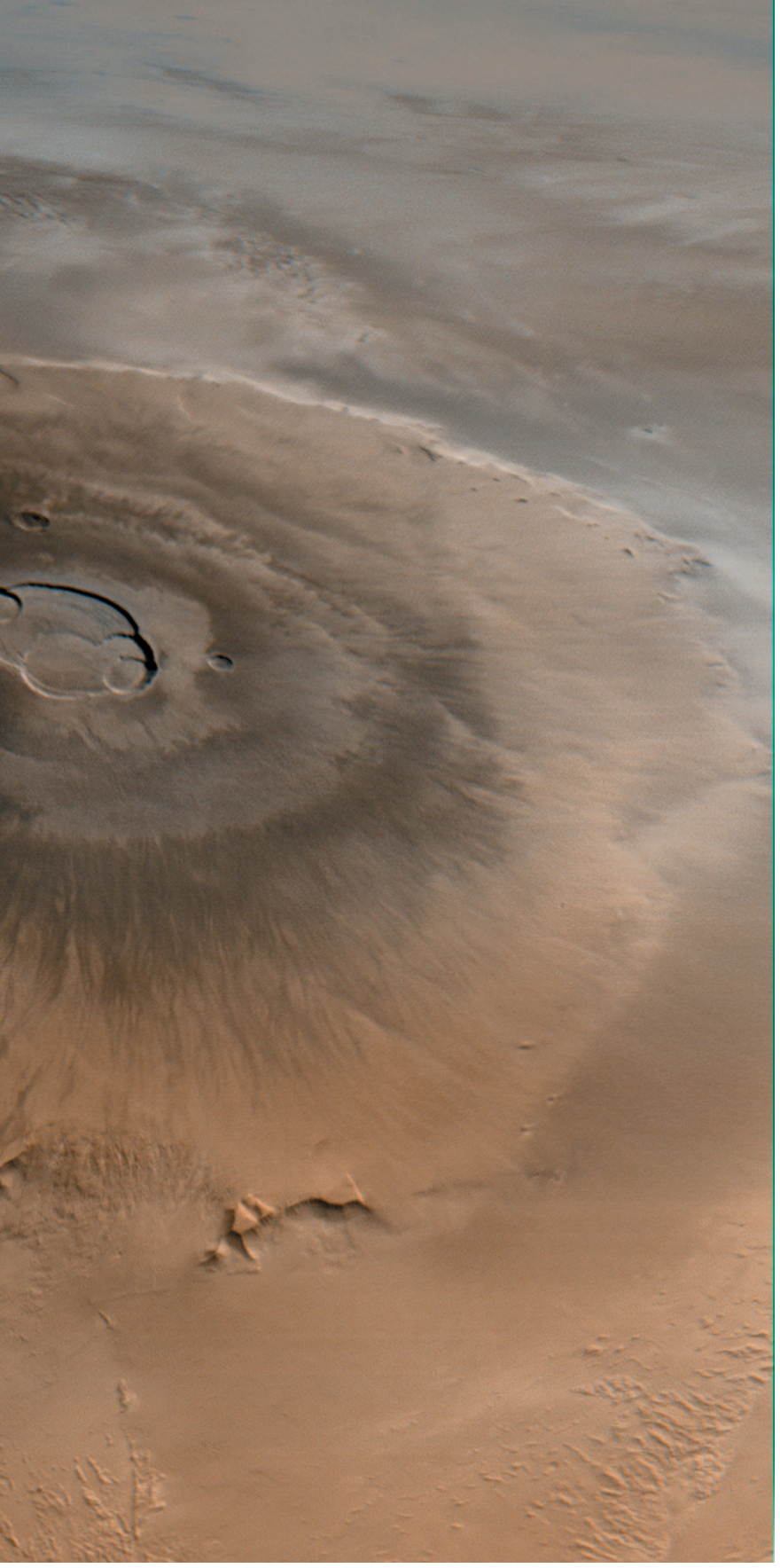
The worst volcanic catastrophes of recent times include the eruption of the Mont Pelée volcano on the island of Martinique in the Caribbean, in 1902, when approximately 29 000 people perished, and the more recent eruption of Nevado del Ruiz in 1985 in Colombia that killed about 23 000 people. The Caribbean island of Montserrat, home to several thousand people, is a single massive volcano. Eruptions of this volcano in the past have already caused the death of countless islanders. In 1995, Montserrat erupted again and posed such a serious threat that the evacuation of the whole island population was considered. More than 30 people have been killed on the island since then as a consequence of volcanic activity. Although volcanic activity on Montserrat has abated somewhat, the threat is still very much in evidence.

The eruption of Mount Vesuvius in Italy (Fig. 39) in August AD 79, which buried the town of Pompeii, home to some 20 000 people

Figure 39: Mount Vesuvius in the densely populated region around Naples, Italy. Note how several of its lava flows have encroached into the urban areas. The dark central cone represents the latest ash deposit. Pompeii lies southeast of Vesuvius, under the present town of Naples. Width of image 19 km. ASTER image, courtesy of NASA.



→ **Figure 40:** An example of how a suboceanic earthquake, triggered by rapid fault movement, can result in the transfer of a large amount of energy into the water column, where it results in wave formation. Initially this wave may only be shallow, with a metre or two of amplitude, but once it reaches shallower water it will be rapidly enlarged and steepened until it may, upon land fall, reach heights of tens of metres. Modified after an illustration by McGuire (1999).



at that time, is a well-recorded historical event. One of the victims, Pliny the Elder, who achieved fame as a natural scientist and author, was the commander of the Roman fleet in the Bay of Naples at the time. On learning of the eruption of Mt Vesuvius, he went ashore to ascertain the cause of the eruption and to reassure the terrified citizens. However, he was overcome by the fumes resulting from the volcanic activity and perished. The town of Pompeii was completely covered by a layer of ash many metres thick that suffocated thousands, but also preserved a fascinating view of life in an ancient Roman city.

In southeast Asia, Indonesia and the Phillipines are frequently subjected to severe volcanic eruptions. There are 129 active volcanoes in the Indonesian archipelago alone, and in the last 200 years (prior to 2004) an estimated 200 000 lives have been lost there as a result of eruptions and related tsunamis (Fig. 40). The eruption of Mount Pinatubo in the Phillipines in June 1991 is considered the most violent volcanic event of the 20th Century. More than 10 km^3 of ash and gases were blasted into the atmosphere, resulting in the lowering of temperatures around the world. Although 200 000 people were evacuated in time, warned by careful monitoring of the impending volcanic threat, some 850 people perished, 42 000 homes were destroyed, and 200 000 acres of land buried in ash.

All of these eruptions pale into insignificance when compared with the eruption of the Toba volcano in Sumatra some 75 000 years ago. This singular event is believed by some researchers to have resulted in an environmental catastrophe that may have wiped out as much as 99 % of humankind – a chilling example of the power of geological events to change the course of global human development.

Earthquakes, like volcanic eruptions, may trigger secondary disasters, such as mudslides (see Fig. 43) or flood waves. In 1970, a huge debris avalanche was triggered by an earthquake in Peru. Soil and rock debris travelled at extreme speed, even spilling over a major

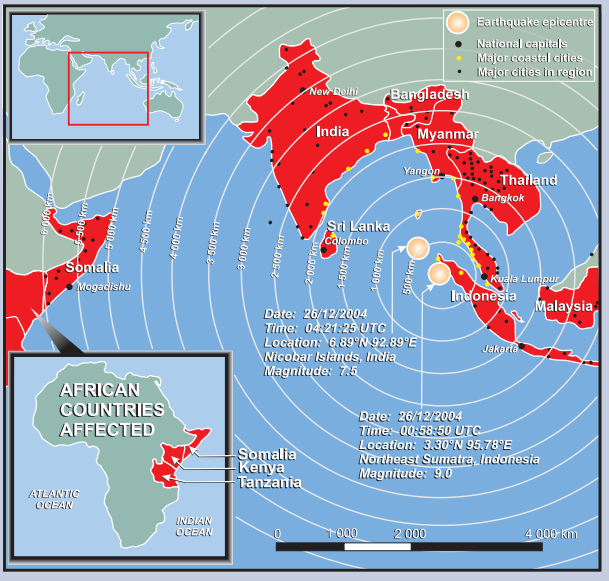
← **Figure 41:** The largest volcano known in the Solar System, Olympus Mons on Mars, is, at an elevation of 25 km, three times higher than Mount Everest on Earth. However, with a diameter at its base of some 600 km, its slopes are not particularly steep. Mars Global Surveyor image, courtesy of NASA.

topographic barrier in the form of a 700 m high hill. Unstoppable, it destroyed the entire town of Yungay, killing 18 000 people. Volcanic eruptions may be particularly hazardous, not because of the primary eruption of lava or ash (that may affect either very limited areas only or, when the ejecta are widely dispersed, is not very dangerous), but because of associated earthquakes and mudflows, or when the heat from a volcano melts an ice cap or glacier on

† **Figure 42:** One of a handful of structures in northwestern Sumatra, Indonesia, not completely destroyed by the 2004 earthquake and tsunami.

Death and destruction

On Boxing Day (26 December) 2004, at about 8 a.m. local time, northern Sumatra in the Indonesian archipelago was hit by an earthquake of magnitude 9.1 to 9.3 on the Richter Scale — the strongest in 40 years (compare Box on page 54). A second earthquake of magnitude 7.5 followed 4 hours later near the Nicobar Islands. The earthquakes occurred along the boundary between the Indian and Burma plates, resulting in the instantaneous formation of a 10 m scarp over a distance of 1 200 km, with vast amounts of water being displaced. Huge, broad but shallow waves formed on surface and moved outwards from the earthquake epicentre at speeds of up to 800 km per hour. Wherever the waves reached shallower water, their speed became reduced but their amplitude (i.e. height) increased dramatically. Waves between 1 and 30 m in height crashed into the various shorelines. Numerous aftershocks, with magnitudes up to 6.5, followed over the next few days. The earthquakes caused immediate surface damage in the regions around their epicentres, especially on northern Sumatra and on the Nicobar Islands. The capital city of the northern Sumatran province of Aceh, Banda Aceh, was destroyed. The earthquake-triggered flood waves that raced across the Indian Ocean devoured coastal regions everywhere in their paths. Sumatra and other Indonesian islands, the western coastal region of Thailand, much of Sri Lanka, southern India, the island archipelagoes of the Indian Ocean, including the Maldives and Seychelles, were hardest hit. Some islands in the Maldives, more than 3 000 km from the earthquake foci, were completely submerged. Loss of life was encountered as far away as Somalia, Tanzania, and Kenya on the east African coast.



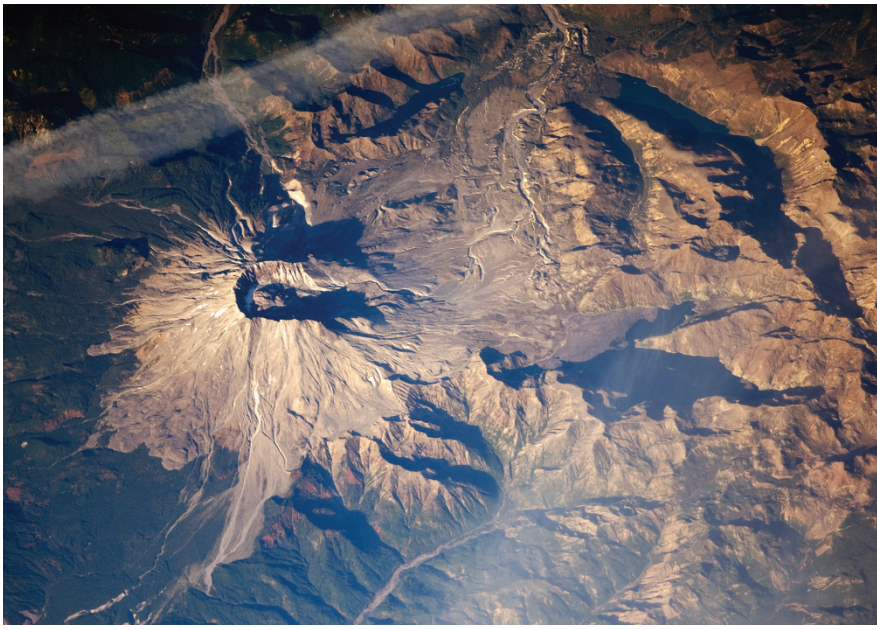
The official death toll is estimated at 230 000, spread over 11 countries, with another 100 000 recorded as missing. Indonesia, the country hardest hit by the disaster, mourned the deaths of more than 230 000 people (including those missing). With corpses being hurriedly buried in unmarked graves to prevent disease, and as the Indonesian president had ordered a halt to the counting of the dead on 18 January 2005, the true figure will never be known. The death tolls in India and Thailand numbered thousands, with thousands more reported missing. Sri Lanka lost some 30 000, with many others missing. Somalia reported 298 dead, Tanzania 10, and Kenya one casualty. Altogether, some 500 000 people were estimated to have been injured by the flood waves, and the damage to infrastructure was catastrophic. Widespread disease resulting from the complete destruction of infrastructure and, especially, the lack of clean drinking water likely raised the total death toll to far beyond 300 000. Many millions of people living in the affected regions lost their livelihoods, and as many as 15 million people lost their homes and possessions. Somalia, 5 500 km from the earthquake area, reported that 50 000 people had lost everything. It is estimated that the southeast Asian economy would take more than 10 years to recover. The thriving tourism establishments situated in many parts of the affected region were decimated. The tsunami hit these popular tourist destinations at the height of the holiday season, with the result that tourists from across the globe lost their lives. Whilst the strong earthquakes and tsunami of 40 years ago in the Pacific region resulted in the setting up of a tsunami early-warning system, no such system existed for the Indian Ocean. In the wake of the disaster, the United Nations called for the establishment of a global early-warning mechanism, which has since been installed throughout the Indian Ocean and beyond.

The epicentres and ripple effects of the massive earthquakes that struck deep below the Indian Ocean on Boxing Day 2004. Countries affected by the disaster are indicated in red.

a mountain, causing massive flooding. Often towns and villages nestle against the slopes of volcanoes, as soils derived from volcanic rocks and ash may be particularly fertile, or because the lee of a large volcano may be climatically favourable. Actually, as has been shown, volcanic chains occur largely in coastal areas along plate boundaries, and coastlines have always been the preferred settlement areas for people.

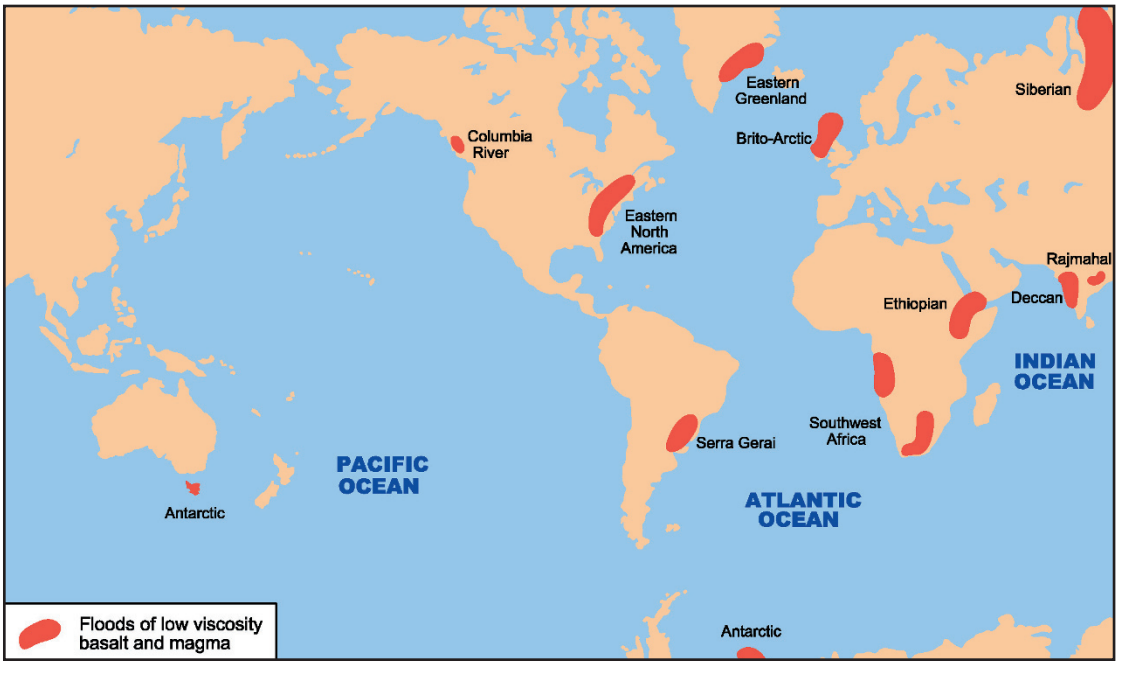
The strongest earthquake ever recorded, of magnitude 9.5, took place on 22 May 1960 near the coast of Chile. It generated a Pacific-wide tsunami that caused the death of some 2 300 people in Chile, while about 3 000 sustained injury. Waves of this tsunami damaged the waterfront of Hilo, the capital of Hawaii, thousands of kilometres farther north, killing 61 people. Hilo was also one of the cities hardest hit by a tsunami resulting from the earthquake on 28 March 1964, of magnitude 9.2, in Alaska, when extensive damage was incurred along the western coastline of North America.

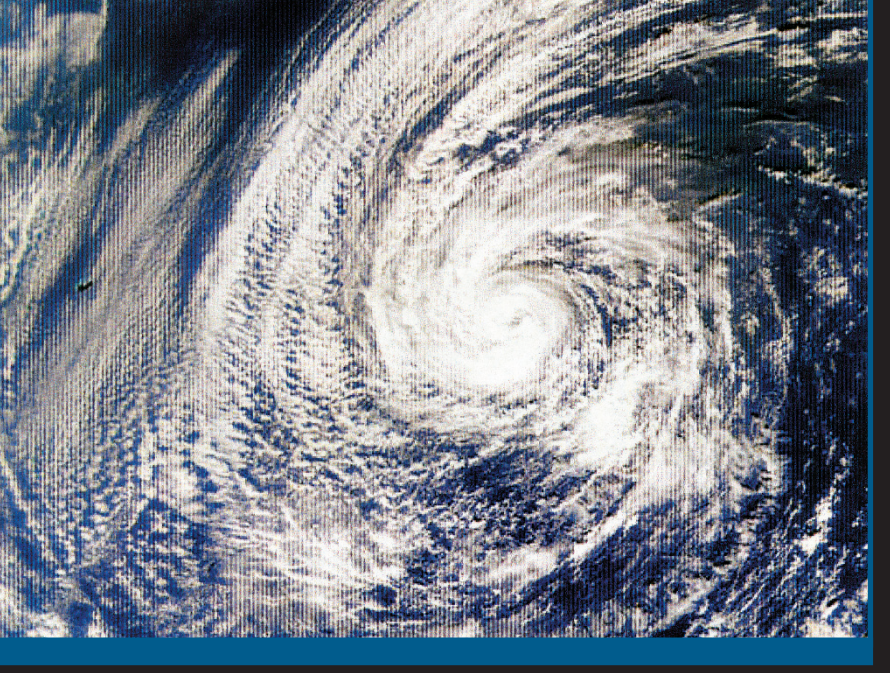
Tsunami-disaster reports pale into insignificance against the catastrophic effects of the magnitude 9 earthquake of Boxing Day 2004, centred just off the northern parts of the Indonesian island of Sumatra (Fig. 42). Loss of life and damage extended over much of southeast



↑ **Figure 43:** International Space Station astronaut photograph (28 October, 2008) of Mount St. Helens volcano in Washington State (USA). The blast zone from the 1980 eruption is still clearly visible north (right) of the volcano. Between 1980 and 1986, lava oozing from vents in the summit crater built a lava dome over 250 m high. A second dome began forming in October 2004, with lava flows continuing until January 2008. Image courtesy of NASA's Earth Observatory.

↓ **Figure 44:** Flood-basalt provinces of the world. After a diagram by McGuire (2002).





↑ **Figure 45:** Image of Hurricane Olga of November 2001, just east of Bermuda island in the Caribbean. Photograph by NASA's Sea-viewing Wide Field-of-View Sensor (SeaWIFS) system. Image courtesy of NASA's Earth Observatory.

Asia and even into eastern Africa. Although the exact numbers of direct and indirect (through disease and famine) casualties are not known, at least 230 000 people perished in the tsunami, making it the most devastating tsunami in recorded history (see Box on page 60).

The region around Seattle, in the American state of Washington, in a densely populated area at the foot of towering (elevation 4 392 m) and snow-capped Mt Rainier, is an area under constant threat from the eruption, and its secondary effects, of this volcano that has been rumbling ominously for years. The drainage off this mountain flows directly into the populated lowlands along the Pacific coastline, and a major eruption, associated with mud- and landslides, or flooding because of the melting of the ice cap, could have dire consequences for many thousands of people in the lowlands.

Many catastrophes are of natural origin, but they may also be triggered by humans who do not understand the underlying geological processes, or choose to ignore them. A case in point is the failure of a large water reservoir, Baldwin Hills Reservoir, in southern California in December 1963. Lives were lost and millions of dollars damage incurred to property. The failure of the reservoir was the result of subsurface erosion along a fault that itself was the result of land subsidence, caused by oil extraction from a nearby oil field. Also deforestation, resulting in destabilisation of the soil, may cause extensive erosion, sometimes in the form of violent landslides.

Catastrophic geological events, such as earthquakes or volcanic eruptions, may have short-term effects on our climate, locally or regionally, and often even globally. The global effect of the ash eruption of Mount Pinatubo has already been mentioned. One of the worst environmental catastrophes of recent times caused by volcanic explosion was the eruption of the Indonesian volcano Tambora in 1815. It ejected about eight times as much material into the atmosphere as the eruption of Pinatubo in 1991. People in the eastern United States spoke of the following year, 1816, as the year without a summer. Some 75 000 years ago, an even more massive volcanic explosion occurred on the island of Sumatra. Two hundred times more material than in the Pinatubo blast of 1991 was ejected into the atmosphere, and a 40 km wide crater was formed, now known as Lake Toba. It is widely believed that this event caused global cooling that triggered one of the coldest phases of the last Ice Age.

It has been hotly debated whether, at various stages in Earth's history, extraordinary volcanic activity could have catastrophically altered the global environment to the detriment of life. Dust accumulation in the atmosphere has the potential to reduce sunlight, thereby causing temperature to fall, and lethal volcanic gases can poison ecosystems. Under such environmental stresses, species may become extinct and life may evolve in new ways. Figure 44 shows the largest flood-basalt provinces on Earth, regions of enormous size that were flooded by lava from large rift systems. We have already mentioned the Karoo volcanics of the Drakensberg and Lebombo regions. Several times in the history of Earth, the extrusion of huge volumes of flood basalt appears to have coincided with major mass extinctions. For example, the Deccan Traps, an up to 2 km thick basalt sequence in India, was extruded around the time of the Cretaceous–Tertiary boundary, and many scientists long favoured a relationship between global pollution from this event and the extinction of many species. Similarly, at Permian–Triassic boundary time, the Siberian flood basalts were extruded. This volcanic province comprises an estimated lava volume of 3 million km^3, some 500 times

the volume of the Toba caldera. The ensuing environmental catastrophe caused by toxic volcanic gases released into the atmosphere during this event could be the cause of the mass extinction at this time.

There are other causes of disaster that affect the atmosphere and hydrosphere of our planet. Movements of the oceans and atmospheric circulation combine to cause massive storms that are known as hurricanes (also known as typhoons or cyclones). These storms wreak havoc in large parts of the world every year. Hurricanes only develop where the water temperature is higher than 24 °C, in the tropics, and when the winds are calm. When thunderstorms occur under such conditions and close to the equator, the rotation of the Earth may cause them to band together around a low-pressure centre. Instead of dying out after a short time, such a storm system may continue growing as air is sucked into its low-pressure interior. Hot, moist air spirals up into a tightening vortex of rotational winds, and if the air pressure continues to drop, wind speeds may increase further, until a distinctive eye develops at the centre of the storm (Fig. 45).

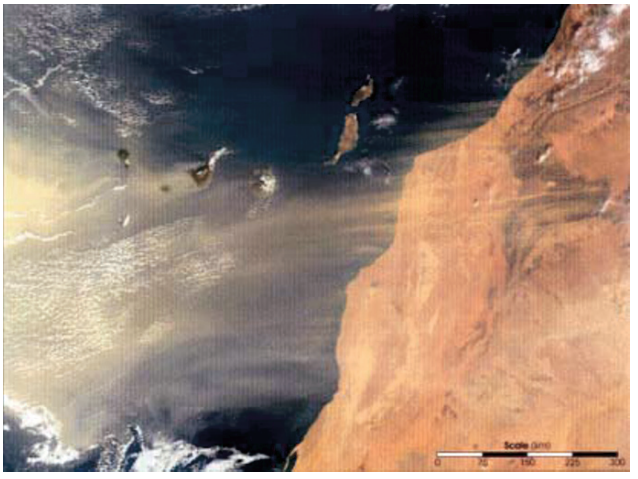
The sixth-strongest hurricane in United States history, named Katrina, made landfall on 29 August 2005. The floodwaves of up to 6 m height caused extensive failure of levees and widespread flooding in southern Louisiana and adjacent states. The major city of New Orleans had to be evacuated and was largely destroyed. One thousand eight hundred people lost their lives in the hurricane and subsequent flooding. More than a million residents of the affected region were displaced, and total damage is estimated to have been between 80 and 150 million US dollars. This makes Katrina the most costly hurricane ever recorded in the United States, despite it being classified as only of intermediate strength. Hurricanes (or typhoons, as they are known in Asia) occur regularly each year, and the possibility exists that global warming could lead to an increase in their frequency and severity.

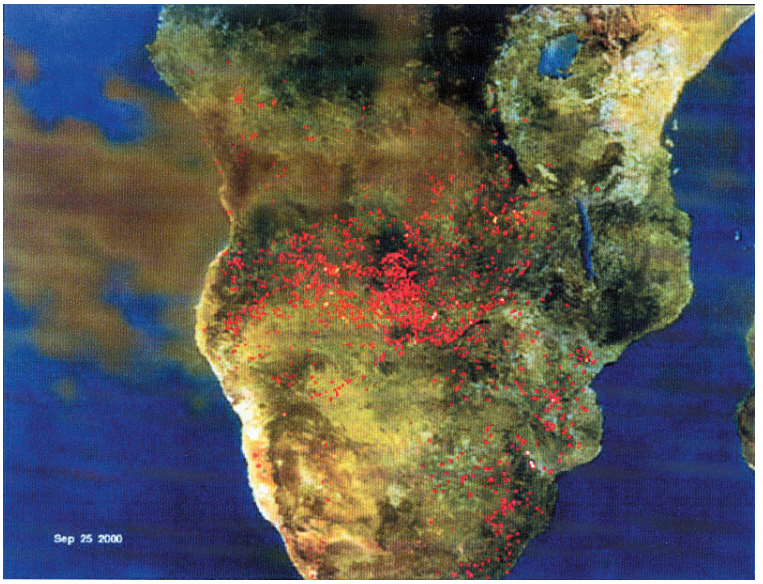
In some parts of the world tornadoes are feared as much as hurricanes. A tornado is a writhing funnel of rapidly spinning air that descends to the ground from the bottom of a large thundercloud. In its centre is a vortex that acts as a giant vacuum cleaner, sucking up and destroying everything in its path. On 18 March 1925, a single, record-breaking tornado travelling at speeds of up to 117 km per hour covered a distance of 350 km through the American states of Missouri, Illinois and Indiana in a mere 3.5 hours, killing 689 people and injuring a further 1 980. A large part of the American Midwest is annually threatened by tornadoes.

It is not only the excessive magnitude of storms that causes havoc; heavy and extended rainfall during a regular monsoon season in the broad region straddling the equator, or perhaps a freak hurricane, may be the cause of widespread flooding with resultant loss of lives and damage to property. This form of natural disaster affects millions of people annually. One of the worst floodings in recent times afflicted parts of China in 1991. The monsoon season started early and ended late, bringing exceptionally heavy rainfall, and some 220 million people, a fifth of the population of China, were affected by the flooding. An estimated 10 million people had to be evacuated from flood-damaged dwellings, and several thousand were drowned or fell victim to landslides triggered by the heavy rains.

The extraordinary rains of early 2000 that caused flooding in much of southern Africa, from Namibia to the particularly flood-ravaged Mozambique, are still very much remembered.

↓ **Figure 46:** A true-colour image by the MODIS system on NASA's Terra satellite, showing a massive dust storm blowing out of the West African Sahara Desert over the Atlantic Ocean in January 2002. The Canary Island archipelago was engulfed in one of the worst sandstorms ever recorded there. Image used with permission from NASA's Earth Observatory.





→ **Figure 47:** In August and September 2000 huge seasonal fires raged in south-central Africa and resulted in a thick cover of smoke. The fires indicated in red on this image were observed by the Advanced Very High Resolution Radiometer (AVHRR) instrument on the NOAA-14 satellite. These observations constituted a part of the SAFARI-2000 field study of air pollution over this region, in which research teams from several southern African countries participated.

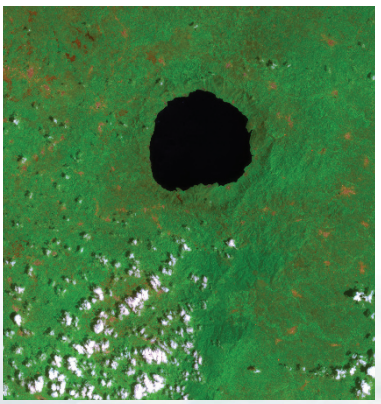
→ **Figure 48:** Aerial photograph of the Tswaing (Pretoria Saltpan) Crater and crater lake. Photograph by Herman Potgieter.

And yet, even limited rainfall can cause serious disaster. When soils become saturated with water, extensive debris flows (also called debris avalanches) can be the consequence. Downpours naturally enhance the danger of landslides and debris flows. Even countries in higher latitudes that are not normally endangered can be seriously afflicted by unexpected floods. For instance, flooding in southern Germany, the Czech Republic and vast parts of Austria, in August 2002, caused massive damage; and subsidiary landslides, especially in the Black Sea region of southern Russia, led to the loss of a significant number of lives.

While persistent rain has caused havoc in Central Europe, parts of Africa, including southern Africa, have experienced prolonged drought. When rainfall diminishes severely, or is absent entirely, over extended periods, drought may be the result. Annually hundreds of thousands of people globally are victims of this scourge, and certainly the African continent has been ravaged by it during this last century. The sad pictures related to the enormous loss of human life and livestock in the Sahel Zone of West Africa during the 1960s and later, or in the drought-ridden parts of Ethiopia and Sudan, are permanently imprinted on our memories. In some instances, human influences — through overextended land use or deforestation, followed by widespread erosion of soils or desertification, or, as recently in southern Africa, political decisions causing late or no planting of staple crops, and even sell-off of staple food reserves — may be contributing factors to such disasters. However, global weather patterns determined by oceanic processes (for example, the to-date still unpredictable influences of El Niño in the Pacific Ocean) and, sometimes, tectonic influences are the underlying factors causing such terrible plight.

A seasonal environmental problem, especially in southern Africa, but as we have seen in recent years also in the Indonesian archipelago, is fires caused by lightning or careless human behaviour, resulting in enormous smoke pollution and, possibly, massive destruction. In 2000, NASA and a number of institutions in southern Africa investigated the extent and consequences of this fire hazard under the SAFARI-2000 banner (Fig. 47).

Much effort by geologists and climatologists is put into the study of the climatic changes during historical and geological time, as they are recorded in the alternating layers of sediment deposits. Sediment records preserved in lake



← **Figure 49a:** LANDSAT 4 colour image (1990) of Lake Bosumtwi in Ghana. Lake Bosumtwi fills much of the 10 km impact structure that was formed about 1 Ma ago. This impact event is also linked to the Ivory Coast tektite-strewn field to the west and southwest of this structure. Image courtesy of NASA-John C. Stennis Space Center, USA.

↓ **Figure 49b:** Panorama of Lake Bosumtwi taken from the southwest of the crater rim. Image courtesy of Christian Koeberl.

beds are particularly important in this regard, as lake sediments may accumulate with far less disturbance than those in ocean environments. Such finely laminated lake deposits bear the climatological imprint of the time when they were laid down. For example, in times of heavy rainfall, sediment layers may be thicker and composed of coarser-grained material than sediment laid down in a drier period. The type of pollen or spores found within sediment layers can also provide a record of wetter and drier periods that would favour growth of different plants.

A 90 m long drill core from the central part of the Tswaing (Pretoria Saltpan) meteorite crater (Fig. 48), located about 40 km north of the city of Pretoria, has provided an exceptional 200 000 year record of past climates and vegetation, not only for that area but for the wider mid-latitudes of the southern hemisphere. Several other meteorite craters are possible sources for similar, or even longer term, palaeoclimatic records. For example, the one million year old Bosumtwi impact crater in Ghana (Fig. 49a, b) is host to a crater lake, at the bottom of which some hundred metres of sediment has accumulated. In July 2004 the crater was drilled to obtain a long-duration palaeoclimatic record for this part of equatorial Africa. Such information of past climates, and past climate change, may help us make predictions about future environmental changes.

Another type of natural affliction, also often caused by human interference, is land subsidence. Extraction of large amounts of oil or groundwater may lead to incidents of subsidence. This is a threat to which wide areas in South Africa are subject, especially those that are underlain by the carbonate rocks of the Transvaal Supergroup and in the immediate environs of the industrial hub of the Witwatersrand. Here, much groundwater has been extracted to satisfy the demands of the mining industry and the large population. The resultant sinkholes disrupt infrastructure and pose a growing safety threat.

Natural deterioration of land in the form of overgrazing is of strong concern in many regions of South Africa, including the vast Karoo basin and semidesert areas of the Northern Cape and Limpopo provinces. Desertification is widespread, and soil erosion, as a result of water run-off and wind, is unhindered because of the lack of vegetation. In many parts of Africa, this process has already caused the loss of vast tracts of arable country.

Storms may affect oceanic or continental regions alike. Another threat that originates in ocean realms is the tsunami. These are giant floodwaves, such as the up to 40 m high waves that were triggered in 1883 by the eruption of one of the volcanoes on the Indonesian island of Krakatoa, and that devastated the coastlines of Java and Sumatra. The waves swept far inland, destroyed hundreds of villages, and killed an estimated 36 000 people. In 1946, an earthquake near the Aleutian Islands in the northern Pacific Ocean triggered a 35 m high tsunami that caused minor damage and killed five people in that rather unpopulated area. But five hours later, a 12 m high wave beached on the east coast of the Big Island of Hawaii, 1 600 km from the source. Most of the island's capital, Hilo, was submerged; 165 people lost their lives and damage amounted to 26 million US dollars. The unprecedented destruction caused by the tsunamis that struck southeast Asia on 26 December 2004 has already been discussed (pages 59–60).

That tsunamis also occurred in the distant past is borne out by the fact that in various places around the Caribbean (for example on the island of Jamaica) rocks of foreign marine origin are found hundreds of metres high, in settings where they can only have been deposited by flood waves of gigantic proportions.

Processes that could lead to the formation of tsunamis (see Fig. 40) could be earthquakes triggered below an ocean causing the displacement of gigantic masses of rock and, consequently, of water, or underwater volcanic eruptions. A 10 m high tsunami beaching at the southwestern coastline of South Africa would not only wipe out most of Cape Town, but also countless people living along the Cape coastline. Particularly large tsunamis capable of transporting large blocks of rock to hundreds of metres above sea level may be triggered by meteorite impacts into oceans. This is a subject of ongoing study by impact-cratering specialists.

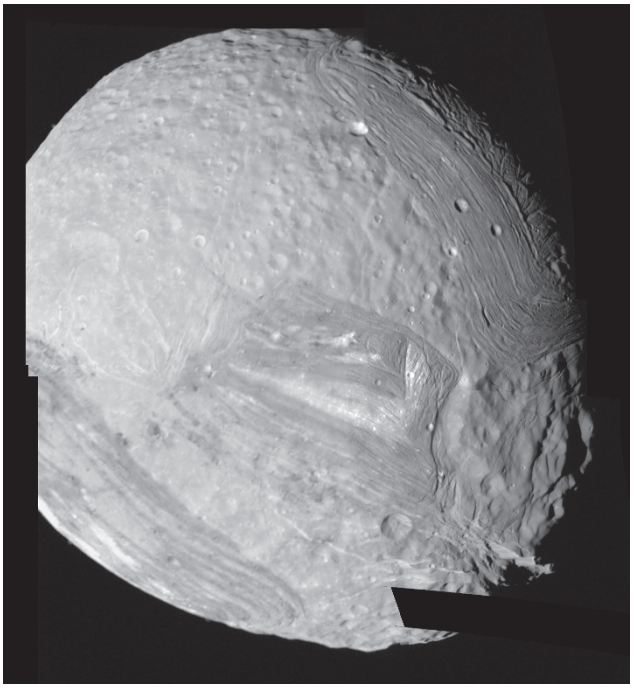
It has been shown that hundreds of thousands of lives may be lost in the worst disasters caused by processes that have their origin within the Earth, or that are caused by freak weather conditions on the surface of the planet. However, despite their proven severity, there remains an even more devastating threat to life on our planet — meteorite impact.

Meteorite-impact catastrophes

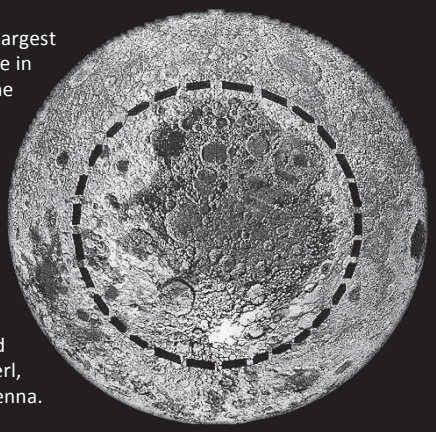
About 2 Ma ago, a large asteroid or comet impacted in the southern Pacific Ocean, near the southern tip of South America, into a 5 km deep water column. A 60 km wide and about 5 km deep crater, formed entirely in water and known as the Eltanin impact, was the result of this event (no crater formed in the ocean crust). Some workers believe that their modelling of this catastrophic event suggests that the tsunami produced could have been the most devastating effect of this impact. Some five hours after the impact, a 70 m high wave would have travelled about 2 000 km and would have just reached the coast of central Chile. After 20 hours, a 20 m high wave would have hit Japan on the other side of the Pacific Ocean. If it happened today, this would cause the death of many millions of people living close to sea level. The entire Pacific Ocean, with all its coastlines, would be affected, as well as a section of the Atlantic, with the tsunami there eventually making landfall along the western coast of Africa, also an extremely densely populated coastal region.

Particularly for impacts of relatively small objects into oceans, tsunamis may well be the form of disaster having the worst effect. The impact of an object not bigger than 400 m (of which there are thousands amongst the known Near-Earth Objects in the asteroid belt) anywhere into the Atlantic Ocean would produce a tsunami of 10 m or more in height that would seriously affect the densely populated coasts on both sides of this ocean. Some scientists think this effect may be overrated; however, society cannot afford being complacent even if there is only a small chance that such a tsunami could be triggered.

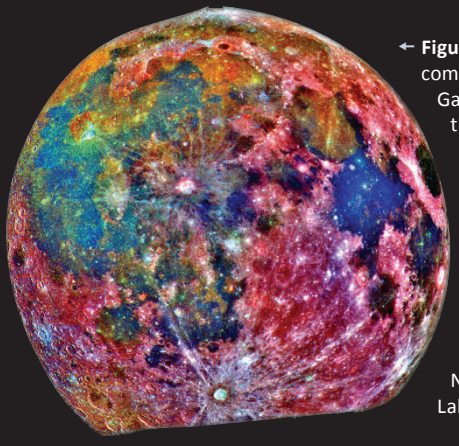
If relatively small impact events can cause catastrophes on several continents, what would be the result of a much larger, perhaps 5 or 10 km size, bolide from Space colliding with our planet? Can the possible damage be estimated at all, and can it happen again to us, or to future generations? To answer these questions, several lines of evidence can be pursued: first, we can look at the records of impact on other planets (such as the Moon, Mars or Mercury — see Figures 51 to 53) and from this past record calculate what the chance of a massive asteroid or comet blow may be in future; second, we can investigate the remaining signs of past impact events and their effects on the geology



→ **Figure 50:** Miranda, a moon of Uranus, of roughly 500 km diameter, consists of a 'jumble' of blocks with strongly different geological appearance. The prominent features of one block are cut off by an adjacent terrain. This has been interpreted to indicate that Miranda at one stage in its long history must have fallen prey to a large impactor, which totally disrupted it. This image (P 29541) was obtained by the Voyager 2 spacecraft in January 1986; courtesy of NASA.



→ **Figure 51a:** The largest known impact structure in the Solar System is the South Pole-Aitkin basin, of about 2 500 km diameter, in the region of the South Pole of the Moon. The crater is heavily impacted by younger structures. Photo courtesy of Lunar and Planetary Institute (Houston) and Christian Koeberl, University of Vienna.



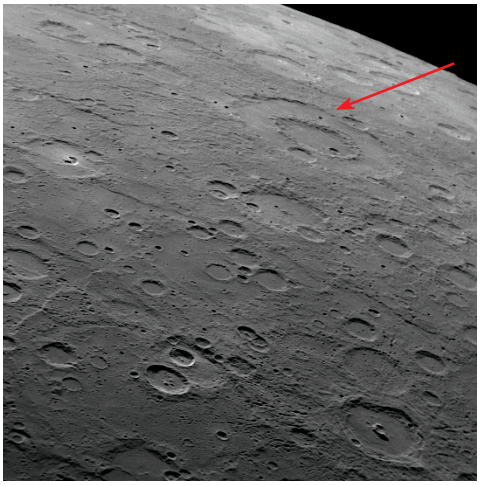
← **Figure 51b:** False-colour composite image, made from 15 Galileo Space Probe images, of the heavily cratered near side of the Moon. The crater at the bottom, with sharp, well-defined rays of ejecta, is the very young impact crater Tycho, of 85 km diameter. It must have formed relatively recently, as the ejecta have not been obliterated by later impact events. Courtesy of NASA and Jet Propulsion Laboratory, Pasadena.

and biological evolution of Earth; and third, we can study meteorite craters on Earth that provide natural and accessible laboratories, and by such detective work obtain clues regarding the catastrophic force of an event of a certain magnitude. Finally, we can use astronomical methods to investigate Space around us to identify potentially threatening bolides and consider protective measures.

All solid planetary bodies of the Solar System have surfaces that are densely peppered with impact craters of different sizes, witnesses of past impact events involving projectiles ranging in size from massive asteroids and comets to tiny dust particles (Figs 50–53). The Moon is a prime example (Figs 19, 51). Even with the naked eye and standing on Earth, about 385 000 km from the Moon, is it possible to discern some of the huge impact features on its surface, some more than 1 000 km across. These dark areas are impact basins that have been flooded by volcanic magma (these dark basins are known as *maria*, i.e. Latin for seas).

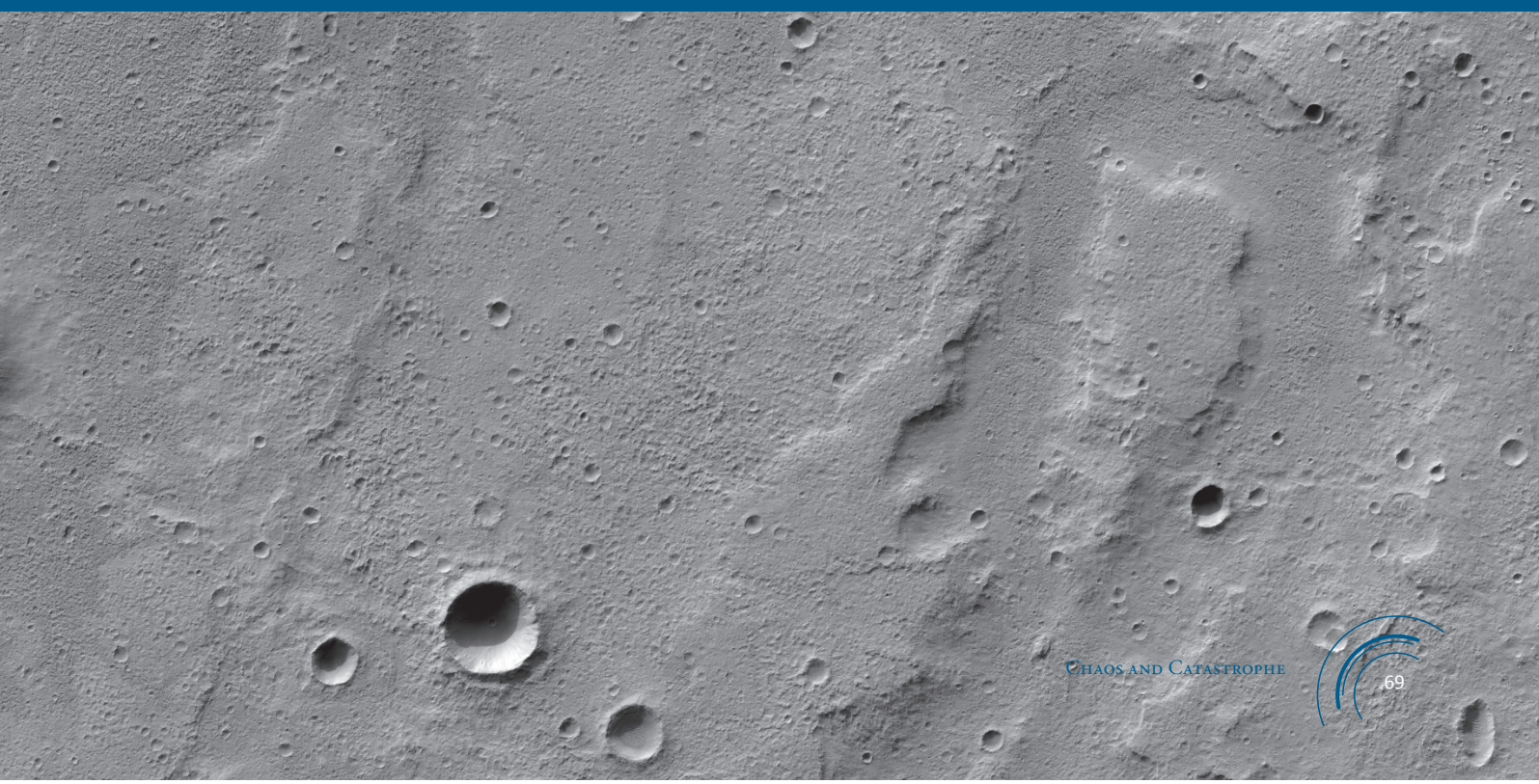
The Moon also reveals changes in the number and sizes of impactors that have bombarded it since the formation of its solid crust. The large impact basins are all about 4 000–3 800 Ma old, as we have learnt from age dating of samples returned from the Moon in the course of the

↑ **Figure 53a:** Oblique view of the heavily cratered surface of Mercury from NASA's Messenger spacecraft, which completed its first close flyby of the planet on 14 January 2008. Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.



↑ **Figure 53b:** Messenger image of Mercury showing a variety of crater forms (simple, central peak, peak-ring), including the 190 km wide Dürer peak-ring crater (arrowed). Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/ Carnegie Institution of Washington.

↓ **Figure 52:** Recent exploration of the surface of Mars by NASA's Mars Reconnaissance Orbiter and its HIRISE (High Resolution Imaging Science Experiment) and the European Space Agency's Mars Express has provided unprecedented high-resolution remote-sensing images detailing the distribution of impact craters on the Martian surface. This image shows a section of the Southern Highlands of Mars. The numerous impact structures, with overprinting of younger onto older structures, demonstrate that this is an ancient surface region; the area shown measures about 15 km by 57 km. Features as small as 7.5 m in size can be resolved by the high-resolution imagery. Image courtesy of NASA and Jet Propulsion Laboratory. http://mars.jpl.nasa.gov/mro/gallery/calibration/images/Release_AEB_000002_0000_Red.jpg).



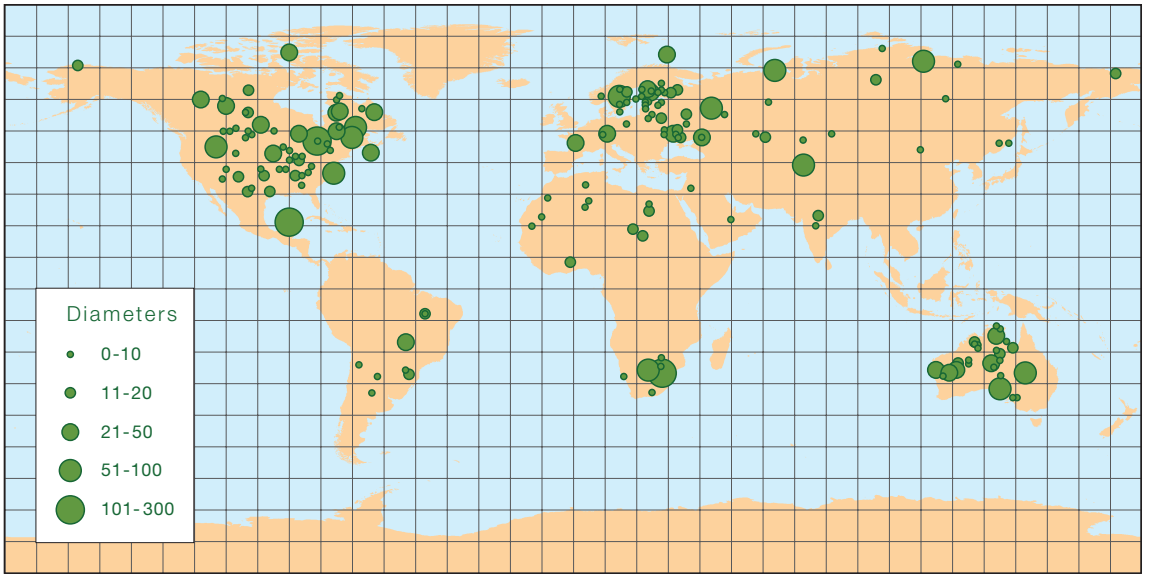


Figure 54: World map with locations of known impact craters and structures. Note the strong concentrations of known impact structures in North America, Europe and Australia. In Africa, impact structures are mostly known from Saharan Africa and southern Africa because of intensive oil exploration in the former and active impact research in South Africa.

American Apollo Space Programme. It appears that after this time large impactors, capable of producing such gigantic impact basins, became very rare in the Solar System.

The second line of evidence about past impact activity comes from direct geological study of the cratering record of Earth. In the 1940s, only five craters on Earth were thought to be meteorite-impact structures. As most geologists up until the early 1980s were convinced that at least the vast majority of crater structures on Earth had to be the result of volcanic activity, it took quite a while to unravel Earth's impact record. Unequivocal criteria for the distinction of impact craters from volcanic structures had first to be developed — and were found in the distinctive types of mineral deformation (known as shock metamorphism) that can only be produced under the ultrahigh pressures that result from a shock wave formed by the impact of a very fast (hypervelocity) body from Space. Today, slightly more than 175 impact structures are known on Earth (Fig. 54). In comparison with the intensely cratered Moon, this number only represents a fraction of the total number of craters that must have formed by impact over the billions of years since the earliest solid crust of the Earth was formed at ~4.4 billion years ago. This reasoning is based on the larger surface of the Earth relative to that of the Moon; what is more, Earth's mass is considerably more than that of its satellite. Thus, Earth has a much stronger gravitational pull on bodies coming into its vicinity, and its larger surface would have been hit proportionally much more often than that of the Moon. Clearly, these factors indicate that Earth must have endured more impacts than the Moon.

However, as discussed in Chapter 1, Earth, unlike the Moon, has remained a dynamic planet with a surface that is continuously recycled. Thus, much of the early impact record, in particular, has been erased. Compared with the significant number of very large impact basins on the Moon, only three such large impact structures, several hundred kilometres in diameter, have been recognised so far on Earth. They are the Chicxulub Structure in Mexico, the Sudbury Structure in Canada, and the Vredefort Structure in South Africa. The impact-crater record for our planet is strongly skewed to a very sizable number of young and small structures, because of their relatively better state of preservation.

Impact-crater statisticians must also consider that almost 70 % of the surface of our planet is covered by oceans. The ocean floor

is difficult to investigate for hidden impact craters and, if there are any, they could well be completely covered by thick piles of sedimentary rock laid down since these cratering events took place. Small impact events would only produce transient craters in the sea itself, which would rapidly disappear. Also, the entire expanse of oceanic crust on the surface of the Earth is recycled over a period of not more than about 200 million years. Much of the present oceanic crust is only 50 to 130 Ma old. In addition, there are large areas of continental surface that have not been studied in detail yet. Under these circumstances, it is no surprise that only a small fraction of the impact craters on Earth have been recognised to date. Only five impact structures are known from continental shelf areas, and none from deep-sea environments.

Despite their scarcity, the impact craters that have been identified on Earth have provided a basis from which much information regarding the nature of impact deformation of rocks and sediment, ejection and distribution of material from impact craters, and the physics of the cratering process itself has been gathered.

↑ **Figure 55:** Christian Koeberl (University of Vienna, Austria) and Uwe Reimold (right) visiting the famous Bottacione Gorge near Gubbio, Italy, to examine the very well-studied section across the Cretaceous–Tertiary (K–T) boundary. The boundary clay layer is visible as a centimetre-thick layer just above the light-coloured rock. Photograph courtesy of Dona Jalufka, Vienna.

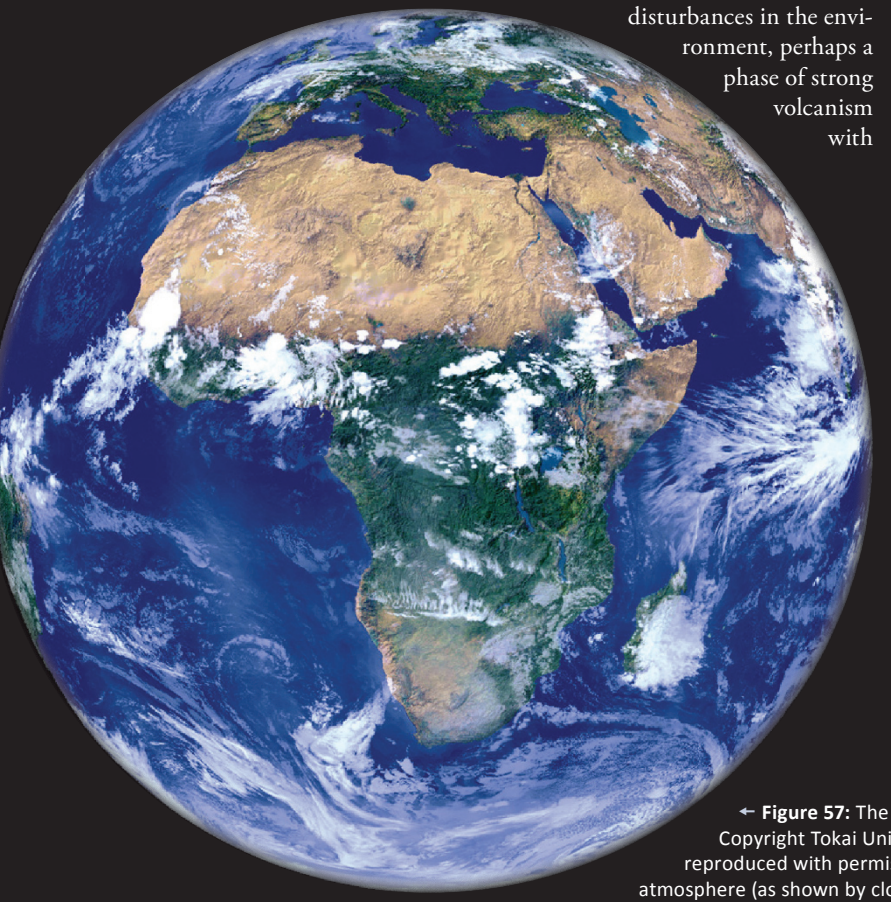
↓ **Figure 56:** Meteor Crater (also known as Barringer Crater or Coon Butte) in Arizona (USA). This classical simple bowl-shaped crater has a diameter of 1.2 km, very similar to the Tswaing Crater in South Africa. But, at just 50 000 years age, Meteor Crater is much better preserved than the ca 200 000 year old Tswaing Crater. Photograph courtesy of the Barringer Crater Company.

Normal (background) versus *mass* extinctions

Since the times when life began to flourish on this planet, especially since the 'explosion of life' in the Cambrian period about 500 to 550 Ma ago, numerous species have become extinct. This is still the case today. Changing climates cause some biological species to lose their habitat and, if they cannot adapt quickly enough, they die out. This is a process that takes place continuously and is known as background extinction. At certain times though, the number of species that has suddenly disappeared has been much larger than the normal background extinction. One could think that small disturbances in the environment, perhaps a phase of strong volcanism with associated ejection of noxious and poisonous gases, or a change in water temperature, or perhaps a reduction in the size of oceans (a so-called regression), could have caused the extinction of some life forms at such times. However, at several times in the biological record large proportions of all existing life forms succumbed, apparently more or less simultaneously (see Box, page 73).

These momentous events in the history of life on Earth include mass-extinction events in the Late Ordovician (~450 Ma) and the Late Devonian (~370 Ma), and at the Permian–Triassic boundary (251 Ma), Triassic–Jurassic boundary (206 Ma), Jurassic–Cretaceous boundary (144 Ma), and Cretaceous–Tertiary (K–T) boundary (65 Ma). The latter is now commonly referred to as the K–P boundary, as the Tertiary period is now referred to as the Palaeogene. Throughout the 1980s, palaeontologists and geologists were embroiled in an intense debate about the nature and cause of the extinction event at the K–T boundary: did these animals and plants die instantaneously or over an extended period, and were they killed by the effects of normal geological processes (such as volcanism or other environmental problems), or as the result of a massive meteorite strike?

This debate was triggered in 1980 by the findings of apparently elevated levels of the element iridium and the other platinum-group elements in rocks at several sites worldwide, exactly at the stratigraphic position of the K–T boundary (Fig. 55). As the platinum-group elements are strongly enriched in extraterrestrial meteo-



← **Figure 57:** The Blue Planet. Compiled from NOAA satellite images. Copyright Tokai University Research and Information Center/EDC, 2004, reproduced with permission. Earth is a unique planet in having both an atmosphere (as shown by clouds) and a hydrosphere (the oceans shown in blue).

ritic matter, the idea that an extraterrestrial projectile was its source was not so far-fetched. In addition, the interelement abundance ratios for these elements also indicated strongly that a meteoritic component was involved. Many palaeontologists were, however, convinced that the extinction of these species, including most of the dinosaurs, was gradual — they had not been wiped out instantaneously by a rock or giant piece of ice. They had to admit, however, that the records were sketchy and somewhat contradictory. Within four years of this debate, shock-metamorphosed quartz was found in the thin rock layer that marks the K–T boundary. Soon this discovery was followed by other impact-diagnostic evidence, such as zircon crystals with microscopic shock-deformation signatures in K–T boundary sediment and spinel crystals that suggested that they were crystallised from a vapour plume caused by an impact event. These crystals contained high abundances of nickel, another element that is enriched in meteorites, in comparison with the rocks of the Earth's crust. Furthermore, presence of soot in the global K–T layer suggested that wildfires had burnt around the world at that specific time.

While the debate about the mass extinction continued, impact workers began the search for the related impact crater, the so-called 'smoking gun'. Much evidence, such as the distribution of shocked-quartz locations and an apparent increase in grain size of shocked-quartz grains, pointed towards a likely site in or around North America, but all impact craters known there were either too small or gave the wrong ages. Then, in 1991, attention was drawn to Mexico, where information from oil exploration (that incidentally had been in the scientific records for nearly twenty years!) had been resurrected. It indicated the presence of a very large crater feature on the edge of the Yucatán Peninsula, centred close to the town of Merida. Once shock-metamorphic evidence from this structure had been collected, it quickly became famous as the Chicxulub impact structure. The size of the Chicxulub Structure, as determined by geophysical analysis, has long been quite controversial. Sizes between 180 and 300 km have been favoured by different groups of scientists. Currently, the 180 km value is favoured by most Chicxulub analysts.

It was not long after this discovery that melt rock was detected in drill core from this structure. Rock crystallised from a melt (magma or impact melt) is very suitable for the application of radiometric-dating techniques. Obviously, impact melt forms as a direct consequence of an impact event, and its age, if well constrained, can be used to assign an age to an impact event. The Chicxulub impact melt and, thus, the impact itself, was dated at exactly 65 Ma, indistinguishable from the accepted age of the K–T boundary and its related mass extinction.

The Chicxulub structure has since been widely accepted as the crater formed by the bolide that ended the era of the dinosaurs. The long debate about its size is not as trivial an issue as it may seem. Indeed, it would be helpful to know what kind of impact magnitude is required to wipe out global life completely, or to

Major mass extinctions in the history of Earth

Period	Time (Million years)	Comments	Calculated loss of species
End-Ordovician	ca 450	26 % of families extinct	84 %
Late Devonian	375–355	22 % of families extinct (several separate events)	79 %
End-Permian	251	51 % of families extinct	95 %
End-Triassic	206	22 % of families extinct	79 %
End-Cretaceous	65	16 % of families extinct	70 %

leave a few remnants of evolved life for future redevelopment. More specifically, the question that needs to be asked is: "Would the formation of an impact crater of 100 or 200 km diameter cause an environmental catastrophe of such magnitude that many (perhaps most) life forms will not survive?"

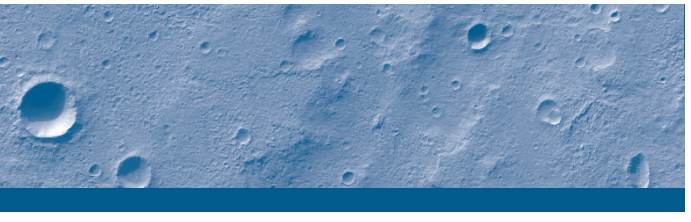
The Smoking gun!
Chicxulub in Mexico

There are a few sceptics remaining who continue to prefer a volcanic cause for the K–T boundary extinction event. They promote a scenario that involves massive degassing of poisonous gases from the gigantic volume of lava that forms the thick layer of magmatic rocks known as the Deccan Traps in central India, although it has been established that much of this event took place at a slightly different time than the K–T boundary. The evidence for shock deformation in K–T boundary rocks from around the world has continued to grow, and leads inexorably to the conclusion that impact played a pivotal role in this mass extinction. Recently, a few researchers have proposed that more than one impact event could have taken place around K–T boundary times. Based on sedimentological studies they suggested that more than one layer of impact ejecta is present in the vicinity of this boundary and that a major impact event occurred some 200 000 to 300 000 years prior to the Chicxulub catastrophe. This is strongly disputed by the majority of K–T boundary and Chicxulub workers who stress that ejection of material from the Chicxulub impact and the mass extinction mark the same short time interval; that is, that the Chicxulub event occurred at the end of the Cretaceous and exactly marks the mass-extinction event.

Modelling of the catastrophic environmental effects of such a large impact event has proven that the results of the impact of a 5 to 10 km size body from Space could easily result in the complete demise of a global population of continental and marine fauna and flora. It has been demonstrated that some species had already died before the K–T mega-impact event and that a good number survived this catastrophe (including a few dinosaur species). Of course, the K–T impact at Chicxulub chanced upon a particularly deadly location in the shallow Caribbean ocean above a crust covered with thick successions of marine carbonate and sulphate (the mineral anhydrite, $CaSO_4$) deposits. This had the effect that thousands of cubic kilometres of dust and rock were ejected from the impact crater, together with vast amounts of water, CO_2 and, especially, SO_2 that were released into the atmosphere. Perhaps as much as 10^{14}–10^{15} kg of sulphur dioxide and nitrous oxides were injected into the atmosphere, where they probably combined with water molecules to form acid rain. On the continents wildfires abounded, as the presence of soot at K–T boundary sites from New Zealand to North America, on opposite sides of the planet, has shown. These consequences must have drastically altered the environment into a hostile realm for nume-rous species. For instance, the acid rain is likely to have killed off all near-surface life in the oceans, especially life forms that had carbonate shells and much of the plankton, including the foraminifera. Wildfires on the continents drastically reduced the vegetation available to plant-eating

animals (herbivores). Thus, the marine and the continental food chains, essential for highly evolved life forms, such as the large dinosaurs, had been destroyed. Those life forms that are considered more resilient, such as the small plankton creatures known as radiolaria, with their silica shells, also perished, probably because of a lengthy period of 'impact winter' resulting from the dust-laden and smoke-filled atmosphere that blocked out the sunlight for many years. This initial cold (for at least a few months) would have been followed by global warming. The temperature would have risen because of the carbon dioxide (CO_2) released from impacted carbonate rock — leading to a greenhouse effect (rapid warming of the surface of the Earth), but on an unprecedented scale. All these effects were felt around the world, killing off the Cretaceous flora and fauna and, inadvertently, creating the opportunity for the rapid development of mammals, which could expand into most of the ecological niches once occupied by the dinosaurs.

In the 1990s, intriguing evidence was unearthed in North America that suggests that the dinosaurs themselves might also have risen to dominance from an impact catastrophe.



These species had been around for some time, but they really came into their own around the time of the Triassic–Jurassic boundary at about 200 Ma ago. A group of researchers has recently detected, in a thin layer of rock deposited at that time, a slight enrichment of the element iridium. This Triassic–Jurassic boundary enrichment in iridium coincides with a sudden spurt in the longer-term record of fern spores, signalling a change in flora and environment, and this particular site is also known for a sudden and very strong increase in the number of observed dinosaur tracks. This could mean that dinosaurs suddenly began to flourish and proliferate at that time, because other species had perhaps been suppressed by dramatic environmental change. Is it possible that an impact event benefited the reign of the dinosaurs and, ironically, another caused their demise?

If Earth had been populated by advanced life forms when the Vredefort Structure formed about 2 billion years ago, a similar global biological catastrophe would have happened. At an original diameter of 250–300 km, this giant impact structure is even larger than Chicxulub, and a global environmental catastrophe would have been inevitable. The Vredefort impactor might have found a shallow sea in its target area, and definitely a thick succession of carbonates of the Chuniespoort Group. Consequently, the atmosphere would have become enriched in CO_2. Dense dust clouds would have been injected into the atmosphere, blocking out the sunlight. Vredefort would have yielded all the ingredients for a decisive alteration of the living conditions on Earth. However, whether the only inhabitants of our planet at that time, the stromatolite-building cyanobacteria, experienced problems because of such a change, is not known.

VREDEFORT
IMPACT AND LIFE...

Ever since impact has been accepted as the cause of the environmental catastrophe at the end of the Cretaceous period, much work has been dedicated to investigating whether large-scale impact could explain the other known mass extinctions in the history of the Earth. Whereas unambiguous evidence for a gigantic impact catastrophe at the K–T boundary has been established and even the 'smoking gun' for this event has been identified, all evidence that has, to date, been presented in favour of large impact events at any of the other mass-extinction times has either remained highly controversial or unconfirmed (such as reports of shock-deformed quartz grains and enrichments of iridium from the Permian–Triassic boundary).

A brief look at the impact record in the Solar System

How did impact science get started?

With forty years of Space-exploration experience behind us, our Space-age generation knows very well what the Moon is, how it most likely came into existence, and what the dark 'spots' on the surface of the Moon are. However, just 400 years ago, when Galileo Galilei and his contemporaries made the first use of the earliest, crudely constructed, telescopes to explore Earth's companion, the Solar System had not even been recognised. Worse, it was considered heresy at the time to believe that planets, such as Earth, were orbiting around the Sun, or even that the Earth was round. The possibility that large solid bodies were able to travel through Space and collide with planets in their path was even more unthinkable at that time.

Galilei saw circular spots and, by watching the switching shadows on their edges, he deduced correctly that these areas represented depressions, i.e. crater forms. He also noted central elevations in many of these features and that some were covered with dark material. However, with regard to the true nature and the origin of these structures, this great scientist did not express a particular opinion. Not long after the first description of Lunar surface features, many other astronomers took up the study of the Moon. In contrast to earlier studies based on visual observations, Lunar maps, much more detailed because of the telescopes now available, were produced from about 1645 on, and many features on the surface of the Moon were named. In the mid-1660s, scientists first began to debate the origin of these circular features. In 1664, Robert Hooke (1635–1703) conducted some proper scientific experiments and concluded that the Lunar structures were similar to the vesicles forming on the surface of a pot of boiling alabaster. Interestingly, he first carried out some simple, but nevertheless real, impact experiments and indeed noted the similarity between his self-made craters and those on the Moon. Alas, he then followed the doctrine of his time and concluded that there are no bodies between the planets that could fall onto the Moon. Consequently, he accepted the second-best option, the one pertaining to the boiling alabaster, and proposed that some kind of gas explosion was responsible for these structures.

Many observers in the 18th and 19th centuries subscribed to a volcanic origin for the Lunar craters. The famous astronomer William Herschel even reported in 1787 that he had observed a volcanic eruption on the Lunar surface. But, occasionally, an impact hypothesis was mooted as well in those early days of modern science. For example, the Bavarian astronomer Franz von Paula Gruithuisen in 1829 discussed a possible impact origin for the Lunar craters. Unfortunately, this same astronomer had earlier reported discoveries of ruins of a city and even of human beings and animals on the Lunar surface, and this obviously did not improve the chances of his new crater theory being accepted.

By the end of the 18th Century, after several meteorite falls had been observed in Europe, the possibility that rocks could come from Space had been recognised. Another hundred years later, in 1890, an American geologist, Grove Karl Gilbert, carried out a series of simple impact experiments in his hotel room: he let little projectiles drop into targets made from clay and studied the crater forms resulting when the size of projectiles and the heights from which they were released were varied. Gilbert was a well-respected geologist. He had become Chief Geologist of the United States Geological Survey and later President of the Philosophical Society of Washington. In 1892, he published a paper entitled 'The Moon's Face; a study of the origin of its features'. Gilbert concluded that the craters on the Moon could be of meteorite-impact origin and pointed out differences between Lunar craters and craters on Earth that could be directly linked with volcanism. He also arrived at the correct deduction that rays

emanating from some craters on the Moon represented ejected material (Fig. 51b). This visionary did, however, blunder badly when it came to the origin of the world's most famous meteorite impact crater: Meteor Crater (also known as Barringer Crater) in Arizona (Fig. 56). This structure was known to Gilbert as Coon Butte and he was convinced that this crater was of volcanic origin — to be precise, of cryptovolcanic origin. (The term cryptovolcanism means some kind of volcanic eruption of cryptic, or unknown, nature.)

In the 1880s, a New Zealander and Professor of Physics, Alexander Bickerton, published some material about 'massive impacts having shaped the face of the planet', but he was largely ignored by the scientific community. Despite these early insights, by the 1920s few scientists accepted the possibility that certain craters on Earth could have been formed by meteorites.

Another eminent scientist with an opinion about the Lunar craters was Nathaniel Southgate Shaler (1841–1906), Professor of Palaeontology and Geology, as well as Dean of the Lawrence Scientific School at Harvard University. In 1903, he wrote: "… the fall of a bolide of even ten miles in diameter…would have been sufficient to destroy organic life of the earth." While this could have been a premonition of the K–T boundary extinction theory, Shaler applied this argument against the impact hypothesis for Lunar craters: "…yet life has evidently been continued without interruption since before the Cambrian time". Shaler believed that Lunar craters were of volcanic origin.

One person who subscribed to the impact theory was Daniel Moreau Barringer, a Philadelphia businessman, who was convinced that Coon Butte was of impact origin. He accepted that small pieces of metal found around the crater represented nickel-iron of meteoritic origin. He also led an ongoing debate with the leading geologists of his time, who summarily subscribed to a volcanic origin for this crater. However, Barringer got one thing wrong: he was convinced that a large mass of meteoritic nickel-iron was buried in the crater floor and that Coon Butte could be a most valuable nickel source (this element had been recognised towards the end of the 19th Century as a strategic metal, as it could be used to harden steel, a discovery particularly valued for its military applications).

In 1903, Barringer secured the land rights over Coon Butte. The first detailed examination of the crater revealed a number of facts that Barringer could not accept as being reconcilable with an internally triggered explosion. For example, huge limestone blocks that had been ejected from the crater were apparently too heavy to be forced outwards by a gas explosion. Whereas most geologists ignored or rejected the presentations of Barringer and his associate and friend Benjamin Tilghman, the well-reputed geologist and secretary of the Geological Society of America, Herman Fairchild, reported their findings in 1906 at the Annual Meeting of this esteemed body and proposed the name 'Meteor Crater', which stuck.

Barringer proceeded to drill the crater, convincing various financial backers to pour vast amounts of money into the exploration of this structure, but remaining unsuccessful. A number of scientists soon came to the conclusion that it was highly unlikely that a significant proportion of the meteoritic bolide could have survived an impact explosion. More than US$ 600 000 was ultimately spent in the unsuccessful drilling of the crater. However, the Barringer family have retained the business rights over Meteor Crater, which is now well developed as a tourist and educational attraction. To the benefit of all impact-cratering science, the Barringer family has for many years supported impact-cratering researchers.

During Barringer's early investigations, another distinguished geologist, George Merrill of the Smithsonian Institution in Washington, visited Meteor Crater and quickly became convinced that the impact theory for this crater was correct. He also observed some strange rock formations, such as a porous type of sandstone that appeared melted and vesicular. Much later when it had been established that this material was silica glass, it was named Lechatelierite, in honour of the famous French chemist, Henri Le Chatelier, who had carried out studies of silicate compounds. In order to produce this glass, a temperature in the order of 1 570 °C is required; a condition that is not easily attained by other geological processes at the surface of the Earth, and that is far hotter than any material erupted from volcanoes.

Another remarkable scientist, this time in Germany, showed true vision. The meteorologist Alfred Wegener had, as early as 1915, published

the basics about the theory of Continental Drift, the theory that the crust of the Earth is composed of plates that move relative to each other. It was this early work on which, much later, in the 1960s, the theory of plate tectonics was based, which now forms a cornerstone of modern geology. In 1921 Wegener published a booklet entitled 'Die Entstehung der Mondkrater' (The origin of the Lunar craters). In this work, he discussed both the 'bubble' and the 'volcanic' hypotheses for their origin and decided that neither provided an acceptable solution. In the winter of 1918–1919, he conducted a systematic series of impact experiments to investigate his own ideas, which he called the 'Einsturztheorie' (Collapse Theory). His admittedly crude experiments comprised throwing, with a table spoon, cement powder onto a target of the same material, then carefully wetting the surface of the deformation features thus created, which allowed him to investigate the resulting 'craters'. These attempts were successful in forming both central elevations and ejecta rays, as observed in the Lunar craters.

Both Wegener and Gilbert had one problem, however: they were disturbed by the fact that all Lunar craters were basically circular, whereas they expected that low-angle impacts should result in elliptical crater forms. Later, it became clear that impact of a large bolide at hypervelocity represents an explosion followed by a spherically propagating shock wave and, largely irrespective of the impact angle, the resultant crater will nearly always be circular. There are, however, some presumed impact features that have decidedly ovoid forms and appear to have been formed when projectiles entered the atmosphere at very low angles or even grazed over the surface, for example the Rio Cuarto crater field in Argentina.

In 1908, a huge explosive event occurred in the region of Siberia known as Tunguska. No crater was found, eventually leading to the conclusion that the bolide exploded in the upper atmosphere. However, study of this event led some Russian scientists to propose an impact theory for the formation of other terrestrial craters as early as the 1930s.

Besides Meteor Crater, the small Odessa Crater in Texas, the Wabar structures in Saudi Arabia, and a group of very small craters in Australia known as the Henbury crater field, were described early in the 20th Century. One American, in particular, took note of these reports: Harvey Nininger. Nininger was a dedicated meteorite collector, but he also visited Odessa and several other so-called cryptoexplosion structures. This coincided roughly with the important discoveries of the first known asteroids, which provided crucial new evidence in the framework of celestial mechanics. In the 1930s and early 1940s, Nininger also wrote about what would happen if much larger projectiles than meteorites would hit the Earth. He was one of the earliest to realise the very real danger of mass destruction and global environmental devastation, and he made reference to certain boundary layers in the geological record as possibly being related to impact.

In the mid-1930s, a number of geologists, quite independently of one another, investigated several crater forms on several continents and concluded that they could represent meteorite impact craters. First, in 1933, H.P.T. Rohleder reported on the Pretoria Saltpan crater (now known as the Tswaing Crater; Fig. 48) in South Africa and compared it with the Steinheim basin in southern Germany. He favoured an impact origin for both of these structures. However, Rohleder also concluded, erroneously, that Bosumtwi Crater in Ghana (Fig. 49) was not of impact origin.

In 1936, J.D. Boon and C.C. Albritton Jr. published a discussion of several large crater forms, including a first reference to the Vredefort Dome (or Vredefort Ring, as it was then known) in South Africa, and proposed that all these structures could be the result of impact of large extraterrestrial projectiles. They particularly discussed the formation of central-uplift structures because of rebound after enormous compression resulting from the impact of a large projectile. However, their findings were not very widely accepted and, unfortunately, they were published in a somewhat obscure journal.

In the opposing camp, Walter Herman Bucher, a well-known professional geologist in America, carried out detailed studies of a number of craters and, especially, of dome-shaped, near-circular features. He received considerable recognition for his publications on a so-called 'cryptovolcanic' origin of these structures in the 1920s and 1930s. By 1936 he had listed six definite examples of cryptoexplosion structures, namely Serpent Mound, Jeptha Knoll, Upheaval Dome, Decaturville, Wells Creek, and Kentland (the majority of which have since been confirmed as impact structures). Others,

such as P.B. King, remarked later that there were similar structures elsewhere, such as the large Sierra Madera Dome in Texas, a structure which, according to him, "invited comparison with the Vredefort Dome" in South Africa. Despite the uncertainty about the actual nature of his favourite cryptoprocess, Bucher's paper continued to be quoted well into the 1970s and 1980s. A prominent South African scientist, Louis O. Nicolaysen, embraced the cryptoexplosion hypothesis, and for many years endeavoured to link crater structures on the surface of the Earth, including Vredefort, with processes perceived to take place deep in the interior of the planet.

At the time when the first list of meteorite craters was produced by L.J. Spencer in 1933, most of the listed structures had been classified on the basis of finds of meteoritic debris. When the eminent meteoriticist, F.C. Leonard, published his list of authenticated meteorite impact craters in 1946, it contained no more than 10 structures: Meteor Crater in Arizona; Odessa in Texas; the Henbury craters of Australia; Wabar in Arabia; Campo del Cielo, Argentina; Kaalijärv in Estonia; Tunguska, Siberia; Haviland in the USA, and the Boxhole and Dalgaranga structures, also in Australia. By the 1950s, only two more sites of probable meteorite-impact origin had been added (Wolfe Creek in Australia and the Sikhote-Alin meteorite field of eastern Siberia), but a few more possible meteorite craters were considered. Amongst these seven were also a number of structures in Africa: Aouelloul in Mauretania and Talemzane in Algeria, and the Pretoria Saltpan and Vredefort in South Africa. The small Pretoria Saltpan crater, located north of Pretoria, resembled Meteor Crater in Arizona in form and size; however, its origin remained controversial until the 1990s, when definitive proof for its meteorite-impact origin was finally obtained after drilling of the crater (see Chapter 3).

By the 1940s, telescope-based astronomy had shown that the Moon is covered by innumerable craters. They had been well described, classified, and labelled, but their origin was not resolved. In the 1940s, two very important contributions about their likely origin were made by Fletcher Watson who, in 1941, published a popular book 'Between the Planets', in which he discussed the various types of small bodies (meteorites, asteroids and comets) travelling through the Solar System. In 1949 Ralph Baldwin published his book 'The Face of the Moon'. Many researchers of the Moon and of impact cratering consider this work one of the most important contributions of the 20th Century. Baldwin compared the geometric characteristics of craters formed by the explosions of bombs with those of crater structures on Earth and on the Moon. His graphic representation of the depth-versus-diameter relationships for these craters linked explosion craters with those natural craters of unknown origin. He demonstrated that the Lunar craters could not be of volcanic origin. Furthermore, Baldwin compared the size distribution of known asteroids with the distribution of sizes of Lunar craters and showed that they matched quite well. He also predicted that the dark *maria* on the Moon's surface represented lava flows filling large impact basins, and he made a direct connection between the explosions that formed craters on the Moon and the disastrous consequences such impacts would have on Earth. It was only after the return of samples gathered by the Apollo crew from the Moon in the 1970s that the full significance of the work of Baldwin was realised.

† **Figure 58:** An oblique view of the 2.5 km diameter Roter Kamm Crater in Namibia. Image courtesy of Christian Koeberl, University of Vienna, Austria.

Two other visionaries were at work in the 1950s: Allan O'Kelly and Frank Dachille published a book 'Target: Earth' in 1953. The

authors suggested that the dinosaurs were wiped out by the impact of a large asteroid, nearly thirty years before this hypothesis was considered in earnest by a wider group of scientists. This early insight also had some hilarious spin-offs: the American film industry of the 1950s embraced anything that spelled doom and chaos, including some memorable Hollywood productions dealing with the danger of asteroid impact. The 1990s saw another spate of such films, obviously spawned by the celestial fireworks of the impact of comet Shoemaker-Levy 9 into the atmosphere of Jupiter. Films such as 'Deep Impact' and 'Armageddon' endeavoured to combine the very real danger of asteroid or comet impact with surrealistic Space adventure and heroism. Despite some obvious inconsistencies, these cinematographic efforts have, nonetheless, provided entertaining educational material.

When the Space Race between the United States of America and the USSR began in the late 1950s, satellite imagery was added to the telescope arsenal for planetary exploration. This further demonstrated the ubiquitousness of craters, on a range of several size scales, on the surface of the Moon. Still later, unmanned Space probes, such as the Pioneer and Voyager crafts of the 1980s sent back pictures that left no doubt that the surfaces of all solid bodies in our Solar System are heavily cratered (for example, Mercury, Figs 10, 53).

Figure 59: Intricate array of small (just a few centimetres high) shatter cones from the Steinheim Crater, southern Germany. Courtesy of Dr Winfried Reiff, Stuttgart.

The next prominent impact-cratering pioneer was Robert Dietz. By the 1940s, Dietz had made a name for himself by embracing and promoting the concept of Continental Drift, which at that time still suffered a general lack of scientific recognition amongst his peers. Then, in the late 1950s, he drew attention, in a number of conference contributions and papers, to some geologic features that he suggested could be used to pinpoint and identify meteorite impact craters. Most important in this regard were his findings regarding a strange fracture phenomenon that he termed shatter cones (Fig. 59). Dietz observed them in abundance in the large Sudbury Structure in Canada, used them to predict that this structure was of impact origin and, in 1959, predicted that they would be found also in the Vredefort Ring in South Africa. Just one year later, the South African geologist, Robert Hargraves, published a paper describing shatter cones at Vredefort.

In the meantime, a small band of geologists had caught up with their largely astronomy-based colleagues studying planetary surfaces and engaged in serious geological analysis of a few confirmed meteorite impact craters such as Meteor Crater. The famous Eugene (Gene) Merle Shoemaker (Fig. 60) and his collaborators pioneered this effort and provided the first ideas of features that could be characteristic of meteorite craters, and could provide definitive recognition criteria. Other geologists, mainly in Canada, investigated a number of circular crater structures of still unknown origin and found the same features in their rocks that had been described from confirmed impact structures.

In the late 1950s another dimension of evidence was added, when geologists and physicists teamed up to investigate in the laboratory what would happen to rock samples impacted by artificial projectiles accelerated to velocities in excess of those achieved by bullets flying from a gun, but similar to those of extraterrestrial bolides. Experimental hypervelocity impact onto rock or mineral samples, the remnants of which could be recovered and studied with mineralogical and chemical techniques in the laboratory, produced the same pressures and temperatures that rocks experience when a huge chunk of extraterrestrial material smashes into the crust of the Earth. These experiments had one advantage, however: they were conducted under known pressure and temperature conditions. It was, thus, possible to determine the

conditions at which naturally formed rock and mineral deformation in impact craters had occurred. These rock and mineral deformation effects, together, are known as shock metamorphism, which refers to the changes induced by the shock wave from a projectile explosion.

Confirmation that these shock-deformation phenomena could be used to identify rocks deformed by impact came when the first rock samples were returned from the Moon by the astronauts of the Apollo Space Mission. The astronauts had been trained in Meteor Crater and in the Nördlinger Ries, a well-studied impact structure in southern Germany. The samples they brought back to Earth contained many of the shock-metamorphic features previously observed in rocks from impact craters on Earth and, by then, in many meteorites. However, no shatter cones, one of the widely accepted impact-recognition criteria, were returned to Earth, and this fact has since been used abundantly by those who still doubt the ubiquitous importance of impact cratering in the Solar System.

Gene Shoemaker, who had instructed the Apollo Mission astronauts about impact craters, never made it to Space — which had been his lifelong ambition; but his ashes were carried aboard the Lunar Prospector probe that NASA crashed into a Lunar crater on 31 July 1999 as part of a mission to investigate whether water is present on the Moon.

New discoveries of impact craters on Earth occur at a rate of one or two nearly every year. The experimental study of shock metamorphism continues, and new techniques with even higher precision are being developed to confirm impact deformation and identify traces of meteoritic projectiles by chemical and isotopic analysis of impact-formed rocks. Improved analysis of planetary surfaces, asteroids and comets continues to increase our understanding of the nature of the projectiles remaining in Space, and dating of large impact events in the rock record of our planet has allowed us to evaluate the past impact record and predict what the chances are of such a catastrophic event recurring in future.

In July 1994, a milestone in impact studies was reached when the fragments of comet Shoemaker-Levy 9 impacted into the atmosphere of Jupiter (Figs 12 and 13, page 26). These first-ever televised impact events brought home to billions of people the power of the impact-cratering process: the small fragments were not larger than 100 to 200 m across, but they ripped open the atmosphere of the giant gas planet, forming holes some ten thousand kilometres across that could easily have engulfed Earth. These impacts on Jupiter also demonstrated that planetary impacts are not merely a feature of the past, but very much a part of the present, and future. Projectiles with diameters up to a thousand kilometres remain in the asteroid belt and as long-period comets in the Oort Cloud and beyond. To comprehend the threat that these massive bodies pose, it must be kept in mind that the bolide that caused the extinction of the dinosaurs only measured a maximum of 10–15 km across.

If it is accepted that all bodies in our Solar System have been subjected to impact, it can be safely assumed that impact cratering has in the past affected, and still does affect, the rest of the Universe as well. Worlds have been built

† **Figure 60:** Unveiling a plaque in honour of the great pioneer of impact-cratering studies, Eugene M. Shoemaker (adjacent), at the Tswaing Crater on 14 July 1999, are Dr Carolyn Shoemaker and Dr Robin Brett. The plaque can now be visited at the crater view site on the southern side of Tswaing Crater.

through impact accretion, and worlds have been destroyed through impact. The asteroid belt between the planets Jupiter and Mars contains the rock debris of numerous planetary bodies that have been fragmented by impact events. Recently, the fantastic observations of the NEAR Shoemaker Space Probe, which ended with a soft landing on the 30 km diameter Eros 433 asteroid, have vastly improved our understanding of asteroids. Its pictures (Fig. 15a, page 27) illustrate that even these small bodies have an extensive history of impact. Many asteroids are, in all likelihood, nothing else but loose rubble piles of impact debris. On 4 July 2005 NASA's Deep Impact Probe successfully deployed a 372 kg copper sphere in the path of Comet Tempel 1 and monitored the resulting impact, gathering important data on the comet's core and the way that impacts occur (Fig. 17b, page 28). Several other missions aimed at studying and sampling comets are also underway or planned.

Craters on the Moon

The large, more or less circular, dark areas on the Lunar surface known as the maria (Figs 19, 51a) are huge impact basins hundreds to thousands of kilometres wide. The projectiles to generate these huge crater structures must have been very large (certainly much larger than 10–20 km in size) asteroids or comets. In the earliest phase of the development of our Solar System there were numerous bodies of such size around that could produce gigantic impact structures. The central basins of these impact structures are commonly surrounded by a number of ring features and, therefore, these impact structures are known as multi-ring basins. The largest impact basin known in the Solar System is located in the South Pole region of the Moon, where it was discovered in the mid-1990s by NASA's Clementine mission. The South Pole-Aitkin basin (Fig. 51a, page 68) measures an enormous 2 500 km in diameter, and has an average depth of 10 km. Clementine also showed that this polar region in all likelihood contains a significant amount of water in the form of a polar ice cap. Water is a major factor in the consideration of future Space travel or even Space colonisation. Not only would human Space travellers require water sources for their survival, but hydrogen could also be a vital component of spacecraft fuel. As Baldwin had already correctly deduced in the 1940s, the dark appearance of the maria is the result of these impact basins being filled with dark lava, which does not reflect sunlight well and, thus, gives the dark colour.

However, the lighter parts of the Moon's surface are not necessarily uncratered. Indeed, it is just the opposite. While the smooth maria surfaces often do not exhibit heavy crater density, implying that they are not very old (the older a region on the Moon's surface and, for that matter, on other planets as well, the more often it has been impacted), the light parts of the Moon's surface represent some of the oldest parts of this body. The oldest ages measured for rocks returned from these so-called Lunar Highlands are of the order of 4 400 Ma, in geological terms very close to the time when the Solar System formed (refer to Chapter 1). Being so old means that the highlands experienced the full brunt of the initial heavy bombardment at the time when the Solar System was still littered with numerous remnant blocks from the initial planet-building phase. Craters abound in the highlands, often overlapping one another. Ejecta were strewn all over, mixed by subsequent impact events, and were churned up again and again. It is estimated that where impact has taken place so often that the surface is saturated with craters, the soft soil covering the surface has been impacted and churned up at least 13 times. This so-called regolith soil is what Neil Armstrong jumped onto and where he left the first human footprint on the Moon, when he exclaimed: "A small step for Man, but a giant leap for Mankind". Regolith is full of the products of impact: glass spherules of impact melted rock, and mineral or rock fragments that display shock-metamorphic deformations. Some small particles may even show microscopic impact craters (so-called zap pits).

From the Moon to the Earth-Moon system

The Moon's origin has an even greater significance for impact scientists and planetologists. For much of the 20th Century debate centred around whether the Moon formed together with the Earth as part of a binary planet system, or whether it was captured by the gravitational attraction of the much larger Earth. However, the intensive geological exploration of the Moon's surface and the subsequent geochemical and isotopic laboratory analysis of lunar samples, some of which were exhumed by very deep impact-cratering events or volcanic activity, as well as geophysical investigation of the Moon's

interior, produced interesting results that did not fit either hypothesis. In addition to being able to study samples exhumed from the interior of the Moon by impact, the geophysical experiments were able to probe the interior of the Moon by following the travel paths and travel speeds of seismic waves through its bulk. Astronomical measurements had already provided very good estimates of the density of the Moon, a necessary parameter if the inner make-up of a planet is to be investigated, and the composition of the outer and inner zones (in analogy to the internal structure of Earth, also called Moon's crust, mantle, and core) debated. These investigations showed that there are distinct chemical differences between the overall (so-called bulk) compositions of the Moon and the Earth. This and some other physical factors provided strong indications that the Moon and the Earth did not form in exactly the same manner. To date, the preferred model for the origin of the Moon is known as the "Giant Impact Model".

A gigantic impact event, by a very large planetary body, roughly the size of planet Mars, which has a diameter of 6 787 km, likely occurred some 4 400 million years ago onto early Earth. This impact was probably not a direct 'head-on' hit that might have caused spallation and complete destruction of the target, but, more likely, a glancing blow that knocked a whole lot of material out of the early Earth. The projectile became completely disaggregated and, under the gravitational influence of the remaining Earth, the debris combined and formed a new planetary body from both projectile and Earth mass, the Moon, that took up an orbit in synchrony with Earth. As already mentioned in Chapter 1, the Moon formed mainly from impactor material, with some mantle material from Earth — which is in keeping with the different bulk compositions of the two bodies. In addition, it is thought that the metallic core of the impactor became part of the Earth, settling through the mantle and combining with the planet's own core. For rocks as old as 4 400 Ma to have formed on the Moon, this event must have occurred very early on in the history of the Solar System.

The impact record on Earth

Knowing what we do about the intense bombardment of the Moon that caused the formation of hundreds of thousands of impact structures, one must wonder whether the Earth was subjected to the same bombardment. The mean diameter of the Earth measures 12 742 km, whereas the Moon is only 3 476 km in diameter. This relates to an enormous difference in mass and, thus, gravitational force. It makes sense then to expect that Earth was hit more often than the Moon. It must be remembered, however, that the heavy bombardment of bodies in the Solar System took place early on in the history of our planet, mostly prior to 3 800 Ma. Since then, the rate of bolide hits has steadily declined. This, however, does not mean that from time to time a big bolide has not hit, or cannot still hit, the Earth!

There are also numerous craters on the Moon that were formed later than 3 800 Ma. For example, we know that lava extrusions and impact melt sheets, formed on the Moon at much later times, are peppered with impact craters. Using both absolute ages obtained in geochronological laboratories for Lunar magmatic rocks and impact melt rocks (that can provide an age for the specific impact event in which they were formed), and crater-counting techniques applied to specific regions on the Moon, it has been possible to calibrate the respective data sets in such a way as to enable scientists to predict an approximate age for a specific area with a particular density of impact craters.

There is a written record by 12th Century English monks of an observation that we now interpret as an eyewitness report of a large meteorite impact on the Moon. It has been debated whether it was this event that formed the very 'young' and well preserved, 22 km diameter, Giordano Bruno Crater.

The reason for the obvious lack of impact craters on Earth lies in the continuing geological activity in and on our own planet that destroys or reprocesses existing crust, or produces new crust elsewhere. In contrast, the Moon has been geologically largely inactive for about 3 000 Ma. Younger igneous rocks are extremely rare in the Lunar sample suite. As shown previously, Earth is a very active planet. This is acutely demonstrated by the often catastrophic volcanic eruptions, earthquakes, or flood waves that prevail in certain regions on our planet. Earth is continuously changing, both inside and outside, every day, even every second. In this regard, Earth is nearly unique in the Solar System, perhaps only rivaled by the volcanically hyperactive Jupiter moon, Io. However, Earth is truly unique in

the sense that it has an active interior (consisting of the outer lithosphere and the inner asthenosphere), as well as both an atmosphere and a hydrosphere. These four spheres are essential for the changes on and inside our world. Without the atmosphere, none of the chemical processes based on oxidation and reduction would take place; and without water, neither weathering of rocks, nor transport and deposition of sediment could happen.

That about 70 % of the surface of our planet is covered by the oceans is the reason why Earth is called the Blue Planet (Fig. 57). To search for impact craters on the ocean floor is not so easy, and, to date, only a handful of impact structures has been identified in the marine realm. Plate tectonics may be a very slow process, whereby plates move perhaps just a few centimetres per year but, in the context of geological time that is measured in millions of years, it is clear that whole slices of crust of thousands of kilometres width or more can be destroyed or modified beyond recognition. It is estimated that it would take no more than 200 million years to obliterate a region the size of the Atlantic Ocean and, thus, any impact craters within it.

These factors may explain why the impact-crater record of Earth is rather limited, at about 177. Only a few new impact craters are discovered, or at least proposed, every year, largely because more and more geologists have become sensitive to the importance of impact studies, and students of geoscience are now better acquainted with the criteria for identifying such structures. By far the majority of these known impact craters falls into two categories: (1) Nearly all of them are younger than about 350 Ma and many of these are small craters. (2) Some of the largest ones are also the oldest. This is because of the relative ease with which geological surface processes can erase small craters and because very old structures have been erased with time by plate-tectonic forces. Also, only a few per cent of the total crust exposed on the surface of the Earth is old enough to have recorded the earliest terrestrial history, the Archaean time. These rocks are usually not pristine, but have been overprinted by one or more stages of geological alteration (metamorphism and tectonism), making it exceedingly difficult to distinguish the telltale indicators for impact structures. Therefore, only three impact craters on Earth older than 1 500 Ma have been confirmed so far: the oldest being the Vredefort Structure, next the 1 850 Ma old Sudbury Structure in Canada, and then the much smaller Dhala Structure in India of ~1 700–2 500 age. One other structure in Russia has been proposed to be even older than Vredefort, but neither its age nor its impact origin has been confirmed. Thus, to date, Vredefort in South Africa remains the oldest known impact structure on Earth.

← **Figure 61:** Several spherule-rich layers in a sample from Sheba Gold Mine, Barberton Mountain Land. This sample is from the so-called S2 layer, that has been studied with the chromium isotope method, showing that a definite meteoritic component is contained in this spherule bed.

A few thin so-called spherule layers (Fig. 61) have been detected in the Archaean rock record. Some of these layers have long been thought to be of volcanic origin (that is, they are thought to represent so-called accretionary lapilli of fragments of glassy lava), but have since been shown to represent 'distal' impact ejecta (meaning that these exposures of ejected material lie far away from the impact site). The spherules represent solidified melt particles ejected from impact craters.

Looking at the global distribution of known impact craters (Fig. 54), it is obvious that, with the exception of Australia, the Southern Hemisphere does not display the same concentration of known impact structures as North America and Eurasia. Lack of crater concentration in Siberia must be blamed on the huge and geologically under-explored extent of this subcontinent, but why there are no confirmed impact structures known in China remains puzzling. In fact, up until 2007 only one confirmed impact structure (Lonar crater in India) had been found between the Mediterranean and southeast Asia. Since then, two more have been added: the 15 km diameter Dhala structure in India, which has a poorly constrained age of between 1 700 and 2 500 Ma that may

yet resolve into an age greater than that of the Vredefort structure, and the 6.5 km diameter Jebel Waqf as Suwwan in the northeastern desert of Jordan (see Fig. 54).

A number of reasons can be given for the fact that the majority of known impact craters occurs in North America and Eurasia: the United States of America and the former USSR were the Space-exploring nations of the second half of the 20th Century, and all phenomena related to planets and their satellites were enthusiastically investigated by the scientists of these countries and their allies. In addition, a small number of Canadian impactologists were at the forefront of this research discipline as early as the 1960s. Australia owes its excellent impact record to a large part to Gene Shoemaker and his wife Carolyn, who devoted many years to exploring crater structures on the ancient land surface of this country.

Only seventeen confirmed impact structures are now known from the African continent (see Box below). The currently known crater structures in Saharan Africa were mostly discovered as a result of oil and gas exploration, as far back as the 1960s and 1970s. The minor concentration in southern Africa stems from the efforts of a small number of impact aficionados based in South Africa. In the other parts of Africa, in fact generally in the developing world, geoscientists are not familiar with impact processes, often because of a lack of access to specific scientific journals or because they are largely limited to reading non-English literature. Large regions on the Southern Hemisphere continents are also either densely overgrown or inaccessible because of prolonged conflicts or other restrictions on travel, and geological and geophysical exploration. The size of Central Africa, for example, in comparison with that of Scandinavia (see Fig. 54) where some 20 confirmed impact structures and many more possible ones are known, suggests that there is a strong likelihood that future major discoveries will be made on the African continent.

Geophysical methods, those techniques that employ seismic waves, gravity (contrasts in the relative densities of materials), and magnetic characteristics of rocks, often for the purpose of exploration for ore resources, have been very useful in recent years for the detection of possible impact structures. Remote-sensing analysis, i.e. the use of aerial photography and satellite imagery, of unexplored areas has also led to the

Confirmed impact structures in Africa

Name	Country	Longitude/Latitude	Diameter (km)	Age (Million years)
Amguid	Algeria	26°05'N/04°23'E	0.45	0.1
Aorounga	Chad	19°6'N/19°15'E	12.6	0.01
Aouelloul	Mauretania	20°15'N/12°41'W	0.36	3.1 ± 0.3
BP	Libya	25°19'N/24°20'E	2.0	< 120
Bosumtwi	Ghana	06°32'N/01°25'W	10.5	1.07 ± 0.2
Gweni-Fada	Chad	17°25'N/21°45'E	14	< 345
Kalkkop	South Africa	32°43'S/24°26'E	0.64	0.25 ± 0.05
Kgagodi	Botswana	22°29'S/27°35'E	3.5	< 60
Morokweng	South Africa	26°28'S/23°32'E	70–80	145 ± 2
Oasis	Libya	24°35'N/24°24'E	11.5	< 120
Ouarkziz	Algeria	29°00'N/07°33'W	3.5	< 70
Roter Kamm	Namibia	27°46'S/16°18'E	2.5	3.7 ± 0.3
Talemzane	Algeria	33°19'N/04°02'E	1.75	< 3
Tenoumer	Mauritania	22°55'N/10°24'W	1.9	2.5 ± 0.5
Tin Bider	Algeria	27°36'N/05°07'E	6	< 70
Tswaing	South Africa	25°24'S/28°05'E	1.13	0.22 ± 0.05
Vredefort	South Africa	27°00'S/27°30'E	250–300	2 020 ± 5

identification of a number of new structures. These image-analysis techniques are standard methods in the exploration for precious metals and minerals and, if more geologists were aware of the importance of impact processes and the need to improve the terrestrial impact-crater record, we could expect a much faster rate of recognition of new candidates.

In addition to the confirmed impact structures in Africa, there are about a dozen others of probable or possible impact origin, but all of these still require definitive proof in the form of shock-deformation features.

The wealth within

Many impact structures are of economic benefit, but none more so than the three really large ones known on Earth. The Vredefort impact structure falls into the first category of impact ore resources, namely those where an impact event took place in an area that already had valuable ore. The Vredefort impact occurred in the region that contained the sedimentary rocks of the Witwatersrand Supergroup, laid down some 700 to 900 million years prior to this impact event. While the Vredefort impact did not produce the resource, it did preserve it from erosion by downfaulting the gold-bearing rocks in the environs of the collapsed central uplift, and by covering it with a thick blanket of impact ejecta and, possibly, impact melt rock. Another such case occurs in the Ukraine, in eastern Europe, where the massive iron-ore deposits of the Krivoi Rog region have been made accessible to mining because of the formation of the Ternovka impact structure. Huge iron-ore deposits were brought close to surface in the central uplift in the interior of this impact structure.

The second of the three giant impact structures known on Earth, the Sudbury Structure in Canada, symbolises the type of ores that form as a direct result of the impact event. The gigantic nickel and platinum-group metal reserves in the famous Sudbury mining district were concentrated and deposited in their present locations as a direct consequence of massive melting and differentiation of target rock that allowed previously dispersed nickel sulphides to settle at the base of the impact melt sheet.

The third very large impact structure, Chicxulub in Mexico, was only recognised in 1991 as an (unintentional) result of oil and gas exploration within and around its area. Hydrocarbons may become concentrated in impact structures, as the broken-up and brecciated rocks of the crater region or its environs form convenient, very porous traps for these mobile materials. The environs of Chicxulub are a major oil- and gas-producing region. In addition, there is a large number of other impact structures in North America, from which petroleum or natural gas are being produced, generating profits estimated at between 5 and 20 billion US dollars annually. All these resources fall into the category of deposits formed after an impact event. Even the relatively small trona deposits of the Tswaing Crater that were mined in the early parts of the 20th Century belong to this type of resource.

Image of Comet McNaught, courtesy of Kevin Crause.

What are the projectiles capable of causing an impact catastrophe?

It has been shown that extraterrestrial projectiles are required to produce these big explosion craters. The largest known meteorite in the world, the Hoba iron meteorite in Namibia (Fig. 62), weighs about 50–60 tonnes, but does not reside in a deep crater structure. That is because it is a relatively small rock (about 2.9 m wide, with a thickness between 75 and 125 cm) that was strongly slowed down during its travel through the atmosphere of the Earth. Presumably, some mass of the original bolide was lost during its descent through the atmosphere. Upon crash-landing, it produced only a shallow 'dent' because of its relatively small size. If it had been about 20 m wide, it may well have created a sizable crater several hundred metres across.

Meteors and meteorites

Anyone watching the sky on a cloudless night will sooner or later observe some bright trails of light: shooting stars, also called meteors. They are the result of burn-up of a small piece of extraterrestrial matter during its passage at hyperspeed through the atmosphere. These particles are mere dust grains, and are incinerated within seconds. The chunks of extraterrestrial matter that make it through the atmosphere and reach the surface of the Earth are what we call meteorites. Tiny meteorites, such as cosmic spherules and interplanetary dust particles, may also reach the ground and accumulate in the sediments deposited onto the Earth's surface. The total mass of extraterrestrial matter accumulated on the surface of our planet every year is estimated at more than 10 000 tonnes! If we consider this amount distributed over the entire surface of the planet, it is a trivial amount per square metre. However, when compared against geological time, we find that, over a period of 100 million years, an amount of 1 000 000 million tonnes can be accumulated.

Figure 62: The world's largest known meteorite, the 60 tonne Hoba iron meteorite near Grootfontein in northern Namibia.

The meteorites that are observed to fall are, obviously, called falls. In the early afternoon of 21 July 2002, a huge fireball was seen over northwestern Lesotho, signalling a significant meteorite fall. A sizable meteorite of at least 30 to 60 kg entered the atmosphere and became superheated. It broke up because of thermal stress between its heated exterior and colder interior, and small particles were incinerated. To date, more than 1 300 pieces, varying in mass from 1 gram to 2.5 kg, have been recovered (see Fig. 158, page 228).

In contrast, Hoba in Namibia (Fig. 62) is termed a meteorite find: its fall, if observed some 5 000 years ago, was not recorded. Meteorites are classified, according to their composition, into three main types: stony, stony-iron and iron meteorites. More than 90 % of all meteorites

collected are stony meteorites consisting of minerals that contain a high proportion of the element silicon, like the rocks forming the crust and mantle of the Earth. There may be some metal as well, which is mostly composed of the elements iron and nickel, and some iron sulphide. When the metal component becomes very abundant, such a meteorite is called a stony-iron; and iron meteorites are overwhelmingly composed of metal. All meteorites are ultimately derived from parent bodies, so-called planetesimals (little planetary bodies) of a kilometre to more than a thousand kilometres in size, from which they are thought to have been broken off because of collisions with other bodies. The different types of meteorites are thought to represent the different regimes in their home planetesimals: stony meteorites are from the silicate-mineral-rich crust, stony-irons from the less-differentiated metal-rich interior, and irons from the metalliferous cores that separated out of their more silica-rich parent when the latter became molten as a result of heating by renewed impact events and radioactive decay.

Meteorites are further classified according to chemical composition, mineral occurrence and abundance, thermal overprint on these minerals, and degree of shock metamorphism. Some of their parent bodies may even have been identified in the asteroid belt between Mars and Jupiter: it has, for example, been widely debated whether a group of meteorites called 'eucrites' could be related to a large (533 km diameter) asteroid called 4 Vesta, that has similar spectral characteristics (minerals absorb certain wavelengths when irradiated with energy, and Vesta's absorption spectrum is very similar to that of a mixture of the minerals that occur in eucrites).

A number of meteorites collected on Earth have properties that are best reconciled with origins from either the Moon or Mars. For example, tiny amounts of gas trapped in impact glasses in several meteorites belonging to a group known as the 'snic' (actually SNC) meteorites (after some prominent members in this group, the Shergotty, Nakhla, and Chassigny meteorites) are very similar to the composition of the Martian atmosphere, as analysed by a Russian Space probe.

Meteorites are very important to us. With the exception of a few hundred kilograms of rock from the Moon, returned by the astronauts of the Apollo Space Programme and a few unmanned Russian Space probes, meteorites provide the only hands-on source of information about extraterrestrial bodies in the Solar System. In comparison with the truly astronomical costs that the Apollo programme incurred, meteorites are also 'dirt' cheap ('the poor man's Space probes') to obtain, as they are delivered at no cost! Meteorites are also the only source of information about the earliest stages of the history of the Solar System; some even contain tiny particles formed in Space prior to the birth of our Solar System.

About 50 meteorites have been recovered from the territory of South Africa. Most likely, there are a few relatively unaltered ones still lying on the surface undiscovered. Sometimes they are difficult to distinguish from local rock, especially when they have begun to weather and are a bit rusty. Deserts, both the hot deserts such as the Sahara or the Namib and the cold deserts of the polar regions, have in recent years been the preferred meteorite hunting grounds. Dark meteorites are relatively easy to discern on ice terranes, and they can, in favourable conditions, be enriched in certain areas owing to the particular climatic conditions in Antarctica. Although in the last decades several thousand meteorites have been obtained from these areas, they have lost nothing of their special attraction.

asteroids shaped like potatoes

Meteorites remain messengers from Space and, still today, new, very rare, types may be found.

Large asteroids and comets

Very large meteorites are known as asteroids. They are small planetary bodies and are also known as minor planets or planetoids. These remnants of planet formation or products of collisions between planetesimals are mostly in orbit around the Sun, primarily between Mars and Jupiter, in the aptly named asteroid belt. Figure 16 shows the orbits of a very large number of tracked asteroids and the numerous instances where such tracks cross the orbit of our home planet. There are two special groups of asteroids, the so-called Apollo and Aten objects, which could present a very real danger to Earth: they are known as Near-Earth Objects or, in short, NEOs. It is estimated that more than 2 000 of these bodies exist in the asteroid belt alone. Hardly a month passes in which a new candidate for an Earth-orbit crossing path is not discovered. In 2001, the NEAR Shoemaker (Near-Earth Asteroid Rendezvous) mission was successfully completed with a soft landing of the probe on the 'back' of asteroid 433 Eros, a potato-shaped asteroid of about 30 km length (Fig. 15a). This experiment provided much information about the surface morphology, density, composition and other physical parameters — all very important factors if we want to understand the nature and origin of these bodies, as well as consider possible defense mechanisms against the impact threat posed by the larger asteroids.

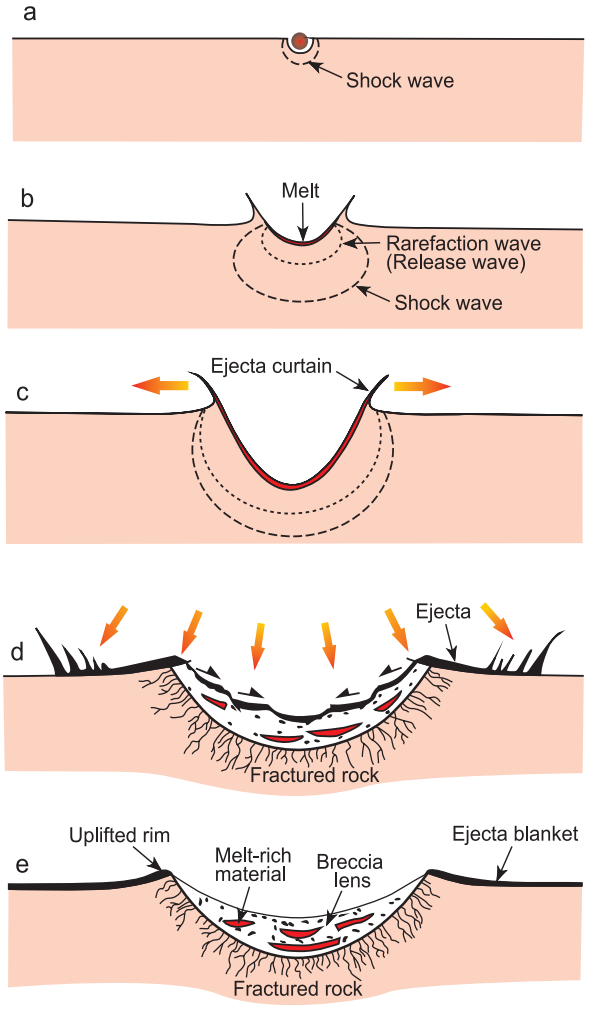
Asteroids generally move at velocities of, on average, less than 30 km per second. This is exceptionally fast and translates into enormous kinetic energies, but is still considerably slower than the speeds at which large comets could travel, which are up to 70 km per second. Comets can also have quite substantial sizes, well in excess of tens of kilometres. The word 'comet' comes from the Greek word for 'long-haired', because of the appearance of a comet as a 'star with a tail'. These bodies are composed of mixtures of some solid material (silicate mainly), with much volatile matter in the form of water ice and other ices. They possess a nucleus (core) and a tail. The tail is composed of vaporised and ionised gases that are blown off the nucleus by the solar wind. Accordingly, the tail of a comet always points away from the Sun. In January 2004, NASA's Stardust mission penetrated the coma (cloud of gas and dust around the nucleus of a comet) of comet Wild 2 and even photographed its core (Fig. 17a).

There are two regions in which comets originate. The first is the so-called Oort Cloud, far beyond the Outer Planets of our Solar System, where an estimated billion million (1 000 000 000 000 000) comets of sizes larger than 1.5 km reside. Then there is the Edgeworth-Kuiper Belt that contains the so-called Trans-Neptunian Objects (TNOs), which are located beyond the orbit of Neptune (with several hundreds of objects of asteroid and/or comet composition), with sizes of up to 500 km. Pluto (always considered a planet such as Earth, but, at 2 300 km diameter smaller than the Moon, and since August 2006 downgraded to a dwarf planet) may well be one of these TNOs, though by far the largest and brightest of them.

Comets may have very variable orbits because of disturbances of orbits caused by the gravity fields of the very large Outer Planets. This means that it can be most difficult to track individual comets, and to predict when and where they may enter a collision course with Earth. Our Solar System, and in fact the immense Space around it, is part of a very dynamic system.

What is an impact crater?

Figure 63: Schematic illustration of the different stages of formation of a simple bowl-shaped impact crater (modified from Grieve, 2007). a. Contact and compression phase, with formation of shock wave. b.–c.Excavation phase, in which material is expelled from the crater (ejecta curtain) and the shock wave penetrates into the target, followed by the release (rarefaction) wave that rapidly overtakes the shock front. d. Modification phase, in which the crater widens by inwards slumping of walls, and becomes shallower. The ejecta blanket is deposited beyond the crater rim and impact breccias accumulate within the crater. e. Final crater showing the raised rim and the breccia lens covering the crater floor above the fractured crater basement. Compare Figs 48 and 56.

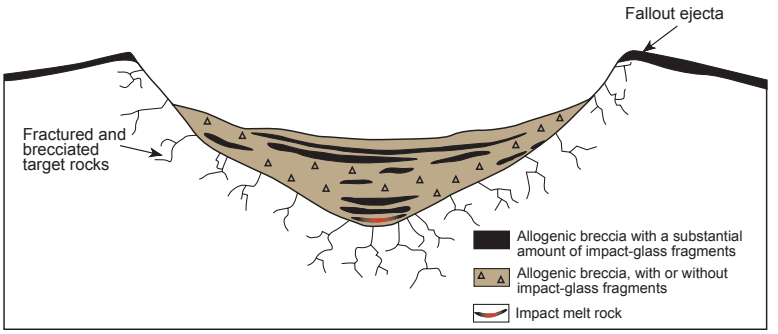


Impact craters can be of economic benefit, but large impactors also pose a potentially lethal threat to humanity. If active impact events cannot be investigated, at least the scars in the Earth's surface, generated by past impacts, provide a natural laboratory from which much can be learnt about the impact process. What actually constitutes a meteorite crater and how one can be recognised in the dynamic geological environment, or in, for example, dense rainforest on Earth, needs to be examined before the fascinating impact structures of South Africa can be discussed.

Irrespective of whether impact craters on the Moon, Mars, Venus, Mercury or Earth are examined, there are two principal types of impact-crater forms. Those craters with diameters of less than 2 to 4 km (depending on the type of rock that was impacted) will generally show a simple bowl shape (Figs 63 and 64). The impact structures of larger size are known as complex impact structures and typically consist of a central uplift feature surrounded by a ring basin. The largest known impact structures, those of hundreds of kilometres size, or even larger, belong to the multi-ring basin type and are characterised by multiple ring structures, such as the 1 000 km diameter Orientale basin on the Moon.

Complex craters (Fig. 65) initially start out like a simple bowl-shaped crater, with a deep excavation crater (called the transient crater); but more or less simultaneously with the collapse of the crater wall, a central uplift develops. Large amounts of material slide into the crater and, along the final crater rim, terraces form. Thus, the originally relatively narrow but deep crater becomes significantly wider and much more shallow.

A series of stages in the formation of an impact crater are distinguished: when the meteoritic projectile makes contact with the target surface, the contact and compression phase begins. During this phase, the projectile penetrates the target by about one projectile diameter and then explodes. The kinetic energy of the projectile is transferred to the compression wave, also known as a shock wave, that rapidly expands

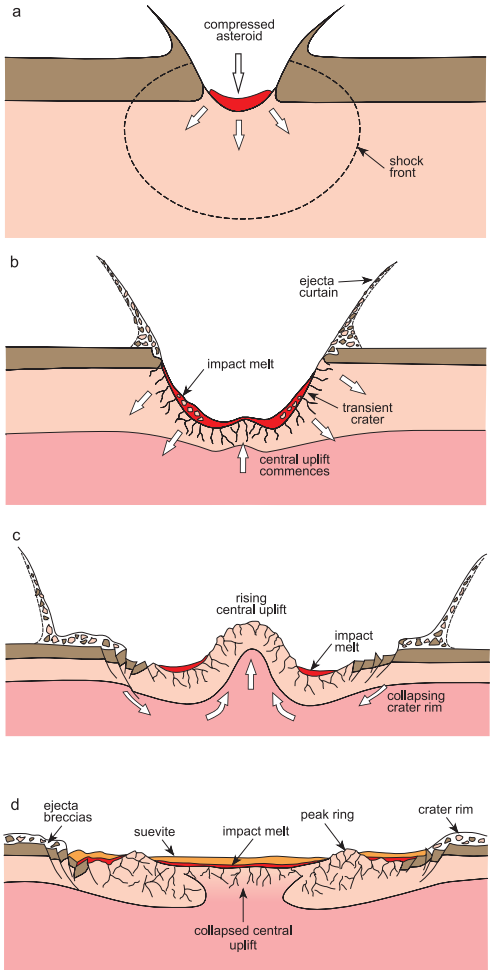


→ **Figure 64:** Schematic cross-section through the final geology of a simple bowl-shaped impact crater. Outside the raised crater rim, one would find a layer of ejected material (fallout breccia, ejecta). The crater itself is filled with the different impact breccias that can be formed. These 'allogenic' (which means 'formed not in the place where they are found') breccias can be rich in impact melt or glass (and then are called 'suevite'), or poor in these materials (and then are termed 'lithic impact breccia'). The crater floor is fractured and locally brecciated (these breccias are composed of fragments of the crater-floor rock only). For types of impact breccia see Figure 94, page 147.

outwards from the explosion point. The compression (shock) pressure in the target rock close to the explosion point is instantaneously driven up to hundreds of gigapascals (GPa) (1 kbar equals ~1 000 atmospheres; 1 GPa = 10 kbar = 10 000 atmospheres); temperatures close to the explosion site will soar to tens of thousands of degrees, of the order of magnitude found only on the surface of the Sun.

The excavation phase, which in the case of a very large impact structure such as Vredefort, may last a few minutes, covers the interval during which the shock wave travels through the target. As the shock wave travels into the target rock, its energy gradually dissipates and its strength diminishes with distance from the explosion site. Consequently, the deformation of the rock will decrease along this path radially away from the explosion centre, until rock strength exceeds the strength of the shock wave; beyond this point no shock-diagnostic deformation will occur, although collapse-related structures may form. The radially expanding shock wave causes a radial and outward movement of target rock particles, which leads to ejection of near-surface rocks lying close to the point of impact out of the growing crater.

Finally, the modification phase involves the broadening of the transient crater (the excavated bowl-shaped crater structure) and shallowing of the impact structure because of the formation of a central uplift as the result of rebound of the strongest-compressed material in the central part of the crater and collapse of the crater walls. Figure 65, stage d, shows, in cross section, what the final Vredefort impact structure would probably have looked like.



↑ **Figure 65:** Schematic illustration of the different stages of formation of a complex (peak-ring) impact crater (modified from http://www.geopark-ries.de/). Note that the scale increases from a to c. a. Beginning of excavation phase, showing the highly compressed asteroid and start of excavation. b. End of excavation phase, showing fragment-laden impact melt lining the transient crater, and commencement of central uplift. c. Modification phase, showing collapsing crater rim and rising central uplift, with deposition of ejecta inside and beyond the crater, as well as formation of an impact melt pool. d. Final crater showing collapsed central uplift forming a peak ring (compare Figs 53b, 98), downfaulted rim, and breccias including an impact melt body within the crater, and ejecta in and beyond the crater.

How can we identify impact structures?

A century ago, most scientists believed that craters at the Earth's surface were caused only by volcanic eruptions. More recently, however, there has been a growing awareness that the impact of an extraterrestrial bolide provides an alternative, albeit rarer, mechanism. It has, thus, become crucial to be able to discriminate between volcanic and impact craters.

If one is lucky, this question is quickly resolved; namely, in those cases of relatively small craters where fragments of the meteoritic projectile may be present. A good example is Meteor Crater in Arizona (Fig. 56, page 71), where numerous small pieces of the iron-nickel bolide, known as the Canyon Diablo meteorite, have been collected. In areas where no volcanic activity has taken place, a crater form, especially if it is roughly circular, will be an anomaly and, as such, may raise the suspicion of impact. But the observation of a circular form is not, by itself, proof of impact, as, for example, sections through kimberlite pipes may also have such shapes, and circular water pans are known in abundance.

The presence of a strongly raised rim may also be an indicator, as volcanic craters usually only have slightly raised rims. Should the originally layered target rocks appear overturned in the rim area, that is, the originally oldest, lowermost rocks are now lying on top of the rim section, this would be a very strong indication for the presence of an impact crater.

In addition to such first-order shape (morphological) indicators, circular geophysical anomalies, related to the magnetic or gravity expressions of the rocks in an area (especially when indicative of a large circular area that appears to be made up of relatively light rocks, i.e. it shows a negative gravity anomaly), in comparison to the regional geophysical expressions, may also be promising indicators. The large mass of brecciated or fragmented rock one expects to find in and below an impact crater has lower density compared with the solid, undeformed country rock. This would result in a relatively reduced gravity signal over the crater area. In recent decades, many impact structures were found on the basis of such observations. One should, however, be cautious, as there are other geological circumstances that could be in evidence, such as the characteristics of kimberlite pipes already mentioned, or other magmatic bodies with near-circular shapes.

Findings of massive occurrences of fragmented rock, called breccia (for example Fig. 66), or of shatter cones (Fig. 59) may also be pointers to an impact structure. However, none of these possible indicators can, alone, be considered conclusive. Proof must in each and every case be procured through geological ground investigation, that is mapping out and sampling, and analysing the rocks in the area of interest. Rock samples need to be investigated in the laboratory for the presence of shock-metamorphic effects, the ultimate proof for impact.

→ **Figure 66a:** A ca 20 cm long slice of impact breccia from Bosumtwi Crater in Ghana. This is a slice from a chunk of impact glass in a suevite sample. Note the inclusions of various target rocks, as well as some schlieren of partially assimilated (incorporated into the melt) target rock.

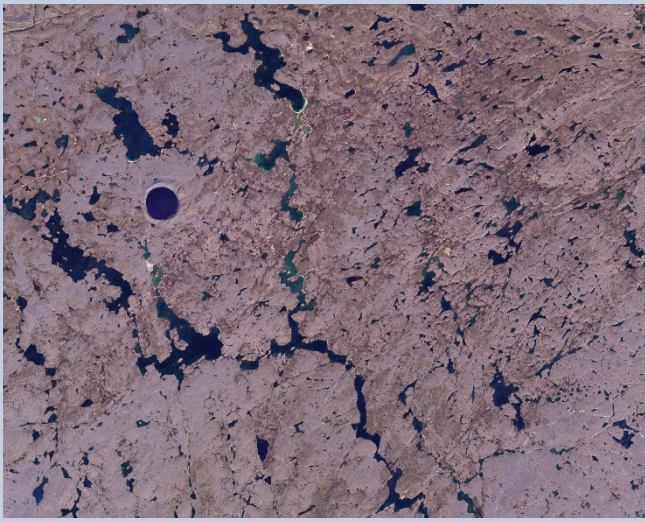
→ **Figure 66b:** A slice of suevite from the Lappajärvi Crater in Finland (ca 30 cm long). Note the grey schlieren of impact melt in an otherwise clastic (i.e. fragments of rock and minerals) groundmass.

Impact craters and other crater features

Impact craters may have distinct crater shapes (an elevated rim and interior depression) or circular geophysical anomalies, but these features are not characteristic of impact craters alone. Volcanic structures may be similar, and sinkholes in regions underlain by carbonate rocks, or depressions formed at intersections of tectonic zones of weakness may also result in shapes reminiscent of impact craters.

On the other hand, impact structures do not have to exhibit absolutely circular crater forms — the craters may have been substantially modified by various geological processes active on and near the surface of the Earth. These include erosion — the gradual removal of material due to the action of wind, water, and glaciers; sedimentation — material may be shed or otherwise deposited on top of eroded impact structures, and crater forms can be completely filled in or even deeply covered by sediment; and tectonics — the movement of parts of the Earth's crust caused by shifting crustal plates (see pages 20 and 21). The latter may distort the impact structure or, in extreme cases, lead to its complete destruction as crust is recycled or intensely metamorphosed.

Images derived from NASA's Earth Observatory website (http://earthobservatory.nasa.gov/) illustrate some of the main variations in surface morphology of impact structures on Earth, which are contrasted with a few examples of crater features that were formed by non-impact processes.



↑ **Figure 67a:** Landsat 7 satellite image of Pingualuit (or New Quebec) Crater in far northern Quebec, Canada. This near-circular crater of about 3.5 km diameter has an obviously raised rim typical of impact craters. The crater was only slightly eroded during the Pleistocene Ice Age about 10 000 years ago. NASA image created by Jesse Allen, using Landsat data provided by the University of Maryland's Global Land Cover Facility.

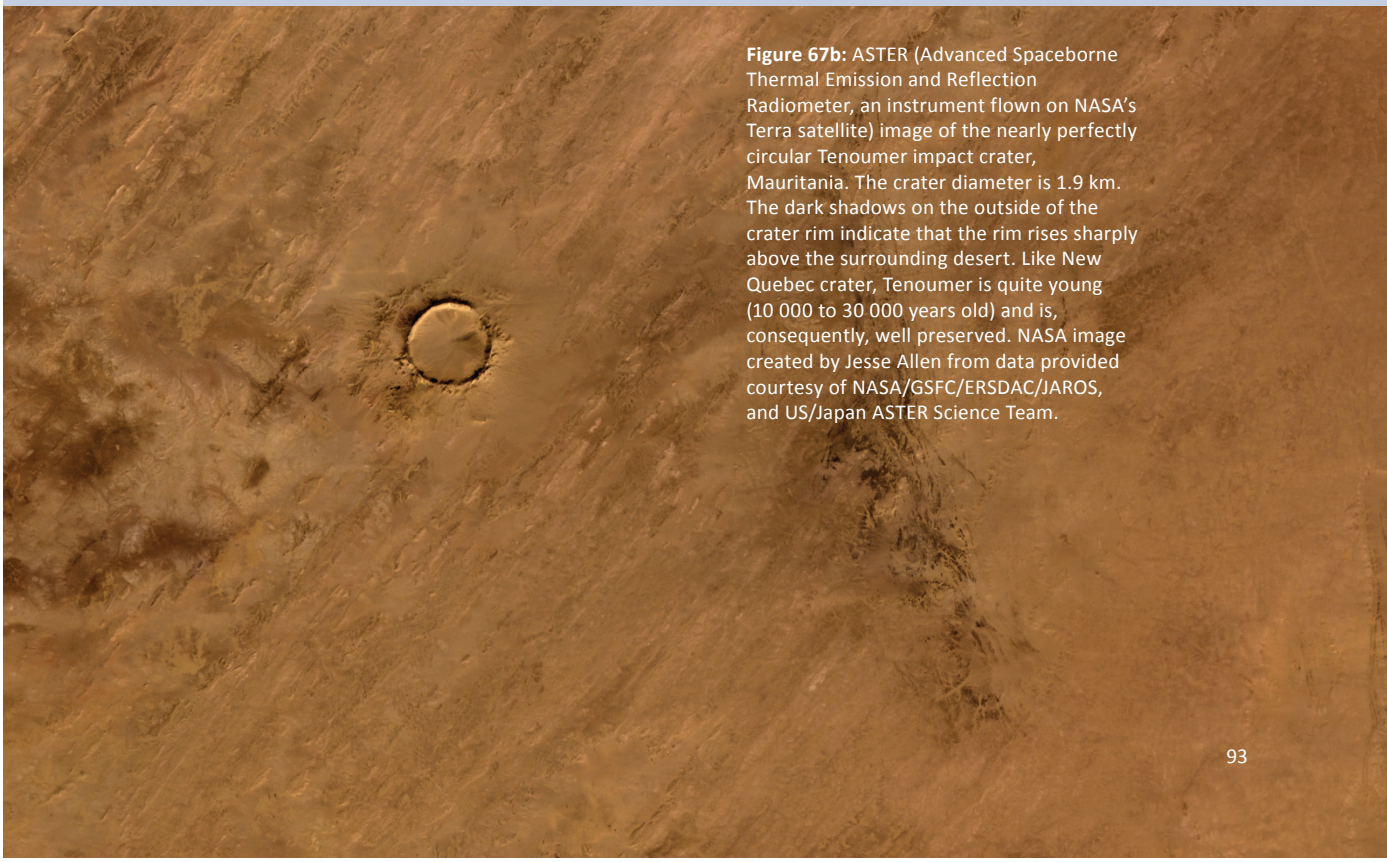
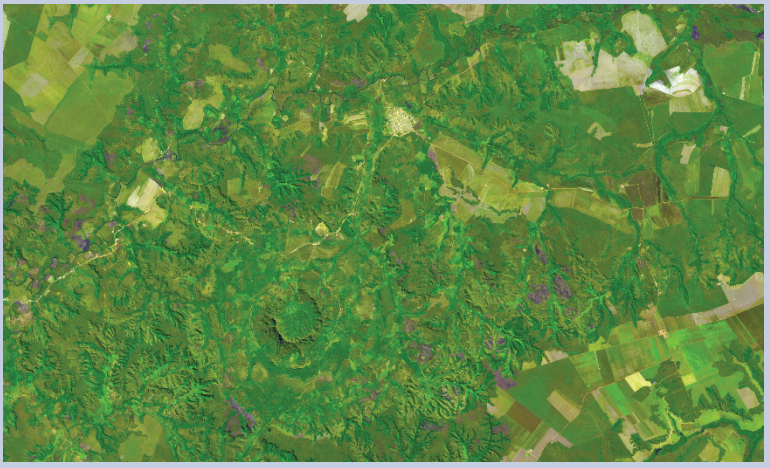
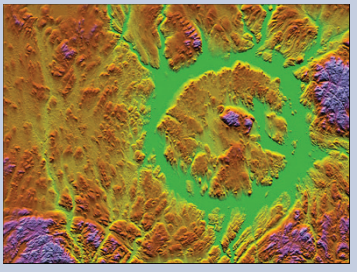


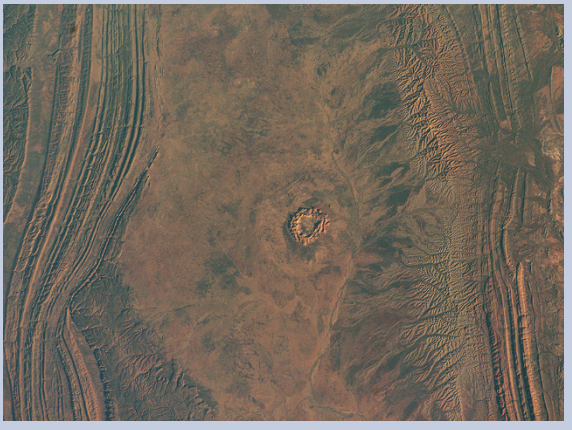
Figure 67b: ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer, an instrument flown on NASA's Terra satellite) image of the nearly perfectly circular Tenoumer impact crater, Mauritania. The crater diameter is 1.9 km. The dark shadows on the outside of the crater rim indicate that the rim rises sharply above the surrounding desert. Like New Quebec crater, Tenoumer is quite young (10 000 to 30 000 years old) and is, consequently, well preserved. NASA image created by Jesse Allen from data provided courtesy of NASA/GSFC/ERSDAC/JAROS, and US/Japan ASTER Science Team.



← **Figure 67c:** ASTER image of the 13 km wide Serra da Cangalha impact structure, northeastern Brazil, which exhibits a complex morphology. The prominent inner ring is the eroded remnant of the central uplift of this structure that stands several hundred metres above the surroundings. A second, comparatively subdued, narrow ring feature is visible just inside the broad, clearly eroded ring basin, which is, in turn, surrounded by the prominent crater rim. Only limited evidence for the impact origin of this structure has been found to date, and studies are continuing. Despite its relatively good state of preservation, indicated by the various ring structures, regional geological studies suggest that this impact could have occurred as much as 350 million years ago. NASA image created by Jesse Allen from data provided courtesy of NASA/GSFC/ ERSDAC/JAROS, and US/Japan ASTER Science Team.



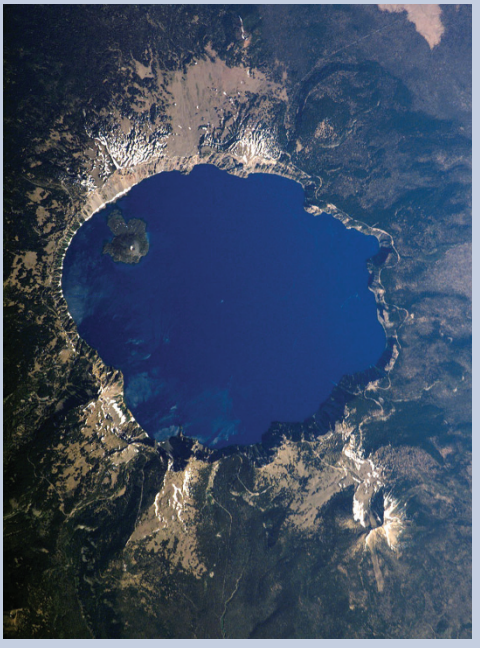
↗ **Figure 67d:** False-colour image of the 100 km diameter Manicouagan impact structure in Quebec (Canada), one of the largest known impact structures on Earth. This image was constructed from data collected by the Shuttle Radar Topography Mission (SRTM) instrument flown on the NASA Space Shuttle. The colours indicate different land-surface elevation, with green indicating lowest elevation, and yellow, red, magenta, and blue consecutively higher values. This 215 Ma impact structure has been strongly affected by ice erosion. The inner part of this structure, with Mount de Babel as the highest area, is the glacially eroded central uplift. It is surrounded by the Manicouagan Lake, a circular reservoir that provides hydroelectric power for much of Quebec. The lake was formed where the more easily eroded crater-fill impact breccias have been removed by the ice sheets. The outer parts of this structure have been strongly degraded, which has completely removed the crater rim but has exposed the pre-impact structures in the crater basement. Image courtesy of NASA/JPL/NIMA.



↑ **Figure 67e:** International Space Station (ISS) astronaut photograph of Gosses Bluff, a 4.5 km wide and 140 million year old impact structure, 160 km west of Alice Springs, central Australia. The prominent elevated circular inner ring is actually the eroded remnant of the central uplift, and the crater rim has been completely removed. The pale broad ring surrounding the inner ring indicates the diameter of the impact structure. The ancient desert surface of Australia lends itself very well to the detection of impact structures by remote sensing image analysis; however, these must be confirmed through detailed geological ground work. International Space Station (ISS) astronaut photograph ISS007-E-05697, NASA Johnson Space Center, Houston.

← **Figure 67f:** NASA Landsat 7 image of the 114 km diameter, 680 Ma, Janisjärvi impact structure in northwestern Russia, near the Finnish border. Erosion is greater than at Manicouagan and Gosses Bluff; the crater rim is completely degraded, with the central uplift recognisable as a few islands in the innermost part of the somewhat elongated lake. The cause for the degradation is that the crater has been overrun repeatedly by glaciers. The islands are made up of impact-generated melt rock that contains distinct shock-metamorphosed target rock fragments. Image courtesy of NASA and the USGS EROS Data Center.

→ **Figure 67g:** Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor image of Teague Ring (now Shoemaker) impact structure. This structure is thought to be ca 700 to 1 600 million years old (Australia's oldest) and is deeply eroded. It is about 30 km in diameter, with the outer diameter best recognised by the curved ridges in the bottom right part of the image. The bright spots are salt deposits in seasonal lakes. In this case, the central uplift — which must have existed in a structure of this size — is completely eroded, whereas sections of the crater rim have survived. Image courtesy of the USGS EROS Data Center.

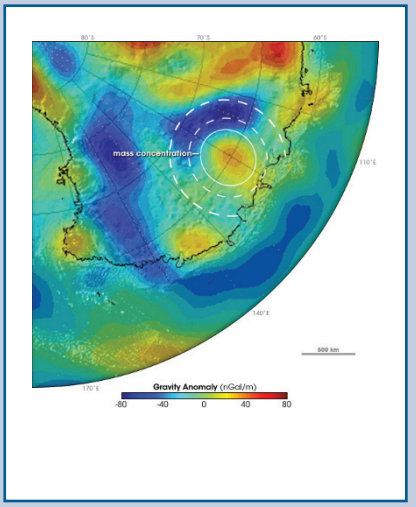


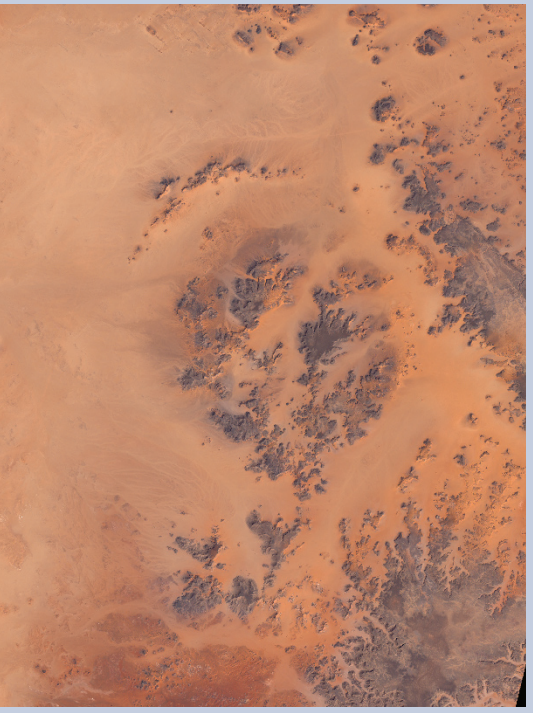
← **Figure 67h:** Astronaut photograph taken from the International Space Station of Crater Lake, southern Oregon (USA). The 594 m deep lake, the deepest in the USA, is 7 700 years old, and 9.7 km long by 6.3 km wide. It was formed by the catastrophic eruption of Mount Mazama. A small volcanic cone on Wizard Island (upper left) still bears witness to its violent volcanic past. Image No. ISS013-E-54243, courtesy NASA Johnson Space Center (Image Science and Analysis Group), Houston.

← **Figure 67i:** Three-dimensional false-colour image, created from ASTER data, of the 6 km wide Kondyor Massif volcanic crater, eastern Russia. The collapsed interior ring and strongly raised outer rim resemble an impact crater. However, these features were created when a magmatic body pushed up and raised sedimentary cover rock layers that were then partially eroded. The image was created by draping the ASTER data over a digital elevation model (DEM) also derived from ASTER data. Vegetation is bright green. Water collecting in the crater drains towards the east via a river. NASA image created by Jesse Allen from data provided courtesy of NASA/GSFC/ERSDAC/JAROS, and US/Japan ASTER Science Team.

← **Figure 67j:** Circular and oval dome structures created by buoyant salt diapirs rising through denser sedimentary rocks on Melville Island, Arctic Canada. Note the radial deformation zones around the domes. The dark island is surrounded by strongly deformed (brecciated) sea ice, and cloud cover over the northern part of the island is seen as a diffuse, cotton-like phenomenon. The width of the image is about 30 km. NASA image created by Jesse Allen, using data obtained from the University of Maryland's Global Land Cover Facility.

→ **Figure 67k:** Gravity anomaly map of part of East Antarctica showing a 400 km wide, near-circular anomaly singled out in 2006 by researchers at Ohio State University as a possible impact structure underneath the Antarctic ice sheet. The Ohio State group went so far as to speculate that the alleged impact event coincided with the Permian–Triassic mass extinction event 251 Ma ago. However, a gravity anomaly alone does not represent conclusive evidence for or against an impact origin, and provides no clues as to the age of the feature. An alternative possibility for this anomaly would be the intrusion of relatively dense magmatic material. NASA Gravity Recovery and Climate Experiment (GRACE) Earth Observatory image, courtesy of Pam Frost Gorder of Ohio State University.



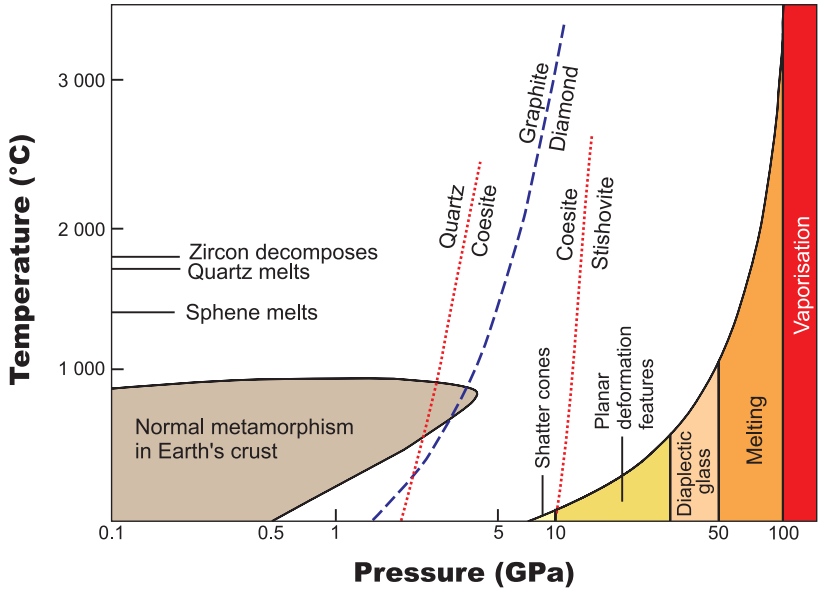


← **Figure 67l:** Landsat 7 image of the so-called 'Kebira structure' in the Libyan Desert, close to the Libya–Egypt border. This 30 km diameter feature was proposed as an impact structure that may have been the source of the nearby strewnfield of the enigmatic Libyan Desert Glass. The outer margin is indicated by the annular exposure in the north and northwest. Little is known of the geology of this remote area and no groundtruth data for the existence of an impact structure at Kebira have been published. NASA image by Robert Simmon, based on Landsat 7 data by the University of Maryland Global Land Cover Facility.

↑ **Figure 67m:** ISS astronaut photograph of two roundish features at Arkenu in southeast Libya. An impact origin was proposed in 2005 based on the alleged occurrence of shatter cones and impact breccia. However, neither of these features has been confirmed and a more recent interpretation proposes that these structures are of likely magmatic origin. Like the Kebira structure, this example demonstrates that field evidence is essential before circular surface features can be confirmed as impact structures. Image ISS017-E-20538, courtesy of NASA Johnson Space Center, Houston, Image Science and Analysis Laboratory.

Shock metamorphism

Impacting extraterrestrial projectiles only affect the outer parts of the Earth, the so-called crust. Even the known impact structures of 200–300 km width have not provided any evidence that mantle material may be excavated or magmatism triggered, as happened in the Lunar maria. Under 'normal' geological conditions (that is, related to processes such as mountain building, faulting, movement of rock masses against each other, volcanic processes, but not impact) the rocks of the crust of the Earth will not be subjected to pressures in excess of 1 gigapascal and temperatures of 1 000 to 1 200 °C (Fig. 68). In stark contrast, when a large bolide from Space impacts on the surface of Earth, pressures up to hundreds of gigapascals and temperatures of tens of thousands of degrees centigrade are reached. Under such abnormal conditions, minerals in the impacted rocks become vaporised in the immediate environs of the impact-explosion site, melted somewhat farther away from it, and, finally, still further out from the explosion centre, deformed or transformed into new minerals that are typical for the local impact pressure and temperature conditions (Fig. 69). Many of these shock-deformation features or mineral transformations (shock metamorphism) are readily recognisable with a geologist's microscope, but sometimes even more sophisticated instrumentation such as electron microscopes may have to be used. Impact melt produced near the planet's surface may be thrown out on long trajectories through the atmosphere, and during this ballistic travel may take on distinctive shapes. These particles, when still glassy, are known as tektites. When they have begun to form small crystals from the melt, they are known as microcrystites. Large fields strewn with such glass blebs and beads have been identified and, in some instances, can be unambiguously linked to known impact craters. For example, Bosumtwi, a 10 km diameter impact crater in Ghana, represents the source crater for the Ivory Coast tektites found on land,



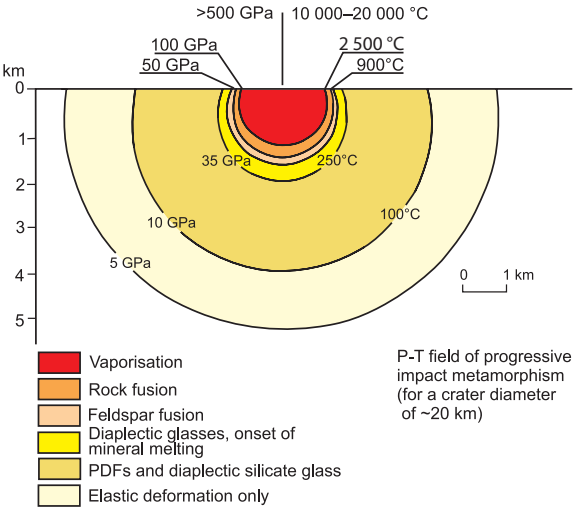
← **Figure 68:** Pressure and temperature conditions of shock (impact) metamorphism, in comparison with the regime of normal metamorphism of crustal rocks. The conditions under which several important impact-generated mineral deformation or transformation effects take place are also shown. For comparison, the graphite to diamond transformation is also indicated, which takes place at depths of the order of 120–150 km in the Earth. Note that the pressure scale is not linear (log scale).

and microtektites found offshore because the tektites have the same age as the impact melt glasses found in and around the crater.

The most abundant minerals in rocks of the crust of the Earth are quartz (SiO_2) and the feldspar minerals that are composed of aluminum, silicon and alkali elements (Na, K, Ca). These and other minerals display a range of shock-metamorphic effects, including the so-called planar deformation features which are very thin, absolutely straight, lamellar features oriented along important directions in the crystal lattices of minerals. An example is shown in Figure 70, and an example of shock-induced microdeformation in a crystal of the mineral zircon is shown in Figure 71.

At even greater pressures, some minerals convert into a glassy phase without direct melting to a liquid phase. These glass-like phases are called diaplectic glass and, where present, represent evidence for quite strong shock pressures of some 25 GPa and more. At high shock pressures, a mineral that is stable at normal conditions (up to a few kilobars and maybe a few hundred degrees centigrade) may change its crystal structure and transform into a different mineral of higher density, while maintaining the exact same composition. For example, at about 3 GPa pressure, quartz will convert to the crystal structure of the mineral coesite, and at 15 GPa to that of an even denser mineral named stishovite. Coesite has been found in kimberlite (the volcanic rock from very deep inside the Earth that may carry diamonds). In contrast, when coesite is formed in rocks that were clearly near the surface of the Earth, coesite is an excellent impact indicator mineral. To date, stishovite has only been detected in impact-deformed rocks.

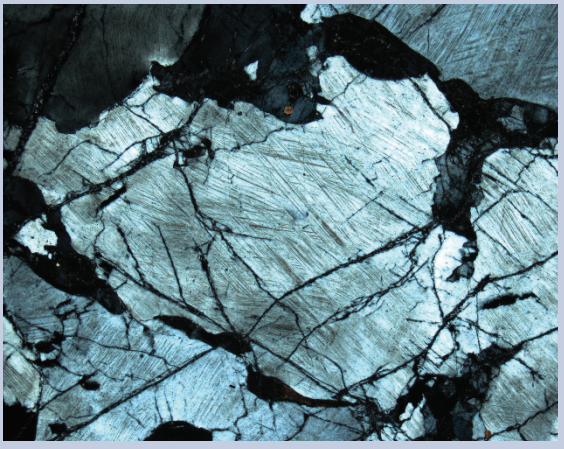
It is well known that diamonds are formed at ultradepths (at least 120 km or more), at very high pressure and temperature, in the interior of the Earth. But when an extraterrestrial projectile hits a carbon-bearing rock, such as coal or graphite, or any carbon-bearing metamorphic rock, the carbon will be instantaneously transformed into its much denser phase and impact diamonds are produced. It is estimated that in the 100 km diameter Popigai impact structure of northeast Siberia millions of tonnes of such impact diamonds occur. Naturally, these crystals are very small (only 10^{-9} m, that is,



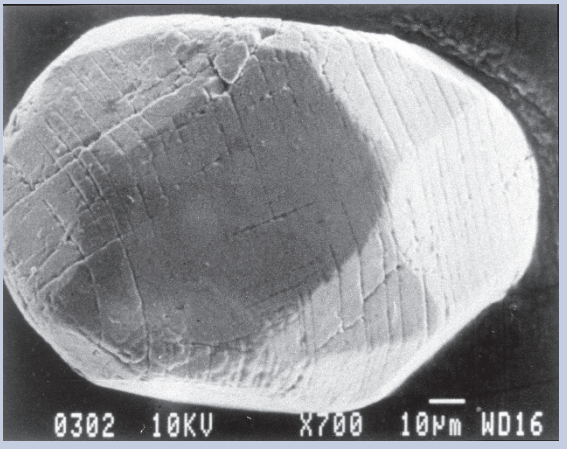
↑ **Figure 69:** Shock deformation decreases radially away from the point of impact. In the zone close to the impact, all target material and the projectile are vaporised. Somewhat further out, rock melting is the dominant deformation effect, followed by selective mineral melting, transformation of minerals into diaplectic glass, and finally formation of planar deformation features, until still further from the explosion site elastic deformation, such as fracturing and local brecciation, are the only effects (after Stöffler, 1971).

1/1 000 000 000 of a metre) and obviously are not gem quality. Aggregates of these tiny crystals may, however, be up to several centimetres in size and could be suitable as abrasives. However, as Popigai is not easily accessible, mining does not appear to be an option.

The mineral zircon ($ZrSiO_4$) is very important to geologists, as it is very hard, resilient against the forces of weathering, and contains uranium and lead in its crystal lattice. Isotopes of these two elements are linked via a radioactive decay scheme (radiogenic lead forms from parent uranium) and, thus, provide a good means of age-dating zircon crystals, and, thus, determining the ages of the host rock, and the geological events in which the rock formed. Zircon transforms into a new phase, with a different crystal structure (similar to that of the tungsten-mineral scheelite [$CaWO_4$]) at shock pressures higher than 30 GPa. At even higher shock pressure and temperature, zircon decomposes to a mixture of silica (SiO_2) and zirconium dioxide (ZrO_2, a mineral known as baddeleyite). This



↑ **Figure 70:** Photomicrograph showing up to three sets of closely spaced planar deformation features (PDFs) — very thin silica glass lamellae — in quartz grains from the Carswell impact structure in Canada. Plane-polarised light. Width of view 5 mm. Image courtesy of Isabel Duhamel and Groupe Omegalpha (Quebec, Canada).

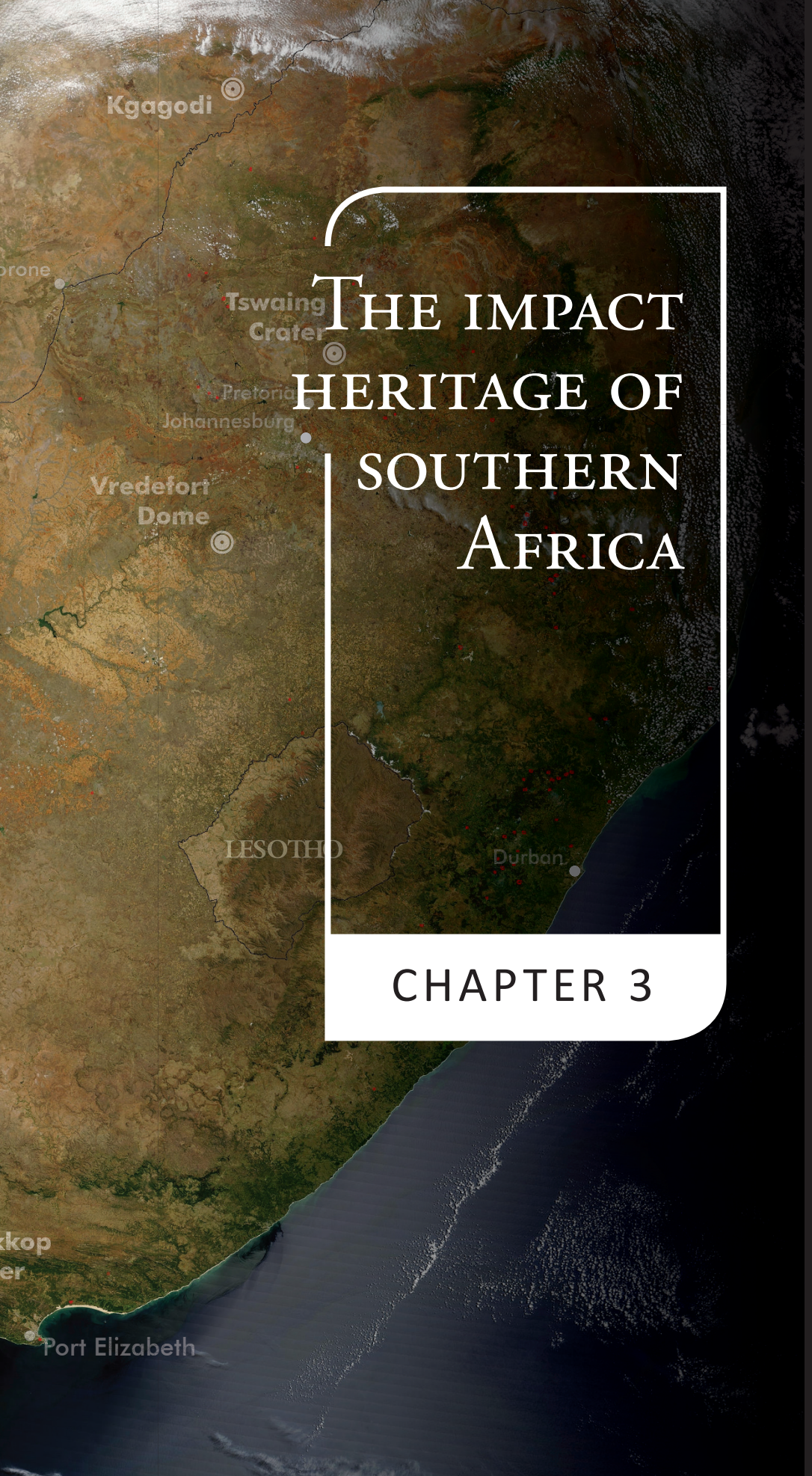


↑ **Figure 71:** Shock- (impact) generated microdeformation in a zircon crystal from a Vredefort rock (scanning electron microscope image; the scale bar at the bottom right measures ten micrometres in width). This kind of deformation is only found in impact-deformed rock. Photograph: Sandra Kamo, Royal Ontario Museum, Toronto.

decomposition requires a temperature of at least 1 000 °C, which requires an exceptional heating mechanism in rocks from the uppermost crust, as such a temperature is only reached at mantle depths (about 60 km) under a normal geothermal gradient and most magmas are incapable of raising temperatures of crustal rocks this high. For zircon to melt requires a temperature of over 1 500 °C — hotter than any magma presently being produced on Earth.

A similar case is that of the mineral quartz (SiO_2), which melts above 1 570 °C. A glass form of quartz known as *lechatelierite* was observed at Meteor Crater in the mid-20th Century. The presence of both decomposed zircon and lechatelierite in tektites confirmed these long-enigmatic glasses as impact products. Charles Darwin encountered tektites during his famous voyage on the Beagle (1831–1836), but concluded that these glass 'beads' were the result of volcanic eruptions (he was presented with his first tektite on the volcanic island of Ascension). Since the 1930s, much evidence has been accumulated by detailed mineralogical, chemical and isotopic analysis that has proven beyond doubt that tektite glasses originate from impact events. They are ejected as jets of melted material from the uppermost target layer. Many minerals in rocks from the Earth's crust are not very stable, especially if they have been fractured or otherwise deformed. They may react with water and break down into their chemical constituents; the process known as chemical alteration and weathering is activated. Feldspar minerals are very susceptible to this ubiquitous geological process, as the alkali elements contained in their crystal lattices can easily be leached out. Also, with geological time, measured in millions of years, shock-deformed minerals may be subjected to enhanced temperatures and also pressures significantly higher than those at the Earth's surface, for example because they are gradually buried underneath younger sedimentary rocks. This process is known first as diagenesis, then metamorphism. Both chemical alteration and metamorphism may lead to the disappearance of shock effects and obliteration of the evidence for an impact structure. Whereas quartz is quite abundant in the Earth's crust, and is rather resistant to alteration, weathering and metamorphism, it is a mineral that does not occur everywhere in crustal rocks, especially not in the rocks that form the oceanic crust of our planet, such as basalt or gabbro.

Windhoek
BOTSWANA
Gaboron
Morokweng
NAMIBIA
Roter Kamm
Crater
Atlantic Ocean
SOUTH AFRICA
N
Kalkko
Crater
Cape Town
0
100
200
300
kilometres



The impact heritage of southern Africa

CHAPTER 3

Tswaing meteorite crater

This small, bowl-shaped crater (Fig. 48, page 64) is located about 40 km north-northwest of Pretoria, in the southern portion of the Bushveld Complex. Driving from Onderstepoort in the direction of the sprawling town of Hammanskraal, the crater becomes visible as a broad, low silhouette, long before it is reached, where the road ascends into a sweeping curve near the town of Soshanguve. This crater has long been known as Zoutpan or Pretoria Saltpan, but a few years ago was renamed Tswaing, which means 'Place of Salt' in the Sotho language. The crater is nearly circular and 1 130 m in diameter (measured from the top of the crater rim on one side to the top of the rim on the opposite side). The rim is composed of granite, which has been visibly tilted upwards, as can be seen from numerous fractures in the rocks that were originally oriented subhorizontally (as can still be observed at some outcrops outside the crater), but are now steeply oriented. Locally, the rim is covered by a breccia layer consisting of mostly angular granite fragments up to 1 m in diameter. The presence of a cover of ejected material on top of the rim also suggests a relatively recent age for the crater, although the shallow slopes at the bottom of the inner and outer rim do testify that some degradation has occurred. The crater rim is elevated by as much as 60 m above the surrounding plains. The maximum elevation of the rim above the crater floor is 119 m.

The crater floor and surrounding areas consist predominantly of Bushveld granite, the so-called Nebo Granite of about 2 060 Ma age. Large parts of the surrounding countryside are covered by coarse sands and grits that have been produced from the weathering of this granite. Other areas show generally small outcrops of sedimentary rock (sandstone, shale, grit) belonging to the 300 to 180 Ma old Karoo Supergroup, or that are recent deposits (alluvium).

The Nebo Granite is very coarse-grained; it contains large, pink feldspar crystals. These are particularly susceptible to chemical attack by water (the weathering process), which is further facilitated by the presence of numerous fractures. The granite weathers into large rounded boulders, or small, mostly angular fragments of quartz, dark amphibole and feldspar. The crater interior is largely filled by mud (as can be seen around the crater lake in Figure 48, and is also known from drilling near the centre of the crater).

Magmatic (plutonic) rocks intruding the Nebo Granite are exposed at many places along the crater rim, especially in the northern sector. These igneous rocks (the specific types include lamprophyres, trachytes, phonolites and carbonatite) occur in the form of thin dykes or sills. They are commonly fractured and displaced by small faults, thought to be the result of the cratering event. Several of these intrusive magmatic rocks have been dated at 1 300 Ma, which, in the light of the youthful appearance of the crater, indicates that they are much older than the cratering event.

For much of the previous century the origin of the Tswaing Crater was highly controversial. Some scientists favoured a volcanic event and others a meteorite-impact origin. Obviously the direct association of magmatic rocks with the Saltpan crater represented the main argument for the proponents of a cryptoexplosive origin, whereas the meteorite-impact advocates drew parallels between the appearances of the Tswaing, Meteor and Steinheim (Germany) craters.

It was long thought that drilling of the crater interior might provide the solution to this dilemma. Several shallow boreholes were sunk in 1972, but drill-core recovery was very poor and did not provide any definitive answers — although no volcanic rocks were intersected. Then, in 1988/89, a breakthrough came when a 200 m long drill core was obtained from near the centre of the crater. The person driving this effort was Professor T.C. Partridge of

the University of the Witwatersrand, whose main research interests include the investigation of ancient climates in order to obtain an understanding of patterns of climatic change extending back thousands to millions of years. Professor Partridge believed that a continuous drill core through the sediments of the crater, accumulated since its formation, would provide a palaeoclimatic record that could be used to predict possible climatic trends for the future. In addition it was hoped that conclusive evidence concerning the formation of the crater would be found.

The upper 90 m of the drill core intersected fine-grained sediments deposited in the crater lake. Below this zone, some 61 m of sandy material, also containing a number of granitic boulders, was penetrated, before fractured (at 150 m depth), and then, at 200 m, solid bedrock, typical Nebo Granite, was encountered. It turned out that the sediments that filled the crater were deposited in a number of successive fresh-water and saline (salt-bearing) lake environments. The lake bottom was inhabited by diatoms, and the fossil pollen found in the sediments shows that in the lake environs different types of vegetation flourished at different times; certain species thrive under different conditions from those favoured by others. The microfossils found within the sediments (diatoms, algae and pollen) have preserved a record of the life in and around the lake, and are also evidence of the climatic conditions at various times after crater formation.

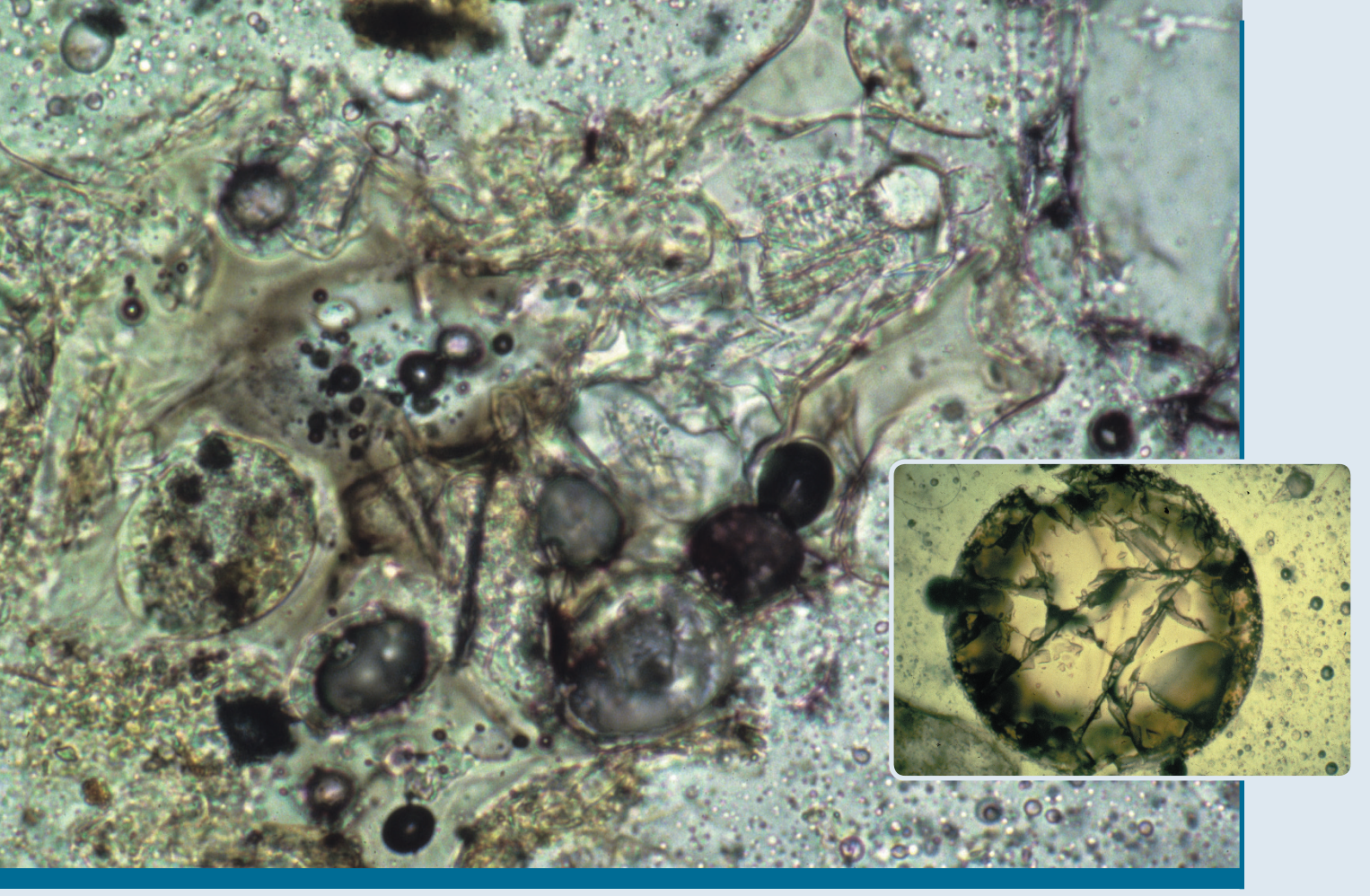
The crater sediments have also been very useful in determining the approximate age of the crater. Carbon contained in core from the upper 20 m was dated at the Council for Scientific and Industrial Research in Pretoria with the radiocarbon method (also known as ^{14}C dating). The results showed that this sediment was deposited over the last 40 000 years. If it is assumed that the rate of sediment accumulation at the bottom of the crater lake remained roughly the same for the entire interval of sediment formation; this result extrapolates to an age of about 180 000 years for the first deposition of sediment in the crater, which is thought to be very close to the age of crater formation.

The crater infill is a rich source of palaeoenvironmental information. The vegetation currently found at Tswaing comprises a combination of plant species which is known as Sourish Mixed Bushveld. This vegetation thrives in a subtropical, dry to subhumid climate. For example, the presence of pollen from the tree called Podocarpus (common name: yellowwood) indicates a subtropical, warm environment, whereas other layers contain pollen of vegetation indicative of relatively cooler periods. Diatoms are, as a species, very sensitive to changing water compositions and climatic conditions. The Tswaing core is unique in providing the only known long-term and continuous diatom sequence for the past ca 200 000 years in southern Africa.

The Tswaing Crater lake has essentially remained closed (it did not have any influx from outside water sources, such as a stream) for the entire period of some 200 000 years. Thus, any change in the chemical composition of the lake water and the nature of the sediment deposited from it represents a record of changes in the climate around the crater area. In particular, it shows changes in the amount of precipitation (rainfall) or evaporation of water (which would increase the salt content (salinity) of the water, and signify drier climatic periods).

Solving the riddle of the origin of Tswaing

As soon as the drill core became available for study, Uwe Reimold took small chips of the granitic bedrock and had thin sections (very thin, translucent slivers) prepared for analysis with a geologist's microscope. The interaction of light with the crystal structure of minerals in such a microscope makes it possible to investigate defects and deformation in the various minerals, including shock deformation. However, none of these specimens showed anything out of the ordinary. Before any further work could be done, Uwe Reimold was to travel to Perth in Australia to present his new findings on Tswaing to the 1990 Meteoritical Society conference. Based on the negative results of this initial core investigation, he concluded that the record did not exclude a volcanic origin for this crater. This conclusion did not find much acclamation, in fact the audience rejected it outright. However, the arguments the audience had available were



† **Figure 72:** Parts of a millimetre-sized, frothy impact-glass particle from the interior of the Tswaing Crater. It also contains tiny, dark, spherical particles of iron sulphide, in addition to vesicles (bubbles) and remnants of crystalline target-rock debris. Such glass particles not only provided chemical traces of the meteoritic projectile that caused this impact event, but also allowed dating of Tswaing by the fission-track method. Plane polarised light, width of image ca 1 mm. † **Inset:** Another, perfectly round impact-glass particle from Tswaing (the sphere is ca 0.25 mm in diameter).

not conclusive either: the fact that the magmatic rocks intruded into the granite and had been dated at 1 300 Ma indicated that they should not be directly related to the cratering event. However, the possibility could not be completely ruled out that the crater formed as a result of a younger magmatic event.

Uwe Reimold returned to Johannesburg and, spurred on by the critique experienced, dedicated time to research the thus-far unstudied parts of the core, especially the loose sandy, locally gravelly zone overlying the granitic bedrock. A whole suite of sand samples was carefully scooped out of the core boxes, and thin sections prepared. When the first such specimen was placed onto the microscope stage, it took only a glance to discover the first quartz grain with planar deformation features (PDFs) in multiple sets of distinct crystallographic orientation. This represented unequivocal evidence of shock metamorphism. In quick succession a whole range of other observations of shock deformation followed, including diaplectic glass of both quartz and feldspar, and many more grains with PDFs. The origin of the Tswaing Crater by meteorite impact was finally proven!

In addition, a large number of round to ovoid, or dumbbell-shaped glass fragments (Fig. 72) were noted. Chemical analysis showed that they were formed by melting of individual minerals that are typically contained in the Nebo Granite, or from combinations of such minerals (quartz, feldspar, amphibole, biotite). The presence of melt meant that this sandy layer is a type of impact breccia (fragmented material), known as suevite, that occurs in many impact craters worldwide. Suevite is composed mostly of fragments of minerals and rocks, but

it does contain at least a small component of melt particles as well (see Fig. 94).

The glass particles also provided a means to try to obtain an independent and absolute age for the cratering event, which would allow scientists to explain the problem of the existence of magmatic rocks in the crater. Large numbers of glass particles were painstakingly handsorted for analysis by a method known as fission-track dating. When uranium atoms in a material undergo radioactive decay and split (the so-called fission process), the daughter products of this process form tiny tracks in the host crystal that can be viewed with a high-powered microscope. The more of these so-called fission tracks that are observed in an area of a thin section, the more time has passed since radioactive decay began; and if one knows the uranium content of a sample, it is possible to calculate an age. Over 400 glass particles were subjected to chemical analysis for uranium content. The fission tracks were then counted by a scientist, Dieter Storzer, in Paris. The age calculated from his results was 220 000 years (admittedly, with an error limit of ± 50 000 years), which not only is very close to the extrapolated age for the deposition of the crater sediments, but is also vastly different from the age of the dated intrusive rocks. Within the error limits of this age, we now know that the Tswaing Crater, despite its 'youthful' appearance, was formed about 220 000 years ago.

The search for the meteoritic projectile

Meteor Crater in Arizona is famous for its numerous pieces of the Canyon Diablo iron meteorite, remnants of the projectile that caused this impact crater. Unfortunately, to date, no pieces of the meteoritic projectile have been found in or around Tswaing, but this does not mean that at least an idea could not be gained of the kind of meteorite that caused the crater. Different kinds of meteorites have different chemical compositions, especially with regard to the concentrations and ratios of abundances of the so-called siderophile elements — those elements that are generally associated with iron, for example the elements nickel or cobalt — and the platinum-group elements, including iridium, rhenium and osmium. There are also vast differences in abundances of such elements between the rocks typically occurring in the outer parts of the Earth and in meteorites (though there is some overlap with the compositions of those rocks that are derived from the interior of our planet, the mantle of the Earth). If it can be shown that rocks in an impact crater are enriched in such elements in comparison with all rock types that could have occurred in the target region, a meteoritic contribution to the chemical composition of an impact-produced rock can be demonstrated.

That the Tswaing meteorite was totally destroyed in the impact event can be deduced from the fact that neither the drill core nor the region around the crater revealed any meteorite fragments. It is thus assumed that it was probably not an iron meteorite (most meteorites found associated with impact craters are), as irons would stand a better chance of not being completely destroyed in the impact than a relatively less-resistant silicate-dominated projectile.

All rock types occurring in the region of the Tswaing Crater and in the drill core were analysed. The loose impact breccia of the drill core contains, unambiguously, a meteoritic component, but the siderophile element data were not sufficient to pinpoint a specific meteorite type. However, there is chemical evidence indicating that Tswaing was formed by a chondrite, a chondrule-bearing type of stony meteorite. Chondrules are roundish, seed-like objects (the term stems from the Greek word for 'seed') that were formed by a melting process, like droplets of melt. Amongst stony meteorites are distinguished those that carry chondrules, the chondrites, and those, the achondrites, that do not.

The much more sensitive rhenium-osmium isotopic analyses since obtained by Christian Koeberl, from the University of Vienna, support this result and show that not more than 0.01 to 0.015 % of meteoritic component occurs in the breccia layer of the crater interior.

What do we know about the landscape in the Tswaing area prior to the impact?

A completely different result of the study of the suevite breccia allowed us to reconstruct what

the landscape was like at the time of impact. The different target-rock particles are undoubtedly in their vast majority derived from Bushveld granite. This means that only a thin veneer of other material could have lain above the granite, as the crater did not sample more than about 300 m of crust. Only a few rare fragments of a fine-grained sediment called siltstone were found in the breccia. That basically no volcanic material was found confirms that the volcanic origin for Tswaing is untenable, and that magmatic intrusions are actually rare in the target region. Yet, many small particles of a rock exclusively formed of diatoms (diatomite) occur; their presence, and the fact that they are commonly deformed, tells us that there must have been a lake in the area into which the meteorite crashed.

What would the catastrophe have been like?

The exact date of impact is not known, although scientific evidence, within error limits, points to about 220 000 years ago. Whether it was day or night, the fireball would have been plainly visible for a vast distance around the target area. Equally unclear is the direction from which the bolide struck. The structure is nearly circular, and ejecta that may have been accumulated in an asymmetric blanket around the crater, from which a possible trajectory of the projectile could have been deduced, have not been proven outside the crater.

In order to calculate the approximate intensity of the catastrophe, a number of parameters must be known reasonably well, such as the exact size of the bolide and its velocity, as well as its density. Velocity is particularly important in the equation used to determine the kinetic energy of the projectile, but this parameter is also not well constrained: the bolide could have been as 'slow' as 11 km per second resulting in a speed of 'only' 37 000 km per hour, or maybe as fast as 30 km per second which translates into some 110 000 km per hour.

The size of a crater can be used as a rough indication of the size of the projectile, and the diameter of Tswaing of little more than 1 km relates to a meteorite about 50 to 60 m in size. Anything smaller than that would have broken into pieces anyway, owing to the frictional and thermal stress on it during its ultrafast passage through the atmosphere.

Possible observers of this event would have seen an enormous flash of light high up in the sky, and heard soon after a tremendous deafening roar. The duration of this spectacle would have been only a few seconds. Upon impact, a gigantic explosion occurred, the magnitude of which is calculated to be equivalent to hundreds of atomic bombs of the type that devastated the Japanese cities of Hiroshima and Nagasaki in 1945. On estimate, the explosive force was equivalent to 20 to 40 million tonnes (megatonnes, MT) of TNT, whereas the explosive force of the 1945 atom bombs was a 'mere' 20 kilotonnes (kT).

Anything in the immediate target area, rock or living being, would have been instantaneously vaporised, including the bulk of the meteorite. Bedrock from below and around this zone was thrown out (ejected) to form the crater cavity. Anything not destroyed by the explosion would have been buried by the ejecta and the overturned rocks at the crater edge, as far out as probably 1.5 km.

However, destruction was not limited to close to the crater. Calculations of destruction around Meteor Crater in Arizona, of very similar size to that of Tswaing, have been carried out by US geologist David Kring and can be applied to Tswaing as well. The explosion would have caused a devastating air blast that would have caused devastation over a wide area. Enormous winds were generated, reaching speeds in excess of 1 000 km per hour in an area of at least 3 km around the crater, gradually weakening further out. In the immediate environs of the crater, everything on surface was stripped off or, in an area as wide as 20 to 30 km from the crater, flattened. At a distance of 40 km, surface destruction would still have been very strong and, even further out, trees would have been at least partially uprooted. Any living being, if not killed by flying objects, would have been strongly compressed. Animals, and any early humans that might have been present, would have died of suffocation or explosion of the lungs. For Meteor Crater, a ca 10 km wide zone of 100 % lung damage has been calculated and the same would have held for the Tswaing impact.

All the flying debris catapulted outwards from the crater over a distance of tens of kilo-

metres was a further hazard for any living being. There is nothing to compare these effects with, neither a tornado nor a giant hurricane; impact devastation is in a class of its own! This relatively small impact event of a 50 m meteorite must have resulted in total devastation over a region of at least 35 km width, that is a minimum of about 1 000 km^2. For comparison, that is about the region of greater Johannesburg, from Midrand to Soweto, and Edenvale to Krugersdorp. Imagine the loss of life if such a 'minor' impact occurred today in such a densely populated metropolitan region!

A question that immediately comes to mind is: "How often can such a 'minor' event occur?" In Chapter 7, the impact hazard is discussed in more detail. Suffice to say here that the known impact-cratering record and estimates of how often such small bodies might approach Earth suggest that such comparatively minor events might happen about once in every 1 600 years. If one subtracts the 70 % of Earth covered by water, this estimate will increase to one impact in 7 000 years on a continent. However, this figure does not imply that the next impact may be 7 000 years from now. In fact, there may be two or three, or even more, in the space of a few years only, followed by a long 'recovery' period, or, for that matter, any other spacings between impact events and relief times. There already is a record of at least one impact event of this magnitude in the 20th Century, namely the Tunguska event of 1908, when a small bolide exploded in the atmosphere, and the resulting blast wave flattened forest over 2 000 km^2. Although it seems that loss of life was minimal compared with if the blast had occurred above a major metropolitan area, it is thought that small nomadic groups and reindeer herds perished in the blast. However, interestingly, it appears that two more such events may have occurred in the 1930s, fortunately also in very remote and mostly unpopulated parts of Amazonia, in Brazil and in Guayana. While the records are poor, it is confirmed that forests were destroyed over wide regions, as in the case of the Tunguska explosion. This indicates that, over the limited time frames which we humans experience, impact-frequency statistics may have very little meaning.

Were there any witnesses of the catastrophic impact at Tswaing?

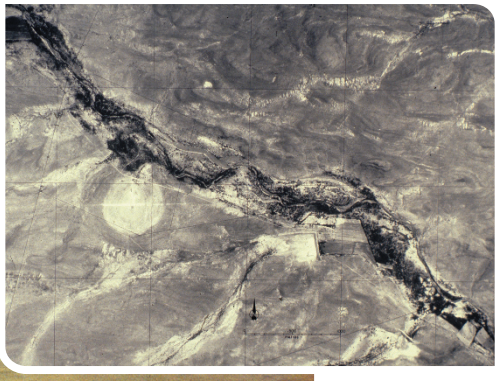
Given the relatively good constraints on the age of the Tswaing impact, it is possible that Stone Age people could have witnessed the event, or even been victims. There is no direct evidence of habitation in the target area and its environs at the time of impact, as any such evidence would have been completely obliterated by the catastrophe itself. However, it is possible to compare with archaeological evidence from relatively close sites, such as Gladysvale or Swartkrans, about 80 km farther south in the Cradle of Humankind area. This may give vital clues as to the kind of animals that could also have lived in the Tswaing area. Indications are that the Highveld plains around Tswaing at the time of impact would not have looked strange to modern eyes: widespread grass cover, scattered bushveld and broken woodland areas. Large herds of mammalian grazers would have inhabited these plains, followed by predators feeding on them. Along streams one would have expected woodland inhabited by various species of monkey. Wetlands would have occurred locally and, as described earlier, there is distinct evidence for a lake having existed in the target area. Animals such as hippo, lechwe and waterbuck could also have been part of the local fauna.

Homo also lived in these plains, mostly as a hunter, as testified by a number of Early Stone Age artefacts that have been found at Tswaing, such as rock scrapers or hand axes. Those possible human witnesses to the event could have been modern in their anatomy: genetic studies have suggested that the earliest modern humans came into existence as early as 220 000 years ago. Anatomically modern humans are known from a number of sites in southern Africa, and a very early site is the 110 000 to 120 000 year old site at Klasie's River Mouth in the Eastern Cape. The people who lived there at the time used very primitive tools, such as flaked tools, scrapers, hammer stones, and unifacial blades that could have been mounted on spears. Unfortunately, as these early inhabitants did not use symbolic or written word, no such record of this impact event exists.

Does Tswaing have a twin?
Kalkkop Crater, Eastern Cape Province

Kalkkop, a small meteorite impact crater, is situated in the Eastern Cape Province. On aerial photographs (Figs 73, 74) the structure stands out clearly as a near-circular, white shape. The name is derived from the light-coloured limestone (Afrikaans 'kalksteen') that fills this crater to the rim (or head: Afrikaans 'kop'). The crater rim is preserved in only a few places as low, deeply eroded, remnants. Kalkkop is only 640 m in diameter. It is located between Jansenville and Graaff-Reinet, along a rather bad dirt road where the Buls River makes a few sharp turns (Fig. 73). The local farmer has assembled a number of exhibits that can be viewed by visitors.

Since the early 1980s, it had been suspected that Kalkkop was a meteorite crater, but only in 1997, when a drill core became available for analysis, was it possible to confirm this through findings of shock-metamorphosed quartz, glass fragments in a thin layer of suevitic breccia, and chemical traces of the meteoritic projectile. The age of the crater is some 250 000 years and, within error limits, overlaps with the age for Tswaing, making it possible, but by no means essential, that the two could be related. Kalkkop is not a very exciting meteorite crater to visit, nevertheless, it is a useful tool for education in natural science, at least for the schools in that region of the Eastern Cape Province.



← **Figure 73:** An old aerial photograph of Kalkkop meteorite crater in the Eastern Cape Province of South Africa. The dark band diagonally across the image is the course of the Buls River, along which some vegetation occurs.

← **Figure 74:** Oblique aerial photograph of Kalkkop, looking south. Photograph kindly provided by Mrs D. Thornton, Graaff-Reinet.

South Africa's other giant impact — Morokweng impact structure, North West Province

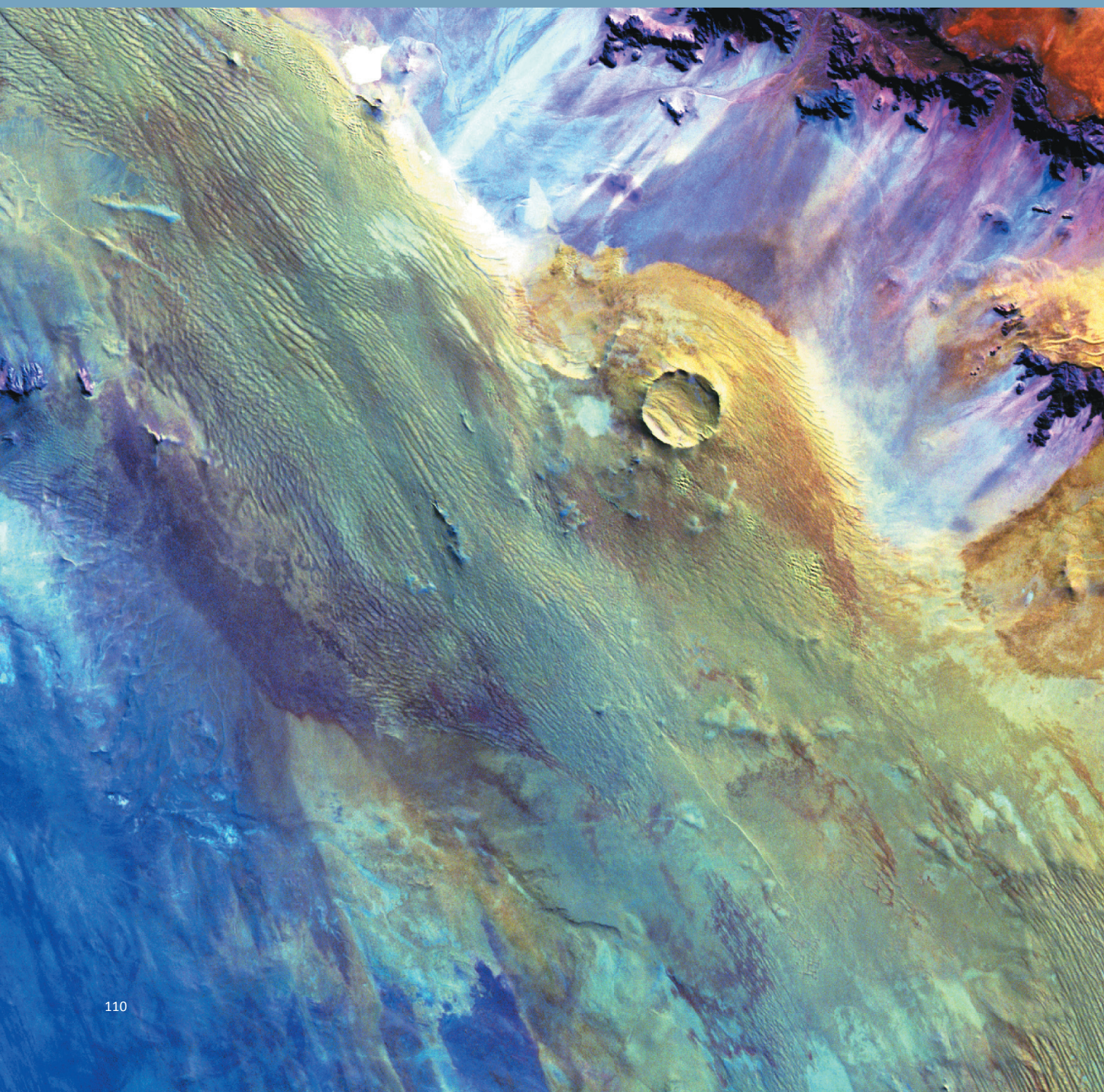
In 1995 Marco Andreoli and his colleagues, from the Schonland Centre at Wits University and from the Rand Afrikaans University (now University of Johannesburg), published a first short report on the possible existence of a large impact structure in the region around the small township of Morokweng, northwest of the town of Vryburg in the far west of the North West Province (see map pp. 100–101). Here, over an area about 40 km wide that is known as the Ganyesa Dome, a strong, roughly circular geophysical anomaly occurs. It had been repeatedly discussed in the literature but, until that year, it was thought to represent an intrusive magmatic body. Marco Andreoli and his group described rocks from a drill core into this geophysical anomaly that showed microscopic evidence of shock metamorphism. They also detected a large body of melt rock that had the characteristics of impact melt. Shortly thereafter, Uwe Reimold and colleagues visited Roter Kamm in Namibia, and, on the way back, also visited Morokweng. This southern part of the Kalahari Desert is mostly sand-covered terrain with calcrete-covered surfaces and only a few outcrops of country rocks, limited mainly to stream beds. Despite the difficult field situation, several rock samples that revealed shock-metamorphic deformation were collected. Detailed drill-core studies followed, further confirming shock deformation and showing that the melt rock contains a meteoritic component. The impact melt rock was dated at 145 ± 2 Ma. At 2–5 % in individual samples, the meteoritic component in the Morokweng impact melt rock is very high compared with impact melt rocks from other impact craters, which generally show extraterrestrial components that are significantly less than 1 %.

The original size of the Morokweng impact structure has remained a matter of debate for years. Initial suggestions of a 200 and even 340 km diameter caused much interest in this structure worldwide; a 340 km diameter would have made Morokweng the largest known impact structure on Earth. What is more, this impact coincides with a comparatively minor, but nonetheless global, mass extinction at 145 Ma. A very large Morokweng impact structure could, in analogy to the Chicxulub Crater in Mexico of K–T-boundary age, represent a smoking gun for a Jurassic–Cretaceous boundary impact-produced catastrophe. Recent work on J–K boundary sections in western Europe has, however, failed to provide geochemical and microscopic evidence for impact.

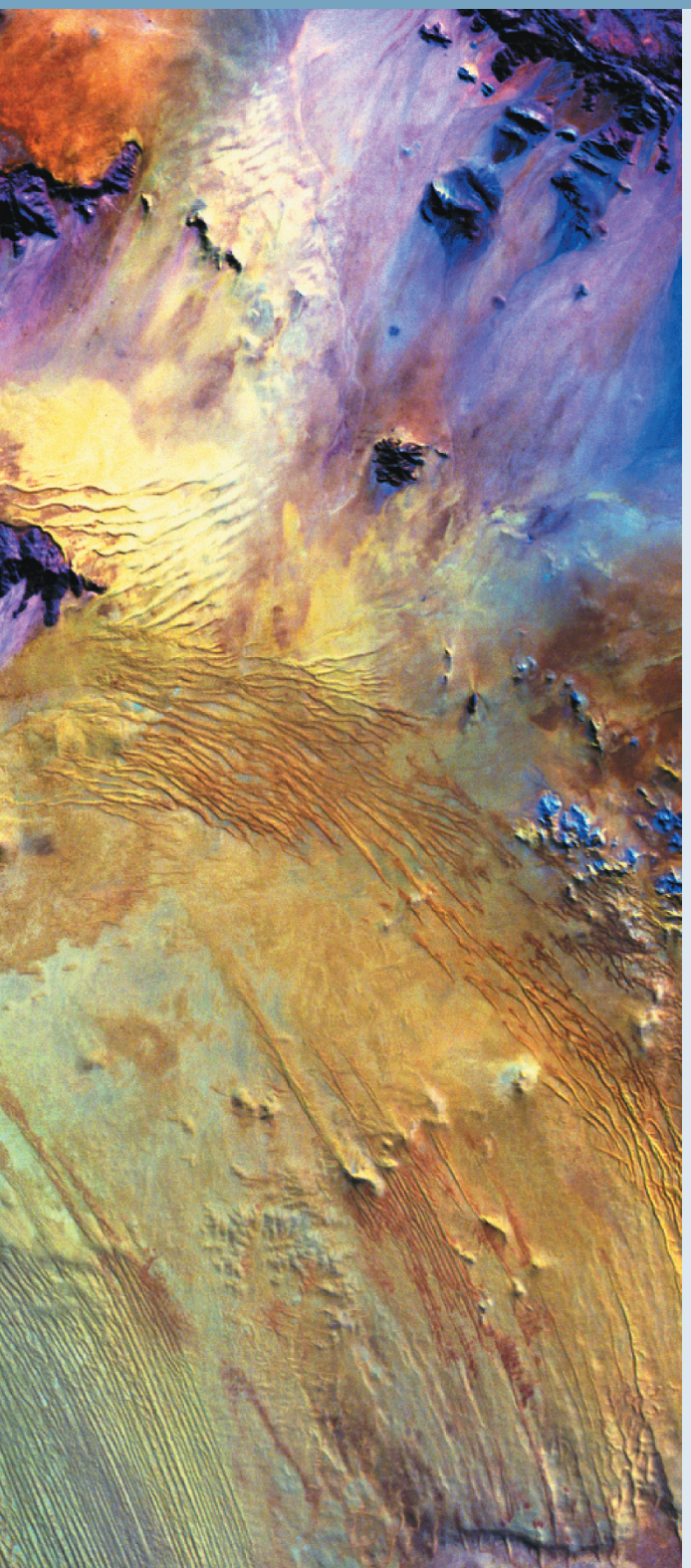
As more work was carried out on Morokweng, size estimates became more varied. In recent years, authors have preferred values between 90 and 200 km. Then, in 2002, the results of a detailed geophysical modelling exercise, carried out by Uwe Reimold, Herbert Henkel of Stockholm and Christian Koeberl from Vienna, across the Morokweng region, became available. This model matched the geometry of a complex impact structure of about 75 km diameter. In addition, permission was obtained from a mining house to study another drill core obtained about 35 km from the assumed centre of the impact structure, providing a continuous rock record to a depth of nearly 3 500 m. Over this whole interval, only a single, 10 cm wide injection of impact breccia, into otherwise completely undisturbed and undeformed rocks, was found. These observations have been interpreted to suggest that this borehole is located just outside the crater rim and, thus, that Morokweng is a 70 km wide impact structure.

However, an impact structure of 'only' about 70 km is nothing to sneer at! This impact event probably did not cause a global environmental catastrophe, but Morokweng is still one of the 10 largest known impact structures on Earth.

It also contains a considerably higher meteoritic contribution than found in most other impact melt bodies; so high, in fact, that mining companies have been carrying out quite extensive exploration for nickel and other metals in this area, albeit with little success.



Our southern African neighbours



Quite a number of impact structures are known from southern Africa (see pages 100–101), in contrast to much of the rest of sub-Saharan Africa. One of these structures, a 2.5 km, very well preserved crater called Roter Kamm, is located about 80 km north of Oranjemund in the Namib Desert of southern Namibia (Fig. 75). Roter Kamm has been known, and suspected to be of impact origin, since the early 1970s. However, only between 1986 and 1989 did detailed geological analysis and microscopic study of rocks from Roter Kamm begin with the work of Roy Miller, from Windhoek, and Uwe Reimold. Conclusive impact evidence was found, rocks of the exposed parts of the largely sand-covered crater rim were mapped and geophysical characterisation of the crater carried out. Initially, only a single sample that could be used for dating of the impact event (a single, fresh piece of impact melt rock) was found. The age obtained is 3.4 Ma, in good agreement with the somewhat rounded but still 'youthful', well-preserved appearance of the crater rim. A more recent attempt to date additional melt samples set an upper limit for the age of Roter Kamm at 5 million years. Roter Kamm is located in pristine desert (Figs 75 and 76). Due to the efforts of the Geological Survey of Namibia, a major part of the Namib Desert area in this country has now been declared the 'Sperrgebiet National Park' and placed under special protection. This includes the area of the Roter Kamm impact crater.

Despite the considerable size of Namibia, no further impact structures have been discovered there, but then much of this country is covered

← **Figure 75:** False-colour image of the 2.5 km diameter, 3.4 Ma old Roter Kamm Crater in the southern Namib Desert, Namibia. Based on original Landsat 4 data. Courtesy of Alan Frantzen, Johannesburg.

↑ **Figure 76:** Early morning at Roter Kamm. Mist from the Atlantic Ocean coast fills the crater bowl.

by desert sands. Yet, the sheer size of this country suggests that there remain a few more undetected impact features.

Another very large country that is mostly covered by sand of the Kalahari Desert is Botswana. Here, to date, only one impact structure is known: the recently identified 3.4 km wide Kgagodi Basin, ca 60 km to the northeast of the town of Palapye in eastern Botswana. Its surface expression is weak, as the crater rim appears to have been completely eroded. Kgagodi was discovered by chance when boreholes (for water) were sunk in the area. Samples from a drill core inside, but close to, the crater rim revealed that a thin impact-breccia layer had been intersected. Quartz with planar deformation features and glass fragments were observed, and chemical analysis showed a slight, but definite, enrichment in the element iridium, in comparison with the country rocks occurring in this area: unambiguously a trace of extraterrestrial origin. Kgagodi is not well exposed, but has the potential to become famous. Its age is not well known, but first indications are that this crater could be as old as 60 Ma. Drilling the centre of the crater could produce a continuous profile through the crater fill that, as in the case of Tswaing, could represent a truly unique long-duration palaeoclimatic profile.

No impact structures are known yet from Mozambique. Zimbabwe, on the other hand, has two candidates: the Sinamwenda and Highbury structures. Indications are good, although final proof is still lacking. Sinamwenda is a very small crater feature in a game reserve south of Lake Kariba. It must be young, as it is well preserved, and is only about 100 m in size. Such small, possible impact craters are virtually impossible to confirm unless meteorites can be found in or around them, as the energy released upon their formation is too weak to generate much impact-characteristic rock and mineral deformation.

A much larger, but deeply eroded, possible impact structure is situated in the Highbury region of north-central Zimbabwe. The structure is about 20 km wide and occurs in an agricultural region with very little rock outcrop. Some rock samples from the surrounding hills show mineral deformation that is quite reminiscent of shock deformation, though a really convincing example of planar deformation features is still lacking. An age of 1 470 Ma has been obtained for a melt rock, but it has not been possible to prove yet that this material truly represents impact melt rock. In all likelihood, detailed geophysical analysis and drilling will be necessary to confirm whether this structure originated by impact.

Testimony of earlier impact catastrophes — Barberton and the Northern Cape Province

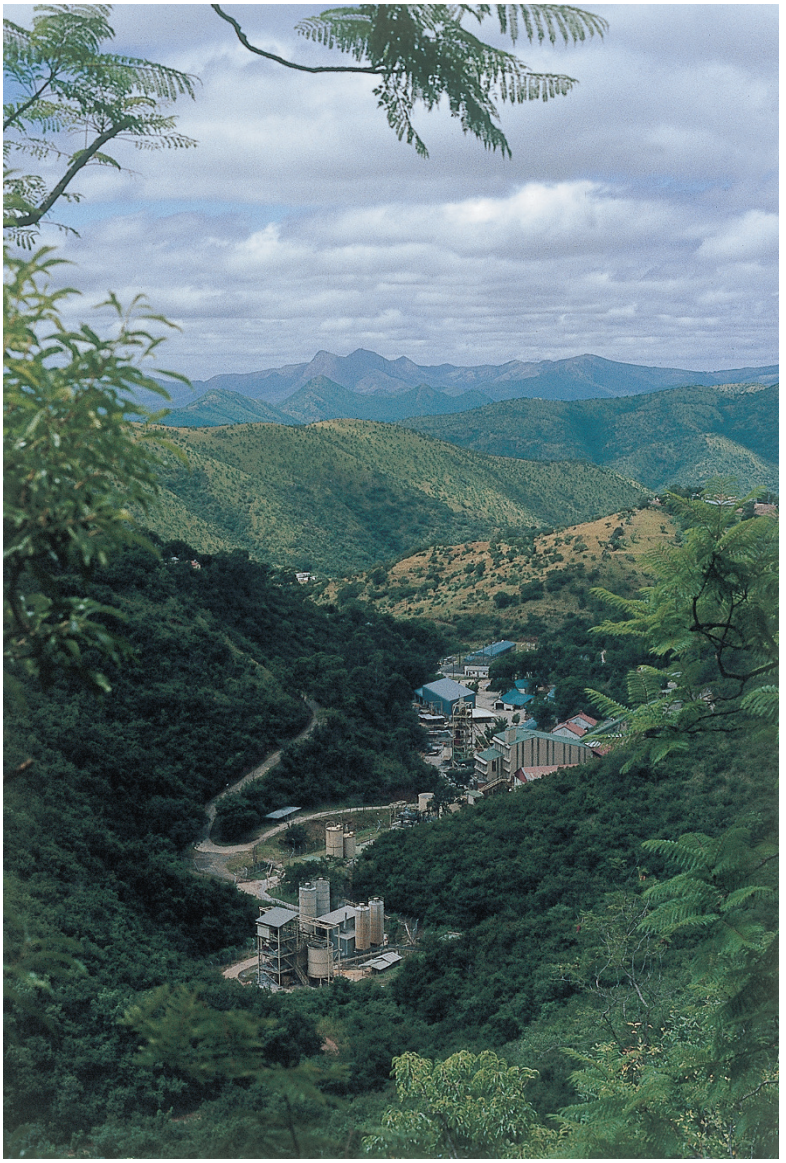
In addition to actual impact-crater structures in southern Africa, a number of rock layers have been identified that represent the remnants of widespread ejecta derived from ancient impact events. These include the currently oldest known impact debris on Earth in 3 400 Ma old rocks from the Barberton Mountain Land. They are characterised by dense accumulations of millimetre-sized, spherical and ovoid particles, so-called spherules (Fig. 61, page 84). These spherules, per se, would not be out of the ordinary, as the fallout from many volcanic eruptions may look very similar. Such volcanic debris particles are known as lapilli, and undoubtedly occur in the rocks of the Barberton Mountain Land as well. However, these volcanic lapilli layers do not show the very substantial concentrations of the platinum-group element iridium, rare in crustal rocks, but relatively enriched in most extraterrestrial matter and in rocks derived from the Earth's mantle, that have been measured in some of the spherule layers. This enrichment suggested to US geologists Don Lowe, Gary Byerly, and Frank Kyte that these layers represented ejecta from very large impact events that took place at that time. Others, including Uwe Reimold, Christian Koeberl and co-workers, were sceptical, as these rocks are highly weathered and have been overprinted by hot, metal-bearing solutions and been metamorphosed. Thus, they advocated that these chemical signatures were not original and directly impact related, but the result of later geological overprints. It took a recent technological advancement, the accurate analysis of ratios between the respective isotopes of the element chromium, to prove beyond doubt that at least several of the spherule layers known from Barberton do indeed have a meteoritic signature, however, others remain to be analysed.

In addition to these Archaean spherule layers in the Barberton Mountain Land, several have been detected in 2 200 Ma old rocks of the Transvaal Supergroup. Bruce Simonson, from Oberlin College in the USA, found a spherule-rich layer in a drill core of the so-called Monteville Formation. In collaboration with Christian Koeberl and Uwe Reimold, as well as Iain McDonald from Cardiff University, he has established chemical characteristics consistent with the presence of a meteoritic component. Interestingly, there are spherule layers in rocks of similar age in western Australia, in the so-called Hamersley Basin, the sedimentary filling of which has been correlated with the rock sequence of the Transvaal Supergroup. Current stratigraphic work in both western Australia and the Transvaal strata of the Northern Cape Province is investigating the possibility that these impact-ejecta layers in Australia and South Africa could be the same layers. If confirmed, this would provide an excellent means of correlating the Palaeoproterozoic rock sequences between South Africa and Australia.

Given the existence of these very old spherule layers of proven impact origin, it is worth speculating on how many more ejecta remnants are still hidden in the 3 800 Ma rock record on Earth. The chances of adding significantly to the list of terrestrial impact-cratering events, especially with regard to the elusive early mega-impacts, is greatly enhanced by searching for such layers, as their distribution is likely to be considerably greater than that of the originating impact structures.

In the year 2000 a 1 m thick spherule layer was discovered in ca 2 000 Ma old rocks in Greenland. Based on the existing, though crude, age constraints for this layer it has been tentatively correlated with the two oldest impact structures known on Earth: either the 1 850 Ma Sudbury Structure in Canada or the 2 020 Ma Vredefort Structure of South Africa. Unfortunately, it has not yet been possible to

reconstruct where the Kaapvaal craton and the Superior Province of Canada were positioned on the globe relative to Greenland at these respective times. Thus, it is not possible to prove, without having better age constraints on the spherule layer, whether this spherule layer belongs to one of these two impact structures, or perhaps is the result of another, still unknown, impact event. In 2005, ejecta from the Sudbury impact were identified by Bill Addison and co-workers in the Lake Superior region of North America, over 650 km east of the impact site.



← **Figure 77a:** Spherule layers are exposed underground in the Sheba Gold Mine in the Barberton Mountain Land (see Fig. 61, page 84). Photograph courtesy of Ian Ward.

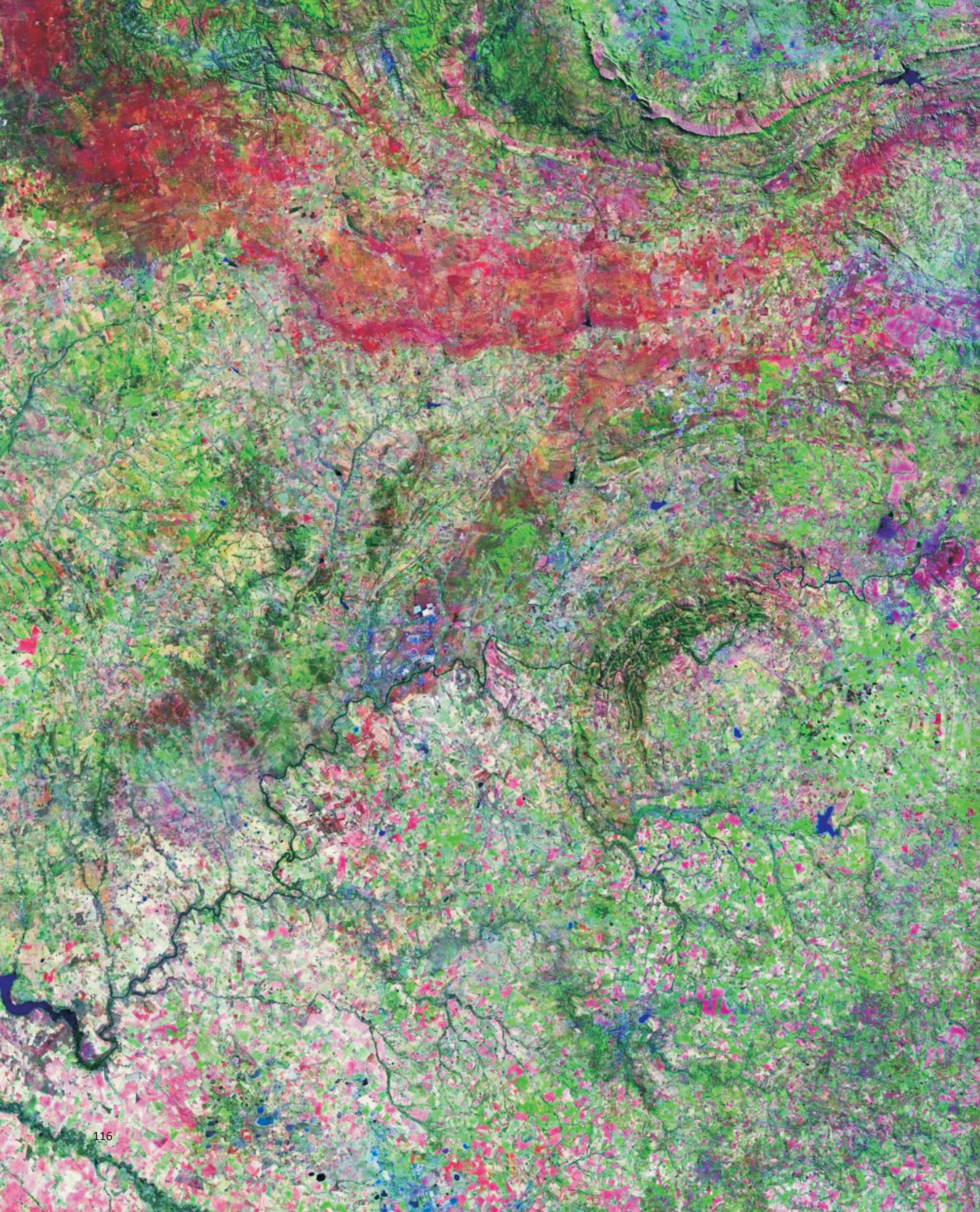
Traces of catastrophe in the Karoo?

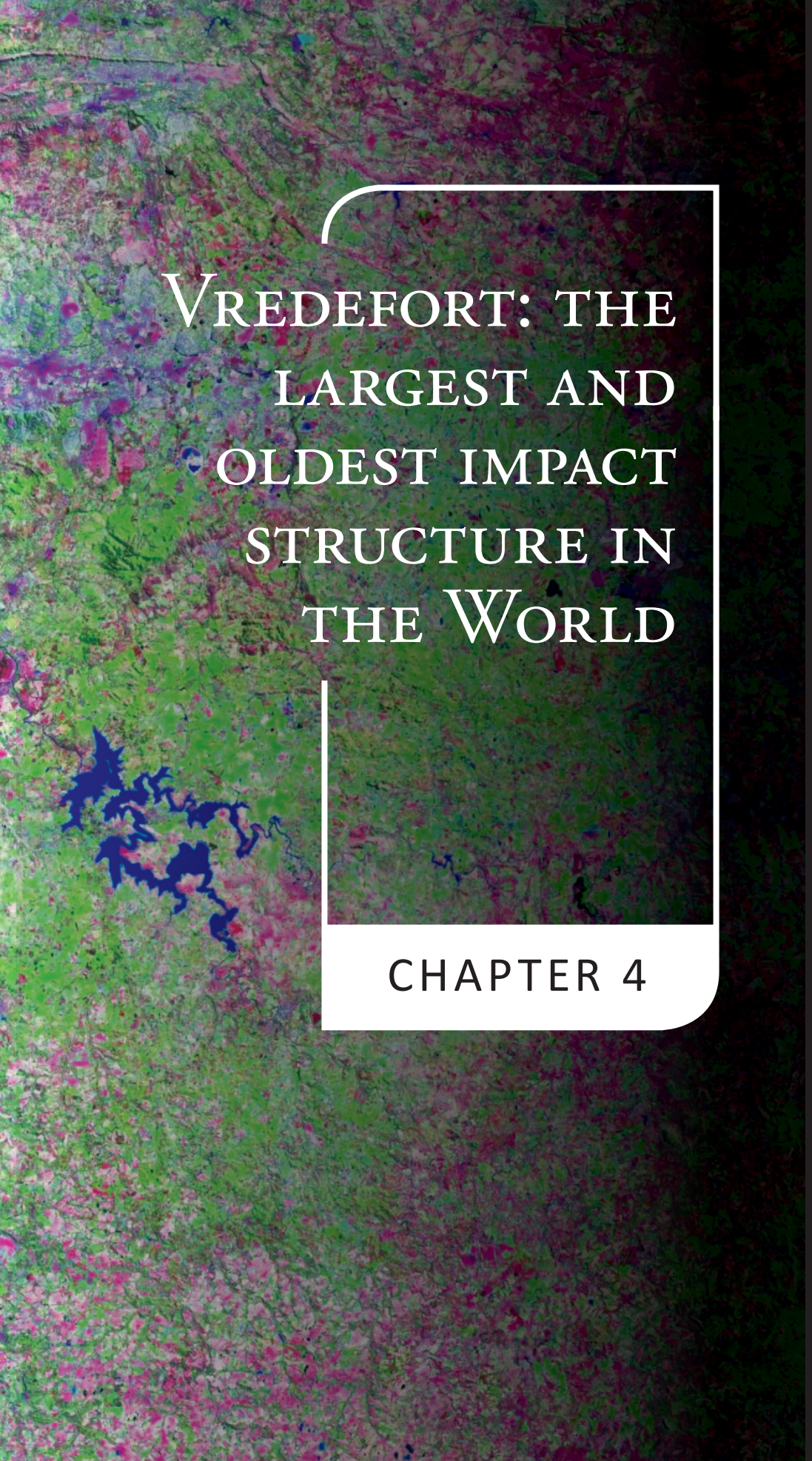
The rock record of South Africa is unique, spanning 3 600 Ma of geological and impact activity. The rocks of the Karoo basin, deposited between about 300 and 180 Ma ago, are the most extensive (Fig. 21, page 34). This interval contains several major extinction events in the global rock record, including the most important one at the Permian–Triassic boundary (251 Ma) and a less severe, though also significant, event at the Triassic–Jurassic boundary (206 Ma) (see Table on page 73).

Rocks straddling the boundary period between the Permian and Triassic eras, at about 251 Ma, are beautifully preserved and accessible in the Karoo basin. South African palaeontologists have extensively investigated the transition from one fauna to another, and they found that only one species, *Lystrosaurus*, survived after this event, and coexisted with an otherwise totally new fauna dominated by dicynodonts. The question of how so many species could be wiped out virtually simultaneously over such a short period of geological time remains unanswered. Given the K–T boundary evidence, one possible option is a large impact event. However, unlike the K–T boundary, no conclusive evidence has been found so far in favour of an impact event. The coincidence of the Permian–Triassic boundary with the eruption of one of the largest flood-basalt sequences in Earth history, in Siberia (Fig. 44, page 61), may point to a more gradual environmental catastrophe. Still another option might be the release of frozen sea-bed methane from the polar regions as a result of rising seawater temperatures. Methane is a far more deadly greenhouse gas than carbon dioxide and its widespread release would trigger dramatic environmental change — a threat that persists today. Although researchers remain undecided about the cause of the Permian–Triassic extinction, it would perhaps be ironic if the Age of Dinosaurs — that ended at 65 Ma as a result of the Chicxulub impact — actually began as a result of another, earlier giant impact!

In this chapter, the southern African impact record has been investigated. However, the foremost of all of these impact features is the Vredefort impact structure, which will be examined in the following chapter.

Figure 77b: Typical Karoo landscape.





Vredefort: the largest and oldest impact structure in the World

CHAPTER 4

The Vredefort Structure revealed

The Vredefort impact structure is enormous! In fact, it is so big (hundreds of kilometres in diameter) that it is not as readily revealed to the casual visitor as much smaller craters such as Tswaing (Fig. 48). A large part of the problem is that the Vredefort Structure is so old that it has been deeply eroded by rivers, which have destroyed all traces of the original crater. It has also been subjected to tectonic events since its formation that have masked and altered some of the impact features. When this erosion is added to the fact that the outer crater edge of large impact structures (multi-ring basins) is notoriously difficult to define precisely, it is perhaps not surprising that geologists continue to debate the size of the Vredefort Structure. Most geologists accept a diameter of about 250 km, which would place the northeastern edge of the crater between Johannesburg and Pretoria, and the gold-mining town of Welkom within the southwestern edge. To view an area this size actually requires an image from Space, such as those from the Landsat and SPOT satellites (Figs 1 and 78, and pages 116–117). Pondering these images, it is understandable why, for many decades, the extent of the Vredefort Structure was thought to be only that of the 80–90 km wide Vredefort Dome. The semicircular crescent of ridges and valleys that runs around the dome forms a 20 km wide zone, known as the collar, that extends up to about 45 km from the centre of the dome. The rugged terrain in the northwestern and northern parts of this ring-shaped zone is known as the Vredefort Mountain Land. Inside this mountain land, the much flatter terrain of the so-called core of the Vredefort Dome can be seen. This area is largely agricultural land with only a handful of small rocky koppies (hills). The N1 route between Johannesburg and Bloemfontein cuts through the eastern part of the dome (Fig. 78).

The Vredefort Mountain Land is cut by a series of deep valleys, sometimes forming narrow and very deep gorges (kloofs), and by the Vaal River, one of the premier rivers of South Africa, that meanders through the north and northwestern parts of the dome (Fig. 78). In the Parys area, the landscape is much less rugged and, consequently, the river has a wider and shallower bed, flowing southwestwards around a large number of islands of variable size (Groot Eiland — Afrikaans 'large island' — is a kilometre wide). Farther downstream, the river follows a northwesterly course along a fault zone, flowing over several gentle rapids that provide river-rafting opportunities. The Vaal re-enters the Vredefort Mountain Land at Kommandonek, a very prominent ridge of highly fractured quartzite that creates a set of fast-flowing rapids. Beyond this narrow portion, the river broadens and flows more peacefully. Its northwestwards flow is arrested by the massive bulk of the Central Rand Group quartzites, and it curves southwestwards, parallel to the curve of the rock layers. It continues past the historical hamlet of Venterskroon before a further fault across the outer collar allows it to leave the dome and assume a more westerly course towards Klerksdorp and the western country (formerly known as the Western Transvaal, now part of North West Province).

The Vredefort Dome is also visible from aircraft flying between Johannesburg and Bloemfontein or Cape Town. The broad curved swathe of the Mountain Land, the Vaal River course, the industrial cities of the Vaal Triangle, the Vaal Dam about 80 km to the southeast of the Vaal Triangle, and the extensive yellowish-grey minedumps of the Carletonville Goldfield, also known as the West Wits Line (Fig. 80, around Carletonville), to the north of the dome, provide excellent orientation. In flight from Cape Town, on a clear day, and as airplanes usually begin their descent long before reaching the Vredefort area, the towns of Parys and Vredefort (marked by a series of grain silos), the large bentonite mines in the otherwise flat and featureless southeastern part of the dome, and all the other landmarks mentioned already are perfectly visible.

Figure 78: SPOT satellite image of the Vredefort Dome, showing in graphic detail the ridge-and-valley region of the Vredefort Mountain Land (in the north and northwest), the Vaal River snaking through it, and the largely agricultural central parts of the dome. P: Parys town, V: Vredefort town, K: Koppies town, I: Inlandsee pan. The prominent road running across the dome from the north-northeast to the south is the freeway (N1) between Johannesburg and Bloemfontein. Image courtesy of the CSIR Satellite Information Centre, Hartebeesthoek.

Getting to know the giant:
By road through the Vredefort Structure

It seems reasonable to assume that most visitors to the Vredefort region will start their journey in Johannesburg. The city lies at the northeastern margin of the Witwatersrand basin (Fig. 23). The first Witwatersrand gold was discovered in a conglomerate horizon on Langlaagte farm, to the southwest of the present city, by George Harrison and George Walker in 1886. Owing to the southward inclination (dip) of the rock formations, the city expanded northwards from a line across Langlaagte which followed the trend of mining. The prominent ridges of Johannesburg represent weathering-resistant quartzite horizons of the Witwatersrand Supergroup (Fig. 20). They include the Roodepoort–Krugersdorp Ridge, the original Witwatersrand (Afrikaans 'ridge of white waters'), which was named for the many waterfalls that cascade down the quartzite cliffs and from which the entire region takes its name. This ridge forms a major watershed (drainage to the north ends up in the Indian Ocean, streams flowing south feed into the Vaal–Orange River system that ends in the Atlantic Ocean). To the north of this ridge the subdued topography is indicative of pre-Witwatersrand granite-greenstone rocks similar to those found in the core of the Vredefort Dome. The stratigraphic names for the quartzite formations, and the more easily weathering shale horizons between them, have been taken from places and suburbs in Johannesburg; for example Orange Grove, Hospital Hill, Jeppestown, Parktown, Brixton and others.

Entering the M1 motorway in the central suburb of Braamfontein, one already finds oneself driving through the lowermost part of the fill of the Witwatersrand basin, an elongate bowl of sedimentary rocks between Johannesburg and Welkom. The Witwatersrand Supergroup rocks exposed in Braamfontein comprise a thick sequence of shale with some interlayered banded iron formation, known as the Parktown Formation. Where these rocks are strongly deformed, they are known as the Contorted Beds. An excellent exposure of these rocks is observed at Jan Smuts Avenue, opposite the University of the Witwatersrand. In fact, the university is built on this layer. The overlying Brixton Formation quartzite is best exposed around the Brixton television tower, from where one also has a wide-ranging view over much of the northern part of Johannesburg and, on a clear day, all the way to the Magaliesberg mountain range along the northern margin of the Johannesburg Dome. Immediately south of the central business district of Johannesburg city (marked close to the freeway by the buildings of the new cultural precinct clustering around the wide square in front of MuseumAfrica), the freeway crosses the belt of early gold mines which extends from Springs on the East Rand to Krugersdorp in the west. Mining in this region, the so-called Central Rand Goldfield, began with the first discovery of gold in 1886 at Langlaagte, situated to the west of the freeway. The discovery site can be visited in George Harrison Park, a National Monument site, at Main Reef Road in Langlaagte.

Several abandoned mine shafts and mine dumps are passed in the direct vicinity of the freeway. The mine dumps — one of Johannesburg's most prominent features — were created between the 1930s and 1950s, but are now disappearing as superior modern gold-extraction techniques are being utilised to extract the remaining gold from the already powderised ore, which may still run to several grams per tonne. Mining in the Central Rand Goldfield progressed from the surface outcrop line of early mines towards the south, following the dip of the gold-bearing strata into the basin. Surface mining of the reefs was possible at Langlaagte, but when mining reached Crown Mines, ca 3 km farther south, ore extraction had reached depths between 800 and 1 400 m. Several projects are currently underway to investigate the prospects of resuming mining to greater depths farther south, maybe

even to depths of as much as 4 000 m. Analysts are currently predicting the possibility of a second phase of gold mining in a region known as the Argonaut Goldfield to the south of the Central Rand Goldfield.

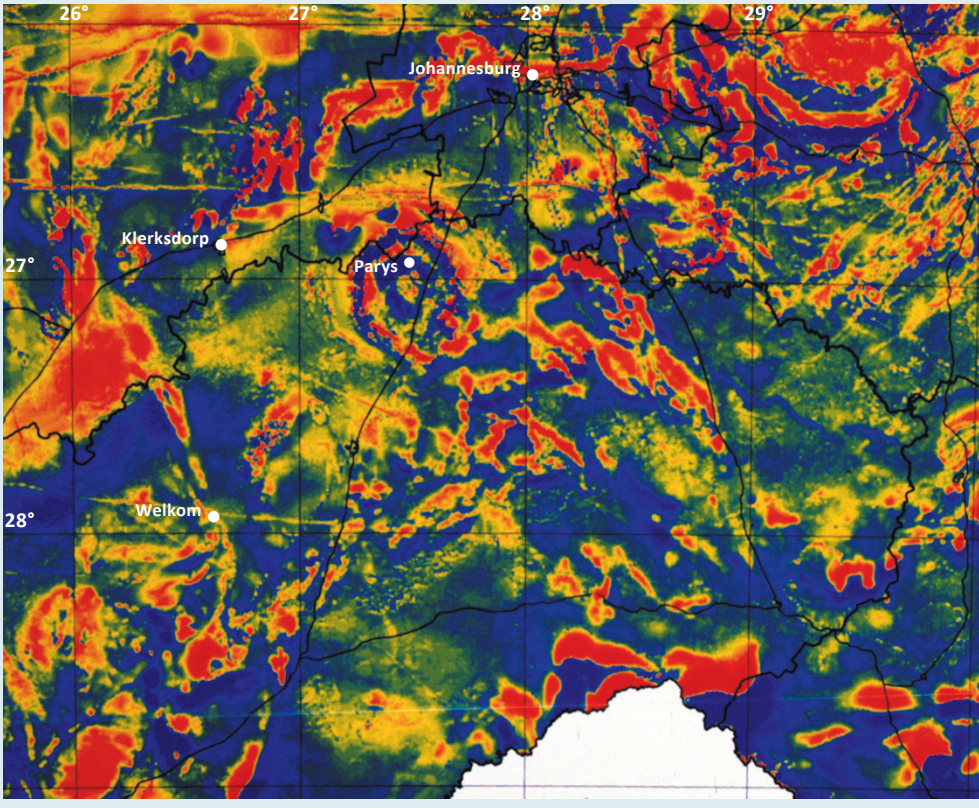
The Crown Mines No. 14 shaft complex has been converted into a tourist gold mine and entertainment-cum-casino complex (Gold Reef City), which incorporates many of the former mine buildings, provides access into a still-maintained stope of the old gold mine, and features live gold pours. From here, the route proceeds southwest towards Potchefstroom. A few kilometres south of Crown Mines, the N1 freeway cuts through a prominent ridge, the Klipriviersberg. Here, some greenish-grey rocks are exposed on the left side of the road, providing a glimpse of the voluminous 2 700 Ma Ventersdorp Supergroup lavas that thickly cover the Witwatersrand Supergroup.

From here, the N1 heads directly southwest towards the Vredefort Dome, crossing rocks of the Transvaal Supergroup that overlie the Ventersdorp and Witwatersrand Supergroups. Towards Vanderbijlpark the dip of the strata changes from southward to horizontal, marking the axis of downsagging that surrounds the dome (Potchefstroom syncline). After crossing the Vaal River, the ridges of the northeastern collar of the dome become visible to the west. These rocks are the same layers that form the quartzite ridges in Johannesburg, except here they have a near-vertical dip. The dome is accessed by turning onto the R59 to Parys.

An alternative, longer, route follows the N12 towards Potchefstroom, a moderate-sized university and agricultural town in the western part of the Witwatersrand. The turn-off is situated shortly after the Doornkop ridge that is underlain by the Klipriviersberg lavas. The road lies north of the broad Klip River valley, which marks the location of the dolomitic Chuniespoort Group. Scattered quartzite boulders along a low ridge in the foreground mark the Black Reef Formation, the base of the Transvaal Supergroup. In a few places on the East and West Rand, the Black Reef has been mined for gold. The opposite side of the valley is underlain by quartzites and shales of the upper Transvaal Supergroup (Pretoria Group). For some 60 km the road continues mostly through countryside with rather subdued topography. The Chuniespoort Group dolomites contain ample evidence of the early life that flourished in the shallow Transvaal Sea some 2 600 Ma ago. The dolomites are usually poorly exposed, forming valleys. They pose a serious threat to mining operations and town planning in the region, as mining-related dewatering of the rocks has caused extensive formation of sinkholes.

The Klip River wetland along the valley floor has proved to be a vital trap for mining and industrial pollution; however, the delicate ecosys-

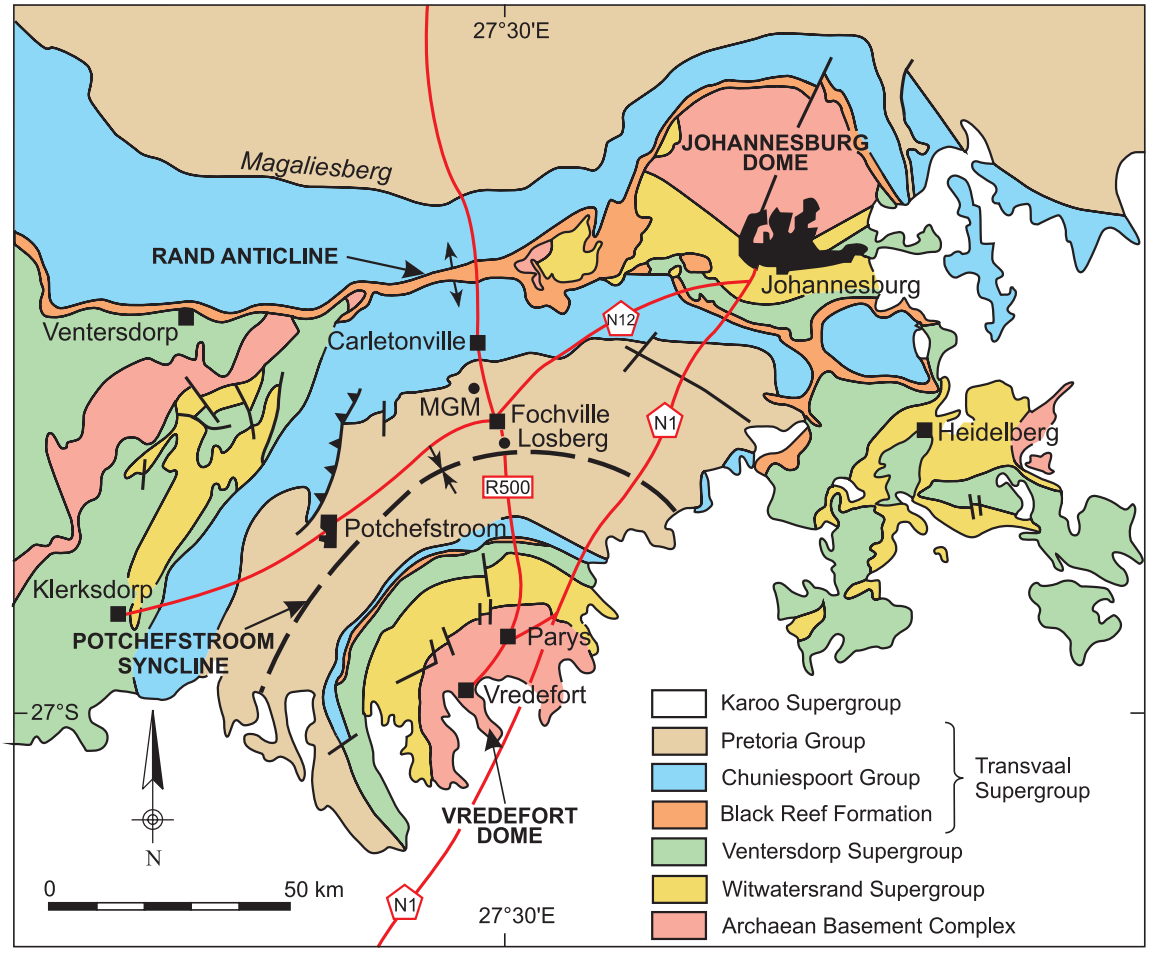
Figure 79: The magnetic signature of the Witwatersrand basin and surrounding region. The outline of the basin itself and the Vredefort Dome in its central area is provided by the highly magnetic Parktown Shale Formation. Red indicates strongest positive magnetic anomalies. Black lines indicate major roads and rivers. Compare with Fig. 24. Image courtesy of the Council for Geoscience, Pretoria.



tem is under threat from increased channelisation related to historic peat mining, irrigation channels and the greatly increased water flow from the water purification facility on its southern side. If not arrested, this channelisation will lead to the death of the vital reed beds and enable pollutants to enter the Vaal River.

The many mine-shaft headgears that are visible along the R29 indicate the extent of the so-called West Wits Line of gold mines. This trend follows the strike of the gold-bearing strata, the same layers of rock that were originally mined in the Johannesburg area, but that here are buried beneath the Transvaal and Ventersdorp layers. A number of mines have passed depths of 3 500 m and, one of them, previously known as Western Deep Levels Gold Mine but recently renamed Mponeng Mine, is fast approaching the 4 300 m mark. The subsurface trend of the gold-bearing conglomerates was discovered mainly because of the pioneering application of a new geophysical technique, ground magnetic analysis, by Rudolph Krahmann in the 1930s. This method, which is based on measuring the strength of the magnetic field in an area, allowed mapping of the subsurface geology based on the strong magnetic signal of the Parktown Shale Formation, which underlies the gold-bearing rocks at depth. The magnetic signatures delineate the overall extent of the Witwatersrand basin (Fig. 79).

Figure 80: Geology of the northern part of the Witwatersrand, showing the two main access routes from Johannesburg, via the N1 and N12/R500. MGM: Mponeng Gold MIne.

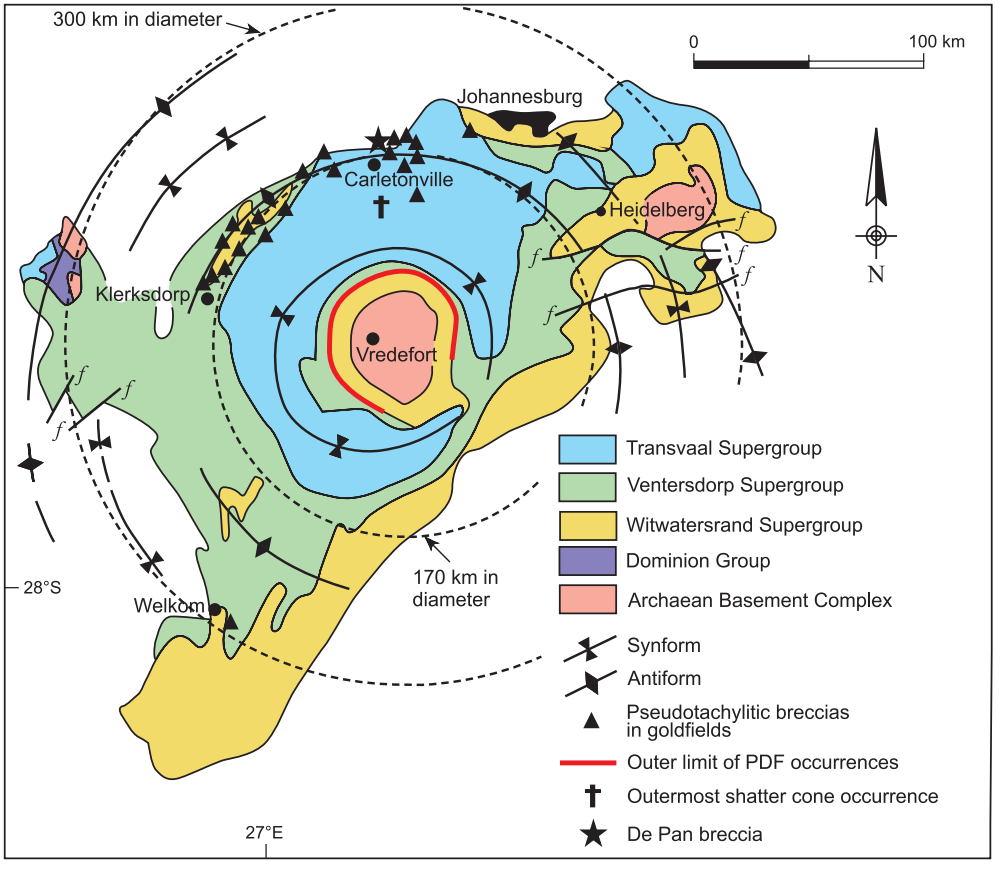


About 6 km after a T-junction with the road leading towards Randfontein, in a dense stand of trees north of the road, is the location of the Nufcor (Nuclear Fuel Corporation) plant. It was built several decades ago, when the Witwatersrand ores were not only exploited for their gold content but also for the ample amounts of uranium that occur in the reefs. Uranium is found, often in association with gold, in the form of uraninite grains. During the 1970s to early 1980s, in particular, significant quantities of uranium oxide were separated and, from some of it, the ^{238}U isotope enriched for nuclear fuel at the Pelindaba enrichment plant north of Johannesburg. But the reserves mined at the time were not fully required, and huge stockpiles remain. It is estimated that a total reserve of some 470 000 tonnes of uranium still remains in the Witwatersrand basin.

The ridge to the south of the road exposes south-dipping Timeball Hill quartzite of the Pretoria Group. From the top of this ridge, the Vredefort Dome is visible 50 km farther south. On a clear day, the Pretoria Group quartzites that form the prominent and scenic Magaliesberg mountain range west of the Johannesburg Dome are also visible. These layers dip to the north, indicating that a major structural arch — the Rand Anticline (Fig. 80) — lies along the northern margin of the Witwatersrand basin.

About 50 km southwest of Johannesburg, the Kloof Gold Mine is located to the left of the

Figure 81: Geological map of the Witwatersrand basin, stripped of Karoo cover rocks, showing the extent of a 300 km diameter impact structure. Smaller crater-diameter estimates cannot adequately explain the distribution of pseudotachylitic breccias. The non-circular shape of the basin may reflect subsequent deformation of the impact structure, or, more likely, the pre-impact distribution of rocks, now modified by the impact deformation. The non-circular shape of the Vredefort Dome is attributed to pre-impact faulting in the southeast of the dome.



road. Kloof is widely believed to have been the richest of all the Witwatersrand gold mines, but it is also a seismically very active mine that has had its fair share of rockburst accidents. Seismic failure is a daily threat in the Witwatersrand gold mines. The rocks mined are strongly deformed, fractured and, in places, brecciated. Kloof Mine is located close to two major north–south-trending faults, the West Rand Fault and the Bank Fault, and their traces are visible as valleys incised perpendicular to the road. The intersecting road marked 'Bank Station' follows the Bank Fault. A quartzite outcrop on the left side of this road, a few hundred metres from the intersection, represents the farthest-known occurrence of shatter cones from the centre of the Vredefort Dome (Fig. 81).

At the intersection of the N12 with the R500, leading to the mining town of Fochville (to the left), turn right and continue uphill for 5.2 km where a sign indicates the entrance to Mponeng Mine (Fig. 81) on the left. At the Kraalkop Game Reserve and Anglogold signs turn left and continue for about 1 km, before turning right onto the road marked 'Training and Development'. If permission to enter is granted at the guardhouse, an excellent viewing spot is provided at the western edge of the grassy area next to the building.

The viewing site is located on shallowly southwards-dipping Pretoria Group quartzite. To the south, a low ridge is visible in the foreground, on which is the tall thin monument dedicated to Danie Theron, a master scout on the Afrikaner side in the Anglo-Boer War (see Chapter 5). This ridge is formed by the Hekpoort Andesite Formation, also of the Pretoria Group. From this site, Mponeng Mine can also be viewed well (Fig. 82).

The low topography beyond this shallow ridge is the spread of the Potchefstroom syncline, into which the rocks in the northern part of the Witwatersrand basin dip at about 20° southwards. This syncline (trough) is filled with the thick carbonate succession of the Chuniespoort Group. In the middle distance a prominent hill can be seen, which is known as the Losberg. The mining town of Fochville is built against its northern flank. When the weather is clear, the rugged mountain land of the Vredefort Dome is visible in the distance, towards the south, and the hills marking the Roodekraal Complex, located immediately south of the town of Potchefstroom, can be seen due west. The Roodekraal Complex has a similar age to that of the Bushveld Complex; its rocks show impact deformation effects.

The view site at Mponeng Mine also provides an excellent impression of the layout of a major gold mine. Mponeng is the deepest mine in the world, and several exploration boreholes have been sunk in recent years to even greater depths to locate the gold-bearing strata farther south. Mining at such depths is obviously a threat to the safety of miners — the immense weight of overburden creates rock stresses that can lead to rockbursts and earthquakes; and although southern Africa's ancient crust possesses a remarkably low geothermal gradient, even the low, 10 °C/km, gradient means that rock temperatures in the lower parts of the mine exceed 60 °C. It is therefore unsurprising that the mine houses a huge refrigeration plant, where enormous amounts of ice are continuously generated in order to pre-cool air that is pumped into the mining shafts and stopes.

← **Figure 82:** View, looking south, across Mponeng Gold Mine (Western Deep Levels) in the West Wits Line Goldfield. This is the deepest mine in the world. In the background the Losberg mountain is visible.

Traversing the outer parts of the Vredefort Dome (Fochville to Parys)

Returning to the intersection of the N12 with the R500, the route continues directly south towards Fochville and Parys. The road passes a number of road-cuts where shallow southwards-dipping sedimentary rocks, as well as volcanic rocks belonging to the Hekpoort Andesite Formation of the Transvaal Supergroup, are exposed, besides several other intrusions of magmatic rock that have been linked with the time of emplacement of the Bushveld Complex at 2 060 Ma. The Hekpoort exposures, on both sides of the road, display some crude shatter cones and related jointing, in some places. Immediately south of the town of Fochville, the Losberg mountain presents a prominent topographic feature. This hill is located in the very heart of the northern part of the Witwatersrand basin, an area that is called the Potchefstroom syncline (a syncline is a geological trough). The syncline encircles the Vredefort Dome on its northwestern to northeastern sides. In this trough the normal sequence of Witwatersrand, Ventersdorp, and Transvaal rocks is found, from bottom to top. But while these rocks in the northern part dip shallowly southwards and towards the dome, in the southern part of the syncline this attitude is reversed — dips are northward, and steepen towards the inner dome.

The Losberg intrusion represents an approximately 120 m thick sill, comprising various mafic to ultramafic (dark rocks that are very iron and magnesium rich, but poor in silicon) magmatic rocks. An age similar to the 2 060 Ma for the Bushveld Complex has been obtained for the Losberg intrusion; and as the rock types are similar to those of the Bushveld Complex, it is thought that Losberg could represent a southwesterly extension of the Bushveld Complex (see Fig. 21). This could mean that the Bushveld Complex was originally much wider than the eroded remnant of 'only' 500 km width seen today.

The uppermost rocks of the Potchefstroom syncline belong to the Transvaal Supergroup. They are strongly deformed and have been squeezed together into huge fold structures of a kilometre scale (see Fig. 1). Because much of this rock sequence is dolomite and shale that are easily eroded, this part of the landscape is relatively flat and dominated by agricultural use. However, once the core of the syncline is crossed, a more dramatic landscape unfolds. After about 40 km from the N12 intersection, low outcrops of quartzite of the Pretoria Group are observed on both sides of the road. The rocks here are quite strongly fractured and contain shatter cones.

South of the Pretoria Group quartzites, the road proceeds through somewhat undulating landscape, which is again underlain by carbonate rocks. Interlayered with these are cryptocrystalline silica-rich rocks, known as chert. Close to where the road crosses the R54 (Vanderbijlpark–Potchefstroom) there are large blocks of chert breccia (Fig. 83). A breccia is a fragmented rock, the pieces of which have been jumbled against each other, with some finer-grained material forming a groundmass (ma-

Figure 83: Brecciated chert from a locality near Potchefstroom. The dark veining is manganese/iron-oxide infill. Lenscap, for scale, 6 cm wide.

trix) in-between. The original rock was composed of very fine-grained silica (the mineral quartz, SiO_2), and it is still possible to see how the angular fragments in the brecciated rock would originally have fitted together.

The dark cement that holds the fragments together is, to a large degree, composed of oxides of manganese and iron that formed from solutions circulating into the pore spaces. Similar-looking brecciation could well be the result of a meteorite impact, but other geological processes can also produce such deformation. For example, where a fault runs through rock, the strain on the walls of this inhomogeneity may cause the rock to fracture and become brecciated. Also, dissolution of carbonate, preferentially along pre-existing fractures, can cause open spaces that could later be filled in completely; or such a partially dissolved carbonate mass could collapse and form a breccia. All of these processes are possible in the area where these chert breccias have been observed around the Vredefort Dome. Faults run along the perimeter of the dome, and abundant caves occur in the area, testifying to the dissolution of carbonate. Breccias of such appearance do occur at many places throughout the Transvaal Supergroup exposures all over north-central South Africa. Breccias of identical appearance are found in the caves in the Cradle of Humankind, near Kromdraai, west of Johannesburg. Breccia samples from Gladysvale and from the outer collar around the Vredefort Dome show strong similarities. Thus, one cannot be certain that this rock deformation is the result of the Vredefort impact.

Farther south along this road, the Ventersdorp rocks follow in the normal stratigraphic succession, but are not very well exposed and only form several low hills some distance off the road, and very small exposures immediately adjacent to the road. At about 36 km from the intersection with the N12, the increasingly rugged topography reveals that the rocks of the Transvaal and Ventersdorp supergroups have been left behind and the Witwatersrand Supergroup, in the inner collar of the Vredefort Dome, is now being entered. These rock layers represent lithified sands and muds that were originally laid down horizontally but which are now dipping more or less vertically or are slightly overturned, i.e. they dip towards the south. The R500 traverses the most rugged portion of the Vredefort Mountain Land, with the topography becoming more subdued towards both the east and the west. The road affords views of spectacular ridge-and-valley scenery, with some viewpoints providing beautiful vistas of the Vaal River valley to the left (east). Some of the extensive road-cuts through these rocks display shatter cones and provide an idea of how intensely these rocks have been deformed (fractured and brecciated).

After a distance of several kilometres, the prominent white portal of the Smilin' Thru holiday resort appears on the left side (Stop 22, see Part II). The road follows a radial impact-generated fault that displaces the quartzite layers (Fig. 84) that, west of the road, form the Bobbejaanrant ridge — an excellent view site from which to survey the Vredefort Mountain Land and the broad undulating plains of the core of the dome to the south. The Vaal River lies 600 m east of the road.

About 2 km beyond the Smilin' Thru resort and 6 km north of Parys, the road cuts across the boundary between the innermost rocks of the collar and the Archaean basement complex in the core of the dome (the oldest part in the interior of the Vredefort Dome, around which the younger sedimentary rocks have seemingly been wrapped). The landscape here becomes much flatter. Unlike in the Johannesburg Dome, the Witwatersrand Supergroup rocks are not in direct contact with the granitoid gneisses — a broad expanse of dense bush marks the position of iron- and magnesium-rich soils covering lavas belonging to the 3 074 Ma Dominion Group (see Chapter 1). In the Klerksdorp area, some conglomeratic sediments of the Dominion Group have been mined for gold throughout most of the 20th Century.

The central part of the Vredefort Dome comprises slightly undulating, largely grass-covered or cultivated plains. However, there are also scattered hills (koppies) with generally elongated 'whale-back' shapes that prominently rise above the surroundings. These hills expose the underlying Archaean basement rocks. Their rounded shapes are possibly the result of erosion by massive ice sheets that covered the region about 300 Ma ago.

The R500 from Fochville ends in the town of Parys, situated on a wide bend of the Vaal

River, and where the R500 forms a T-junction with the R59 to Vredefort and Kroonstad in the southwest. Immediately north of the Vaal River, the prominent Leeukop hill (Stop 7c) is visible to the south. Many of the gneiss koppies in the dome are cut by thick veins and dykes of pseudotachylitic breccia, which may have increased the resistance to erosion by the Dwyka ice sheets 300 Ma ago. Similar dykes can be seen in the rock pavements exposed during periods of low water in the Vaal River alongside the bridge and further downstream (Stop 6). These may mark the 'pseudotachylyte' discovery site first investigated by S.J. Shand in 1916. Whilst the northern part of the core of the dome has much rock exposure, outcrops are rare in the southern parts, which are mostly soil covered and cultivated. This is largely because the rocks of the dome are covered in the south by much younger Karoo-age rocks that are more susceptible to weathering (Fig. 86; see Stop 2). In the north, less-fertile grassland occurs, which is extensively used for cattle and game farming.

Visitors entering the dome from Potchefstroom along the R53 will see much the same landscape and geology as described along the R500. The road from Potchefstroom also runs along a radial, though somewhat zig-zagging, trend with respect to the centre of the Vredefort Dome. Again, the first stretch across the Potchefstroom syncline is relatively flat, but the last kilometres through the Witwatersrand Supergroup are very scenic. The R53 forms the northeastern boundary of the buffer zone surrounding the Vredefort Dome World Heritage Site (WHS), an area of 34 000 hectares that is bounded to the southeast by the Parys–Vredefort segment of the R59, and to the southwest by the Vredefort–Schoemansdrift–Potchefstroom R501 road. The northwestern border is broadly defined by the outer limit of outcrop of the Witwatersrand Supergroup rocks (marked by the most extreme topography in the collar). Strictly speaking, the World Heritage Site comprises only the central parts of this area; however, legislation requires that the actual site be surrounded by a 5 km wide buffer zone which is also subject to development restrictions. Most of the land within the WHS is privately owned. The choice of the boundaries of the WHS was made on the basis of creating a manageable representative area that highlights most of the geological, archaeological, cultural-historical and natural heritage that can be seen in the dome. As will be seen in Part II, not all the best sites could be included in this way in the World Heritage area.

↑ **Figure 84:** Along the road past the entrance to the Smilin' Thru resort, a prominent fault extends roughly north–south, displacing the rock layers of the Witwatersrand Supergroup. In this photograph, taken from the quartzite hill known as Bobbejaanrant, opposite the entrance to the resort and looking east, it is obvious how the quartzite has been dragged into the fault line, indicative of movement of the eastern ridge towards the north (left). See Stop 22.

The traveller has a choice of only two bridges to cross the Vaal River — at Parys, and some 30 km west at the Schoemansdrift causeway. Parys is a small town of about 50 000 inhabitants. It largely grew out of the needs of the agricultural communities in the surrounding region for basic supplies and for places of worship (see Chapter 5). In recent years, however, a vibrant tourism infrastructure, with numerous restaurants, accommodation facilities and arts-and-crafts shops, has been developed. The old N1 road (now R59) runs through the town, towards Vredefort in the southwest and Sasolburg, Vanderbijlpark, and the connection to the N1 freeway to Johannesburg and Bloemfontein in the northeast. The extension of the N1 freeway

from Johannesburg towards Kroonstad posed an economic threat to Parys — it was feared that most traffic would by-pass Parys and the even smaller town of Vredefort that were now located along the 'old', alternative route. Much effort was made at the time to spruce up Parys

Parys – jewel of the Vaal

(see Fig. 167). In October 2004 Parys hosted the first Dome Adventure Festival, offering not less than 18 sports events including a marathon and a mountain-bike race. The border between the North West and the Free State provinces is formed by the Vaal River. The river enters the dome along the major fault in the rocks of the collar that was described in the Smilin' Thru area. From Parys, it leaves the dome towards the northwest, again along a major fault. Along both sides of the river numerous resorts, conference centres and recreational facilities are situated. Obviously the mountainous northwest and north sectors of the collar of the dome are suitable for hiking and climbing activities, whereas the stretches along the river offer many watersport facilities.

The hamlet of Vredefort, in contrast to Parys, has remained largely undeveloped. Situated along the main thoroughfare, the R59, Vredefort offers only a handful of small shops and cafes. It is, however, the starting point for visitors to the dome, and hosts the World Heritage Site Visitor Centre (see Fig. 165) on its outskirts. With only a few, mostly small, industrial establishments based in Parys and Vredefort, the closure of the dimension-stone quarries, and a limited agricultural sector, these towns are increasingly relying on tourism for their livelihood.

The route along the N1 freeway from Bloemfontein is largely through the Karoo Supergroup cover rocks. The dome may be accessed either from Kroonstad towards Vredefort, or from the R59 Sasolburg/Parys off-ramp to Parys. On a clear day, the ridges of the Mountain Land are visible west of the freeway, which passes east of the centre of the dome near the Greenlands offramp and Engen service stations on the N1. Approaching Vredefort from Kroonstad, the road traverses low ridges of the southwestern collar, which are far less dramatic than their counterparts towards the north.

Before proceeding with a more in-depth discussion of the geology of the Vredefort Dome, it is worth reviewing several salient points that have been made in the preceding pages. The first of these is that the Vredefort impact crater no longer exists. Broadly speaking, impact craters are bowl-shaped depressions with rims that are slightly raised relative to the surrounding landscape, but are relatively easily destroyed by erosion. If the crater still existed, the hole would extend from Johannesburg to Welkom and would likely have to be over 1 km deep — hardly a feature that could be missed! It would also be filled with impact breccias that would cover the older rocks into which the bolide slammed. That it is the pre-impact rocks and not the breccias that are seen between Johannesburg and Welkom tells us that the crater has been substantially eroded. For this reason, we speak of the Vredefort impact structure, which refers to the volume of rock that shows signs of having been damaged by the impact event, but whose outer limits are increasingly hard to define as erosion progresses.

The second point is that the Vredefort Dome is not synonymous with the Vredefort Structure — the dome forms only the central part of the original impact structure, the boundaries of which may have extended beyond Johannesburg and Welkom.

The third point is that a dome is a geological feature formed by the upward rise of rocks in the centre that has pushed the overlying rocks outwards and rotated them to steep dips (see Fig. 3b). It is quite obvious that the present landscape of the Vredefort Dome does not resemble an upside-down bowl, with the highest point in the centre; in other words, it is not a topographic dome (such as Paarl Rock in the Western Cape Province or the koppies in the core of the Vredefort Dome). The partial circular pattern seen from above is exactly what you would expect to see if you sliced an inverted bowl or, more specifically, an onion, horizontally. In the Vredefort Dome, this 'slicing' took many hundreds of millions of years to achieve through weathering and erosion of the rock layers. A variety of independent methods has established that between 8 and 10 km of erosion has

taken place. This does not mean that central South Africa once lay higher than the Himalayas. Rather, erosion is the natural consequence of any part of the land surface being exposed above sea level. So, small amounts of uplift of a few tens to hundreds of metres above sea level, repeated many times over hundreds of millions of years, will create the same effect. The driving force for these changes in the elevation above sea level is plate tectonics.

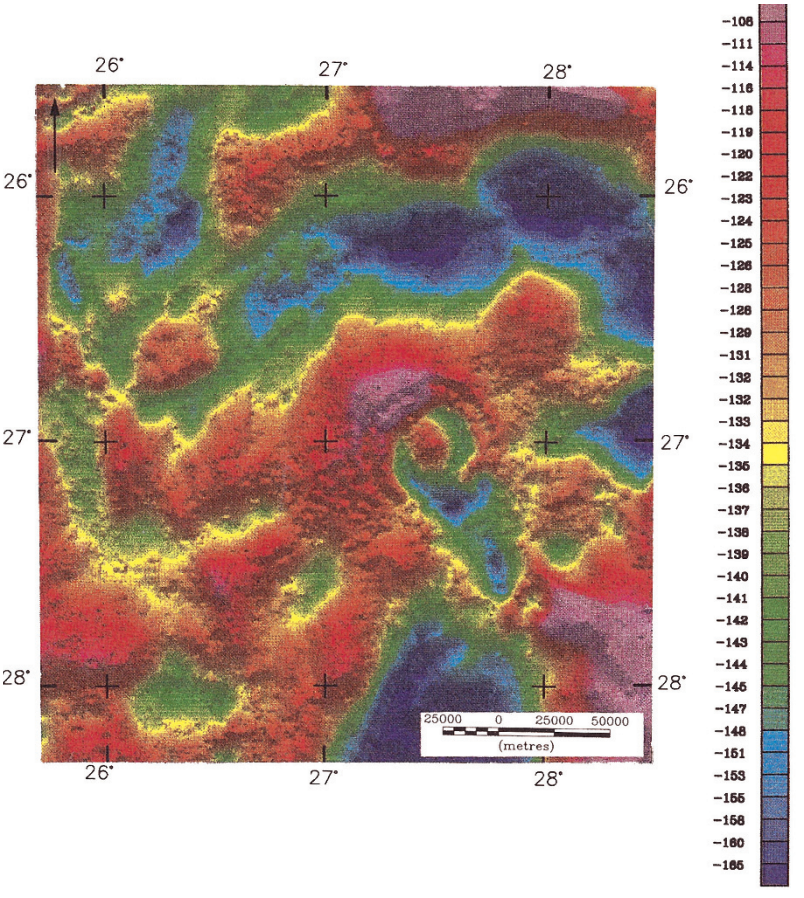
Finally, the Vredefort Dome is not presently completely exposed. Its southern and southeastern parts are covered by rocks that were laid down less than 300 Ma ago along the edge of the great Karoo sedimentary basin (see Fig. 21). Their age indicates that they were too young to have formed part of the target for the impact, hence, they are not deformed into a dome shape. The processes of weathering happening today at the land surface mean that these Karoo-age rocks have virtually completely decayed into soil.

Vaal River view, looking south from Donkervliet.

The Geology of the Vredefort Dome

The crescent shape of the Vredefort Mountain Land reflects the circular arrangement of geological formations that show varying degrees of resistance to weathering and erosion. The dome-shaped arrangement of these formations was confirmed by geophysical methods (regional magnetic and aeromagnetic surveys, Fig. 79; and gravity maps that image the density contrasts between different rock types, such as Fig. 85). The surface distribution of rock types was mapped in detail in the 1920s, when Louis T. Nel spent several years traversing the area on a motorbike and sidecar. The only other map of the entire area published since is that by Professor A.A. (Billy) Bisschoff of Potchefstroom University (now North West University), published in 2000.

The rocks of the Vredefort Dome (Fig. 86) are well exposed in its northern and northwestern sectors, but are largely hidden underneath younger rock formations in the south and southeast sectors. Here, the surface cover is widespread fertile soil that formed from the underlying shales and dolerite intrusions belonging to the 300 to 180 Ma old Karoo Supergroup. Nevertheless, it has been determined by geophysical means and detailed geological study of the scattered outcrops that the older rocks lie close to the surface below this cover. This central area is surrounded by the approximately 20 km wide collar that consists of generally vertical, or even overturned, sedimentary and volcanic rock layers belonging to the Dominion Group (ca 3 074 Ma old), and the Witwatersrand (2 950 to 2 710 Ma old), Ventersdorp (about 2 710 Ma old), and Transvaal (2 650 to 2 150 Ma old) supergroups, as described in Chapter 1. In the environs surrounding this 90 km wide structure occurs the so-called Potchefstroom syncline, which is about 50 km wide and extends to the northern margin of the Witwatersrand basin which is defined by an anticlinal structure known as the Rand Anticline (Fig. 80). Along this boundary, a number of exposures of granitic



← **Figure 85:** Gravity anomaly map of the Vredefort Dome and environs. In the core of the dome a near-circular, small, positive gravity anomaly is visible, which for a long time was taken as an indication that relatively heavy, possibly mantle-related, rocks were exposed, or at least lie close to the surface. This has since been refuted, but this anomaly does indicate that mid-crustal rocks form the basement in this area (after Henkel and Reimold, 1998). The 'tail' of low-density rocks extending southeast from the dome appears to be related to the pre-impact faults that have uplifted basement granite-gneiss.

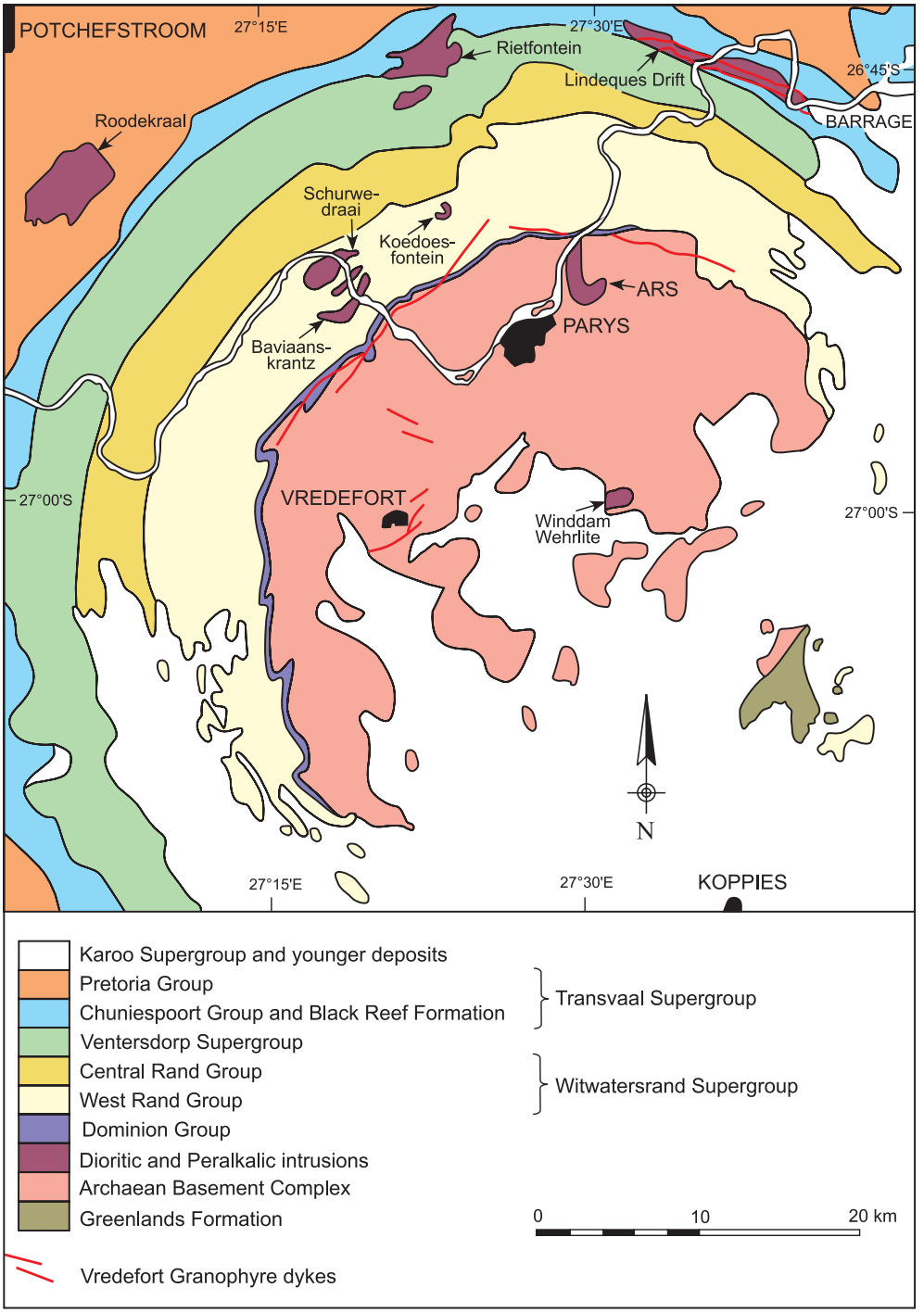
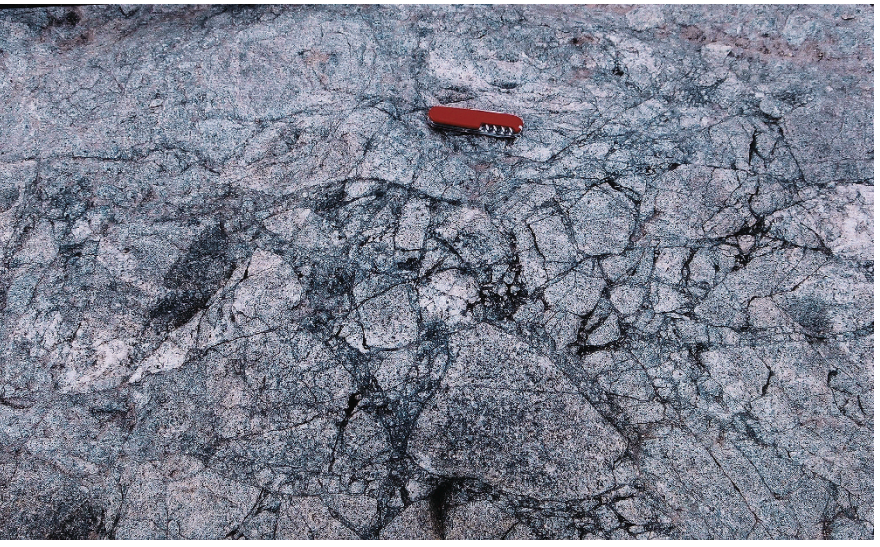


Figure 86: Simplified geology of the Vredefort Dome.



↑ **Figure 87:** A small area within the large breccia occurrence on De Pan (north of Carletonville town) on the Rand Anticline. This breccia in places looks like pseudotachylitic breccia from the Vredefort Dome, but it does not contain any melted material and, thus, is classified as cataclasite. The extensive nature of this breccia may, however, support its development during an unusual event such as the Vredefort impact. Knife, for scale, 9 cm long.

basement of the Kaapvaal craton are found, for example, just north of the town of Carletonville, at a place known as De Pan (see Fig. 81), which contains breccias that may be linked to the impact event and, thus, may provide constraints on the size of the Vredefort Structure (Fig. 87).

The rocks in the core of the Vredefort Dome are mostly granitoid gneisses, but include highly metamorphosed shales, ironstones and mafic to ultramafic lavas (see Stops 1–7, Part II). In the southeastern sector of the dome the lavas are metamorphosed to lower grades and still locally preserve pillow structures that indicate formation underwater. These lavas, called the Greenlands Formation (Fig. 86), are very similar to the greenstones in the Barberton region, and could be as old as, or older than, 3 400 Ma. Detailed analysis has shown that the granitoid rocks are basically identical to the granitoid basement exposed elsewhere on the Kaapvaal craton, such as in the Johannesburg Dome and around Barberton. The exceptional uplift and rotation of rock strata that occurred during the formation of the Vredefort Dome, together with many excellent outcrops and three-dimensional quarry exposures, provide a rare window into the deep interior of the ancient continental crust that forms the Kaapvaal craton.

A comprehensive description of the sedimentary and volcanic strata in the collar of the dome is provided in Chapter 1. These rocks are intensely faulted and locally folded (Figs 88, 92). In addition, however, there are several generations of younger intrusive igneous rocks in both the core and collar of the dome. At least two generations of pre-impact mafic sills seem to be present, related to the Ventersdorp and Bushveld magmatic events. These bodies intruded parallel to the sedimentary layers and probably represent parts of the feeder systems to the related volcanic rocks and shallower-level intrusions. The largest of these bodies appears to be the Losberg Complex near Fochville, which has been interpreted as a Bushveld-age intrusion. Geochronological studies by Sybrand de Waal and co-workers, as well as Jock Harmer and colleagues, have established that a number of kilometre-scale bodies of alkali granitic and dioritic to mafic rocks found in the collar of the dome and the Potchefstroom syncline are also of Bushveld Complex age (2 050–2 060 Ma). These bodies are, from west to east (compare Fig. 86): the Roodekraal, Schurwedraai, Baviaanskrantz, Koedoesfontein, Rietfontein and Lindeques Drift intrusions. These bodies are all affected by the deformation related to the formation of the Vredefort Dome, confirming that they are of pre-impact age.

In contrast to these pre-Vredefort intrusions, there are several intrusive rock types in the Vredefort Dome that are undeformed and, consequently, must have been emplaced either during or after the dome-forming event. Amongst these is a highly unusual rock with numerous rock inclusions and that has a granophyric microscopic texture. This texture involves a fine-grained, so-called granophyric, intergrowth of the minerals quartz and feldspar. Dykes of this rock occur straddling the boundary between the core and collar of the dome, and as a few isolated occurrences in the interior of the core (Fig. 86). This rock is known as the Vredefort Granophyre. Although it superficially somewhat resembles

← **Figure 88a and b:** In many parts of the collar of the dome, the rocks, even the brittle quartzites, have been folded. These folds were created during uplift to form the dome as the layers were squeezed into a tighter space. **a.** Oblique aerial photograph of an impact-induced fold in the lower Witwatersrand Supergroup quartzite near Parsons Rus (Habula Lodge), northwestern collar. **b.** View of the same folds from Habula Lodge.

the more common pseudotachylitic breccias, it displays several important differences. First, the clasts within it include rocks that are found several kilometres away, and which would have originally overlain the basement rocks in which the dykes now occur. In addition, the granophyre displays a remarkably constant composition, indicating that it formed from an exceptionally well-homogenised melt. This composition is also highly unusual; it is highly enriched in iron and magnesium with regard to the amount of silicon and aluminum determined. This composition has no known counterpart amongst igneous rocks, and it came as no surprise when Christian Koeberl and co-workers finally, in 1996, isolated a small meteoritic contribution to its chemical composition, confirming that it represents the impact melt from the Vredefort event.

A second undeformed melt rock in the dome is typified by a 100 m thick body of gabbro known as the Anna's Rust Sheet, northeast of Parys (ARS, Fig. 86). On the opposite side of the Vaal River from the Smilin' Thru resort, this body is well exposed in numerous blocky outcrops that have prominent vertical columnar jointing and that locally are made up of rounded boulders with a distinctive onion-like weathering appearance (*spheroidal weathering*). It is now known that this is part of a flat, sheet-like intrusion (sill) into the granite that extends southwards below the surface and that probably intruded around 1 050 Ma ago.

The central parts of the dome contain several other types of melt rock. In addition to Karoo dolerite that underlies large areas, small bodies of granite and unusual breccia veins with crystalline granitoid matrices are found in the gneisses. These are related to the intense temperatures during and immediately after the impact event. An unusual ultramafic olivine-rich rock, called wehrlite, is found on the farm Winddam near the centre of the dome.

The unique rock formations and deformation in the Vredefort Dome

After more than a century of investigations into the Vredefort Structure and its origin, modern scientists are in a privileged situation compared with the early Vredefort geologists. A vast dataset of field and laboratory observations is now available, much of which has only been compiled in the last 30 years. Final confirmation of the origin of the dome was only possible once the data became available.

That the Vredefort Dome was something special was, however, anticipated by the earliest geologists who worked on other exposures of basement rocks in the wider Witwatersrand region. Initial comparisons were made between the Vredefort Dome and other structures, such as the Johannesburg Dome, and internal origins proposed involving rising magmas, faults and/or interfering mega-fold structures by some of South Africa's pre-eminent geologists. Louis Nicolaysen believed that the Vredefort Dome lay at the intersection between a major arching (anticlinal) structure extending northwestwards from Bethlehem and a northeast-trending structure defined by the axis of the Witwatersrand basin.

What was also clear, however, was that there are some unique deformation features in the Vredefort rocks that distinguish this area from any other basement exposure in the region. The most obvious product of this deformation is pseudotachylitic breccia (Fig. 89). The breccias are mostly dark-grey or black veins, less than a centimetre to a few centimetres wide, but locally forming huge occurrences up to more than a kilometre long and 100 m wide. They have an extremely fine groundmass that carries numerous inclusions derived from the rocks that host them, and they occur in both the granitic rocks of the core and in the volcanic and sedimentary rocks of the dome collar.

Veins of similar appearance, but always very narrow, occur in numerous places in the world, where they are interpreted by geologists as the product of rapid movement along faults. If this process only leads to fracturing, the result is a cataclasite — a breccia composed of clastic rock fragments only. However, rapid sliding of two rock masses past each other also causes friction heating (even hands rubbed together can produce significant heat). If sufficient heat is generated along a fault it may even melt the adjacent rock. Once sliding stops, this melt immediately freezes, forming a dark glass that may contain wallrock fragments. Such a breccia occurring along a fault is then called a *pseudotachylite.* This term (original spelling 'pseudotachylyte') was first coined by an early Vredefort worker, Professor S.J. Shand, in 1916, which makes the Vredefort Structure its type locality. However, melt-hosted breccias are also produced in impact structures, some of them by the intense shock compression, because the increase in pressure leads to a simultaneous increase in temperature. Given the uncertainty that this raises about the formation mechanism(s) for the Vredefort veins and dykes, the term *pseudotachylitic breccia* is used for these occurrences.

The Vredefort Dome pseudotachylitic breccias are exceptional for two reasons. First, they are ubiquitous, occurring in virtually every rock outcrop within 25–30 km of the centre of the dome. Second, the largest dykes are orders of magnitude larger than any known friction-melt occurrences in fault zones. In this regard, they resemble the massive occurrences of the so-called Sudbury Breccia from the Sudbury impact structure in Canada. The Vredefort Dome breccias are well exposed in the quarries in the core of the dome. The largest quarry exposures that can be easily viewed occur in the Leeukop (Fig. 89; Stop 7c) and Salvamento (Stop 7a) quarries north of Parys (see Part II, pages 240–277). Overall, the pseudotachylitic breccias in the dome form a

complex three-dimensional network, with veins and dykes of varying widths showing no obvious signs of cross-cutting relationships.

In the early decades of Vredefort research, pseudotachylitic breccias were only known in the region from the Vredefort Dome area. But in the late 1980s and early 1990s, several workers in the Witwatersrand basin compiled underground data from a large number of gold mines (Fig. 81). They noted that there are several distinct horizons along which massive manifestations of rock breccia, including many with apparent melt groundmass, occur. However, it is basically impossible to distinguish cataclasites and pseudotachylitic breccias without detailed microscopic analysis. Whilst a significant number of radiometric ages obtained on the breccias suggest that the bulk of them formed during the Vredefort event, there is also evidence to suggest that some of the breccias in the wider Witwatersrand basin are older than the Vredefort event. A particularly significant concentration of breccia occurs immediately below or above one of the most important gold reefs in the basin, the Ventersdorp Contact Reef. Individual gold values of up to 1 500 parts per billion (15 g per tonne), have been measured in this breccia. It has been shown that the breccias cutting reefs contain gold crystals that have grown within the veins. This is accepted as an indication that some of the Witwatersrand gold was remobilised as a consequence of the Vredefort event.

The second unique deformation phenomenon in the rocks of the Vredefort Dome is the shatter cones (Figs 59 and 93). These are conical structures with striations on their outside, which come together at the apex of a cone. The Vredefort shatter cones will be described in more detail later as they were important evidence in the controversy about the origin of the Vredefort Structure. It needs to be mentioned here that shatter cones are a trademark of many meteorite-impact structures, and have never been described from geological structures formed by other, internal, geological processes.

In the early 1960s, local and overseas geologists began to study Vredefort rocks for evidence of mineral deformation on a microscopic scale that could have been caused by intense shock pressures (Fig. 68). However, whilst features resembling planar deformation features (PDFs) diagnostic of impact (shock) deformation (compare Figs 70 and 95b) were noted in quartz grains of many rock types, the lack of glass in the lamellae was puzzling. It was only in the 1990s that the accumulated evidence was regarded as conclusive enough to indicate a shock origin for these microdeformation features. A key aspect of this involved the recognition of unusual thermal metamorphism caused by the impact that had led to the recrystallisation of the glass.

Since the earliest geological report on the Vredefort Dome by G.W. Stow (1878), it has been known that the rocks of the Vredefort Dome had been subjected to a regionally unique metamorphic overprint. These mineral assemblages indicate that these rocks were once much hotter than those anywhere else in the Witwatersrand

Figure 89: View into the quarry at Leeukop hill, north of Parys. The massive exposure of mid-crustal granite shown here is about 15 m high. Successive quarry benches expose a dyke of pseudotachylitic breccia in which the large granitic gneiss clasts have settled towards the bottom contact. Each bench is approximately 3 m high.

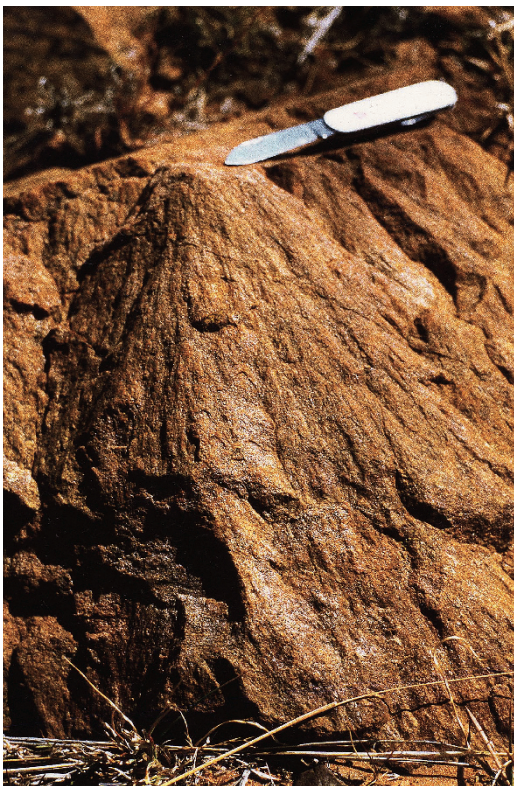
↑ **Figure 90:** An exposure of massive pseudotachylitic breccia (this one on the farm Samaria in the south-central part of the dome). The rock inclusions (clasts) are all quite well rounded, probably as a result of thermal corrosion by the hot melt. Exposure approximately 3 m long.

↓ **Figure 91:** Dyke of Vredefort Granophyre on Daskop farm showing the characteristic prominent large boulders containing isolated clasts, and the sinuous dyke shape caused by the merging of *en echelon* fractures (compare Fig. 181). A Bushman petroglyph resembling a ceremonial apron (B. Smith, personal communication) is seen in the foreground. Image courtesy of Ben Smith.

region. The estimated metamorphic temperatures also decrease radially outward, indicating that the heat source for this metamorphism is spatially linked to the dome. By the 1990s it was recognised that residual heat from the impact played a significant role in metamorphosing the rocks in the dome and, thus, in modifying the PDFs so that no glass remained.

Today, the importance of the Vredefort Dome and its specific rock-deformation phenomena is largely understood, and scientists have an idea of the events that occurred about 2 020 Ma ago. However, to reach this point took vast amounts of painstaking field and laboratory work. In retrospect, the Vredefort Dome provides a good example of how different scientific disciplines may need to be harnessed to answer a problem and how it may take decades before the necessary rigorous scientific proof is accumulated to support a correct hypothesis.

↑ **Figure 92:** Oblique aerial photograph of the inner collar of the Vredefort Dome northwest of Parys, showing the Vaal River exploiting a fault cutting the lower Witwatersrand Supergroup. The prominent Hospital Hill Subgroup quartzite (centre) is bent and offset to the north (left) on the far side of the river relative to the rocks on the west side of the river (compare Fig. 84, page 127). The flat area to the left is underlain by alkali granite (see Fig. 86, page 131).



← **Figure 93:** A shatter cone from Hospital Hill quartzite in the northern collar of the Vredefort Dome. Knife, for scale, 18 cm long.

The findings of the early Vredefort geologists

The first geological report about the Vredefort Dome was presented in 1878 by G.W. Stow, who was at that time in the employ of the government of the then Republic of the Orange Free State and was tasked to evaluate the possible ore deposits of the northern part of the Republic, especially possible energy resources such as coal. Stow provided a rather detailed description of his travels, but he devoted by far most of his time to traversing the low-lying parts of the Orange Free State, which were covered by Karoo rocks (see Fig. 21), where he would have expected to find coal beds (South Africa's wealth of coal, one of its foremost export commodities, is mined in the rocks of the upper Karoo Supergroup). Only towards the end of this endeavour did he traverse the Vredefort Dome from the northeast (around today's town of Vanderbijlpark) towards the southwest via the then fledgling settlement of Parys. Stow encountered the steeply dipping Witwatersrand rocks and observed that the whole succession of rocks was strongly 'altered' (metamorphosed), which he attributed to some kind of volcanic centre that caused "the action of intense heat [that] has, in no questionable degree, left its mark upon the surrounding rocks". He then proceeded to traverse the entire granitic core of the dome with its igneous intrusive rocks, which he believed to be the result of "great lava outpourings".

Further geological interest in this region only developed after 1891, a few years after the discovery of the Witwatersrand goldfields. Following the discovery of gold in Johannesburg in 1886, and a year later in the Vredefort Dome, many prominent South African geologists, including G.A.F. Molengraaff, D. Draper, F.H. Hatch and E.J.P. Jorissen, studied the rocks of the dome collar because of their general similarity to the gold-bearing strata in the Johannesburg area. They concluded that these rocks belonged to the same sequence and recognised the overturning of the sediments in the Vredefort area. Regarding the enhanced metamorphic grade of the dome rocks, the cause favoured at the time was contact metamorphism around a central granite intrusion.

It was only in the mid-1920s that a comprehensive geological study of the entire dome was carried out. Geologists of the Geological Survey in Pretoria, Louis T. Nel and his director, A.L. Hall (the latter in conjunction with an eminent Dutch geologist, G.A.F. Molengraaff), provided the first detailed geological map and description of the entire structure. Their view was that the notable and enigmatic deformation structures in the rocks were related to possible gas explosions — similar to Bucher's view expressed in his cryptoexplosion theory from the 1930s.

Nel's explanation to his map provides some stratigraphic detail, but regarding the origin of the Vredefort Dome he remained vague. A much more detailed work on the geology of the dome was published in 1925 by Hall and Molengraaff, entitled 'The Vredefort Mountain Land in the southern Transvaal and the northern Orange Free State'. The authors remarked, while referring to the circular arrangement of the hills of the Vredefort Mountain Land around the central granite complex, that "the grand simplicity of the design at once suggests a corresponding broad simplicity in the major cause; almost inevitably one is reminded of the ring-like features displayed by the craters of the moon, or the physiography accompanying a gigantic caldera, or the maare [volcanic gas explosion vents] ... in the volcanic region of the Eifel, or even of the geological history of the Rieskessel [the Ries Crater] in Bavaria." This astute observation was then, however, tempered by a cautioning note: "The authors do not wish to suggest, however, that such analogies necessarily possess genetic significance in the case of the Vredefort Mountain Land."

Some of the difficulties faced by the early authors were the following: they observed that earlier Vredefort workers had voiced very different opinions and made very different observations. They noted that both the Bushveld Complex and the Vredefort Dome contained intrusions of alkali-rich granites, and some workers of the time saw a remarkable coincidence in this. Hall, in 1932, concluded that "some magmatic relationship exists between the alkaline events in the Vredefort Mountain Land and those of the Pilanesberg [a large volcanic structure in the western Bushveld Complex], based on the persistence of some of the alkaline dykes from one to the other region, and suggesting, as a remarkable speculation, a concealed but extensive source of alkaline magma". We know today that the Pilanesberg volcanism took place some 1 300 Ma ago, actually some 700 million years *after* the Vredefort event. The alkali granitic intrusions in and around the Vredefort Dome were all also emplaced prior to the Vredefort event and, thus, belong to an entirely different suite of intrusions.

Another milestone publication in the history of scientific exploration of the Vredefort Dome was the 1916 paper by S.J. Shand of the University of Stellenbosch, who described "The pseudotachylyte of Parijs (O.F.S.) and its relation to 'trap-shotten gneiss' and 'flinty crush-rock'". This paper represents the first detailed description of the most prominent rock-deformation phenomenon in the Vredefort Dome. While this strange material does look glassy, detailed microscopic study revealed that it actually was crystalline. Thus, Shand coined the term 'pseudotachylyte' (i.e. pseudovolcanic glass). Shand distinguished this material from a type of rock then known as 'flinty crush-rock', where it was thought that some melting was the result of heat produced upon crushing of rock. And 'trap-shotten gneiss' was thought to be gneiss that had been brecciated violently, also under the production of heat. Shand provided an enormous amount of observation and decided that this dark rock was not a magmatic intrusion of sorts but a rock melt, in fact formed by melting of the host rock itself. He then concluded that "the pseudotachylyte has originated from the granite itself through melting caused ... not by shearing but by shock, or alternatively, by gas-fluxing."

Hall and Molengraaff supported Shand's conclusion regarding the origin of this melt rock: they noted strong evidence for crushing involved in the formation of pseudotachylite, and this long before John Spray of the University of New Brunswick in Canada showed conclusively in the 1990s that melting caused by frictional heating could produce pseudotachylite along a rock-fracture surface. Hall and Molengraaff also drew attention to another of Vredefort's enigmas: the so-called enstatite-granophyre (enstatite is a pyroxene mineral that later turned out not to be present in this rock; thus, it was decided to rename this rock Vredefort Granophyre). This rock type superficially resembles the pseudotachylite, with its generally dark-grey, slightly brownish alteration colour at the surface, but very dark, extremely fine-grained appearance on a fresh surface, and its numerous inclusions of different types of rocks occurring in the Vredefort Dome (compare Fig. 91) Hall and Molengraaff thought that this strange rock could represent "a glorified version of pseudotachylite".

A major geological expedition to study some enigmatic areas in southern Africa, known as the Shaler Memorial Expedition, took place in 1922. This afforded a number of renowned international geologists an opportunity to interact with their colleagues from South Africa, and to jointly investigate the strange Bushveld Complex and Vredefort Structure. One outcome of this international investigation was that features of the South African structures became better known to overseas workers, which allowed them to draw some parallels with geological sites in other parts of the world. P.B. King, in 1930, for example, observed strong similarities between the 13 km wide Sierra Madera structure in Texas and the Vredefort Dome. Though being much smaller than Vredefort, Sierra Madera also had an apparent symmetrical layout and a collar of steeply dipping upper-crustal sedimentary rocks. King, like Hall and Molengraaff, favoured an internally generated 'push-up' of these dome structures, an idea that has been entertained, as recently as 1995, by the British structural geologist Mike Coward for the Vredefort case. Today, we know that the Sierra Madera structure and the Vredefort Dome both represent eroded central uplifts of large impact structures.

In stark contrast, J.D. Boon and C.C. Albritton, in 1936, voiced another thought: "Could anything other than a violent explosion have produced this vast amount of crushed rock?" Shand had suggested that the flinty crush-rock was formed as a result of shock caused by a "gigantic impulse or series of impulses". They proceeded to question: “Is it possible that this impulse was the impact and resulting explosion of a gigantic meteorite which struck the area in pre-Carboniferous time?" They proposed a very bold hypothesis, which they followed up with the listing of 'questionable meteoritic structures' in 1938, including both the Vredefort and the Sierra Madera structures.

SOME OF THE MOST REVERED GEOLOGISTS OF THE TIME COULD NOT AGREE ABOUT THE ORIGIN OF THIS REMARKABLE FEATURE

It took another decade for this hypothesis to be picked up again. R.A. Daly, another well-known geologist of his time and one who had been a member of the Shaler Memorial expedition in the 1920s, published a detailed review of the various earlier writings and musings about the origin of the Vredefort Dome in 1947, and expressed some discomfort with all of those envisaging that forces from within the Earth could have triggered the updoming at Vredefort and associated rock deformation. He argued that Boon and Albritton's impact hypothesis had the potential to explain many of the inherent problems: the updoming of the granitic core could be the result of pressure release after upper crustal material had been blown off by the impact explosion; the high-temperature metamorphism in the environs of the granitic core was the result of heat created at an impact explosion; and the strange up- and overturning of the collar rocks was also some result of the explosion. In the end, Daly remarked that "absolute proof that the deformation resulted from impact is manifestly impossible". Although it took nearly 50 more years, this proof was eventually found.

Not much attention was paid worldwide to the ideas first mooted by Boon and Albritton and then taken up by Daly. There were, however, a few notable exceptions, for example the cryptoexplosionist Walter Bucher. Kathleen Mark, in her book 'Meteorite Craters', reports a story that Daly and Bucher met at an exhibition in the Metropolitan Museum of Art in 1948 and got into such a dramatic argument over the origin of the Vredefort Structure that they were both evicted from the building! R.B. Baldwin, in the 1940s, also argued for the possibility that Vredefort could be an impact structure. But the eminent South African geologist Alexander du Toit (an early supporter of Wegener's Continental Drift Theory) favoured a purely tectonic origin, through multiple episodes of fault-related uplift. In his benchmark 1948 book 'Geology of South Africa', he rejected "the fantastic view of meteoritic impact proposed by Daly".

By the middle of the 20th Century, it was clear that some of the greatest names in world geology were unable to reach agreement on the origin of the Vredefort Dome. Two things were required in the elusive search for the dome's origin: tools for the identification, beyond doubt, of meteorite-impact structures, and a fresh look at the peculiar features of the Vredefort Dome.

The second phase:
evidence of impact?

The problem facing scientists studying the Vredefort Dome in the 1950s was that, even after 20 years of scientific debate, the only recognised impact structures on Earth were those craters that contained at least some remnant of a meteoritic projectile. No other criteria had been developed that could be uniquely and unequivocally related to hypervelocity impact of extraterrestrial bolides.

In the mid-1940s Robert Dietz had joined the debate about the origin of circular structures of 'cryptic' origin and proceeded to comment on the need to understand the origin of the crater structures on the Moon, suggesting that they were similar to the so-called cryptoexplosion structures on Earth. Dietz stated in 1946 that "These features are sufficiently alike to suggest that they were all formed in a similar manner and they differ sufficiently from other known geological structures to indicate that they form a specific structural type". He also noted that the Sierra Madera structure in Texas, which had been drilled to a considerable depth, seemed to "die out" with depth, rather than indicating some magmatic vent from beneath.

Dietz is much revered for his contribution to the major 20th Century revolution of the geological sciences, the Theory of Plate Tectonics. However, his name is also synonymous with the fracturing phenomenon known as shatter cones. These rock deformations are conical fractures that are characteristically densely striated. Striae emanate from a mutual point, the so-called apex. Typical examples from the Vredefort and Steinheim structures are shown in Figures 59 and 93. Dietz concluded from observations on such conical fractures from Kentland in the United States that the geometric arrangement of these cones suggested a formation mechanism involving an explosion from above, whereas he suspected that an internal explosion would result in such cone fractures being indicative of explosion from below (Dietz, 1947). Over the next ten years, Dietz collected observations on the occurrence of shatter cones. In 1959, similar features were observed at the site of an underground nuclear explosion, and their origin was linked with the related shock wave. In the same year, Dietz discovered shatter cones in the Sierra Madera structure, a finding rapidly followed by shatter cone discoveries at several other cryptoexplosion sites. Strangely, however, no significant striated fractures were found at Meteor Crater. Many supporters of the meteorite-impact theory for the enigmatic circular, sometimes dome-shaped, structures on Earth accepted shatter cones as a good recognition criterion for meteorite impact craters, but doubts lingered. Dietz and a few others suggested that evidence of impact was present where it was obvious that large volumes of rock had been strongly shocked (shattered, fractured, brecciated).

Another possible criterion for the recognition of meteorite-impact structures was identified in the 1950s: under very high pressures (10 to 30 gigapascal, GPa), the mineral quartz is converted to a denser form (same chemical composition, but different crystal structure) called coesite (named after its discoverer, Loring Coes). These pressure conditions are certainly much more extreme than those typically found in the Earth's crust (usually less than 2 GPa). In 1960, E.C.T. Chao of the United States Geological Survey discovered coesite in a sample of sandstone from Meteor Crater, a discovery soon confirmed by Gene Shoemaker and colleagues.

In the same year, Shoemaker visited the Ries Crater in southern Germany. This crater was widely known, and some reports about peculiar rock deformation associated with it had been published. However, the then prevailing opinion was that the Ries Crater was the result of a volcanic event (volcanism indeed is widespread in this part of southern Germany).

Shoemaker investigated a strange type of rock occurring in the Ries structure and, in accordance with its origin in the German region of Suevia ('Schwaben'), termed it suevite (Fig. 94, page 147). He noted a strong similarity of some of its constituents to the enigmatic breccias from Meteor Crater, and could not find any similarity to, or relationship with, volcanic phenomena. Shoemaker mailed a suevite sample to Chao, in Washington, who did not take long to identify coesite in it. Accordingly, these pioneering researchers concluded that the Ries Crater was likely of meteorite-impact origin. A further occurrence of coesite was soon reported from a sample from the Wabar Crater area on the Arabian Peninsula.

A second high-pressure form of silica was reported in 1961 by two Russian experimentalists, S.M. Stishov and S.V. Popova. Even higher pressures than those necessary to generate coesite were needed to produce this very dense form of silica, which later was named stishovite. Like coesite, stishovite was detected in Coconino sandstone from Meteor Crater in the same year. What is more, the Canyon Diablo iron meteorite, fragments of which had been found in abundance around Meteor Crater, contained diamonds. Already in 1956, Harvey Nininger had raised the question of whether diamonds could be produced by impact. With the ultrahigh pressures needed to form coesite and stishovite confirmed, the presence of diamonds in the remnants of the meteorite projectile that formed Meteor Crater no longer seemed so unusual.

By the late 1950s, after finding shatter cones in several other cryptoexplosion structures, Robert Dietz turned his attention to the Vredefort Dome. At the time, most South African geologists did not even consider the possibility that this large structure could be of impact origin. However, Dietz wrote to several South African geologists, suggesting they search for shatter cones in the Vredefort Dome. Robert Hargraves, of the Economic Geology Research Unit of the University of the Witwatersrand (later a professor at Princeton University), took up the challenge. He found excellent examples, in great abundance, in the upturned rocks of the collar of the Vredefort Dome. He also speculated that if the now-upturned strata were restored to their presumed originally horizontal attitude, the cones would project to a single point in the sky above the dome. This point he interpreted as the source of the shock wave that had caused the formation of the shatter cones, above the dome, prior to erosion to the currently exposed level. In 1961, Hargraves reported his findings and concluded that "a gigantic explosion of some sort appears to have been intimately related to the formation of the Vredefort ring structure". Dietz, for one, was convinced — the Vredefort Structure had to be an impact structure.

Dietz's conclusion was received with interest by his colleagues in North America, whereas South African geologists refused to accept this hypothesis. Dietz was not deterred, and even suggested that the Vredefort and Bushveld structures could be closely related, like the closely spaced Ries and Steinheim crater structures in southern Germany that are only 40 km apart, and could be the result of the impact of two related projectiles. In his opinion, the larger of the two South African structures, the Bushveld Complex, was formed by a larger projectile than that responsible for the formation of the Vredefort Dome. He recognised that, if the Bushveld Complex with its layered igneous-looking rocks could be of impact origin, then the same might apply to the giant Sudbury layered intrusion in Canada. In 1962, Dietz indeed detected shatter cones in Sudbury and, in 1964, laid out a case for Sudbury to represent a very large impact structure. It should be noted that, unlike Sudbury, an impact origin for the Bushveld Complex has not been supported by any conclusive evidence, to date.

Hargraves' findings prompted the first systematic work on deformation features in the Vredefort Dome. First, Willy Manton, at the time a student at the University of the Witwatersrand, conducted a detailed study of the occurrences of shatter cones in the Vredefort Dome and further supported Hargraves' results regarding the orientation of shatter-cone apices. However, South African geologists strongly resisted accepting this as proof of impact, consistently arguing for a tectonic or volcanic origin for the dome. Louis O. Nicolaysen, for example, who, at the time, carried out pioneering age-determination studies at the Bernard Price Institute for Geophysical Research at the University of the Witwatersrand, obtained the first

Implications of the age of the Vredefort event

The exact age of the Vredefort event was only revealed in the late 1990s but, since Louis Nicolaysen's original chronological work of the early 1960s, an age of roughly 2 000 Ma had been accepted. This fact caused an interesting debate: if Vredefort was of 'just about' the same age as the Bushveld Complex, could it be possible that both structures were formed simultaneously by the same or similar mechanisms from inside the Earth? Furthermore, did the Bushveld event play a major role with regard to the metamorphism of the Vredefort rocks? When a vast quantity of magma is emplaced into the Earth's crust, a huge region can experience intense heating and metamorphism. Some researchers suggested that the degree of metamorphism decreased away from the alkali granitic intrusions into the collar strata and, thus, that these intrusions were the heat source for the metamorphic changes; however, this was challenged by others. Some of the earliest Vredefort geologists had favoured the alternative idea that the metamorphism of the collar rocks was related to the emplacement of the domical mass of the granitic core. The most recent results suggest that the rocks of the dome record at least three separate metamorphic events, the youngest of which was caused by the impact itself.

age data for the alkali granitic intrusive rocks in the collar of the Vredefort Dome. These results suggested strongly that this magmatic event had taken place at about the same time as the major event that produced the Vredefort ring structure. He concluded that this was a strong indication that violent processes from within the Earth had played a part in the formation of this structure. Others compared the appearance of the dome, with its collar of upturned rock layers, with the geometric structure of a salt dome, a so-called diapir, again favouring an origin of the Vredefort Dome by internal processes. They proposed that the most likely mechanisms were either the thrusting of one rock mass above another, thus resulting in an asymmetrical raised feature (proposed by Alex du Toit), or a relationship to a point of weakness in the Earth's crust thought to have existed at the intersection of two deep faults.

Across the Atlantic, at Texas A & M University, Neville Carter was studying microscopic deformation features in quartz from a number of Vredefort samples, and he noted that some lamellar microdeformations were more akin to experimentally produced high-pressure mineral deformation than to that normally produced in tectonically and metamorphically affected rocks. This, and other findings of mineral deformation in Vredefort rocks, by Carter in 1968 and by Howard Wilshire and co-workers in 1971, further contributed to the wide acceptance of an impact origin for the Vredefort Structure by American workers; however, the South African geocommunity was still not persuaded. Wilshire, who had worked on the enigmatic pseudotachylitic breccia from Vredefort, concluded that this material also represented an impact-produced rock type, and made a first comparison between this breccia and some breccias returned only shortly before from the Moon.

In South Africa, Billy Bisschoff carried out a range of detailed studies on the Vredefort Dome. By the 1960s, he had contributed detailed observations on the occurrence of pseudotachylitic breccia. Then, in 1969, he completed his Ph.D. thesis on the intrusive and metamorphic rocks in the dome. He concluded that the alkali granitic and mafic intrusions into and around the collar of the dome were responsible for the regionally anomalously high metamorphism of the rocks of the Vredefort Dome, thus favouring igneous (magmatic) processes for the formation of the Vredefort structure. Bisschoff also worked on the granophyre of the dome and proposed that it represented a magma derived from the Earth's mantle that had assimilated a large component of granitic and sedimentary inclusions during intrusion into the upper crust. These studies, promoted mostly in the South African geological literature, contributed significantly to the reluctance by South African geologists to consider an impact origin for Vredefort.

Craters and breccias

While early breakthroughs regarding the recognition of impact structures were made in the United States and Germany, the general debate about the unknown origin of cryptoexplosion structures was still continuing. A large number of enigmatic crater structures were investigated by Canadian geologists. The round shapes of these geological structures, lack of associated volcanic rock formations, raised rims and lack of meteoritic debris at first caused consternation. The slightly more than 3 km wide Brent Crater in northern Ontario was studied in great detail, both geologically and geophysically. When surface studies failed to reveal the nature of this structure, Brent became the first 'cryptoexplosion structure' to be subjected to an extensive drilling project. An enigmatic layer of breccia, with possible melt components, was detected below the younger sedimentary crater fill. These discoveries were made during the 1940s, when the initial debate about the possible origin of Lunar craters and some structures on Earth by meteorite impact had just begun. Geologists of the Geological Survey of Canada continued to search for similar structures, and indeed identified several others that shared similarities with Meteor Crater. However, at the time no definitive criteria confirming a meteorite impact were known. Circularity of crater structures and lack of geophysical anomalies that might suggest another origin, such as the presence of dense magmatic rocks, were all that was available.

In the 1960s, Mike Dence of the Geological Survey in Ottawa compared the geological structures of all suspected Canadian meteorite craters, large and small, and found that their structure in cross-section could be generalised: small structures up to a few kilometres wide were characterised by simple bowl shapes, whereas larger ones had a pronounced central mound (uplift), where originally deep-seated crustal rocks had been brought to surface. Dence noted that this complex geometry was akin to that of the Vredefort ring structure in South Africa, and also to that of many of the so-called cryptoexplosion structures.

Gene Shoemaker, in the late 1950s and early 1960s, carried out comparative geological analysis on sites where volcanic gas explosions had occurred (this type of volcanic feature is known as a 'maar' after the structures of this type in the Eifel region, Germany) and at the Meteor and Odessa craters in the USA. He noted that volcanic gas-explosion sites had a deep-rooted volcanic vent, whereas the Meteor and Odessa craters were characterised by breccia occurrences and fractured bedrock. He showed that the rims of volcanic-explosion centres were formed by volcanic debris, whereas those of possible impact craters were formed by raised bedrock. Where sedimentary layering was present, the rims of suspected impact craters were shown to comprise overturned flaps. Shoemaker observed the same features at the edges of nuclear-explosion sites.

Another country where extensive studies of suspected impact craters and cryptoexplosion structures were undertaken, was the former Soviet Union (USSR) where, over several decades, extensive research, including drilling, was carried out, often in very remote areas. One incentive for these efforts was the recognition — especially by Viktor Masaitis in Leningrad (now St Petersburg) that some of these structures contained possibly significant mineral resources.

Whilst these strides were being made in building up a set of impact-diagnostic characteristics, Walter Bucher continued to promote the idea that these features could be reconciled with gas explosions, triggered at pre-existing structural (tectonic) features in the Earth's crust. Even the high-pressure modification of silica (SiO_2) could be the result of such a high-power gas explosion. Based on the knowledge at the time, many geologists were not prepared to accept impact as a common geological process on Earth, and Bucher's arguments were repeatedly used in discussions about the Vredefort Dome, even as late as the 1990s.

Shock metamorphism — the undeniable evidence!

By the late 1950s/early 1960s interest in the impact/cryptoexplosion controversy had grown and quite a number of geologists, mostly from the Northern Hemisphere, had begun to think that bolide impact might be a realistic process for crater formation. Geologists had long recognised that strong forces were continuously operating in the Earth's interior, and that these were both forming new rocks and deforming rocks, and raising the rocks to the Earth's surface. They realised that rocks from deep in the Earth had to have experienced substantial pressures and temperatures, very different from what is happening close to or even at the surface. Coesite had been discovered in Meteor Crater, and soon thereafter, stishovite. Diamond was synthetically produced under very high artificial pressures and temperatures, and diamond had been found in a small number of meteorites. Some scientists started to think about possible connections between pressure, temperature, formation of planetary bodies, and even shock produced by the impact of large bodies onto one another.

In addition, at the time when the Cold War was at its height, new materials were sought by the military to strengthen armour. When the Space Race developed in earnest in the late 1950s, ultrahard materials were needed to coat spacecraft against the onslaught of Space debris (dust-sized meteoroids). Another issue of importance was the understanding of the nature and behaviour of ultrafast explosion waves, so-called shock waves, and physicists developed experimental techniques to study the influence of shock waves on materials. Thus, geologists and physicists simultaneously engaged in high-pressure and high-temperature studies, and shock experimentation, both for geological and materials development purposes.

Other geoscientists investigated the products of tectonic deformation, and began to compare mineral and rock deformation in naturally deformed rocks with those in experimentally deformed samples. Naturally deformed samples included, of course, rocks from suspected meteorite craters and meteorites themselves.

Thus, three new lines of evidence came together: information about rock deformation sustained under 'normal' geological conditions, rocks from suspected impact structures, and samples from experimentally deformed rock. The latter work included experiments with both low-pressure/temperature and high-pressure/temperature to ultrahigh pressure conditions. It quickly became clear that some of the rock deformations found in possible meteorite impact craters matched artificially (experimentally) produced deformation features induced under pressures of many gigapascals and hundreds, if not thousands, of degrees centigrade. The concept of *shock metamorphism* was born.

Shock experiments involved the shooting of small projectiles, at controlled though extreme velocities, at a target material. In the case of military experimentation, this involved shooting at a metal or alloy to be tested for its suitability as, for example, tank armour. In the case of meteorite-impact simulation, scientists would accelerate projectiles made of various materials, such as plastics or metal, onto a rock, or single-crystal mineral, target. Pressure upon impact could be varied by changing the type of projectile, its mass and its velocity. The deformation effects thus induced in the target material were then studied under the microscope or, after its inception in the 1950s, the electron microscope.

Shock experimentation provided the means to determine the precise pressure and temperature conditions for the formation of different deformation features. It also allowed direct comparison of experimentally produced deformation features and naturally occurring ones in suspected meteorite impact craters. The similarities were striking. Using this new experimental

evidence, some scientists studying known and suspected meteorite impact craters were able to establish that the degree of shock metamorphism, as characterised by specific deformation features, decreases radially away from the centres of many crater structures. This is consistent with decreasing shock pressures away from a central point where the shock wave originates (compare Fig. 69, page 98). Many fundamental findings about the nature of shock metamorphism and its distribution in impact structures were made on the German Ries Crater, by scientists such as Wolf von Engelhardt and Dieter Stöffler.

Further confirmation of patterns of shock metamorphism was obtained from nuclear-explosion sites. Not only did they display the same kind of deformation features produced under controlled experimental conditions up to several tens of gigapascal shock pressures, but nuclear-explosion sites also showed a regular decrease in degree of deformation with distance from the explosion centre. At the same time as these developments in the 1960s, similar deformation features were noted in mineral grains from meteorites. For example, a peculiar type of glass, with the composition of the feldspar mineral plagioclase that had kept all the original features of a mineral grain (inclusions, grain shape, fractures, etc.), was discovered in the meteorite Shergotty (a member of the SNC group of meteorites now regarded as material ejected by impact from Mars), and soon also in the Ries Crater and other impact structures. This type of glass, formed by solid-state transformation of plagioclase under intense shock pressure, was given the name of *maskelynite* (after British mineralogist M.H. Story-Maskelyne) and is now understood to belong to the group of diaplectic glasses that form under shock pressures between 25 and 40 gigapascals.

As the scientific momentum grew, a first conference on Shock Metamorphism of Natural Materials was convened in Maryland (USA) in 1968, bringing together all the pioneers in this field, both geologists and shock physicists. This conference laid the groundwork for the characterisation of shock-metamorphic deformation in most of the common rock-forming minerals, and has been an indispensable reference for researchers studying meteorites, Lunar and Martian rocks, and terrestrial impact structures such as Vredefort. In the section on 'Shock Metamorphism' (Chapter 2), the most important shock-metamorphic effects have already been introduced.

Whilst it seems, with hindsight, that clear milestones in the understanding of impact processes were achieved at regular intervals, the truth is that scientific discovery is almost always an incremental process, in which information is accumulated gradually and 'Eureka moments' are rare. However, it cannot be denied that the 1960s was a period of monumental and exciting progress in the geosciences. The decades-long controversy about plate tectonics reached its climax and tilted in favour of those who had started promoting the theory of sea-floor spreading and subduction. New technological advances, to a large degree spawned by the developing Space Race and the race to land the first human on the Moon, provided, in rapid succession, new geological and geophysical tools. For example, seismic and magnetic geophysical methods were much refined, and dating of rocks was revolutionised with the advent of the mass spectrometer that led to the development of a succession of new dating techniques in the 1960s to 1980s. Impact studies were boosted by the Apollo astronauts who returned with a treasure trove full of Lunar rock samples, many of which turned out to be shock metamorphosed and to contain the same shock-metamorphic deformation phenomena recognised in terrestrial crater structures.

The next phase of impact-crater studies involved the application of the newly discovered tools of shock metamorphism to terrestrial craters. More and more so-called cryptoexplosion structures were shown to contain shock-metamorphosed rocks, and a number of such structures also displayed shock zoning, the regular decrease in shock degree on traverses from the centre outward. By the end of the 1970s, some 120 impact structures had been confirmed, mainly on the basis of remnants of a meteoritic projectile or evidence of shock metamorphism. This represented a five-fold increase in the number of known impact structures in only about 20 years!

These detailed investigations of crater structures on Earth, later in comparison with mineral deformation in Lunar rock samples, also showed

that there is a distinct suite of rocks typically formed by impact events, the so-called impactites (Fig. 94). The range includes pure melt rock (impact melt rock), or, when melt fragments are contained in a groundmass of fragmented target rock, suevite, and purely fragmented (clastic) material, previously known as fragmental impact breccia but now called lithic impact breccia. Impact melt rock commonly resembles igneous, especially volcanic, rock, and it is no wonder that, in the past, it has often been mistaken for such. By the late 1970s, detailed classification of the Lunar sample suites from the Apollo missions had documented that the same variety of impactites described from terrestrial impact craters also occurs on the Moon. In addition, many meteorites have also been identified as impact-generated breccias.

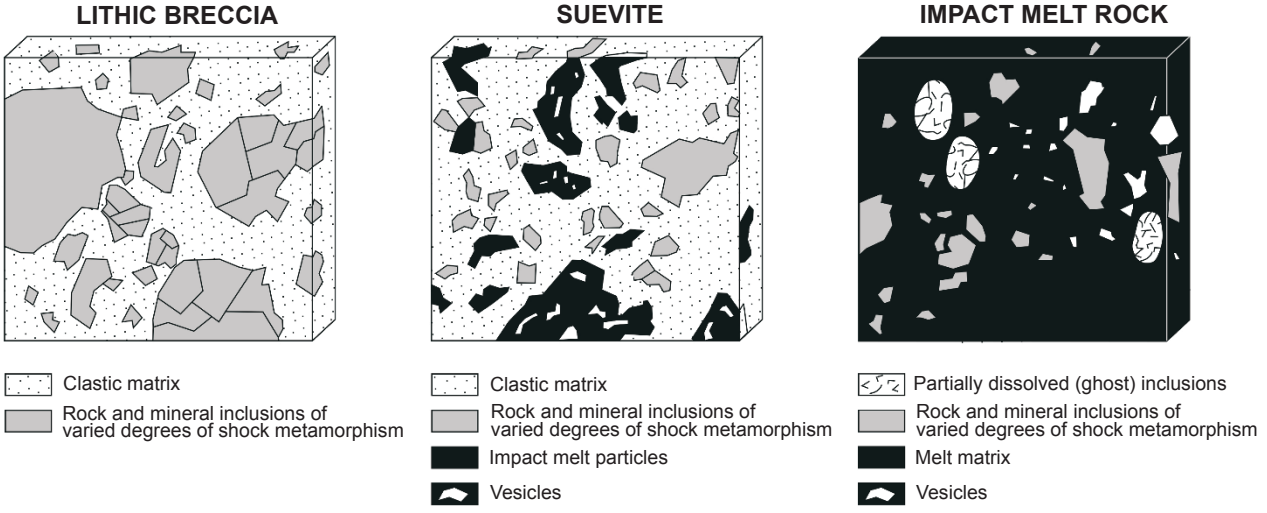


Figure 94: The different types of impact breccia: lithic breccia (previously known by the redundant term 'fragmental breccia') consists exclusively of fragmented rock and minerals, so-called clastic material. In contrast, suevite comprises both clastic and melt fragments in varying proportions, but the groundmass (matrix) is mostly clastic fragments. At the other end of the spectrum, the impact melt breccias are dominated by melt material (either glassy or crystallised), with a more or less important clastic component of mineral and rock inclusions.

The Vredefort structure in the 1970s and 1980s: a time of confusion... but hard work!

The development of geological research on the Vredefort Structure until the early 1970s, and on the massive pseudotachylitic breccias, the shatter cones, and planar microdeformations in the mineral quartz, has been described. Consequently, overseas, the Vredefort case was closed: at European and North American universities students were taught that the Vredefort Dome was one of the largest impact structures known on Earth.

In South Africa the situation was entirely different. In the second half of the 1970s, much detailed work was done on the Vredefort Dome by staff and students from the Bernard Price Institute of Geophysical Research in Johannesburg. The results were widely publicised in South Africa, though not so much in impact-cratering and planetological circles abroad. First, in 1976, W.F. Slawson sampled the granitic rocks across the core of the Vredefort Dome and analysed these samples for their potassium, rubidium and strontium contents, as well as the isotopic composition of strontium. The rubidium-strontium isotope system was, at that time, widely used for the dating of rocks, but strontium isotopes can also be used as tracers for the origin and geological history of magmatic rocks, for example, to establish whether rocks were formed by melting of crustal material or were derived directly from mantle material. Slawson noted that the rocks from the central parts of the core of the Vredefort Dome gave significantly lower isotope ratios than those from the outer parts of the core and that abundances of these three elements changed along traverses from the centre outwards. He concluded that the core of the Vredefort Dome represented a cross-section through a large part of the Earth's crust, with progressively deeper material exposed at surface in the direction of the centre of the dome. From this the idea that a significant portion of the deep crust is exposed on-edge as a result of the doming event and subsequent erosion gathered momentum.

The South African Geodynamics Year of 1978 produced vast amounts of new data on the geology of several extraordinary terranes in South Africa. This involved, for example, multidisciplinary investigations of the northernmost part of South Africa, the southern and central parts of the Limpopo Belt that forms the connection between the Kaapvaal and Zimbabwe cratons, and also of the Vredefort Dome. Four individual contributions to the geology and geophysics of the Vredefort Dome were made. Duncan Stepto carried out detailed geophysical (gravity) studies in the central core of the dome and produced the most-detailed outcrop maps to date. He proposed that the core terrane be divided into two broad zones: an outer one, which he termed the Outer Granite Gneiss, that comprised quite heterogeneous rocks of different granitic or somewhat more mafic composition and that had experienced a metamorphic degree called amphibolite facies (500–700 °C and 0.25 to 0.4 GPa pressures), and an inner zone that was more homogeneous and composed of a rock comprising mainly quartz and potassium feldspar, which he termed the Inlandsee Leucogranofels because of its light colour (Greek: leuco is 'light') and granular texture (a term that refers to the appearance of minerals and the intergrowth relationship between them). Stepto noted that the rocks from the central zone had experienced a distinctly different metamorphic grade, granulite facies, than the Outer Granite Gneiss.

A third component recognised by Stepto was called the Steynskraal Metamorphic Zone, after the farm where these rocks are best exposed. In this area, close to the boundary between Outer Granite Gneiss and Inlandsee Leucogranofels, so-called xenoliths of highly metamorphosed sedimentary rocks occur that represent relics of very old crustal rocks. Based

on his results, Stepto strongly supported the crust-on-edge model.

A concurrent geochemical investigation was carried out by Rodger Hart on the different rock types recognised by Stepto. These were also analysed for their rubidium-strontium and uranium-thorium-lead isotopic compositions in order to further trace their origin in the crust or possibly upper mantle, and to attempt to date these rocks. The dating attempts provided intriguing results. It appeared that the Outer Granite Gneiss rocks were formed around 3 080 Ma, but the Inlandsee Leucogranofels apparently was younger, formed at 2 800 Ma. In stark contrast, the rocks of the Steynskraal Metamorphic Zone appeared to be much older, at least 3 500 Ma, and, as the workers at the Bernard Price Institute concluded, possibly even 3 800 Ma old, which would make them some of the oldest crustal rocks then known on Earth. Hart deduced that the rocks from several kilometre-wide annular zones had distinct chemical compositions and indicated that the Inlandsee Leucogranofels was chemically different from the Outer Granite Gneiss. On the basis of these differences, Hart suggested that lower crustal rocks were exposed near the centre of the dome. Together with his co-workers, he later proposed that parts of the upper mantle were exposed in the centre of the dome — an extremely rare phenomenon.

Peter Lilly's doctoral studies and Carol Simpson's M.Sc. research dealt with the rock deformation in the collar rocks of the Vredefort Dome and the surrounding Potchefstroom syncline. Lilly proposed, in contrast with the widely held opinion by overseas geologists, that a single impact-generated shock event affected the Vredefort rocks, that two consecutive and distinct deformation events could be identified in the collar rocks. This interpretation was based on apparent evidence of recrystallisation of some lamellar microdeformation features in quartz, but not others. This was disturbing evidence, as it was unlikely that two impacts could have happened in the same place at different times. Simpson's rock-deformation studies in the Potchefstroom syncline compounded matters. She identified a breccia (so-called fault gouge) that was formed along a fault plane thought to be related to the Vredefort deformation event. This, by itself, did not mean much, but she reported that this fault gouge was itself deformed and overprinted by a shatter cone. Naturally, this evidence raised further doubt on the single-stage deformation (impact origin) of the dome and, for a change, this observation was widely discussed in the international literature.

Throughout these investigations, the very prominent South African geologist and geophysicist, Louis Nicolaysen, entertained the idea that a gigantic gas explosion, triggered deep inside the Earth, could have caused the formation of a shock wave so strong as to account for all the deformation phenomena observed in the Vredefort Dome. Nicolaysen had made outstanding contributions to geoscience; he was one of the pioneers of the rubidium-strontium method for the absolute dating of rocks, and of the U-Th-Pb method of dating and isotopic tracing of geological phenomena. He attracted numerous high-profile visitors to the Bernard Price Institute of Geophysical Research, which was amongst the leading isotope geological institutions in the world. Nicolaysen also travelled widely to international conferences, where he promoted the notion that cryptoexplosion structures were found in many parts of the world aligned with other obviously internally caused geological features, such as the Ries Crater in Germany along a prominent tectonic and magmatic trend of the Hegau and the Schwäbische Alb. He often caused animated debate, drawing further attention to the Vredefort controversy.

A very significant piece of evidence was contributed in 1978 by Jacques Martini of the Geological Survey of South Africa (now Council for Geoscience). He confirmed the presence of both coesite and stishovite in Vredefort rocks, thus making a major contribution to the early acceptance of an impact origin for the Vredefort Structure by non-South African workers. However, at about the same time, coesite was discovered as a mineral in a South African kimberlite, which provided some local geologists with a means of refuting this new support for the impact hypothesis for the Vredefort Structure.

This was the situation in the early years of the 1980s. Around the world, scientists believed that there was no problem with the origin of the

Vredefort Dome by impact, whereas in South Africa the overwhelming proportion of geoscientists adhered to the belief that this structure was the result of some kind of cryptoexplosion. Statements about an impact origin were often challenged by questions, such as "How could a meteorite 'know' to hit in the direct centre of the Witwatersrand gold deposit, or into an area of pre-existing localised granite intrusions and metamorphism?"

In 1984 Uwe Reimold joined the Bernard Price Institute with the brief to investigate the mineral deformations in the rocks of the Vredefort Dome. On arrival in South Africa he was told by Louis Nicolaysen that he was now a member of the Organising Committee for an International Conference on Catastrophes in the Geological Record and Cryptoexplosion Structures that would take place in July 1987, in Parys, in the Vredefort Dome, at the heart of the controversy! The idea was to assemble an elite group of scientists who promoted either meteorite impact or cryptoexplosion, and had wide-ranging multi-disciplinary expertise, to show them, over the duration of an entire week, the critical field evidence of the Vredefort Dome, to acquaint them with the facts and, hopefully, contribute to solving the controversy between protagonists of exogenic (impact) and endogenic (gas explosion) origins. Another factor that raised the level of interest in this conference was the proposal made just a few years earlier that massive impact could decisively affect life on Earth, in conjunction with the debate about the cause of the mass extinction at the Cretaceous–Tertiary boundary and the demise of the dinosaurs.

What do dead elephants in Leningrad have to do with the Vredefort Structure?

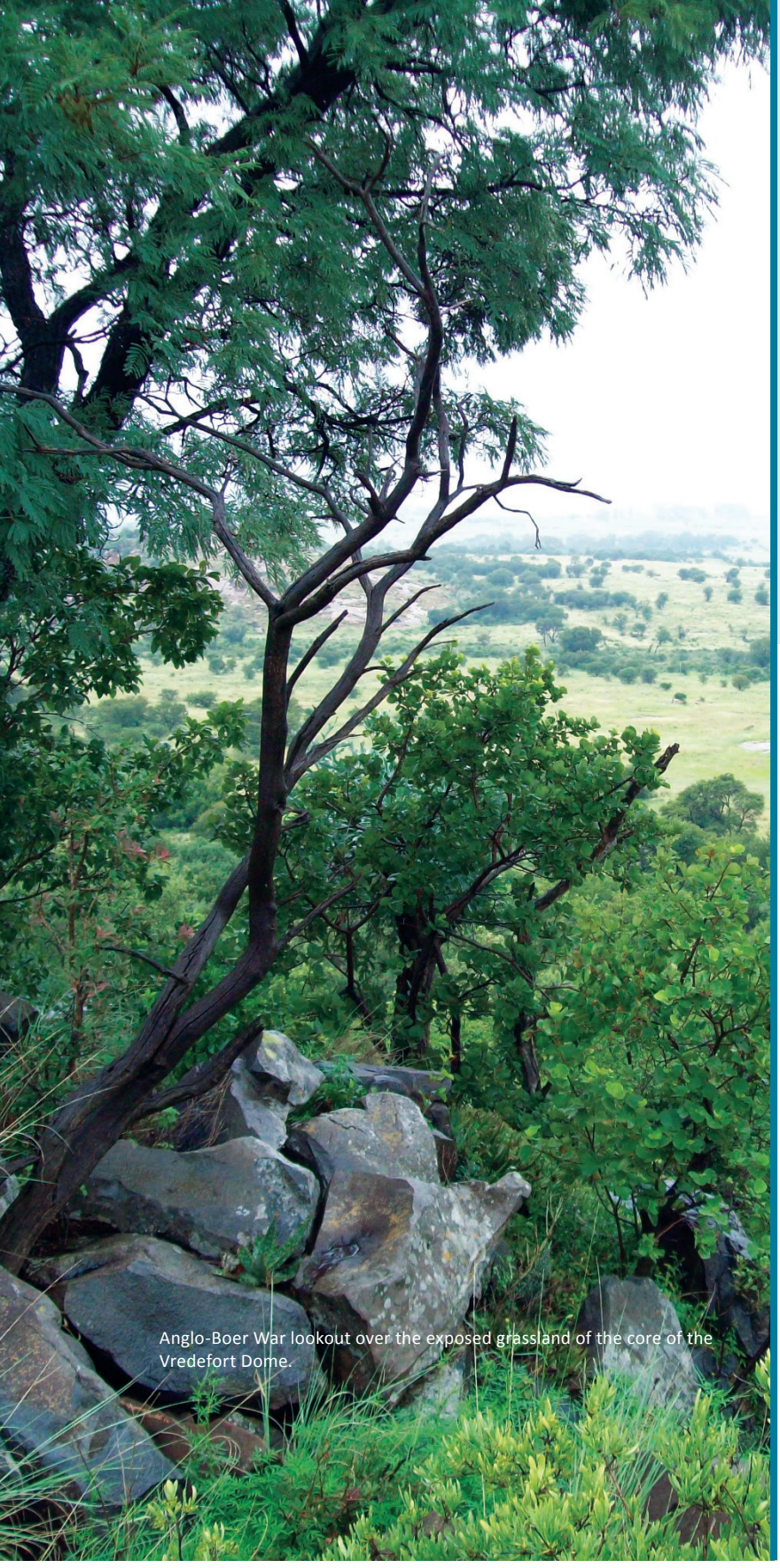
On 11 July 1987, some 120 geoscientists from South Africa and abroad assembled in the Echoes Hotel in Parys. This establishment boasted a somewhat rural Moulin Rouge charm, but was the only place in the area at that time that could accommodate the group.

The focus was on impact versus cryptoexplosion. Half the time was spent in lectures about Vredefort geology, shock metamorphism, mass extinctions, and alternative scenarios to impact, and the other half on field visits to prominent rock exposures. At the beginning of this conference, an unofficial opinion poll of the question about the origin of the Vredefort Structure indicated a sharp division: South African participants were either supporters of some 'gastrobleme' mechanism, involving an internally driven gas explosion, or carefully avoided being pinned down; the majority of participants from overseas supported the impact hypothesis.

Researchers from the University of the Witwatersrand presented a series of talks on their new field and laboratory results. They introduced the general geology of the region and, specifically, of the dome, the regional geophysics and how this could be reconciled with a peculiar crustal setting that could have triggered a gas explosion, and new field and laboratory findings regarding the rock and mineral deformations in the rocks of the Vredefort Dome (for example, Figs 95a and b). In addition, for the first time, the geology and geophysics of the wider Witwatersrand basin were considered in the context of the Vredefort Structure. For example, the fact that many occurrences of massive breccias that closely resembled the pseudotachylitic breccias from the dome had been recorded in underground workings of Witwatersrand gold mines, was, for many, an astonishing new observation that prompted a flurry of discussion about the size of the Vredefort Structure.

Uwe Reimold gave several talks about his field and microscopic results, which appeared to further complicate matters. He reported evidence for more than one generation of pseudotachylitic breccia (Fig. 96), which did not appear consistent with a single catastrophic event. This evidence came in the form of field observations, as well as first geochronological data on pseudotachylitic breccia samples from the dome that indicated ages between 2 200 and 1 100 Ma. He had observed some evidence under the microscope that suggested not only two deformation events (supporting Peter Lilly's earlier conclusions), but also raised doubts as to the nature of the straight and crystallographically controlled microdeformations in quartz, which lacked glass, as being the equivalent of impact-diagnostic planar deformation features (PDFs). In contrast, the group from the Geological Survey of Canada suggested the microdeformation features were PDFs, and that they detected a decrease in shock pressure outward from the centre of the dome.

Reimold presented another controversial finding — shatter cones apparently superimposed on pseudotachylitic breccia — made just before the conference by Wayne Colliston, from the University of the Orange Free State in Bloemfontein, on a farm in the western part of the collar of the dome. Like Carol Simpson's work on shatter cones on Vredefort-related fault breccia, published several years earlier, this also did not favour impact, in which scenario shatter cones would form upon interference of the shock wave on its path through the target with defects in the rocks, very early on in the impact event. Reimold's search for traces of a meteoritic component in the Vredefort Granophyre and for shock-characteristic microdeformation in rock and mineral inclusions in this melt rock was negative, like several earlier searches in the preceding decade. He also questioned why, if



Anglo-Boer War lookout over the exposed grassland of the core of the Vredefort Dome.

for the first time, the geology and geophysics of the wider Witwatersrand basin were considered in the context of the Vredefort Structure

the microdeformation features in quartz were shock-induced, no shock-metamorphic evidence had been found in other minerals. Nicolaysen questioned how several spatial and temporal coincidences could be reconciled with an impact origin. Amongst these was the location of the dome at the intersection of the long axis of the Witwatersrand basin and a northwest-trending crustal upwarp, as well as the perceived concentration of alkali granite and mafic intrusions and higher metamorphic grades in the vicinity of the dome. He also challenged the delegates to explain why no shatter cones had been sampled on the Moon.

In response to Nicolaysen's challenge to explain these 'coincidences', a very prominent meteorite and Lunar rock researcher from Houston, the late Elbert King, countered by asking Nicolaysen to explain why the first artillery shell fired into the city of Leningrad by German forces in the Second World War happened to kill the only elephant in the zoo! This was the style of interaction, banter and dispute. When a vote was taken at the final conference dinner, a slight majority of participants favoured impact. However, the most important outcome of this conference was the opening up of a large body of new evidence to wider scrutiny and a renewed interest in the Vredefort Structure. This led to collaborative research efforts over the next few years that would ultimately solve the riddle of the Vredefort Dome.

The third phase —
solving the riddle, at last!

With regard to the Vredefort Structure, the 1990s were entered with the publication of many of the papers presented at the Cryptoexplosion and Catastrophes Conference. These Conference Proceedings reflected the controversy about the origin of the Vredefort Structure. While several overseas contributions took an impact origin for this structure for granted, Louis Nicolaysen and his collaborators used this medium to draw links between regional geological features, such as the occurrence of magmatic rocks in the collar of the dome, interpretations of the regional magnetic and gravity fields in conjunction with the geophysical expressions of the dome, and the Vredefort-specific deformation phenomena. Nicolaysen and John Ferguson, a former staff member of the Department of Geology at the University of the Witwatersrand, who had also promoted a volcanic origin for the Pretoria Saltpan crater, continued to insist that doming and deformation could be explained by an internally triggered gas explosion.

The real bonus produced by the 1987 conference was that many new contacts between South African and international researchers had been forged. Also, a range of new techniques was now available to address the Vredefort conundrum. Rodger Hart and his co-workers from the universities of the Witwatersrand and Cape Town entered the fray with new ideas about the composition of the basement of the Vredefort Dome. They concluded from their, mostly chemical, work that a crustal-scale fault or shear zone existed between the Outer Granite Gneiss and the Inlandsee Leucogranofels that, in their view, represented upper and lower crustal, respectively. When core from a borehole near the centre of the dome became available that showed the presence of ultramafic rock types, they went so far as to suggest that even rocks from the upper mantle had been brought to surface by the updoming event.

In 1989, Bevan French, at that time at NASA Headquarters in Washington, published new chemical data on the Vredefort Granophyre. He and his co-workers confirmed the remarkable homogeneity of this enigmatic rock type, and showed with calculations that mixtures of regionally occurring rock types could result in chemical compositions that were nearly identical to that of the granophyre. This paper preceded a publication by Uwe Reimold and co-workers on the same topic by only a few months. The local group were also unable to identify a chemical signature indicative of admixture of meteoritic material. Contrary to French and co-workers, however, they carried out mixing calculations with the rock types that were actually observed in the form of inclusions in the granophyre, and showed that this different mixture could also account for the composition of the granophyre. There was still no definite evidence in favour of or against impact, though both groups agreed that it was not necessary to draw on a magma from great depth, in contrast to the earlier hypothesis by A.A. Bisschoff.

Reimold also published his work on the microdeformations in quartz from Vredefort rocks (Figs 95a and b). He went to great pains to demonstrate that they were not identical to the planar microdeformations that had been described from many confirmed impact structures and from the Cretaceous–Tertiary boundary layer. He also suggested, together with Günther Brandl of the Geological Survey of South Africa (now Council for Geoscience), that similar features, admittedly very rarely, could be produced in tectonic deformation zones, for example, in the Limpopo Belt in northernmost South Africa, as a result of relatively fast (though in impact terms at a snail's pace) movement on large faults.

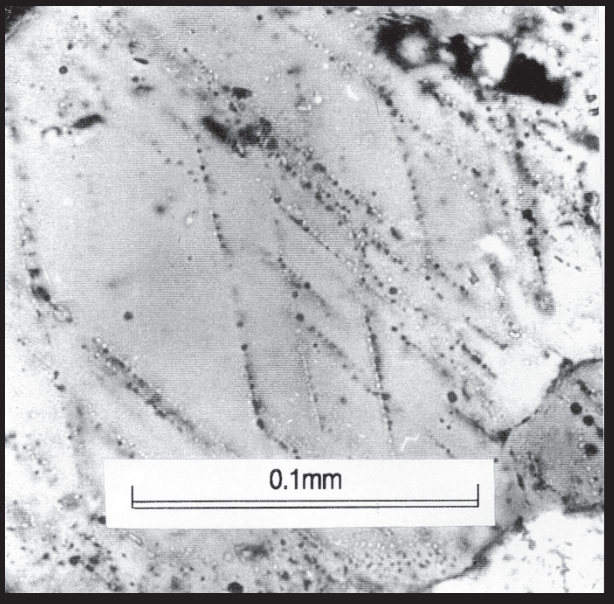
In collaboration with Fred Hörz of the Johnson Space Centre in Houston, a series of discs cut from Hospital Hill quartzite, sampled

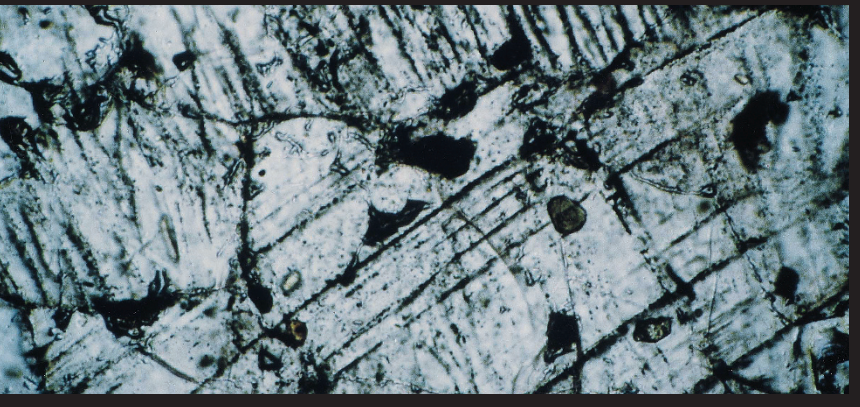
in the Krugersdorp area, west of Johannesburg, where this rock does not exhibit any deformation features, were experimentally shocked to pressures up to more than 30 GPa, and, in what was a first, these shock experiments were also done on samples that had been pre-heated to 400 and 600 °C. The purpose of these experiments was to simulate the conditions for these rocks, now exposed in the Vredefort Dome, at the time of the deformation event more than 2 000 Ma ago. The resulting shock deformations did not, however, resemble those microdeformation features actually observed in samples of the same quartzite from the collar of the dome. This ambiguity continued to frustrate researchers; however, a new technique was about to enter the fray.

Since the early 1990s, a number of impact workers had been drawn to Transmission Electron Microscopy (TEM) as a means to verify the true nature of microdeformations in a number of minerals from different geological settings. In 1992, Uwe Reimold had met an eminent TEM specialist from the Université de Lille in France, Professor Jean-Claude Doukhan, whose Ph.D. student, Hugues Leroux, agreed to analyse a few samples from Vredefort.

By this time, Roger Gibson had joined the Department of Geology at the University of the Witwatersrand. His particular research focus was the causes and conditions of metamorphism found in crustal rocks. He began to assess the unique metamorphic situation in the dome, where much higher metamorphic grades are found than elsewhere in the region. Based on his analysis he was able to recognise a strongly variable metamorphic overprint, ranging from ultrahigh-temperature granulite facies in the central parts of the dome, to amphibolite facies in the inner collar and greenschist facies in the middle collar, that postdated the formation of the pseudotachylitic breccias. This metamorphism was superimposed on metamorphic mineral assemblages related to at least two separate metamorphic events in the collar and core of the dome. He was able to show that the pre-impact metamorphic events occurred when the rocks were much more deeply buried than they were at the time of the post-impact metamorphism, indicating that the rocks had been uplifted to form the dome between these events. The exceptional temperatures and absence of any directed stresses in the rocks during the post-impact event pointed to an exceptional heating mechanism, which could only have been achieved by

↓ **Figure 95a:** Typical shock microdeformation (decorated planar deformation features: PDFs) in a quartz grain from granitic rock from the central part of the Vredefort Dome, near the Inlandsee pan (taken in plane polarised light). Instead of glass lamellae, the PDFs are defined by tiny fluid inclusions. Plane polarised light. Image courtesy of Hugues Leroux, Université de Lille.





↑ **Figure 95b:** Another example of microdeformation in quartz from Vredefort rocks. The narrowly spaced and straight features shown here are both fractures and planar deformation features (PDFs), the latter of which are characteristic of impact deformation. Width of the image ca 1.1 mm (taken in plane polarised light).

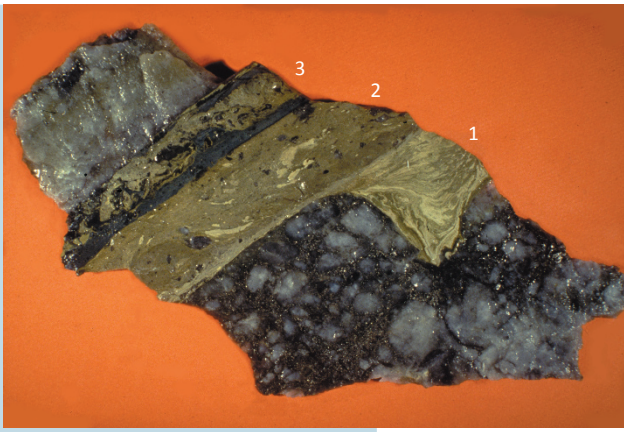
an intense impact-induced shock that decreased radially outward.

In the meantime, Hugues Leroux had obtained TEM results on Vredefort quartz crystals that, once and for all, laid to rest the controversy about the microdeformation features. After painstaking thinning of individual quartz crystals separated from Vredefort rocks, he obtained slivers so thin that electrons shot at them could actually penetrate the crystal, providing information about the atomic structure inside. His findings were unambiguous: these crystals contained very narrow lamellar features that could be nothing else but crystal twins (planes along which the orientation of the crystal lattice changes) of a type known as Brazil twinning. There are only two known natural occurrences of Brazil twins in the mineral quartz: (1) as the result of growth of quartz crystals from hot aqueous solutions, and (2) caused by the enormous pressure of a shock wave travelling through the crystal. The first option could be discarded, as one would not expect to see such hydrothermally produced twins in quartz from massive Archaean granite. After nearly 30 years, an undisputed shock origin could be assigned to the PDFs from the Vredefort Dome!

Shocked zircon and a precise age for the impact event

Soon thereafter, collaboration between Uwe Reimold and Wayne Colliston with scientists from overseas not only provided further unambiguous evidence of shock metamorphism in Vredefort rocks, but also obtained a well-constrained age for the Vredefort impact. Until the 1980s, most dating studies employed the Rb-Sr and Sm-Nd dating techniques. Since then, more and more groups have focused on radiometric dating of individual crystals of the mineral zircon. Zircon contains uranium, a radioactive element that decays to lead, and this mother-daughter relationship can be used for dating of rocks. Zircon is stable up to considerable temperatures and is very resistant against chemical attack (alteration). Thus, it is a much better medium for dating than Rb- and Sr-carrying minerals, which are more easily altered or metamorphosed.

Sandra Kamo and Tom Krogh from the Royal Ontario Museum in Toronto teamed up with Uwe Reimold and Wayne Colliston to date zircon from Vredefort rocks. Krogh, Kamo and their colleagues had previously successfully employed the single zircon U-Pb dating technique for dating the Cretaceous–Tertiary impact event in rocks from the Chicxulub impact structure in Mexico, and reported findings of shock-metamorphosed zircons from the Sudbury and Manicouagan impact structures. Uwe Reimold thought that the impact-related rocks from Vredefort, the granophyre and pseudotachylitic breccias, provided good targets for the application of this technique. Not only did the selected samples contain a large number of zircon grains, but they also comprised two different types: (1) grains that had been deformed and showed the same types of microdeformation (Fig. 71, page 99 and Fig. 97) that had already been observed in Chicxulub, Sudbury, and Cretaceous–Tertiary boundary zircon, and (2) smaller, fresh-looking, totally undeformed grains of igneous appearance.



→ **Figure 96:** An example (about 20 cm long) of multiple breccia generations from a major fault zone in the northern Witwatersrand basin (from Elandsrand Gold Mine). Three different fault breccias can be recognised 1: yellow, 2: olive green, and 3: dark grey. Each of these would have been generated by very rapid movement along this fault. However, it is not impossible that all three generations of breccia could be related to the violent rock deformation triggered by the impact event. At various times during this short-lived, but catastrophic, event material was moved about, first outwards from the point of impact, then back into the collapsing crater. Image courtesy of Chris Roering (formerly RAU, Johannesburg), reproduced with the permission of the Geological Society of South Africa.

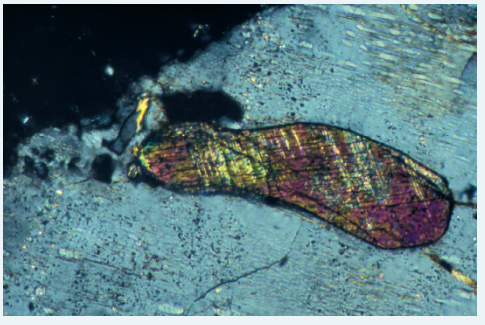
Using a scanning electron microscope, the team detected typical shock deformations in the larger, deformed grains that gave ages of about

3 100 to 3 200 Ma. The fact that these grains had experienced shock deformation indicated that they were derived from the precursor rocks for the breccias and granophyre, likely the rocks that constitute the basement to the Vredefort Dome. In contrast, the tiny, clear grains gave an age of 2 023 Ma (the error on this figure is estimated at 4 Ma, just 0.2 %). The well-crystallised forms of these zircon grains implied that they had formed from melts, the respective matrices of the pseudotachylitic breccias and the granophyre. The melting event had to be the impact, and, consequently, the ages obtained had to pinpoint the time of the impact. Not only was this age the oldest ever determined for an impact structure on Earth, but it also separated the Vredefort impact event from the Bushveld igneous event by some 30 Ma — not that much in geological terms, but sufficient to lay to rest the nearly a century-old hypothesis that the two were related. Two other groups have since obtained very similar ages for Vredefort breccias, and the entire database can be combined to a best estimate of 2 020 ± 5 Ma for the impact event.

What had happened to Uwe Reimold's 1987 notion that there could be several generations of pseudotachylitic breccia in the Vredefort Dome? Initially, further age data seemed to support this assumption, and Witwatersrand geologists did indeed find further evidence for repeated formation of such breccia, for example in the form of cross-cutting breccia relationships (Fig. 96). But with the advent of new dating techniques, it became clear that the ages of about 1 100 Ma obtained in the 1980s represented the effect of low-temperature overprint on impact-related breccias, long after they had been formed. In addition, there is obviously no problem with having the odd occurrence of tectonically formed, pre- or even post-impact breccia in the region of the Witwatersrand basin. The entire region has been subjected to tectonic deformation ever since the Witwatersrand rocks were formed, not much less than 3 000 Ma ago.

Another problem was laid to rest in 1996. When the impact origin of the Vredefort Structure was confirmed through findings of shocked quartz and zircon, it was clear that the homogeneous granophyre had to represent impact melt rock. However, hundreds of Vredefort Granophyre samples had been analysed in vain attempts to identify possible traces of a meteoritic component. The chemical analyses did not show unusual (for crustal rocks) abundances of elements of possible meteoritic origin. One of the reasons for this was that one of the country rocks that had to have been admixed into the impact melt, the Witwatersrand shale, is in fact quite rich in elements such as Cr, Co, Ni, and iridium, so that the admixture of a small fraction of extraterrestrial material was readily blanketed by this terrestrial component.

One of the participants in the 1987 Cryptoexplosion Workshop in Parys was an Austrian researcher, Christian Koeberl, whose interest was in the origin of tektites. At the time, both impact and cryptoexplosion lobbies were laying claim to these glasses. Koeberl's expertise lay in high-precision geochemistry. In the mid-1990s, he and Steven Shirey from the Carnegie Institution in Washington, pioneered a new technique for the detection of meteoritic projectile traces in impact breccias. Extraterrestrial rocks, like rocks from the Earth's mantle, are enriched in the element osmium, compared with another platinum-group element called rhenium, in stark contrast to all crustal rocks that are relatively enriched in rhenium. In addition, the ratio between the two osmium isotopes, ^{188}Os and ^{187}Os, is much lower in extraterrestrial and mantle rocks than in crustal rocks. Thus, if one can exclude that mantle rocks are part of a system



↑ **Figure 97:** Planar microdeformation features in a zircon crystal enclosed in alkali feldspar from a metapelitic granulite from Stop 5. Crossed polarisers. Field of view 0.3 mm wide.

being investigated, the abundances and isotopic ratios for the elements osmium and rhenium can be a powerful tracer method for the presence of even small meteoritic components. This method has worked in a number of cases; for example, when samples of impact breccia from the small South African impact craters Kalkkop and Tswaing were analysed, the Re-Os isotope method proved beyond doubt the presence of a meteoritic component in each.

Koeberl analysed a series of Vredefort rocks, including granophyre and the various possible target rocks. He found that the granophyre is significantly enriched in osmium and that the osmium-isotope ratios determined for this rock are much lower than those for the possible target rocks. An unequivocal trace of a meteoritic component had finally been detected in the Vredefort Granophyre! Not surprisingly, it amounted to only a very small component; only 0.2 % of the granophyre mass is derived from the meteorite. The proof that the Vredefort Granophyre is impact melt rock removed the final obstacle remaining for acceptance of the impact origin for the Vredefort Dome and, coming close on the heels of the confirmation of the shock microdeformation in quartz, finally laid to rest the cryptoexplosion hypothesis.

The next milestone study was a geophysical investigation by Herbert Henkel of the Royal Institute of Technology in Stockholm, Sweden, who, together with researchers of the University of the Witwatersrand, modelled the entire geophysical database (gravity, magnetics and seismic information) over the Witwatersrand basin, in order to investigate a possible link between the Vredefort Dome and the surrounding basin feature. The resulting model matched a cross-section through a 300 km wide impact structure with a wide central uplift (dome feature) in the centre, surrounded by a deep ring basin (compare the structure of Fig. 98). Consequently, Henkel and Reimold concluded that the entire Witwatersrand basin represented the remnant of the Vredefort impact structure (see Fig. 81, page 123).

Henkel and Reimold's modelling also suggested that, despite the large crater size, the amount of vertical uplift in the Vredefort Dome would not have been sufficient to expose mantle rocks in the centre of the dome, which would have lain between 35 and 40 km below the surface at the time of impact. Only a shallow warp of lower crustal rocks was detected. These results concurred with Roger Gibson's metamorphic and structural results that suggested that the maximum depth of exhumation in the dome was 'only' about 27 km, and have recently been confirmed by computer simulations of the Vredefort impact by Russian researcher Boris Ivanov.

How big is 'big'?

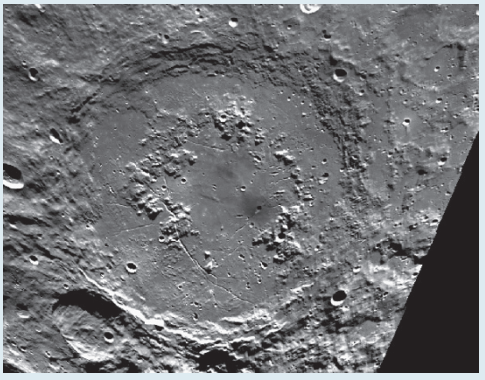
Ever since it was proposed in the 1930s that the Vredefort Dome was the product of impact, there has been speculation on the size of the impact structure. For much of this time, only the Vredefort Dome itself was considered as the impact structure. In fact, still today one can visit places in and around the Vredefort Dome where a total diameter of 40 km is promoted, maintaining that the up- and overturned collar rocks mark the circumference of the impact structure. Others, in past decades, have variously suggested that the core and collar of the dome represented a crater structure of 70 to 90 km diameter, and a diameter of 140 km was also proposed.

In 1997, however, Ann Therriault and Richard Grieve of the Canadian Geological Survey in Ottawa, together with Uwe Reimold, discussed an interesting topic: when one compared the various limits to which impact-deformation phenomena at Vredefort — occurrences of pseudotachylitic breccia, shatter cones and shock deformation in quartz (Fig. 81, page 123) — could be observed, with the distributions of such deformation phenomena at other known impact structures, one had to conclude that the original (prior to erosion) Vredefort impact structure could have been as large as 300 km in diameter. A year later, Herbert Henkel and Uwe Reimold published their geophysical modelling findings and arrived at the same conclusion: the subsurface structure modelled for the crust underneath Vredefort corresponded to a 250 to 300 km wide impact structure, with the Vredefort Dome marking a ca 100 km wide central uplift. Then, in 1999, a group at Greenwich University (UK) interpreted satellite imagery of the

whole region and proposed that the Vredefort Structure could have been even larger, maybe as wide as 340 km.

Estimates as large as 380 km have been proposed; however, significant uncertainties remain. For example, it is not known exactly by how many kilometres the original impact structure has been eroded. Roger Gibson's calculations based on metamorphic mineral assemblages produced by the impact heating indicate between 8 and 10 km of post-impact erosion. As impact structures have a broadly bowl shape, erosion reduces the apparent diameter of impact-deformed rock. In addition, ancient structures are susceptible to tectonic deformation which may alter the diameter of the structure and mask impact effects (such as at Sudbury). The periphery of a large impact structure also contains structures which cannot be unequivocally proven to be impact induced — a case in point being the De Pan breccias near Carletonville (Fig. 87, page 132). If such breccias are impact induced, they may provide a counterargument against recent computer modelling results that have suggested that the Vredefort crater diameter was actually originally considerably less than 200 km — however, none of them included the final, crater-widening collapse phase. Nonetheless, even at a reduced original diameter, Vredefort would remain one of the three largest impact structures currently known on Earth (together with Chicxulub on the Yucatán peninsula and Sudbury in Canada).

In terms of South African geography, a 200 to 250 km diameter means that the impact structure covers the bulk of the Witwatersrand basin, between Johannesburg in the northeast and Welkom in the southwest (Fig. 81, page 123). The basin itself appears to be largely a remnant of the impact ring basin around the central uplift (Fig. 98). The downwarping around the dome led to the preservation of the gold-bearing strata, which reach depths approaching 13 km north of the dome. Immediately after the impact, the ring basin would have been filled with impact breccias, including impact ejecta that would have thickly covered the Witwatersrand rocks. The heat from these impact breccias and the central uplift would have driven giant hydrothermal systems that probably played a role in remobilising and recrystallising gold in the reefs. To some extent, the geological feature called the Witwatersrand basin is the Vredefort ring basin, not the original sedimentary basin in which Witwatersrand Supergroup sediments were deposited. This is borne out by the widespread occurrence of Witwatersrand Supergroup rocks beneath younger cover beyond the limits of the basin, which has been established from geophysics and drilling. Various workers have speculated that the fact that the basin is not circular may indicate post-impact deformation, possibly related to northwest-directed thrusting between the craton and another crustal plate in the KwaZulu-Natal region about 1 000 Ma ago. Alternatively, the basin's shape may reflect pre-impact tectonic structures. Pre-impact faults have been suggested as the cause of the 'tail' extending southeastwards from the Vredefort Dome, as seen on the gravity and magnetic images (Figs 79 and 85), which indicates that the collar rocks do not complete an unbroken circle.



← **Figure 98:** Schrödinger crater on the far side of the Moon (mosaic of Clementine Mission images; image processing by Ben Bussey and Lunar and Planetary Institute). The impact structure is 320 km in diameter — roughly of the same order of size as assumed for the original Vredefort impact structure. This crater structure represents a typical example of a peak-ring structure. The peak ring (ca 150 km diameter) is the result of collapse of the original central uplift; it is about 75 % complete. The smooth surface of the crater interior represents impact melt rock. A large number of relatively younger impacts have occurred onto the impact melt body. Clementine images courtesy of NASA.

Vredefort research in the 21st century

As discussed in the previous sections, persistent and collaborative research, making use of ever-evolving state-of-the-art analytical techniques, finally solved the riddle of the origin of the Vredefort Dome. Particularly since 1990, a large database has been assembled from both general field mapping and focussed studies of not only the Vredefort Dome and its features, but also the surrounding region. Based on the groundwork laid in the previous decades and concurrent research in the discipline of impact-cratering studies worldwide, major strides have been made in the understanding of the structural and metamorphic geology, geophysics, geochemistry, geochronology, mineralogy and economic mineralisation of the Vredefort impact structure.

Groups of researchers and students from several South African and overseas universities continue to investigate the Vredefort impact structure. Much progress has been made on understanding the evolution of the Archaean basement rocks in the core of the Vredefort Dome. High-precision geochronological studies by Rodger Hart and colleagues, and Cristiano Lana have shown that the pre-impact metamorphism occurred between 3 080 and 3 100 Ma and that most of the granitoid rocks appear to be younger than 3 120 Ma, which is significantly younger than similar rocks in the Barberton and Johannesburg Dome areas. Paula Ogilvie has further refined the pressure and temperature estimates for both the Archaean and impact-induced metamorphism in the central core of the dome that show that these rocks were (a) derived from crustal levels somewhat higher than the base of the crust, and (b) subjected to post-impact temperatures that locally exceeded 1 000 °C. Roger Gibson and Uwe Reimold have identified a range of shock-metamorphic features in minerals, such as plagioclase, alkali feldspar, biotite and amphibole, that indicate shock pressures in excess of 40 GPa in the rocks in the central parts of the dome. The magnitude of these pressures explains how the high post-shock temperatures could be achieved and the temperatures assisted in annealing the sensitive shock-deformation features in the mineral grains. Hart and co-workers have attributed unusual magnetic properties in some rocks of the core of the dome to shock effects. This group and Johanna Salminen from the University of Helsinki, in conjunction with Reimold and Gibson, have investigated the magnetic characteristics of Vredefort rocks, also with regard of what they could tell about the position of the Kaapvaal craton on the Earth — some 2 000 million years ago. It is interesting to note that the position consistently obtained relates the then craton position to the parts where today Egypt is located in northeast African latitudes.

Renewed investigation of shock effects, such as shatter cones, has been undertaken by Amir Sagy and co-workers, and Frank Wieland; with Sagy proposing that cone angles increase away from the centre of the dome, whereas Wieland suggested that the angle is linked to rock type. Wieland also showed that the orientation of cone apices may be strongly variable on an outcrop scale, countering earlier studies that suggested that the cones point towards the centre of the dome if strata are rotated back to their pre-impact orientation. Wieland also documented the patterns of faults and fractures in the collar of the dome, which he related, together with kilometre-scale folds, to formation of the central uplift. In 2004, Paul Buchanan and Uwe Reimold identified the first shock-deformed inclusions of quartzite and granite in Vredefort Granophyre. They found a previously undescribed type of shock deformation in quartz, the result of local and crystallographically controlled melting of quartz grains, that obviously requires very high temperature. More recently, new work by Reimold and Gibson,

together with Ulrich Riller, Daniel Lieger, and Tanja Mohr-Westheide, has been directed at investigating the pseudotachylitic breccias in the dome in an attempt to determine whether melting was induced by frictional or shock heating processes. This new information is reviewed in Gibson and Reimold (2008).

The Vredefort Dome and, indeed, the entire Witwatersrand basin, remains a giant laboratory in which to investigate the Vredefort impact event and its processes. The gold mines provide unprecedented three-dimensional exposure, but they also indicate the complexity of the structural history of the rocks that needs to be unravelled if the impact effects are to be identified. The vast geological and geophysical archives of the Witwatersrand mining houses that have explored the basin for gold for over a century contain an immeasurable wealth of information about the entire Vredefort impact structure, and will continue to vastly enrich our knowledge about the three-dimensional structure of such large impact basins in general. There is little doubt that new data and observations on the Vredefort Structure will continue to receive prominence in scientific journals dedicated to the investigation of the process of impact cratering.

↓ **Figure 99a:** Craters on the far side of the Moon centred at 20°S, 162°E, in the Keeler-Heaviside basin. The large complex crater in the centre is Keeler (169 km); the smaller fresh crater on the east (left) wall of Keeler is Planté (38 km); the degraded crater in the lower left is Stratton (71 km). Image courtesy of NASA, Apollo 12 frame H-4961.

Vredefort — an open book about the history of Earth and the nature of Earth's interior

The history of geological endeavour in the Vredefort Structure has been explored in this chapter. It has been shown how this exploration was intricately linked with the evolution of knowledge about an important fundamental process: impact cratering. The history of the long road to the solution for the riddle of the origin of the Vredefort Structure has also been recounted.

The geology of the Vredefort Dome spans at least 3 400 Ma. The dome provides us with a laboratory where rocks that originally resided more than 25 km deep in the Earth can be studied. The deepest boreholes in the world, in the Kola Peninsula of Russia, in Germany and North America, have only reached depths of 7 to 12 km and provide only small volumes of material with which to work. The detailed mapping of the rocks from Vredefort, derived from enormous depths, has already provided much knowledge about how the crust of the Kaapvaal craton is constituted and how it has evolved through time. But even more can be learnt by studying the rocks on a smaller scale, in much more detail.

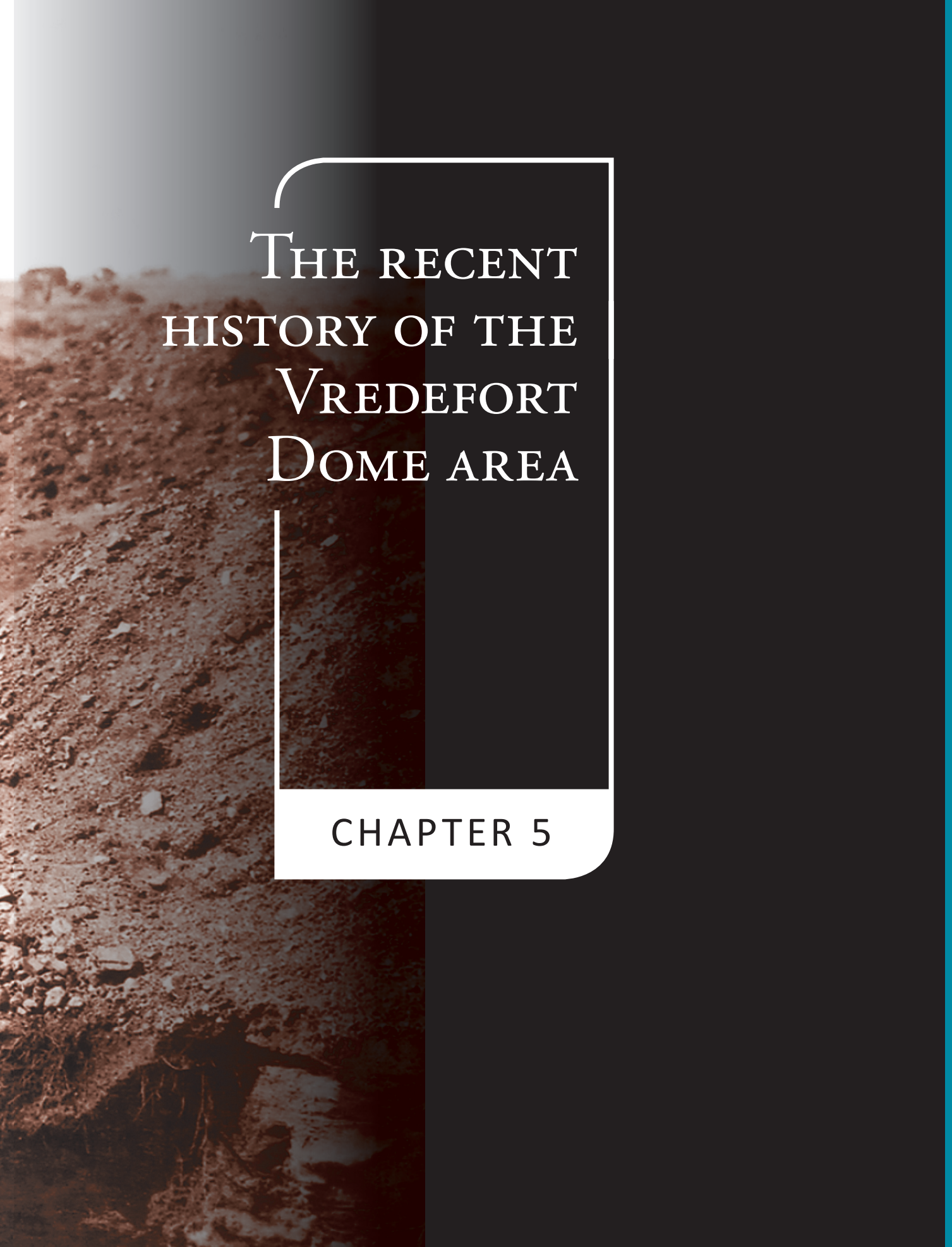
The rocks exposed in the collar of the Vredefort Dome are of successively younger age, from between 3 074 and 2 150 Ma. The study of these metamorphosed sedimentary and volcanic rocks is still far from complete. Much remains to be learnt from them about the environmental conditions that prevailed during their deposition, as well as the behaviour of these rocks under the enormous stresses imposed by the Vredefort impact event.

The Vredefort impact structure is one of the small group of truly giant craters; in comparison with Sudbury in Canada and Chicxulub in Mexico, Vredefort is the most deeply eroded. Consequently, it does not allow us to study the crater fill, the impact breccias and their distribution (with the exception of the dykes of Vredefort Granophyre), but it is the only large impact structure that allows a good look into the bowels of such a complex structure. The Vredefort Dome, with its excellent exposures, as well as the deep gold mines of the Witwatersrand, affords scientists a unique opportunity to investigate the deeper parts of a large impact structure.

Whilst the primary focus of research in the Vredefort Dome remains on its intriguing rocks, the more recent history of the region and its links to the geology must also not be forgotten. The next chapter describes the archaeological, cultural-historical and biological features of the dome area that present a microcosm of the rich tapestry of human development in southern Africa.

Figure 99b: Earthrise over the lunar horizon; image taken by the SELENE lunar probe. Image reproduced courtesy of Japan Aerospace Exploration Agency (JAXA).

Workers developing a mining trench in a gold-bearing reef in the late 1890s. Historical photograph, courtesy of the National Cultural History Museum, Pretoria.



The recent history of the Vredefort Dome area

CHAPTER 5

SECTION 1

Travelling through time:
archaeology and the Vredefort Dome

Anton Pelser

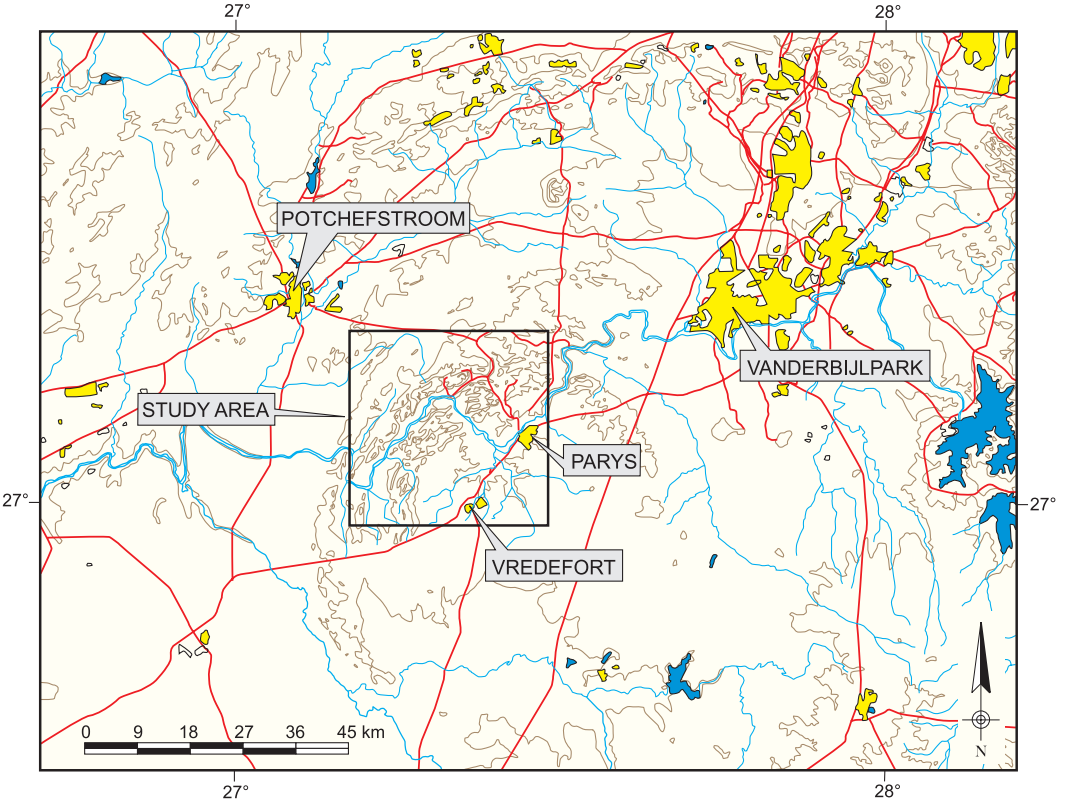


Figure 100: General map showing the location of the archaeological study area.

Introduction

Most residents of and visitors to the Vredefort Dome are unaware that the area has an extremely rich cultural heritage, and a past that stretches back many thousands of years. Many of the same reasons that have attracted people to the dome in the recent past, and even today, probably lured Stone Age hunter-gatherer bands (people who hunted wild animals and gathered plants for food) and groups of Iron Age farmers and cattle herders here. These attractions include the ample water resources, the geology, for example the abundance of caves and rock formations providing shelter, good climate conditions, and the vegetation and fauna. The many stone tools, utilised rock shelters, stone-walled remains of Iron Age settlements, the remnants of early European homes, the historical marks of the late 19th and early 20th Century gold mining, and those related to the Anglo-Boer War (1899–1902) are clear evidence of mankind's interaction with and utilisation of the Vredefort Dome and its natural resources (Figs 100 and 101).

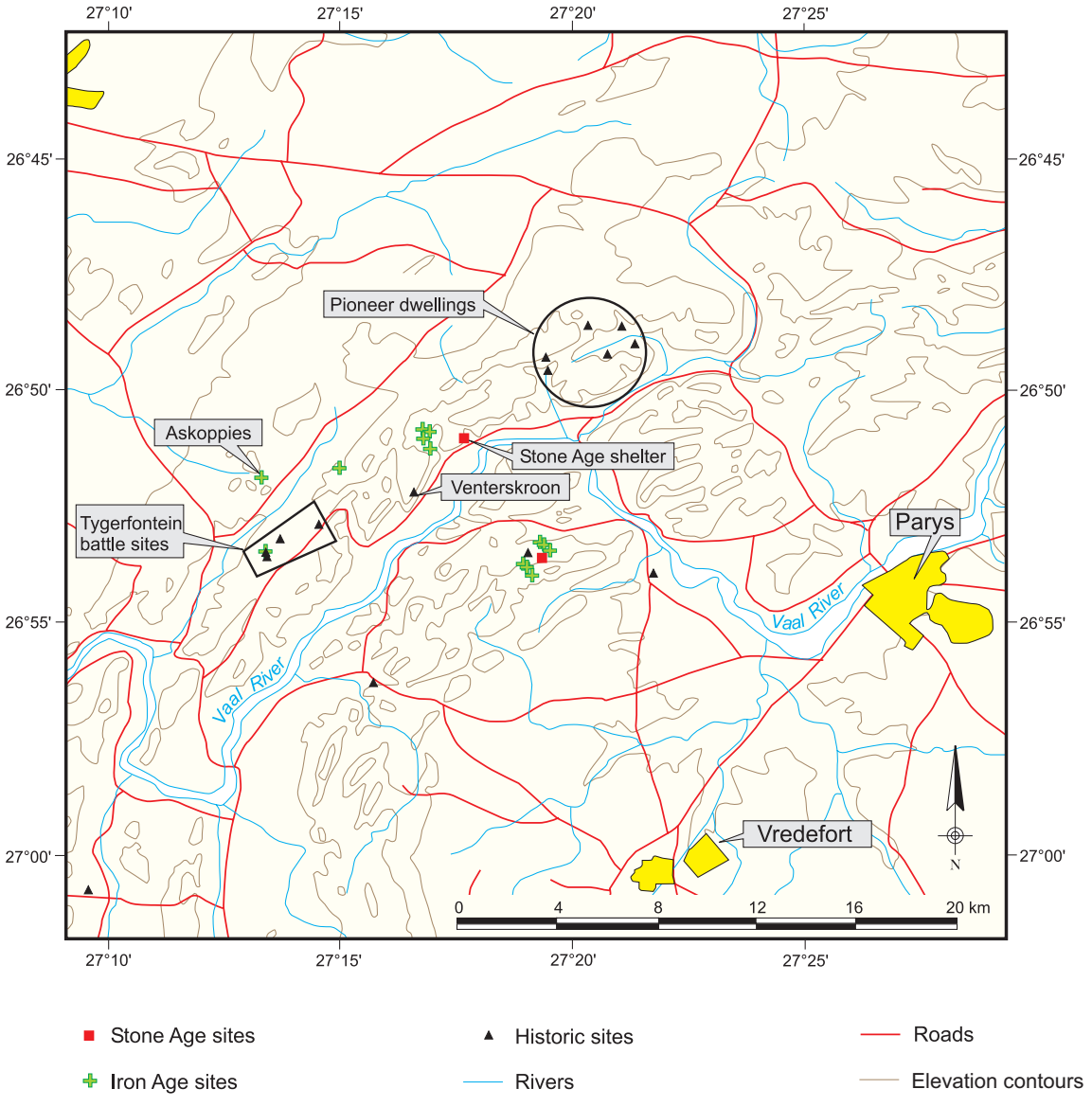


Figure 101: Map indicating locations of investigated archaeological sites in the study area.

Stone Age Vredefort Dome

The South African Stone Age is divided into three main periods, namely the Early, Middle and Later Stone Age (abbreviated ESA, MSA and LSA). Stone Age hunter-gatherer people followed a nomadic lifestyle (living for only short periods of time in one place). Caves and rock shelters were therefore seasonal, rather than permanent settlements. However, these seasonal shelters were used over and over again, for very long periods of time.

The ESA dates between 2 Ma and 200 000 years Before Present (BP). There are a number of stone-tool industries associated with it, including the Olduwan, Acheulean and Faure-smith industries. These industries were named after the places where these types of tools were first identified. The ESA is characterised by fairly crude and rather informal tools, including hammer stones, flakes and cores, and hand axes and cleavers (Fig. 102). Bone was also used and several polished long-bone fragments come

Figure 102: Typical Early Stone Age tools. Included here are hand axes and picks. The life-size hand indicates the size of the tools. Scale in centimetres.

Figure 103: Typical Middle Stone Age tools. The tools shown here include points, blades and scrapers. Scale in centimetres.

Figure 104: Typical Late Stone Age tools. They are much smaller than the products of earlier industries, and include blades, scrapers and small flake tools. Scale in centimetres.

from sites, such as Drimolen, Sterkfontein and Swartkrans, in today's Cradle of Humankind area northwest of Johannesburg.

The MSA dates roughly between 200 000 and 25 000–20 000 BP. There are various industries, such as that at Howieson's Poort, associated with the MSA, and stone-tool manufacturing techniques became more refined with a larger range of tools being produced. Typical MSA stone-tool assemblages include various kinds of scrapers, blades, points and flake tools (Fig. 103). These stone tools are generally smaller than those of the ESA. Bone tools were also used, with a few examples found at some MSA sites in South Africa.

The LSA roughly dates between 25 000–20 000 and 2 000 years BP. Although the precise transition between the MSA and LSA is sometimes difficult to discern, there are some clear differences between MSA and LSA stone-tool assemblages. The most distinctive difference between the LSA and the earlier Stone Age periods is the sometimes very small size of stone tools of the later period. Stone-tool assemblages also contain a wider range of tools, including scrapers, small blades and cores, backed knives and borers (Fig. 104). Bone tools are also more varied, and include needles, awls, points and arrow shafts. Most of the San rock paintings are also associated with the LSA.

Very little is known about the Stone Age sites in the Vredefort Dome, and most of what is known is based on scattered finds of stone tools from the area (Fig. 105). A number of cultural-resource surveys conducted here have located some Stone Age occurrences and sites. Individual stone tool and flake scatters have been identified at different locations around the dome. Most are typical of the MSA and LSA. The tools were mainly found on the gravel roads and farm tracks in the area, which are exposed to erosion and the periodic grading of the roads. The types of tools identified include flake tools, scrapers, blades, cores and core tools.

Only a few Stone Age sites have been identified during foot surveys in the Vredefort area. The first one is located on the southern side of the Schoemansdrift bridge over the Vaal River (Fig. 106) and consists of a relatively large concentration of both MSA- and LSA-type stone tools, found on the bank of the river and on

← **Figure 105:** Stone Age hand axe found along a dirt road northwest of Schoemansdrift bridge. The artefact is about 10 cm long.

↓ **Figure 106:** Stone Age site on the bank of the Vaal River, at the Schoemansdrift crossing over the river in the western collar. The arrow indicates the approximate position of the site underneath the bridge.

the gravel road next to it. The tools identified include scrapers, blades, cores, flake tools and small microlithic flakes. Although it is difficult to determine whether or not these tools are *in situ* (in the position where they were left), or whether they have been washed down by the river over time, the large number of tools found at one specific place does suggest that this might have been an area where tools were manufactured. Certainly, sufficient raw material was available close by. Animals also keep close to water sources, and this would have attracted the Stone Age hunters to the spot as well.

The second site is a small cave on the farm Buffelskloof (near the Thabela Thabeng Conference Centre outside the hamlet of Venterskroon). This is the only cave or shelter identified so far in the Vredefort Dome with any physical evidence of human occupation. The cave contains fairly extensive cultural deposits, including stone tools and bone material. The stone tools are typically MSA and/or LSA in age, and include scrapers, blades and flake tools. There are also a number of potsherds inside and outside the cave, possible evidence of overlapping deposit from the LSA and from later Iron Age inhabitants of the area. It might also indicate the use of the cave as a refuge during Iron Age times. No rock art has been identified in or near the cave.

Two sites are located on the farm Parsons Rus 465, in the northwest collar south of the Vaal River, both probably dating to between the MSA and LSA. The smaller of the two is an eroded area close to an old stream bed. It consists of a small scatter of stone tools, including some flakes, points and blades. The stone tools found here could have been washed down by the stream, and are in all probability not *in situ*. Site 2 (Fig. 107) is significant as it contains a fairly large number of stone tools, flakes, cores and hammer stones concentrated in one area. It could possibly be a stone-tool 'factory' site, located in an eroded area close to the old stream bed. A similar, albeit larger, site was recently excavated in the Loskop Dam Nature Reserve in Mpumalanga Province.

The exact age of the petroglyphs found at three sites in the dome (see Stop 8 in Part II) is not known; however, they appear to all be of Bushman origin.

Figure 107: Open-air Stone Age site on Parsons Rus. The stone tools are in a cluster around the centimetre scale (facing north).

The Iron Age

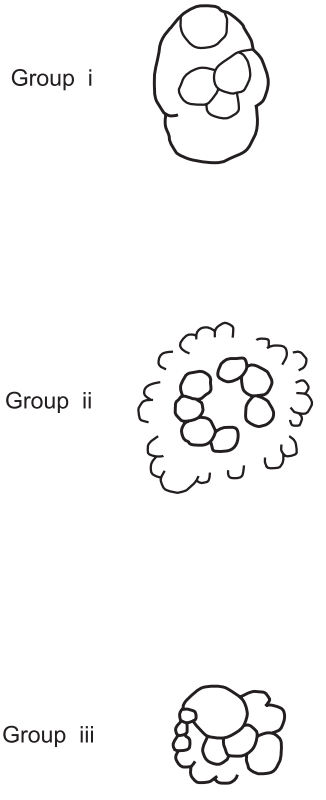
Since the early 1960s, the Iron Age, covering the last 2 000 years, has been a topic of intense archaeological research. That the Early Iron Age (EIA) involved regions south of the Limpopo River before the middle of the 1st millennium has been clearly demonstrated. Some of the earliest evidence for Iron Age settlement in South Africa is found at Klein Afrika in the Soutpansberg, Broederstroom in the Magaliesberg, and Silver Leaves near Tzaneen. No evidence for EIA settlement has been found to date in the Vredefort Dome, with all the stone-walled sites occurring in this area belonging to the Late Iron Age (LIA).

The LIA, dating from approximately 1 300 AD, covers the period when ancestors of present-day groups of Sotho-Tswana and Nguni speakers dominated the South African landscape. Over the greater part of the central plateau (the highveld) of present-day South Africa, the majority of Bantu-speaking people belong to the Sotho-Tswana language group.

Much research has been done on LIA settlement patterns and stone-walled sites. Detailed knowledge of settlement patterns is important for the understanding and reconstruction of the cultural history and earlier ways of life. Although there are many different classes and types of settlement that have been identified by researchers, they are all variations of the Central Cattle Pattern (CCP, Fig. 108). The CCP is a model for the organisation and use of space in settlements based on Adam Kuper's 1982 analysis of recent Nguni (Zulu) and Sotho-Tswana settlements.

Generally, the centre of the settlement contains cattle kraals and smaller livestock enclosures, sunken grain pits or raised granary platforms, as well as an assembly area where men met to resolve disputes and make decisions. From the recent past, a public smithing area is also sometimes found there. Men were buried in the cattle kraals. The outer residential zone is the domain of married women. This area contains individual homes, each with a front courtyard where visitors were received, and a back courtyard where the private granaries and the graves of women are located. Settlement layout is also based on status. A hut is often divided into left female and right male sides, with households arranged on both sides of the senior residence according to an alternating system of status. For

Figure 108: The Central Cattle Pattern layout of typical Late Iron Age settlements. Different types of settlement with the same underlying plan are shown (from Taylor, 1979).



example, the first wife will be located to the left or right of (next to) the head of the homestead, the second wife next to her, and so on. The location of individual settlement units around the chief is also dependent on this status principle.

The thousands of stone-walled settlements in the North West Province, in southern Gauteng and in Free State Province were built by the close ancestors of people living in South Africa today, making these sites appealing to Iron Age archaeologists. Furthermore, there are oral traditions about many of these settlements and, in some cases, they were vividly recorded by the first European travellers and missionaries (for example Campbell, 1822; Broadbent, 1865).

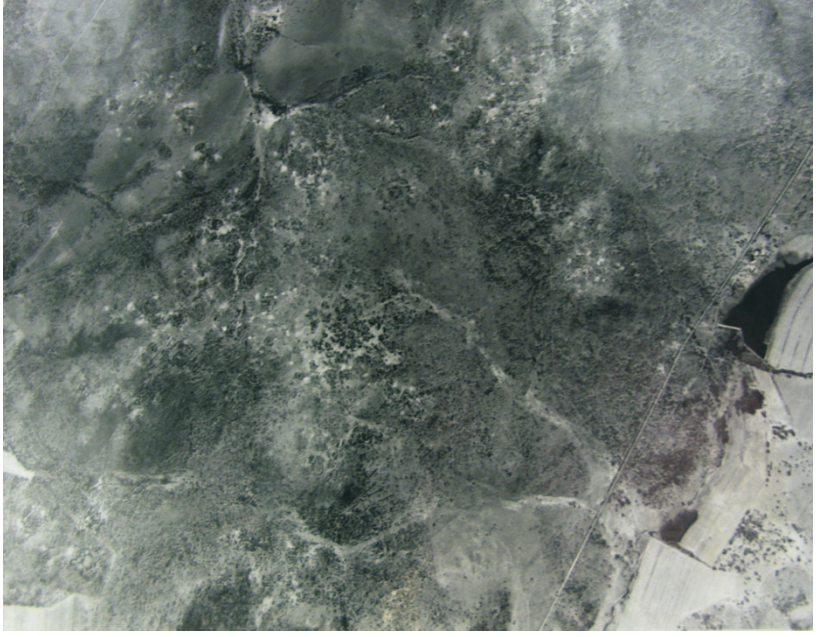
Since the late 1970s, Iron Age archaeological research has taken place on the Vredefort Dome. Tim Maggs argued that the concentration and variety of Iron Age settlements on the Vredefort Dome made it a valuable area for research, and that such research might help to explain the origins of and relationships between settlement types in southern Gauteng and the Free State. As a result, Mike Taylor started the first in-depth archaeological research on Late Iron Age settlements on the northern edge of the Vredefort Dome (in the Buffelshoek area) in 1979.

The research of Taylor and Jannie Loubser (1985) in the Buffelshoek area provided a broad understanding of the local Iron Age in terms of its cultural material and settlement organisation. Research by Maggs and Taylor also showed that several settlement types could be recognised in the dome area. According to Taylor, his so-called Group II settlements on Buffelshoek were related to Maggs' Type Z settlements in the Free State, and both were related to the so-called Rolong group. Elsewhere, Group II is associated with the Kwena people. Recent archaeological research on Askoppies in the northwest sector of the collar has strengthened the argument regarding the value of the area with regard to Iron Age research, and has contributed towards a better understanding of the Vredefort Dome Iron Age in terms of the time span of settlement, settlement organisation, domestic economy and cultural identities.

In addition to this first research, recent surveys carried out in the area identified numerous Iron Age settlements. Ten Late Iron Age sites (Figs 109 and 110), including the site at Askoppies, have been positively identified so far. Although many of the sites are stone-walled settlements, a few sites consist only of single features such as stone heaps or platforms. The features found at most of these sites include cattle kraals, ash middens (refuse dumps), huts and raised granaries (stone-built platforms), upon which woven-grass grain baskets or ceramic storage vessels were kept, and built-up agricultural terraces were found at one site. Artefacts such as pottery, bone and grinding stones were identified on nearly all of these sites. The remains of

↓ **Figure 109:** The site of a possible metal-smelting furnace on the farm Buffelskloof. Pieces of slag and furnace clay lie scattered around the area.

→ **Figure 110:** Stone walling on Askoppies. This is typical of the LIA, and similar to other sites in the Vredefort Dome.



→ **Figure 111:** An aerial photograph of the Askoppies site, with the middens clearly visible as light patches. Area shown about 1 km wide.

↑ **Figure 112:** One of the midden excavations at Askoppies. Thousands of artefacts, including pottery, metal objects, pieces of bone and shell, and utilised stone objects were found here. Also found were two burial sites.

↑ **Figure 113:** One of the huts excavated at the site. This hut clearly burnt down and its outline is well preserved as a result. An ivory bangle was found on the floor, as well as metal spears.

a possible metal-smelting furnace are located at one of the settlements on the farm Buffelskloof.

Archaeological research on the Askoppies Late Iron Age site

The Askoppies Late Iron Age settlement complex in the northwestern Vredefort Dome is one example of thousands found all over the southern highveld of South Africa. The name 'Askoppies' alludes to extensive ash heaps associated with prominent stone walling. The site is situated on the farm Tygerfontein 488 IQ. The aims of the archaeological research at the site were to determine the time span of Iron Age settlement, domestic economy (trade activities, diet, farming practices, etc.) of the settlement, the settlement layout, and the cultural identity ('who were they?') of the inhabitants. The Askoppies Late Iron Age settlement complex covers an extensive area of several square kilometres. The archaeological research concentrated on an area containing at least 20 individual settlement units. These units consist of about 8 to 15 scallop-shaped areas containing hut bays (Figs 111 and 113), in addition to circular enclosures for cattle and small stock. There are hundreds of ash middens (Fig. 112) associated with the stone-walled features, some over 30 m in diameter.

Dating of the settlement

Taylor's (1979) Group II sites date between AD 1 650 and 1 800. The radiocarbon dates obtained for Askoppies material are in agreement with this. Most dates fall between the late 1670s/early 1680s and early 1800s. It must be remembered that these dates only represent a time span

and not a specific date for settlement. A glass bead from a burial site in Askoppies' Midden 2 is similar to beads found by Jill Kinahan in the Khuiseb Delta in Namibia and dates between the 18th and mid-19th centuries. Finally, the lack of European artefacts suggests that Askoppies was abandoned by its inhabitants by the 1830s when the first European settlers arrived in the Vredefort Dome area.

Domestic economy

Domestic economy includes such aspects as agriculture, cattle herding and slaughtering practices, hide working, personal adornment, trade and metalworking.

Agriculture played an important role in the domestic economy of the settlement, and sorghum was evidently the principal crop. The lower grinders (the stones on which the grain is placed to be ground) are all relatively small with shallow grinding hollows, indicating that soft grains, such as sorghum, were used. On average, there are at least two private granaries (platforms for the grain-storage vessels) behind each house, and seven raised communal grain-bin stands in each settlement unit. The number and the size of the granaries attest to the success of agriculture. The lack of evidence for the presence of maize is significant. It might mean that the area was too dry for maize production, or that maize had not reached this far west by that time.

The functions of many of the ceramic vessels were associated with agriculture. These included cooking and preparation of food, storage of water, beer, cereals and other foodstuffs, and for eating and drinking purposes. Some of the vessels are small and coarsely made, similar to vessels found and described by Maggs from Free State sites. These might have been model or toy vessels made by children from leftover clay. Application for ritual functions, or for use in the preparation of medicines, is also possible. A number of small vessels contained ochre and haematite (Fe_2O_3) residues, and might have been used for storing these colouring agents. Once broken, some fragments were used for smoothing the surface of pots, working skins, or as milk strainers.

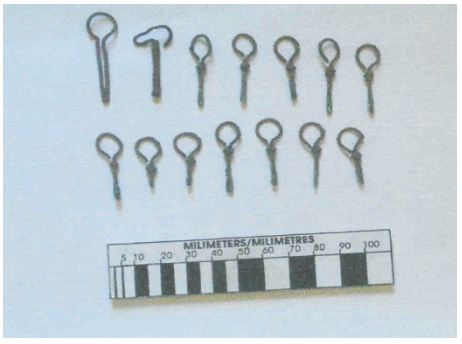
The settlement plan at Askoppies reflects a society that preferred cattle as the main source of bride wealth; cattle were also used as a trade item to obtain wives. Therefore, cattle were the main form of wealth, and essential to normal life. Some clay-oxen figurines (Fig. 114) found at Askoppies have features typical of the so-called Sanga and Afrikaner cattle. These cattle brands are short horned and short legged, and have large humps on their backs.

Although they were the main source of wealth, cattle were also used for food. Their importance, however, is also shown by the fact that most animals were either adult or old by the time they were butchered. The scientific analysis of animal bone found during the excavations also showed that in addition to cattle, sheep, goat, chicken, steenbok, springbok, blesbok and zebra were also consumed. Around 50 % of all slaughtered animals were non-domestic (wild), with sheep and goat contributing the other half of the domestic-meat sample. Other meat sources included springhare and scrubhare, tortoise and guineafowl. Riverine food sources included barbel and other fish, crab and freshwater mussel, and land snails may have supplemented the diet. These remains show that the diet was rich in meat. Thus hunting, fishing and gathering also played a part, in addition to herding.

A fairly large number of bone and stone tools are evidence of hide working. The tools include bone scrapers, needles and awls, and stone scrapers. The stone scrapers have an Iron Age origin and came from both hut and midden excavations, although the midden samples were more numerous. There are also some edge-abraded potsherds that could have been used for hide working. The remains of aardwolf, cheetah and leopard in the samples are a further indication of hide or skin working. These animals were probably hunted or snared for their skins, rather than for their meat. Hides were

Figure 114: Clay oxen and other figurines found during excavations at Askoppies. Scale in millimetres.

← **Figure 115:** Bone pendants recovered from one of the midden excavations at Askoppies. They were used for personal adornment and worn around the neck. Scale in millimetres.



← **Figure 116:** Copper earrings from the Askoppies excavations. Three types were recovered, and came from a burial and hut floors on the site. Scale in millimetres.

also used as trade items, especially those of the cheetah and leopard. The aardwolf, however, is a burrowing animal, and it might have ended up in the midden in this fashion.

Although ivory was used for trade, its main use was for producing artefacts for personal adornment, such as bangles. Ivory bangles indicated the status of the wearer as well. Two hut excavations produced ivory bangles, and a hippo tusk came from the floor of another. Other artefacts indicating personal adornment are a glass bead, cowry shells, bone pendants (Fig. 115) and copper earrings (Fig. 116) found in some of the excavations. The treatment of the cowry shells, by cutting sections away, shows that they were attached to clothing, as personal adornment, or used for decoration on objects such as baskets. The cowry shells and glass beads were also used in trade activities and indicate links with the East Coast of Africa.

In total, sixteen copper earrings were recovered, one from a burial in an ash heap, one from a hut, and fourteen from another hut in the chief's settlement unit. Evidence from the Madikwe Game Reserve, approximately 250 km to the north, indicates that Sotho-Tswana people smelted copper in the back courtyard. No copper furnaces have been found at Askoppies, but a fragment of a whetstone (a stone used for the sharpening of spears and working and shaping of metal objects) from the floor of the hut in the chief's area, found with the 14 copper earrings and some hammer stones, suggests that copper was worked here.

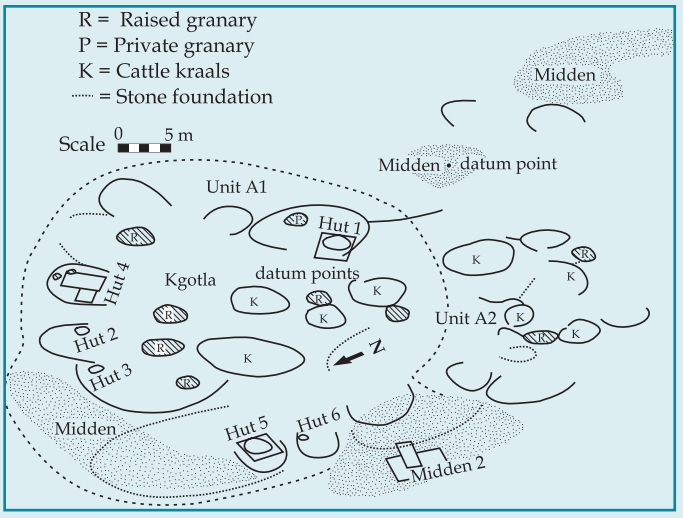
As a rule, iron smelting was performed outside and smithing inside the residential area. The smithing unit (rock anvil) inside the chief's area at Askoppies conforms to this. The iron remains show that hoes, adzes and spears were produced at the settlement. Fragments of clay blowpipes (tuyeres) and metal slag also indicate that metal was worked on site.

The settlement layout

The main characteristics of Askoppies are the extensive stone walling and middens. Some middens are so massive that they appear on aerial photographs (Fig. 111). Askoppies consists of a number of individual settlement units (Fig. 117) that together form the larger settlement complex, an extensive area covering a few square kilometres.

Askoppies is related to Taylor's Group II sites, which consist of a 'discontinuous series of semicircular walls (instead of a clear perimeter wall) facing inward towards a central ring of smaller enclosures'. More specifically, the Askoppies settlement layout seems to be related to Group IIb, with discontinuous boundary walls made up of scallops containing huts. Each scallop is separated from its neighbour by an open gateway at both ends of the scallop.

It is also known that the settlement layout at Askoppies follows the Central Cattle Pattern. To help determine a settlement plan, two individual settlement units were mapped and drawn. Settlement Unit A comprises about 15 semicircular stone scallops that contain individual households and form the outer boundary of this particular homestead. This part was the domain of married women and contains sleeping huts, kitchens and private granaries. The burnt remains of clay, or daga, structures, evidence of huts (Fig. 113), were identified in a number of the stone scallops. Most are located in and to the side of the stone walls, in contrast to other settlements, for example Kaditswene and Olifantspoort in the North West Province, where huts are located in the centre of the scallops. Both are typical Type IIa settlements and,



← **Figure 117:** The settlement layout at Askoppies. Note the cattle kraal in the centre, surrounded by huts; hence the term Central Cattle Pattern.

with Askoppies a Type IIb, the location of huts might indicate a further difference between the two types.

The large open area in front of the largest stone scallop was probably the men's meeting area. This hut more than likely belonged to the head of the homestead, and the location of the kgotla (meeting place) here would make sense. It is also situated close to the main concentration of central cattle enclosures, the domain of the men. The smaller enclosures would probably have been used for calves, while sheep and goats were possibly kept there as well. Settlement Unit A has eight of these enclosures.

Four large communal middens are associated with Unit A (Fig. 117). Two are located on its western side, with the other two to the east. Smaller, private middens were not identified. Numerous granaries are present and small private grain-bin stands were located in the back courtyards of three of the households. Seven raised communal granaries are present, many of which are solid stone constructions. They were raised to keep cattle and other livestock from reaching the grain. Communal granaries are in the centre of the settlement, sometimes attached to cattle enclosures.

Settlement Unit A can be divided roughly into two sections, A1 and A2. Unit A1 is the main section, with A2 a smaller, individual unit that was added later. This addition, together with the foundations of older scallops, is evidence of shifts within the settlement, with the population numbers increasing and/or new groups moving into the settlement.

Settlement Unit B is located northeast of Unit A. Seven individual hut bays form the outer residential zone. The burnt remains of daga structures were identified in some of these scallops. One of these was eventually excavated. Huts were located in and to the side of the stone scallops. There are seven cattle enclosures in this unit, with the five largest enclosures clustered together. An open area to the north, and between the homestead and main cluster of cattle kraals, probably served as the kgotla. Large communal middens occur to the east and west of the residential zone, respectively. There are two raised communal granaries, one inside the settlement unit and the other attached to the cluster of cattle enclosures. Figure 117 shows an artist's impression of the settlement layout at Askoppies (compare with Figure 118).

Determining cultural identity

Pottery from Askoppies (Fig. 119) shares decoration characteristics with samples from two types of sites in the Free State Province that were termed Type V and Type Z by Maggs. At Askoppies, rim notching, alone or in combination with incisions and finger or

pinched impressions, is common, while comb stamping with ochre bands or ochre areas is also present. This is similar to decorated pottery from Makgwareng, a Type V site. Type V shapes include subspherical and spherical pots and bowls with short upright rims, as well as large bag-shaped and U-shaped pots. The vessels from Askoppies are much more similar to those from Type Z sites, which include mainly spherical pots with short upright necks, or necks that are slightly at an angle, and open or subspherical bowls. Some decorations from Type Z sites also occur on Askoppies pottery, such as parallel horizontal rows of stylus impressions and ochre burnish. Decorated pottery from Taylor's Buffelshoek site is the same as that found at Askoppies.

Who then were the inhabitants of Askoppies? Taylor's Group II settlements are related to Maggs' Type Z, and Group II/Type Z are related to the Rolong people's settlement type. Taylor's Group II encompasses two groups. Group IIb is related to the southwestern Sotho-Tswana, and it is clear that the Askoppies settlement plan belongs to IIb. Group IIb settlements on the Vredefort Dome should be related to the Rolong people. Based on ethnographic and historical records, Maggs argues that Type Z is closely related to the Rolong and Thlaping people, and that the area of Rolong settlement just north of the Vaal River is contiguous with Type Z distribution.

On the basis of the settlement plan and pottery, the original occupants of Askoppies were most likely the Rolong people, or at the least a group that was part of the southwestern Sotho-Tswana. However, the impact of the *difaqane*, or period of upheaval, stretching from the 1820s to the 1830s, should not be disregarded (see Chapter 5, Section 2: History). In order to protect themselves from Mzilikazi's marauders, many different groups aggregated into larger communities, and it must be assumed that intense interaction took place. One specific group, therefore, might not have been solely responsible for the ceramic assemblage at Askoppies.

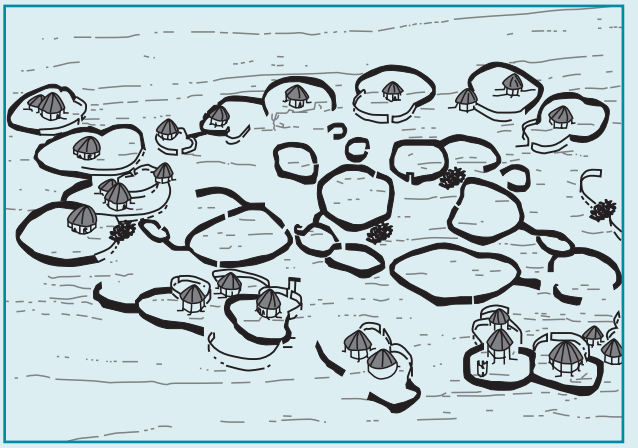


Figure 118: An artist's reconstruction of the Late Iron Age settlement of Platberg (from Mason, 1986). Note the cattle kraals in the centre with the huts surrounding it. The layout is similar to that of Askoppies (Fig. 117).

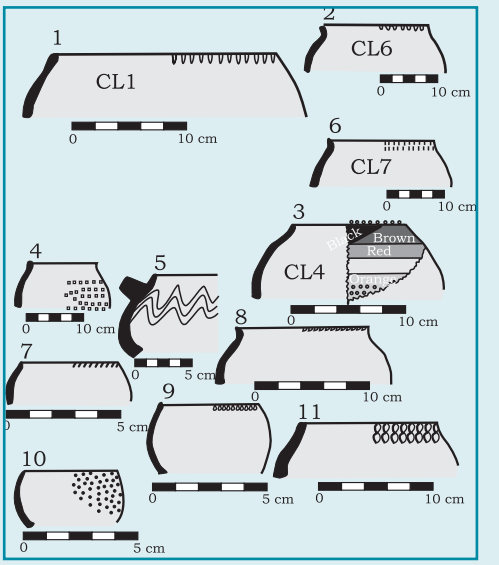


Figure 119: Drawings of pottery found during excavations at Askoppies. The decorated pottery helps in determining a date for the settlement, as well as the identity of its occupants.

Archaeology of the historical period on the dome

The Vredefort Dome's rich recent past stretches back to the mid-19th Century, and remains dating to this period are of both historical and archaeological importance. However, no in-depth historical-archaeological research has yet been carried out here. The only work done in this regard includes some surveys by archaeologists of the National Cultural History Museum in Pretoria. During these surveys, more than 20 historical sites have been identified and recorded.

Historical sites identified in the Vredefort Dome area include blockhouses and camp sites dating to the Anglo-Boer War (1899–1902), old pioneer houses (mid-19th Century), so-called *bywonershuisies* (dwellings of 'share-croppers') (early 20th Century), gold-mining sites (late 19th to mid-20th centuries), farm-labourers' houses, farmsteads (late 19th to mid-20th centuries), and cemeteries.

Anglo-Boer War

Five sites dating to the Anglo-Boer War (1899–1902) have been identified so far, although there should be many more. All five are related to the time of the Battle of Tygerfontein and directly thereafter. This battle was fought on the 6th and 7th of August 1900 between British forces, under Lord Methuen, and the Boer commando of General C.R. de Wet (see pages 189–195).

The first site related to the Anglo-Boer War involves the remains of a British blockhouse, probably erected soon after the Battle of Tygerfontein, to cover the road between Potchefstroom and Venterskroon. The site consists of the round-shaped remains of a stone structure, possibly the base for a prefabricated corrugated-iron structure. Two other sites on the farm Tygerfontein, near the Suikerbosrand holiday resort, are represented by a number of British and/or Boer stone redoubts or gun emplacements. A stone flake that could have been a gun flint was recovered from one of these redoubts. The fourth Anglo-Boer War site is the location of the Elswick Battery cannon emplacement on Suikerbosrand. The unit's name is engraved on a rock near the stone wall of the emplacement (Fig. 120).

↑ **Figure 120:** Site of the Elswick Battery cannon emplacement on Tygerfontein. This unit fought at the Battle of Tygerfontein and was stationed here afterwards.

Archaeologically, the last site is probably the most important. This is the possible camp site of the British, used after the Battle of Tygerfontein. Besides some low stone walling, there are also a number of ash middens here that could be investigated by means of archaeological excavation. The site is also located near the Suikerbosrand resort.

Pioneer dwellings

Three of these sites were recorded, although, according to local inhabitants, there are many more in the Vredefort Dome area. All three are located on the farm Koedoesfontein and date from the late 1840s to 1850s, when the first European farmers moved into the area. These dwellings are stone and mud-brick constructions (Fig. 121), one or two of which are fairly well preserved. At the first site, a stone-built pigsty was identified, while an old gold-mining shaft, dating to the late 1880s, is also located close by. The second site, in Koedoeskloof, also has some other unidentified outbuildings besides the main house, as well as a possible grave. The last of these sites, next to the Kleinspruit stream, is one of the best preserved of these houses. It has quite a large pigsty and a cattle kraal, as well as a water well, indicative of the relative affluence of the inhabitants.

Bywoners' dwellings

The term '*bywoners*' refers to poor people, mainly Afrikaners but also Black people, who

↑ **Figure 121:** Ruins of one of the pioneer houses on Koedoesfontein. These houses were mainly built of stone and mud brick, and had one or two rooms.

↑ **Figure 122:** Ruins of a bywoner's house on Koedoesfontein. The bywoners' dwellings date mainly to the period directly after the Anglo-Boer War and the Great Depression of the 1930s.

were landless and in the employ of landowners. A rough translation is subfarmers, squatters or sharecroppers. They often lived and worked on farms belonging to relatives, had no fixed rights, and had to share what they produced with the landowner. Although this practice started before the Anglo-Boer War, it became more common after the war and during the Great Depression of the 1930s.

Two such sites (Fig. 122) have been recorded in the Vredefort Dome area, both on Koedoesfontein. The first bywoner's house belonged to the Jackson family and dates to the 1910s. They apparently lived here until the 1960s. The house is very well preserved and was constructed of stone and clay brick. There is also a stone-walled cattle kraal near the house. The second site, similar to the other but smaller and less well preserved, also dates to within the first two decades of the previous century; it is situated in Kastaiingskloof.

Farmsteads and farm-labourers' houses

Although only six of these sites were recorded, many more are known to exist. The problem is that most are inaccessible, being fenced in and located on private property. These sites should, however, be fully documented during future surveys.

The first site (Fig. 123), located on Koedoesfontein, is a farm-labourer's house. Although the exact age is unknown, it could be older than 60 years. It is a stone and clay-brick construction with clay-plastered walls. The walls are decorated with typical Sotho patterns on the outside, as well as on the bedroom walls inside. A stone-walled pigsty and an ash midden are also associated with the structure. The farmstead on the farm Sweethome is fairly well preserved, and was constructed of clay brick. The walls are plastered, and the house had wooden window and door frames. On the front veranda are two columns, and the remains of a number of outbuildings are associated with the farmstead. The remains of an old farmstead, similar to others recorded, were also identified next to the S959 dirt road. The ages of none of these sites are

← **Figure 123:** Ruins of a farm-labourer's house on Koedoesfontein.

known, but could date to the late 19th and mid-20th centuries.

The three sites on Parsons Rus are quite extensive and well preserved. The first is the most extensive and consists of the ruins of two homesteads, constructed of clay, mud-brick and stone, each with two to three rooms. Other features found on the site include a pigsty and a few graves of unknown people. These were probably farm-labourers' houses, related to the existing farmhouse situated not far from there. It is difficult to determine the age of these structures, but it is possible that it could also date between the late 19th and mid-20th centuries.

A second site, also a possible farm-labourer's house and not far from the first one, consists of a similarly constructed rectangular structure with two rooms. Other features include a number of unidentified circular stone structures, a large grinding stone on a platform, and a grave. The third site on Parsons Rus could be one of the most important historical sites on the farm. It consists of the foundations of a rectangular structure, built with red clay brick and stone. At least four rooms are visible, while pieces of glass, porcelain and metal also indicate the existence of a house. The decorations on some of the pieces are similar to late 19th Century ceramics found at other historical sites. It is quite possible that these are the remains of the first farmstead on the farm, demolished when the existing house was built in the late 1930s/early 1940s.

Gold-mining sites

Archaeologically and historically, these sites are some of the more important, and visible, ones in the Vredefort Dome area. Besides the ones recorded, there are many other gold-prospecting and/or gold-mining sites in the dome area.

The first two sites are both located on the farm Tygerfontein, near Venterskroon. Features of these sites are prospecting holes and trenches, dating to the late 19th Century gold mining that took place in the dome area and specifically near Venterskroon. Sections of exposed gold-bearing reef are visible throughout the area where the sites are found. It is these reefs that attracted the miners to the area in the late 1800s. The next site is that of the Rooderand Goldfield near Venterskroon (Fig. 124). This goldfield was proclaimed on 11 June 1887, but mining activity in the area did not last long and development ceased within a short period of time. The site contains a number of features spread over a fairly extensive area. They include prospecting holes and trenches, old mine dumps, mine tunnels, refuse middens, and the remains of various structures, probably living quarters and other buildings associated with the gold-mining period.

Figure 124: A site near Thabela Thabeng relating to the Rooderand Goldfield period. The recorded sites include the remains of miners' houses and other mining-related structures.

Figure 125: Workers developing a mining trench in a gold-bearing reef in the late 1890s (historical photograph).

The last site associated with the gold-mining period in the dome is the small historic town of Venterskroon. The site contains the old mining commissioner's house (dating to 1889), the Old Imperial Inn, the schoolmaster's house, a stable, police station and jail, as well as other buildings. The site is currently used by the Dome Hiking Trails Company as a base camp.

Cemeteries

A cemetery (Fig. 126) on the farm Rensburgs Drift 432 contains 28 graves, of which 15 are without any headstones. Of the identified graves, nine are of the Janse van Rensburg family, one each De Beer and Fourie, and two Badenhorst. The youngest date of death is 1970 and the oldest 1910. The others date between the late 1920s and 1940s. An Anglo-Boer War cemetery and concentration camp memorial (Fig. 141) occur near Koppies in the southeastern part of the dome. There are undoubtedly many more graveyards and unknown graves in the Vredefort Dome area that need to be identified and recorded.

↑ **Figure 126:** The cemetery on the farm Rensburgs Drift. This is the only cemetery recorded so far on the dome, although there are many more.

Other historical sites

The last site with a historical-archaeological link represents the remains of a possible refuse midden. It was identified in the parking area of the Thabela Thabeng Conference Centre on Buffelskloof. The site is characterised by a fairly large amount of decorated and undecorated pieces of ceramics, similar to those found on other late 19th Century sites in Pretoria and Krugersdorp, as well as glass fragments and metal objects.

Concluding remarks

The presence of mankind in, and man's interaction with, the Vredefort Dome stretches back thousands — and maybe even tens of thousands — of years. The many stone tools and Stone Age sites, Late Iron Age settlements, the ruins of later European settlement, late 19th and early 20th Century gold mining and Anglo-Boer War remains found in the area are ample evidence for this. Although some detailed archaeological work, specifically on the Iron Age, has been conducted, such as that by Taylor at Buffelshoek and by Pelser at Askoppies, most of what we know is based on information obtained through surveys done in the area on foot. Based on this information, human activity in the dome area may date back beyond 200 000 years ago.

In order to correctly interpret and reconstruct the prehistory and history of the Vredefort Dome in more detail, further in-depth research is needed. This research would include surveys to locate, identify, interpret and document all sites, features and objects of cultural importance in the area. Archaeological excavations on some of the more important sites should also be considered. Further archival and literary research still needs to be carried out. This is especially true for the historical period, and will complement any archaeological work conducted on historical sites in the area. The recording of oral histories is also important, and could play a substantial role in the interpretation and understanding of many of the sites and features found on the Vredefort Dome.

Future archaeological investigations in the dome region should focus on a number of different aspects regarding the prehistory of the area. A main focus area should be the Stone Age, concentrating on determining a more exact time frame for Stone Age activity in the region, as well as the nature of the activity. In Iron Age research, aspects such as trade links and metalworking need to be looked at, while early European settlement and late 19th Century gold mining will also be priorities.

SECTION 2

Beyond the frontier history of the Vredefort Dome area

Mauritz Naudé

The landscape of the Vredefort Dome with its hills, ridges, water sources, vegetation and possibilities for shelter set the scene for a long history of settlement by humans, of which the last phase was introduced when white adventurers, cattle farmers and settlers came to the region in the 19th Century.

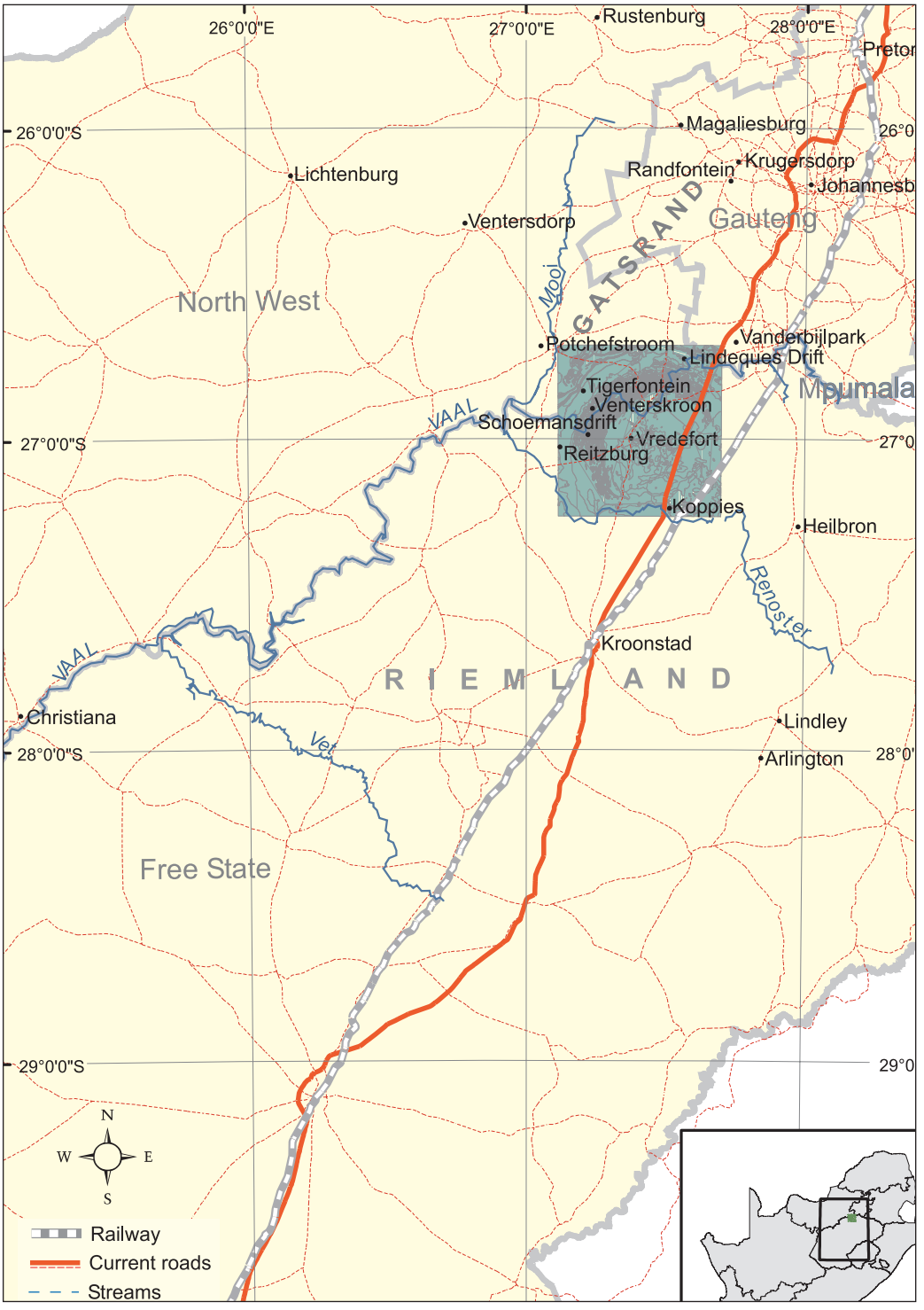
Two events dominated the 19th Century history north of the Vaal River: the *difaqane* (destruction of indigenous political systems) and the Great Trek (Afrikaans: Groot Trek, meaning 'Great Journey') of the Voortrekkers. The difaqane is associated with the migration of Nguni-speaking people (later known as the Matabele), under their leader Mzilikazi, into the interior of central-southern Africa, resulting in turmoil in the power structures of indigenous peoples in the region. The Great Trek was a migration of white farmers from the Cape Colony, resulting in the introduction of a foreign political structure and new land-management systems.

In 1824, Mzilikazi, an exceptional warrior under Zulu king Shaka, fled across the Drakensberg from Natal, with approximately 20 000 followers. They settled near the area where Pretoria was later founded. Fearing Shaka's successor, Dingane, Mzilikazi moved farther north in 1832 and established two strongholds along the Marico River: Mosega and Kapain.

Even earlier, at the beginning of the 19th Century, the northern part of what later became the Orange Free State was home to San (Bushmen) hunter groups and the Leghoya, a Bantu-speaking group from the northern parts of Africa. The peaceful coexistence of these groups came to an end with the difaqane, and the remaining population was pestered by attacks by Matabele from the north and by Griquas and Korannas from the south. Remnants of settlements from this time have been discussed in the section on Iron Age history. A branch of the Kwena group settled around 1823 on an isolated hill, later known as Kokosi (today known as 'Losberg', near Fochville north of the Vredefort Dome), in the southern areas of the Gatsrand, the region around the town of Potchefstroom to the northwest of the Vredefort Dome (Fig. 127). These people were scattered throughout the Free State and Lesotho regions as a result of the conflict between them and the Matabele.

The history of white settlement in this area followed the same pattern as elsewhere along the Vaal River. This era began with the advent of the Voortrekkers, the first white settlers to move into the region from their original settlement areas in the Cape Colony. Their 'migration' history started when frontier farmers, settled along the outskirts of 'civilisation' in the Cape Colony, penetrated deep into the interior of southern Africa in search of better grazing, and during hunting expeditions. The most impressive of these migrations became known as the Great Trek (1836), when scores of white families left their farms in the Cape Colony in a quest for independence from British rule, to look for better pastures and to establish new farms. These migrants ('Trekkers') became the first settlers, each living on their own large farm. Their economy was based on subsistence farming, and hunting was another important economic factor as game was plentiful at the time.

One of the leaders of the Great Trek, Andries Hendrik Potgieter, and his party reached the Vet River (Fig. 127) in 1836. They encountered the remains of the Bataung clan under their chief Makwana, who asked Potgieter to protect them against Mzilikazi and his Matabele bands. The parties agreed to a treaty, whereby Makwana was protected against the Matabele, and Potgieter and his people became the owners of the land between the Vet and Vaal rivers. The treaty also included an exchange of



† **Figure 127:** Map indicating the location of the Vredefort Dome in relation to various towns, rivers, and connecting routes discussed in this section.

cattle. While Potgieter was away to inspect the country farther north, his party split up, with several families scattering across the landscape. The family of Barend Liebenberg, who had even crossed the Vaal River, camped at a site almost across the river from the present-day town of Parys (the current farm Rietpoort 518 IQ). They were attacked by the Matabele, and almost all of them were killed; three Liebenberg children were kidnapped.

Upon Potgieter's return, he discovered that Mzilikazi's impis had murdered forty people. Several expeditions were sent out to avenge these attacks, and Mzilikazi and his people were forced to flee across the Limpopo River to what is now Zimbabwe, where he founded his new capital Bulawayo.

As a sign of goodwill, Potgieter rewarded the Barolong people for their assistance in the battles against the Matabele by allowing them to return to the far-western Transvaal (now part of western North West Province). Chiefs Machavie, Tawana and Gontse, and their followers settled at Machaviestad, about 24 km west of Potchefstroom, in 1841. Here they remained until 1971, when the descendants of the clan were forcefully relocated to Rooigrond in the former homeland of Bophuthatswana.

Even prior to crossing the Vaal River permanently, Potgieter and his party realised the potential of the area through which the Mooi River flows. They first settled at a site that later became known as 'Oude Dorp', but soon after settled at Potchefstroom (in 1841), where they constructed the first water furrow. In March of the same year, the first major church service was held and 188 children were baptised on the occasion. All the earliest farms were described in the farm register at the time as being next to the Mooi River ("aan Mooijrivier"). Potgieter left Potchefstroom between 1844 and 1845, but the loss was neutralised by a large contingent of people from Natal who settled in the area at about the same time.

In the beginning the District of Potchefstroom was enormous. It included the entire territory north of the Vaal River, as far as the Soutpansberg, just south of the present northern border of South Africa with Zimbabwe. The western boundary of the Potchefstroom District was the edge of the Kalahari desert, and eastward it extended as far as Rhenosterpoort. Several communities were established in the District of Potchefstroom, but not in the area now defined as the Vredefort Dome.

The geographic setting

The Vredefort impact structure covers a vast, approximately 250 km wide area. No comprehensive cultural and historical research has been done on settlement and the development of the region. The only information available covers some smaller cultural regions within the dome area, including the settlement history of the towns of Vredefort, Parys and Potchefstroom, or historical events in the larger region of the northern Free State and southern Transvaal (now southern Gauteng Province). The reason for this is that the Vredefort Dome was not a well defined or judicially demarcated district, or a unique cultural region; at the same time, however, it indicates that the area was not an isolated cultural region, but part of the larger cultural landscape. Although there are no defined boundaries for them, two cultural regions are closely associated with the Vredefort Dome area: the 'Riemland' and 'Gatsrand'. The Riemland is located to the south of the dome, in the northern Free State Province, and the Gatsrand on the northern side of the dome (Fig. 127).

In the past, prior to white settlement, the Riemland region boasted large numbers of game, and Bushmen hunting clans roamed the grassland flats and ridges. During the early years of white settlement, hunting was the principal industry, and the name Riemland relates to the large quantities of hides and thongs (Afrikaans: rieme) that were produced and 'exported' to other towns.

The Riemland is usually associated with undulating grassland, and includes the towns of Bethlehem, Reitz, Lindley, Petrus Steyn, Frankfort, Senekal and Heilbron. The dome area did fall within the economic and cultural impact zone of the Riemland. The first written evidence of the term appears in the Free State Monthly magazine of 1878, which referred to the area through which Voortrekker Piet Retief moved on his way to Natal as "… one half lying among the ranges of the Wittebergen and the other in the open country of the Riemland". The most-

significant rivers cutting through the region are the Vaal and Rhenoster rivers.

Game such as wildebeest, blesbok, quagga, tsessebe, springbok and ostrich, which once roamed the open grassland, are gone now, extensively exploited by both the indigenous peoples and, in particular, by the Voortrekkers. After the annexation of Natal (today KwaZulu-Natal) by the British, the Voortrekkers moved to the dome area and environs where they relied on the abundance of game, and not commercial farming, for household subsistence needs and as a readily available economic resource with which to trade and barter. The size of the 'industry' is indicated by a report of 1866: one company in Kroonstad exported 152 000 blesbok and hartebeest hides. Over a period of two years, 485 780 hides were exported through the harbour of Port Natal (today, Durban).

Because of the frontier existence of these white settlers, they were often regarded as unsophisticated and of lower social class than their town-dwelling contemporaries. They were referred to as 'backvelders' (Afrikaans: bekvelders) or as 'plattelanders' or 'veldskoendraers', meaning 'from the country' and 'wearing home-made shoes', respectively, and eventually they were nicknamed 'Riemlanders'. The name also appeared in popular literature, such as the 1943 novel of Sannie Steyn called 'Riemlandse Nooientjie' ('Girl of the Riemland'), in which the author set the key figure in the story against this region. The term was also used as a place name. A halt, bearing the name Riemland, is located 43 km northeast of Lindley on the railway from Arlington to Heilbron (Fig. 127).

The other cultural region more closely associated with the Vredefort Dome is the 'Gatsrand'. According to Van Eeden (1988), "The Gatsrand [as a series of ridges] is not only a well-known geographical feature in the western Transvaal, but also features prominently as a definite area in the settlement history of the whites in the Transvaal". The first farms in this area were registered simultaneously with farms in the adjacent Mooi River area. The earliest farm registers indicate that the first Voortrekkers arrived in the Gatsrand area in 1839. According to these registers it is clear that the farmers used the term 'Gatsrand' to indicate the relative location of their farms. With Dutch a common language at the time, the area was referred to as "Gat zijn rand" ('rim of the hole'). The descriptions of the location of these farms were expressed in several ways: "Gelegen aan gat zijn rand" ('located near the rim of a hole'), "Gelegen aan gat zijn kant" ('located next to the hole'), "Gelegen aan den gat zijn rand annex de plaats Boshoek" ('located at the rim of the hole next to the farm Boshoek') and "Gelegen aan de zuid zijde van de gat" ('located along the southern side of the hole'). The name did not refer to the ridges in the area but to the location of individual farms in relation to a big hole or in the vicinity of a hole.

Today the name Gatsrand refers to an area defined by a range of hills on a plateau at 1 200 to 1 500 m altitude, extending from close to Potchefstroom for approximately 120 km in a northeasterly direction, to the area southwest of Johannesburg, where it merges with the hills of the Witwatersrand. The region owes its name to the numerous sinkholes and caves in the foothills of the plateau, in the carbonate rocks of the Pretoria Group. An abundance of underground water is found in the dolomite formations and may be found by drilling or may gush from a so-called ‘eye’ (Afrikaans ‘oog’, a spring), such as the Wonderfontein oog or the Mooi River oog. This latter ‘oog’ feeds the Mooi River that runs through the town of Potchefstroom.

Initially, the Potchefstroom market was the nearest outlet for products. Later, products were also sold in Johannesburg, Randfontein and Krugersdorp (Fig. 127). The Gatsrand was a ward or 'wyk' in the Potchefstroom District consisting mainly of farms, with Potchefstroom the main town and urban support centre for these early farmers.

Prior to the establishment of large, formalised gold mines (since 1937) in the northern areas of the Gatsrand, development in this region was mainly dependent on the subsistence needs of the surrounding towns. In this respect, the building of roads from the southwest to places like Krugersdorp, Randfontein, Pretoria and Johannesburg was beneficial to the Gatsrand, as all the routes passed through this area. Administrative duties were first performed by a field cornet and later by a justice of the peace, who was subordinate to the magistrate of Potchefstroom.

In a similar fashion, education matters were handled by the Potchefstroom School Board. Until 1948, with the exception of the Klipdrift School at Potchefstroom, there were only primary schools on several farms in the area that had from one to four teachers. Medical services in Potchefstroom rendered assistance to the Gatsrand community. Initially the nearest place for worship was also in Potchefstroom. The first congregation in the Gatsrand was founded in 1926 at Fochville. Since 1937, with the development of the first significant gold mine at Kromdraai, economic development has steadily increased. By 1948 it was apparent that the development in the Gatsrand would be phenomenal because of rich gold-ore discoveries.

Between 1841 and 1896 there were only 20 farms in the Gatsrand area. The farm Buffelshoek (471 IQ) was the first to be registered in 1841. According to Article 7 of the Constitution of the Zuid-Afrikaansche Republic (1858), farms could not be larger than 3 000 morgen (2 569.59 hectares). Every farmer was allowed two farms, one for cultivation and the other for keeping stock and cattle. This resulted in a low density of people. The most-important farming activity was cattle farming, although stock was also kept. Cultivation of crops was the exception and only practised for subsistence purposes.

The systematic subdivision of the once large farms in the Gatsrand indicated how the land-use pattern changed. The original 20 farms recorded in 1896 were subdivided to such an extent that in 1910 there were 70 farms, each with its own deed. Another 263 units were established between 1911 and 1940, bringing the total number of farms in the Gatsrand area to 333. By 1945 the figure was 450 and by 1983, after the consolidation of some of the farms, the figure was 447.

Development of towns

Several towns are significant, as they are either located within the central dome area or along the periphery of the dome. Vredefort and Parys are both located on the northern periphery of the 'Riemland', while the other main urban centre is Potchefstroom, located in the 'Gatsrand' region.

The town of Vredefort is located approximately 15 km southwest of Parys and 76 km northeast of Kroonstad (Fig. 127). Some authors (for example Raper, 1987) believe that the origin of the name is unknown, whereas others tell the following history.

As the farmers of the area had to travel long distances to Kroonstad and Potchefstroom for Holy Communion (Dutch or Afrikaans 'Nagmaal'), they had been debating and canvassing for a place nearer to their farms to congregate for this purpose. When the decision was taken to establish a settlement with a church in their vicinity, they agreed to use the name 'Vredefort', meaning 'place of peace' ('vrede'), signifying that the farming community was at peace at long last. Another author (Bulpin, 2001) is of the opinion that the name originated from a farm name during the period when the presidency of the Transvaal Republic was in dispute. A commando, under Marthinus Wessel Pretorius that had invaded the Orange Free State was halted at Laerplaas on 19 May 1857. Negotiations took place and everybody returned home in peace ('vrede'), without any casualties.

Some authors are of the opinion that the town was laid out on the farm Vischgat in 1876, but only proclaimed a town in 1881. Others indicate that the town was laid out on the farm Vredefort. Vredefort became a staging post along the important north–south road and soon expanded into a booming agricultural centre, especially after the discovery of gold on the farm Weltevreden in 1886, and later on the farm Lindequesfontein. In 1890, Vredefort became a municipality.

The larger of the two towns, Parys, is located on the southern bank of the Vaal River, 120 km southwest of Johannesburg, 15 km northeast of Vredefort, and 50 km southeast of Potchefstroom. It was laid out on the farm Klipspruit in 1876. The farm belonged to four Van Coller brothers and a widow, Mrs Davel. In 1874, they were approached by Messrs Wouter de Villiers, J.G. Luyt, J.C. Fleck and a land surveyor, who tried to convince them to have the town established on their land. After intense deliberations, the landowners refused. The negotiating team was forced to approach the owners of the land 16 km downstream on the farm Vischgat, with the same proposal. An agreement was reached and the town of Vredefort was established.

The owners of the farm Klipspruit soon realised their mistake and went back on their decision. In April 1876, Mr Fleck surveyed 158 erven (properties) on the farm Klipspruit (No. 244 in the Ward Onder Rhenoster River of the Kroonstad District), and another 142 in August 1877. A village was established in 1881. The name 'Parys' does not appear on any maps at the time. It is assumed that the town was probably named after Paris in France, a name suggested by a German surveyor, C. Schilbach, who allegedly had participated in the siege of Paris in the Franco-Prussian War (1870–1871). A number of other European names are found in the vicinity of Parys, including Dover, Calais and Heilbron.

For the first years after the establishment of both villages, none of them showed any signs of growth and expansion, as they continued to compete with each other for official and political recognition. Eventually Vredefort was granted town status in May 1881 and Parys in 1882.

In the beginning, the demand for produce from Parys and its surrounding district was low, as the largest urban centre with an appropriate demand was Kimberley, about 480 km away. However, the discovery of gold on the Witwatersrand stimulated growth as more and more travellers began to move through the town and settled in the area of Johannesburg. The gold mines were only 120 km from Parys, making the supply of produce more viable.

The discovery of gold in Johannesburg and the economic impact it had on Parys is reflected in the demographics of the times. In 1890 the white population of Parys was 375. This placed Parys among the ten biggest towns in the Orange Free State at that time. This 'boom' came to an abrupt end with the outbreak of the Anglo-Boer War in 1899. Parys, then, was part of the Heilbron District and Vredefort part of the Kroonstad District. Initiatives were introduced to amalgamate the two into a single district. The district was called 'Vredefort', with Vredefort as the principal town. The residents of Parys led a petition against this decision, as Parys was the larger of the two towns. A Provincial Commission then decided that Parys would be the principal town and that the magistrate would be located there. However, the name of the district remained Vredefort.

In December 1838, Hendrik Potgieter had declared the area north of the Vaal River the property of the Voortrekkers and settled with his party next to the Mooi River, about 11 km northeast of the present-day town of Potchefstroom, at a place that later became known as 'Oude Dorp'. In 1841, because of bad soil conditions in this area, they moved farther south to the present-day location of Potchefstroom.

In the early years, Potchefstroom was known by many names: Mooirivierdorp, Potchefspruit, Potchefstroom, and after the signing of the Sand River Convention, Andries Pretorius named it Vryburg. The present name first appeared on a document dated 16 October 1840. In 1853, the Reverend Dirk van der Hoff wrote: "The official name is Potchefstroom, in memory of Potgieter as 'chef' [sic] and situated on the Mooi River" ('stroom'). In 1858, Section 17 of the Transvaal Republic constitution was amended to read: "Potchefstroom shall be the capital of the Republic and Pretoria the seat of government".

Potchefstroom became one of the most significant towns in the history of the trans-Vaal River area. The first president of the Transvaal Republic took his oath of office here and the 'Vierkleur', the Transvaal national flag, was officially hoisted here for the first time in 1857. Here, the first constitution for the territory beyond the Vaal River, the 'Thirty-three Articles', and also the first constitution of the Transvaal Republic, were drafted.

The first shot in the First Anglo-Boer War was fired at Potchefstroom on 16 December 1880. The First Anglo-Boer War, also known as the First Transvaal War, lasted from 16 December 1880 till 23 March 1881. It was fought between Transvaal burghers ('citizens'), helped by volunteers from the Orange Free State, and British forces. The Transvaalers fought the war in order to regain their independence after the annexation of the Transvaal Republic by the British on 12 April 1877.

In June 1900, during the Second Anglo-Boer War, Potchefstroom was occupied by the British and, after signing of the peace treaty in 1902, a British garrison was stationed here until 1914. This resulted in the establishment of a military camp that, in 1965, became the headquarters of the Western Transvaal division of the South African Defence Force. In 1914 the

Union Defence Force took over the camp and during both World Wars it was used as a military training centre.

The first printing works in the Transvaal were established in Potchefstroom when Cornelis Moll arrived from Natal in 1857 with two primitive hand-printing presses. On 25 September 1857 he produced the first printing proofs of the Staats Courant (Government Gazette) of the Transvaal Republic.

One of the smaller, though not altogether insignificant, towns in the Vredefort Dome area is Venterskroon. Today, little of the town is left, but during those early years it was quite a bustling village, associated with several rugged figures. Following the discovery of gold, the mining town of Venterskroon was established around 1887. Prospecting had already started on one of the nearby farms, Nooitgedacht, around 1886, and mining leases for the farms Rooderand and Buffelskloof, to the north and northwest of Venterskroon (Fig. 128), were registered between 1887 and 1888. The detailed legal history of these farms is contained in the Fleischack document collection of the Potchefstroom (now North West) University.

Venterskroon is located on the farm Rooderand, which borders Buffelskloof located to the northeast. The first prospectors and adventurous businessmen associated with Venterskroon were not rich, except for one Iver Hjul (of Danish origin), who owned property in Kimberley, the Orange Free State, a mill in Potchefstroom, the farm Buffelskloof, and several gold-mining claims in the Venterskroon area. One of his rivals, and coowner of Buffelskloof, was one A.F. Lonngren.

The ownership of the farm Buffelskloof can be traced back to the 1860s. The farm was transferred on July 1 1864 from Miss Maria Elisabeth Bekker to Pieter Albert Venter, after whom Venterskroon was named. Venter also owned the neighbouring farm Rooderand, on which the town Venterskroon was established in January 1887. A special 'landdrost', a justice of the peace, was appointed for Rooderand (Venterskroon). Pre-war Venterskroon township had specially registered properties (stands) and street names such as Wolmarans Street and Persson Street. Even though these streets still exist, the names have disappeared; only the Venterskroon Road is presently marked.

Treading on territorial toes

The history of the region is characterised by conflict amongst the Voortrekkers and the first settlers, who lived through the 'frontier period' of the area. With a tradition of strife amongst the Boers, it is understandable that place names and boundaries had to be determined in such a way as not to cause any further conflict. A central issue during the frontier period was the division of water, land and the exploitation of resources, with the Vaal River very prominent in these debates.

Besides the Vaal River being the border between the Orange River Colony and the Transvaal Republic, it was the most significant water source for the southern Transvaal and the northern Orange River Colony. Kimberley began drawing water from the Vaal River in 1883, the Douglas diversion scheme was built in 1890, and it is believed that the Griqua chief Andries Waterboer had already constructed a weir and furrow in the early 1890s.

There are hundreds of islands in the Vaal River, particularly between Lindeques Drift, north of Parys, and in the Christiana area (Fig. 127). The islands are closest together near Parys, Doods Drift and Christiana, resulting in the river being divided into several streams. All of them are thickly forested, adding to the lush and verdant character of this land. Golf Island, in the municipal area of Parys, is the largest island, comprising an area of about 70 ha.

In 1883 a number of Vaal River landowners, who farmed on the northern banks of the river across from Parys, drafted a petition to the Transvaal Volksraad ('State Assembly'). They complained that the black squatters, inhabiting some of the islands opposite their farms, not only stole the farmers' cattle but also kept their own cattle, infected with diseases, there. However, no steps could be taken as the islands were regarded as neutral territory, leading also to white fugitives using the islands as a refuge from service in the local commandos.

At the end of the 19th Century, the islands in the Vaal River became a contentious issue between the Orange River Colony and the Transvaal Republic. The State Attorneys of the two countries did not subscribe to the view that the islands were neutral territory: according to the Transvaal, the islands belonged to the coun-

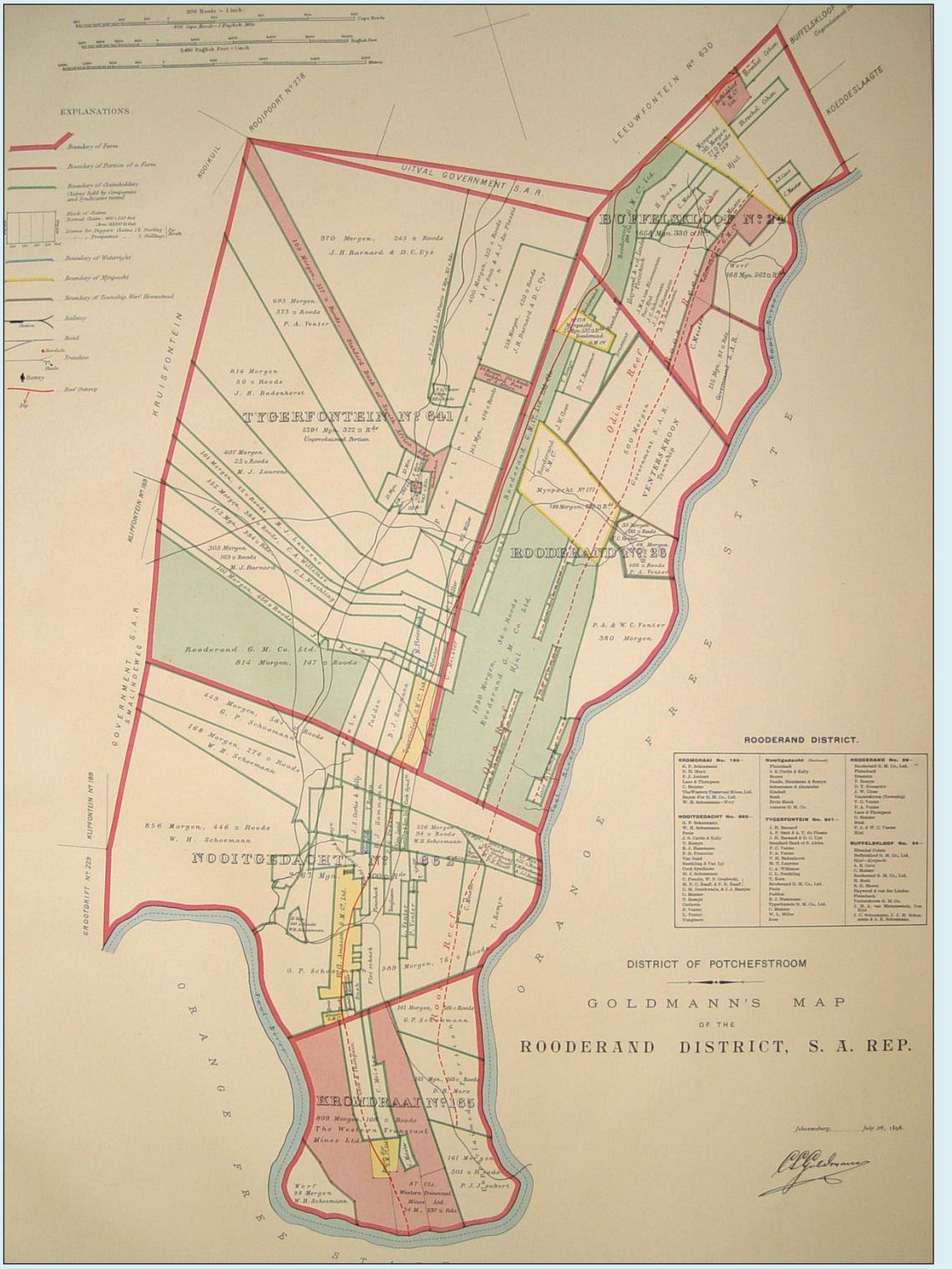


Figure 128: Map of the Venterskroon (Rooderand) Goldfield of 1899 (source: the Goldmann Atlas, 1899).

← **Figure 129:** One of the historical buildings, dating back to 1889, in the hamlet of Venterskroon; relic of the peak of the gold rush.

try to which they were most closely situated, whereas the Orange Free State's view was that the middle of the stream was the dividing line and that the islands had therefore to be divided in the middle. Eventually both governments appointed island commissions, each including a land surveyor. It was decided that islands could only be allocated as a whole, no boundary lines were to be drawn across an island.

The commission met for the first time in November 1887 at Parys and began their work the next morning on a 12 ha island just below Lindeques Drift. The islands were numbered from this point down to Christiana (Fig. 127). Interestingly, on 25 November, when they crossed the river at the last island, they did so with dry feet; ten hours later the water was allegedly 6 m deep. The division agreed on awarding the Transvaal 101 islands and the Orange Free State 94 islands, with a number of islands too small to be considered. The result of the survey was finally compiled and approved as the 'Vaal River Island Treaty' in 1895 by President Paul Kruger of the Transvaal Republic and Acting President P.J. Blignaut of the Orange Free State. It was agreed that the two river banks would be the normal border. In the case of the islands, the main current was taken as the border, except at Parys and Christiana, where the border was indicated on land-surveyors' maps.

Mineral resources

In 1853, rumours of gold in the Transvaal were spurred on when P.J. Marais applied for permission from the Volksraad to prospect for gold on the Transvaal side of the Vaal River. His application was approved on 1 December 1853, and on 7 January 1854 he reported his findings. However, mining did not commence immediately, and several newspapers began to publish contradictory reports. The Graaff-Reinet Herald reported on 4 March 1854 that the Transvaal government had closed down the diggings to decide whether they (the government) wanted to mine the gold themselves, suggesting also that the government feared the region would be invaded by foreigners. The same accusation was published in The Friend, a Free State paper, on 18 March 1854. Even though these reports were common at the time, gold prospecting and small-scale gold mining occurred throughout the Transvaal. This led to a resolution by the Volksraad, in September 1858, that the owners of all farms where minerals had been found had to either sell or rent their farms to the government. The following year the resolution was lifted and the only condition was that all mining had to be done with the approval of the government. In 1869 Rooderand was proclaimed a public goldfield giving anyone the right to prospect on the farm. In 1882 the Potchefstroom Exploration Syndicate was established and started mining gold on the farm Kromdraai (509 IQ) in the western collar of the Vredefort Dome. Extensive mining activities occurred in the Potchefstroom and Vredefort goldfields known in 1887 as the 'Vaal River Diggings' (Figs 128 and 129).

Legend has it that large numbers of diggers even left the Witwatersrand goldfields to explore

↑ **Figure 130:** Presumed remnants of Anglo-Boer War sniper or lookout post at Broodkop hill (Stop 4).

↑ **Figure 131:** Remnant of a British heliograph station on the prominent quartzite ridge above Boplaas on the farm Tygerfontein 488IQ. Mirror signals were sent from prominent elevations, in relay fashion, providing an important means of communication over considerable distances.

the possibility of a better future on the claims in the Vredefort Dome area. Some were of the opinion that the Vaal River diggings were to become the centre of the gold-mining industry and would expand beyond those of Johannesburg (since 1886) and the even older Barberton Goldfield established in the early 1860s.

Heavy machinery was ordered and installed at the most promising reefs, with the Vaal River Company mining six reefs. One hundred and fifty-eight claims were sold on the farm Nooitgedacht (508 IQ), and speculators and opportunists bought claims, only to sell them in Europe and Britain at a profit. Large transactions were done on the farm Rooderand, after the government bought a portion of the farm on 11 June 1887 to establish the town of Venterskroon.

Unfortunately, the Vaal River diggings were not located on the Main Reef and the gold-bearing reef became too deep to mine, resulting in the closure of mines, even on the farm Rooderand. The last of these mines continued until the 1920s. Today, the remains of the diggings can still be seen along the outcrops of conglomerate. Only a police station, a shop and some dwellings have remained of the former mining town of Venterskroon.

The Second Anglo-Boer War (1899–1902)

The Second Anglo-Boer War was a significant historical event in the history of South Africa, and also had an impact on the Vredefort Dome area. Most of the male population left the area to fight in the war, especially in the struggle in Natal, and the remaining inhabitants suffered badly from the British drives to capture the Boer General Christiaan de Wet (Fig. 133).

The area of Parys and environs, and the Vaal River valley, was an ideal landscape for guerrilla warfare and snipers, and several forts (outposts) can still be visited in the hills around the town (Figs 130 and 131). The Vredefort Mountain Land, with its prominent ridges, was also important for communication, with a number of heliograph stations still recognisable (such as the one on the farm Tygerfontein, Fig. 131).

General Christiaan de Wet (Fig. 133), the so-called 'Boer pimpernel', known for his prowess and cat-and-mouse tactics with the British forces, continually slipped through British lines early in the war. One of the oldest maps of British initiatives to capture De Wet with traditional military tactics was published in 1900 under the name: 'The first De Wet hunt July–August 1900' (Fig. 137). According to F. Pretorius, a well-known historian and the author of several publications on the Anglo-Boer War, one of the reasons why General De Wet and 2 500 of his burghers were not captured between July and August 1900 was his ability to utilise and interpret the landscape (hillocks and ridges interspersed with open land) of the Vredefort Dome area to his advantage. De Wet masterfully eluded the British forces, again and again (see adjacent box).

Between March and August 1901, more than 70 000 livestock, 1 012 vehicles and 1 000 bags of flour were removed, and destroyed,

(continued on page 195)

↑ **Figure 132:** Genl. De Wet was asked to escort President M.T. Steyn (shown here) and his executive council to Potchefstroom. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 30.

The First De Wet Hunt

Probably the best description of the historic landscape along the southern and western portion of the Vredefort Dome appears in the map (Fig. 137) drafted to indicate the movements and various locations of De Wet in relation to those of the British forces during the so-called 'hunt'. De Wet (Fig. 133) originally had no intention to cross into the Transvaal himself, but merely wished to secure a safe passage for President Steyn of the Orange River Colony (Fig. 132) before returning across the Rhenoster River into the Free State. On 15 July 1900, Christiaan de Wet marched from Slabberts Nek, with a force of 2 500 men and a convoy nearly three miles (5 km) long, northeast towards Bethlehem, along the Lindley road.

17 July: De Wet and his men were located southeast of Lindley but that night they had already reached a point north of Lindley.

18 July: De Wet sent a patrol to Lindley after he had decided on a longer, and less dangerous, route for his convoy. The forces of the British commander, Colonel

↑ **Figure 133:** General C. de Wet who became known for his prowess and slippery escape tactics during the first years of the Anglo-Boer War (1899–1902). Photograph courtesy of the National Cultural History Museum, Pretoria.

↑ **Figure 134:** Brigadier General R.G. Broadwood, who was in charge of the De Wet hunt in the Free State. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 86.

↑ **Figure 135:** Danie Theron, the leader of the Theron scouting corps, who was part of the group of young scouts that assisted De Wet on his march to Potchefstroom. Photograph courtesy of the National Cultural History Museum, Pretoria.

↑ **Figure 136:** Brigadier General C.P. Ridley, who joined Broadwood on 17 May 1900. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 45.

Little, met De Wet head-on at Paardeplaats, 7 miles (about 13 km) northwest of Lindley. The battle raged until dusk, resulting in 18 casualties: 13 British and 5 of De Wet's troops. Colonel Little reached Waaihoek, along the way adding to his forces, now totalling 800 men. Brigadier General Broadwood (Fig. 134) reached the deserted laager of Danie Theron (Fig. 135), the well-known scout for General De Wet. Leaving in a hurry, they met Theron's convoy at two o'clock at Palmietfontein, 20 miles (about 39 km) north of Lindley. A running battle took place for about eight miles (about 15 km), with Brigadier General Broadwood's brigade in the centre and Brigadier General C.P. Ridley's (Fig. 136) troops on either flank. Theron escaped with no injuries or loss of men and managed to join his convoy that had kept moving while he was in battle with the British troops.

General De Wet succeeded in keeping the forces of Little and Broadwood apart, and that night De Wet joined Theron's convoy at Paardeplaats. Although both Little and Broadwood received their orders from Lord Roberts (Fig. 139), and were very close to one another, they did not communicate for the next three days.

19 to 21 July: De Wet sent his convoy ahead towards the railway, dividing his men into two divisions: one under Theron to keep watch and the second with himself keeping south to cover an attack from the direction of Lindley. De Wet had an excellent intelligence service courtesy of his two scouting corps under Theron and Gideon Scheepers. Although during the next three days both Little and Broadwood's patrols were occasionally in touch with the Boer forces, De Wet was able to shake them off and he reached the railway line on the night of 21 July. As usual, he divided his forces, himself crossing at Serfontein and sending Theron to cross at Honingspruit. En route, Theron stopped a passing train, stocked their supplies, and joined the Boer forces at Mahemspruit, about 6 miles (about 11 km) west of Koppies (Kopjes) Station (south of Vredefort town). Here, the Boer forces celebrated the promotion of Theron to the rank of commandant.

22 and 23 July: De Wet continued his journey northwest and passed through Wonderheuvel and Vlakkuil. Broadwood arrived at Roodewal; after hearing that De Wet was at Mahemspruit, he tried to reach him. He then returned to the Rhenoster River

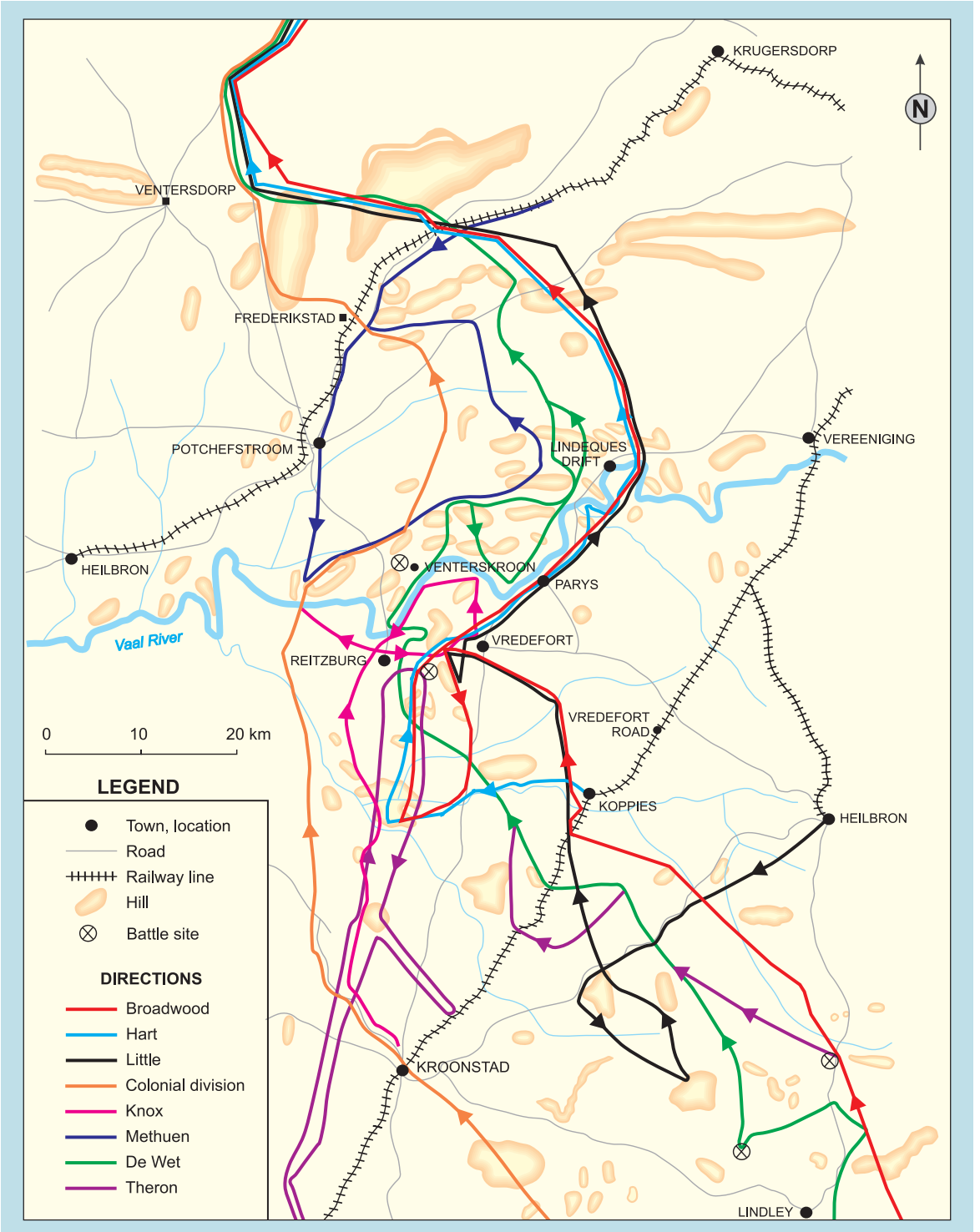


Figure 137: A map redrawn after a historical depiction of the troop movements during the 'First De Wet Hunt of July and August 1900'. Source: Spottiswoode and Co. Ltd. Lith, London.

← **Figure 138:** Lord Methuen. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 117.

bridge and reached Shepstone Drift west of the railway on July 23. On the same day, Little crossed the line at Roodewal and, for the first time, communicated with Broadwood.

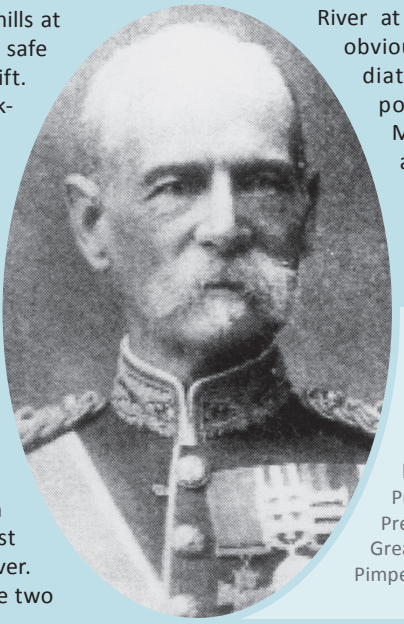
24 July: After a week of travelling through flat monotonous country, De Wet arrived at the hilly district south of the Vaal River in the vicinity of Reitzburg (in the western Vredefort Mountain Land). A sharp encounter took place between the opposing forces at Stinkhoutboom, between Vredefort and Reitzburg. The British troops secured the Boer wagons, but their mounted infantry was unable to hold their ground against the attack of Theron's scouts, and retreated with the wagons. Reinforcements from Little's brigade arrived and drove the Boers beyond the hills.

25 July: De Wet's main 'laager' (camp) on the farm Rhenosterpoort, near Reitzburg, was protected from the east by the forbidding semicircle of hills at Stinkhoutboom. It also gave him command of a safe place to cross the Vaal River at Schoemansdrift. For 20 miles (about 39 km) south of Stinkhoutboom he had outposts on the ridge, as far as Rhebokfontein, a prominent hill situated in the loop of the Rhenoster River, commanding the drifts on both sides of the 'loop'. For some time he was content to rest at this safe retreat, though remaining vigilant. He had several outposts, and some near Rhebokfontein had encounters with Broadwood's patrols. De Wet sent Theron's troops to Rhenoster Kop, a hill about 12 miles (about 23 km) south of Rhebokfontein that dominates the neighbouring country. Although De Wet was cut off from crossing the river to the east, nothing prevented him from crossing the Rhenoster River, at a drift west of Rhebokfontein, or even crossing the Vaal River.

28 July: From Rhenoster Kop, Theron made two attacks on the railway line; the first, on July 28, was unsuccessful, but in a second, on August 2, he managed to stop a train at Holfontein between Kroonstad and Ventersburg and took some prisoners. On returning to Rhenoster Kop he had to defend himself against Major General W.G. Knox, lost some wagons and cattle, but safely reached De Wet's laager on August 6.

After the capture of Middelburg on July 27, Lord Roberts concentrated his energy on capturing De Wet. His plan was to surround De Wet on the south and force him across the Vaal River into the forces of Methuen (Fig. 138). Roberts decided to send Kitchener (Fig. 140) to take command of the driving columns. By August 3, the columns south of the Vaal River were strong enough to prevent De Wet breaking back south and east. Unfortunately, Methuen was ordered to watch the crossings between Scandinavia Drift, south of Potchefstroom, and Lindeques Drift, forty miles (68 km) farther east. Even though the strategy was perfect, it did not take account of the fact that between Scandinavia Drift and Lindeques Drift there were no less than 12 crossings to guard and Methuen's forces were thinly spread.

6 August: The semicircle executed by Roberts was completed and De Wet was forced to pull back all his men from their outposts to his main laager. All access to the Free State was blocked, but north of the Vaal River the net had not been drawn so closely. De Wet decided to cross the Vaal River at Schoemansdrift, the obvious crossing immediately behind his position. One of Methuen's patrols already dis-covered on August 3 that De Wet had started to move, but on the



← **Figure 139:** Field Marshal Lord Roberts, who coordinated the first De Wet hunt from his headquarters in Pretoria. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 183.

same day he was ordered by Kitchener to leave the area with most of his men to Scandinavia Drift, farther downstream. On August 6, he was ordered to send another detachment to Winkels Drift on the Rhenoster River in support of the Colonial Division. This gave De Wet the opportunity to cross the Vaal River unchallenged.

7 August: Methuen heard about De Wet's tactics and hurried east with his entire force. On this day he reached Tygerfontein, north of Schoemansdrift, where three successive ridges separated him from the Vaal River. Behind these ridges De Wet was thrusting forward with his convoy of wagons towards Venterskroon. The north bank of the Vaal River was well suited for his elusive tactics, as the road becomes almost invisible between these ridges. In some places no space exists between the river and the hills. De Wet kept his rear covered. Methuen took command of the road from Schoemansdrift to Potchefstroom, but De Wet had already secured his way through the pass at Buffelshoek, above Venterskroon. Kitchener expected De Wet to cross at Lindeques Drift and returned to the Free State, thus missing the opportunity to catch the Boer general.

8 August: De Wet secured his position at Buffelshoek and arranged part of his convoy to move southeast and the other part northeast. Colonel Younghusband managed to capture six wagons and a quantity of stock of the convoy moving northeast. De Wet sent a small party under Theron along the southeasterly road, 'confirming' the impression amongst the British commanders that he would return to the Free State. Several of the commanders followed suit and some even fired at part of Theron's party.

9 August: All pursuing parties lost touch. De Wet continued northeast to Losberg near Fochville, where Theron's unit rejoined them, and headed straight for the Gatsrand, where Liebenberg was holding the passes for them. The British commanders realised their misjudgement and chased after De Wet in hot pursuit. De Wet relentlessly continued with his trek without relaxing or resting. One advantage the Boers had over the British was that the farmers in the country were friendly and cooperative, and they obtained plenty of supplies.

10 August: At the foot of the Gatsrand, Methuen had a skirmish with the back of De Wet's convoy that was protected by Liebenberg. De Wet and Steyn travelled all night, crossed the railway near Welverdiend, and reached the drift of the Mooi River at daybreak on August 11. At that stage, Potchefstroom had been evacuated and reoccupied by the Boers.

12 August: De Wet was now heading in a westerly direction towards Ventersdorp. Methuen was able to take a shortcut and arrived at a point a little north of Syferbult, where he shelled De Wet's rearguard so vigorously that the Boers had to abandon a gun, captured at Stormberg, some wagons and sixty of the English prisoners travelling with the convoy.

13 August: Methuen started as usual at 3 o'clock in the morning, only to find that De Wet had already left, heading in the direction of Olifants Nek, a pass through the Magaliesberg. Methuen assumed that Olifants Nek was held by the British and, when he saw De Wet heading in that direction, assumed he would turn back to join forces with De la Rey on the Elands River or to go through the Magato Pass across the Magaliesberg to Rustenburg. Methuen decided to head west in order to cut off De Wet's retreat. Unfortunately for Methuen, the nek had not been held, and De Wet's last wagons passed through Olifants Nek early in the morning.

15 August: The British commanders knew that they had lost the chase. News arrived amongst the disconsolate British commanders, Methuen, Kitchener, Broadwood, Little, Hart and Hamilton, that Colonel Hore was still holding out at Elands River.

16 and 17 August: Magato and Olifants Nek were retaken by Methuen and Ian Hamilton. De la Rey moved away after receiving the news that relief columns were arriving. Methuen went off to see what could be done by going through Magato Nek. On August 17 Ian Hamilton retook Olifants Nek.

18 August: Hamilton came up to De Wet's rearguard, which he shelled and drove farther north. De Wet had already left Theron and his scouts while at Mooi River.

25 August: President Steyn reached Machadodorp and the

→ **Figure 140:** Lord Kitchener, who took charge of the British forces in the vicinity of the Vaal River. Source: Pretorius, F., 2001. The Great Escape of the Boer Pimpernel, p. 176.

bulk of the Free Staters were put under the command of Commandant Steenekamp of Heilbron, who led them through the bushveld towards Nylstroom. General De Wet, General Phillip Botha, Commandant Prinsloo, 200 men and Gideon Scheepers' corps of thirty scouts turned back towards the Free State.

When De Wet's party came across Kommandonek in the Magaliesberg, they found it guarded by the Border Regiment left there by Hamilton. The Argyll and Sutherland regiments were at Silkaats Nek, and Kitchener was at Wolhuter's Kop on his return journey from Elands River. It seemed as if De Wet was caught between three forces, but he eluded them all. He decided to cross the Magaliesberg towards the south using a precipitous route west of Kommando Nek. He visited Potchefstroom and reached his old camp at Rhenosterpoort. The columns engaged in his pursuit had already been dispersed before he reached the Orange Free State.

↑ **Figure 141:** The concentration camp at Vredefortweg.
a. The entrance to the Anglo-Boer War cemetery near the Greenlands siding in the southeastern part of the Vredefort Dome.
b. Inside the memorial.
c. Anglo-Boer War memorial at the concentration camp.

from ten Orange Free State districts, including Heilbron, of which Parys was part. Lord Kitchener later confirmed in a progress report, of May 1901, that no supplies had been left in the Parys–Reitzburg area. A small British concentration camp (for women and children) was located at Vredefortweg ('Vredefort Road', northeast of Koppies, Fig. 141), a siding next to the main railway line, at the present-day settlement of Greenlands siding, in the southeastern part of the Vredefort Dome. It is said that just to the north, on the farm Hattingsrust, a concentration camp for black people was located, but this is still to be confirmed. Other concentration camps in the area were located at Potchefstroom and Heilbron.

After the war

The first years after the Anglo-Boer War were characterised by extreme poverty amongst the Boer families, and the term 'poor whites' became a common reference. It became an accepted term when the Carnegie Commission started their work in the rural areas of the interior of South Africa and published the results in five volumes (the Carnegie Report was the result of an extensive survey on the so-called 'poor whites' in South Africa that was published in 1932). After the war, two strategies were followed to settle returning Boer families, black workers and British loyalists in such a way as to endorse British law and to introduce Britain's policy of unifying South Africa under British rule.

As High Commissioner of British South Africa, Governor of the Orange River Colony and Transvaal Colony, Lord Milner introduced a system of allocating land to British settlers amongst Afrikaners and on farms amongst Afrikaans-speaking farmers. In November 1901 he expressed his vision as: "...an increase of the British element was a condition precedent to the establishment of the administrative union of the South African colonies compatible with the maintenance of British ideals". This was the start of artificial land reform and the first clear example of social engineering in the 20th Century in South Africa. It was introduced for both economical and political reasons. To achieve this goal, the government obviously had to budget for large-scale acquisitioning of land.

The government found itself in the predicament that it had to do something regarding the thousands of people returning from concentration and prisoner-of-war camps, who had been stripped of any income or livelihood. Even the families who were able to return to their farms had no place to stay, as everything had been destroyed or burnt down. Worse off were the numerous landless people, who had nowhere to go. A former State Secretary of the Orange Free State pointed out to the Orange River Colony government that the people, who had been 'bywoners' before the war, had lost everything during the war. These people's only property consisted of the clothes they wore on their backs.

The government reacted promptly and in July 1902 established relief works in the Orange River Colony. One of the first five work camps erected in the Colony was started in January 1903 at Parys on the Vaal River. The objective was to construct a canal, leading off from the Vaal River (above the town), running to a point some 16 km southwards. While this pro-ject was in progress, work was also started on the main railway line. On 27 May 1904, during the fourth session of the Legislative Council of the Orange River Colony, the Acting Lieutenant Governor, H.F. Wilson, announced in his opening speech: "…the earthworks near Grootvlei siding, which have been entirely constructed as relief work, are nearing completion, and it is hoped that this small but useful addition to the railway system may be handed over fully equipped, with the exception of the rolling stock, to the authorities of the Central South African Railways before the conclusion of the year". However, the Dover–Parys railway line was only completed in December 1905. The relief work programmes were only partly successful, as the general scenario after the war was negative, and none more so than the conditions in the agricultural sector.

South Africa was hit by a devastating drought in 1903. Farmers who had returned to their farms and were only starting to set up some form of subsistence, faced the complete failure of their crops. The numbers of poor whites increased daily. According to a report of a commission appointed to inquire into the position of the farming communities in the Orange River Colony, 40 poor-white families

(about 250 souls), of which 175 were children, were living in Parys in about 1907. In most cases the families survived off home gardening.

It was Milner's goal to reward loyal British soldiers who applied for land in South Africa. Awarding them land in the Orange River Colony would guarantee loyalty to the Crown in the territory of the predominantly Afrikaans-speaking colony. The largest of the ex-soldier groups was the Scottish Settlers Association, formerly known as the Scottish Sharpshooters Association, under Colonel Hill. His group of 43 soldiers was given farms all over the colony, including eight farms in the vicinity of Sannaspos, Thaba Nchu, at Vredefortweg Station, and on the banks of the Vet River.

According to Milner, the British government inherited both the surplus and financial liabilities of the previous government, and he used this argument to claim interest on the pre-war loans to Afrikaner farmers. Most of the farmers were unable to pay these interests and were not financially assisted by the government from the repatriation funds made available for farmers returning from the prisoner-of-war camps. Milner was also of the opinion that Boer farms were far too large to be developed into viable units. This created an ideal scenario to force Boer farmers to sell portions of their farms to the government, which Milner then allocated to British settlers.

20th Century development and growth

Even though the war had damaged the entire economy of the country, and none more so than those smaller pockets of economic activity in rural towns, the discovery of gold in the Witwatersrand region prior to the war and the continuing mining of this commodity after the war ensured some impetus in the dwindling economy. The most significant change in the region resulted from the discovery of gold in the last decades of the 19th Century, resulting in the movement of people from rural to urban centres. The change in the demographics of the region was also the result of the influx of foreign capital into the interior of the Transvaal. It was the first step to economic development in the 20th Century. The influx of foreign capital had a direct impact on the development of the region's infrastructure. Between 1901 and 1915 approximately 644 km of new railway lines were constructed. Developed agricultural areas, irrigation schemes and towns were connected to the national railway network (Parys was linked up in 1905). In 1908, a weir was constructed to supply irrigation water to Parys. During 1912, power stations were erected to supply Parys and Potchefstroom with electricity. A telegraph line was constructed between Parys and Vredefort in 1891, and a bridge over the Vaal River, at Parys, was completed in 1915.

By 1899 two post offices existed in the Venterskroon area: Nooitgedacht/Schoemansdrift (near the Vaal River) to the west and one in the town of Venterskroon. The Rietpoort (Transvaal) post office was located to the south of the Vredefort Mountain Land. Aasvogelrand, located south of the Vaal River (Fig. 127), and the farm Buffelskloof also served as postal agencies between 1905 and 1917.

Schoemansdrift is located on the southern side of the Vaal River and was served by the postal route running between the farms Nooitgedacht 662 and Welkom 612. It opened around 1887/1888, but then was closed for an unspecified time. It reopened in January 1892, but was closed again in December 1896. The Venterskroon post office (1888–1968) may be considered as the main service centre for the northern part of the dome area. It opened on 1 January 1888, closed during the Anglo-Boer War, but reopened on 6 January 1903. When the farm Rooderand was established as 'gold diggings' in 1888, it instigated Free State farm workers to frequent Venterskroon canteens. To keep the peace between returning workers and residents in the Orange Free State, the government of the Orange Free State sent peace-keeping officials to Aasvogelrand. A community developed on Aasvogelrand, resulting in the need for a postal service. The Aasvogelrand postal agency opened on 15 November 1905, with Vredefort as its main office up to 1910, after which Venterskroon became the main office. Around 1911, postal needs in the vicinity of Venterskroon were sufficient for the Postmaster-General to motivate the establishment of an official mail runner between Venterskroon (Transvaal) and Aasvogelrand (Orange Free State). The contract time to

Vredefort Jewish Community

The earliest Jewish settler in Vredefort arrived around 1899. The 1904 census noted the presence of 34 Jews in the town. This number did not vary until the 1960s. Thereafter the community decreased sharply until the 1980s when there was no Jewish community left in the town. Amongst the earliest Jews was Max Kaplan, who fought for the Boers during the Anglo-Boer War when he was just 16 years old. He took part in the siege of Ladysmith and fought in the battles of Spitzkop, Spioenkop and Tugela. He was imprisoned on Bermuda Island after having been captured during the battle of Majuba Hill. Another Jew, Tonias Talpis was a member of the commando called up to capture the rebels in the 1914 rebellion. One day, while raiding a Jewish-owned general-dealer shop, he overheard the owners speaking in Yiddish. He answered in the same language, paid for everything he took, and that night was invited for dinner. Another Jew, Louis Uberstein, worked in a shop in Vredefort that was looted during the 1914 rebellion.

The Vredefort Jewish congregation was formed on 20 March 1921. Until the mid-1930s, a rented house was used for festival services conducted by Benza Tachel and Louis Miller. Mr Tachel was born in Riga in Latvia, and lived in Vredefort from 1910. The Vredefort Jewish community had always been closely associated with that of Parys and after 1930 generally joined them on the High Holy Days. However, by 1934 the number of men in the Vredefort congregation had decreased, and by 1950 there was talk of affiliation with the Parys congregation. Parys had always been a popular holiday resort on the Vaal River. In the earlier years, members of the Jewish community from as far as Johannesburg often spent their honeymoon there at the Dorfan's Kosher Boarding House. Today Parys is popular as a venue for camps and outings for the Jewish youth movements and day schools.

In Vredefort, the Jewish community worked mainly as general dealers and shopkeepers. Other occupations included hotelkeeping, and there was a Jewish doctor, Mr Korff, who owned a tobacco works from 1921, and Louis Hare who owned a sheet-metal factory.

The Vredefort Jewish community was very active socially. Miss Sarah Miller's engagement party in 1911 and wedding in 1913 were attended by residents from the whole region. As early as 1915, the Vredefort Jewish community had already held a ball to raise money for Russian refugees. They contributed to the Jewish War Appeal during the Second World War, attended cultural lectures and family days organised by the South African Jewish Board of Deputies, and festivals and celebrations for Israel, very often held in Parys.

Contributed by the SA Friends of Beth Hatefutsoh.

complete the journey on foot across the Vaal River to the Orange Free State was 20 minutes. The contract was terminated in 1917, when the Aasvogelrand postal agency was closed. During this period the Venterskroon post office was considered one of South Africa's principal posts with the lowest postal incomes.

In terms of the mail-running contract between the contractor and the Department of Posts, the contractor had to undertake to send a runner from Venterskroon to Aasvogelrand, arriving there within 20 minutes, to deliver the mail. The person, usually a local black male person, had to run with the postal articles from the Venterskroon post office towards the southeast. He had to cross the Vaal River (even when in flood) and deliver the mail at the Aasvogelrand postal agency in the Orange Free State. The rate per round trip amounted to about 1s.2d. The contractor risked being fired if the 20-minute time limit was exceeded. The route was one of five Orange Free State postal routes served on foot. The other routes operated either by using carts or horses.

After the Anglo-Boer War, several relief schemes were initiated in and around Parys. After the construction of the weir in the Vaal River, the Town Council decided to use some of

the excess water to generate electricity. In December 1912, electricity was introduced after the completion of the town's own power station.

The first factory in Parys was a jam factory, which was soon followed by other industries. Shortly after South Africa became a Union, in 1910, a condensed-milk factory was established with financial assistance from the government and the Town Council. The establishment of a spinning and weaving factory, manufacturing cloth, blankets and rugs, followed. The Vaal River Boeren Tabak Maatschappij was established to handle the locally grown tobacco crop on cooperative principles. In 1919 the brothers Max and Louis Benjamin erected a roller mill, known in 1978 as the Parys Roller Milling Co. (Pty) Ltd.

The new colonial administration realised that the agricultural sector had to be boosted and that farming had to be elevated from its frontier state of subsistence farming into commercial farming. One way of doing this was the establishment of experimental farms. The first experimental farm was established at Potchefstroom in 1902 by F.B. Smith (Director of Agriculture in the Transvaal) and Alex Holm (the first general manager). Its objective was the rehabilitation of the impoverished farming communities in the region. In 1909 an agricultural college was established on the experimental farm and in 1939 it was transformed into the Potchefstroom College of Agriculture and Experimental Farm.

The irrigation system of Potchefstroom was greatly improved after the war, and the Potchefstroom Dam was constructed in 1909; the basin was developed with a proper irrigation system connected to the tributaries of the Mooi River.

Between 1930 and 1933 the region experienced a severe drought, and crop farming replaced cattle farming as the most important economic activity. Maize became the dominant commodity and large areas were ploughed. Small irrigation farms became popular during the 1930s, mainly to accommodate the high number of 'poor whites'. Irrespective of these positive developments, the drought had dire consequences for the agricultural sector. Grazing was destroyed; water sources dried up and cattle numbers shrank dramatically. This resulted in a complete depression of land values, and numerous farmers left their farms in search of other sources of income.

Development of infrastructure

Infrastructural elements, such as roads and railway lines connect towns and villages, based on the assumption that these towns serve as nodes supporting the surrounding rural areas and farming communities. The most significant natural landscape elements essential for a healthy subsistence remain land and water. In the case of this region around Parys and Vredefort, the Vaal River was the main supply of water, and crossing and taming the river became a history of its own. By 1930 the Vaal River was one of the most thoroughly investigated rivers in South Africa.

Two of the reasons why Parys became a significant town were its location next to the Vaal River and the fact that the main road from the Cape Colony to Johannesburg passed through the town. The gold rush of 1886 on the Witwatersrand brought prosperity and wealth to Parys, as it became a popular stopover and trading post. When the river could not be crossed, wagons had to remain in town, resulting in increased spending and the creation of particular needs that had to be served. One of these services was the installation of a ferry service to cross the river to the Transvaal and to one of the islands. The Woody Island ferry service was established, taking people from the mainland to Woody Island, and from there another ferry completed the crossing into the Transvaal. Unfortunately, the ferry service became known for the many accidents that happened, and farmers on the Transvaal side preferred to travel to Potchefstroom, 48 km away, rather than face the trouble and expense of the ferry crossings.

Towards the end of 1913, tenders were asked for a reinforced concrete bridge over the Vaal River, and the contract was awarded to a Mr Warren. Work started in May 1914, but the outbreak of the First World War caused extensive delays in the construction. The bridge was finally completed in December 1915. It had an almost immediate positive impact on the local economy, as more people started using this route, resulting in an influx of capital into the town.

The completion of the railway line to Parys in 1905 suddenly made the town more accessible to the public, which, in turn, had a positive

impact on the town's industrial development. In 1925 it was determined that only 50 % of the land suitable for intensive maize production was being used, because of insufficient transport. In 1925, the Railways Board recommended the extension and completion of the Dover–Parys line to Vredefort as an incentive to boost regional development.

Christiana already had a furrow from the Vaal River since the 1890s, and at Parys irrigation furrows had existed before the turn of the 19th Century. The water furrow feeding water to the properties in Parys was maintained by the residents, as they did not pay tax on water. The need for water eventually resulted in the construction of a turbine pump. Expansion and economic development eventually dictated the construction of a more extensive weir. One of the most significant landmarks in the history of the development of the infrastructure of Parys was when a 1 000 m long weir across the Vaal River was completed in 1910. The weir and canals immediately made it possible to irrigate approximately 2 000 acres of land in the region. At the same time a lake, approximately 8 km long, was created, introducing the potential for vast recreational activities and secondary infrastructure aimed at the tourist market. Higher up in the Vaal River, the so-called 'Barrage' was erected. Included in the construction was a road bridge, about a kilometre north of Parys, built by the Rand Water Board just after the First World War. It was opened by Prince Arthur of Connaught on 27 July 1923.

The Vaal basin now contains one of the most highly developed urban-industrial complexes in southern Africa. The reason for this development is based on the abundant occurrence of three of the world's most important minerals, i.e. diamonds, gold and coal, in the wider region, and the coal-based energy industry.

Development of tourism

The location of Parys in relation to the Vaal River and the occurrence of various islands are ideal for the development of leisure activities and large-scale holiday tourism. The construction of weirs and dam walls in the river has led to the creation of various dams, attracting thousands of holidaymakers every year.

A bioscope and several cottages already existed on Woody Island in 1912. However, it was not a successful development, as no proper transport system across the river existed at the time. Instead, the development of cottages for holidaymakers was focused on the banks of the river.

Today, the numerous camping and holiday facilities at and near Parys are used by people from the Pretoria–Witwatersrand–Vereeniging metropolitan area, the towns of western Gauteng, the Free State towns (such as Kroonstad and Bloemfontein), and from the Free State goldfields.

Workers and forced removals

Since the introduction of apartheid legislation after 1948, the free movement of black people became more and more restricted and thousands of black people eventually ended up in so-called homelands. Between 1960 and 1983 approximately 3.5 million people were affected by the resettlement policies of the South African government. Several groups of the dominantly Tswana-speaking people living in the Vredefort Dome area were removed to Bophuthatswana. The homeland of Bophuthatswana consisted of several territories scattered through the former Transvaal Province. The nearest part of this homeland to the Vredefort Dome centred around the town of Mafeking (today Mafikeng). These forced removals had dire consequences for the black people of the town of Potchefstroom and other towns in the region.

One of these new townships was Itsoseng, about 30 km from Lichtenburg. About 90 % of the 25 000 people in the township had been evicted from towns in the Western Transvaal during the 1970s. Most people came from Lichtenburg, Klerksdorp, Potchefstroom and Carletonville, and a few from Sannieshof and Ottosdal. The houses were erected by the former Western Transvaal Administration Board. The old people were brought in first, then the families of those who worked on the mines.

One of the pivotal cases regarding the translocation of the Barolong ba ga Madiboa people involved the residents of Machaviestad, 12 km outside Potchefstroom, who were removed to Rooigrond, about 18 km southeast of Mafikeng, some 120 km to the northwest. The history of settlement at Machaviestad goes back to those

days when Andries Hendrik Potgieter moved into the region with his party of Voortrekkers. Since their settlement, the people of Machaviestad and the municipality of Potchefstroom have been at loggerheads about the ownership of the area. The Town Council of Potchefstroom took legal advice as early as 1923 and informed the residents that their occupation of municipal land was illegal. In turn, they would be relocated onto land in the black township of Potchefstroom. Although 30 June 1929 was set as the eviction date, nothing happened. In March 1934, and once again in 1945, the Town Council requested the Department of Native Affairs to remove the Barolong. The Department could not find alternative land for the Barolong and, as a result of the refusal of the people to move, the relocation plans were shelved again.

At a meeting on 13 August 1952 the Machavie villagers were informed that they had to move because the area was needed urgently by the Department of Defence. A few months later the Chief Native Commissioner of Potchefstroom was informed that the Town Council had to assist the Department of Native Affairs with the removal process by relocating the people to the town's own location to maintain some of the work force essential in Potchefstroom. To prevent people returning to their homes, it was decided by the Town Council to demolish all buildings left redundant after the residents had been evacuated. The process was halted because of a dispute between the Town Council and the Department of Native Affairs.

In 1967, twenty seven Machaviestad residents applied for accommodation in Ikageng, the local location. This was interpreted as the first move of a larger contingent, which later proved to be a wrong assumption by the local authority. In May 1970, the government offered to show them the proposed site for resettlement at Leeufontein in Bophuthatswana, but they refused to move there. Threats by the Town Council to have them forcefully removed continued. In 1971 the Machaviestad people finally succumbed to the pressure applied by the Town Council, and 140 families moved to the black residential area of Ikageng. In the meantime the Machavie chief, Israel Mokate, negotiated with Chief Montshiwa of Bophuthatswana to allow the remaining people, about 44 families, to settle temporarily at Rooigrond.

During their stay at Rooigrond the former residents of Machaviestad continued with their battle to regain the rights to their ancestral lands. In the meantime, the Town Council leased Machaviestad to white farmers. One option was to return to the site and occupy it 'peacefully'. In December 1990, members of the Barolong Action Committee requested permission from the Town Council to visit Machavie-stad to attend to their ancestral graveyards with the long-term purpose to occupy Machaviestad permanently. Permission was granted for the period 22 December 1990 to 26 December 1991. The latter date was a typing error, but the people who asked for permission refused to accept a correcting letter from the Town Council. They also refused to leave Machaviestad on 26 December 1990. A charge of trespassing was laid and 25 people were arrested. The case eventually had to be resolved in the Potchefstroom Magistrate's Court, resulting in withdrawal of the charges of trespassing.

On 24 February 1995, a delegation of the Town Council was given a hearing on the issue by Derek Hanekom, then Minister of Land Affairs, and it was agreed that the Department would acquire the land from the Council in order to restore it to the Barolong people. Chief Simon Makodi accepted the agreement, but indicated that his people would need more land than the agreed portion of 1 330 hectares. The Department offered to buy the additional land, and, on 26 April 1995, it was decided to sell 3 489 hectares at R600 per hectare to the central government. However, it was agreed that the Town Council retained the mineral rights to the land.

On 28 April 1995, the first twenty members of about 110 Barolong families returned to their ancestral land. The property was handed over to Koos Komani, official of the Department of Land Affairs, who, in turn, handed it over to Chief Makodi.

SECTION 3

Flora and fauna of the Vredefort Dome — what, where and why?

Kevin Balkwill

Plants in the Vredefort Dome reflect a variety of natural and human influences, both past and present. On the one hand, geology, topography and historical and present climate, and, on the other, farming and mining activities have been major factors in determining the current biological diversity. The types of vegetation and their distribution in the Vredefort Dome region, and the factors that have contributed to their establishment, are discussed in this section.

The Vredefort Dome plants (flora) in a geographical context

According to Werger's geographical classification of flora in southern Africa (the relationships of the taxa — a taxon is a unit in a classification system — that occur in different areas), the Vredefort Dome is part of the so-called Palaeotropical Kingdom (Werger, 1987; Werger and Coetzee, 1987). The Vredefort Dome lies within the Zambezian Domain of the Sudano-Zambezian Region, specifically on the border between the Highveld and the Transvaal Plateau centres of endemism (confinement to a specific region) (see Fig. 142). The area is predominantly covered by Moist Cool-Temperate Grassland, with elements of Upland (Temperate) Subhumid Mountain Bushveld on rocky outcrops.

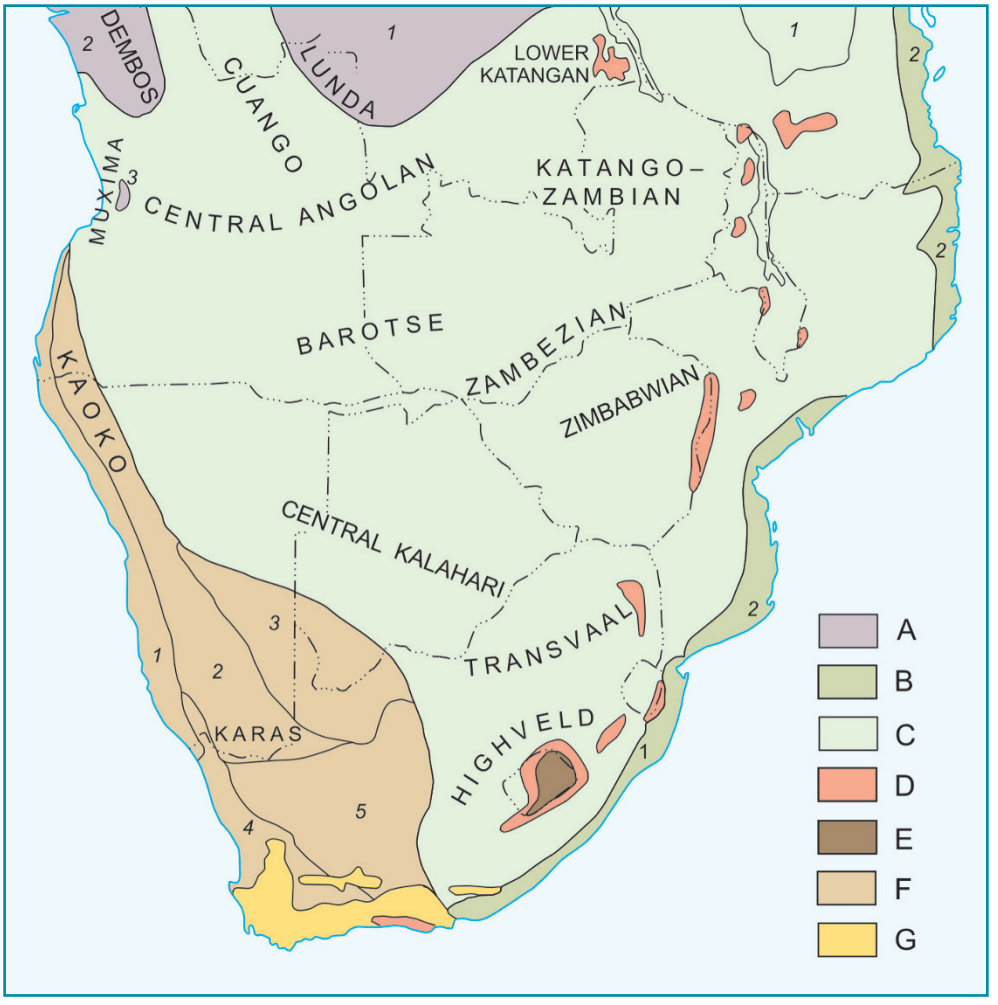
The composition of the flora

An angiosperm flora of 392 taxa (species and infraspecific groups) has been recorded in the Vredefort Dome. This represents approximately 1.7 % of the entire southern African flora. The list in Appendix 1 has been compiled from records in the National Herbarium and the C.E. Moss Herbarium. However, if these two lists and the list of trees from the dome are used as a capture-recapture experiment, it can be calculated that there might be between 600 and 1 300 species of vascular plants on the Vredefort Dome. Three hundred and three of the listed species are dicotyledons and 79 are monocotyledons, with the other ten being ferns, fern allies, liverworts and mosses. These taxa fall into 89 families; 67 of the families are dicotyledonous and 13 are monocotyledonous. The biggest families are *Compositae*, *Graminae*, *Cyperaceae Leguminosae, Labiatae* and *Liliaceae sensu lato*. All of these larger families occur worldwide, although the Cyperaceae are especially distributed in damp, temperate and subarctic habitats (Heywood, 1978).

The largest genus on the Vredefort Dome is *Cyperus* (Table 1). The genus is most likely so prevalent because of the damp areas associated with the Vaal River and its flood plain. Surprisingly, many of the other large genera prefer tropical or subtropical environments (for example, *Eragrostis*, *Indigofera* and *Solanum*).

Table 1: Genera with more than three taxa on the Vredefort Dome, with the number of taxa that are on the Vredefort Dome and the family to which the genus belongs.

Genus	Number of taxa	Family
Cyperus	13	Cyperaceae
Solanum	10	Solanaceae
Helichrysum		Compositae
Hermannia	6	Sterculiaceae
Eragrostis	5	Graminae
Rhus	4	Anacardiaceae
Polygala	4	Polygalaceae
Indigofera	4	Leguminosae
Vernonia	4	Compositae
Ipomoea	4	Convolvulaceae
Aristida	4	Graminae
Hibiscus	4	Malvaceae



† **Figure 142:** Phytochorological subdivision of southern Africa (names of some centres are included in the map). (From Werger, 1978.)

A. Guineo–Congolian Region
   - A1. Congolian Domain
   - A2. Nigerian–Cameroonian Domain (including Littoral South Atlantic Domain)
   - A3. Amboim Selection of A2

B. Indian Ocean Coastal Belt
   - B1. Tongaland–Pondoland Regional Mosaic
   - B2. Zanzibar–Inhambane Regional Mosaic

C. Sudano–Zambezian Region (Zambezian Domain)
   - C1. Oriental Domain

D. Afromontane Region

E. Afro-Alpine Region (Aistral Domain)

F. Karoo–Namib Region
   - F1. Namib Domain
   - F2. Namaqualand Domain
   - F3. Southern Kalahari Subdomain
   - F4. Western Cape Domain
   - F5. Karoo Domain

G. Capensis

Which biome occurs on the Vredefort Dome?

Rutherford and Westfall (1986) have classified southern African vegetation on the basis of the physical attributes of the plants that occur in certain areas. The units thus defined are called *biomes*; there are seven biomes in South Africa. In this classification, the Vredefort Dome would fit into the Grassland and Savanna biomes (see Fig. 143). Gibbs Russell (1987) used the areas designated as biomes and the data on the computer system of the National Herbarium to characterise the various biomes according to the occurrence of plants (compare Fig. 143). She has indicated the rank of each of the larger families in the biomes (Table 2). Interestingly, the ranks of the largest families on the Vredefort Dome do not correlate well with the ranks for families in either the Grassland or Savanna biomes. This is probably largely because of the influence of the Vaal River on the composition of the vegetation along its banks and on its flood plain, the unusual geomorphology in the area as a result of the meteorite impact and subsequent erosion, and possible omissions in the database caused by undersampling of the vegetation of the area.

Table 2: Ranks of major families in the Grassland and Savanna biomes and the Vredefort Dome, with numbers of taxa for the latter in brackets.

Grassland	Vredefort Dome	Savanna
Compositae	Compositae (42)	Graminae
Graminae	Graminae (24)	Leguminosae
Leguminosae	Cyperaceae (22)	Compositae
Liliaceae *sens lat.*	Leguminosae (20)	Rubiaceae
Scrophulariaceae	Labiatae (15)	Cyperaceae
Asclepiadaceae	Liliaceae *sens. lat.* (11)	Acanthaceae
Orchidaceae	Convolvulaceae (10)	Euphorbiaceae
Labiatae	Euphorbiaceae (8)	Asclepiadaceae
Iridaceae	Rubiaceae (8)	Scrophulariaceae
Rubiaceae	Scrophulariaceae (8)	Labiatae
Euphorbiaceae	Solanaceae (8)	Malvaceae
Mesembryanthemaceae	Malvaceae (7)	Convolvulaceae
Crassulaceae	Polygonaceae (6)	Orchidaceae
Convolvulaceae	Acanthaceae (6)	Aizoaceae
Amaryllidaceae		Sterculiaceae
Malvaceae		Iridaceae
Umbelliferae		Amaranthaceae
Acanthaceae		Cucurbitaceae
Anacardiaceae		Anacardiaceae
Cyperaceae		Liliaceae *sens. lat.*
Selaginaceae		Verbenaceae
Solanaceae		
Cruciferae		

Veld types on the Vredefort Dome

A vegetation survey conducted between 1945 and 1952 of the whole of South Africa, Swaziland and Lesotho produced a vegetation classification, presented as a map, and a description of 70 veld types with 75 variations (Acocks, 1988). A veld type was defined as "a unit of vegetation whose range of variation is small enough to permit the whole of it to have the same farming potentialities". Acocks selected representative samples of the vegetation in good condition; thus, the areas drawn on the map were not all the same as the samples, particularly in the areas he regarded as being badly managed. Acocks predicted that without appropriate management, significant changes in vegetation would occur, especially involving the northwestwards movement of the drier desert, semidesert and Karoo vegetation. Since this map was compiled, human activity and possibly local and regional climatic changes have caused some major modifications in the vegetation of South Africa.

The Vredefort Dome supports two veld types: a pure grassveld type and a false grassveld type. The pure grassveld type is *Cymbopogon-Themeda* Veld (Northern Variation), whereas the latter is Bankenveld (Central Variation), which correspond to Acocks' veld type numbers 48b and 61b, respectively. *Cymbopogon-Themeda* Veld occurs in the North West, Free State and Gauteng provinces in undulating, relatively flat countryside lying at an altitude between 1 350 and 2 000 m above mean sea level, which experiences between 450 to 750 mm of rainfall per annum and severely frosty winters. The Northern Variation of this veld type occurs in the Free State and Gauteng Provinces, between 1 300 and 1 500 m above mean sea level, and with rainfall between 500 and 700 mm per annum. This variation is sparser and more tufted (meaning that grass occurs in clumps, with open spaces between them) than the Southern Varia-

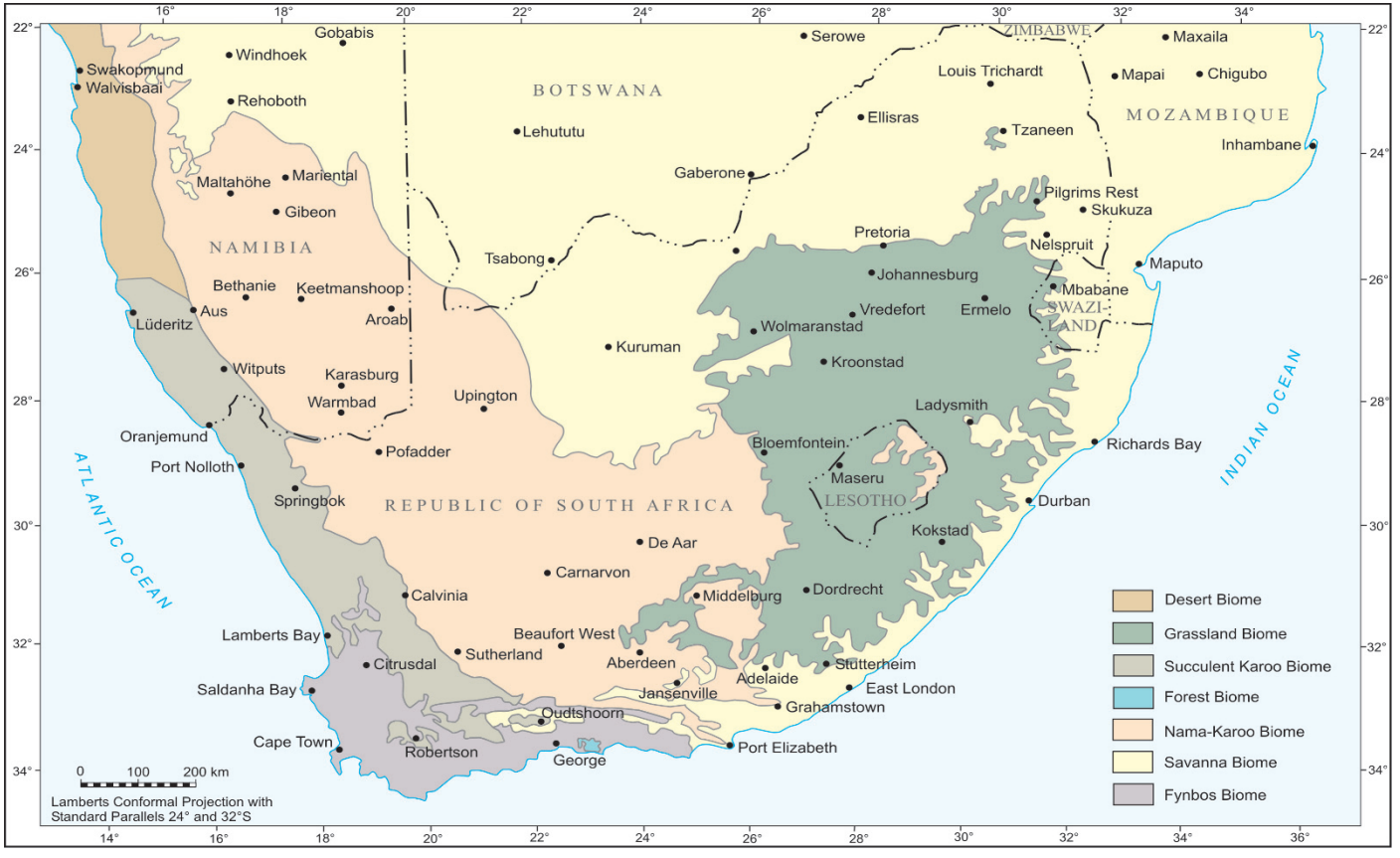


Figure 143: The biomes of southern Africa (from M.C. Rutherford and H. Westfall, 1994).

tion. Species of general occurrence (in order of density) include:

Setaria sphacelata (Schumach.) Moss var. *sphacelata*
Themeda triandra Forssk.
Heteropogon contortus (L.) Roem. & Schult.
Eragrostis racemosa (Thunb.) Steud.
E. chloromelas Steud.
Elionurus muticus (Spreng.) Kunth
Cymbopogon plurinodis (Stapf) Stapf ex Burtt Davy
Brachiaria serrata (Thunb.) Stapf
Eragrostis obtusa Munro ex Ficalho & Hiern
Vernonia oligocephala (DC.) Sch.Bip. ex Walp.
Eragrostis gummiflua Nees
Diheteropogon amplectens (Nees) Clayton
Eragrostis capensis (Thunb.) Trin.
E. lehmanniana Nees
Setaria nigrirostris (Nees) T. Durand & Schinz
Scabiosa columbaria L.
Eragrostis plana Nees
Ziziphus zeyheriana Sond

Species occurring less generally (although they may be quite common where present) include:

Digitaria argyrograpta (Nees) Stapf
Cynodon dactylon (L.) Pers.
C. incompletus Nees
Helichrysum rugulosum Less.
Anthospermum rigidum Eckl. & Zeyh. ssp. *pumilum* (Sond.) Puff
Conyza pinnata (L.f.) Kuntze
Felicia filifolia (Vent.) Burtt Davy ssp. *filifolia*
Panicum coloratum L. var. *coloratum*
Sporobolus discosporus Nees
Aristida congesta Roem. & Schult. ssp. *congesta*

Bankenveld is an extremely sour and wiry type of vegetation with a climax that is probably sour bushveld or at least an open savanna of *Acacia caffra*. The vegetation is sparse, tall and tufted, with forbs (non-grassy herbs) playing an important role. The Central Variation of this veld type occurs on the Vredefort Dome, especially on hills sloping down to the Vaal River. The soils are mainly poor and acidic, as well as sandy or stony. This variation occurs at an altitude between 1 450 and 1 750 m above mean sea level, and with rainfall between 700 and 750 mm per annum. Severe frosts and veld fires maintain this veld type. Rocky hills and ridges carry bushveld vegetation, with *Protea caffra* Meisn. ssp. *caffra*, *Acacia caffra, Celtis africana* Burm.f., *Protea welwitschii* Engl. and *Xerophyta retinervis* Baker. Sheltered areas support temperate forest species such as *Celtis africana*, *Kiggelaria africana* L., *Halleria lucida* L., *Leucosidea sericea* Eckl. & Zeyh. and *Buddleia salviifolia* (L.) Lam. Species that typify the grassland include:

Trachypogon spicatus (L.f.) Kuntze
Tristachya leucothrix Nees
Elionurus muticus
Heteropogon contortus (L.) Roem. & Schult.
Panicum natalense Hochst.
Diheteropogon amplectens
Schizachyrium sanguineum (Retz.) Alston
Loudetia simplex (Nees) C.E.Hubb
Brachiaria serrata
Tristachya rehmannii Hack.
Bewsia biflora (Hack.) Gooss.
Monocymbium ceresiiforme (Nees) Stapf
Digitaria monodactyla (Nees) Stapf
D. tricholaenoides Stapf
Setaria sphacelata ssp. sphacelata
Setaria nigrirostris
Eragrostis racemosa
E. chloromelas
E. capensis
E. sclerantha Nees
E. gummiflua
Themeda triandra
Urelytrum agropyroides (Hack.) Hack.
Aristida aequiglumis Hack.
Melinis nerviglumis (Franch.) Zizka
Cymbopogon excavatus (Hochst.) Stapf ex Burtt Davy

Forbs (weeds or broadleaf herbs) that are common in the Bankenveld include:

Sphenostylis angustifolia Sond.
Senecio coronatus (Thunb.) Harv.
S. inornatus DC.
Helichrysum acutatum DC.
H. pallidum DC.
Nidorella hottentotica DC.
Indigofera hilaris Eckl. & Zeyh.
I. velutina E.Mey.
Indigastrum fastigiatum (E. Mey.) Schrire
Geigeria burkei Harv.
Justicia anagalloides (Nees) T.Anderson
Cycnium adonense E.Mey. ex Benth. ssp. *adonense*
Pearsonia cajanifolia (Harv.) Polhill ssp. *cajanifolia*
Vernonia natalensis Oliv. & Hiern
Pentanisia prunelloides (Klotzsch ex Eckl. & Zeyh.) Walp.
Castalis spectabilis (Schltr.) Norl.
Parinari capensis Harv. ssp. *capensis*
Pygmaeothamnus zeyheri (Sond.) Robyns var. zeyheri

Factors that affect the vegetation

The major factor that determines the vegetation in an area is climate. Topography then interacts with climate to provide microclimatic conditions on a smaller scale. The type of soil may influence vegetation on an even finer scale.

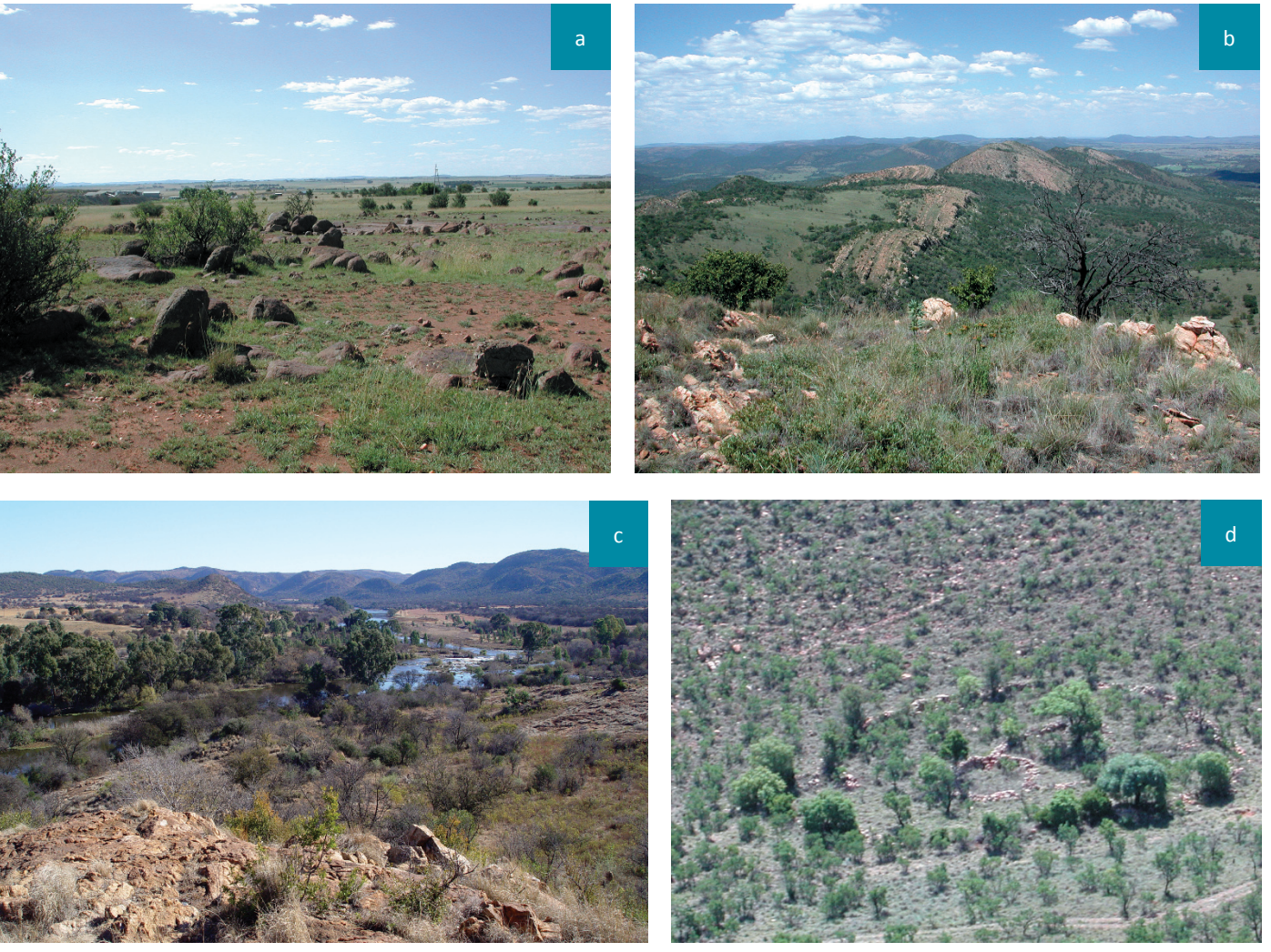


Figure 144:
a. View of grassland in the core of the dome showing how trees are concentrated around rocks where seedlings are protected from fire.

b. View from Dwarsberg (also known as Steenkampsberg; Stop 18) looking northeast, showing the dependence of vegetation on the geology.

c. View of the Vaal River at Schurwedraai (Stop 11), showing dense alien invader species along the river and woody vegetation associated with rocky hillsides.

d. Ruins of Iron Age settlement below Dwarsberg (Stop 18). Note how the trees associated with the old walls differ from those in the surrounding vegetation.

The habitats on the Vredefort Dome

The climate of the Vredefort Dome has changed over the last 8 500 years (Wadley, 1987); the present climate is characterised by dry winters and some dry spells during summer, and frost in winter. This limits the plant variety to those species that are tolerant of drought and very cold conditions. Many such plants overwinter underground, and their annual above-ground parts form dry fuel that is burnt in fires during the winter months. An assemblage of such plants is called a grassland. The type of habitat (i.e. flat areas with deep soils) where grassland occurs dominates the centre of the Vredefort Dome. On some of the rockier ridges, the rocks take up surface area and, thus, the amount of grass and similar plants is less. Consequently, the heat and frequency of fires on these ridges is less, allowing trees tolerant of cold and drought to flourish (e.g. *Combretum molle* and *Cussonia paniculata*). Other habitats on the Vredefort Dome include marshes and pans and riverine areas with forest, shallow running water, and temporarily inundated areas.

The effect of geology on the vegetation of the Vredefort Dome

The interaction of erosion and varying hardness of different rock types causes the relief (topography) features in the dome and, hence, a range of habitats. However, the chemical properties of these same rock types may lead to more subtle differences in soils that otherwise appear similar. These different soils interact with relief and microclimate to produce unique conditions, under which various plant communities can establish themselves. The effect of different rock types on the composition of woody communities on rocky ridges was studied by Mogg (1961). As discussed earlier in this book, the geology on the Vredefort Dome is complex. Mogg found that the effect of geology on the vegetation was only marked where bedrock is close to the surface. Some species are ubiquitous and show no preference for soils derived from any particular rock type. These include: *Clematis brachiata* Thunb., *Diospyros lycioides* Desf. ssp. *guerkei* (Kuntze) De Winter, *Gymnosporia buxifolia* (L.) Szyszyl., *Rhus magalismontana* Sond. ssp. *magalismontana*, *Rhus pyroides* Burch., *Vernonia natalensis* Sch.Bip. ex Walp., V. *oligocephala* (DC.) Sch. Bip. ex Walp., *Zanthoxylum capensis* (Thunb.) Harv. and *Ziziphus mucronata* Willd.

The pH of a soil appears to be the most important edaphic (chemical or physical) factor, so that different parent material that produces soil of a similar pH may support a similar suite of species. In many cases, it is the density of a particular species that differs between rock types, rather than an absolute presence or absence of specific species. On silica-rich quartzites and weathering-resistant granite, soils with a pH between 3.5 and 4.5 support the following characteristic species: *Aristida transvaalensis* Henrard, *Asclepias stellifera* Schltr., *Berkheya seminivea* Harv. & Sond., *Cyperus leptocladus* Kunth, *Indigofera melanadenia* Benth. ex Harv., *Lopholaena coriifolia* (Sond.) E.Phillips & C.A.Sm. and *Phymaspermum athanasoides* (S.Moore) Källersjö. On soils derived from the same rocks, but with a pH between 4.7 and 5.0, *Pavetta zeyheri* Sond. and *Vernonia galpinii* Klatt are characteristic. *Vernonia hirsuta* (DC.) Sch.Bip. ex Walp. is characteristic on acidic shales where the pH is between 3.5 and 7.3. These shales usually occur between bands of Central Rand Group quartzites. *Acacia caffra* (Thunb.) Willd. occurs on the shales (and many other rock types), but not on the quartzites, and thus emphasises the differences between these substrata (Fig. 144b). On soils derived from granites with a pH between 4 and 5, *Gymnosporia buxifolia*, *Maytenus undata* (Thunb.) Blakelock, *Myrothamnus flabellifolius* Welw. and *Rhus pentheri* Zahlbr. are characteristic; where the pH is between 4.5 and 6.5, *Diospyros austro-africana* De Winter var. *microphylla* (Burch.) De Winter is characteristic. Species that characterise quartzites include: *Clematopsis scabiosifolia* (DC.) Hutch. ssp. *stanleyi* (Hook.) Brummitt, *Helichrysum chionosphaerum* DC., *Gymnosporia tenuispina* (Sond.) Szyszyl. and *Vernonia staehelinoides* Harv., whereas *Gymnosporia polyacantha* (Sond.) Szyszyl. is characteristic of all soils derived from the weathering of silica-poor rocks, such as many of the (Fe, Mg)-rich magmatic intrusions.

Mogg found that some factors are more important for determining whether certain woody species occur on particular rocks but not on others:

← **Figure 145:** *Tulbaghia leucantha* is a relative of onion and garlic.

trolling chemical and physical factors come into effect, the seedling will die rather than establish in the area.

Much useful insight could be gained from repeating Mogg's study, especially in the Vredefort Dome area. The woody vegetation on the dome would be particularly good for exploring the relationship between geology and distribution of woody vegetation, because the paucity of species means that patterns may well be clearer and more easily detected than in more species-rich areas.

Recent changes in habitats on the Vredefort Dome

The most significant changes that have come into effect on the Vredefort Dome by recent habitation include agriculture, which would have transformed natural grassland into monospecific stands of crop plants, which when left fallow, will return via *seres* (a series of plant or animal communities formed by succession), including many weedy species, to a more-or-less natural

1. Nurseries need to be available for seedlings to be able to establish. A seedling of a woody species that establishes in a grassland will be damaged by a hot fire, while protection from fire is afforded between rocks, where there is little fuel for a fire (Figs 144a and 147).

2. Dispersal agents are required to carry the seeds to the area.

3. The chemical and physical properties of the soil (edaphic factors) must be compatible with the physiology (biochemical processes and interactions that take place within an organism) of a species. If the physiology of certain plants is unsuited for the conditions on a particular substratum, then the seed may well germinate and the seedling will survive for a short period on the reserves from the cotyledons (seed leaves), but once the con-

↓ **Figure 146:** *Berkheya pinnatifida* has thorny leaf margins and latex to reduce herbivory.

↑ **Figure 147:** *Ehretia rigida*, displaying its characteristic tangled branches that give it its popular name 'puzzle bush'.

↓ **Figure 149a** and **b:** *Protea caffra* dominates the vegetation in the valley west of Dwarsberg (Stop 18).

↓ **Figure 148:** *Plumbago auriculata*, a popular garden plant, occurs naturally in the dome area.

↑ **Figure 149c:** *Brachylaena rotundata,* showing how growth from previous years has been killed by frost.

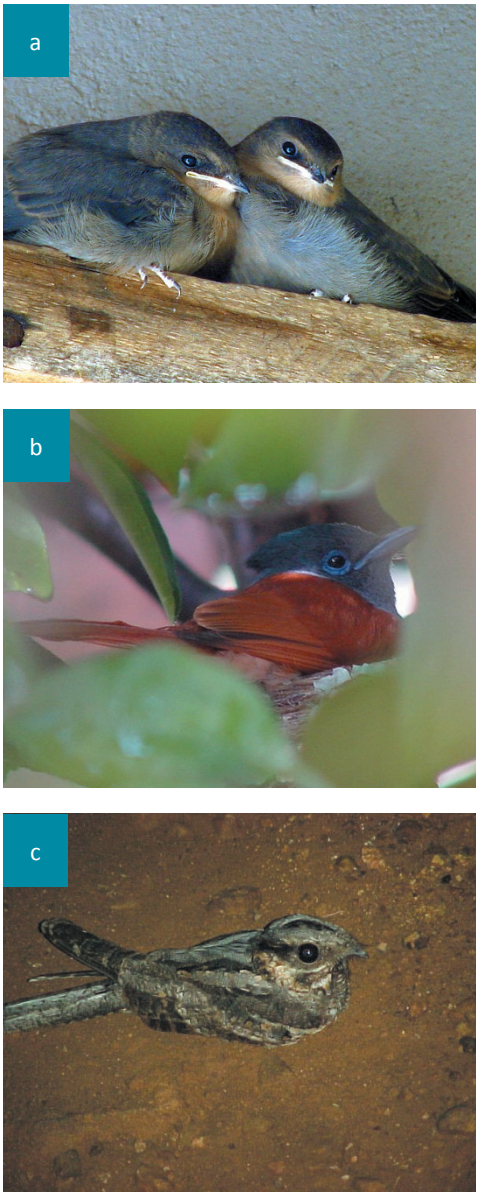
grassland again. Around homesteads on farms and within towns, many trees, most often not indigenous, have been introduced. Mining too, has caused disturbance in the region, leading to local extinction of natural flora, which is often replaced by exotic weedy species. Many exotic species, prominent amongst them various eucalyptus species, have invaded the area and are particularly prevalent along the banks of the Vaal River, where they have ousted the indigenous vegetation. These are now being targeted by control programmes such as Working for Water. Water hyacinth (*Eichornia crassipes*) is a major problem in the rivers in the area and is an indicator of high nutrient levels.

Woody vegetation in the Vredefort Dome

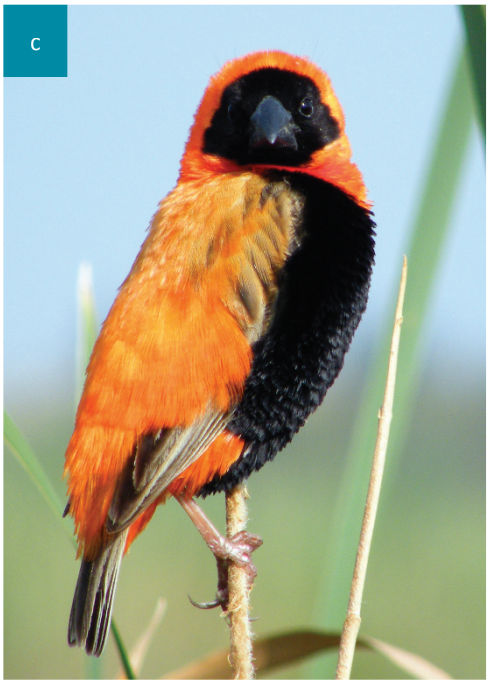
Fifty-five indigenous species with tree numbers, and a further 20 shrubby species that are woody at the base, have been recorded in the Vredefort Dome area. This is considerably less than what has been recorded on the wider Witwatersrand, not very far north of the dome. The major factor contributing to this vegetation of fewer species is most likely frost, which kills the above-ground parts of the trees. Those that cannot resprout from the base or have some other protection against frost, will not survive the more severe winters. It appears that particular trees are restricted to or are dominant on various geological formations (for example, *Acacia karroo* is restricted to rock types that are likely to produce more nutrient-rich soils, e.g. shales, rather than quartzites). Various woody plant communities have been described from the dome (Du Preez and Venter, 1990a, 1990b) and the geological formations on which they occur are indicated. This needs further investigation, however, and an opportunity awaits a keen researcher. An identification guide for the trees and some of the shrubs of the Vredefort Dome is provided in Appendix 1.

Fauna in the Vredefort Dome

The widely varying landscape and vegetation in the dome have created a diverse range of habitats for fauna, ranging from insects to reptiles, amphibians, birds and small and large mammals. The Vaal River with its wooded



† **Figure 150:** A selection of birds seen at Habula Lodge (Parsons Rus; Stop 20).
a. Rock Martin (chicks).
b. Paradise Flycatcher.
c. Freckled Nightjar.
Photographs courtesy of Susan Love.



↑ **Figure 151:** Birds of the Vredefort Dome. **a.** Amethyst Sunbird. **b.** Red-faced Mousebird. **c.** Red Bishop Bird. **d.** Greater striped swallow. Photographs courtesy of Craig Symes.

banks provides excellent habitat for a wide range of bird species (Figs 151, 152). A checklist of the 235 bird species that have been sighted in the dome is provided in the Appendix. With the reduction in agriculture, large parts of the dome area are being repopulated with many antelope species (impala, springbok, sable, roan, gemsbok, hartebees), zebra, wildebeest and giraffe that were formerly present. These join smaller antelope, such as duiker and klipspringer which, together with Vervet monkeys, baboons, jackals and various small cat species have survived despite human encroachment. Unconfirmed reports exist of leopard surviving in the rugged mountain land, and the Savannah Ranch has re-established cheetah in the area. The Johannesburg Zoo's Rietkuil Breeding and Research Farm houses some lion from the zoo and is involved in breeding the endangered wattled crane, as well as buffalo and a variety of antelope. Rocky outcrops in the dome abound with lizards, skinks, rodents and dassies (rock hyrax, Fig. 152c), and porcupines are common. The Vaal River, its numerous tributaries, small wetlands and dams provide abundant habitat for frogs and toads.

← **Figure 152:** The Vredefort Dome contains a wide variety of insects, reptiles, amphibians, birds and mammals, examples of which include:
a. Dung beetle.
b. 'Bloukoppie' (Afrikaans 'blue head') lizard. **c.** Rock hyrax ('dassie').

→ **Facing page: d.** Red-faced Mousebird.
e. African Darter.
f. Pied Kingfisher.
g. Eland.
h. Zebra.

d

e

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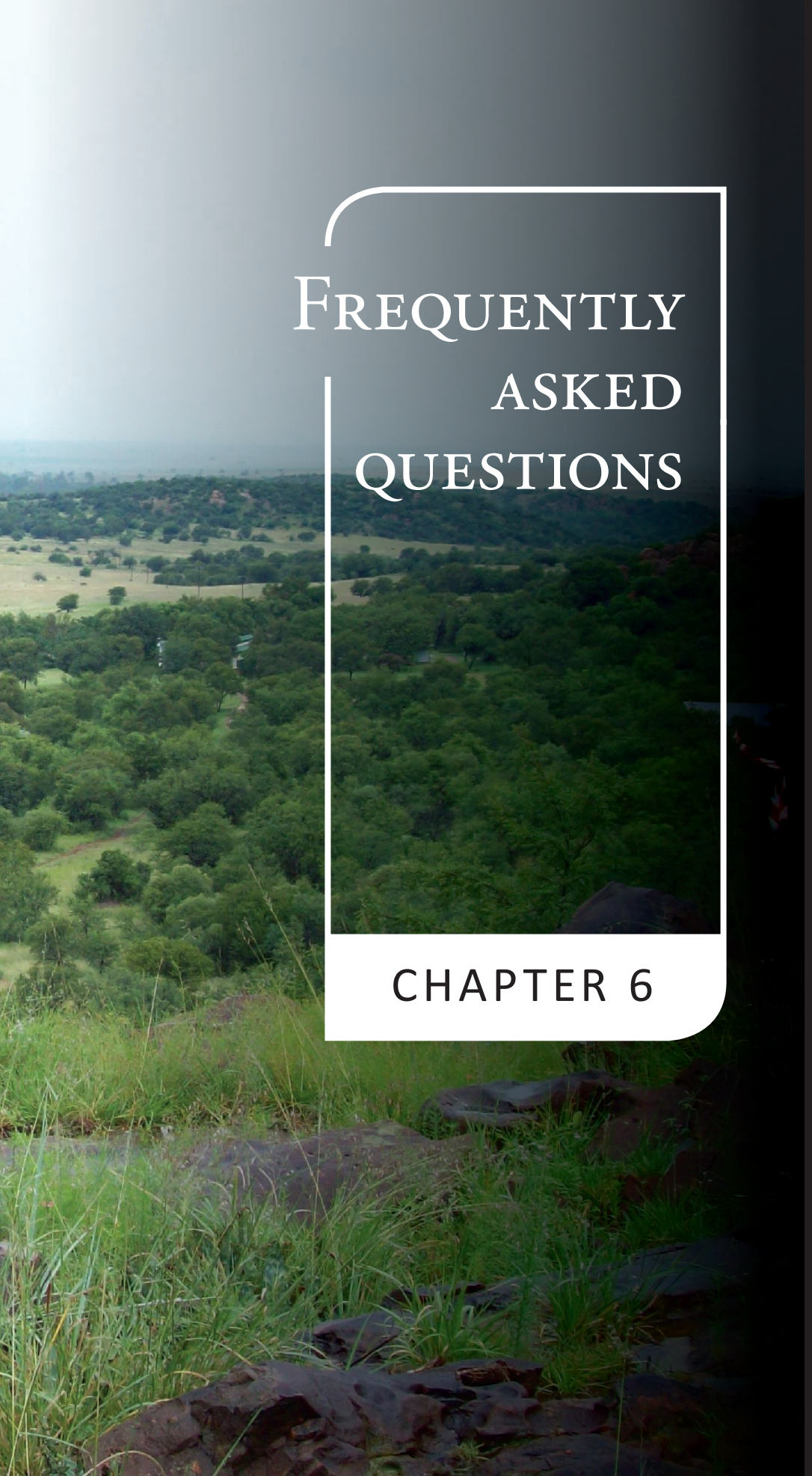


Frequently asked questions

CHAPTER 6

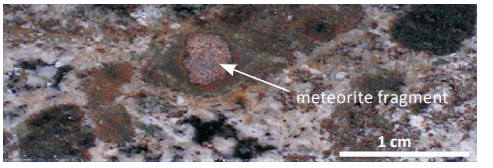
Frequently asked questions about the Vredefort impact event

Where is the projectile responsible for the Vredefort impact?

When an extraterrestrial projectile at hypervelocity (on average 25 km per second) slams into the Earth's crust and explodes, by far most of its mass is entirely vaporised and, consequently, distributed over a vast area. The remainder may be melted, incorporated into impact melted rocks (the so-called impact melt), or may survive as a small fraction of solid particles. With the exception of a few cases where iron-meteoritic projectiles have been retrieved from very small, simple bowl-shaped meteorite craters (for example, Meteor Crater), only in three cases have solid fragments of the projectile been detected within larger craters: in Chicxulub, a particle that is only a few thousandths of a millimetre in size was found in impact melt rock; in the case of the Eltanin meteorite impact into the southern Pacific, several larger, centimetre-sized fragments of the projectile were discovered in deep-ocean drill core; and in South Africa's Morokweng Structure, several chondritic meteorite fragments of up to 20 cm size (which is quite exceptional) were recovered from the impact melt rock (Fig. 153).

The proportion of the projectile component in impact melt rock is normally very small. In most cases where such a component has been traced by chemical analysis, it does not normally exceed 1 % in the melt rock and is usually much smaller. The extraterrestrial chemical component in melt rocks or impact glasses from South Africa's impact structures ranges from mere traces in the Tswaing and Kalkkop craters to 0.2 % in the Vredefort Granophyre and an exceptional 2–5 % in the Morokweng impact melt rock.

It is also not known what kind of projectile — stony, iron or comet — formed the Vredefort impact structure. Chemical techniques available to fully identify the types of projectiles in impact melt rock require a certain minimum amount of projectile incorporated, which is not the case for the exposed Vredefort Granophyre.

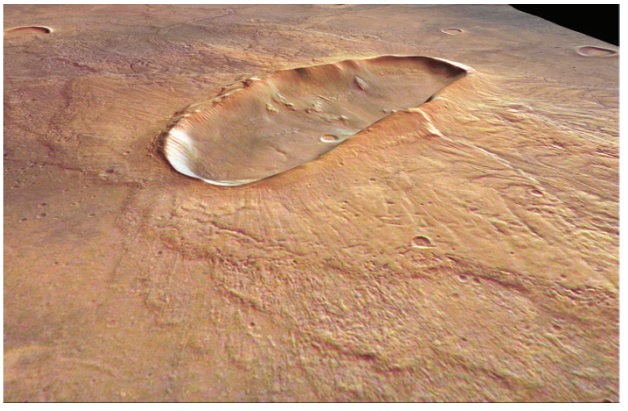


↑ **Figure 153:** A sample of drill core from near the base of the Morokweng impact melt breccia that contains a small chondritic meteorite fragment. Preservation of actual bolide fragments in impact melt rock appears to be extremely unusual. Photograph courtesy of Wolfgang Maier.

Do we know from which direction the Vredefort bolide came?

This question is often asked, especially as people note that the Vredefort Dome appears highly asymmetric (Fig. 1), with a pronounced overturned collar in the northwest and northern sectors that seems to be lacking in the southern parts (see Fig. 78, page 119). There are several possible ways to answer this question. First, the law of averages would suggest that the Vredefort bolide impacted at an angle of about 45°; however, projectiles arriving at great speed will always explode on impact in a manner that produces a shock wave that will expand outwards from the explosion centre in a spherical form. Thus, the shock deformation and crater excavation patterns will almost always have a circular geometry on surface. Only when a projectile impacts at a very low angle (less than 15°) can a significant crater asymmetry (Fig. 154) be expected to develop, as the projectile's momentum directs a larger component of the explosive force downrange (that is in the direction of the projectile path; Fig. 154b). Grazing impacts can result in

↑ **Figure 154a:** The strongly eroded Matt Wilson impact structure in Australia is the first documented asymmetric impact structure on Earth. Its elliptical shape (6.3 km wide by 7.5 km long) is the result of a low-angle (less than 15°) impact from the northeast. A further clue to the oblique impact is indicated by the central peak which is also elliptical and displays northwest–southeast trending 'wings' formed by erosion of blocks thrust to the southwest by faults during the impact. Aerial photograph courtesy of Thomas Kenkmann, reproduced from Delamere colour aerial photograph, Run 7, No. 6 Photography, Northern Territory of Australia.



← **Figure 154b:** Elliptical impact crater on Mars produced by a very low angle of impact. The 24.4 km long and up to 11.2 km wide crater was photographed with the high-resolution stereo camera (HRSC) on board of the European Space Agency's Mars Express spacecraft. It is called a 'butterfly crater' because of the lobes of ejecta lying on either side of the elongate crater. The distribution of the ejecta indicates that the bolide was moving towards the left when it impacted. The absence of ejecta in the up-range and down-range directions is a feature of impact angles that are not much lower than 30 degrees. Image reproduced with permission of Gerhard Neukum, Geowissenschaften, Freie Universität Berlin. http://www.geoinf.fu-berlin.de/projekte/mars/hrsc217-ButterflyCrater.php.

very elongated, shallow crater forms, as for example those known from the Rio Cuarto crater field in Argentina, but a survey of thousands of craters on the Moon shows that non-circular shapes such as the one shown in Fig. 154b from Mars are extremely rare.

Second, the fact that the topographic expression of the dome is asymmetric (see Fig. 172, page 247) can be explained by the dome being covered in the south and southeast by flat-lying, highly weathered rocks of the Karoo Supergroup (compare Figs 3b, 86 and 172). In other words, the dome may originally have been exposed at surface as a circular feature, but the southern half was planed off 300 Ma ago by the Dwyka glaciation, and then covered by younger sediments.

The third component of this problem is structural — the few outcrops of collar rocks that are found in the southeastern part of the dome do not seem to show the extreme overturning seen in the northwestern collar and have been the source of much speculation by geologists. For instance, it has been proposed that the projectile impacted from the southeast, that the impact structure was tilted down to the northwest after it formed, or that the layers were tilted down to the northwest before the impact. To explain the asymmetry purely through regional tilting is impossible, because the angles required are too large; however, more localised disruption of the layers could achieve this. The gravity and magnetic images (Fig. 79, page 121, and Fig. 85, page 130) indicate that the collar strata do not complete a simple circle in the southeast. It is believed that this reflects two or more large pre-impact faults in the target rocks, and that these faults also caused rotation of the strata in the southeastern sector before the dome formed. This scenario is fully in agreement with regional studies in the Witwatersrand basin that show several generations of faulting, folding and block rotation prior to the impact at 2 020 Ma. In short, it would be naïve to think that the Vredefort bolide hit a crust that was made up of a series of exactly horizontal layers.

Further work is needed to fully answer the question of the Vredefort bolide's direction, but the answer may never be found. With regard to the other South African impact structures, one notices that Kalkkop is perfectly circular (Fig. 74). The Tswaing Crater must have been circular at crater formation, but appears hexagonal on some imagery (for example on Landsat satellite images) because of the presence of some radial fractures that have segmented the crater rim. Morokweng is deeply eroded and barely exposed in the Kalahari Desert. Whereas the geophyscial images seem to indicate some ovoid shape for the central impact melt body, this does not necessarily mean that the whole crater structure was originally of asymmetrical geometry.

Do we know how large the bolide was that caused the Vredefort catastrophe?

This is another difficult question to answer. While it is possible, in principle and with the help of some empirical (based on some observations that have been generalised) equations, to calculate roughly how much energy would have been needed to produce a 250–300 km impact structure, it is more difficult to translate this number into projectile size. Ignoring for the moment that there is a significant variation in size estimates for the crater, the main problem is that there are four variables involved if we are working backwards from the crater size to the projectile size. The energy to form the crater comes from the kinetic energy of the projectile. The equation to determine kinetic energy is $E_k = 2\ m\ c^2$. Both unknowns — the projectile mass (m) and the velocity (c) — are, in the case of Vredefort, unconstrained. Mass, in turn, is controlled by both the size and the density of the projectile. Without clues to the composition of the bolide (i.e. stony, metallic, a mixture of silicates and metal, or a rock and ice comet), we have no means to constrain the size. On average, comets travel much faster than asteroids. Then there are other variables, such as the angle of impact, that may have to be taken into account. Inputting end members for these variables results in possible bolide diameters between 5 km (for a dense, very fast body) and 15 km (a relatively low-density comet travelling at average comet speed). Of course, given the known shapes of asteroids and comets (Fig. 15), it is highly unlikely that the Vredefort bolide would have been perfectly spherical.

Could any life forms have perished in this catastrophe?

As discussed earlier, at the time of the impact, about 2 020 Ma ago, the most sophisticated life forms on Earth were unicellular, in essence equivalents to today's algae. We know that the Transvaal Sea covered a large region of the Kaapvaal craton up until at least 2 150 Ma and we know that algae were thriving in this environment because stromatolites (see Figs 25–27) are common in the Transvaal Supergroup dolomitic rocks found in the vicinity of the dome. However, we cannot be absolutely certain that at 2 020 Ma the shallow sea actually still existed in the area that was hit. It is equally possible that the impact occurred into dry land.

Would this impact have influenced further development of life?

Primitive life forms seem to be generally rather resilient, even to global catastrophe. A perfect example is the cockroach that first evolved some 600 Ma ago and has never really had to change significantly since then, despite several mass extinctions in the intervening years.

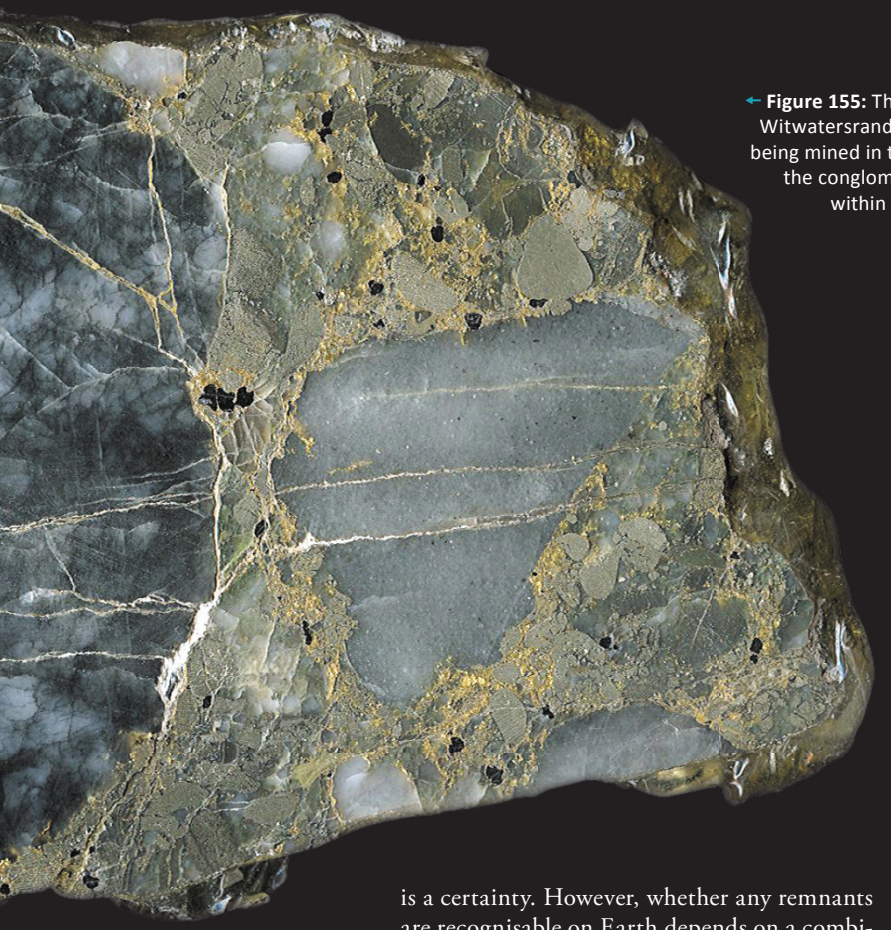
Thus, it is safe to assume that at least some algae species survived the Vredefort impact. It is, however, not impossible that the ensuing global environmental catastrophe caused a slight setback in the development of further life, but our very limited fossil record for the long interval between the Proterozoic algal domain and the first explosion of life in the Cambrian (ca 600 Ma; see Fig. 8) does not allow a reconstruction of this path of development to verify the possibility. It is equally possible that the impact-induced environmental catastrophe could have resulted in accelerated diversification of life forms.

In addition, there is no reason to assume that the Vredefort impact was the only catastrophe of such magnitude on Earth during the entire interval between 2 020 Ma ago and the major mass extinctions known to have occurred after about 450 Ma ago. Indeed, there was at least one other massive catastrophe that we know of, the Sudbury impact, about 170 million years after the Vredefort event. Projections regarding the frequency at which such large impact events take place suggest that one could have happened as frequently as about every 100 million years. This means that there must have been more of these catastrophes between the Vredefort event and the massive diversification of life in the Cambrian. Every one of these events may have caused a change in the evolution path of life on Earth. For instance, there is a school of thought that maintains that, before their reign was abruptly terminated by the Chicxulub impact 65 Ma ago, the dinosaurs could have received a helping hand from another impact 145 Ma ago that wiped out countless other species. As was already noted, however, global environmental catastrophes leading to mass extinctions may also be driven by internal mechanisms on Earth as, for instance, may have been the case on Earth 251 Ma ago.

Can there be other impact structures of the size of Vredefort, not yet discovered on Earth?

Without doubt, the known record of impact structures on Earth is not complete. Slightly more than 175 impact structures have been confirmed (see http://www.unb.ca/passc/ImpactDatabase/ for an updated list), with many unconfirmed structures remaining to be proven. Furthermore, considering how much of the Earth's surface has not yet been thoroughly explored by geologists, especially by geologists who are familiar with impact recognition criteria, many others remain to be discovered. The fact that few craters are known from the Developing World indicates that raising awareness of cratering as a geological process may be the most important factor in finding new discoveries. For instance, only one sizeable impact structure has to date been discovered in the entire vast region between the Mediterranean Sea and India (Jebel Waqf as Suwwan in Jordan) and Africa's crater distribution is symptomatic of the differing levels of sophistication in geological knowledge across the continent.

There have no doubt been many craters even larger than Vredefort — we only need to look at the 2 500 km diameter South Pole-Aitken Basin on the Moon (Fig. 51a, page 68) and the larger asteroids and comets still remaining in the Solar System to know that this



← **Figure 155:** The Ventersdorp Contact Reef — the youngest unit in the Witwatersrand Supergroup — is the richest of the gold reefs currently being mined in the Witwatersrand basin. The gold occurs mainly within the conglomerate matrix but has also been mobilised into fractures within the quartz pebbles. Image courtesy of Carl Anhaeusser.

is a certainty. However, whether any remnants are recognisable on Earth depends on a combination of fortuitous circumstances: they must have impacted into continental crust that cannot have undergone significant deformation, uplift or burial since their formation — which is rare in a planet with an active geosphere such as Earth.

Major diamond, gold and platinum resources lie close to the Vredefort Dome. Why have no major ore deposits been found in the dome itself?

It is not entirely correct to assume that no precious-metal deposits have been found in the rocks of the Vredefort Dome. Since the earliest prospecting for gold in the conglomerates of the Witwatersrand Supergroup in the region around Venterskroon in the second half of the 19th Century, it has been known that gold is present in reefs (conglomerates (Fig. 155) in the rocks of the Venterskroon area as well. However, the historic mining activity of the late 19th and early 20th centuries has shown that gold is not as abundant in the dome as it is in the same rocks around the margins of the Witwatersrand basin. The reason for this goes all the way back to the time of deposition of these rocks at about 2 800 Ma ago, some 800 million years before the impact event. It has been well established that the gold was derived from mountain belts made up of rocks similar to those exposed today in the Barberton Mountain Land. There, granitic rocks older than 3 000 Ma intruded even older (up to 3 600 Ma old), so-called greenstone rocks. These greenish rocks are the alteration products of the first oceanic crust developed on this planet. In many places within the Barberton Mountain Land gold occurs in mostly quartz-rich veins and networks of veins, and has been mined there for more than a century.

When, many millions of years from now, the Barberton Mountain Land will have succumbed completely to erosion, the debris from this region will have been deposited in a low-lying sedimentary basin. Within these sediments will be the remaining Barberton gold. This is exactly the same process that happened 2 800 Ma ago: granitic and greenstone material was shed from its original highlying source area into the lowlands that became the Witwatersrand basin. Streams, often braiding in the fashion of deltas, deposited the sediment that also contained appreciable amounts of gold. As gold is heavy, the bulk of it would have been deposited from the streams in the upper reaches, whilst less-dense, and finer particles would have been swept farther downstream. It is thought that the areas in the outer parts of the Witwatersrand basin represent areas closer to the original source of the gold, whereas the rocks belonging to the same layers, but occurring farther south in the area

of the Vredefort Dome, represent downstream deposits. Thus, the gold grade, the amount one would recover per tonne of rock mined, is less in the area of the dome than in the traditional mining areas of the Golden Arc. In summary, despite the fact that the richest gold mines in the Witwatersrand basin lie within the area of the Vredefort impact structure, the gold deposits predate the impact. There was not — as some have speculated — a golden meteorite. The only effects of the impact on the gold deposits were the structural disturbances that tilted, downsagged and upthrusted the layers, and limited redistribution of the gold in the reefs by hydrothermal fluids circulating through the impact structure.

Since the mid-1990s several mining companies have investigated the possibility of mining the reefs in the northwestern part of the Vredefort Mountain Land. Open-cast mining would be the most viable option as it is much cheaper than underground mining. However, the environmental consequences for this scenic region would be severe, not only in terms of noise, dust and water pollution but also for aesthetic reasons. A positive spin-off of the exploration in the 1990s was the consolidation of the interests of the local landowners in establishing the dome as an ecotourism destination that, ultimately, led to the World Heritage Site declaration.

In the southeast, in the rocks of the Greenlands greenstone area, gold-bearing quartz veins were investigated for a few years from 1889. Some small, though allegedly rich, pockets of gold and silver were opened up, similar to those found near Barberton, but the ores were too small and scattered to warrant profitable exploitation.

Louis Nel, in his explanation to the first-ever geological map of the Vredefort area in 1927, reports that diamond diggings in the dome were, in contrast to the gold-mining activity, quite successful. He provided a figure of profit, for the years 1919–1926, of 21 275 pound sterling, in those days quite a sizable sum. Diamonds were extracted from gravels dug up in the old river terraces along the Vaal River. Such diggings can still be found in many places extending from the northeast of the dome (for example, near the Savannah Resort to the north of Parys) along the river into the Venterskroon valley.

A considerable volume of dimension stone (quarried blocks of a building or ornamental stone that have specific dimensions) has been mined from a number of quarries that operated for some 50 years in the outer core of the dome until the mid-1990s. The very attractive stone, known as Parys Granite or as African Jiparano (after a similar-appearing rock from Brazil), was cut into big, rectangular blocks in the quarries and then transported to the Parys railway station, from where the blocks left by train and/or road to the coastal harbours. Most of this granite was shipped to Italy, for the production of polished ornamental slabs (for example for the cladding of building faces), but some prominent buildings in South Africa are also adorned with Parys Granite (see Fig. 182).

Is Vredefort truly unique?

'Oldest', 'biggest', 'most deeply eroded' are all adjectives used to describe the Vredefort impact structure. It may not hold on to all, or any, of these titles in the years to come as scientific investigation spreads around the world and becomes ever more sophisticated; however, it is instructive to note how the scientists themselves view the structure and, particularly, the Vredefort Dome. In terms of its size and the level of exhumation, the Vredefort Dome is exceptional. Comparisons with other impact structures show that the quality of the rock exposures and the ease of access make it unique. Whilst other impact structures are associated with mineral deposits, the scale of the gold deposits in the Witwatersrand basin make it, arguably, one of the top two ore deposits in the world. Finally, the considerable scenic attraction, the natural heritage and the largely undiscovered archaeological and cultural-historical heritage of the dome area add considerably to its uniqueness. What has been less well known is that the uplift that formed the dome has exposed a continuous section of the Kaapvaal continental crust that is over 25 km thick — one of only a few places in the world where such a deep crustal section is exposed. That this section is made up of some of the oldest rocks on Earth is a further bonus. Therefore, the short answer to this question is that the Vredefort impact structure is one of the great geological wonders of the world!

← **Figure 156:** Mrs Ples, the most complete skull in South Africa of what was later identified as *Australopithecus africanus*, was discovered by Dr Robert Broom in the Sterkfontein caves (Cradle of Humankind) in 1947.

The Cradle of Humankind is a World Heritage Site

Is the Cradle of Humankind related to the impact structure?

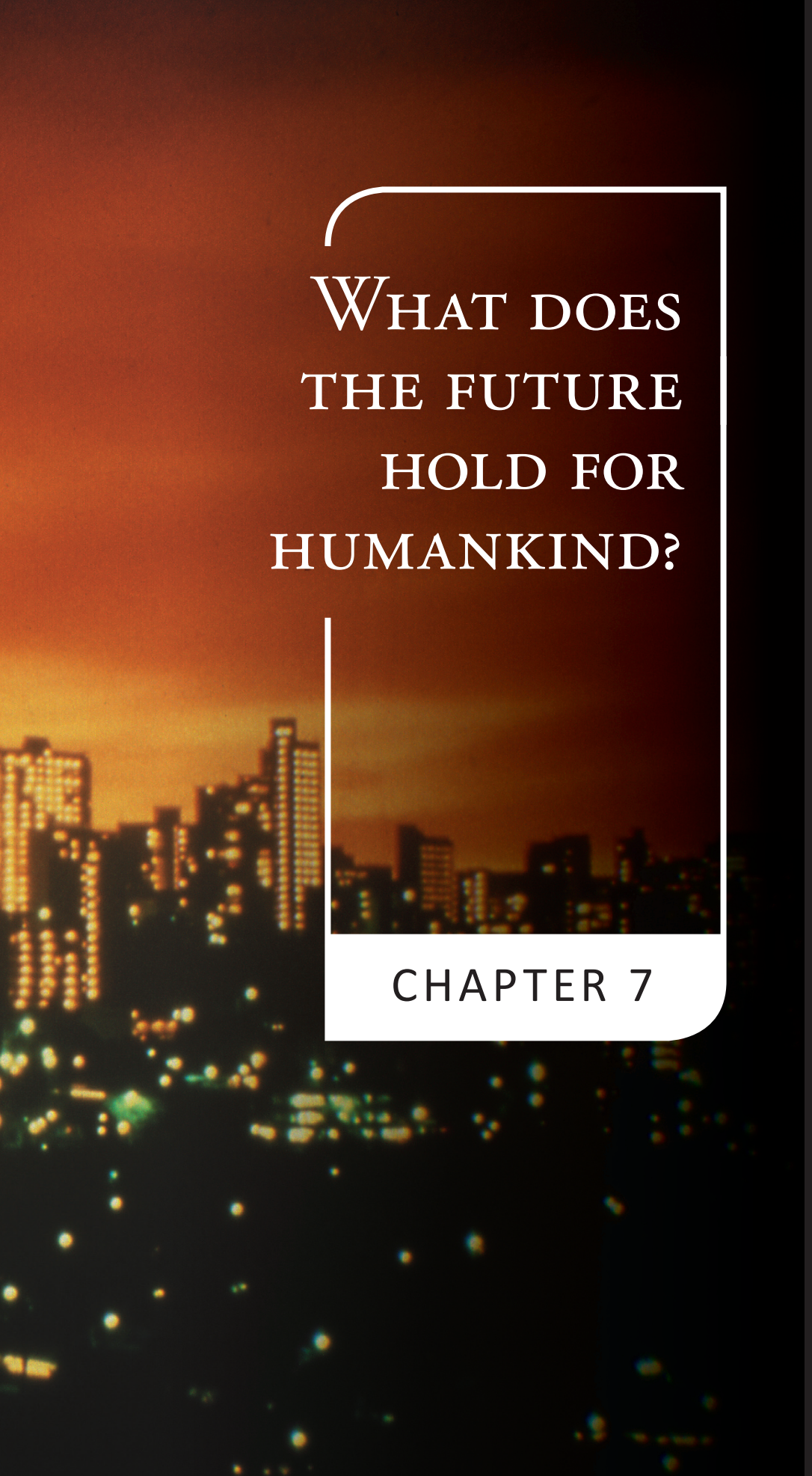
To the northeast of the Witwatersrand basin lies one of South Africa's premier heritage areas, the Cradle of Humankind. This fantastic area, with fossil-rich caves and diggings, was declared a World Heritage Site in 2001 because of its rich evidence of hominin life dating back perhaps as far as 3 Ma (Fig. 156). The Cradle of Humankind lies about 40 km northwest of Johannesburg and the Witwatersrand basin, in the area where today we would assume the edge of the impact structure to have been (Fig. 81). This important site is situated just north of the mighty quartzite ridge that gave its name to the Witwatersrand. One only has to look at the rocks exposed along the ridge, for example in the Walter Sisulu Botanical Garden (Fig. 33) or farther east towards the Johannesburg suburb of Florida, and it becomes obvious what gigantic forces must have been at play to deform or shatter these rocks.

Sterkfontein and the other caves in the Cradle of Humankind occur in dolomite rock of the lower Transvaal Supergroup, where they were formed when weakly acidic groundwater penetrated the fractured rock and dissolved the carbonate minerals. Some geologists in recent years have questioned whether it is possible that the original fracturing and brecciation of these rocks could have been caused by the Vredefort impact. Although brittle impact deformation is, indeed, likely to have extended as far as this area, there are many other deformation events — both before the impact and in the ensuing 2 000 million years — that could also have produced fractures. This far from the impact site there are no shock-diagnostic features that could help to discriminate impact deformation from normal tectonic deformation. Thus, whether an impact-induced crack or breccia pod occurred exactly where the Sterkfontein Caves developed, is impossible to say. The caves themselves appear to be only a few tens of millions of years old and cannot be directly linked to the impact or its aftermath. The fact that the cave breccias contain hominin and other fossils indicates that brecciation is not necessarily evidence of impact.

Whatever happened, the fact that the Cradle of Humankind World Heritage Site is located close to the edge of the world's largest known impact structure, between what many geologists regard as the world's two greatest ore deposits, is truly remarkable.

↑ Iniekom Farm – scenery along one of the hiking trails (compare description of Stop 9)

Johannesburg at dawn. Image courtesy of SA Tourism.



What does the future hold for humankind?

CHAPTER 7

What does the future hold for humankind?

July 17 1994: impact on Jupiter! The world held its breath as the first fragment of Comet Shoemaker-Levy 9 smashed a hole the size of Earth into the largest planet in our Solar System (Fig. 13, page 26). During the following days the entire string of comet fragments impacted and the planet was encircled by a series of dark impact scars in its atmosphere that remained visible for months. These fragments were only 100–200 m in diameter, but caused gigantic impact features into which Earth would have fitted snugly! Bombardment of such relatively small cometary or asteroidal bodies into Earth's rocky crust would not have caused quite such dramatic holes, but the resultant craters would still have been between 1 and 3 km in diameter and, critically, would have been surrounded by broad regions up to tens of kilometres wide that would have been devastated by the air blast wave. Any marine impacts in shallow water would have raised the additional threat of tsunamis along adjacent coastlines.

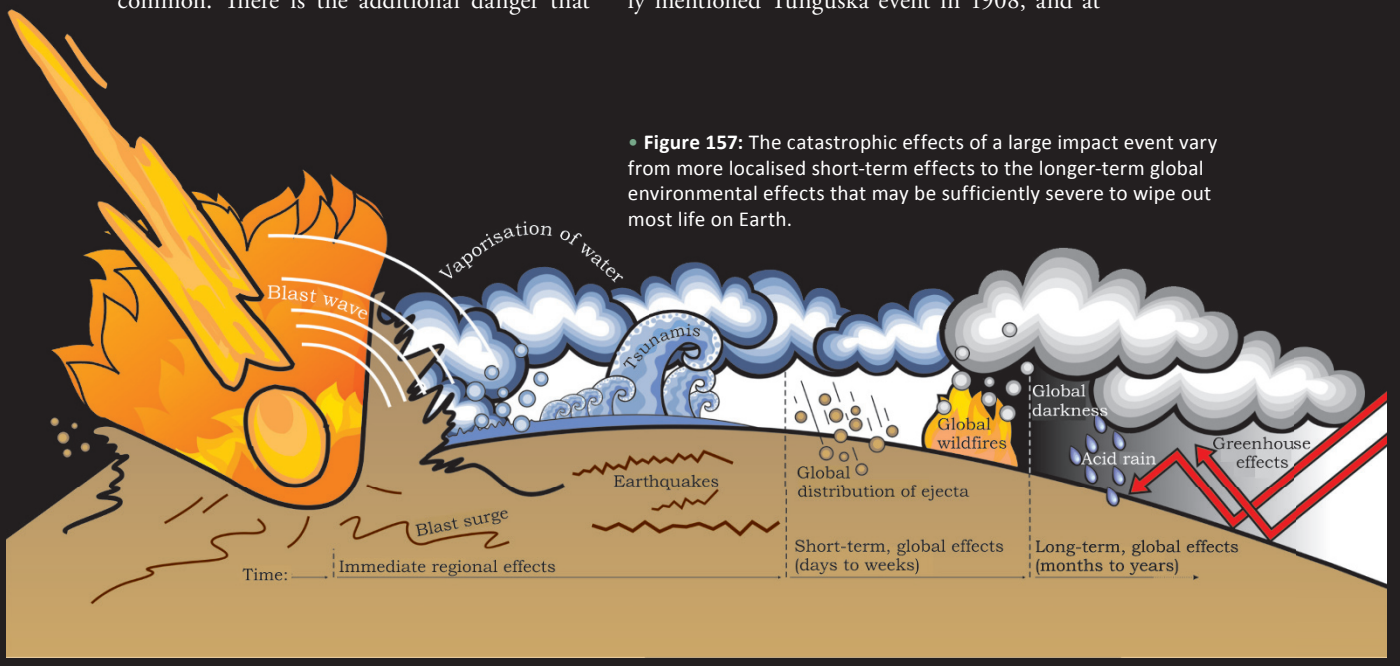
In trying to assess the threat posed by impacts it must be recognised that, as with volcanoes, this threat exists at two levels. These levels are the actual event that may last only seconds to minutes, and the longer-term environmental effects (Fig. 157). As with volcanoes, the longer-term effects become more important as the size of the initial event increases. Short of being struck directly by a falling meteorite fragment, the chances of a bolide of less than 50 m diameter threatening life is negligible. Nevertheless, damage to buildings and property by falling meteorites has been rare in the past. Whilst individual 'stones' ranging from centimetres to fist-sized are more common, the Thuate meteorite fall of July 21 2002 in Lesotho provides an example of what happens when a larger body enters the atmosphere and breaks up as a result of the severe stresses caused by the atmospheric resistance. This 'shotgun-blast' produced over a thousand stony meteorite fragments (Fig. 158) that rained down over a 7.4 x 1.9 km strewn field. The 60 tonne Hoba iron meteorite in Namibia — the largest single meteorite in the world — indicates that not all meteorites break up into small pieces. Iron meteorites, as a rule, have much more strength than stony meteorites. Impacts of such relatively small meteorites are sufficiently violent to cause small craters in soil. For instance, on 15 September 2007 a small meteorite impacted near the town of Carancas in Peru, forming a 14.2 m diameter crater (Fig. 159).

Small impact craters in rock on Earth, such as Meteor Crater and the Tswaing Crater, are about 1 km in diameter and involve bolides in the 50–100 m range. Energy estimates for the creation of such craters suggest a 15–20 Mt (megatonne) explosion. It is instructive to note that many tactical nuclear warheads, designed to destroy a large city, are in the 1 to 2 Mt range, and the weapons used at Hiroshima and Nagasaki at the end of World War II were both considerably less than 0.05 Mt. Thus, the formation of even the smallest impact crater on Earth is a devastating event. If an impact of the magnitude of the Tswaing event occurred in the wider Pretoria–Johannesburg region today, the result would be the loss of possibly as many as several million lives, and the devastation of the economic heartland of South Africa. A century ago (1908) a similar-sized explosion of an extraterrestrial projectile in the upper atmosphere over Siberia devastated over 2 000 km^2 of tundra forest in the remote Tunguska region. If the bolide had entered the atmosphere no more than a few minutes earlier or later, it could have devastated any one of dozens of densely populated cities in Europe or China.

The strike from a 1 km sized bolide would produce a crater in the 10 to 20 km diameter range, but devastation would extend over a 1 000 km wide zone — in other words, over much of a country the size of South Africa. Astronomers searching for asteroidal and cometary bolides and trying to identify those in Space that could present a real danger to Earth, have charted about 5 000 asteroids, many of which have sizes between 100 m and 1 km. (There are far more asteroids in the size range between 10 and 100 m — at least 10 million!) Many of these are likely to remain in orbits that do not cross the planetary orbits. However, the orbits of some — such as the Apollo and Aten asteroids, could potentially cross Earth's path. The Apollo, Aten — and a third group, called the Amor asteroids that cross the orbit of Mars and approach that of Earth, but do not cross it — together form the class of Near-Earth Objects (NEOs) that are being catalogued by astronomers.

Comets (Figs 18, 160) are even more of an unknown threat than asteroids because they occur mostly undetected in the outermost limits of the Solar System and beyond and their orbits are, for the most part, uncharted. They are also far more numerous than the asteroids, travel faster, and are generally larger, with diameters of tens to hundreds of kilometres being common. There is the additional danger that their orbits may be subject to periodic change because of interference from the gravitational fields of large planetary bodies, such as Jupiter, that could drag previously harmless comets onto Earth-crossing trajectories.

Calculated flux rates of extraterrestrial bolides onto Earth and the known impact-cratering records for various planets and satellites in the Solar System provide a basis for probability estimates on how often impact events of certain magnitudes might be expected to happen on Earth. Bearing in mind that Earth's dynamic surface has led to the destruction or burial of most of its craters, and acknowledging that the cratering flux rate was considerably greater during the early history of our Solar System, it is possible to make some general predictions. According to these calculations, a global catastrophe capable of threatening most life on Earth with extinction could happen once every 100 million years or so. Events of smaller magnitude, causing impact craters in the 20–50 km size range and continental-scale devastation, could occur as often as once in every 500 000 to several million years. Smaller impacts, of the size of the Tswaing event, are much more common and may occur as often as every thirty to hundred years. The 20th Century saw at least two of these 'small' impact events: the previously mentioned Tunguska event in 1908, and at



• **Figure 157:** The catastrophic effects of a large impact event vary from more localised short-term effects to the longer-term global environmental effects that may be sufficiently severe to wipe out most life on Earth.

least one other in the 1930s in the South American rainforest. Documented impacts on Earth during the 1990s (based on published military records) included 23 events caused by objects with diameters between 2 and 39 m. Fortunately, the 39 m projectile landed in the Pacific Ocean, and the next-largest bolide impacted into the sea some 1 000 km from the nearest shoreline. Regularly updated websites, such as: http://tin.er.usgs.gov/meteor/index.php; http://www.cfa.harvard.edu/icq/meteorites.html, and http://www.jensenmeteorites.com/New%20meteorites.htm, provide evidence of the continuous bombardment of our planet, including such notable events as the 3 m Carancas meteorite on 15 September 2007, and a meteorite strike in a remote corner of Sudan on 6 October 2008 that has the distinction of being the first time that a meteoritic projectile was discovered before it struck Earth's surface and was tracked to its fall site.

Given the frequency of smaller meteorites colliding with Earth, it is only a matter of time before an asteroid large enough not to be slowed down by atmospheric drag collides with our planet, with violent consequences. As our detection systems become better attuned to the threat, it is clear that such asteroids are continually passing close to Earth. Asteroid 2007 TU24, estimated at 250 m in size, passed within 538 000 km of Earth on 29 January 2008. A much larger asteroid — the 4.6 x 2.3 x 1.9 km 4179 Toutatis — passed 1.5 million km from Earth on 29 September 2004. The second-largest Near-Earth Asteroid, the 34.4 km long and 11.2 km wide 433 Eros, has a 5 % probability of colliding with Earth during its likely lifespan of 50–100 million years, but not in the near future, which is a relief considering that it is at least twice the size of the Vredefort impactor!

The only way to further improve our knowledge of the potential threat inherent in the known and unknown asteroid and comet populations is to continue, with all means available, to chart Space for still unknown asteroids and comets. Several organisations, such as the British Spaceguard venture, the US-based Catalina Sky Survey, and the Siding Spring Survey based in New South Wales, Australia, have embarked on such programmes; but Earth could benefit from a more broad-based programme with better funding. In addition, the Space Agencies of several countries are investigating the composition and internal structure of asteroids and comets (see Fig. 17) to better understand their nature and, thus, their likely behaviour during impacts. Geologists who study meteorites and impact craters both on Earth and on our planetary neighbours also attempt to identify the composition of the projectiles that caused these impacts, thus contributing to our understanding of the nature of possible intruders and the physical consequences of catastrophic impacts.

Catastrophes such as earthquakes, volcanic eruptions, gigantic storms and floods have been part of Earth's history since it formed. Such ca-

↓ **Figure 158:** Two of the more than one thousand fragments of the Thuate meteorite that fell in Lesotho on 21 July 2002. An 8 cm long, 450 g, fragment (at left) shows a shiny fusion crust and smoothed edges caused by ablation. A smaller, unusually shaped fragment (at right) shows a lighter patch where the fusion crust has been chipped off. Images courtesy of Ronnie McKenzie, Pretoria.

tastrophes contribute to the steady background of extinctions of regional or local importance that may affect species. With the exception of massive volcanic eruptions, such individual disasters are not seen as globally threatening to life and, more specifically, to humankind. However, this does not apply to the threat from a large meteorite impact. A single blow from a projectile of the size that wiped out the dinosaurs and their companions 65 Ma ago could virtually annihilate humankind and would set civilisation back centuries, if not millenia. Smaller impacts, involving 1–2 km bolides, will not be globally as destructive, but could be significant enough to cause global famine because of short- to medium-term environmental effects caused by the large quantities of dust and aerosols ejected into the atmosphere and stratosphere, and are likely to be far more common.

Bearing in mind that both the size and the frequency of impacts contribute to the threat they pose to humanity, a danger scale for large impact events was created by the Spaceguard Foundation in 1995. Analogous to the Richter Scale for earthquakes (see page 54), the Torino Scale combines the size (energy potential) of the event with its predicted frequency. The size of the event is directly translated into the scale of damage (local, regional, or global devastation). In contrast to the Richter Scale, which provides a continuous measure for the direct energy release of an earthquake, the 10 levels of the Torino Scale are discontinuous; this is because the Scale factors in several independent parameters.

Figure 159: The 14.2 m wide Carancas crater was formed on 15 September 2007 in Peru by a small (less than 5 tonnes) stony meteorite. Note the somewhat raised rim and distribution of ejecta blocks on and around the crater rim. Photograph courtesy of Thomas Kenkmann, Berlin.

The probability of an impact is calculated on the basis of data, such as the terrestrial cratering record or the abundance of asteroids of specific size ranges. If the mass and approximate speed of a projectile are known, the likely kinetic energy released on impact can be calculated. For example, an event of Torino Scale level 5 would generate kinetic energy of about 100 to 400 Mt (0.1 to 1 km bolide), which clearly poses a threat on a regional scale. However, the bolide may only have a probability of collision with Earth as low as one per cent. An event of similar energy release may also be classed as 1, if the probability that it could occur is considered much lower. However, if such a bolide had a probability of collision with Earth of more than 99 %, it would be rated as a 9 or 10 on the Torino Scale.

THE TORINO SCALE

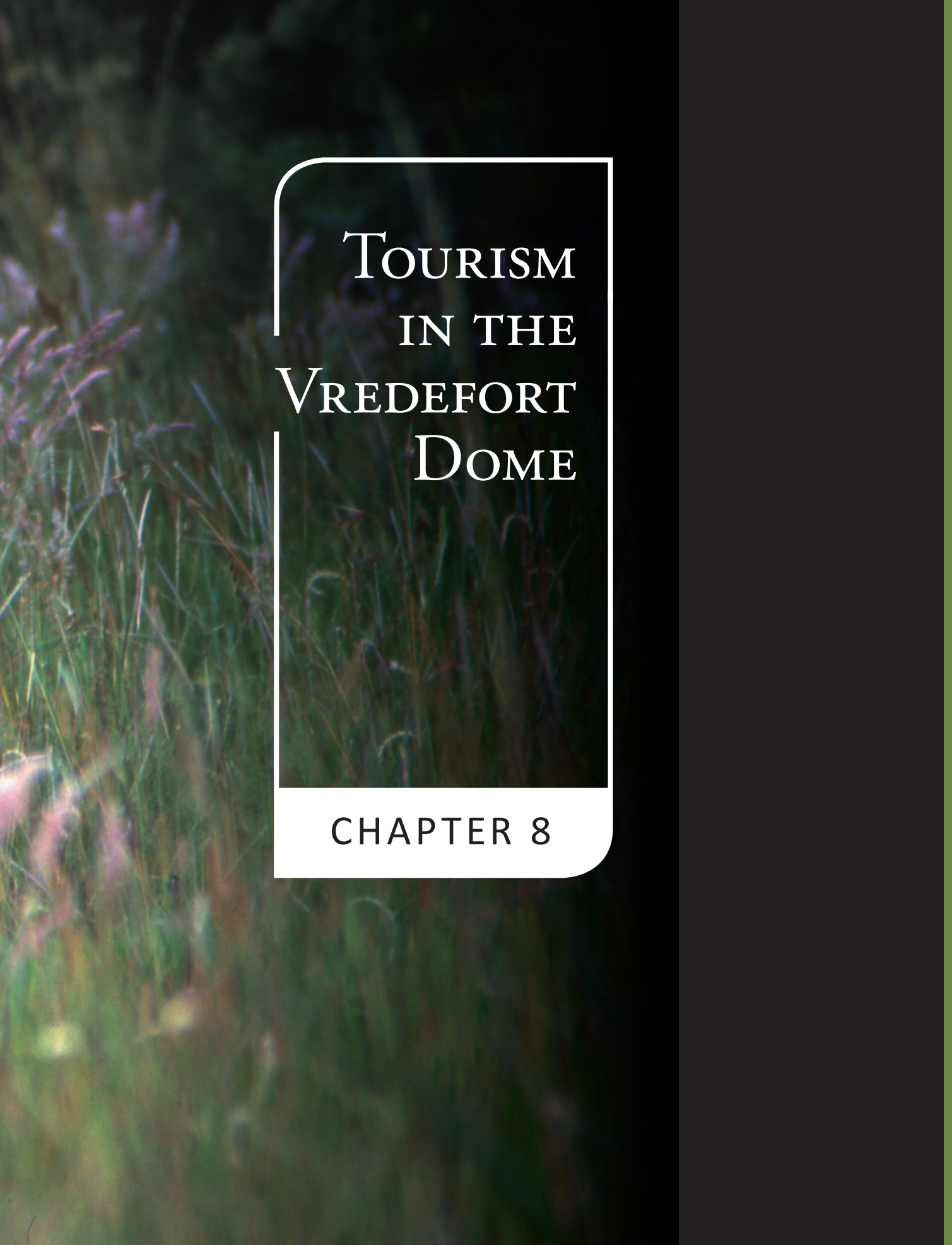
ASSESSING ASTEROID AND COMET IMPACT-HAZARD PREDICTIONS IN THE TWENTY-FIRST CENTURY

No hazard	0	Zero likelihood of collision; also applies to small objects that are unlikely to reach Earth's surface intact if a collision occurs.
Normal	1	Likelihood of a collision is extremely low and no cause for public concern, with further measurements likely to re-assign it to Level 0.
Meriting attention by astronomers	2	A somewhat close but not unusual pass near Earth; no cause for public concern, with further measurements likely to re-assign it to Level 0.
	3	A close encounter with a ≥1 % chance of collision capable of causing localised destruction. Bring to public attention if encounter is within the next ten years. Further measurements likely to re-assign it to Level 0.
	4	A close encounter with a ≥1 % chance of collision capable of causing regional devastation. Bring to public attention if encounter is within the next ten years. Further measurements likely to re-assign it to Level 0.
Threatening	5	A close encounter posing a serious but still uncertain threat of regional devastation. Government contingency planning needed if encounter is within the next ten years.
	6	A close encounter posing a serious but still uncertain threat of global catastrophe. Government contingency planning needed if encounter is within the next thirty years.
	7	A close encounter posing a serious but still uncertain threat of global catastrophe. International contingency planning needed if encounter is within the next century.
Certain collisions	8	A certain collision capable of causing localised destruction (average frequency every 50 to 1 000 years).
	9	A certain collision capable of causing regional devastation (average frequency every 10 000 to 100 000 years).
	10	A certain collision capable of causing global climatic catastrophe that would threaten civilization (average frequency every 100 000 years or more).

So what are the chances of death by meteorite impact? In 1994, Clark Chapman and David Morrison published accidental-death statistics in the journal Nature. They concluded that the odds of a person dying in an automobile accident are 1 in 100, in a homicide 1 in 300, accidental shooting 1 in 2 500, and in an aircraft crash 1 in 10 000 to 30 000. In contrast, dying of a snake bite or insect sting was assigned much-reduced odds of 1 in 100 000, and death in a fireworks accident has odds of 1 in 1 million. These authors calculated that the average accidental-death probability for impact is of the same magnitude as that of death by aircraft crash, at about 1 in 10 000 to 30 000. From an insurance perspective, this means that it is much more dangerous to move in traffic than to live in a busy Solar System. However, just as the odd aeroplane crash that kills hundreds of people in a single event appears much more disastrous on a given day when many more people die in road accidents, so too would a single impact event. Part of the fear stems from the realisation that, whilst we have special safety measures that give us a chance of surviving many types of road accident, suitable technology has not yet been deployed to protect us from any future impacts or, for that matter, from an aircraft falling out of the sky. The crux of the matter is that a global impact catastrophe could happen at virtually any time and at any place. However, since the Shoemaker-Levy 9 impacts into Jupiter, the recognition of the threat posed by asteroids and comets has prompted concerted international efforts to not only quantify, but also to try to reduce, the threat. Bearing in mind that less than 40 years ago the possibility of impact being a common occurrence on Earth was dismissed by most scientists, we have made tremendous strides. Impact studies continue apace, and through initiatives such as the Spaceguard, Catalina and Siding Spring Surveys, and the missions to asteroids and comets in recent years, including the Deep Impact mission, anti-bolide defence plans are developing. Given sufficient time it is possible that we might avert the fate of the dinosaurs and many other species that were defenceless against a rock fragment that hurtled in from Outer Space — an event that, for all its tragedy, ultimately allowed the rise of a new species that may, for the first time, have within it the ability to protect its home planet.

↑ **Figure 160:** Comet McNaught was visible in the Southern Hemisphere in January and February 2007. It was the brightest comet seen on Earth in nearly 40 years. Image courtesy of Kevin Crause.

Cheetah on Savannah Ranch.



Tourism in the Vredefort Dome

CHAPTER 8

Outlook: the Vredefort Dome's potential to become an international heritage asset

The Vredefort Dome and, more specifically, the Vredefort Mountain Land, is an area of remarkable scenic beauty that lies close to South Africa's largest population centre and the main international airport in Johannesburg. Historically, tourism has been locally based, with the Vaal River providing the hub for a variety of recreational and adventure tourism activities (Fig. 161). During the 1990s, however, the tourism infrastructure expanded both in terms of the number and range of tourism establishments available, and in the types of activities open to visitors. The latter has been dominated by ecotourism initiatives. Several large farms have been converted to resorts that offer game viewing or hunting (Fig. 162). Many owners of guest houses and guest farms have made considerable efforts to arrange hiking trails, ranging from short walks of a few hours to multi-day hikes, especially in the Mountain Land in the northwestern part of the dome around Venterskroon. The absence of the 'Big Five' game animals makes it possible to enjoy the serenity of nature at a level not commonly experienced in the larger game parks. Given the fact that most land is privately owned, coordination of activities is highly variable, but is continually improving. Nonetheless, it is important for visitors to acquaint themselves with local rules before engaging in activities and to refrain from trespassing on private land.

Adventure tourism activities include ballooning, hang-gliding, abseiling, mountain bik-

Figure 161: The Vredefort Dome is a popular base for a variety of adventure and ecotourism activities, with additional recreational tourism centred on the Vaal River upstream of the dome.

Figure 162: The strong ecotourism focus of recent years in the Vredefort Dome has resulted in the re-introduction of large numbers of game animals, such as gemsbok and giraffe.

ing, climbing, hiking, quadbiking, river rafting, canoeing, swimming, fishing, fly-fishing and hunting. Leisure accommodation (Fig. 163) ranges from secluded luxury chalets to upmarket resort hotels and more-rustic chalets, as well as camping and caravanning. Educational tourism (Fig. 164) has historically lagged behind adventure and recreational tourism in the dome, but the publicity around the World Heritage Site and the construction of a dedicated Visitor Centre (Fig. 165) that incorporates an educational component has broadened the access to school and family groups. Not surprisingly, the primary focus in this sector has been on the geology of the dome, but an increasing archaeological and cultural-heritage component is being added as research into these resources is conducted by appropriate experts. The biodiversity of the area and the Vaal River provide important additional educational resources. The dome remains a popular venue for conferences, business breakaway meetings and workshops (Fig. 166).

Over 50 tourist establishments, comprising over 2 000 beds, are available in the dome, ranging from upmarket conference hotel facilities to small bed-and-breakfast and self-catering facilities. Parys (Fig. 167) provides additional infrastructural support in terms of shops, restaurants, entertainment and medical services, with Potchefstroom lying relatively close to the northwestern edge of the dome, and the larger towns of Sasolburg and Vanderbijlpark to the east. Given the size of the area, additional amenities, such as public picnic sites and ablution facilities catering for the day-visitor market are still required. Historically, the state of the gravel roads within the dome has not been good, particularly as traffic volumes increased in the late 1990s. A comprehensive roads programme aimed at tarring most of the roads in the World Heritage Site south of the Vaal River is facilitating tourist access and will likely be extended to the north of the river in due course.

The large area and mainly private land ownership in the dome present specific management challenges for the World Heritage Site and wider dome area. Particular efforts have been directed towards providing visitors with a 'sense of place'. The Vredefort Dome is both extremely large and extremely old, requiring that visitors take the time to understand what the area has to deliver. A first stop at the Visitor Centre outside Vredefort, or the reading of some of the relevant geotourism literature that can be obtained at most of the tourism establishments in the area, is essential if the full benefits of the geological heritage are to be derived. The true beauty of the Vredefort Dome can, however, only be really appreciated by experiencing the full range of its attractions over several days or, if possible, several visits!

† **Figure 163:** Tourist accommodation in the Vredefort Dome ranges from camping and self-catering chalets to upmarket resort hotels and conference facilities. **Clockwise from top left:** Aerial view of Sunwa River Lodge (Stop 7b in Part II); Stonehenge Resort; view from across the Vaal River of the African Village, Smilin Thru Resort (see Stop 22); the rustic Bundu Camp accommodation on Tygerfontein farm, built amongst the ruins of an Iron Age kraal (see Stop 15).

The International Significance of the Vredefort Dome

To understand the significance of the Vredefort Dome, it is necessary to recap the earlier chapters of this book. It has been shown that impact cratering is a fundamental process in the Solar System. Our planet and its neighbours were formed by the initial low-velocity collisions of tiny dust grains in the presolar nebula and then successively larger bodies. The surfaces of the neighbouring rocky planets (Figs 52, 53, 99) indicate that asteroidal and cometary bombardment in the early history of our Solar System was, unsurprisingly, incessant and cataclysmic. The energy of these impacts contributed to the switching on of planetary 'heat engines' that, in turn, gave rise to the differentiation of the planetary interiors, forming dense cores surrounded by progressively less-dense layers of rock. In Earth's case, however, there were at least two possible additional benefits. First, icy cometary showers from the outer Solar System may have deposited much of Earth's water, forming the nursery in which Life later evolved. Second, a giant oblique impact of a planet-sized body into the juvenile Earth by a rogue planet created our Moon, and may have caused the tilt of Earth's axis of rotation that is the key to our seasonal climatic patterns. Our Moon has helped stabilise Earth's rotation, and its tidal effects are an important aspect of our planet's dynamic surface.

Recent studies have shown that it is possible that primitive life may have spread between the planets via meteorite impacts that blasted microbe-bearing fragments of rock from one planet that ultimately collided with, and seeded, another (*panspermia*). More recently, the fragility of more complex life forms to the environmental consequences of impact catastrophes has been exposed in the Cretaceous–Tertiary boundary mass-extinction event on Earth.

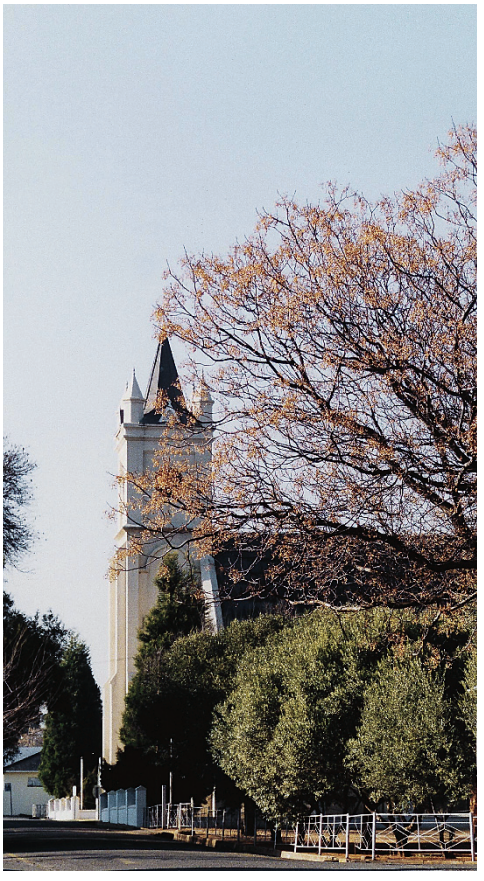
What is evident from this is that Life continues, albeit in forms that were not necessarily present prior to such catastrophes. Today, for the first time in the history of our planet, a life form may have evolved that is capable of preventing impacts from threatening us.

Compared with its neighbours, our planet has a short 'memory'. Atmosphere, oceans, rivers, ice and a thriving biosphere conspire to rapidly remove traces of catastrophes on Earth's surface — even the largest earthquake scars may survive for only a few years or centuries; towering volcanic mountains may survive for millions of years but, if they do not self-destruct, ultimately succumb to rain, wind and water; the traces of floods, tsunamis and extreme weather are even more ephemeral. However, the rocks can retain 'memories' of such events, by preserving at least

← **Figure 164:** Educational tourism in the dome is growing and has the potential to integrate geology and environmental education with archaeological and cultural-historical studies.

↓ **Figure 165:** The Vredefort Dome World Heritage Site Visitor Centre, located near Vredefort, is one of the few museums worldwide that is dedicated to impact cratering, and is the gateway to the dome.

↓ **Figure 166:** The Vredefort Dome is a popular conference venue. Seen here are delegates to the Fourth International Large Meteorite Impacts and Planetary Evolution Conference, held at Sunwa River Lodge in August 2008. Photograph courtesy of David Powars, Washington, DC.



↓ **Figure 167:** Parys provides a range of historic sights, restaurants and shopping and entertainment options for visitors.

part of the record of these catastrophes either directly during their formation or in chemical, mineralogical or deformation effects.

For two centuries, geologists have been gathering the information that has allowed these past events to be unlocked. As outlined in Chapter 1, geologists initially trumpeted the uniformitarianist view of geological change as a triumph of scientific reason over superstition; however, Lyell's concept of a planet dominated by slow, steady change has been shaken in recent decades by the realisation that periods of relative quiescence are punctuated at frequent intervals by mega-disasters that ravage Earth's surface. Given that our very future depends on recognising the warning signs and — unlike the tens of millions of species to have lived on Earth that have already gone extinct — devising ways to counter the threat, reading the history of disasters in our planet's rocks and on its surface has required an opening of our minds to the possibility that such disasters could occur again. The rocks of the Vredefort Dome have stood for two thousand million years as a reminder of what is possible and what threatens our survival. The cryptic messages in the rocks have not been as obvious as might have been the case if a large, still-smoking hole existed in the ground. Nonetheless, once uncovered and their full significance understood, they cannot be ignored — a comparatively small fragment of rock is capable of rendering our planet virtually uninhabitable by driving the delicate balance of our atmosphere, hydrosphere and biosphere over the edge. Although we see increasing proof that our planet will survive such an event and ultimately re-establish its equilibrium, the question is whether the delicate carbon-based life-forms that shelter on its surface — ourselves included — will remain part of that equilibrium equation.

The evidence is undeniable — the Vredefort impact event affected every part of Earth. Both the short-term (blast-wave, tsunamis, ejecta debris fallout) and longer-term (acid rain, surface water pollution, upper atmosphere global dust cloud, greenhouse) effects involved the entire surface of the globe, whilst huge seismic disturbances affected the interior of our planet. Few geological events can lay claim to such a comprehensive disturbance; hence it is fitting that at least a portion of the Vredefort Dome is recognised by humanity as a site that is part of our shared history.

The declaration of part of the Vredefort Dome as a World Heritage Site on July 14 2005 acknowledges not only the dramatic event of 2 020 million years ago. The rocks of the dome additionally expose an even more ancient story of the early Earth that spans the formation of the first continents, the first steps in the evolution of life and the creation of some of the world's greatest ore deposits. Perhaps nowhere else in the world is it as clear how human development is tied to the geology beneath our feet. It is in the rocks, once again, that the more recent history of human habitation in the dome is to be seen — stone tools, rock engravings, ruins of centuries-old towns, trenches, tunnels and shafts dug in search of gold, and fortifications built in times of war, caused by competition for the tremendous wealth locked in these rocks, are all preserved in the Vredefort Dome. That there is a second World heritage Site, the Cradle of Humankind northwest of Johannesburg, so close to the Vredefort Dome World heritage Area further underlines the international importance of this remarkable region. With its additional proximity to both South Africa's economic hub and major population centre and the major international gateway to South Africa, the Vredefort Dome has every opportunity to entrench its international heritage status and to become a world leader in geological tourism.

Askoppies Iron Age settlement.

Part II

Tour guide through the Vredefort Dome

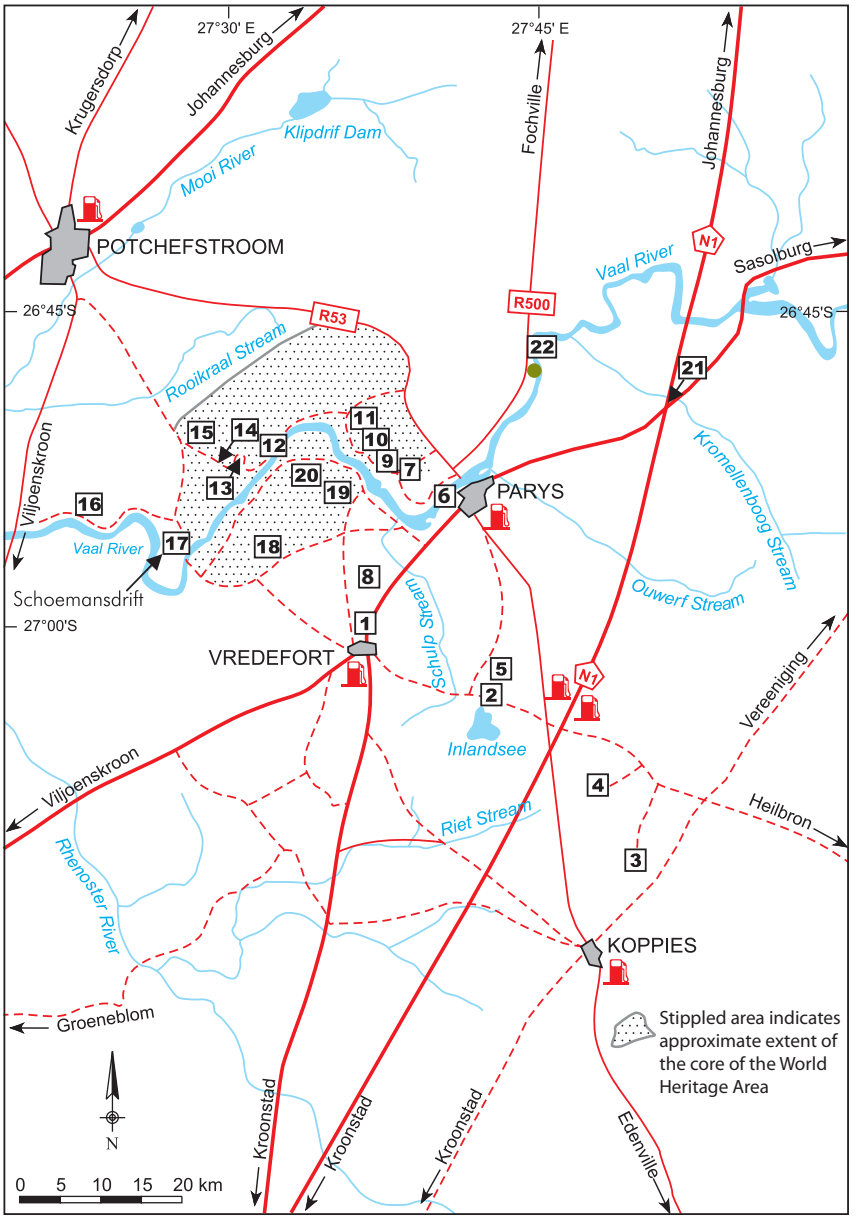
This section presents a set of the most easily accessible localities that cover the most significant aspects of the geology of the Vredefort Dome, together with some of its archaeological and cultural heritage. Several sites essentially duplicate one another, but are listed here as they may include specific features that have contributed to the development of ideas about the Vredefort Dome and the rocks it exposes, or because they may provide alternatives for route planning for self-guided tours. Trying to visit all the sites would take more than two full days based in the dome! However, visiting these listed sites is not essential — every rock outcrop in the dome presents the opportunity to explore some aspect of the geological history of the dome and the Vredefort impact event. The interested visitor staying in the area may also wish to explore walking trails in the World Heritage Site area, and at private resorts in the dome. Guided tours that cater for a wide range of interests, from geological to botanical and cultural, are also available. Information on these can be obtained from the tourism resorts, the Parys Info office and the Vredefort Dome World Heritage Site Visitor Centre at Stop 1. A comprehensive geological guide by Gibson and Reimold (2008) listing additional sites for the geological expert is available from the Book Shop of the Council for Geoscience in Pretoria (http://www.geoscience.org.za).

Most of the sites listed here are situated on private land. The authors cannot accept any responsibility for changes to the access status of various properties as a result of change of ownership. Before entering any site it is necessary to obtain permission from the landowners or their designated representatives, and any access fees requested have to be paid. Visitors must accept that entry to these sites is at their own risk and should ensure that no littering or damage to outcrops, information boards or vegetation occurs, and that noise is kept to a minimum. Fires are a constant threat in the area and may have devastating consequences, therefore visitors are requested to abide by the fire-safety regulations. In the interests of preserving the tourism potential of the Vredefort Dome, no attempt must be made to remove rock samples from the outcrops from any of the sites. Be aware that most of the damage done to outcrops relates to previous unsuccessful attempts to remove souvenirs, which have left unsightly scratches and crushed places on the outcrops.

This chapter provides simple access maps and directions to each of the sites. Various waypoints, turns and sites are indicated with GPS coordinates to aid location. Future conservancy and tourism infrastructure development is likely to add other sites to the list of options. Figure 168 is a map of major access roads, as well as the general locations of the exposures described in the following section, to assist with route planning. Be aware that large parts of the dome are only accessible via dirt roads, some of which become difficult to navigate after rain, and that it is the responsibility of drivers to check local conditions before proceeding. The routes also traverse remote areas where there is no cellphone reception or nearby habitation from which assistance can be obtained in times of emergency. Note that the only bridges across the Vaal River are situated at Parys and at Schoemansdrift (Stop 17, Fig. 168), and reliable fuel supplies are only available at Vredefort, Parys, Potchefstroom and along the N1 to the east of Stop 2.

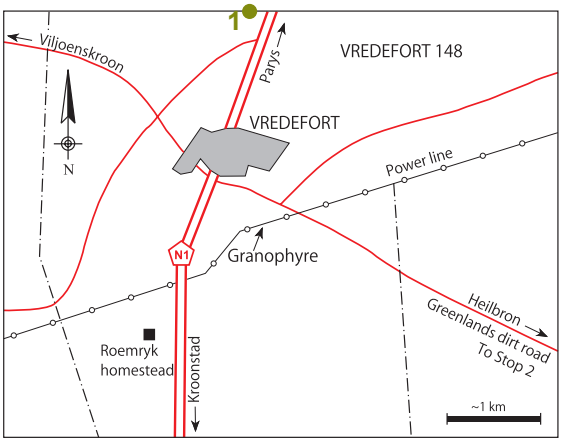
Some of the descriptions provide general background information about the Vredefort Dome, its origin and rock-deformation features. Whilst some of this information has already been covered in Part I, it is believed that the user of this field guide will appreciate having the facts to hand at each site.

Figure 168: Road map of the Vredefort Dome showing the main geological sites described in Part II.



Stops 1–9:
THE CORE OF THE VREDEFORT DOME

STOP 1
Vredefort Dome World Heritage Site Visitor Centre



† **Figure 169:** Main roads around Vredefort town, location of Stop 1 and access to Stop 2.

The VDWHS Visitor Centre (Fig. 165) lies perched on a small dome-shaped hill alongside the R59 close to Vredefort (26°59'17.6"S, 27°22'17.0"E; Figs 168, 169). Completed in 2009, this is one of only a few museums worldwide dedicated to impact cratering and is an essential first stop. Visitors should allow at least a couple of hours to explore the Centre, which includes a comprehensive exhibition, audiovisual presentations and interactive displays on meteorites, impact craters and the geology of the Vredefort impact structure. An arts-and-crafts market, tourist information, a restaurant, and rest room are also provided and the Centre is the principal starting point for guided tours of the dome.

The hill (Afrikaans: koppie) on which the Visitor Centre stands occupies a special place in Vredefort Dome lore. A few months after a courtesy visit to the Vredefort Town Council by Uwe Reimold in the early 1990s, during which he explained the worldwide significance being attached by geologists to the Vredefort Dome, he returned to find two signs along the R59 pointing to the koppie, inscribed *Meteoriet* and *Vredefort Koepel* (Afrikaans for 'meteorite' and 'Vredefort Dome', respectively), making it clear that only part of his message had been understood. The implication, that the little dome-shaped hill on the outskirts of town was the world-famous Vredefort Dome, the site of the world's largest meteorite strike, serves to illustrate the problems many people have with understanding the sheer size of the Vredefort impact event. Nor is this misunderstanding restricted to non-scientists. The hill is one of the few places on the ground from where one can obtain a sense of the curved ring of hills making up the crescent of the Vredefort Mountain Land around the edge of the relatively flat core of the dome. Up until the 1990s, many scientists themselves believed that the Mountain Land marked the upturned crater rim. It is now known that the Mountain Land was produced by differential erosion of harder (quartzite) and softer (shale) upturned rock layers making up the inner collar of the Vredefort Dome after the impact event, and that the dome is only the central part of the original impact structure. The centre of the dome lies in the unremarkable landscape some 8 km east of the Visitor Centre.

The rock outcrops that form the koppie present several significant aspects of the geology of the most ancient rocks of the Vredefort Dome, as outlined in Chapter 1 (pages 35–37). *Extreme caution must be exercised on the outcrop as the slopes steepen towards the outer parts of the koppie and loose rocks may give way underfoot.* Permission must be obtained from the Reception to walk on the koppie and all route markers must be followed.

The bulk of the outcrop consists of rocks of broadly granitic composition that are smeared out and folded like toothpaste, indicating that they were deformed at very high temperatures. In places, large crystals of pink alkali feldspar, up to several centimetres across, are preserved. Although the characteristic pink colour of granite is seen in places where fresh rock surfaces are exposed (Fig. 170), the rock is more commonly green-brown, indicating that it is a special type of granite called *charnockite*. This name derives from the tombstone of the founder of Calcutta in India, Job Charnock, which was carved from this unusual rock type. Numerous cuts, drill-holes and excavations around the base of the hill indicate that it was explored by dimension-stone companies seeking to mine this rock. The greenish-brown colour reflects the presence of pyroxene in the rock, which indicates that the granite either crystallised, or was metamorphosed, at very high temperatures, estimated to be >800 °C here. Large black hornblende crystals indicate that the rocks were infiltrated by water, probably from other magmas, as they cooled down.

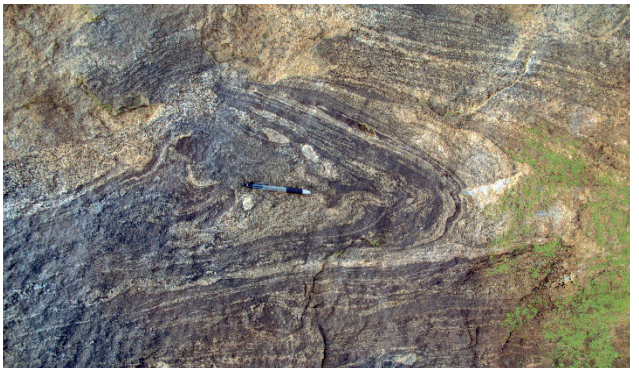
The charnockite contains hundreds of angular to rounded fragments of a black rock that have been pulled apart (boudinaged), intruded and even assimilated to varying extents by the granitic magmas (Fig. 170). These *mafic granulite* xenoliths represent a highly metamorphosed magnesium- and iron-rich (*mafic*) rock that was originally either basalt lava (see Stop 3) or a doleritic intrusion that formed primitive oceanic crust. Tiny zircon crystals extracted from outcrops in the vicinity of the koppie indicate that these mafic rocks may be over 3 400 million years old and, thus, the oldest rocks in the dome. They appear to have been recrystallised, melted, intruded by granites and deformed into gneisses at about 3 090 Ma when it is believed the rocks lay on the southeastern edge of the Kaapvaal continent and a volcanic arc, similar to modern-day Japan, was formed. Pressure and temperature estimates from nearby rocks indicate that the koppie granulites and charnockites lay over 20 km below the surface and that the intense heat was caused by the large volumes of magma feeding the volcanic arc (see Fig. 5b, page 20). As these gneisses cooled, deformation continued in narrow zones, forming finer-grained *mylonites* (Fig. 171) where the coarse granulites were forced to recrystallise as the rocks sheared past one another. A good example of such a mylonite is found close to the start of the access ramp.

Looking closely at the outcrop reveals that the flowing fabrics of the gneisses and mylonites are cut by sharply defined black veins that look glassy and that contain pale angular fragments. These *pseudotachylitic breccias* are one of the products of the 2 020 Ma impact event and are discussed in more detail at Stops 6 and 7.

The rounded nature of the koppie is reminiscent of the countryside around Paarl in the Western Cape Province and Nelspruit in Mpumalanga Province, both of which have many *exfoliation domes* caused by unroofing of granite that contains no significant layering or jointing. However, the Vredefort granite-gneiss koppies may have an even longer history, dating back to the Dwyka ice sheet that covered southern Africa 300 million years ago (see Stop 7a).

Figure 170: Greenish-brown charnockite enclosing and assimilating fragments of older mafic granulite at Stop 1. The evenly spaced holes are part of an abandoned dimension-stone quarrying exploration operation.

Figure 171: Mylonitic gneiss at Stop 1 showing tightly folded banding. The lighter bands are granite veins.



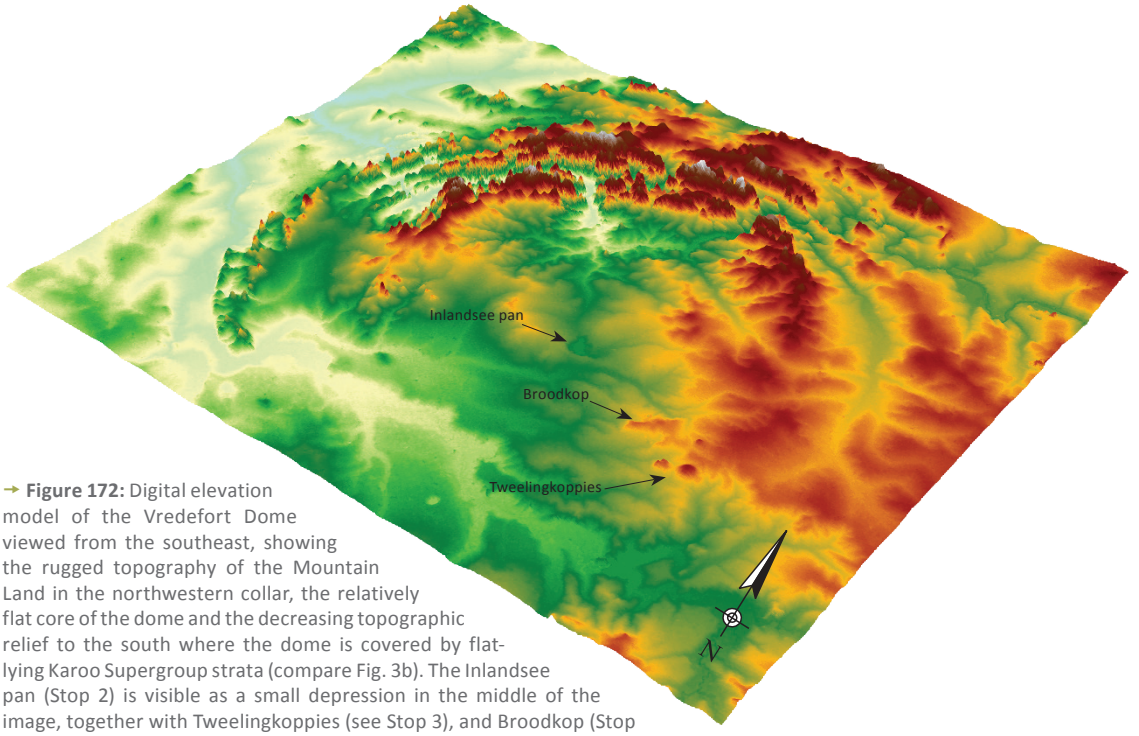
Stop 2

Inlandsee pan and the centre of the Vredefort impact structure

From Stop 1, continue south through Vredefort on the Kroonstad road. Turn left towards Greenlands (R720 gravel road) immediately after the town (27°00'42.1"S, 27°22'12.5"E; Fig. 169). Beneath the power lines on the south (right) side of the road, a line of boulders marks the Vredefort Granophyre (impact melt rock) dyke occurring closest to the centre of the dome, that contains spectacular spherulitic textures (see Fig. 184c). The Inlandsee pan lies 13 km from Vredefort along the Greenlands road. It is a shallow, 1 km wide depression (Fig. 172) that fills with water and occasionally hosts flocks of waterbirds, such as flamingoes, in the rainy season. The landscape of the centre of the Vredefort Dome is otherwise unremarkable (see Figs 78 and 172), except that the black clayey soils derived from the 200 Ma old Karoo shales and 180 Ma dolerite intrusions that make the area good for farming, also make the roads treacherous after rain. The topography may, in fact, be very close to the landscape sculpted by the Dwyka ice sheet 300 Ma ago, and the depression in which the pan lies may represent an ice-erosion feature. In the 1970s, credence was given to this when a large quartzite boulder containing shatter cones was found north of the pan. Geological investigation showed it to be a glacial erratic — a boulder transported from the nearby Mountain Land by the Dwyka ice sheet and dumped when the ice melted. Although not very thick, the extensive flat-lying Karoo cover (see Fig. 3b) restricts exposures of the rocks affected by the impact event to a few sporadic and highly weathered rubbly outcrops. In the 1970s, Louis Nicolaysen coordinated the drilling of a series of shallow boreholes in the area in his search for the volcanic vent that he saw as the source of the Vredefort cryptoexplosion. He never found a vent, but several of the cores have proved invaluable in interpreting the unusual shock-metamorphic phenomena in the rocks that were beneath the impact ground-zero.

Although comparisons were drawn by early workers between the Inlandsee pan and volcanic crater lakes, the geographic centre of the Vredefort Dome actually lies approximately 4 km north of the pan (see Fig. 86) and is covered by a Karoo-age dolerite sill that clearly postdates the impact. However, several small borrow-pits scraped into this sill for road aggregate along the north side of the road near the Klipkraal homestead (27°02'27.2"S, 27°28'31.9"E) contain grey-white and pink boulders of granitic gneiss dumped from the adjacent farmlands. This rock is what Duncan Stepto described as Inlandsee Leucogranofels (Fig. 173a). The name derives from the light colour (*leuco*cratic) and the microscopic appearance of the crystals making up the rock — they are very fine grained and randomly oriented (*granofels* texture). Whilst leucocratic granofelses occur at many sites around the world, what is particularly unusual about the Inlandsee Leucogranofels is that it preserves the outline of the coarse-grained (centimetre to millimetre scale) Archaean gneiss textures, but is completely recrystallised to a very fine-grained aggregate with an average grain size of one-tenth to one-hundredth of a millimetre. Clues to this extremely fine-grained recrystallisation can be seen in the unusual shiny patina on broken surfaces and the absence of the usual cleavage planes in the feldspars. This rock is also extremely hard and breaks in an irregular way, like glass, rather than along the gneissic foliation. If granites are coarse grained because they crystallise slowly deep below the surface, the extremely fine-grained nature of the leucogranofels indicates unusually rapid cooling from high temperatures.

Just how high these temperatures were has only come to light in recent years (see Stop 5) — temperatures close to the Earth's surface exceeded 1 000 °C and may have been as high as 1 350 °C, sufficient to melt individual feldspar grains. Such metamorphic temperatures close to the Earth's surface cannot be produced outside of large impact structures. This heat was generated by the intense pressure wave experienced by the rocks immediately below the point of impact, where shock pressures in excess of 45 GPa were achieved. This is the same mechanism that causes a tyre being pumped up to higher pressure to get hot — this relationship is shown by the curved line towards the right on the pressure-temperature graph (Fig. 68). In a smaller impact closer to surface, mineral grains in rocks subjected to such shock pressures would have either melted and immedi-



→ **Figure 172:** Digital elevation model of the Vredefort Dome viewed from the southeast, showing the rugged topography of the Mountain Land in the northwestern collar, the relatively flat core of the dome and the decreasing topographic relief to the south where the dome is covered by flat-lying Karoo Supergroup strata (compare Fig. 3b). The Inlandsee pan (Stop 2) is visible as a small depression in the middle of the image, together with Tweelingkoppies (see Stop 3), and Broodkop (Stop 4). Image processed by Matt Rowberry from SRTM (Shuttle Radar Topography Mission) data provided on the CGIAR-CSI GeoPortal (srtm.csi.cgiar.org).

ately quenched into a glass, or been compressed directly into a dense glass. Th ese distinctive impact glasses are no longer seen in the Vredefort Dome because the rocks that are seen today were still buried deeply enough after the impact that these glasses were able to recrystallise as the rocks cooled.

Most of the rocks in the Inlandsee area show signs of this intense recrystallisation whilst retaining their Archaean gneissic fabric. However, in places the rocks are cut by grey breccias usually from a millimetre to up to 10 cm wide (Fig. 173b). Although these breccias are interpreted as pseudotachylitic breccias, they contain two unusual features not seen in the pseudotachylitic breccias beyond the central zone: the breccia margins are poorly defined and clast margins are also vague; and the breccia matrix shows clear evidence of crystals having grown from a melt. These features have been interpreted to be the result of the slower cooling experienced by the pseudotachylitic melts in the Inlandsee rocks because their host rocks were heated to much higher temperatures by the shock wave compared with the outer parts of the dome.

Stop 3

Ancient oceanic crust at Greenlands

Stop 3 is accessed from Vredefort by turning left off the Kroonstad road towards Greenlands (R720 gravel road) and continuing past Stop 2. The N1 freeway is crossed approximately 20 km from Vredefort and, at the T-junction immediately thereafter, turn left and continue for 11 km. Turn right at 27°06'53.6"S, 27°37'57.5"E onto the track marked 'Blaauwbosch Mine' and, at the next fork, turn left onto the farm track towards the Hattingsrust farmhouse, where permission to look at the rocks in the vicinity of the house should be obtained. Continue along the track to the left and stop behind the farmhouse (27°08'35.6"S, 27°37'29.6"E; Fig. 174). Shallow outcrops are found to the right of the track and along the western fence.

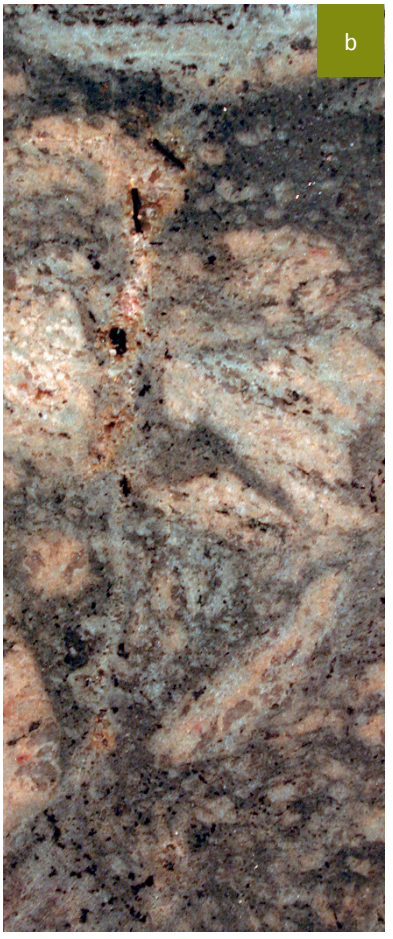
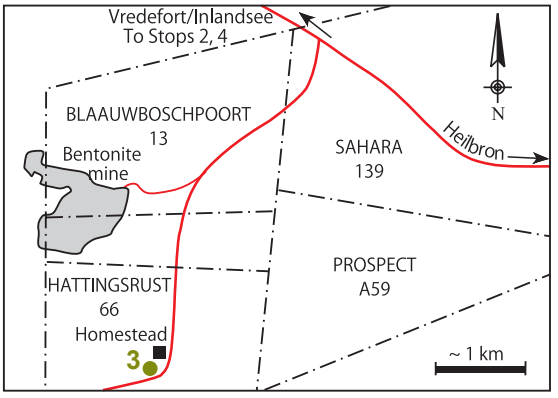


Figure 173: a. Boulder at Stop 2 showing 5 cm thick, grey pseudotachylitic breccia cutting granitic leucogranofels. Note the glassy appearance of both rocks, caused by the rapid post-impact cooling. The dark-grey clasts are quartz.

b. A 5 cm wide piece of drill core from the Inlandsee pan showing a granulitic breccia with a fine-grained dark-grey matrix and irregular granite clasts. Note the indistinct clast margins compared with pseudotachylitic breccias in the outer part of the collar (Stops 1, 6, 7). The breccia is, in turn, cut by a thin vertical granite vein containing large black biotite crystals. Both the breccia and the granite have given 2 020 Ma ages. The indistinct clast margins, together with the granite vein, indicate that the rocks in the centre of the dome were at high enough temperatures to partially melt after the impact.

The gently undulating farmland used for cattle grazing or crops, such as maize or sorghum, gives way near Greenlands to slightly larger hills formed where lower Witwatersrand Supergroup rocks of the collar of the dome protrude through the Karoo rocks (Fig. 86, page 131); quartzites occur on two hills south of the road between Koppies and Heilbron, known as *Tweeling*koppies (Afrikaans for twin; Fig. 172). These hills lie west of the Greenlands railway siding, site of an Anglo-Boer War concentration camp. The Anglo-Boer War cemetery (Fig. 141, page 194) may still be visited. The town of Koppies was founded in 1904 by Anglo-Boer War hero General Christiaan de Wet (see Chapter 5).

In contrast to the granulite gneisses at Stop 1, the rocks exposed around the Blaauwboschpoort and Hattingsrust farms experienced maximum metamorphic temperatures of only about 400 °C. Along the track to the Hattingsrust farmhouse small outcrops of schist can be seen. The jagged and slab-like shape of the rocks reflects a strong *schistosity* caused by alignment of amphibole, chlorite and talc crystals as a result of strong deformation. The rocks have a distinctive soapy feel when rubbed and their green-grey colour identifies them as greenstones. Clues to the origin of these rocks are best preserved around the Hattingsrust farmhouse where largely undeformed *pillow lavas*, still containing chilled margins and amygdales (silica-filled former gas bubbles), indicate that these rocks are lavas that formed on the ocean floor. The bulbous pillows (Fig. 175, compare Fig. 22) were created when hot magma met cold water, causing the magma in contact with the water to freeze, whilst the pressure of the magma inside the chilled crust forced the crust to expand like a balloon. Between the pillows, lenses and cusps of white quartz mark recrystallised cherty deposits that precipitated from the hot fluids escaping with the magma as these were cooled by the seawater. The Greenlands greenstones bear a striking resemblance to rocks near Barberton and in the southwestern parts of the Johannesburg Dome (such as at the Walter Sisulu Botanical Gardens), and may be almost as old (>3 400 Ma). Unlike modern ocean-floor basalts, these ancient lavas had a very high magnesium content, which indicates that they formed from extremely hot



↑ **Figure 174:** Access map to Stop 3.

(>1 500 °C) magmas. They are called *komatiites*, after the Komati River near Barberton where they were first recognised, and indicate that Earth's mantle was probably considerably hotter in Archaean times than it is today.

The outcrops locally display small, generally upward-pointing shatter cones that formed during the impact event (see Stops 14 and 18).

Stop 4

Broodkop shear zone and bentonite mines

In order to reach the Broodkop site from Stop 3, visitors must return to the Vredefort–Greenlands gravel road and retrace their route 2 km northwards (Fig. 176). Turn left onto the road to the Oceaan Mine. A number of trenches and pits are visible in the fields to the right of the road. These were dug in the early 1900s when prospectors recognised the similarity of the Greenlands rocks to those of the Barberton area. By then, Barberton had long been the location of a major gold rush and was a thriving gold-mining town, even with its own Stock Exchange. Prospectors did find some gold and some silver in narrow quartz-vein systems at Greenlands, but only in small amounts, and the diggings were soon abandoned. After 2 km, the Oceaan Bentonite Mine is visible on the right. Bentonite is the name of a rock that is mostly composed of the clay mineral montmorillonite. This material is widely applied in industry, for example as a binding agent for foundry sands, as a carrier for pelletising animal feeds, as a filler and thickener for drilling muds as well as paints, and also in the manufacture of ceramics. In 2001, bentonite gained notoriety as the powdery white substance that was used as a carrier of anthrax bacteria in terrorist attacks in the USA and several other countries. The Greenlands deposits are the largest occurrences in South Africa. Mining of surface deposits began in the 1950s and several decades of reserves remain. The two open-cast mines (Blaauwbosch and Oceaan) exploit lenses in Karoo shale, buried up to 12 m below the surface. Microscopic evidence of volcanic textures in the bentonite, including altered glass shards, indicates that the lenses represent fine-grained volcanic ash that filled channel-like surface structures in Karoo times and then underwent alteration to bentonite.

Near the Oceaan Mine, cross the road that leads down to the mine (27°06'23.6"S, 27°36'34.4"E) and continue along a narrow farm track for 3 km to a prominent whaleback hill, similar to that seen at Stop 1, on the left of the road (27°07'25.5"S, 27°35'14.7"E; Fig. 176). *Note that this track should not be attempted during or after wet weather.* Permission to visit Broodkop hill must be obtained at the

↑ **Figure 175:** Pillow lava, extruded under water, in the Greenlands Greenstone Complex, southeastern Vredefort Dome. The white patch is quartz (recrystallised chert). Compass for scale ca 10 cm wide. Photograph courtesy of Cristiano Lana.

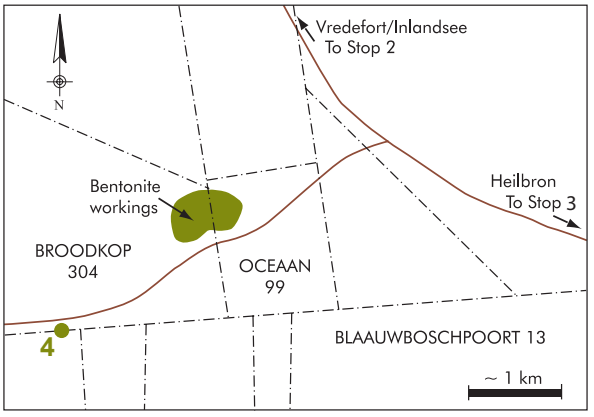


Figure 176: Access map to Stop 4.

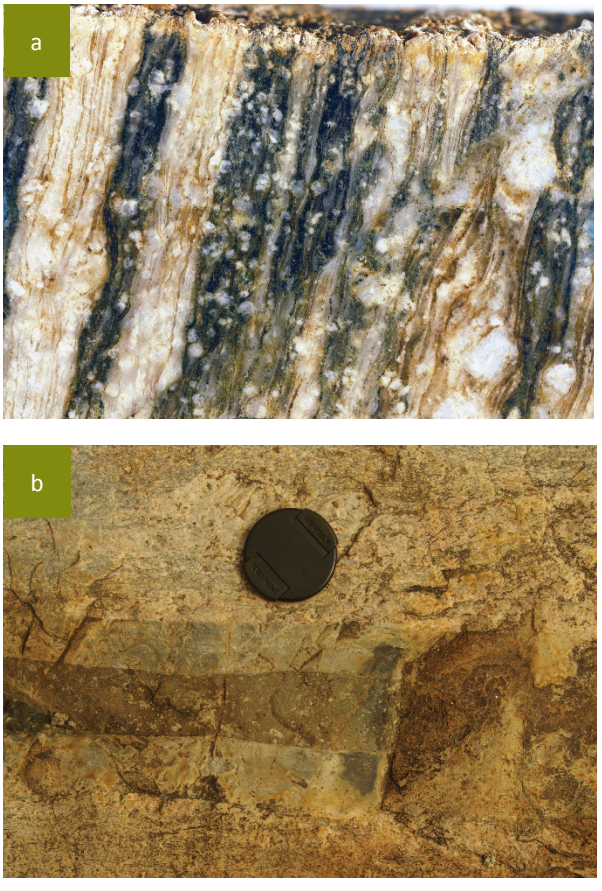


Figure 177: Features at Stop 4. **a.** Polished hand specimen of the Broodkop mylonite (horizontal edge is 5 cm across) showing the very fine-grained, strongly streaked-out foliation wrapping around larger feldspar grains (white). **b.** Pseudotachylitic breccia with dark, clast-rich breccia enclosed in light-grey, more homogeneous pseudotachylitic breccia. Both breccia generations have been dated at 2 020 Ma.

Enkelbosch farmhouse 1 km farther along the road and visitors should not cross fences on the hill itself.

The rocks at Broodkop provide an explanation for the considerably lower grade of metamorphism in the Greenlands rocks compared with the rest of the core of the Vredefort Dome. The hill is made up of rocks of granitic to trondhjemitic compositions, with fragments of darker amphibolite. In a broad sense, these rocks are identical to those at Stop 1 except that the mineral assemblages within them lack pyroxene, indicating that they never quite reached the temperatures necessary to produce charnockites. The most striking feature, however, is the evidence of intense deformation seen in the strong, northeast-trending, vertical planar foliation in the rocks (Fig. 177a). In fact, these rocks form part of a 500 m wide mylonite zone that separates the greenstones in the southeast from the gneisses in the rest of the dome. Detailed analysis of the mylonite textures suggests that deformation started shortly after the rocks experienced peak metamorphic temperatures and continued as the rocks cooled. This, together with the immense size of the mylonite zone, suggests that these rocks once formed part of a major zone of shearing that accommodated tens of kilometres of slip, thereby bringing hotter deep-crustal rocks into contact with cooler shallow-crustal rocks represented by the greenstones. If the strong rotation of about 100 to 120° caused by the formation of the central uplift during the impact event is removed, the shear zone appears to have had an original shallow northwestward dip and a slip vector that caused rocks above the shear zone to slide northwestwards. This geometry is consistent with a period of crustal stretching (extension), and such a period existed immediately after the 3 080–3 090 Ma peak of metamorphism in the Archaean Basement Complex in the Vredefort Dome, during the deposition of the Dominion Group at about 3 074 Ma. Such extension would have greatly assisted the rapid exhumation of deep crustal rocks that exposed them at the surface prior to the eruption of the Dominion lavas that now directly overlie them (see Stop 9).

Broodkop also contains a large pseudotachylitic breccia along its western edge that contains disoriented clasts (fragments) of mylonite up to several metres across. A smaller vein

contains what appear to be boudinaged lenses of a darker breccia in the lighter-grey breccia (Fig. 177b). Although initially thought to prove that these pseudotachylitic breccias were formed during more than one event, subsequent geochronological analysis indicates that both breccias have the same 2 020 Ma age as the impact event. A black rock that occurs close to the fence on the northwestern edge of the hill is a dyke of coarse-grained dolerite that intruded after the gneisses were sheared. It must have intruded before the impact, as it is included as clasts in the pseudotachylitic breccia.

The flat rock surface on top of the hill, slightly to the southwest, contains a series of small, shallow, leaf-shaped depressions, up to 20 cm long, that locals believed may have been used to sharpen spear blades, but that seem more likely to have been produced by grinding of tough grains, such as millet, by Iron Age people. A low stone wall along the base of the hill (Fig. 130) may be a sniper post dating from the Anglo-Boer War (see Chapter 5).

Stop 5

Steynskraal pelitic granulites — a thermal record

Outcrops on Steynskraal farm, south of Parys, contain rocks that have played a crucial role in helping geologists to unravel both the impact thermal history of the central parts of the Vredefort Dome and the older, Archaean metamorphic history. The rocks are highly metamorphosed shales (*pelites*) whose complex chemistry makes them very sensitive to changes in pressure and temperature. From the R720, turn north at 27°02'24.8"S, 27°27'40.8"E onto the unmarked gravel road ~9 km east of Vredefort (~4 km west of the Inlandsee pan). Continue for about 7 km until the road passes under power lines. A few hundred metres further on dark-brown rocks occur alongside the road on the right where a rough farm track leads between the farmlands (26°58'59.5"S, 27°27'09.1"E). If travelling from Parys, turn off the R59 onto the Tumahole/Heilbron road at the 4-way stop southwest of the R59-R500 intersection. Cross the railway line and continue south-southeast past the Tumahole township and water reservoir before turning south (right) 500 m after the end of the tar road (26°56'10.7"S, 27°28'12.9"E). The dirt road continues for several kilometres until the large Steynskraal homestead appears in a thick stand of trees on the left of the road. Some 500 m past the homestead, and before the powerline, scattered outcrop is visible on the left side of the road in the vicinity of a farm track.

Close examination of the outcrops reveals that they contain faint layering that is mostly vertical and trending north to northwest, as at Stop 1. Locally, small folds occur in the layering. The layering is defined both by thin granite veins that were produced by melting of the pelites (Fig. 178), and by changes in grain size of round, red-brown garnets that range from 1 mm to 1 cm in diameter. Microscopic examination of these garnets shows that they formed at a temperature of about 875 °C when these rocks — original muds that would have been deposited onto the ocean floor prior to 3 100 Ma — were buried to a depth of 27 km during the same 3 080 to 3 090 Ma metamorphic event that formed the charnockites. During the impact the garnets were strongly fractured and then partially replaced by unusual fine-grained worm-like intergrowths of the minerals orthopyroxene, cordierite, spinel, biotite and feldspar. Under the intense shock pressures (25–35 GPa), feldspars in the rock were largely converted to

† **Figure 178:** Pelitic granulite from near Stop 5, showing large round garnet crystals and cream-white granitic layers formed by partial melting of the granulite during the 3 080–3 090 Ma Archaean metamorphic event.

diaplectic glass that was subsequently recrystallised to granofels-textured aggregates, and planar deformation features formed in quartz and were also recrystallised. The post-impact temperatures in these rocks reached 920 °C but at unusually shallow depths of burial of between only 8 and 10 km, signifying that the rocks had already been uplifted by formation of the dome. Only 3 km to the northwest towards Vredefort, similar pelitic granulites contain garnets that are only slightly replaced by orthopyroxene-cordierite intergrowths, and feldspars are largely unscathed. The post-impact temperature calculated for these rocks is only about 740 °C, indicating the remarkable decrease in temperature away from the centre of the dome — one of the key clues that this metamorphism was caused by the unusual mechanism of energy deposited into the rocks by the impact shock wave. In places, the pelitic granulites are cut by black veins of pseudotachylitic breccia up to 2 cm wide.

Stop 6

Pseudotachylitic breccia and gneisses, Parys

For those looking for a quick stop in a scenic setting, the outcrops along the edge of the Vaal River in Parys (26°54'08.7"S, 27°26'40.9"E) are probably the same outcrops from which S.J. Shand first described 'pseudotachylyte' in 1916. The exposure is dependent on the water level, and in the dry season large breccia networks are also visible from the bridge. An easily accessible locality lies downstream of the bridge (turn left off the R500 before the bridge, into Boom Street and then first right into Noorder Street). Stop in the parking lot along the river and walk down on the left side to the sloping outcrops. The water-worn outcrops show the abundance of black pseudotachylitic breccia veins in a predominantly granitic host. Towards the water a large breccia network, up to several metres wide and containing rounded clasts up to 1 m wide, occurs. The granite is locally gneissic. For the more serious visitor, a selection of outcrops north of the Vaal River is described in more detail under Stop 7.

For those interested in cultural tourism, the Parys Info office provides maps and information about historic buildings (see Fig. 167), several of which are over a century old, and other aspects such as the furrow irrigation system in the town. Information is available on nearby historic sites such as Liebenbergkoppie, site of the 1836 massacre of Voortrekkers by Mzilikazi's forces, and Vlugeiland, so named because the survivors of the massacre sought refuge there. The website (http://www.parysinfo.co.za) contains an excellent summary of the highlights, as well as information about arts-and-crafts, shopping, restaurants and entertainment in the town.

Stop 7

Pseudotachylitic breccia and gneisses in the outer core

Three separate sites are included here, from which only one needs to be selected in order to examine the very large pseudotachylitic breccias and granitic gneisses that occur in the outer core of the dome. These rocks experienced lower grades of metamorphism during both the Archaean and impact events than the rocks at Stops 1, 2 and 5. From the R59 in Parys, turn onto the R500 (Fochville, Potchefstroom) road that crosses the Vaal River. After crossing the Vaal River, the prominent Leeukop hill is visible on the left. The hill and its surrounds host most of the dimension stone quarries from which 'African Jiparano' or 'Parys Granite' was extracted (see Fig. 179). These quarries are now closed but provide exceptional rock exposures.

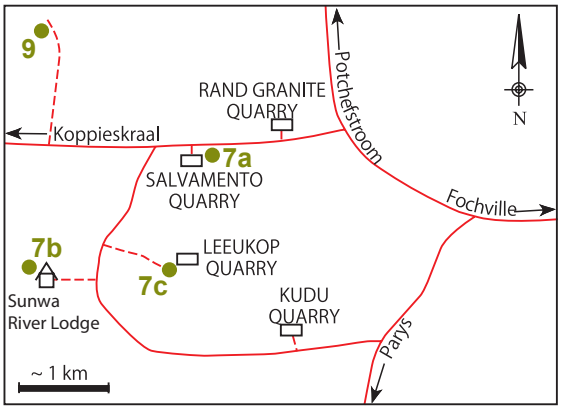
Stop 7a – Salvamento Quarry: Two kilometres after crossing the Vaal River from Parys, turn left onto the R53 (Potchefstroom) and, after 2.2 km, left again onto the Koppieskraal road. After 2.5 km, stop at the building-sand operation on the left to ask permission to visit the Salvamento quarry. The quarry (26°53'21.9"S, 27°24'08.9"E) lies on the left, 500 m farther on, and is accessed via a short dirt track that leads to dozens of rectangular dimension-stone blocks lying in the veld approximately 200 m from the road. The irregular size of the blocks and the lack of similarity in their internal structure, together with the low proportion of pink granite, led to the blocks being graded as inferior quality, which ultimately caused the premature closure of this quarry. The quarry lies in the grass behind these blocks. *Extreme caution must be exercised in*

the quarry, which comprises a number of deep cuts and benches and contains much loose rubble.

The quarry illustrates the pervasive nature of the pseudotachylitic breccia phenomenon in the core of the Vredefort Dome. Dykes, up to several metres thick and containing large clasts of the host rocks (Fig. 180a), are linked in a complex network with centimetre- and millimetre-thick veins, with no obvious sign of cross-cutting relationships (Fig. 180b). Given that pseudotachylites in fault zones elsewhere in the world seldom exceed a few centimetres in width, these volumes are staggering and are matched only by the breccias in the Sudbury impact structure in Canada. The rounding of the clasts is attributed to thermal corrosion by the hot pseudotachylitic melt. Despite its dark-grey colour, the breccia matrix has essentially the same composition as the clasts, indicating that it was derived by melting of the rocks in its immediate vicinity (compare the Vredefort Granophyre, Stop 9). The darker colour mainly reflects the much smaller grain size of the matrix. Close examination of the thin veins shows that the matrix colour actually varies from grey-black to light grey to pink, depending on whether it was derived from iron-rich minerals (biotite, hornblende), plagioclase feldspar or alkali feldspar, respectively.

Despite intensive study, the exact mechanism of formation of these breccias remains elusive. Whilst there is no doubt that rocks in the dome moved considerable distances very rapidly during the impact event, a clear relation between faults and pseudotachylitic breccia volumes that would support a friction-melting origin has not been found, and proving a shock-melting origin is problematic given the high levels of recrystallisation caused by the impact heating.

The main rock type in the quarry is grey trondhjemitic gneiss that displays a sinuous steeply dipping layering. The layering is caused by variation in the proportions of quartz (grey, glassy), plagioclase (white) and iron-rich minerals (biotite ± hornblende), and in the grain size, which is sufficiently large for individual crystals to be visible. The gneiss is intruded by coarse-grained granite to granite-pegmatite veins that additionally contain large pink alkali feldspar crystals. Small dark-grey dioritic and black amphibolite boudins are also present (Fig. 180c). Although earlier researchers had suggested that the principal rock types in the centre of the dome differed from those in the outer core, Cristiano Lana did not find any significant differences



† **Figure 179:** Access map to Stops 7 and 9, showing the dimension-stone quarries near Parys.

apart from the grade of metamorphism, which increases from amphibolite facies to granulite facies towards the centre, consistent with the central rocks having been originally more deeply buried. His geochronological work also suggested that the granitoid rocks forming the bulk of the core all formed in a relatively short interval between about 3 120 Ma and 3 080 Ma. He concluded that the rocks exposed throughout the core of the dome are best described as a *migmatite* ('mixed rock') and that they represent mid-crustal levels of the Archaean crust formed at about 3 100 Ma beneath a volcanic arc on the edge of the Kaapvaal continent.

The exfoliation surface on top of the quarry illustrates the difference in the level of detail visible on the weathered outcrop surface compared with the freshly exposed surfaces. The difference is particularly evident in the pseudotachylitic breccias, which have a pale brown-grey weathered appearance and are far more difficult to see on the weathered surfaces. Excellent three-dimensional exposure of the large breccia dyke is seen on the top surface and in the upper bench. On the northern side of the outcrop a small step exposes parallel striations on the pseudotachylitic breccia that may have been caused by rock fragments embedded in the 300 Ma Dwyka ice sheet (Fig. 180d). The ice could also have sculpted the rounded hills in the core of the dome. The quarry provides an idea of how the large and very heavy dimension-stone blocks were excavated. Hot compressed air was used to cut several-metre deep, rectangular fissures into the solid rock. In other places, small explosive

↑ **Figure 180:** Features at Salvamento quarry (Stop 7a). **a.** Large pseudotachylitic breccia dyke (approximately 40 cm wide) showing rounded to angular clasts in various stages of disaggregation. **b.** Detail of quarry face showing the complex three-dimensional nature of the pseudotachylitic breccia network (image 20 cm wide). **c.** Detail of quarry face showing the migmatitic nature of the granitoid gneisses in the outer core of the Vredefort Dome. The older, dark-grey trondhjemitic layers are boudinaged, whereas the granite (pink) appears to have been at least partially molten at the time (image 1.5 m wide). **d.** Striations on pseudotachylitic breccia believed to have formed during the Dwyka glaciation 300 Ma ago (image 50 cm wide).

charges placed in rows of closely spaced drill holes (see Fig. 170) were used to break rectangular blocks, each weighing several tonnes, off the quarrying benches. Large mechanised loading machines were then used to move the blocks out of the quarry.

Stop 7b – Sunwa River Lodge: From Stop 7a, the Lodge is reached by continuing for 300 m along the Koppieskraal road and turning left. After 1.5 km, the entrance to the Lodge is seen on the right (Fig. 179). Permission to visit the riverbank outcrops (26°54'02.3"S, 27°23'13.9"E) must be obtained from the Reception Office, and indemnity forms signed. The pseudotachylitic breccias at Sunwa, although two-dimensional, provide compelling evidence that they were emplaced when the rocks that enclose them split apart simultaneously in di-

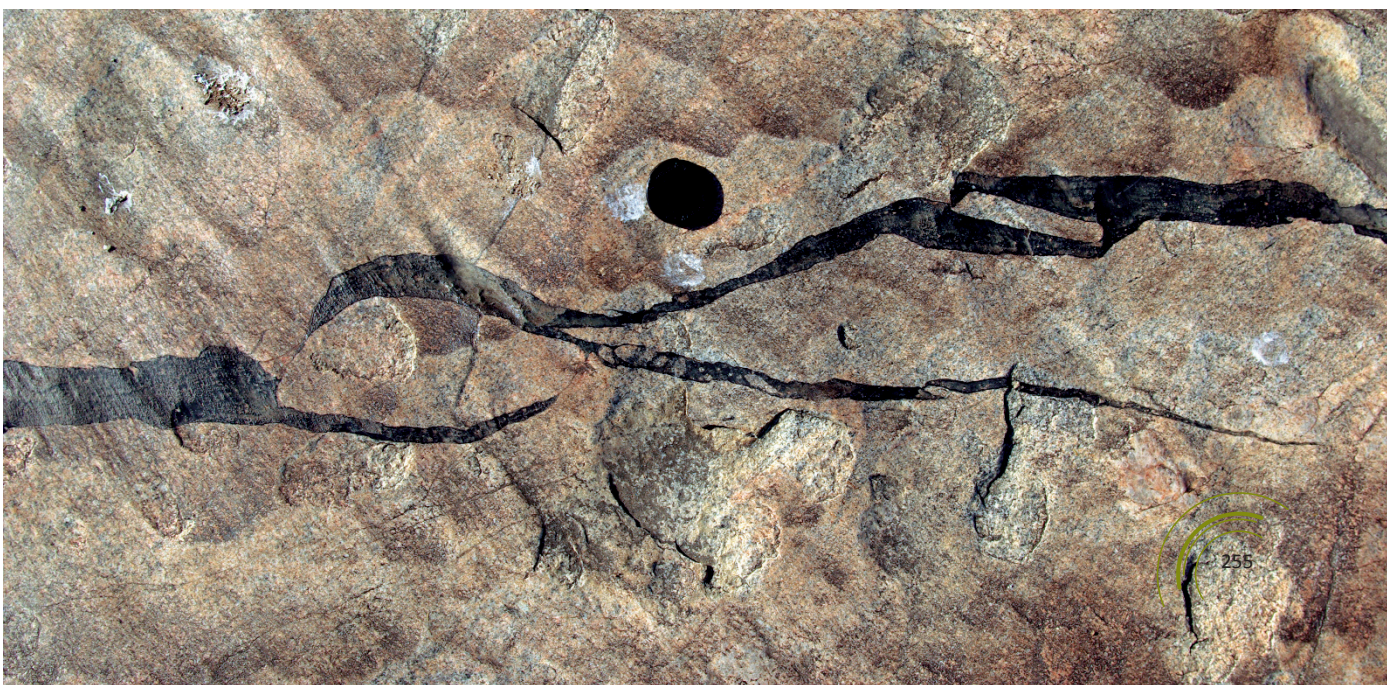
rections that are both radial and tangential to the dome (Fig. 181). This stress pattern occurred when the central uplift of the Vredefort impact structure started to collapse outwards during the final stages of its formation (see Fig. 65d). The veins form a complex network and contain fewer clasts than the Salvamento and Leeukop quarries. The thicker veins, in particular, display proof that their margins were pulled apart rather than sheared (the edges are irregular and can be matched on both sides of the veins). The fact that rare mafic gneiss clasts are found in the breccias, but not anywhere else in the outcrop, indicates that the melts must have moved at least tens of metres. Movement is also indicated by flow folds preserved in the veins. Locally, the veins display lighter- and darker-grey layers that appear to have formed simultaneously, in contrast to the feature seen at Broodkop (Fig. 177b). The veins are located predominantly in a pink granodioritic gneiss that contains bands of older, more strongly foliated, layered, grey, trondhjemitic gneiss.

The rock pavement is strongly polished and grooved (Fig. 181), with gentle, low-relief, asymmetric steps in the surface that indicate transport of abrasive sediment in a south-south-westward direction — essentially opposite to the present flow of the Vaal River. The polished nature of the surface and the fact that it postdates river-generated pothole formation suggest recent scouring by windblown sand rather than ice. It is likely that this occurred during the last Ice Age, over 10 000 years ago, when southern Africa was exceedingly arid.

Stop 7c – Leeukop hill: Access to Leeukop hill has, from time to time in the past, been restricted. Enquiries about access can be made at the Sunwa River Lodge. From Sunwa, turn left and, after a few hundred metres, turn right onto the dirt track towards the hill (Fig. 179).

The quarry at Leeukop (26°53'48.5"S, 27°24'27.8"E) was the largest of the dimension-stone quarries mining the Archaean granitic gneisses of the dome. 'Dimension stone' is the name given to rock quarried for the purpose of making slabs for the construction industry. Large blocks of specific dimension (hence the name) are extracted. This quarry was in production for more than 10 years before it was closed in 1998 because of problems with water build-up in the quarry, the depth of the quarry pit that hampered extraction of the blocks, the deteriorating quality of the rock being excavated, and destabilisation of the very high backwall of the main quarry. The dimension stone mined was called Parys Granite or African Jiparano, after a stone product from Brazil of similar appearance. A large volume of this rock was exported overseas, but some prominent applications can be observed in and around Jo-

↓ **Figure 181:** Black pseudotachylitic breccia veins at Stop 7b, showing the sinuous *en echelon* pattern characteristic of melts intruded into fractures (see also Fig. 91) and how clasts with lengths greater than the vein width can be created by veins linking up (right of black camera lenscap). The diagonal streaks across the surface are believed to be wind-erosion features from the last glacial period.



↑ **Figure 182:** Facade tiling and decoration with dimension stone from the Vredefort Dome are found on and in many prominent buildings in Johannesburg. The exterior of the former Receiver of Revenue building in Rissik Street, shown here, is adorned with Vredefort granite, also locally showing veinlets of pseudotachylitic breccia.

hannesburg. For example, many support pillars in the older parts of O.R. Tambo International Airport in Johannesburg were clad with polished slabs of this stone, many with prominent black veins of pseudotachylitic breccia. The former Receiver of Revenue building in Rissik Street in Johannesburg (Fig. 182) is partially faced with granite from this area, and the floor in the entrance hall of the Council of Mineral Technology (MINTEK) on Beyers Naude Drive in Randburg (north of Johannesburg) is also tiled with this material. A very prominent application is also found in the Voortrekker Monument south of Pretoria. There, the sarcophagus in the main chamber of this monument is made from Parys Granite. The welcome signs to Parys are, understandably, also made of Parys Granite. The decline of the dimension-stone industry in the Vredefort Dome in the late 1990s is a consequence of two main factors: a preference for more homogeneous stone, and similar material being produced more cheaply in several Asian countries.

The main quarry (Fig. 183) extends from east to west along the length of Leeukop hill. When quarrying stopped, 'rehabilitation' of the site was started, which included spraying rock faces and boulders with ferrichloride to artificially rust them. Fortunately, this was stopped before the main quarry faces and cuttings could be affected. The main quarry face shows very homogeneous banding, which made the stone more marketable. The face contains a few darker sausage-like blobs (boudins) produced by the pulling apart of older, more mafic rock layers.

The main attraction of this site is the large pseudotachylitic breccia (Fig. 183) exposed on several benches towards the base of the quarry face. The breccia represents a sheet-like layer inclined steeply towards the north. A sample from this breccia was dated in 1996 by Sandra Kamo and her co-workers, giving the now generally accepted age for the impact event of 2 020 Ma. Another good exposure of this breccia is reached on a somewhat overgrown trail around the east-

← **Figure 183:** Main face at Leeukop quarry (Stop 7c) showing the north-dipping pseudotachylitic breccia body intersected in two benches. Note the concentration of clasts along the bottom contact, consistent with settling prior to melt crystallisation.

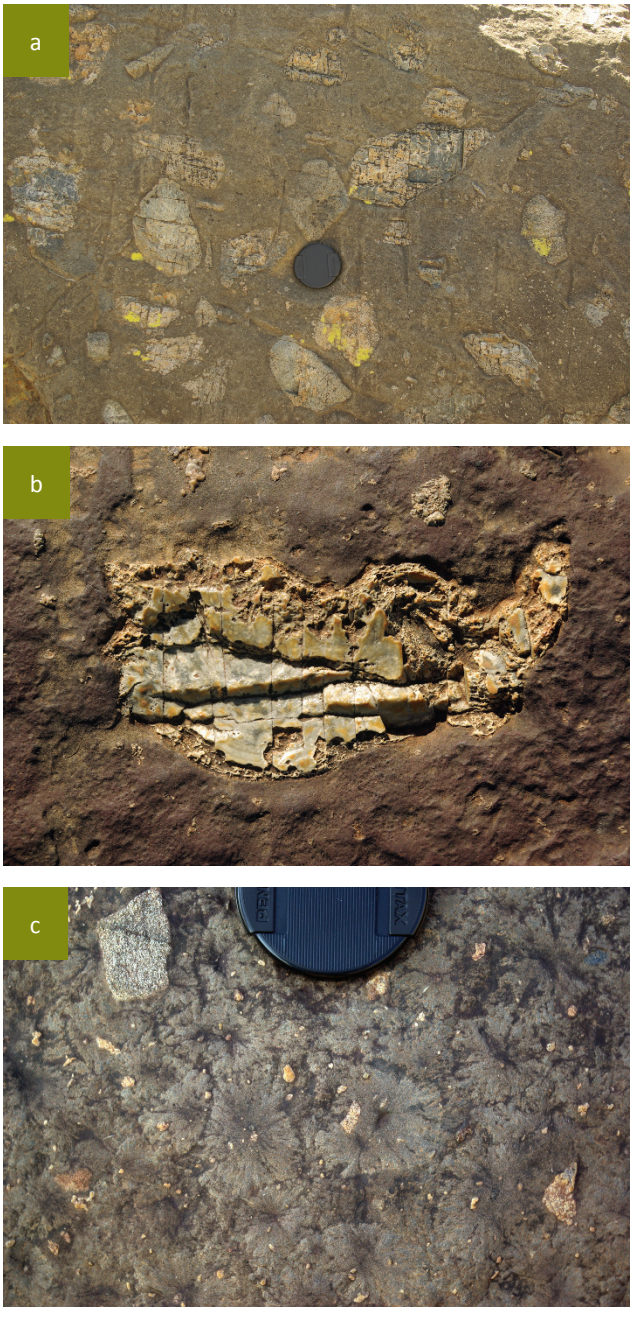
ern (left) side of the hill, leading to the top of the hill above the main pit, in another exploration cutting. The top of the hill provides a panoramic view of the collar of upturned Witwatersrand Supergroup rocks encircling the flatter core of Archaean basement to the north, and southward over the town of Parys and the loop of the Vaal River. Those adventurous enough to attempt the climb should, however, be aware that the hill is not only known for its large population of *dassies* (hyrax, Fig. 152c) but also for the frequent sightings of deadly black mamba snakes that prey on them. A slightly less dramatic view can be obtained from the western side of the berm in front of the quarry.

Stop 8

Vredefort Granophyre and Bushman petroglyphs, Daskop

Although not currently open to members of the public, owing to its sensitivity as an archaeological site and the need for further research on the nature and extent of the petroglyphs (rock engravings), it is hoped that the Daskop petroglyph site may be fully catalogued and opened to guided tours in the future. Such precautions are necessary as parts of the site have been vandalised in the past. A preliminary interpretation of the site is provided at the Visitor Centre.

The Daskop farm lies north of the Visitor Centre. A sinuous dyke of Vredefort Granophyre (Fig. 91) contains the highest proportion of clasts of any of the impact melt rock dykes found in the dome (contrast Stop 9) (Fig. 184a). Clasts of quartzite and granite dominate and display a variety of shapes, indicating partial to complete melting and high-temperature toffee-like plastic strain, including unusual hook shapes. Some granite clasts show melted rims (Fig. 184b) and a vesiculated (porous) texture that is produced by melting of water-bearing mineral phases. Close inspection of the Granophyre matrix reveals small spherules (1–2 cm spherical shapes) with needle-like pyroxene crystals radiating from their centres, which are best seen where the rock surface has been etched by weathering. These are smaller than the 5 cm wide spherules found in the dykes south of Vredefort (Fig. 184c). In places, thin, fine-grained



↑ **Figure 184:** Characteristics of Vredefort Granophyre. **a.** Quartzite and granite clasts in Granophyre. Clasts are generally more angular and more varied than in the pseudotachylitic breccias. **b.** Granite clast showing evidence of melting (streaky internal texture, irregular flowing margins). **c.** Spherulitic texture formed by needle-like pyroxene crystals growing outwards from a central nucleus — a sign of rapid cooling of a superheated melt. Spherulites are coarsest in dykes closest to the centre of the dome and are not found in dykes near the collar of the dome (see Stop 9).

granular layers, similar to the texture seen in the dyke at Stop 9, occur within the dyke.

The petroglyphs engraved on the outcrops include eland, hippopotamus, black and white rhinoceros (Fig. 185), possible hyena or zebra, and partial human figures, as well as parallel and crossing lines. In places, boulders have been polished smooth, suggesting their use as rubbing stones by wild animals. The rocks have also clearly been broken in places by human agents. Whereas geological sampling sites are still 'fresh', these broken surfaces display much more advanced weathering, consistent with samples having been removed probably several thousand years ago. It is possible that these fragments were used for tools, but they may have had religious significance. Preliminary interpretation of the site by Ben Smith of the Rock Art Research Institute at the University of the Witwatersrand suggests that the Daskop site was used by Bushman people for rain-making ceremonies. The sinuous shape of the dyke outcrops in the otherwise grassy veld (Fig. 91) is reminiscent of a serpent, which is a powerful water-spirit in Bushman mythology. The hippopotamus and rhinoceros are regarded as rain spirits, the hippo representing the female aspect that produces the beneficial, more gentle rain, whereas the male rhino spirit is associated with thunderstorms. The patina on the engravings suggests they are at least several thousand years old, and evidence exists for different ages of engravings with, in one case, an eland's head being replaced by a larger head of an unknown animal (Fig. 185c). Some of the animals appear to be cut by lines, which may represent the symbolic cutting of the spirit animals to release their power (B. Smith, personal communication, 2008).

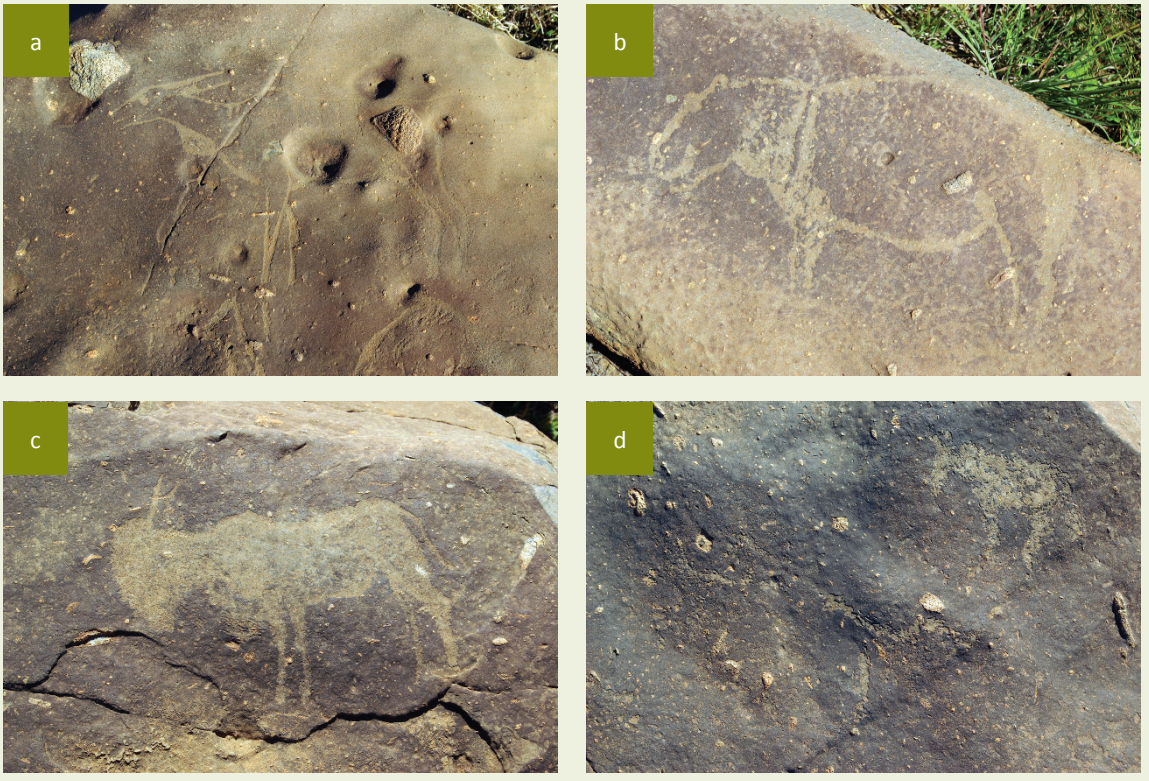
Stop 9

Vredefort Granophyre and Dominion Group lavas, Iniekom

The entrance to Kopjeskraal Country Lodge on Iniekom farm lies 1 km from Stop 7a (26°53'18.6"S, 27°23'21.6"E; Fig. 179). The lodge lies 1 km from the gate, close to the contact between the core and collar of the dome (26°52'53.2"S, 27°23'09.3"E) and caters for visitors through a variety of guided walks, talks and audiovisual presentations that cover the geology, history, botany and fauna of the area. The walking trails (Fig. 187b) are accredited by the North West Province Parks and Tourism Board, and trees along the trails are tagged. Booking is essential (leisure@domebookings.co.za) and an entrance fee is charged.

In addition to providing one of the few sites where the Vredefort Granophyre can be accessed, Iniekom displays a rich cultural history (Fig. 187). Artefacts retrieved from the site include Stone Age tools, several Iron Age farming implements, milling stones for grain, a Bushman arrowhead, and ammunition from the Anglo-Boer War. The ruins of several Iron Age kraals, a pioneer dwelling from the 1840s showing the typical mud and stone construction, and a nearby sniper's post from the Anglo-Boer War are also found. The trails are complemented by a rock display that includes a spectacular polished slab of pseudotachylitic breccia from the area.

The lodge and farmhouse are located on granite that creates several distinctive, heavily vegetated koppies in their vicinity. The Dominion Group — the oldest layer in the sequence of rocks making up the collar of the dome — lies to the northwest of the lodge towards the farmhouse. The low outcrops of very fine-grained, grey-black lava are largely unremarkable and the steep southerly dip is not readily apparent. Higher up the slope, boulders containing millimetre- to centimetre-sized quartz-filled amygdales (Fig. 186) are common. Some amygdales retain the original, irregular, gas-bubble shapes, but others are elongated, either as a result of stretching in the flowing lava or from subsequent deformation during metamorphism. The Dominion Group in the dome is made up exclusively of basaltic andesite. It has a maximum thickness of 250 m, but thins and disappears to the southeast (Fig. 86). In contrast, around Klerksdorp it is up to 2.7 km thick and also contains conglomerates that are locally gold-bearing. The type of rocks and the highly variable thicknesses are consistent with deposition in a rift basin formed by stretching and splitting apart of the crust. The age of 3 074 Ma obtained for the lavas indicates that they were deposited within a remarkably short time of the 3 080–3 090 Ma volcanic arc crust seen in the core of the dome, which may indicate that the rifting was somehow related to the collapse of this arc (see also Stop 4).



↑ **Figure 185:** Bushman petroglyphs on Vredefort Granophyre dyke, Daskop farm. **a.** Eland with portion of head and foreleg of an inverted rhino (bottom). **b.** Hippopotamus. **c.** Evidence of two ages of petroglyphs — an earlier eland's head can be vaguely identified beneath a younger large head. **d**. Unconfirmed figures — possibly a hyena and partial human figure (left). Thin lines between the figures may have additional significance.

The lava and granite outcrops contain abundant evidence of pseudotachylitic breccias, with the breccias in the lavas having a light-grey colour and streaky appearance. The lavas also contain white quartz veins that are displaced along numerous fractures. The gap in the high quartzite ridge to the north is the product of faulting that has shifted the layers, and these fractures may be related to the same event.

The Vredefort Granophyre exposed on Iniekom is the largest of the 9 dykes found in the dome. These dykes are oriented either radially or tangentially with respect to the dome (see Fig. 86), indicating that they intruded into large fractures that formed when the central uplift of the Vredefort impact stucture collapsed. The dykes are between 4.5 and 9 km long and 20 to 65 m wide; thus, they dwarf the pseudotachylitic breccias which they superficially resemble. Indeed, early workers believed

↑ **Figure 186:** Dominion Group lava at Stop 9, showing former gas bubbles now filled with quartz (amygdales).

Figure 187: Archaeological heritage (**a** and **c)** on Iniekom farm (Stop 9). **a.** Stones used for grinding grain. The larger rock is Vredefort Granophyre and the smaller one granitic gneiss. **b**. Sign for one of the walking trails on Iniekom farm**. c.** Iron Age farming implements found during excavations at Iniekom. The metal heads would have been attached to sticks for hoeing and/or chopping of wood. **d.** Polished slab of Parys Granite from Iniekom showing intricate pseudotachylitic breccia network. Photographs courtesy of Christo Meyer and Attie Gerber.

the two rock types were related because both clearly were originally molten and both contain rock clasts. However, there are two principal differences: whereas the pseudotachylitic breccia compositions and clasts reflect their adjacent host rocks, the chemical composition of the Granophyre matrix is highly unusual (high silicon and calcium contents) and is identical in all the dykes, and the clasts are a mixture of a number of different rock types that are otherwise not found close together. These features indicate that the dykes are offshoots of a single, well-homogenised melt body and that they have intruded over distances of kilometres. Both the chemical homogenisation and the intrusion distances support a very fluid, and therefore very high-temperature, melt. The high initial melt temperature (at least higher than the melting temperature of quartz of about 1 700 °C) is indicated by textural evidence of extremely rapid cooling of the matrix (spherulitic texture, see Fig. 184c) and evidence of melted and plastically deformed clast edges. In 1996, an international team led by Christian Koeberl isolated a meteoritic component in the chemical make-up of the dykes using the trace elements rhenium and osmium, which finally confirmed the long-held suspicion that the Granophyre dykes formed from an overlying impact melt body that intruded downwards into fractures formed during collapse of the central uplift (see Fig. 3a). Some clasts also contain microtextural evidence that they experienced shock pressures considerably higher than the rocks hosting the dykes, although most shock features are extensively annealed because of heat from the surrounding melt. The Granophyre matrix is made up of fine-grained orthopyroxene, plagioclase and orthoclase feldspars, quartz, biotite, magnetite and ilmenite.

↓ **Figure 188:** Granophyre dyke seen on Iniekom farm (Stop 9) showing gritty texture (compare Fig. 184c) and small rounded to angular clasts of mainly granite and quartzite.

STOPS 10–22:
THE COLLAR ROCKS OF THE VREDEFORT DOME

STOP 10

Rocks and metamorphism of the Central Rand Group (Witwatersrand Supergroup), Donkervliet valley

Returning to the dirt road that runs past Iniekom, continue west towards the Vaal River (Fig. 189). The road climbs slightly from the Vaal River floodplain, passing over the wide dyke of Vredefort Granophyre seen at Stop 9. Shortly thereafter, the Vaal River and the prominent overturned and strongly fractured quartzite of the Kommandonek ridge (Stop 19) becomes visible. To the east of the road the densely forested slopes cover the contact between the Archaean Basement Complex and the Dominion Group lavas and include a large grove of wild olive trees.

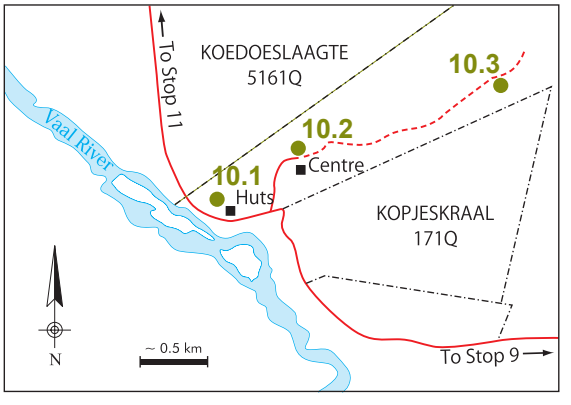
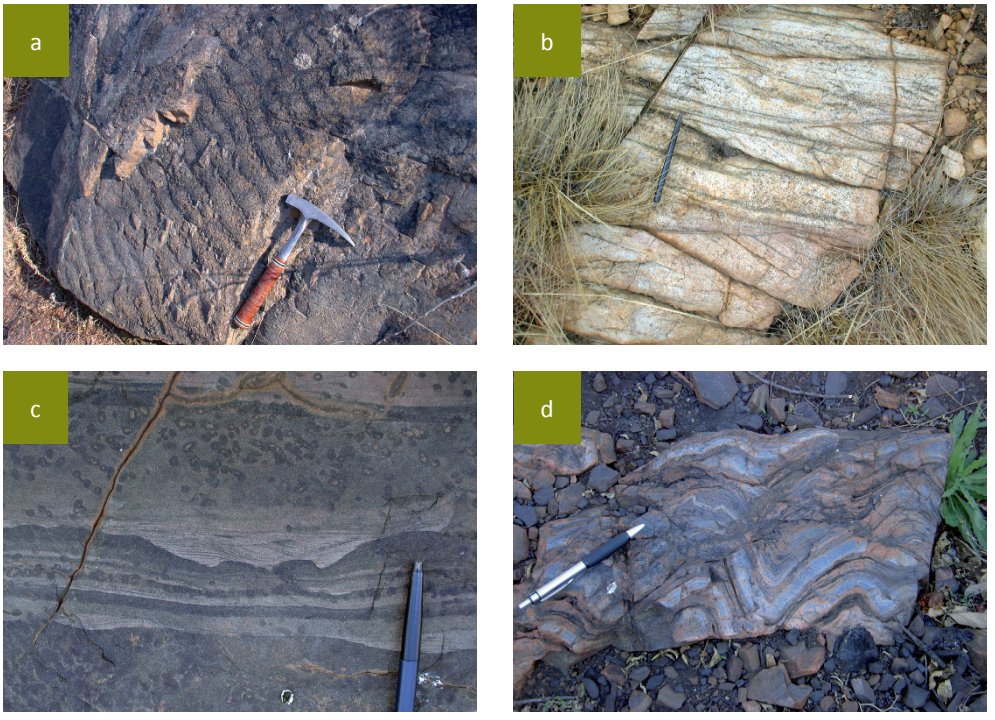


Figure 189: Access map to Stop 10. Numbers refer to the three sites described in the text.

The Donkervliet valley lies between two quartzite ridges (Fig. 92) — to the north, the prominent Witkop ridge is made of the Brixton Formation quartzite that is also found at Kommandonek (Stop 19, on the opposite side of the river, and the southern ridge is marked by a thinner quartzite of the Orange Grove Formation. The valley is underlain by metamorphosed pelites (shales) and banded iron formations of the Parktown Formation. Together these units form the Hospital Hill Subgroup, the lowermost part of the West Rand Group (the lower Witwatersrand Supergroup, Fig. 20). The Donkervliet Centre is utilised for educational purposes, and it is hoped that plans to open it to the public on a more regular basis will bear fruit.

The outcrop features at Stops 10 and 19 are broadly similar and there is no need for both to be visited. The Brixton Formation and Orange Grove Formation quartzites belong to the same units that crop out in the suburbs of the same names in Johannesburg, and the Parktown Formation shale and banded iron formation units are the same as those exposed on the campus of the University of the Witwatersrand and alongside Jan Smuts Avenue in Johannesburg where the rocks are spectacularly contorted and folded. However, a significant difference is the grade of metamorphism between the two areas. In Johannesburg the layers contain unremarkable lower greenschist facies assemblages (about 350 °C), but in the Vredefort Dome the same rock layers reached mid-amphibolite facies grades (about 600 °C), which resulted in the growth of coarse crystals of minerals such as andalusite, cordierite, garnet, staurolite and biotite in the metapelites (Figs 190c and 191) and garnet, chlorite, iron-rich amphiboles and magnetite in the meta-ironstones. Despite this recrystallisation, the rocks still preserve features formed as the sediments were deposited some 2 900 Ma ago. This allows interpretation of the original environments in which the sediments formed:

- The quartzites represent original beach sands, the original millimetre-sized sand grains of which are still visible. Exposed bedding surfaces may preserve fossil ripples (Fig. 190a) and



↑ **Figure 190: a.** Ripple marks on a bedding surface in Hospital Hill Subgroup quartzite, Donkervliet valley (Stop 10). **b.** Cross-bedding in quartzite. The darker lines are formed by oxidation (rusting) of iron-rich minerals that were deposited on small underwater sand dunes. Geologists use the shape of the cross-beds to tell which way up the layers are — the cross-beds are concave-up and their top edges are usually cut off by younger cross-beds. This photograph was taken looking vertically down onto an outcrop. It shows that the beds become younger upwards in the photograph but in reality the beds are overturned. **c.** Parktown Formation metapelite showing lighter-coloured sandy layers with cross-beds, and dark layers originally made up of clay and silt that now contain oval cordierite porphyroblasts. The variable thickness of the sandy layer in the centre indicates that it was deposited into a channel scoured into the underlying silt and clay. **d.** Folded banded ironstone from the lower Parktown Formation in the Donkervliet valley. The thicker, lighter-coloured layers are chert.

sections through the beds preserve dark, curved lines that trace the outlines of the original small sand dunes and ripples that formed by water currents. In places, these cross-beds (Fig. 190b) curve in opposing directions in successive layers, resulting in a structure that looks like a fish skeleton. This herringbone cross-bedding indicates that the sand dunes moved in opposing directions — a situation which occurs on beaches where waves and tides move sand back and forth.

• The metapelites formed from repeating sets of fine sand, silt and mud layers ranging from a few centimetres to 20 cm thick (Fig. 190c). The outlines of centimeter-scale ripples are common in the sandy layers. These sets are interpreted as individual undersea avalanches of sediment cascading down the front of a river delta, which is called *turbidites*.

• The banded iron formation is a largely chemical sediment that precipitated from the seawater as a result of chemical changes in the seawater. In particular, rising levels of oxygen in the water would have made dissolved iron insoluble and forced it to precipitate. Once this process was temporarily exhausted, silica deposition from the seawater would have formed an iron-poor chert layer, creating the characteristic couplet of magnetite- and quartz-rich layers that distinguish banded iron formations (Fig. 190d). These layers formed in deeper water beyond the reach of river-borne sediment.

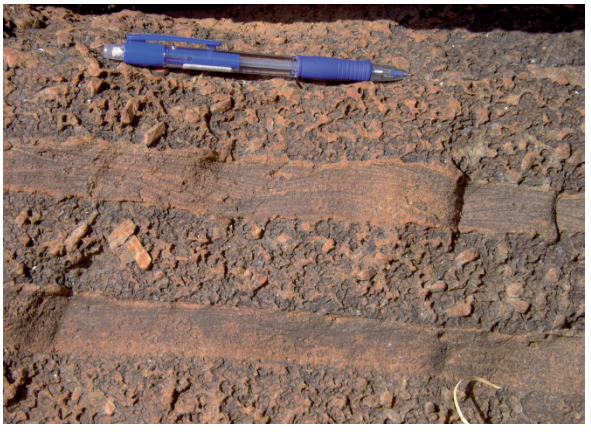
A number of geologists, including Louis Nicolaysen, suggested that the higher metamorphic grades in the rocks in the Vredefort Dome indicated that the dome itself had to be the heat source for the metamorphism. The presence of alkali granite intrusions relatively close to this site (Fig. 86; Stops 11, 20) was used to suggest that the dome was a centre of magma intrusions. Consequently, these geologists concluded that the formation of the dome itself was also related to magmatic and tectonic activity and, therefore, that an impact origin was not plausible.

In the 1990s, however, Roger Gibson showed that the West Rand Group rocks in the dome experienced two distinct heating events. In the first, temperatures reached ~600 °C, which allowed the coarse-grained metamorphic minerals to grow. These minerals are cut by pseudotachylitic breccia (see Stop 19, Fig. 202), and they occur as fragments in the breccia. As the pseudotachylitic breccia is related to the formation of the dome, this first metamorphism must have occurred prior to the impact event at 2 020 Ma. Also, pressure estimates from the mineral assemblage indicated that the rocks lay about 14 km below the surface at the time of metamorphism. Given the total thickness of rock layers exposed in the collar around the dome (see Fig. 20), it is clear that this level of burial could only have been achieved after the deposition of the Transvaal Supergroup, which finished at about 2 150 Ma ago. Gibson argued that the reason why a similar metamorphic grade was not achieved in the West Rand Group rocks anywhere else in the Witwatersrand basin is because these units were buried to only 7–10 km in the goldfields at the time of metamorphism because of repeated episodes of earlier tectonic uplift along the northern margin of the Witwatersrand basin. This pattern indicates that the source of the heat must have been in the lower crust. Gibson concluded that the most likely explanation for the metamorphism is hot magmas related to the 2 060 Ma Bushveld event that intruded into the lower crust.

The second metamorphism that can be traced in these rocks was not as hot as the first; temperatures only reached about 525 °C. The metamorphic minerals that grew during this event are too fine-grained to be seen without a microscope, which indicates that cooling must have been quite fast (just as for the granofelses in the centre of the dome, see Stop 2). Pressure estimates show that this metamorphism also took place only once the rocks had been lifted closer to the surface (to about 8 km depth, exactly as for the pelitic granulites at Stop 5). These metamorphic minerals overgrow the pseudotachylitic breccias and, hence, indicate that the second metamorphism must have occurred after the formation of the dome.

Depending on time available, visitors may wish to pursue one of three options (Fig. 189). The first (Stop 10.1, Fig. 189) is to stop a few hundred metres past the gate to the Donkervliet Recreation Centre at a track past the ruins of some huts on the east side of the road and a water pumping station on the river side. Walking past the huts and turning left, angling up the hill for about 100 m reveals rounded boulders of a variety of metapelitic (meta-shale) rocks in the long grass (26°52'51.9"S, 27°21'33.5"E). The most prominent are marked by oval, centimetre-sized cordierite porphyroblasts that form dark depressions on weathered surfaces and orange-brown to white tabular andalusite porphyroblasts up to 1.5 cm in length (Fig. 191). Small round red garnets and elongate, black, biotite crystals are also present. The metapelites are finely layered, with the lighter-coloured sandy layers typically showing ripple cross-bedding (Fig. 190c). The orientation of the ripples indicates that the layers are overturned; however, bedding is more chaotic here because of rotations caused by a large fault formed during the impact that displaces the strata and which is best seen in the prominent Hospital Hill Formation quartzite (Fig. 92). Irregular fractures contain grey pseudotachylitic breccia. Planar fractures with a millimetre spacing also formed during the impact event. If time permits, cross the road towards the river and examine the steeply south-dipping Hospital Hill quartzites that preserve excellent cross-bedding (indicating that the strata are overturned), as well as impact-formed fractures. The quartzites also contain thin, grey pseudotachylitic breccias that are generally bedding parallel.

Similar metapelitic rocks can be seen north of the Donkervliet Centre buildings (26°52'32.4"S, 27°21'52.2"E; Fig. 189; Stop 10.2), but here they are accompanied by a metamorphosed Ventersdorp-age gabbro intru-



↑ **Figure 191:** Parktown Formation metapelite from Stop 10 showing sandy-silty layer sets with ripple cross-bedding in sandy beds. Cordierite porphyroblasts form pits on the surface whereas rectangular, khaki andalusite porphyroblasts (left) are more resistant (compare Fig. 202).

sion. This tabular sill intruded parallel to the sedimentary layering and is also exposed farther eastward along the valley. It contains spectacular needles of amphibole, up to 15 cm long, that were formed when hot water, released from the pelites, reacted with the rock during the older metamorphism. Heading south past the camp, the dry stream exposes scattered boulders of metamorphosed iron formation that preserve the magnetite-chert (now recrystallised quartz) layering, but now include millimetre-sized amphibole needles and round garnets. Iron formation underlies the entire southern slope of the valley, but exposure is very poor.

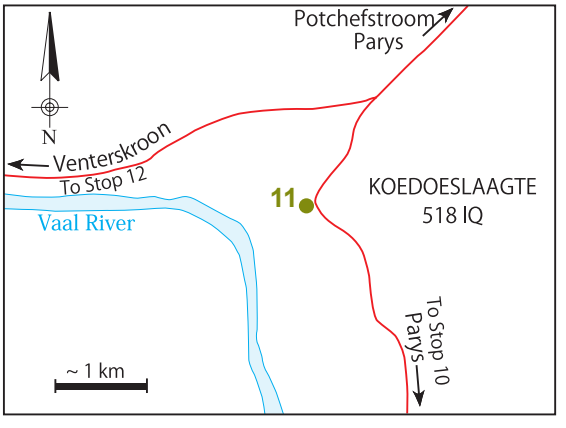
For visitors with more time or who are staying at the Donkervliet Centre, the eastern parts of the Donkervliet property provide an exceptional range of exposures (Stop 10.3). The quality of the track beyond the camp varies, and may require 4WD options beyond the flat grassy area approximately 1 km up the valley. Otherwise it is a 20–30 minute walk from the camp to a series of large outcrops of metapelite where the valley narrows (26°52'11.7"S, 27°22'52.5"E; Fig. 189). To the north of the track is the same metamorphosed sill described near the camp. The metapelite outcrops on the south side of the valley show all the metamorphic features found to the west, but sedimentary features are clearer and bedding is more strongly overturned, dipping 30° to the south. Towards the western edge of this outcrop, rubble of Vredefort Granophyre is found on a horizontal step towards the top of the outcrop. This rubble represents the northeastern termination of a narrow offshoot of the much larger dyke seen at Stop 9. Clasts are typically <5 cm in diameter, with a high proportion in the millimetre range, which gives the Granophyre outcrops a gritty appearance (see Fig. 188). Clasts are predominantly basement gneiss, granite and quartzite, with rare mafic fragments. Clast shapes vary from round to angular and elongate. Towards the southwest, the metapelites grade into iron-richer units that, in turn, grade into banded iron formation towards the barbed-wire fence. If permission has been obtained to cross the fences onto Iniekom farm (Stop 9), walking into the valley to the south of these outcrops exposes banded iron formation with contorted, folded layers (Fig. 190d). The Orange Grove quartzite is missing in the gap in the southern ridge as a result of two impact-related faults. The valley exposes Dominion Group meta-lavas and another mafic sill, and ultimately ends at the Iniekom farmhouse.

Stop 11

Vaal River view site and alkali granite

The road from Donkervliet continues northwestwards along the east bank of the Vaal River. The gentle topography around the river

↓ **Figure 192:** Access map for Schurwedraai view site, Stop 11.



↑ **Figure 193:** Panoramic view from Stop 11, looking west over the Schurwedraai bend of the Vaal River (see also Fig. 144c). The flat area south of the bend is underlain by the Schurwedraai alkali granite pluton — the same rock that is found at Stop 11. To the north, the buttress of the quartzites of the upper Witwatersrand Supergroup forms the highest ridges of the Vredefort Mountain Land.

marks the positions of two intrusions of alkali granite into the Witwatersrand Supergroup rocks (Fig. 86). The view across the river shows the prominent white bands of quartzite along the ridge crests, one of which has been bent into a fold shape during the formation of the dome (see Stop 20).

Low, rounded outcrops and rubble of alkali granite are visible along the road. Some 7 km from Donkervliet, the road curves up and to the left around a hill. At the sharp bend marking the highest point on the road, a rocky outcrop extends to the left (26°51'13.3"S, 27°20'14.0"E; Fig. 192). Care must be taken here to park the vehicle away from the bend, well to the side of the road, to avoid problems from the occasional traffic. If the gate is open, visitors can follow the path for some 40 m, where a panoramic view of the Vaal River is visible (Fig. 193). Alternatively, good views are available from the road. From the view site, the river can be seen to the left cutting across the quartzites and shales of the West Rand Group in a direction radially away from the centre of the dome. The much flatter cultivated lands mark the locations of the alkali granite intrusions. At Schurwedraai, however, the river turns sharply westwards, cutting into the thick, easily eroded shales of the Roodepoort Formation of the Jeppestown Subgroup — seen in road-cuttings towards Venterskroon — that form the uppermost unit of the West Rand Group. The total thickness of the West Rand Group strata approaches 5 km (Fig. 20). The reason for the sharp bend in the river is obvious — to the right a largely unbroken 2 km thick sequence of massive quartzites of the upper Witwatersrand Supergroup (Central Rand Group, Fig. 20) forms an impenetrable barrier and the most rugged part of the Vredefort Mountain Land. The section of river from Parys to Venterskroon is most popular for kayaking and river-rafting activities.

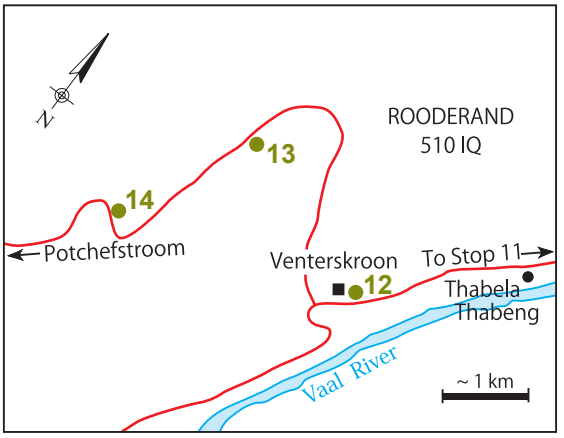
The alkali granite bears a passing resemblance to the granites in the core of the dome; however, there are several significant differences. It has a more homogeneous — but nonetheless coarse — grain size with less quartz than the basement granites, and it lacks a gneissic foliation. White plagioclase feldspar dominates over pink alkali feldspar, and the dark minerals are pyroxene and biotite. U-Pb dating of zircon crystals indicates that these granites are the same age as the Bushveld Complex (2 050–2 060 Ma). The fact that the granite is cut by pseudotachylitic breccia and striated cone-like fractures confirms that it predates the impact event.

These granites were suggested by several geologists to be the heat source for the unusual metamorphism seen in the West Rand Group in the Vredefort Dome and were also claimed by Louis Nicolaysen as proof that the dome was a centre of magmatic activity before the doming event and, thus, that the dome must have had an internal origin. However, intrusions of the same age are now known to be scattered throughout much of the Kaapvaal craton, and it is clear that the metamorphic grade does not increase towards the intrusions. Indeed, the Schurwedraai alkali granite is in contact with low-grade shales along the road. Thus, despite their similar age to the pre-impact metamorphism in the collar rocks, they could not have been the heat source for this metamorphism.

Stop 12

Gold mining in the Venterskroon area

Continuing north from Stop 11, a T-junction is reached after 1 km. Turn left (southwest) towards Venterskroon village. The road follows the Vaal River, past a number of entrances to



↑ **Figure 194:** Access map for Stops 12–14.

resorts, fishing camps and holiday homes. After 6 km, the Thabela Thabeng resort (26°51'39.6"S, 27°17'15.7"E; Fig. 194) offers swimming and restaurant facilities, as well as a small rock collection and display on the natural history of the Vredefort Dome. The Tourism Office in Venterskroon, 3.5 km farther on (26°53'11.7"S, 27°16'09.0"E), also has a small rock collection and posters, and both contain information about a range of hikes that include many aspects of the gold-mining history that can be found in the surrounding hills. The Vredefort Mountain Land offers a number of well sign-posted hiking trails, such as the Rooihaas trail starting at Thabela Thabeng. There are also several camps and huts scattered throughout the area offering overnight accommodation to hikers, including at Venterskroon. At Thabela Thabeng several secluded cottages are available in the Buffelskloof gorge above the resort.

Venterskroon sprang up in gold-rush times (see also Chapter 5, and the box on the next page), at the end of the 19th Century. There are still a number of fine old buildings in this little village dating back to the late 19th Century, for example the former police station dating from 1889 (Fig. 129) and the Old Imperial Inn. Most places are now utilised for recreational tourism enterprises, including hiking or river-tour operations.

Remnants of the ancient gold diggings abound in the hills around Venterskroon (Fig. 195). Numerous adits, shafts and trenches occur. Rehabilitation of these sites is ongoing — extreme caution should be exercised in their vicinity and they should only be approached accompanied by qualified guides. Partially overgrown mine dumps, as well as remnants of miners' houses and of a mining-related wagon-trail, are also found. The rugged mountains contain many deep and secluded gorges with little waterfalls and a wide array of ecosystems reflecting local microclimates and geological controls.

Stop 13

Shatter cones in the Booysens Formation, Rooderand

West of Venterskroon, the road climbs into the hills. After about 2.5 km, a sharp turn to the left exposes a 200 m long road-cutting of highly fractured shale on the left (26°52'40.3"S, 27°15'07.0"E; Fig. 194). It belongs to the Booysens Formation and is the only non-quartzitic unit in the Central Rand Group (Fig. 20). On the opposite side of the valley several old gold-mine adits surrounded by rubble dumps, now heavily overgrown, are visible within the quartzites.

Closer examination of the road-cutting shows that the 'shale' is actually metamorphosed, with shiny muscovite crystals glittering on the surface. This, and the colour, indicate that the rock should be called a *phyllite*. The metamorphic temperature is estimated to have been approximately 350 °C, similar to that seen in the upper Witwatersrand Supergroup exposures and in the gold mines around the margins of the Witwatersrand basin. The rock has essentially the same composition as the metapelites at Stops 10 and 19, so the different mineralogy reflects the much lower metamorphic temperature. This is consistent with the fact that, at the time of the pre-impact metamorphism, these rocks would have lain some 5 km closer to the surface than the lower Witwatersrand Supergroup rocks exposed in the Donkervliet valley and, thus, were farther from the deep crustal heat source that caused the metamorphism.

The main attraction of this stop are the numerous curved fractures that display diverging lines (striations; Fig. 196a). These partial shatter cones were the first impact-diagnostic feature

Vredefort and the Witwatersrand gold

As discussed, the Vredefort impact structure encompasses almost the entire Witwatersrand basin (Figs 24 and 81) and, if not for the Vredefort impact event, the wealth of the basin might have been lost forever.

The Witwatersrand basin represents the world's richest gold province. Roughly 40 000 to 45 000 tonnes, at an estimated value of more than US$50 billion, have been mined here. Most of this gold has been mined from the Witwatersrand Supergroup, especially its upper succession, the Central Rand Group. Only subordinate amounts of gold have been won from Transvaal Supergroup strata, mainly from the Black Reef Formation in the regions northwest and east of Johannesburg. Minor gold-mining activity has also taken place in Dominion Group strata underlying the Witwatersrand Supergroup, in an area to the west of the town of Klerksdorp, along the western margin of the Witwatersrand basin. In addition to these vast amounts of gold, some 150 000 tonnes of uranium have been mined from the Witwatersrand basin, mainly as a by-product of gold mining, but also from several gold-poor reef horizons. Mining in the Witwa-tersrand has been a mainstay of the South African economy for more than a century and, by supporting numerous migrant workers, has been beneficial to the economies of many neighbouring southern African countries as well. It is estimated that today, gold mining only accounts for 2 per cent of South Africa's gross national product, but that 200 000 miners and their dependents, in total several million people, directly or indirectly, still owe their livelihood to the Wit-watersrand gold-mining industry.

The major mining camps of the Witwatersrand basin are located within a semi-circular pattern around the Vredefort Dome, known as the Golden Arc (from Welkom, via Klerksdorp, Carletonville and Johannesburg, to Heidelberg and Evander; Figs 24 and 81). Most mines, to date, are active at depths between about 800 and 4 300 m, but exploration activity and technological advancement are aiming at even greater depths. This will mean that stoping could be carried forward down-dip in the direction towards the Vredefort Dome.

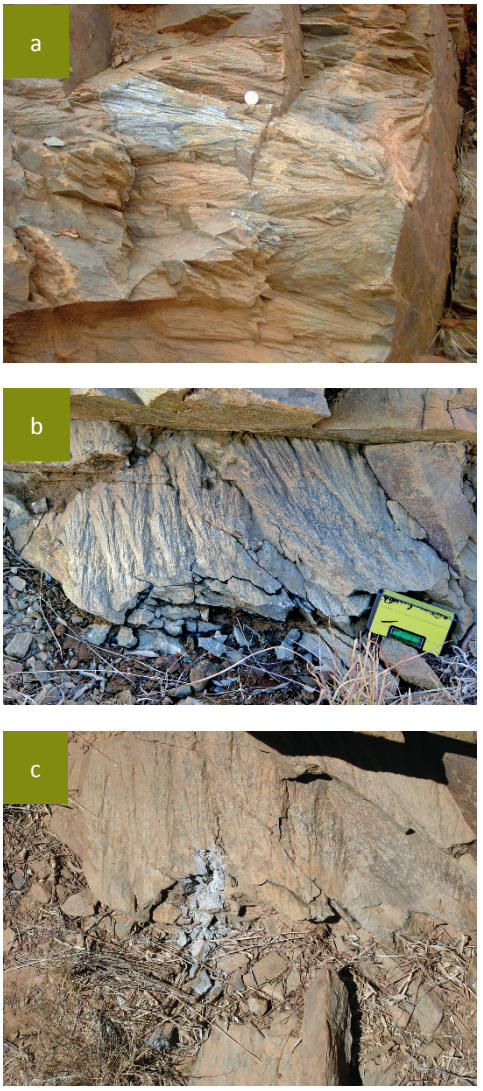
A long-standing debate has centred on the origin of the Witwatersrand ores. One school of thought favours an origin of the Witwatersrand gold by accumulation as purely detrital ore, brought into the basin by streams that deposited coarse gravels derived from an eroding hinterland and that was subsequently winnowed by wind and/or wave action along the sea shore. Other workers subscribe to a pure hydrothermalist view, meaning that they believe the gold was introduced into the basin after the deposition of the sedimentary layers by hot (ca 350 °C) hydrothermal fluids. Such fluids could originate from magmatic events, such as the Ventersdorp igneous event at 2 700 Ma, or fluids liberated from the Transvaal Supergroup rocks after they had been deposited on top of the Witwatersrand strata. Today, however, most Witwatersrand workers, especially most of those who in recent years have carried out detailed studies of the ores, support the so-called 'modified placer theory': gold was brought into the basin as sediment, but in later times was overprinted by other events that involved fluids circulating through the basin rocks. The timing of these events is, however, still not fully resolved, with events at 2 700, 2 500 to 2 300, 2 060, 2 020, and even 1 000 Ma being discussed. Many geologists do, however, agree that there is compelling evidence that fluids were active at impact times and modified the gold ore, likely as a direct consequence of the Vredefort impact event, and that this may have erased much of the evidence of earlier events.

In the Vredefort Dome itself, gold mining has taken place in rocks of the Upper Witwatersrand Supergroup during two periods: first, in the years prior to the Anglo-Boer War (1899–1902), the Kimberley reefs, locally known as the Amazon reef, were mined in the Venterskroon Goldfield (also known as the Rooderand Goldfield) in the

western collar of the dome. Mining was proclaimed in 1887, but because of unsatisfactory results, operations were discontinued in 1911. Main mining operations in the early 1900s included the Amazon Mine, which was opened in 1910 on the farm Rooderand in the Transvaal Republic, and a mine on the farm Elandslaagte No. 28, located in the then Orange Free State. Resurgence in mining occurred in the 1930s when the Great Western Mining Company re-opened the mine on Elandslaagte and extended its operations into the Transvaal Province on the northern side of the Vaal River. In numerous places around the collar of the dome the remnants of gold-exploration trenches, shafts (Figs 125 and 195) and adits can still be seen in the strata of the Kimberley Formation and some other conglomeratic horizons. The renewed mining operations were not altogether very successful, and the Great Western Mining Company ceased production in 1937. The total recorded amount of gold extracted from Vredefort sites amounts to merely some 130 kg, although these records are incomplete. In the late 1990s, Randfontein Estates Gold Mining Corporation (REGM) acquired prospecting rights for the Kimberley Reefs along the entire northwestern sector of the Vredefort Dome. The steep-standing reefs were attractive because of their accessibility to relatively inexpensive open-cast mining and because near-surface ore seemed to indicate excellent gold content. However, the residents of the most scenic part of the Vredefort Dome, the so-called Bergland Conservancy, opposed these plans and responded with an initiative to have the region declared a protected conservancy. This was the beginning of the drive that led, ultimately, to the declaration of the World Heritage Site. The fall in the gold price in the late 1990s and ownership changes at REGM led to the cessation of the mining project; however, applications for prospecting rights continue in areas beyond the borders of the World Heritage Site.

Figure 195: Three impressions of remnants of mining activity in the Venterskroon Goldfield, at the end of the 19th Century.
a. Dr Martin Brink (Potchefstroom) showing the entrance to a mining adit.
b. Foundation walls of an old mining-related building.
c. The quartz-rich conglomerate that was mined in this area. Pocket knife for scale ca 10 cm long. All three sites can be visited in the mountains above the Thabela Thabeng resort, northeast of the Venterskroon hamlet.

Figure 196: a. Shatter cones at Stop 13. **b.** Cone-in-cone structures developed on horizontal surface at Stop 13. **c.** Damage to the outcrop shown in b caused on 22 August 2008. Such illegal attempts to remove samples invariably lead to the perpetrators walking away with nothing, but the outcrops are permanently scarred.



to be identified in the Vredefort Dome in 1961. The origin of shatter cones is still not fully understood, but it is believed that they could form where the shock wave encounters an obstruction, such as a large mineral grain or a fracture in the rock that sets up a complex interference wave that causes fracturing. Studies in small impact craters initially suggested that the cones point towards the source of the shock wave. Several researchers have attempted to reconstruct the geometry of the Vredefort shock wave in this way; however, the complex rotations that occurred during the formation of the central uplift make this difficult. The shatter cones at this stop indicate a further complication: detailed measurement of cone axes by Frank Wieland showed that the cones in this outcrop have a wide range of orientations.

The outcrop displays partial cones with lengths of up to 50 cm that point mainly to the west (right; see opposite the road sign); however, farther down the road, cone-in-cone features (Fig. 196b) have a more northerly orientation. Over the years some visitors have tried to remove samples and, in so doing, have ruined parts of the outcrop (Fig. 196c). As it now forms part of the World Heritage Site, any damage to the outcrop is illegal. Furthermore, the highly weathered and fractured nature of the rock makes it impossible to remove individual cones; all that such attempts achieve is to ruin the outcrop for others. The outcrop is also somewhat unstable, and blocks of varying sizes regularly become dislodged. *Please refrain from standing too close to, or climbing, the outcrop. Please also be aware of vehicles travelling on the road.*

Very close to this stop, a farm track (marked Oudewerf/Birdsong Farm) forms part of one of the beautiful hiking trails through the mountains around Venterskroon. Below the road, this trail follows a stream that has carved a deep gully that locally exposes blue-grey ground that contains centimetre- to decimetre-size rock fragments. It is believed that this formation represents debris deposited during the Dwyka glaciation 300 Ma ago. Permission to hike the trail should be sought at the farm or at the World Heritage Site office in Venterskroon.

Stop 14

Amazon gold reef, Rooderand

Continue along the road for 1 km where a sweeping bend to the right crosses the valley (26°53'08.7"S, 27°14'28.7"E; Fig. 194). Permission to climb through the fence and visit the ridge of resistant quartzite on the right of the road (26°53'08.7"S, 27°14'28.7"E) must be obtained from the owner of Birdsong Farm. A

↑ **Figure 197:** Typical quartz-pebble conglomerate of the Amazon reef, as it was mined in the past on the farm Rooderand 510 IG in the Venterskroon Goldfield. The pen, for scale, is 12 cm long.

footpath leads to the quartzite that contains several layers of conglomerate (Fig. 197). As with most of the rocks in the collar of the dome, the layers are steeply dipping and are, in fact, overturned (dipping southeast towards the centre of the dome). The rocks belong to the Kimberley Formation of the upper Witwatersrand Group (Central Rand Group, Fig. 20). The Kimberley Formation is the most widespread gold-bearing rock formation in the Witwatersrand basin. It contains up to eleven pebble conglomerate horizons, generally known as the K1 to K11 reefs. In the early days of gold exploration in these hills, the main conglomerate layer exposed in this outcrop was named the Amazon Reef. The reef outcrop is pitted with small diggings. It is quite obvious that it is rich in pyrite (iron sulphide, or 'fool's gold'), which occurs with the gold and which oxidises when exposed to air to produce sulphuric acid and a rusty residue. This oxidation process, which explains the distinctive yellow colour of the mine dumps around Johannesburg, is a major pollution threat to groundwater quality in the region.

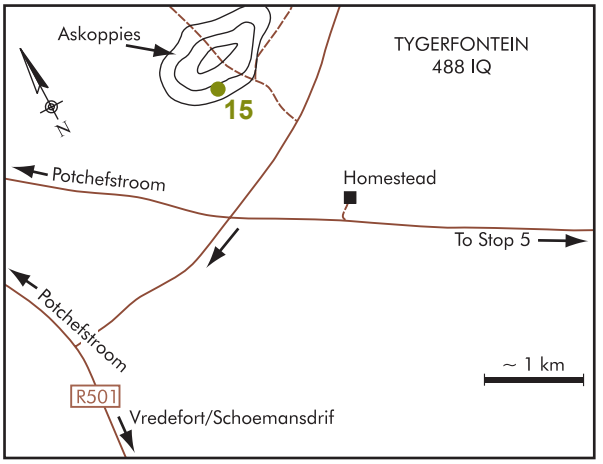
Conglomerate is a lithified gravel. The pebbles are predominantly smoky white to grey vein quartz, but black chert pebbles are also found. The pebbles are well rounded, indicating that they were transported in streams over large distances. A crude size layering is seen in places, indicating different current strengths at different times when these individual layers were deposited. The adjacent quartzites show cross-beds that indicate that they represent sandy shoreline deposits. Unlike the West Rand Group, which is dominated by submarine mud deposits with somewhat less sand, the sand-plus-gravel deposits of the Central Rand Group indicate a much more energetic environment, most likely with mountains close to the shoreline, such as the modern southern Cape coast. This package of sediments suggests that the gold was deposited on a sea shore where successive tectonic uplifts or drops in sea level caused river gradients to periodically steepen, thereby increasing the current strength and allowing gravel and dense pyrite and gold nuggets to be transported downstream (see Chapter 1). That the Vredefort reefs occur over 40 km from similar conglomerate reefs in the major gold mines at Carletonville indicates that these disturbances had widespread effects. Most Witwatersrand geologists favour a model for the gold involving initial deposition of nuggets with the gravels and then its subsequent mobilisation and/or recrystallisation during one or more metamorphic events up to and including the aftermath of the Vredefort impact event (modified-placer theory, see Box, pages 268–269). Microtextural evidence shows that no nugget shapes remain and that the gold in many reefs clearly recrystallised as a result of the heating that was triggered by the impact.

From the crest of the quartzite ridge, the remnants of an old wagon road are visible. The two spaced tracks made by heavily loaded wagons with iron-cladded wheels are clearly recognisable in the quartzite floor. This old road leads to one of the mine adits that can be seen from Stop 13.

Stop 15

Ventersdorp lavas, Askoppies Iron Age settlement and Anglo-Boer War sites on Tygerfontein farm

From Stop 14, the road continues for a few hundred metres to the crest of the hill. The crest lies close to the contact between the Witwatersrand Supergroup quartzites and the basalts of the Ventersdorp Supergroup that underlie the valley and the hills beyond. The change in topography is striking, as the iron-rich basalts weather readily to clay soils that are easily eroded. The deep, fertile soils of the Tygerfontein val-



† **Figure 198:** Access map for Stop 15.

ley make it prime agricultural land. Despite the presence of the valley, it is obvious that the land surface towards Potchefstroom lies at a higher altitude than the core of the Vredefort Dome, so it is perhaps not surprising that early geologists saw the dome landscape as a 50 to 60 km wide crater with a raised rim.

The irregular hills on the opposite side of the valley have the same knobbly rounded appearance as the Klipriviersberg ridge south of Johannesburg, which is also underlain by Ventersdorp basalts and is noticeably different from the more common white quartzite ridges. These basalts are fine-grained, grey-green and contain quartz amygdales (infilled gas bubbles). They form a basalt sequence up to 2 km thick that flooded across the Kaapvaal continent, swamping the Witwatersrand basin and terminating the deposition of the gold-bearing conglomerates at 2 714 Ma. The lavas are metamorphosed, but the metamorphic grade is considerably lower than the meta-lavas of the Dominion Group at Stop 9, consistent with their shallower burial prior to the impact. They contain pseudotachylitic breccia veins and elongate partial shatter cones. Outcrop is generally poor, but features may be seen in the settlement walls at the Askoppies site (26°51'25.0"S, 27°13'20.0"E; Fig. 198) and the surrounding hills, as well as on the road to the Elgro Lodge (see Stop 16).

Permission to visit the Askoppies site must be obtained from the Tygerfontein homestead, on the right before crossing the small stone bridge (Fig. 198). A fee may be charged. The farm also contains secluded camp sites and rustic huts on the quartzite ridge, one of which is located within the ruins of an Iron Age kraal (Bundu Camp, Fig. 163d). This ridge also hosts the fortifications of a heliograph station used by the British forces during the Anglo-Boer War (Fig. 131), and a blockhouse and other fortifications lying south of the road on Suikerbos farm. The military structures were clearly sited here because of the commanding views which they allow in all directions. Askoppies and the farms form part of a popular hiking trail that continues to Venterskroon.

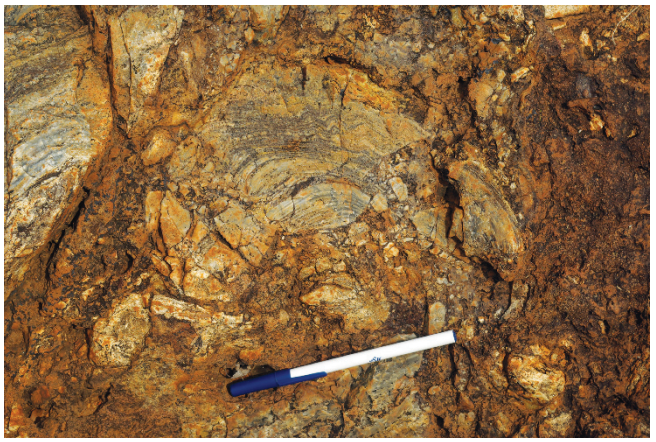
The Askoppies site is reached by continuing to the crossroads and turning northeast (right; Fig. 194). A gate approximately 1 km from the crossroads provides access to a farm track that continues for 1.5 km into the midst of the site described in Chapter 5 (26°51'24.9"S, 27°13'20.0"E) that was occupied from about 1670 until the early 1800s, when it was destroyed during the *difaqane.* The settlement comprises 20 similar units extending over several square kilometres (Fig. 111). Its location probably reflects the proximity of fertile soils for farming and its final size may reflect defensive needs during the difaqane. The low, scallop-shaped drystone walls mark the individual family units (see Figs 117, 118). Care should be taken not to disturb or damage the walls. A somewhat decayed thatch shelter marks one of the huts that was excavated by archaeologists (Figs 111, 113). Other excavations were performed in the ash middens that lie around the site and which give the hill its name. Smaller Iron Age settlements can be seen throughout the Vredefort Dome (e.g. Stops 9, 18).

Stop 16

Stromatolites and cave in Transvaal rocks of the western collar

From the Askoppies crossroads, continue across the Venterskroon–Potchefstroom road towards Schoemansdrift. After 2.8 km turn left at the T-junction onto the tarred road (Fig. 198). The road passes a distillery making traditional South African spirits called *mampoer* (a peach brandy) and *witblits* (literally 'white lightning'). After 4.5 km turn right onto the road to Skan-

Figure 199: Chert breccia from Dewetsdrift farm (Stop 16) showing the dislocated chert fragments (white) and the red to blue-black iron- and manganese-oxide matrix.



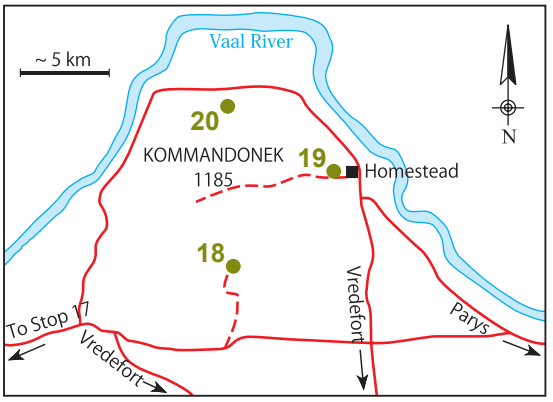
dinawiedrift. After 1.3 km, boulders of Ventersdorp lava are visible near the Elgro Lodge to the north of the road. Follow this road for 8 km to the entrance to Dewetsdrift farm (26°55'17.2"S, 27°07'59.0"E). The flat landscape away from the river marks the location of the dolomitic Chuniespoort Group (Transvaal Supergroup). At the entrance to the farm large boulders of brecciated chert with red to blue-black iron- and manganese-oxide infilling (Fig. 199) form part of a low ridge extending on both sides of the road. The chert ranges from white to black and is commonly finely laminated. In places, convolutions in the laminations resemble centimetre-scale stromatolitic domes, for which the Chuniespoort Group is famous (see Fig. 26). Domical features (Figs 26, 27), as well as flatter but undulating mat growths mark the remains of algal colonies that existed in shallow water along the margins of the Transvaal Sea prior to the impact event. The breccia is also well exposed in a cave to the north of the road on farm Grootdrif. The origin of this breccia remains controversial, but similar breccias can be produced by normal tectonic faulting or dissolution/solution processes caused by groundwater percolation in carbonate rocks.

Stop 17

Schoemansdrift Bridge shatter cones

Returning past Elgro Lodge, turn south (right) and continue for 6 km to Schoemansdrift (26°58'12.6"S, 27°12'33.6"E). The road meanders through the upper Witwatersrand Supergroup, but the topography is less extreme than around Venterskroon, and occasional views to the south show that the ridges die out and disappear under the Karoo sediments (see Fig. 172). The shatter cone outcrop occurs close to the water's edge less than 30 m upstream from the bridge. The best exposure (Fig. 200) is located on a metre-wide quartzite boulder next to a large tree stump. It displays composite cone-in-cone features with horsetail striations. This exposure, one of the most well known in the world, has already been vandalised by irresponsible visitors, who have tried to chip off samples. Please do not further damage it. Additional shatter cones occur on similar-facing surfaces on adjacent quartzite outcrops and are best seen in low-angle light where shadows emphasise the irregular surface and the striations. The host rock is a quartzite of the Jeppestown Subgroup (West Rand Group) that, unlike most of the other stops, is not actually overturned. As with Stop 13, back-rotation of the quartzite bed-

Figure 200: Cone-in-cone shatter cones with curved horsetail-like striations in quartzite at Stop 17.



↑ **Figure 201:** Access map to Stops 18–20.

ding to a horizontal orientation does not restore the cones to an orientation that points their apices towards the centre of the dome.

Stop 18

Dwarsberg (Steenkampsberg) view site

After crossing the Schoemansdrift bridge, turn left at the T-junction towards Parys/Vredefort. After 9.6 km, as the road emerges into the core of the dome, take the left fork towards Parys (Fig. 201). After 4 km, turn north (left) onto the farm road marked 'Thwane Bush Camp'. Continue 5 km to Thwane Camp, passing the Johannesburg Zoo's Rietkuil breeding and research facility for endangered species. The road crosses a dyke of Vredefort Granophyre in the collar rocks just before reaching the Dampoort homestead. A short distance beyond this it passes the dam that gave the farm its name.

From Thwane Camp, after having obtained permission to proceed, continue on a well-marked track in a general northerly direction. It would be useful here to have 4WD-vehicle support, but there is the option to hike. The track climbs steadily up a valley that contains a wide variety of protea and fynbos species (Fig. 149), for which the mountains of the Western Cape Province are famous. It also passes several circular drystone ruins that are usually heavily overgrown (a consequence of enrichment of the soil by livestock dung; see Fig. 144d). The track ends some 60 m below the highest hill, close to more Iron Age ruins (26°54'33.5"S, 27°18'24.1"E). A spectacular view is provided from this site, but an even better one is afforded by climbing to the top of the hill to the right. Towards the east, a wide sweep of the expanse of the granitic core of the Vredefort Dome can be seen, with Leeukop hill visible in the north and the towns of Parys and Vredefort (note the group of large grain silos) being prominent orientation points.

The rocks underlying Thwane hill are lower Witwatersrand Supergroup quartzites. To the north, the quartzite visible along strike of the hill displays highly variable rotation associated with folding and faulting caused by the formation of the dome (see Fig. 144b, page 206). Another deformation phenomenon is exposed along this ridge where, at several places, an up to 5 cm thick vein of dark-grey pseudotachylitic breccia, displaying a number of offshoots, cuts the cream-white quartzite.

Stop 19

Rocks and metamorphism of the lower Witwatersrand Supergroup, Kommandonek Nature Reserve

This stop (Fig. 201) lies on the west side of the Vaal River opposite Stop 10, and presents similar features to Stop 10. From Parys, it is accessed via the Schoemansdrift road (turn north from the R59, 2.5 km south of Parys) and from Vredefort by heading past the Visitor Centre on the R59 Viljoenskroon road and almost immediately turning north. At the crossroads north of the Visitor Centre (26°56'48.7"S, 27°21'26.2"E), which intersects the Schoemansdrift–Parys road from Stops 17 and 18, continue north for about 8 km towards the prominent white quartzite ridge. The Kommandonek Nature Reserve is located where the road converges with the Vaal River (Figs 92, 201) and crosses a prominent quartzite ridge (26°53'10.4"S, 27°21'29.7"E). The best exposures are about 1 km west of the entrance, along a farm track parallel to the quartzite ridge (Fig. 201). Permission to enter the property must be obtained at the Reception and a fee may be payable.

The prominent quartzite ridge at this site is the uppermost quartzite of the Hospital Hill Subgroup. It is overturned and dips steeply to the southeast. It shows very prominent fracturing (jointing), which is an obvious part of the

impact-induced deformation. In the valley below the ridge and close to the track, the metamorphosed, finer-grained rocks of the Parktown Formation can be examined. The metamorphosed pelites show overturned bedding and fine-scale sedimentary structures, such as upward-fining grain size and cross-bedding consistent with their deposition as offshore deltaic turbidites (see Stop 10). The mineral cordierite is visible as black oval depressions, up to 2–3 cm wide, on weathered rock surfaces. Andalusite forms rectangular, orange-white crystals up to 1.5 cm in size. The rocks are cut by numerous fractures, many of which have pseudotachylitic breccia associated with them. The large cordierite and andalusite porphyroblasts are cut and displaced by the fractures (Fig. 202), indicating that they predated the impact. Climbing from the track towards the quartzites, the rocks display unusual convoluted and disrupted bedding that suggests soft-sediment deformation. Such features occur when sediments are disrupted by earthquake tremors or slumping down slopes. Magnetic banded iron formations, commonly with small red garnets up to 1–2 mm in size, occur towards the top of the slope, where another andalusite-bearing layer is found.

A steep but pleasant hike from the Reception provides excellent views of the Vaal River and its numerous rapids, and the flat landscape of the alkali granites to the north. To the east, the Donkervliet valley exposes the strongly bent quartzite layer along its northern edge (Fig. 92) that indicates that the river exploits an impact fault that has displaced rocks to the east of the fault towards the north (see also Stop 22).

Stop 20

Impact-induced fold and view site, Parson's Rus

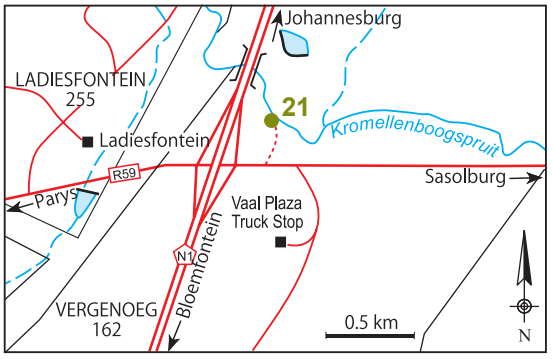
About 3.7 km north of Kommandonek Nature Reserve, Habula Lodge provides access to Stop 20 (26°53'58.6"S, 27°19'11.3"E; Fig. 201). Permission to use the hiking trail to the fold must be obtained from the Lodge office (26°53'26.0"S, 27°19'11.9"E). The 90-minute round trip requires negotiating steep slopes.

The kilometre-scale fold structures in the Hospital Hill Subgroup quartzites (Fig. 92) are best seen from the air and on satellite images.

Figure 202: Fracture cleavage in andalusite-bearing metapelite from the Hospital Hill Subgroup at Stop 19 (compare Fig. 191). Note the displacement of the white andalusite crystals to the right of the lenscap, indicating that they grew before the fractures, which contain pseudotachylitic breccia. Lenscap, for scale, approximately 6 cm.

They occur mainly in the northwestern collar of the dome. The presence of networks of pseudotachylitic breccia within their cores and their close spatial relation to impact-age radial faults indicate that they are related to the impact event. Together with the drag folds seen against impact faults, such as at Stops 10 and 22 (Figs 84 and 92), these folds indicate that the rocks in the collar were squeezed together at some stage during doming. Detailed analysis of the sequence of development of structures in the collar rocks and computer modelling of the formation of large central uplifts during impact events show that central uplifts undergo limited amounts of shortening tangential to the dome during the intermediate stages of their formation. What is unexpected is that such rapid movements of rock could produce ductile bending of layers to produce folds, in addition to faults. The latter stages of central uplift formation in the Vredefort structure were dominated by radial and tangential extension as the central uplift collapsed outwards. It was at this stage that the larger pseudotachylitic breccias, such as seen at Stop 7 and in the hinge of the Parson's Rus fold, are believed to have been emplaced. Much of the jointing seen in the quartzites also appears to date from the collapse phase.

The walk to the fold initially traverses alkali granite (see Stop 11) and traverses through the



↑ **Figure 203:** Access map to Stop 21.

overturned stratigraphy of the lower Government Subgroup of the West Rand Group, which contains metamorphic assemblages similar to those seen at Stops 10 and 19. The limbs of the fold are truncated by faults that have displaced it radially outward by between 0.5 and 2 km, consistent with further tangential squeezing. Layering in the western limb is right-way-up but the eastern limb is overturned (Fig. 88). Spectacular views are obtained from the fold locality south towards the centre of the dome and over the Vaal River and the alkali granite intrusions.

Stop 21

Coesite-stishovite-bearing quartzite, Kromellenboog Stream

The site lies immediately north of the intersection of the N1 freeway with the Parys–Sasolburg (R59) road (26°50'50.5"S, 27°38'33.7"E). Along the R59 from Parys, cross the freeway, and 300 m on, stop in a bay on the left side of the road, nearly directly opposite the access road to the Vaal Plaza Truck Stop, where permission to visit this locality should be obtained (Fig. 203). At the site, an old footpath runs parallel to the Kromellenboog Stream, along low outcrops of quartzite. Here, Jacques Martini from the Geological Survey (now Council for Geoscience) in Pretoria obtained the samples in which he discovered the high-pressure minerals coesite and stishovite. Like much of the evidence of shock deformation in the Vredefort Dome, this evidence is not visible with the naked eye.

Martini searched for many years for the dense polymorphs of quartz and, even then, he located only 17 sites in the dome where they are present. With the exception of a single sample from a quartz vein in Ventersdorp lava, all of these lie in quartzites of the Central Rand Group. The reason for this limited range is twofold: coesite and stishovite form over a limited shock pressure range (see Fig. 68) and these dense polymorphs revert to quartz if they are subjected to elevated post-shock temperatures for a prolonged length of time. As post-shock temperatures increased significantly towards the centre of the dome, and these rocks were buried beneath 8 to 10 km of overburden, much of the coesite and stishovite may have subsequently reverted back to ordinary quartz.

Martini found the coesite and stishovite crystals within and immediately adjacent to narrow veins of pseudotachylitic breccia (Fig. 204). The crystals are less than one-tenth of a millimetre

← **Figure 204:** Typical thin veinlet of pseudotachylitic breccia from the Kromellenboog locality, where such material contains the high-pressure mineral phases coesite and stishovite. Stishovite, to date, has only been found in rock from impact structures. Pen, for scale, 14 cm long.

across and their presence was initially confirmed by X-ray diffraction analysis (the scattering of X-rays passing through a crystal differs depending on the arrangement of atoms or ions in the crystal structure). Despite their small size, these crystals are exceptionally large for impact structures, indicating that the shock pressure pulse was more prolonged in the Vredefort event than in other, smaller, impacts. This provided more time for crystal growth.

Although coesite has also been found as inclusions in garnets from rocks that were tectonically subducted to mantle depths, stishovite has only ever been detected in samples from meteorite-impact craters. The quartzite along the Kromellenboog Stream was never buried more than 10 km below the surface, so only an impact shock wave could have generated sufficiently high pressures to cause the transformation. What is intriguing is that the coesite and stishovite do not occur throughout the rock. This suggests that the shock pressure was locally amplified and that this amplification may be linked to the formation of pseudotachylitic breccia-type melts. This may have consequences for the formation of pseudotachylitic breccia in the Vredefort Dome as a whole, as the friction melting hypothesis remains problematic (see Stops 7, 20 and 22).

The quartzite at this stop contains numerous grit layers and cross-bedding that indicates that the layers are overturned. Individual sand grains are clearly visible. The rocks contain partial shatter cones on iron-stained fracture surfaces and 1–2 mm wide veinlets of bluish-greyish pseudotachylitic breccia (Fig. 204), from which Martini identified coesite and stishovite.

Stop 22

Witwatersrand Supergroup quartzite, impact fault and Bobbejaanrant viewpoint, Smilin' Thru Resort

Some 8 km north of Parys, the R500 to Fochville passes the Smilin' Thru resort, a popular fishing and hiking venue on the Vaal River (Fig. 168). The quartzite outcrops lie east of the resort gate (26°49'43.9"S, 27°29'51.7"E). Permission to access this site and to climb the Bobbejaanrant must be obtained at the resort Reception.

The Bobbejaanrant ('Baboon Ridge') shows the typical expression of the Witwatersand quartzites — relatively straight ridges, up to several kilometres long, whose crests are marked by white rock. The hiking trail that leads up the ridge west of the road offers a view over much of the core of the Vredefort Dome to the south and northeast, as well as parts of the Vredefort Mountain Land to the west. The view to the east, across the resort, shows that the road follows the trace of a fault that has displaced the quartzite on the far side to the north (left) and that has bent the quartzite layers (Fig. 84). This fault is one of many radial and oblique faults related to the formation of the dome (see also Fig. 92). To the east of the road, the quartzites continue as a low, but nonetheless prominent, ridge. This particular quartzite layer belongs to the Hospital Hill Subgroup. It represents an ancient, 2 900 Ma old beach sand, now lithified and turned on-end by the Vredefort doming event. Close inspection shows the original sand grains that were deposited along the ancient shoreline. A key piece of evidence that these are beach sands is the herringbone cross-bedding representing the traces of sand ripples that were created by waves and tides washing back and forth along the shoreline.

Signs of the impact event include the closely spaced fracture sets in the quartzite that increase in intensity towards the road, which marks the trace of the fault. Veins of black pseudotachylitic breccia up to 5 cm wide occur parallel to, and locally cutting, layering (bedding). Closer to the road, the breccias become more voluminous (locally up to 1 m wide) and form an irregular network. Whilst some workers have used this to suggest that the breccias formed by frictional melting in the fault zone, other workers have suggested that the faults only provided dilational sites where the pseudotachylitic melt could accumulate (see Stop 7b) and that it formed elsewhere. Rare partial shatter cones (see Stop 13) are found, but these are not very common at this site.

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Sources cited in and related to the text, as well as some further reading providing an entry to all aspects of Vredefort research, on the other South African impact structures, and related topics. Sources suitable for the non-specialist are given in italics.

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About Earth history, especially plate-tectonic movement:	http://www.scoteses.com/
Astrobiology web	http://www.astrobiology.com/
Astronomical Society of SA, Johannesburg	http://www.assajhb.co.za
Council for Geoscience Bookshop	http://www.geoscience.org.za
Earth's impact-crater record	http://www.unb.ca/passc/ImpactDatabase/
European Space Agency (ESA)	http://www.esa.int/
Geological Society of South Africa	http://www.gssa.org.za
Harvard-Smithsonian Center for Astrophysics	http://www.cfa.harvard.edu/icq/meteorites.html
Jensen Meteorites	http://www.jensenmeteorites.com
Lunar and Planetary Institute	http://lpi.usra.edu
Meteoritical Society	http://meteoritics.org http://tin.er.usgs.gov/meteor/index.php
Natural History Museum, London	http://www.nhm.ac.uk
NASA	http://www.nasa.gov/NASA_homepage.html
NASA Earth Observatory	http://earthobservatory.nasa.gov/
NASA Image Archive	http://photojournal.jpl.nasa.gov/
Northern Free State District Council	http://tourism@nfsdc.co.za
Northern Free State Tourism Association	http://www.nfstourism.bizland.com
North West Province Tourism	http://www.tourismnorthwest.co.za
Parys Tourism Information	http://www.parysinfo.co.za
Smithsonian Institution	http://www.si.edu/science_and_technology/
Vredefort Dome World Heritage Site	http://www.vredefortdomewhs.co.za

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Glossary

(Note: selected cross references are indicated in italics)

A

Absorption spectrum: Any element that is heated will give off light of various wavelengths, the spectrum of which forms a unique fingerprint for this element. A gas of a specific element will absorb light of exactly the same wavelength that it would emit. Using a spectrograph, it is possible to determine the wavelengths emitted from, for instance, the Sun. Analysing the wavelengths corresponding to the dark lines in such an absorption spectrum allows the identification of the components of a *planet*'s atmosphere.

Accretion: The process of growth of an inorganic body or particle by the addition of new material to its surface.

Achondrite: Stony meteorite that does not contain *chondrules*; also does not contain much nickel-iron; of all *meteorite* types that which most closely resembles terrestrial rocks.

Adit: A horizontal passage from the surface into a mine.

Aeromagnetic (e.g. map/anomaly): A magnetic signature of the rocks underneath a certain terrain, acquired with instrumentation mounted on an airplane.

Aerosol: Solid or liquid particles dispersed in a gas (e.g. mist).

Afromontane: Associated with the mountains of Africa.

Afromontane archipelago: Pockets of vegetation that occur on African mountains, and that are like a group of islands in a sea of lowland vegetation.

Aggregated/aggregation: The moving together of large numbers of people from different groups into one large settlement. This happens specifically during times of war, for defensive reasons.

Alabaster: Firm, fine-grained variety of gypsum ($CaSO_4.10\ H_2O$). Used as interior decorative stone and for statuary.

Albite: One of the end-member minerals of the *plagioclase-feldspar* mineral series. Albite has the composition $NaAlSi_3O_8$.

Algae: Photosynthetic, aquatic plants, ranging in size from unicellular, minute forms to several metre-large kelp.

Alkaline/alkalic: Containing significant amounts of the alkali elements, especially sodium (Na) and potassium (K).

Alkali granite: A granitic rock that is enriched in the alkali elements and possibly calcium.

Alteration: Any change in the mineralogical composition of a rock because of physical or chemical processes, especially by reaction with low- to moderate-temperature solutions.

Alluvium: General term for unconsolidated sediment (mud, sand, gravel, etc.) as deposited by streams, floods, landslides, in stream beds or on flood plains, or at the bottom of mountains.

Amino acid: One of a group of organic compounds, which are the building blocks of proteins and, thus, essential for life processes.

Amor asteroids: The orbits of the Amors cross the *orbit* of Mars.

Amphibole: A family of silicate minerals that have crystal structures with double chains of silicate tetrahedra and contain hydroxyl groups in their structure. Upon heating they may decompose to a *pyroxene* mineral with related crystal structure under release of the hydroxyl.

Amphibolite facies: A particular regime of temperature and pressure in which metamorphic rocks that contain minerals of the amphibole group of silicates will form. Generally, moderately high pressure and temperature are required (ca 0.2 GPa and 400–600 °C).

Amygdale: An original gas cavity/vesicle in an igneous rock, now generally filled with secondary minerals.
Andesite: Fine-grained igneous rock similar to basalt, but somewhat richer in silica than basalt.
Angiosperm: Plant with seeds borne in ovaries, belonging to the group Angiospermae.
Anhydrite: Mineral of the composition $CaSO_4$.
Anorthosite: An igneous rock consisting mostly of *plagioclase*. A major constituent of the Lunar Highland crust.
Anticline (opposite of *syncline*)**:** Arch-shaped fold in rocks, closing upward (in the case of layered rocks) with the oldest rocks in the core. In the case of a very large structure, one could speak of an 'anticlinal form' or 'anticlinorium'.
Apartheid: Policy of racial segregation practiced by the former white minority government of South Africa.
Apollo asteroids: A group of small *Near-Earth Objects* (asteroids) in orbits that cross that of Earth.
Apollo programme: A series of manned space-flight missions of the late 1960s and early 1970s, first preparing to travel to the *Moon*, then successfully visiting the Moon; in the course of this, the first human set foot on this planetary body and many *Lunar* rock samples were returned to Earth.
Archaean: The earlier part of *Precambrian* time, until about 2 500 Ma ago.
Archaeology: The study of the past by scientific analysis of the remains of human culture. For more recent times, written records are used to supplement material evidence.
Artefact: Something made by humans, such as a stone tool or a painting.
Asteroid: A rocky or metallic body, ranging in size from metres to 950 km, in orbit around the Sun. Many asteroids are found in the so-called *asteroid belt* between the orbits of Mars and Jupiter.
Asteroid belt: A region between the orbits of Mars and Jupiter, where most of the asteroids are located.
Asthenosphere: The partially molten zone of the uppermost mantle of the Earth.
Astrobleme ('star wound'): A crater formed by the explosion of a *meteorite*, *asteroid* or *comet* upon impact onto Earth.
Astronomical Unit (AU): 1 AU = average distance between Earth and Sun = 150 000 000 km.
Aten asteroids: Near-Earth Asteroids that are related to the group of Apollo Asteroids, but that are smaller and have orbits inside that of Earth.
Atmosphere: (1) The mixture of gases that surrounds the Earth and primarily consists of nitrogen (78 %), oxygen (21 %), argon (0.9 %), and carbon dioxide (0.03 %). Gravity holds an atmosphere close to the surface of the planetary body it surrounds. (2) Physical measurement for pressure; 1 atmosphere (atm) corresponds to the pressure of Earth's atmosphere at sea level, 1 kg/cm^2.
Atom: Smallest building block of a substance, comprising a core (nucleus) of protons and neutrons, and an outer zone of electrons; between core and electrons, electronic neutrality is achieved that characterises an atom — in contrast to the variably charged ions.
Avalanche: A large mass of a material (such as snow, ice, mud, soil, rock) flowing very rapidly under the force of gravity.

B

Banded ironstone (also known as Banded Iron Formation): Sedimentary rock consisting of alternating layers of iron-oxide and silica-dominated material. Constitutes the world's most important iron-ore deposits.
Basalt: A dark, fine-grained rock, formed by crystallisation of lava on the surface of a planetary body; composed mostly of the silicate minerals *plagioclase*, *pyroxene* and *olivine*.
Basin: A large, bowl-shaped land form.
Bedding: Layering of sheet-like units, called beds or strata (plural of *stratum*), which are the smallest distinguishable units of a layered *sedimentary rock*.
Bentonite: A soft, plastic rock composed basically of montmorillonite (a group of minerals in the *phyllosilicate* group of the silicate minerals). The result of chemical alteration of an originally glassy material, such as a volcanic ash. When absorbing water, bentonite can increase its volume dramatically, and therefore it is a sought-after substance, especially for the drilling industry.
Big Bang: Gigantic explosion thought to have generated the Universe.
Billion: 1 billion = 1 000 million = 10^9
Biome: A vegetation type defined by the structure of dominant plants.
Biotite: An important rock-forming mineral of the mica group of the *phyllosilicate* group of the silicate minerals. Can occur in all categories of rock (*igneous*, *metamorphic*, *sedimentary*).
Bolide: An exploding or exploded extraterrestrial projectile.
Boudin/boudinage: French, meaning 'sausage'. Used to describe strongly stretched rock volumes that have thinned out and may even have ruptured at the thinnest parts, producing a string of parts resembling a line of sausages.

Breccia: Material consisting of angular fragments, usually of different sizes, held together by a fine-grained matrix (also called cement or groundmass). Fragments have usually been somewhat rotated against each other. When derived from rock violently broken during an impact event, it is called *impact breccia*.

Brecciation: Formation of a *breccia* by crushing of a rock into (angular) fragments. Advanced brecciation leads to a mixture of finer-grained matrix and coarser-grained inclusions called *clasts*.

Buoyant: Able to remain on, or suspended in, a more-dense phase, such as a crustal *plate* being able to remain on top of a hotter, thus less-dense, layer of the *mantle*.

Bushveld: Vegetation comprising a grassy layer with clumps of shrubs and trees.

C

Calcite: The mineral of the composition $CaCO_3$.

Caldera: A large volcanic crater or depression, usually the result of collapse of the upper parts of a *volcano* once the interior has been emptied of magma.

Cape Fold Belt: The large mountain chain just inland from the south coast of South Africa. The result of a large *orogeny* between 600 and 300 Ma.

Capture-recapture experiment: An experiment where organisms are captured, marked and released, and when organisms are captured again at a later stage, the proportion that are newly captured as opposed to recaptured enables calculation of the total population size.

Carbonates: A group of minerals that contain the group $[CO_3^{2-}]$. Includes such important minerals as *calcite* ($CaCO_3$) and *dolomite* ($MgCa[CO_3]_2$).

Carbonatite: A carbonate rock of apparent magmatic origin.

Cataclasite: A brecciated rock produced by fracture and grain rotation from its massive precursor rock, generally without addition or removal of material (see also clastic).

Catastrophism: The theory that sudden catastrophic events have decisively affected Earth's geological evolution, as well as the evolution of life on this *planet*. In contrast to the theory of *uniformitarianism*.

Ceres: Asteroid 1 Ceres, the largest asteroid known and the one first discovered in 1801.

Charnockite: An orthopyroxene-bearing granitic rock, generally only found in high-grade metamorphic rocks, especially those of the *granulite* facies.

Chert: A microcrystalline to cryptocrystalline rock entirely formed of silica. It is thought that it may form because of coagulation of silica molecules to form a gel from aqueous (i.e. water) solutions. Forms the silica layers in *banded ironstone*.

Chondrite: Stony meteorite that contains *chondrules*. These meteorites represent aggregates of materials formed very early on in the evolution of the *Solar System* and that have not been melted since.

Chondrule: Small, roundish bodies (grains; after a Greek word for 'grain'), often made up of the minerals olivine and pyroxene, thought to represent primitive material formed by crystallisation from material in a *nebula*, prior to the formation of solar systems.

Clast/Clastic: An individual grain or fragment of a rock, representing the result of mechanical disintegration of a larger rock mass.

Clay blowpipes: These blowpipes were used in metal-smelting furnaces to help heat up the fire. Animal-skin bellows were used with them to blow air into the furnace through holes in the side of the furnace.

Clementine: A NASA robot space probe launched in 1994 to the Moon. It surveyed this body and returned images for a detailed, global photo mosaic and other data on surface features.

Climax: An endpoint in the succession of vegetation that occurs on a particular site.

Coesite: A rare form, a so-called *polymorph*, of the SiO_2 mineral (at normal conditions: quartz) that occurs at elevated pressure. Found in meteorite craters and in *kimberlite*.

Coma: The vast cloud of gas and dust around the solid core of a *comet*.

Comet: A body orbiting around the Sun that is composed mainly of volatile materials, such as water ice or ices of other compounds, besides some organic compounds and more-or-less rocky material.

Commando: Boer fighting unit, a force of Boer troops (especially during the Anglo-Boer War).

Compression: A system of forces onto the outside of a material (for example, a rock volume) that results in reduction of the volume (or length) of this material. Typical results of compression of rock volumes that are quite rigid are the deformations known as *fault*ing and *fold*ing.

Condensation: Formation of a solid or liquid from a gas.

Conglomerate: A layer of sedimentary rock that is composed of generally rounded pebbles deposited in a river or beach environment. In the Witwatersrand, such layers are called 'reefs' if they have proven to be gold bearing and, thus, are of economic value; another term used in the past for Witwatersrand reefs is 'banket'.

Conservancy: An area in South Africa that has a certain status of protection. That is, it is recognised by the national or a provincial government as being in need of protection, perhaps because it is a sensitive area, such as a wetland, has special scenic beauty, or represents a unique geological terrain. Vredefort has the so-called Bergland Conservancy that singles out the most scenic part of the collar.

Contact metamorphism: The change in rocks (that is, *metamorphism*) incurred only around a *magmatic* body, in the contact zone to this hot material. Thus, this kind of *metamorphism* is characterised by high temperature and not much additional pressure.

Continent: One of the Earth's major land masses (a continent includes the dry land mass, as well as the shelf territory).

Continental: Formed on land (rather than in the sea, which would be *marine*); includes deposits of lakes, swamps, by wind or from a stream, or of volcanic origin.

Continental drift: The movement of continents relative to each other, as a consequence of *plate tectonics*.

Convection: Heat transfer through a fluid, gas, or — in the case of the Earth's mantle — molten or semimolten material. The heated material becomes lighter than the cooler phase and will rise (it will become *buoyant*), whereas the cooler material will sink.

Core (of the Earth): The innermost part of the Earth, a 3 500 km wide, largely metallic (iron and nickel plus minor silicon) zone.

Cosmic dust: See *interplanetary dust*.

Cosmopolitan: With a worldwide distribution.

Cotyledon: One of the two major groups into which the *angiosperms* are traditionally divided (see also *dicotyledons*).

Country rock: The rock one finds in the immediate vicinity of a specific material or geological formation. For example, the country rock to the *Vredefort Granophyre* in the core of the Vredefort Dome is *granitic gneiss*.

Crater: General term for a circular, funnel- or bowl-shaped depression, produced either by a *volcanic* or *impact* process. When produced by impact, known as an *impact crater*.

Craton: Also known as shield. A geologically stable part of a continent's crust that has remained largely undeformed since its formation.

Cretaceous–Tertiary boundary: (also known as K–T boundary, for K: Kreide and T: Tertiär, German) A major stratigraphic boundary on Earth marking the end of the Cretaceous and the beginning of the Tertiary period at 65 Ma. This time coincides with a major, global mass extinction, during which altogether some 70 % of species were wiped out, including nearly 100 % of the dinosaurs.

Crust (of the Earth): The thin, outermost solid layer of the Earth, comprising <1 % of the Earth's volume. Varies in thickness from about 5 km below oceans to ca 60 km below continents.

Crypto-: Meaning 'unknown' (thus, any process that is not understood) or so small that it cannot be resolved (for example with a microscope). For example, very small crystals, individuals of which cannot be recognised, are called cryptocrystalline.

Crystal: Natural body with plane surfaces that are the outside expression of the regular arrangement of atoms or ions in the interior. Crystallisation is the process by which crystals form.

Crystalline: General term applied to igneous or metamorphic rocks formed by the process of crystallisation of minerals from solid or liquid precursor materials (such as liquid *magma*), in contrast to many *sedimentary rocks* that are aggregates of solid particles not jointly crystallised.

Cyanobacteria: A group of micro-organisms formerly called 'blue-green algae', capable of producing oxygen through photosynthesis. The massive development of these organisms between about 2.6 and 2 billion years ago is responsible for the oxygenation of Earth's *atmosphere*.

Cyclone: An atmospheric low-pressure system with a closed, roughly circular wind motion. Synonyms *hurricane*, *typhoon*.

D

Daga: Cement, mortar: also any of several mixtures for building and/or smearing floors, mud and clay, cowdung with mud, blood and earth, etc.

Dassie: Also known as 'Rock Dassie' or 'Hyrax'. Small, rabbit-size *mammal* living in rocky areas.

Density: Measurement for how much mass is kept in a specific volume. Water has the density of 1.0 = 1 g per cubic cm. Earth's average density is 5.52 g/cm^3.

Diamictite: A mixture of rock debris of very different grain size, from boulder to sand size, the origin of which is not known. Compare: *tillite*.

Diapir: A domal structure in which underlying material is squeezed upwards through the overlying material whereby the overlying material may rupture due to the squeezing out of material from the core of this structure. Typically formed when less-dense plastic volumes of salt or other relatively soft rock materials (mudstone, siltstone, shale) are deformed by *compression*.

Diaplectic glass: A glass-like phase produced by *shock metamorphism* without material entering a molten stage (thus, a result of solid-state transformation).

Diatom: A microscopic, single-cell plant, which grows in both *marine* (that is, salty) and fresh water. The cell walls are composed of silica (SiO_2).

Dicotyledons: One of the two major groups into which the *angiosperms* are traditionally divided, with two seed leaves (*cotyledons*) in the embryo.

Difaqane: See *Mfeqane*.

Differentiation: The process of developing and changing. For example, more than one rock type can form from one *magma* of changing composition; or an originally well mixed, homogeneous planetary body may differentiate into different layers, each with its own characteristics (such as the Earth, with core, mantle and crust).

Dimension stone: Building stone that is quarried and prepared in the form of regular blocks.

Dinosaur: Reptiles of specific species that dominated life on Earth between the Triassic and late Cretaceous periods.

Diorite: A *magmatic*, *intrusive* rock that is of general *granitic* appearance, but contains relatively more dark-coloured (*mafic*) minerals than a *granite* that is basically composed of light-coloured *quartz* and *feldspar* plus a few per cent of *biotite* or *amphibole*. A diorite has appreciably more of these latter minerals. Its SiO_2 content is of the order of 60 to 65 weight per cent (wt.%), that of granite may be as high as 80 wt.%.

Dip: The attitude of a rock layer perpendicular to its extent (the *strike*). A horizontal layer would have a dip of 0 degrees, whereas a vertical layer one of 90 degrees.

Distal: Meaning 'far from…' (opposite: proximal = nearby).

Dolomite: A *carbonate* rock composed of the mineral 'dolomite' ($CaMg[CO_3]_2$)

Drakensberg: A huge mountain chain in central South Africa, part of which has been incorporated into a World Heritage area. The Drakensberg is actually an *escarpment* formed by the *erosion* of massive *lava* flows that erupted at about 180 Ma ago because of large-scale rifting.

Drill core: A cylindrical section of rock, some 10 cm or less in diameter, obtained by drilling from a borehole, and brought to surface for examination.

Drought: Extended period of lack of rainfall.

Dyke: Also spelled 'dike'. A sheet-like (tabular) body of *intrusive igneous* rock that cuts across the bedding or structural planes of the host rock.

E

Early Stone Age: The early part of the time when human endeavour was characterised by the use of stone tools, especially crude tools. In South Africa, this was the time before about 150 000 years ago.

Earthquake: Instantaneous release of a vast amount of energy pent-up in the Earth, because of a *tectonic* movement. Intensity of earthquakes is measured against the so-called *Richter Scale*.

Eclogite: A granular rock essentially composed of *pyroxene* and *garnet* minerals. It is typical for the metamorphic regime characterised by very high pressure. Occurs at depth in the Earth's mantle, as known from eclogite inclusions recovered from kimberlite.

Edaphic: Chemical and/or physical.

Ejecta: Any material that is ejected from a growing *impact crater* (or, for that matter, from a *volcano*).

Ejecta blanket: A deposit surrounding a crater, consisting of material ejected from the crater during its formation.

Electron: A negatively charged particle in an atom.

Electron microscope: See *scanning electron microscope*.

Element: A substance that cannot be resolved by chemical means into more primitive/simpler substances.

El Niño: The phenomenon that involves significant warming of the eastern Pacific Ocean, with an extreme effect on global weather.

Endemic: Confined to a given region.

Endogenic: A process taking place or originating inside a *planet*.

Enstatite: A *pyroxene* mineral of the composition $MgSiO_3$.
Equator: An imaginary great circle around a body, such as a *planet*, that divides this body into a northern and a southern hemisphere, thereby being at any point along the circle at the same distance from the two extreme points, the poles.
Erosion: The process that involves the wearing away of the land surface by mechanical (stream, wind, or ice) or chemical action.
Escarpment: A long, more or less continuous, cliff or steep slope facing consistently into a particular direction. South African examples are the *Drakensberg* escarpment in the KwaZulu-Natal Province, and the Great Escarpment in the Mpumalanga Province, where a huge drop from the Highveld to the Lowveld occurs.
Estuary: The mouth of a river where fresh water comes into contact with sea water.
Ethnographic/ethnography: The description of the way of life and customs of people.
Eucrite: A group of *achondrite* meteorites of the composition of a *basalt*.
Evaporite: Rock produced by evaporation of a saline solution, whereby chemical sediment remains.
Evolution: The gradual development of something, such as a *planet*, a *continent*, or living organisms.
Exfoliation dome: A large, rounded rock outcrop formed in massive, homogeneous, coarse-grained rock.
Exogenic: A process taking place at or near the surface of a *planet*
Extension: The opposite of *compression*. Similar to 'stretching'. Increasing the length of something.
Extinction: Disappearance of all the individuals of a *species* of life; or more than one species.
Extraterrestrial: From outside the Earth, from Space.
Extrusion/Extrusive: The emission of *lava* onto the Earth's surface, forming *volcanic* rocks.

F

Fabric: The spatial and geometric arrangement of the parts of a rock (for example, the alignment of minerals in deformed rocks, or the pattern of particles in a sedimentary rock).
Facies: Temperature/pressure conditions under which a specific type of metamorphic rock forms.
Fall: A meteorite recovered shortly after its fall had been observed.
Fault: A fracture in rock, along which the sidewalls have been visibly displaced.
Fault gouge: Soft, pulverised, extremely fine-grained, and not-cemented, material derived by movement of rock masses along a fault.
Fauna: The entire animal population, living or *fossil*.
Feldspar (minerals): A group of important rock-forming minerals of the general formula $[M(Al,Si)_3O_8]$, where M can be K, Na, Ca, Ba, Rb, Sr, and Fe. Feldspars form the most abundant minerals in the Earth's crust (about 60 %), and basically can occur in all rocks.
Feldspathoid minerals: A group of minerals that form in a rock, instead of corresponding feldspar minerals, if the environment (for example, a magma) does not contain enough silica (SiO_2) to allow formation of the feldspar mineral (an example: the feldspathoid leucite ($KAlSiO_6$) would then form instead of the *feldspar* mineral orthoclase ($KAlSi_3O_8$).
Felsic: An igneous rock that has abundant feldspar and quartz, and consequently is quite light coloured. Opposite of *mafic*.
Find: A meteorite recovered by chance, without its *fall* having been observed.
Fireball: The appearance of a *meteor* (synonym shooting star), a small amount of extraterrestrial material that is burning up in the *atmosphere*.
Fission-track age dating: When ^{238}U atoms spontaneously decay, they produce charged particles that leave trails of damage in the host material (certain minerals or natural glass). The number of such tracks in a certain area (for example, the area of a thin section of a rock) is a function of the age and uranium content of the mineral, and is a basis for the dating of this phase.
Flood basalt: Huge volume of lava erupted over a very large area. The lava must have had low viscosity in order to be able to flow for large distances, covering large geological areas (provinces).
Flood plain: The relatively flat-lying terrain adjacent to a river channel that is flooded and where *sediment* is deposited when the river flows over its banks.
Flora: Plants that occur in an area (the entire plant population, living or fossil).
Fold: A bend in a rock *stratum* (bed) or other planar feature of rock.
Foliation: General term for a planar arrangement of textural or structural features in any rock.
Foraminifera: Skeletal remains of small marine and freshwater organisms that consist of single chambers of calcite, or of

multiple chambers that may form aggregates. Very useful for dating of rocks through evaluation of their microfossil content.

Form: The smallest category used in classification of *fossils*.

Formation: A body of rock that has specific characterisations, such as rock type, or (geological) position in a sequence of rocks. Used to subdivide large successions of rock (for example, Brixton Quartzite Formation).

Fossil: Any remains, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since this form was alive.

Fossilisation: The burial of a plant or animal in sediment and eventual preservation.

Fragmental impact breccia: (Synonym: lithic impact breccia) Impact-generated breccia composed of only clasts, not containing any impact-melted material. Compare *suevite*, *impact melt*.

Friction: Rapid sliding of rock masses against each other, along a fault, produces heat and may even lead to friction melting (compare *pseudotachylite*).

G

Gabbro: A *plutonic rock* type of the same composition as the volcanic *basalt*, but emplaced within the Earth, and, therefore, crystallisation is slower and resulting grain size comparatively coarser.

Galaxy: A huge number of *stars*, together with vast amounts of dust and gas, that is held together by mutual gravity. Our Milky Way is such a galaxy. It contains more than 100 billion stars, of which our Sun is only one.

Galileo Galilei: (1564–1642) Italian astronomer and physicist, who first used the then newly developed telescope to study the sky. Discoverer of sunspots, the phases of Venus, and of the four largest moons of Jupiter.

Gas Giant: Any of the four huge *planets* Jupiter, Saturn, Uranus and Neptune.

Gastrobleme: Crater structure that is the result of an explosion triggered in the interior of a *planet*.

Genus: A group of species.

Geochemistry: The analysis of rocks and minerals by chemical methods in order to investigate the origin of these materials.

Geochronology: That discipline of geoscience that deals with the determination of ages of rocks.

Geological time: The entire time interval since the formation of the *planet* Earth.

Geology: The study of the *planet* Earth, specifically the materials it is made from and the processes that make or act on these materials. Also the study of the history and evolution of Earth and of its past fauna and flora.

Geomorphology: The study of the evolution and configuration of landforms.

Geosphere: The 'rock part' of *planet* Earth. Other parts of the *planet* are the *hydrosphere*, *atmosphere* and *biosphere*.

Geothermal gradient: The rate of increase of temperature in the Earth with depth. The approximate average geothermal gradient in the Earth's crust is about 25 °C/km.

Gigapascal: The unit that replaced 'kilobar' for the quantification of pressure. One gigapascal (GPa) = 10 kilobars = 10 000 atmospheres.

Gneiss: A type of metamorphic rock formed from igneous rock, such as *granite* or diorite, with a well-formed banded structure.

Gondwana: An ancient *supercontinent* that comprised all of what is now Africa, South America, Australia, Antarctica and India.

Granite: A coarse-grained, generally light-coloured intrusive rock composed of the minerals quartz (SiO_2), feldspar and some dark minerals (such as biotite and/or amphibole).

Granitoid: Igneous or metamorphic rocks composed of the minerals typically occurring in *granite*; not necessarily a fresh igneous rock, can be metamorphosed.

Granodiorite: Another rock type comprising the same minerals as *granite* and diorite, but with an intermediate composition in terms of silica percentage and proportions of felsic and mafic minerals, respectively.

Granofels: A field name for a medium- to coarse-grained granoblastic metamorphic rock with little or no foliation or lineation.

Granophyre: A rock composed of irregular intergrowths of quartz and feldspar minerals, on a microscopic scale; adjective: granophyric (e.g. *texture*).

Granular: If a rock is made of particles with approximately similar grain size, it is said to be of granular texture.

Granulite facies: That regime of metamorphism where pyroxene and feldspars, also garnet, are dominant minerals. Relatively high pressure (in excess of 0.5 GPa) and temperature (>650 °C). Minerals with water or hydroxide in their crystal structure cannot exist in such conditions.

Grassland: Vegetation with grasses and herbaceous plants.

Gravity: The force on any body at or near the Earth's surface due to the attraction of the Earth itself (or, for that matter, another body); adjective: 'gravitational'. The gravitational field of a planetary body is that region of space in which it manages to attract matter.

Greenhouse effect: Warming of the *atmosphere* and the surface of a *planet* as a result of the absorption of infrared radiation by atmospheric gases (such as CO_2).

Greenstone: A *mafic* or *ultramafic* (very mafic) rock that is greenish because of the colour of the minerals that resulted from alteration. The iron- and magnesium-rich minerals change to greenish secondary minerals, such as chlorite, or certain amphibole minerals.

Greenstone belt: A whole region of a *Precambrian* shield that is characterised by greenstones.

H

Hadean: The very first part of the evolution of the Solar System, prior to ca 3 900 Ma, and best preserved in the Lunar rock record.

Harzburgite: A very mafic (*ultramafic*) igneous rock composed mostly of olivine and pyroxene.

Herringbone cross-bedding: Cross-bedding that dips in opposite directions in successive beds, indicating opposing current directions and, therefore, a beach or near-shore depositional environment.

Highlands, Lunar: The ancient crust of the Moon, consisting mostly of a rock type known as *anorthosite* that comprises mainly *plagioclase*. These regions have relatively high topography, where their name comes from, and are heavily cratered.

Hinge (of a fold): Where the maximum curvature occurs in a *fold* structure.

Historical age: The time after the first European settlement in South Africa, although it overlaps with the Late Iron Age.

Hominin: Ape that walked upright and that is found in the family tree of humankind.

Homo: The name given to the descendants of the hominids with more advanced characteristics, eventually ending with modern mankind, homo sapiens.

Hornblende: A mineral of the group of *amphiboles*, a group of silicate minerals based on double chains of silicate tetrahedra.

Hunter-gatherer: A term used to describe the lifestyle of *Stone Age* people. They mainly hunted wild animals and gathered plants for food.

Hurricane: See *cyclone*.

Hydrocarbon: An organic compound made up of carbon and hydrogen.

Hydrosphere: All the waters of the Earth, including oceans, rivers, lakes and other bodies of surface water, as well as the frozen water.

Hypervelocity impact: The impact of a projectile onto a surface at a velocity in excess of several kilometres per second.

I

Igneous rock: Literally 'Rock by Fire'. A rock formed as the result of magmatic processes (*volcanism* that produces magmatic rocks extruding onto the surface of a *planet*; or *plutonism* that emplaces molten rock (magma) into the interior of a planet).

Impact: Collision between two bodies.

Impact basin: A very large, complex impact structure with a wide central region that resembles a flat *basin*. It may have one or more concentric ring structures, in the latter case it would be known as a multi-ring basin.

Impact breccia: A type of *impactite* formed entirely from fragments of rock or minerals. These fragments can either be crystalline or glassy (melt) material.

Impact crater: A crater form formed as a result of the impact of an extraterrestrial projectile travelling at *hypervelocity*, that is at speeds between 11 and 72 km per second.

Impact glass: Glassy material produced by fusion of target rock; when crystalline (that is, devitrified), called *impact melt* (rock).

Impact melt: Close to the explosion of an impacting projectile all target rock is completely vaporised, but somewhat further from this point, rock is melted and then becomes impact melt (after solidification: impact-melt rock).

Impact structure: The result of an impact event; can be a well-defined, simple bowl-shaped crater, or a complex crater form. If it is not possible to describe a specific crater form, the term impact structure is used.

Impactite: Any rock that is formed and deposited as the result of an impact event. It may represent an agglomerate of fragmented material (a breccia), or mixtures of fragmented and melted materials (*suevite* or *impact-melt* rock). Glassy melt, such as *tektites* or *impact glass*, are also types of impactites.

Impi: A band of armed Zulu warriors or soldiers in precolonial times (mid-19th Century).

Inner Planets: Mercury, Venus, Earth and Mars, which have orbits that are inside of the orbits of the asteroids of the *asteroid* belt.

***In situ*:** Meaning 'in place', or at a location where it was used.

Interplanetary dust: Tiny particles in Space, not larger than some tens of micrometres (tens of thousandths of a millimetre).

Intertidal: Coastal environment between high-water and low-water levels.

Intertidal zone: Zone at the margin of an ocean where high-water and low-water stands are in contact or alternate.

Intrusion/intrusive: A body of *igneous rock* that has forced itself into/between pre-existing rocks, for example along a definite structural feature (a fracture or *fault* perhaps) or a contact between two rock types, or by deforming older rocks and cross-cutting them. Intrusion refers to the emplacement of such a body. Intrusive rock is also known as *plutonic rock*.

Iridium: Chemical element (Ir); one of the platinum-group elements.

Iron Age: The period dating back to between 200 AD and the late 19th century (roughly the last 2 000 years). During this period people acquired the ability to smelt and work metal (to a large extent iron) into tools.

Iron meteorite: Meteorite composed mainly of iron-nickel metal.

Island arc: A usually arc-shaped series of islands built by volcanism above a *subduction* zone.

Isotope: One or two or more species of a specific chemical element. Isotopes have the same number of protons in their nucleus, but different numbers of neutrons. Thus, their atomic weights differ. They may have the same chemical characteristics, but possibly have very different physical properties.

J

Joint: A fracture in a rock, without visible relative movement (displacement) of the two sides adjacent to the fracture.

K

K–T boundary: See *Cretaceous–Tertiary boundary*.

Kaapvaal (*craton*): The craton that represents the ancient core of the geology across South Africa. It is bordered by younger belts.

Karoo Supergroup: A stratigraphic sequence of the South African (and other southern African countries) rock record, of 300–180 million year age. This predominantly sedimentary sequence of rock formations preserves some of the most remarkable *fossil* heritage worldwide, including some of the earliest dinosaurs and *mammals*. This period also includes one of the most wide-ranging *extrusive* magmatic periods in Earth History: the Karoo *flood basalt* province epitomised by the volcanic rocks of the *Drakensberg* mountain range.

Kimberlite: An *alkaline* igneous rock that occurs in pipe-like structures. This material is derived from great depths within the Earth's *mantle*, where it may have picked up diamonds.

Kinetic energy: The energy that a body possesses while it is in motion. It is the product of the mass of the body and the square of its velocity.

Komatiite: After the 'Komati Valley' in the Barberton area of Mpumalanga Province, where it was first discovered. An *ultramafic* volcanic rock that is only known from the *Archaean* rock record. Adjective komatiitic.

Kgotla: Meeting place in Iron Age settlement.

Kraal: Cattle enclosure.

Kuiper-Edgeworth Belt: A region beyond the *orbit* of Pluto that contains many icy bodies in orbit around the Sun, leftover from the formation of the Solar System. It is believed that some types of *comet*, with orbits of less than 200 years, originate from this belt. Named after two prominent astronomers, Gerard Kuiper and Kenneth Edgeworth.

L

Lamprophyre: A dark-coloured igneous rock, with a high percentage of dark minerals, such as *biotite* and *pyroxene*, that form larger crystals (known as *phenocrysts*) set into a fine-grained groundmass (matrix) of the same minerals, plus *feldspar* or *feldspathoid* minerals.

Landslide: Rapid sliding of a rock or soil mass down a slope.

Lapilli: *Volcanic* ejecta of a grain size between 2 and 64 mm.
Lava: Molten rock at the surface of a planetary body.
Leuco-: A prefix meaning 'light-coloured'. Opposite of 'mela-'.
Lithosphere: The upper, approximately 100 km thick, solid (rigid) portion of the Earth, which includes the crust and upper parts of the mantle of the Earth.
Lunar: Pertaining to Luna (Latin), the Moon. For example, Lunar rock = Moon rock.

M

Maar: A low, broad volcanic crater caused by explosive *volcanism*.
Macroscopic: Anything that is too large to observe directly in its entirety. (As compared to mesoscopic = anything that can be observed in its entirety, but is too large to be studied by a microscope; microscopic = something that cannot be observed without the assistance of a microscope).
Mafic: A rock that has abundant iron- and magnesium-rich minerals and consequently is quite dark coloured. Opposite of felsic.
Magaliesberg: The range of ridges and valleys to the north and northwest of Johannesburg, marking the southern limit of the Bushveld Complex.
Magellan: NASA spacecraft that between 1990 and 1994 used radar to map the surface of *planet* Venus at high resolution, thus penetrating this planet's dense cloud cover.
Magma: Liquid (molten) rock that forms deep beneath the surface of a planetary body.
Magmatic rock: The result of crystallisation of a magma. It can be an *extrusive* magmatic rock (known as lava) or *intrusive* magma.
Magnetic anomaly: A zone or area of, or near, the Earth's surface that is more magnetic (a positive anomaly) or less magnetic (a negative anomaly) than the surrounding region. Such anomalies can be quite easily determined with a small portable probe (a magnetometer) or by means of instrumentation attached to an airplane (in the latter case, a very useful tool for exploration of *ore* resources). See also *aeromagnetic*.
Mammal/mammalian: All *vertebrates* belong to the mammalian class of *faunal* species. They are characterised by having warm blood and, in part, hair, and they give birth to live young and nurse them. First mammals developed in Jurassic times, some 140 Ma ago. But mammals only became dominant at the beginning of the Tertiary period at 65 Ma.
Mantle (of the Earth): A zone about 2 300 km thick between the Earth's crust and the core.
Mare (plural: maria): Latin for 'ocean/sea'. Name given by early *Moon* observers to the large, dark plains on the Moon. Many of them are flooded *impact craters*.
Marine: Pertaining to ocean/sea, for example, *marine life* (the *fauna* found in and adjacent to a sea) or marine biology.
Mariupolite: Synonym for *nepheline-syenite*.
Maskelynite: *Diaplectic glass* of plagioclase, formed as a result of shock metamorphism.
Matrix: Also 'groundmass'. Fine-grained material between fragments, for example of a *breccia*, or clasts (in an impact-melt rock).
Meta-: Greek, meaning with or after. A prefix implying a change that, for example, has taken place in a rock (compare *metamorphism*).
Metamorphism: The change a rock may undergo owing to the change of its physical metamorphic environment, especially temperature and pressure, but also differences in the chemical environment. When a rock is moved from the surface of the Earth to a deeper level characterised by higher temperature and pressure; adjective: metamorphosed.
Metapelitic: A metamorphic rock formed from a fine-grained clay- and/or silt-rich sediment.
Meteor: (Synonym: *shooting star*) The fiery streak in the atmosphere produced upon the entry and subsequent burn-up of a small extraterrestrial body, a *meteoroid*.
Meteorite: A fragment of extraterrestrial material that has fallen onto the Earth's surface (adjective meteoritic).
Meteoroid: A small extraterrestrial body, much too small to be called an *asteroid*, but larger than *interplanetary dust*.
Mfeqane: A time of intense social turmoil at the beginning of the 19th Century, when Zulu clans violently moved into the interior of southern Africa and clashed with other tribes. Also *difaqane*.
Microcrystite: Tektites that have begun to crystallise, i.e. to form small crystals from the originally fully glassy material.
Microlithic: Little stone artefact.
Microscopic: At a scale that is less than a millimetre, where it becomes necessary to resort to a microscope to achieve the necessary resolution.

Midden: A refuse dump, onto which humans threw all their discarded objects.

Middle Stone Age: A period in South Africa's cultural history, from ca 150 000 to 30 000 years ago, associated with the production of stone tools smaller and more diverse than those of the earlier time, the so-called *Early Stone Age*.

Mid-ocean(ic) ridge: A continuous, seismically active mountain range along the central parts of the Atlantic, Indian and Pacific Oceans. These ridges are locations where new crust is produced by extrusion of *lava*. The volcanic island of Iceland is part of the mid-oceanic ridge through the North Atlantic Ocean.

Migmatite: A composite rock composed of igneous or igneous-looking and/or metamorphic materials which are generally distinguishable megascopically.

Mineral: A naturally occurring inorganic element or compound of elements, which has an orderly internal (crystal) structure and a fixed chemical composition.

Mineralogical composition: The composition of a rock in terms of its proportions of different minerals.

Mineralogy: The study of minerals with regard to their formation, occurrence, properties, composition, classification and use.

Minoan (culture): Bronze Age culture centred on the island of Crete in the Mediterranean Sea, about 1600 BC. Thought to have been terminated owing to a gigantic volcanic explosion that destroyed the island of Santorini (Thera).

Minor planet: *Asteroid* or *comet*.

Miranda: One of the satellites of Uranus that seems to be a body reassembled from large chunks that must have been created by a massive impact event.

Modification stage (of the impact event): The period after impact-crater formation (which represents the *compression* and excavation stages), during which the steep unstable crater walls collapse under the force of *gravity*.

Molten: Melted by heat. *Magma* is molten rock, and *lava* is molten rock that reaches the surface of a planetary body and solidifies.

Monocotyledons: One of the two major groups into which the *angiosperms* are traditionally divided, with one seed leaf (*cotyledon*) in the embryo.

Monospecific: Comprising only a single species.

Monsoon: A mid-latitude wind system that periodically changes direction. Very important for the livelihood of many people, as it determines whether flooding, drought, or good harvest can be expected.

Montmorillonite: See *bentonite*.

Moon: Our neighbour in Space, thought to be the result of a collision between Earth and a Mars-sized *planetesimal*. Also synonym for *satellite*.

Mountain Belt: See *orogen*.

Mudslide/-flow: Rapid sliding of a large mass of very fine-grained material off a slope. This material basically behaves like a fluid. Can be triggered by volcanic activity or by excessive rain. Termed a 'lahar', when the 'mud' represents fine-grained volcanic material (for example, ash) along the slope of a volcano.

Mylonite: A compact rock with a banded structure formed because of reduction of grain size and movement related to shearing of rock mass.

N

Near-Earth Object: (abbreviation NEO) *Asteroid* with an *orbit* that brings it closer than 0.3 AU to the orbit of our *planet* Earth.

Nebula: A large cloud of gas and some dust, in Space.

Nepheline: A *feldspathoid* mineral of the composition $(Na,K)AlSiO_4$.

Nepheline-syenite: (also *mariupolite*) A plutonic rock composed essentially of alkali feldspar and *nepheline*.

Normal fault: A *fault* in which the hanging wall (that block above the fault plane) appears to have moved downward relative to the footwall. The fault angle is generally 45–90°.

Nuclear fusion: The union of the cores (nuclei) of atoms to produce the nuclei of heavier elements, whereby enormous amounts of energy are released.

Nucleus: Latin: core. The extremely tiny core of an atom.

O

Olivine: A group of green to brown minerals rich in iron and magnesium, with the composition $(Fe,Mg)_2SiO_4$. Forming a continuous series of compositions from the pure iron to the pure magnesium end member.

Oort Cloud: A spherical zone in Space that contains more than one trillion *comets* that are thought to orbit the Sun very

slowly at a distance of 20 000 to 100 000 AU, and from where many of the observed comets must originate. Named after Dutch astronomer Jan Oort.

Orbit: The movement path of a planetary body or particle revolving around another.

Ore: A metal-bearing rock, from which this metal can be extracted for profit.

Orogen: An extended belt of rock that has been deformed, folded, during an *orogeny*.

Orogeny: A mountain-building episode, as the result of collision between two continents, or a *continent* and an *island arc*.

Overgrazing: When cattle deplete the growth of vegetation in an area to such an extent that is does not retain soil anymore, and *erosion* may become accelerated.

Overturning: When a rock mass is rotated out of its original position further than the vertical.

Oxidation: Opposite of *reduction*. A chemical reaction, in which oxygen combines with, or hydrogen is removed from, a substance. A reaction in which an *atom* loses electrons.

P

Palaeo-: Referring to great age or involving ancient conditions.

Palaeo-anthropology: The study of ancient humans and their culture.

Palaeoclimate: The climate of a past interval in Earth's history.

Palaeontology: The study of *fossil* life forms, animals (*fauna*) and plants (*flora*).

Palaeotropical kingdom: Vegetation types that are grouped into the tropical kingdom of the Old World.

Panspermia: The name for the theory that life exists and is distributed throughout the Universe in the form of germs or spores and that Earth was 'seeded' with life when celestial objects collided with the Earth.

Parent body: Planetary body from which meteorites originate and have been produced because of impact events.

Partial melting: Melting of a rock that does not immediately result in complete melting. Certain minerals of this rock will melt earlier than others, which leads to a succession of different melt compositions.

Pastoralists: People whose lifestyle and livelihood is based on the herding of cattle.

Pelite: A sediment or sedimentary rock composed of the finest sedimentary detritus (clay and silt).

Peninsula: An elongated stretch of land surrounded by water and connected to the mainland by a neck.

Period: Geological time interval lower than era and higher than epoch. Cretaceous, Tertiary, Jurassic, Cambrian, etc. are periods.

Petroglyph: A rock carving (or scratching).

pH: Measure of hydrogen concentration (i.e. acidity) in a solution (or, in the case of geology, in a soil).

Phenocryst: Relatively large and often well-formed crystal set into a finer-grained groundmass (*matrix*). Rocks with phenocrysts are said to be *porphyritic.*

Phonolite: A fine-grained *intrusive* rock primarily composed of alkali feldspar [$(K,Na)AlSi_3O_8$] and containing *feldspathoids*.

Phyllite: A metapelitic rock commonly formed by regional metamorphism and intermediate in metamorphic grade between slate and mica schist.

Phyllosilicate: An important group of silicate minerals. The crystal structure is made of sheets of silicate tetrahedra, giving these minerals a strong cleavage. Examples are biotite, muscovite, chlorite.

Physiology: Biochemical processes and interactions that occur within organisms.

Phytochorological: Description and delimitation of distributional ranges based on plants.

Phytogeographical: Subdivision and relationships of areas based on the complement of plant *species* that occur there.

Pillow lava: When basaltic lava erupts under water, the *lava* forms a distinct pillow shape because of the rapid cooling/hardening of the immediate outer zone of lava.

Plagioclase: A group of *feldspar* silicate minerals that form a continuous series of compositions of different proportions of sodium and calcium. Very important minerals in all groups of rock (*igneous*, *sedimentary* and *metamorphic*).

Planar deformation feature (PDF): Microscopic features that form in a mineral when it is subjected to high shock pressure of at least 100 kilobars (10 GPa).

Planet: A large, non-luminous ('not shining') body that *orbits* around a *star*, like the eight *planets* of our *Solar System* orbiting the Sun.

Planetesimal: Small planetary bodies thought to have been abundant in the early days of the Solar System; it is believed that our *planets* were formed from the aggregation of planetesimals.

Plate: A segment of the *lithosphere* which itself is relatively stable (that is, it has little *volcanic* or *seismic* activity), but which is bounded by more active belts. These plates float upon and travel over the underlying *mantle*.

Plate tectonics: The theory in which the *lithosphere* consists of a number of rather stable and rigid plates that move horizontally against or past each other, resulting in *seismic* and *tectonic* activity along these plate boundaries. Study of these processes.

Platinum-group elements: The elements ruthenium, rhodium, palladium, rhenium, osmium, and iridium. These elements are significantly enriched in extraterrestrial materials compared with the crustal rocks on Earth.

Pluton: An igneous intrusion.

Plutonic rock: Pertaining to igneous rock as formed/emplaced at depth (compare *intrusion/intrusive*).

Polymorph: When a mineral has more than one crystal form, but only one chemical composition, such as *quartz* and *coesite*, or graphite and diamond.

Porphyritic: Texture of an igneous rock, whereby larger crystals (*phenocrysts*) occur in a fine-grained *matrix*.

Porphyroblast: A metamorphic crystal that is considerably larger than crystals of other minerals in the rock.

Precambrian: That geological time including all time from the beginning of formation of the earliest rock on this *planet* to the onset of the Cambrian period at about 560 Ma. This includes the *Archaean* and *Proterozoic* eras.

Proterozoic: The later part of the *Precambrian*, from the end of the *Archaean* (2 500 Ma) to the beginning of the Cambrian (560 Ma).

Protoplanet: A *planet* in the process of forming. Similar to *planetesimal*.

Province: A geological province means a large area that has a common geological character, such as a large *flood-basalt* province, or a province dominated by granitic rocks, etc.

Pseudotachylite/Pseudotachylitic breccia: A glassy or finest-grained rock formed from *cataclasis* (brecciation) followed by melting. Found in many tectonically produced *faults* worldwide, and also in *impact structures*. The Vredefort Structure is the type locality. However, based on detailed work in the Vredefort Structure, a debate has developed in recent years whether such rock in impact structures is only the result of the same process envisaged for fault-related occurrences, namely *cataclasis* followed by melting caused by rapid shearing (*friction* melting), or whether the ultrarapid shock compression of the impact process can cause formation of such material with or without associated shearing/friction. Thus, Uwe Reimold proposed in 1995 that for all those occurrences where *friction* melting is not proven, the term '**pseudotachylitic breccia**' instead of 'pseudotachylite' should be used.

Pyrite: An important iron-sulphide mineral of composition FeS_2.

Pyroxene: A group of dark-coloured silicate minerals of the general formula ($ABSi_2O_6$), with A = Ca, Na, Mg, Fe^{2+} and B = Mg, Fe^{2+}, Fe^{3+}, Cr, Mn, Al. This group contains important minerals present in many *igneous* and *metamorphic* rocks, and also in *meteorites*.

Q

Quartz: The mineral with the composition SiO_2; basic constituent of many sands.

Quartzite: A rock predominantly composed of the mineral quartz (SiO_2). See also *quartz*.

R

Radioactivity: Property of certain atomic nuclei to break down by emitting particles (such as *electrons*, neutrons, etc.); adjective: radioactive.

Radiocarbon method: For age dating of carbon-bearing materials. A method of *radiometric dating*, which is based on the accumulation of *radiogenic* ^{14}C in dead organic matter and assuming that no further ^{14}C will be taken up from the moment of death of an organism.

Radiogenic isotope: The *isotope* of a specific element that was formed as a result of radioactive decay of a different *element*. For example, when uranium decays, it forms *isotopes* of the element lead.

Radiometric dating: Determination of ages for geological materials by measuring the amounts of relatively short-lived *radiogenic isotopes* formed from a radioactive element (such as ^{87}Rb, ^{235}U, and others) in comparison with abundances of other isotopes of this element. When the rate of growth of the amount of the *radiogenic isotope* with time is known, the changing ratios between radiogenic isotope and the other *isotopes* can be used to calculate an age for the moment when the formation of the radiogenic isotope began. This may be the time when a magma began to crystallise and the radiogenic isotope began to accumulate in a new mineral, or when a strong metamorphic event affected a mineral.

Recumbent fold: An overturned *fold*, the axial plane of which is horizontal.

Reduction: Opposite of oxidation. The process of electron uptake in a chemical reaction.

Reef: Miners' term for the quartz-pebble *conglomerates* of the Witwatersrand basin that, in outcrop, resembled a coral reef in the sea.

Regolith: A general term for fragments of unconsolidated rock overlying solid bedrock. In the case of the *Lunar* regolith, the 'topsoil' on the Moon, the fragments were produced by bombardment with impacting projectiles.

Remote sensing: The collection of information by a recording device that is not in direct contact with the object or area being studied. For example, imagery from aeroplanes or satellites provides important information on a geological area.

Rhyolite: The finer-grained *extrusive* rock equivalent to the *intrusive granite*.

Richter Scale: A scale that measures the magnitude (size) of an earthquake.

Rift: A long, narrow trough in a *continent* that is bounded by *normal faults*. A rift is currently developing in northeast Africa, where a part of the continent is splitting off the continent. The rift produces a surface expression that is a 'rift valley'.

Rock: An aggregate of one or more minerals, or of undifferentiated mineral matter (for example, *granite* or coal).

S

Saline: Salt bearing.

San: The Bushmen people of southern Africa.

Sarcophagus: A coffin or tomb of stone; a 'stone chest'.

Satellite: A relatively small planetary object in orbit around the Sun or a *planet*. It was long thought that the Moon was a satellite to Earth; also artificial bodies such as spacecraft.

Savanna: Vegetation comprising a grassy layer as well as a tree layer, and trees often clumped.

Scanning electron microscope: An electron microscope where a finely focused beam of *electrons* is moved over a sample. The signal from the sample is collected by detectors and converted into an image. Magnification of many thousand times can be achieved.

Sea-floor spreading: See also *plate tectonics*. The idea that the oceanic crust grows at *mid-oceanic ridges* owing to upwelling of *lava* and spreading of crust away from these ridges.

Secondary mineral: The primary (original) minerals of a rock are eventually replaced by later, secondary minerals, as a result of chemical *alteration* or *metamorphism*.

Sediment/sedimentary rock: Solid particles (or material) that originate from the *weathering* of rocks and are transported or deposited by air, water or ice, or that accumulate by other natural processes and form layers on the Earth's surface. Such a natural process could be *impact*, which ejects material from a crater, which is then deposited in the environs of the impact site.

Sedimentation: The deposition of geological material, for example out of the *atmosphere*, or suspension in water (streams, lakes or oceans), or from wind.

Seismic wave: A wave generated by an *earthquake*.

Seismics/seismic waves: Seismic waves are vibrations that are transmitted from the point where an earthquake occurred, either through the Earth or along the surface. Seismics is the study that investigates the origin of such waves and attempts to explain the cause of *earthquakes*.

Sere: Stage within a succession from one vegetation type to another.

Settlement pattern: The way in which a settlement is organised. For example, cattle kraals are in the centre, with huts surrounding them, whereas other features such as *middens* also have a specific place in each settlement.

Settlement unit: A settlement unit is made up of a number of individual households (huts) and other features such as cattle kraals.

Shale: A consolidated (lithified) mud or silt that breaks along finely spaced layers (cleavage) parallel to its bedding.

Shatter cone: Cone-like, striated fracture in rocks.

Shear zone: A zone of slip between large masses of rock, in which the rock has not fractured. Ductile flow causes extreme grain-size reduction, producing a *mylonite*.

Shelf: The outermost part of a continent that is always under seawater.

Shock metamorphism: The changes in a mineral or rock induced by the ultrahigh pressures and temperatures raised by the impact of an extraterrestrial projectile at *hypervelocity*.

Shock pressure: The pressure in a material resulting from its *compression* because of a blast/explosion wave.

Shock wave: A *compression* wave formed upon the impact of a projectile at *hypervelocity*. The amplitude of the shock wave is in excess of the elastic limit of a compressed compound. Produced by an explosion of sorts (for example, from explosives or a meteorite impact).

Shoemaker-Levy 9 comet: A *comet* that broke into 21 pieces before impacting into the *atmosphere* of Jupiter in July 1994.

Shooting star: See *meteor*.

Siderophile (elements): Elements that do have a generally weak affinity for oxygen and sulphur, but that are readily soluble in iron (e.g. nickel, the platinum-group metals, gold).

Silica: Silicon dioxide (SiO_2).

Silicate: Any of the large number of minerals that are mostly composed of the elements silicon and oxygen. The bulk of the Earth's crust and mantle consists of silicate minerals.

Sill: A sheet-like (tabular) body of *igneous* rock that conforms to, or intrudes, the host rock parallel to its *bedding* or other structural planes.

Smithing: The working of metal into tools.

SNC meteorites: *Achondrite* meteorites that originate from Mars (short for Shergotty, Nakhla, and Chassigny meteorites).

Solar System: The community of all the planetary bodies (*planets*, *satellite* bodies, *asteroids*, *comets*) that is tied to the Sun by its *gravity*.

Solar wind: Constant outflow of charged particles from the Sun.

Sourish Mixed Bushveld: A region characterised by a mixture of trees, shrubs and grasses.

South Pole-Aitken basin: A huge impact basin on the hidden far side of the Moon, about 2 500 km in diameter.

Space: The space between planetary bodies.

Space probe: A device sent into Space from Earth to study other planetary bodies and the space in between.

Species: Any plants or animals that may interbreed and produce fertile offspring. A category in the classification of *fauna* or *flora*.

Spherule/spherulitic: A little sphere or spherical body/the shape of a sphere.

Star: A massive, very bright glowing gas sphere, the energy of which is generated by *nuclear fusion*. The Sun in our *Solar System* is a star of average size.

Stishovite: A high-pressure *polymorph* of *quartz*, only known as the result of shock deformation in impact structures.

Stone Age: A period dating back to ca 2 million years and up to ca 2 000 years ago. Stone was mainly used in the making of stone tools used by the Stone Age *hunter-gatherer* people.

Stone-tool factory site: An open area where stone tools were manufactured, resulting in large accumulations of flakes, chips and tools in one place.

Stony meteorite: *Meteorite* composed mostly, but not only, of silicate minerals.

Stony-iron meteorite: Meteorite composed of both silicate minerals and iron-nickel in roughly the same proportions.

Stratigraphy: The study of stratified rocks (*sediments* or *volcanics*), especially their sequence in time, the character of the rocks, and the correlation of beds occurring at different localities. Clearly *radiometric dating* of strata is very important for stratigraphic work.

Stratum (plural: strata): A sheet-like layer of *sedimentary rock*, clearly distinguishable from the layers above and below.

Stress: A measure (S) of the intensity of a force (F) acting upon a body as a function of the affected area (A): S = F/A.

Strewn field: The ground distribution over which meteorites of a particular *fall* (usually forming an elliptical strewn field) and *tektites* are found.

Strike: The direction in which a rock mass trends, for example, the layers parallel to the south side of Johannesburg strike from east to west, that is at 270°.

Stromatolite: Domed structure in *sediments*, representing the fossilised remains of ancient algal colonies.

Structure: (1) The construction/make up = *tectonics* of the geology in an area; the arrangement of geological units with respect to each other, or the deformation of rock; (2) the megascopic features of a rock, such as the banding, system of fractures, inclusions of one rock type in another, etc.

Subarctic: Between 58° and 66.5° latitude.

Subduction/subducted: A *plate-tectonic* process whereby one *plate* descends underneath another.

Sub-Saharan: South of the Sahara Desert.

Subsidence: Sinking or downward settling of the Earth's surface.

Substratum: Sediment, surface or medium upon which an organism grows.

Suevite/Suevitic: An impact-generated rock type composed of rock and mineral fragments as well as at least some *impact melt* or glass (in contrast to purely clastic lithic impact breccia or pure impact melt with only a small component of rock and mineral fragments).

Supercontinent: A very large continent in the past comprising a number of smaller continents that eventually split off this huge landmass. Compare *Gondwana*.

Supergroup: A package of individual rock formations that all belong to a major sequence of geological formations with a linked origin (such as the Witwatersrand Supergroup which includes a thick pile of *sedimentary rocks*, in turn overlain by the Ventersdorp Supergroup of predominantly *volcanic* rocks, which is followed by the sedimentary succession of the Transvaal Supergroup).

Supernova: An exploding *star* that is observed astronomically by very bright light. Supernova explosions can produce, and distribute, heavy elements in Space. They eject large portions of their mass into Space.

Syncline: (Opposite of *anticline*) Where *strata* form a convex-down trough shape (layers dip towards the fold *hinge*). Where a very large syncline with internal structure is concerned, it is called a synclinorium.

T

Target rocks: The rocks occurring at the site on the surface of a planetary body where a *bolide* will explode. All that material in the environs of the explosion site that will be affected by the impact event.

Taxon (singular), taxa (plural): Recognised taxonomic unit of any rank, e.g. family, *genus* or *species*.

Tectonics (synonym tectonism): That branch of geosciences that deals with the broad architecture of the *lithosphere* (that is, the arrangements of rocks with regard to each other and the deformation processes that lead to these arrangements); adjective: tectonic.

Tektite: Small glassy bodies, often droplet shaped, formed from impact (shock) melted rock that was shaped during its ballistic trajectory through the atmosphere. Some tektite *strewn fields* have been unambiguously linked to specific impact craters (e.g. the moldavites of the Czech Republic and environs to the Ries Crater in southern Germany).

Temperate: Of vegetation that usually occurs in latitudes between the tropics and polar circles, with moderate climates.

Terrestrial planet: Any of the four *Inner Planets*: Mercury, Venus, Earth and Mars, that are similar with regard to size and average density. From 'terra', Latin for Earth.

Texture: The general appearance of a rock, in terms of the mutual arrangements of and relationships between the particles constituting the rock. Megascopic to microscopic character of a rock. See also *macroscopic*.

Thrust (fault): A *fault* with a dip of 45° or less, on which the hanging wall (the block above the fault plane) appears to have moved upwards relative to the footwall.

Tillite: A mixture of rock debris of very different grain size (boulder to sand), similar to a *diamictite*, deposited at the foot of a glacier.

Tonalite: A granitic rock, largely composed of quartz and dominant *plagioclase*.

Topography: 'The lay of the land', the geometry of the surface in an area (adjective topographic).

Torino Scale: The Torino Scale provides a measure to assess the danger posed by individual *asteroids* and *comets*, evaluating the chance that a collision between Earth and such a body can occur and what the likely catastrophic outcome could be.

Tornado: A small-scale *cyclone*, a funnel-like feature with extremely strong winds.

Trachyte: A fine-grained *extrusive* rock type that commonly contains *phenocrysts* in a fine-grained *matrix*, and is composed of alkali feldspar and some dark minerals such as *biotite* and/or *pyroxene* as major constituents.

Transient crater: The crater form resulting after completion of the movement of the shock wave through the target region, prior to the beginning of the *modification phase* of the impact-cratering process.

Transmission electron microscope: An electron microscope that transmits a very strongly accelerated *electron* beam through the crystal structure of a very thin sample, thus allowing the electrons to image the internal structure (that is, the arrangements of building blocks: ions and atoms) of crystals.

Trans-Neptunian Object: One of several hundred *asteroids* and *comets* on *orbits* beyond that of Neptune. They form the *Kuiper-Edgeworth Belt*.

Trona: A mineral that occurs in the salt-rich (saline) residues of evaporated lakes. It is a main source of sodium compounds, and its chemical formula is $[Na_3(CO_3)(HCO_3)\cdot 2H_2O]$.

Trondhjemite: A sodium-rich granitic rock.

Tsunami: Giant floodwave, the result of an underwater explosion, maybe through *volcanism* or *earthquake*, but also through *impact* into an ocean.

Tufted: Growing in clumps.

Tundra: Treeless plains of the arctic and *subarctic* regions.

Turbidite: *Sedimentary rock* deposited from a very turbulent flow.

Twinning (of a mineral): Intergrowth of two or more single crystals of a mineral.

Typhoon: See *cyclone*.

U

Ubiquitous: Widespread and relatively common.

Ultramafic: An *igneous* rock that consists almost entirely of generally dark Fe, Mg-rich minerals and has less than 45 wt% SiO_2.

Uniformitarianism: The theory that all geological processes, as they take place today, have taken place like this throughout geological time, and that, in turn, past geological processes can be explained by what happens today. 'The present is the key to the past'.

V

Vascular plants: Those plants with specialised tissue for conducting water, i.e. mosses and more derived groups.

Vein: A tabular or sheet-like body composed of minerals, intruded into a *joint* or fissure in a rock. Most vein fillings are of igneous origin, related to fluids expelled from a *magma*. Veins may also be filled as a result of *sedimentary* processes (for example, when sand is blown into cracks of bedrock and subsequently covered by a later rock formation).

Vertebrate: *Species* that have an internal skeleton of cartilage or bone.

Volcanic: Related to the activities, structures and rock products of *volcanism*.

Volcanism: The process whereby material (*lava*, gas) is expelled from the interior of a planetary body.

Volcano: A spout in the crust of a planetary body through which molten rock, ash and gases can be ejected onto the body's surface. Gradually built up from such materials into a mountain.

Voortrekkers: Groups of white settler-farmers, who emigrated from the region of the Eastern Cape Province and settled in the present KwaZulu-Natal and the regions north of the Orange and Vaal rivers in the 1830s and 1840s.

Vredefort Granophyre: The name for the *impact-melt* rock in the Vredefort Structure.

W

Weathering: The effects on a rock caused by its interaction with oxygen, water, wind, or ice, leading to the breakdown or dissolution of minerals.

X

Xenolith: A foreign inclusion in an igneous rock (for example, a block of another rock type).

Z

Zap pit: Tiny *impact crater* on the surface of a crystal, caused by the impact of a *cosmic dust* grain.

Zircon: The mineral zirconium silicate ($ZrSiO_4$). Has high uranium content and, thus, lends itself to radiometric age dating using the radioactive decay of uranium to lead.

Appendices

Appendix 1

*List of **VASCULAR PLANTS** collected on the Vredefort Dome, and recorded in the C.E. Moss Herbarium (University of the Witwatersrand), or the National Herbarium (National Botanical Institute, Pretoria). Exotic species indicated with: **

ACANTHACEAE
Barleria obtusa Nees
Barleria pretoriensis C.B.Clarke
Blepharis angusta (Nees) T. Anderson
Blepahris squarrosa (Nees) T. Anderson
Hypoestes forskaolii (Vahl) R.Br.
Thunbergia neglecta Sond.

AIZOACEAE
Trianthema sp.

ALISMATACEAE
**Alisma plantago-aquatica L.*

ALLIACEAE
**Nothoscordum borbonicum* Kunth
Tulbaghia leucantha Baker

AMARANTHACEAE
Amaranthus capensis Thell. subsp. *uncinatus* (Thell.) Brenan
Amaranthus thunbergii Moq.
**Guilleminea densa* (Willd. ex Roem. & Schult.) Moq.

AMARYLLIDACEAE
Boophone disticha (L.f.) Herb.
Crinum bulbispermum (Burm.f.) Milne-Redh. & Schweick.
Scadoxus puniceus (L.) Friis & Nordal

ANACARDIACEAE
Rhus leptodictya Diels
Rhus magalismontana Sond. subsp. *magalis-montana*
Rhus pyroides Burch. var. pyroides
Rhus rigida Mill. var. *margaretae* Burtt Davy ex Moffett
Smodingium argutum E.Mey. ex Sond.

ANEMIACEAE
Mohria vestita Baker

ANTHERICACEAE
Chlorophytum cooperi (Baker) Nordal
Chlorophytum fasciculatum (Baker) Kativu

APIACEAE/UMBELLIFERAE
Ammi majus L. var. *glaucifolium* (L.) Godr.
Centella asiatica (L.) Urb.
Cyclospermum leptophyllum (Pers.) Eichler
Heteromorpha arborescens (Spreng.) Cham. & Schltdl. var. *abyssinica* (A.Rich.) H.Wolff

APOCYNACEAE
Ancylobotrys capensis (Oliv.) Pichon
Gomphocarpus tomentosus Burch. subsp. *tomentosus*
**Nerium oleander* L.
Pachycarpus schinzianus (Schltr.) N.E.Br.
Sarcostemma viminale (L.) R.Br. subsp. *viminale*

AQUIFOLIACEAE
Ilex mitis (L.) Radlk. var. *mitis*

ARALIACEAE
Cussonia paniculata Ekl. & Zeyh.

ASPARAGACEAE
Asparagus flavicaulis (Oberm.) Fellingham & N.L.Mey. subsp. *flavicaulis*
Asparagus laricinus Burch.
Asparagus suaveolens Burch.

ASPHODELACEAE
Aloe greatheadii Schönland var. *davyana* (Schönland) Glen & D.S.Hardy
Bulbine abyssinica A.Rich.
Bulbine narcissifolia Salm-Dyck
Kniphofia ensifolia Baker subsp. *ensifolia*
Kniphofia typhoides Codd
Trachyandra saltii (Baker) Oberm. var. *saltii*

ASTERACEAE/COMPOSITAE
Adenostemma caffrum DC.
Arctotis arctotoides (L.f.) O.Hoffm.
Artemisia afra Jacq. Ex Willd.
Athrixia elata Sond.
Berkheya pinnatifida (Thunb.) Thell. subsp. *ingrata* (Bolus) Roessler
Berkheya pinnatifida (Thunb.) Thell. subsp. *pinnatifida*
Berkheya zeyheri (Sond. & Harv.) Oliv. & Hiern subsp. *zeyheri*
Brachylaena rotundata S. Moore
Chrysocoma ciliata L.
Cineraria albicans N.E.Br.
Cotula microglossa (DC.) O. Hoffm. & Kuntze ex Kuntze
Denekia capensis Thunb.
Dicoma anomala Sond. subsp. *anomala*
Dicoma anomala Sond. subsp. *gerrardii* (Harv. ex F.C.Wilson) S.Ortííz & Rodr.Oubiñña
Dicoma macrocephala DC.
**Eclipta prostrata* (L.) L.
Felicia muricata (Thunb.) Nees subsp. *muricata*
Gazania krebsiana Less. subsp. *serrulata* (DC.) Roessler
Geigeria aspera Harv. var. *aspera*
Haplocarpha scaposa Harv.
Helichrysum callicomum Harv.
Helichrysum cerastioides DC. var. *cerastioides*
Helichrysum paronychioides DC.
Helichrysum rugulosum Less.
Helichrysum setosum Harv.
Helichrysum zeyheri Less.
Nidorella anomala Steetz
Osteospermum muricatum E.Mey. ex DC. subsp. *muricatum*
Pentzia globosa Less.
Phymaspermum athanasioides (S.Moore) Källersjö
Picris echioides L.
Pseudognaphalium oligandrum (DC.) Hilliard & B.L.Burtt
Senecio hieracioides DC.
Senecio inaequidens DC.
Senecio serratuloides DC.
Tripteris aghillana DC. var. *aghillana*
Ursinia nana DC. subsp. *leptophylla* Prassler
Vernonia natalensis Sch.Bip. ex Walp.
Vernonia oligocephala (DC.) Sch.Bip. ex Walp.
Vernonia staehelinoides Harv.
**Zinnia peruviana* (L.) L.

AZOLLACEAE
**Azolla filiculoides* Lam.

BORAGINACEAE
Ehretia rigida (Thunb.) Druce subsp. *rigida*
Heliotropium ciliatum Kaplan
**Lappula heteracantha* Ledeb.
Trichodesma angustifolium Harv. subsp. *angustifolium*

BRYACEAE
Bryum argenteum Hedw.

BUDDLEJACEAE
Buddleja saligna Willd.
Buddleia salviifolia (L.) Lam.
Nuxia congesta R.Br. ex Fresen.

CAPPARACEAE
Cleome monophylla L.
Cleome rubella Burch.
Maerua cafra (DC.) Pax

CARYOPHYLLACEAE
Corrigiola litoralis L. subsp. *litoralis* var. *litoralis*
Silene undulata Aiton

CELASTRACEAE
Gymnosporia buxifolia (L.) Szyszyl.
Gymnosporia tenuispina (Sond.) Szyszyl.
Maytenus undata (Thunb.) Blakelock
Mystroxylon aethiopicum (Thunb.) Loes. ssp. *burkeanum* (Sond.) R.H. Archer
Salacia rehmannii Schinz

*CELTIDACEAE (*previously *ULMACEAE)*
Celtis africana Burm. f.

CHENOPODIACEAE
**Chenopodium ambrosioides* L.
**Chenopodium multifidum* L.
Chenopodium phillipsianum Aellen

COMBRETACEAE
Combretum molle R.Br. ex G.Don

CONVOLVULACEAE
Convolvulus dregeanus Choisy
Convolvulus sagittatus Thunb.
**Cuscuta campestris* Yunck.
Dichondra sp.
Evolvulus alsinoides (L.) L.
Ipomoea crassipes Hook.
Ipomoea magnusiana Schinz
Ipomoea obscura (L.) Ker Gawl. var. *obscura*
Ipomoea *ommaneyi* Rendle
Seddera capensis (E.Mey. ex Choisy) Hallier f.

CRASSULACEAE
Crassula lanceolata (Eckl. & Zeyh.) Endl. ex Walp. subsp. *transvaalensis* (Kuntze) Toelken
Crassula obovata Haw. var. *obovata*

CUCURBITACEAE
Cucumis zeyheri Sond.

CYPERACEAE
Abildgaardia ovata (Burm.f.) Kral
Bulbostylis burchellii (Ficalho & Hiern) C.B.Clarke
Carex glomerabilis Krecz.
Coleochloa setifera (Ridl.) Gilly
Cyperus difformis L.
**Cyperus eragrostis* Lam.
Cyperus fastigiatus Rottb.
Cyperus haematocephalus C.B.Clarke
Cyperus indecorus Kunth var. *decurvatus* (C.B.Clarke) Kük.
Cyperus margaritaceus Vahl var. *margaritaceus*
Cyperus marginatus Thunb.
Cyperus marlothii Boeck.
Cyperus obtusiflorus Vahl var. *flavissimus* (Schrad.) Boeck.
Cyperus rupestris Kunth var. *rupestris*
Cyperus semitrifidus Schrad.
Cyperus squarrosus L.
Cyperus usitatus Burch.
Eleocharis dregeana Steud.
Isolepis fluitans (L.) R.Br. var. *fluitans*
Schoenoplectus decipiens (Nees) J.Raynal
Schoenoplectus muricinux (C.B.Clarke) J.Raynal
Scirpoides burkei (C.B.Clarke) Goetgh., Muasya & D.A.Simpson

DICRANACEAE
Campylopus introflexus (Hedw.) Brid.

DIPSACACEAE
Scabiosa columbaria L.

ELATINACEAE
Bergia decumbens Planch. ex Harv.

EQUISETACEAE
Equisetum ramosissimum Desf.

EUPHORBIACEAE
Acalypha caperonioides Baill.
Acalypha glabrata Thunb. var. *pilosa* Pax
Acalypha segetalis Müll.Arg.
Clutia pulchella L. var. *pulchella*
Euphorbia pubescens Vahl
Euphorbia serpens Kunth
Jatropha zeyheri Sond.
Tragia rupestris Sond.

FABACEAE/LEGUMINOSAE
Acacia caffra (Thunb.) Willd.
Acacia karroo Hayne
Acacia robusta Burch. ssp. *robusta*
Chamaecrista stricta E.Mey.
Crotalaria brachycarpa (Benth.) Burtt Davy ex I. Verd.
Crotalaria distans Benth. subsp. *distans*
Indigofera comosa N.E.Br.
Indigofera filipes Benth. ex Harv.
Indigofera heterotricha DC.
Indigofera zeyheri Spreng. ex Eckl. & Zeyh.
Lotononis subulata B.-E.van Wyk
Mundulea sericea (Willd.) A.Chev.
Neorautanenia ficifolius (Benth.) C.A.Sm.
Pearsonia cajanifolia (Harv.) Polhill subsp. *cajanifolia*
Pearsonia uniflora (Kensit) Polhill
Rhynchosia nervosa Benth. & Harv. var. *nervosa*
Rhynchosia sordida (E.Mey.) Schinz
**Vicia sativa* L. subsp. *sativa*
**Vicia villosa* Roth subsp. *villosa*
Vigna oblongifolia A.Rich. var. *parviflora* (Baker) Verdc.
Vigna unguiculata (L.) Walp. subsp. *stenophylla* (Harv.) Maréchal *et al.*

FLACOURTIACEAE
Dovyalis zeyheri (Sond.) Warb.
Scolopia zeyheri (Nees) Harv.

GERANIACEAE
Monsonia angustifolia E.Mey. ex A.Rich.
Monsonia burkeana Planch. ex Harv.

HALORAGACEAE
**Myriophyllum aquaticum* (Vell.) Verdc.
Myriophyllum spicatum L.

HYACINTHACEAE
Dipcadi gracillimum Baker
Drimiopsis burkei Baker subsp. *burkei*
Ledebouria cooperi (Hook.f.) Jessop
Ledebouria luteola Jessop
Ledebouria marginata (Baker) Jessop
Ornithogalum juncifolium Jacq.
Ornithogalum ornithogaloides (Kunth) Oberm.
Ornithogalum tenuifolium F.Delaroche subsp. *tenuifolium*

HYPERICACEAE
Hypericum lalandii Choisy

ICACINACEAE
Cassinopsis ilicifolia (Hochst.) Kuntze

IRIDACEAE
Gladiolus permeabilis D.Delaroche subsp. *edulis* (Burch. ex Ker Gawl.) Oberm.
Moraea pallida (Baker) Goldblatt
Moraea simulans Baker

JUNCACEAE
Juncus dregeanus Kunth
Juncus effusus L.

LAMIACEAE
Acrotome hispida Benth.
Aeollanthus buchnerianus Briq.
Ajuga ophrydis Burch. ex Benth.
Leonotis ocymifolia (Burm.f.) Iwarsson var. *schinzii* (Gürke) Iwarsson
Leucas capensis (Benth.) Engl.
Leucas martinicensis (Jacq.) R.Br.
Mentha longifolia (L.) Huds. subsp. *polyadena* (Briq.) Briq.
Ocimum angustifolium Benth.
Ocimum obovatum E.Mey. ex Benth. subsp. *obovatum* var. *obovatum*
Plectranthus madagascariensis (Pers.) Benth. var. *ramosior* Benth.
Pycnostachys reticulata (E.Mey.) Benth.
Salvia stenophylla Burch. ex Benth.
Stachys hyssopoides Burch. ex Benth.
Teucrium trifidum Retz.

LEMNACEAE
Lemna gibba L.
Spirodela polyrhiza (L.) Schleid.

LOBELIACEAE
Cyphia assimilis Sond.
Cyphia stenopetala Diels
Lobelia angolensis Engl. & Diels
Monopsis decipiens (Sond.) Thulin

MALPIGHIACEAE
Sphedamnocarpus pruriens (A.Juss.) Szyszyl. subsp. *galphimiifolius* (A.Juss.) P.D.de Villiers & D.J.Botha
Sphedamnocarpus transvalicus (Kuntze) Burtt Davy

MALVACEAE
Abutilon piloso-cinereum A.Meeuse
Hibiscus calyphyllus Cav.
Hibiscus microcarpus Garcke
Hibiscus pusillus Thunb.
Hibiscus trionum L.
Pavonia burchellii (DC.) R.A.Dyer
Sida dregei Burtt Davy

MARSILEACEAE
Marsilea macrocarpa C.Presl

MENISPERMACEAE
Antizoma angustifolia (Burch.) Miers ex Harv.

MESEMBRYANTHEMACEAE
Chasmatophyllum musculinum (Haw.) Dinter & Schwantes
Delosperma floribundum L.Bolus
Delosperma pontii L.Bolus
Hereroa sp.
Mossia intervallaris (L.Bolus) N.E.Br.
Ruschia sp.

MOLLUGINACEAE
Limeum pauciflorum Moq.
Limeum viscosum (J.Gay) Fenzl subsp. *viscosum* var. *glomeratum* (Eckl. & Zeyh.) Friedrich

MYROTHAMNACEAE
Myrothamnus flabellifolius Welw.

MYRTACEAE
**Eucalyptus camaldulensis* Dehnh.

NYCTAGINACEAE
Commicarpus pentandrus (Burch.) Heimerl

OLEACEAE
Olea europaea L. subsp. africana (Mill.) P.S.Green

ORCHIDACEAE
Eulophia ovalis Lindl. var. *ovalis*

OROBANCHACEAE
Alectra orobanchoides Benth.
Buchnera sp.
Graderia subintegra Mast.
Striga elegans Benth.

PEDALIACEAE
Pterodiscus speciosus Hook.

PHYTOLACCACEAE
Phytolacca heptandra Retz.

PLUMBAGINACEAE
Plumbago auriculata Lam.
Plumbago zeylanica L.

POACEAE/GRAMINAE
Andropogon schirensis A.Rich.
Aristida canescens Henrard subsp. *canescens*
Aristida congesta Roem. & Schult. subsp. *congesta*
Aristida diffusa Trin. subsp. *burkei* (Stapf) Melderis
Aristida stipitata Hack. ssp. *graciliflora* (Pilg.) Meldris
Brachiaria nigropedata (Ficalho & Hiern) Stapf
Cymbopogon excavatus (Hochst.) Stapf ex Burtt Davy
Digitaria sp.
Ehrharta erecta Lam. var. *erecta*
Eleusine coracana (L.) Gaertn. subsp. *africana* (Kenn.-O'Byrne) Hilu & de Wet
Enneapogon cenchroides (Licht. ex Roem. & Schult.) C.E.Hubb.
Enneapogon pretoriensis Stent
Eragrostis curvula (Schrad.) Nees
Eragrostis lappula Nees
Eragrostis patentipilosa Hack.
Eragrostis racemosa (Thunb.) Steud.
Eragrostis trichophora Coss. & Durieu
Eustachys paspaloides (Vahl) Lanza & Mattei
Heteropogon contortus (L.) Roem. & Schult.
Loudetia simplex (Nees) C.E.Hubb.
Sporobolus festivus Hochst. ex A.Rich.
Trachypogon spicatus (L.f.) Kuntze
Triraphis andropogonoides (Steud.) E.Phillips
Tristachya rehmannii Hack.
POLYGALACEAE
Polygala gracilenta Burtt Davy
Polygala hottentotta C.Presl
Polygala rehmannii Chodat
Polygala transvaalensis Chodat subsp. *transvaalensis*

POLYGONACEAE
Fallopia convolvulus (L.) Holub
Persicaria attenuata (R.Br.) Soják subsp. *africana* K.L.Wilson
Polygonum aviculare L.
Polygonum hystriculum J.Schust.
**Rumex crispus* L.
Rumex sagittatus Thunb.

POTAMOGETONACEAE
Potamogeton pectinatus L.
Potamogeton schweinfurthii A.W.Benn.

POTTIACEAE
Trichostomum brachydontium Bruch

PROTEACEAE
Protea caffra Meisn. subsp. *caffra*

PTERIDACEAE
Cheillanthes eckloniana (Kunze) Mett.

RANUNCULACEAE
Clematis brachiata Thunb.
Clematis villosa DC. subsp. *stanleyi* (Hook) Kuntze
Clematis villosa DC. subsp. *villosa*
Ranunculus rionii Lagger

RHAMNACEAE
Berchemia zeyheri (Sond.) Grubov
Helinus integrifolius (Lam.) Kuntze
Ziziphus mucronata Willd. subsp. *mucronata*
Ziziphus zeyheriana Sond.

RICCIACEAE
Riccia atropurpurea Sim
Riccia okahandjana S.W.Arnell
Riccia rosea O.H.Volk & Perold
Riccia volkii S.W.Arnell

ROSACEAE
Rubus rigidus Sm.

RUBIACEAE
Anthospermum hispidulum E.Mey. ex Sond.
Anthospermum rigidum Eckl. & Zeyh. subsp. *rigidum*
*Pavetta zeyher*i Sond.
Pentanisia angustifolia (Hochst.) Hochst.
Rubia horrida (Thunb.) Puff
Rubia petiolaris DC.
Tapiphyllum parvifolium (Sond.) Robyns
Vangueria infausta Burch. subsp. *infausta*
RUTACEAE
Coleonema pulchellum I.Williams
Zanthoxylum capense (Thunb.) Harv.

SALICACEAE
**Salix babylonica* L. var. *babylonica*
Salix mucronata Thunb. subsp. *capensis* (Thunb.) Immelman

SAPINDACEAE
Pappea capensis Eckl. & Zeyh.

SCROPHULARIACEAE
Cycnium adonense E. Mey. ex Benth. ssp. *adonense*
Halleria lucida L.
Limosella longiflora Kuntze
Lindernia nana (Engl.) Roessler
Selago burkei Rolfe
Selago densiflora Rolfe
Selago sp.
Sutera levis Hiern
Sutera patriotica Hiern
Veronica anagallis-aquatica L.

SOLANACEAE
**Cestrum laevigatum* Schltdl.
Solanum catombelense Peyr.
**Solanum chenopodioides* Lam.
Solanum tomentosum L. var*. coccineum* (Jacq.) Willd.
Solanum panduriforme E.Mey.
Solanum retroflexum Dunal
Solanum supinum Dunal var*. supinum*
*Solanum villosum Mill. subsp. *villosum*

STERCULIACEAE
Hermannia depressa N.E.Br.
Hermannia floribunda Harv.
Hermannia grandistipula (Buchinger ex Hochst.) K.Schum.
Hermannia lancifolia Szyszyl.
Hermannia linnaeoides (Burch.) K.Schum.
Hermannia sp.
Melhania prostrata DC.

TECTARIACEAE
Ctenitis lanuginosa (Willd. & Kaulf.) Copel

THYMELAEACEAE
Gnidia burchellii (Meisn.) Gilg

TILIACEAE
Grewia flava DC.
Grewia occidentalis L. var. *occidentalis*

VERBENACEAE
Lantana rugosa Thunb.
Lippia scaberrima Sond.
Priva meyeri Jaub. & Spach var. *meyeri*

Appendix 2

*Key to **TREES AND SHRUBS** of the Vredefort Dome*
(adapted from Key to the Trees and Shrubs of the Witwatersrand, Magaliesberg and Pilanesberg[1])

Key to Groups

1 Plants thorny . . . . . **Group 1**
Plants without thorny structures 2
2(1) Leaves simple 3
Leaves pinnatisect. . . . . **Group 3**
Leaves compound . . . . . **Group 4**
3(2) One leaf at each node (leaves alternate) 4
Two or more leaves at each node (leaves opposite or whorled). . . . . **Group 5**
4(3) Margins of leaves entire. . . . . **Group 6**
Margins of leaves toothed or notched . . . . . **Group 7**

Group 1: Plants with thorns

1 Thorny structures derived from the epidermis (called prickles, usually scattered) . . . **Group 1B**
Thorny structures derived from stipules (usually paired at the base of alternately arranged petioles). . . . . **Group 1A**
Thorny structures derived from branches (usually borne in the axils of the leaves) 2
2(1) Leaves simple 3
Leaves compound . . . . . ***Rhus pyroides* var. *pyroides***
3(1) Margins of leaves serrate. 4
Margins of leaves crenate . . . . . **Group 1C**
Margins of leaves entire. 5
4(3) Margins of leaves involute or not rolled 6
Margins of leaves revolute. . . . . **Group 1D**
5(4) Lamina of leaves 11–40 mm long . . . . . **Group 1E**
Lamina of leaves 41–80 mm long . . . . . **Group 1F**
6(5) Petioles pubescent . . . . . **Group 1G**
Petioles glabrous. . . . . **Group 1H**

Group 1A

1 Leaves simple; margins of leaves serrate 2
Leaves compound; margins of leaflets entire . . . . . **indigenous species of *Acacia* Group 2**
2(1) Trees or upright shrubs . . . . . ***Ziziphus mucronata***
Underground shrubs (only tips of branches are above ground) . . . . . ***Ziziphus zeyheriana***

Group 1B

1 Leaves once compound; resinous or gummy latex at wounds absent 2
Leaves twice compound; resinous or gummy latex at wounds present . . . . . **indigenous species of *Acacia* Group 2**
2(1) Secondary veins ending at the margin; leaflets without transparent glands . . . . ***Rubus rigidus***
Secondary veins looping before the margin; leaflets with transparent glands . . . . . ***Zanthoxylum capense***

Group 1C

1 Margins of leaves or leaflets not rolled 2
Margins of leaves or leaflets revolute 3
2(1) Leaves clustered on short shoots; lenticels absent from branchlets . . . ***Gymnosporia buxifolia***
Leaves not clustered; lenticels present on branchlets . . . . . ***Scolopia zeyheri***
3(2) Petioles pubescent; young stems with eglandular hairs . . . . . ***Dovyalis zeyheri***

[1] Balkwill, K., Cron, G.V. and Balkwill, M-J, 1994. Key to the Trees and Shrubs of the Witwatersrand, Magaliesberg and Pilanesberg. Informally published by the C.E. Moss Herbarium, University of the Witwatersrand, Johannesburg.

Petioles glabrous; young stems glabrous . . . . . ***Scolopia zeyheri***

Group 1D

1 Midrib of leaves raised above upper surface 2
Midrib of leaves level with upper surface . . . . . ***Scolopia zeyheri***

2(1) Leaves clustered on short shoots; petioles green. . . . . ***Gymnosporia polyacantha***
Leaves not clustered; petioles pink or purple . . . . . ***Scolopia zeyheri***

Group 1E

1 Lamina of leaves 11–20 mm long . . . . . ***Gymnosporia polyacantha***
Lamina of leaves 21–40 mm long 2

2(1) Leaves clustered on short shoots 3
Leaves not clustered. . . . . ***Scolopia zeyheri***

3(2) Midrib of leaves raised above or level with upper surface; leaves not glossy. 4
Midrib of leaves channelled into upper surface; leaves glossy . . . . . ***Dovyalis zeyheri***

4(3) Dentition mainly on upper half of margin; thorny structures brown; leaves darker above than below . . . . . ***Gymnosporia***
Dentition along the whole margin; thorny structures grey; leaves as dark above as below . . . . . ***Gymnosporia tenuispina***

Group 1F

1 Leaves 0–10 mm wide 2
Leaves wider than 11 mm 3

2(1) Dentition mainly on upper half of margin; thorny structures brown; leaves darker above than below . . . . . ***Gymnosporia buxifolia***
Dentition along the whole margin; thorny structures grey; leaves as dark above as below . . . . . ***Gymnosporia tenuispina***

3(1) Leaves clustered on short shoots 4
Leaves not clustered. . . . . ***Scolopia zeyheri***

4(3) Dentition mainly on upper half of margin; thorny structures brown; leaves darker above than below . . . . . ***Gymnosporia buxifolia***
Dentition along the whole margin; thorny structures grey; leaves as dark above as below . . . . . ***Gymnosporia tenuispina***

Group 1G

1 Margins of leaves not rolled . . . . . ***Gymnosporia tenuispina***
Margins of leaves revolute. . . . . ***Dovyalis zeyheri***

Group 1H

1 Leaves clustered on short shoots 2
Leaves not clustered. . . . . ***Scolopia zeyheri***

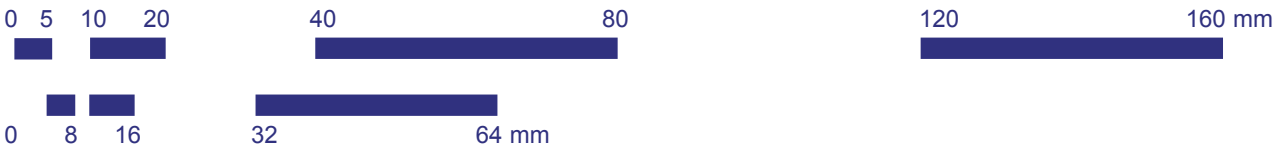
2(1) Leaves darker above than below. . . . . ***Gymnosporia polyacantha***
Leaves as dark above as below . . . . . ***Gymnosporia tenuispina***

Group 2: Indigenous species of *Acacia*

1 Thorny structures hooked; scattered on young stems and branches and on rachis . . . . . ***Acacia caffra***
Thorny structures straight; restricted to pairs at the nodes 2

2(1) Pinnules 1.2– 2.5 mm wide; short shoots forming insignificant cushions on branches . . . . . ***Acacia karoo***
Pinnules 2.5–7.5 mm wide; short shoots forming conspicuous cushions on the thick branches . . . . . ***Acacia robusta* ssp. *robusta***

Ruler for measuring structures on trees, in increments used in the key



Group 3: Plants with pinnatisect leaves

1 Leaves darker above than below; young stems cream or whitish; young stems with eglandular hairs; leaves not glaucous; margins of leaves serrate. . . . . ***Artemisia afra***
Leaves as dark above as below; young stems green; young stems glabrous; leaves glaucous; margins of leaves entire . . . . . ***Phymaspermum athanasoides***

Group 4: Plants with compound leaves

1 Trees or upright shrubs 2
Climbers or scandent shrubs . . . . . **Group 4A**
Underground shrubs (only tips of branches are above ground) . . . . . **Group 4B**
2(1) Leaves clustered at tips of long shoots or on short shoots **or** leaves in a single rosette at the top of the trunk . . . . . **Group 4C**
Leaves not clustered. 3
3(2) Leaves once compound 4
Leaves twice compound. . . . . **Group 4D**
4(3) Primary leaflets pinnately arranged 5
Primary leaflets palmately arranged 6
5(4) Leaves with 3 leaflets . . . . . ***Heteromorpha arborescens***
Leaves with 4 or more leaflets . . . . . **Group 4E**
6(4) Lateral leaflets petiolulate . . . . . **Group 4F**
Lateral leaflets sessile 7
7(6) Widest lateral pinnae 0–10 mm wide. . . . . **Group 4G**
Widest lateral pinnae 11–20 mm wide. 8
Widest lateral pinnae 21–40 mm wide . . . . . ***Rhus pyroides* var. *pyroides***
8(7) Petioles pubescent . . . . . **Group 4H**
Petioles glabrous. . . . . **Group 4I**

Group 4A

1 Tendrils present; terminal leaflets petiolulate . . . . . ***Rhoicissus tridentata***
Tendrils absent; terminal leaflets sessile . . . . . ***Rhus rigida* var. *margaretae***

Group 4B

1 Terminal leaflets ovate or elliptic . . . . . ***Rhus rigida* var. *margaretae***
Terminal leaflets obovate . . . . . ***Rhus magalismontana* ssp. *magalismontana***

Group 4C

1 Primary leaflets pinnately arranged . . . . . ***Heteromorpha arborescens***
Primary leaflets palmately arranged . . . . . ***Cussonia paniculata***

Group 4D

1 Pinnae paripinnate; terminal leaflet not identifiable . . . . . ***Acacia caffra***
Pinnae imparipinnate; terminal leaflet identifiable . . . . . ***Heteromorpha arborescens***

Group 4E

1 Lamina of terminal leaflets narrower than 20 mm . . . . . ***Mundulea sericea***
Lamina of terminal leaflets wider than 21 mm . . . . . ***Heteromorpha arborescens***

Group 4F

1 Petioles pubescent; secondary veins of leaflets raised above upper surface . . . . . ***Rhus pyroides* var. *pyroides***
Petioles glabrous; secondary veins of leaflets level with upper surface . . . . . ***Maerua cafra***

Group 4G

1 Terminal leaflets ovate or elliptic . . . . . ***Rhus rigida* var. *margaretae***
Terminal leaflets obovate 2
2(1) Margins of leaflets serrate; tips of terminal leaflets acute 3
Margins of leaflets entire; tips of terminal leaflets apiculate . . . . . ***Rhus lancea***
3(2) Leaflets narrower than 25 mm . . . . . ***Rhus leptodictya***
Leaflets broader than 25 mm . . . . . ***Smodingium argutum***

Group 4H

1 Lamina of terminal leaflets up to 40 mm long . . . . . ***Rhus rigida* var. *margaretae***
Lamina of terminal leaflets 4–80 mm long . . . . . ***Rhus pyroides* var. *pyroides***

Group 4I

1 Young stems round in cross section; margins of leaflets not undulate 2
Young stems oval (very markedly flattened) in cross section; margins of leaflets undulate . . . . . ***Rhus pallens***

2(1). Lamina of terminal leaflets 11–80 mm long; lateral leaflets with 6–15 secondary veins on each side of main vein . . . . . ***Rhus rigida* var. *margaretae***
Lamina of terminal leaflets longer than 81 mm; lateral leaflets with more than 15 lateral veins on each side of main vein . . . . . ***Rhus lancea***

Group 5: Plants with opposite or whorled leaves

1 Trees or upright shrubs 2
Climbers or scandent shrubs . . . . . **Group 5A**
Underground shrubs (only tips of branches are above ground) . . . . . ***Salacia rehmannii***
Parasites or semiparasites . . . . . ***Viscum rotundifolium***

2(1) Liquid latex present . . . . . ***Asclepias fruticosa***
Liquid latex absent 3

3(2) No stipules present 4
Interpetiolar stipules present 10
Paired, adnate (to petiole) stipules present; leaves fan-shaped . . . . ***Myrothamnus flabellifolia***
Paired, free stipules present at base of petiole . . . . . ***Berchemia zeyheri***
Stipules present as ridges on stem . . . . . **Group 5B**

4(3) Two leaves at a node (opposite) 5
Three or more leaves at a node (whorled) . . . . . ***Nuxia congesta***

5(4) Leaves petiolate 6
Leaves sessile . . . . . ***Buddleia saligna***

6(5) Margins of leaves toothed or notched . . . . . **Group 5C**
Margins of leaves entire 7

7(6) Leaves glaucous . . . . . ***Euclea crispa* ssp. *crispa***
Leaves not glaucous 8

8(7) Young stems round or oval in cross section 9
Young stems square in cross section . . . . . **Group 5D**

9(8) Petioles pubescent . . . . . **Group 5E**
Petioles glabrous or granular or with scales . . . . . **Group 5F**

10(3) Margins of leaves crenate or leaves with 2 or more major veins from the base . . . . . ***Buddleia salviifolia***
Margins of leaves entire and leaves with only one main vein from the base 11

11(10) Leaves with scattered dark nodules; crushed leaves with a foetid (unpleasant) smell . . . . . ***Pavetta zeyheri***
Leaves without scattered dark nodules; crushed leaves with no smell or a beany smell . . . . . **Group 5G**

Group 5A

1 Liquid latex present . . . . . ***Ancylobotrys capensis***
Liquid latex absent . . . . . ***Barleria obtusa***

Group 5B

1 Two leaves at a node (opposite); young stems square in cross section . . . . . ***Buddleia saligna***
Three or more leaves at a node (whorled); young stems round in cross section ***Nuxia congesta***

Group 5C

1 Margins of leaves serrate . . . . . ***Halleria lucida***
Margins of leaves crenate . . . . . ***Euclea crispa* ssp. *crispa***

Group 5D

1 Lenticels present on branchlets . . . . . ***Olea europea* ssp. *africana***
Lenticels absent from branchlets 2

2(1) Up to 15 secondary veins on each side of main vein . . . . . ***Barleria obtusa***
More than 15 secondary veins on each side of main vein . . . . . ***Buddleia saligna***

Group 5E

1 Large woody shrubs or trees ; upper surface of leaves quilted (puckered and wrinkled) . . . . . ***Combretum molle***
Weak shrubs or creepers; upper surface of leaves not quilted (not puckered and wrinkled) . . . . . ***Barleria obtusa***

Group 5F

1 Leaves 21–60 mm long. . . . . ***Tapiphyllum parvifolium***
Leaves longer than 61 mm. . . . . ***Vangueria infausta***

Group 6: Plants with alternate, entire leaves

1 Trees or upright shrubs 2
Climbers, scandent shrubs, underground shrubs (only tips of branches are above ground) . . . . . ***Helinus integrifolius***
2(1) Leaves petiolate 3
Leaves sessile. 19
3(2) Leaves clustered at tips of long shoots . . . . . **Group 6A**
Leaves clustered on short shoots 4
Leaves not clustered. 6
4(3) Widest point of leaves at or near the middle . . . . . **Group 6B**
Widest point of leaves near the tip 5
5(4) Lamina of leaves 6– 20 mm long. . . . . **Group 6C**
Lamina of leaves 21– 80 mm long. . . . . **Group 6D**
6(3) Leaves glaucous on both surfaces or markedly glaucous on lower surface. . . . . **Group 6E**
Leaves not glaucous 7
7(6) Upper surface of leaves quilted (puckered and wrinkled) . . . . ***Diospyros lycioides* ssp. *guerkei***
Upper surface of leaves not quilted (not puckered and wrinkled) 8
8(7) Widest point of leaves near the base. 9
Widest point of leaves at or near the middle 11
Widest point of leaves near the tip 18
9(8) Petioles 0–5 mm long. 10
Petioles 6–10 mm long. . . . . ***Scolopia zeyheri***
10(9) Petioles pubescent, granular or with scales . . . . . ***Cassine burkeana***
Petioles glabrous. . . . . ***Scolopia zeyheri***
11(8) Sides of leaves parallel. . . . . ***Pappea capensis***
Sides of leaves not parallel 12
12(11) Secondary veins ending at the margin. . . . . ***Pappea capensis***
Secondary veins looping before the margin 13
13(12) Bases of leaves cuneate. 14
Bases of leaves rounded 17
Bases of leaves truncate, cordate or deeply cordate . . . . . ***Diospyros whyteana***
14(13) Petioles pubescent. 15
Petioles glabrous. 16
15(14) Secondary veins with hairy pockets in axils . . . . . ***Dovyalis zeyheri***
Secondary veins without hairy pockets in axils. . . ***Diospyros austro-africana* var. *microphylla***
16(14) Petioles 0–5 mm long . . . . . ***Scolopia zeyheri***
Petioles 6–10 mm long. . . . . **Group 6F**
Petioles longer than 11 mm. . . . . ***Ilex mitis***
17(13) Petioles 0–5 mm long . . . . . ***Cassine burkeana***
Petioles longer than 11 mm. . . . . ***Ilex mitis***
18(8) Petioles 0–5 mm long. . . . . **Group 6G**
Petioles longer than 6 mm. . . . . ***Ilex mitis***
19(2) Leaves clustered on short shoots . . . . . ***Stoebe vulgaris***
Leaves not clustered. . . . . **Group 6H**

Group 6A

1 Secondary veins ending at the margin . . . . . ***Pappea capensis***
Secondary veins looping before the margin . . . . . ***Diospyros lycioides* ssp. *lycioides***

Group 6B

1 Midrib of leaves raised above upper surface 2
Midrib of leaves channelled into upper surface 3
2(1) Bases of leaves decurrent . . . . . ***Plumbago auriculata***
Bases of leaves cuneate . . . . . ***Gymnosporia tenuispina***
3(1) Secondary veins with hairy pockets in axils; lenticels present on branchlets . ***Dovyalis zeyheri***
Secondary veins without hairy pockets in axils; lenticels absent from branchlets
. . . . . ***Diospyros austro-africana* var. *microphylla***

Group 6C

1 Leaves 0–5 mm wide . . . . . ***Diospyros austro-africana* var. *microphylla***
Leaves 6–10 mm wide 4
Leaves 11–20 mm wide 10
Leaves 21–40 mm wide . . . . . ***Dovyalis zeyheri***
Leaves 41–80 mm wide . . . . . ***Turraea obtusifolia***
2(1) Leaves darker above than below. . . . . ***Diospyros austro-africana* var. *microphylla***
Leaves as dark above as below . . . . . ***Ehretia rigida***
3(1) Leaves darker above than below. . . . . ***Dovyalis zeyheri***
Leaves as dark above as below . . . . . ***Ehretia rigida***

Group 6D

1(1) Bases of leaves decurrent . . . . . ***Plumbago auriculata***
Bases of leaves cuneate 2
2(1) Secondary veins with hairy pockets in axils. 3
Secondary veins without hairy pockets in axils. 4
3(2) Leaves as dark above as below . . . . . ***Ehretia rigida***
Leaves darker above than below. . . . . ***Dovyalis zeyheri***
4(2) Petioles pubescent 5
Petioles glabrous. . . . . ***Gymnosporia tenuispina***
5(4) No stipules present. . . . . ***Ehretia rigida***
Paired, free stipules present at base of petiole . . . . . ***Gymnosporia tenuispina***

Group 6E

1 Leaves 6–20 mm wide 2
Leaves more than 21 mm wide 6
2(1) Lamina of leaves 11– 40 mm long 3
Lamina of leaves longer than 41 mm 4
3(2) Upper surface of leaves green. . . . . ***Plumbago auriculata***
Both surface of leaves grey-green . . . . . ***Osyris lanceolata***
4(2) Bases of leaves decurrent; margins of leaves undulate . . . . . ***Plumbago auriculata***
Bases of leaves cuneate or rounded; margins of leaves not undulate 5
5(4) Trees with upright branches . . . . . ***Salix mucronata ssp. capensis***
Trees with drooping branches. . . . . ***Salix babylonica***
10(1) Lamina of leaves 11–40 mm long. . . . . ***Osyris lanceolata***
Lamina of leaves longer than 41 mm . . . . . ***Protea caffra***

Group 6F

1 Midrib of leaves raised above or level with upper surface . . . . . ***Scolopia zeyheri***
Midrib of leaves channelled into upper surface . . . . . ***Ilex mitis***

Group 6G

1 Petioles pubescent . . . . . ***Dovyalis zeyheri***
Petioles glabrous. 2
2(1) Mature leaves less than 15 mm long . . . . . ***Diospyros austro-africana* var. *microphylla***
Mature leaves longer than 15 mm . . . . . ***Diospyros lycioides* ssp. *lycioides***

Group 6H

1 1 major vein from base of leaf 2
2 or more major veins from base of leaf . . . . . ***Lopholaena coriifolia***
2(1) Bases of leaves decurrent 3
Bases of leaves cuneate 5
3(2) Lamina of leaves narrower than 10 mm. . . . . ***Phymaspermum athanasoides***
Lamina of leaves 11 mm or wider 4
4(3) Lamina of leaves 11–40 mm long; young stems oval (very markedly flattened) in cross section . . . . . ***Osyris lanceolata***
Lamina of leaves 81–160 mm long; young stems round in cross section. . . . . ***Protea caffra***
5(2) Widest point of leaves at or near the middle 6
Widest point of leaves near the tip 7
6(5) Lamina of leaves 11–40 mm long . . . . . ***Osyris lanceolata***
Lamina of leaves 81–160 mm long . . . . . ***Protea caffra***
7(5) Leaves narrower than 10 mm . . . . . ***Phymaspermum athanasoides***
Leaves broader than 11 mm . . . . . ***Protea caffra***

Group 7: Plants with alternate, toothed or notched leaves

1 Trees or upright shrubs 2
Underground shrubs (only tips of branches are above ground) . . . . . ***Salacia rehmannii***
2(1) 1 major vein from base of leaf 3
2–3 major veins from base of leaf. 12
4 or more major veins from base of leaf . . . . . **Group 7A**
3(2) Leaves clustered at tips of long shoots or on short shoots . . . . . **Group 7B**
Leaves not clustered. 4
4(3) Margins of leaves dentate . . . . . **Group 7C**
Margins of leaves serrate. 5
Margins of leaves crenate . . . . . ***Dovyalis zeyheri***
5(4) Leaves glaucous on both surfaces or markedly so on lower surface . . . . . **Group 7D**
Leaves not glaucous 6
6(5) Petioles pubescent, granular or with scales 7
Petioles glandular . . . . . ***Myrsine africana***
Petioles glabrous. 9
7(6) Petioles 0–5 mm long. 8
Petioles longer than 6 mm. . . . . **Group 7E**
8(7) Secondary veins ending at the margin . . . . . ***Brachylaena rotundata***
Secondary veins looping before the margin . . . . . **Group 7F**
9(6) Petioles 0–5 mm long. . . . . ***Scolopia zeyheri***
Petioles 6–10 mm long. . . . . **Group 7G**
Petioles longer than 11 mm. . . . . ***Ilex mitis***
10(2) Margins of leaves dentate. . . . . ***Grewia flava***
Margins of leaves serrate. 11
Margins of leaves crenate . . . . . ***Acalypha glabrata***
11(10) Secondary veins ending at the margin. . . . . **Group 7H**
Secondary veins looping before the margin 12
12(11) Petioles 0–5 mm long . . . . . **Group 7I**
Petioles longer than 6 mm. . . . . **Group 7J**

Group 7A

1 Margins of leaves dentate 2
Margins of leaves serrate. 3
2(1) Lenticels present on branchlets . . . . . ***Dombeya rotundifolia***
Lenticels absent from branchlets . . . . . ***Hibiscus calyphyllus***
3(1) Secondary veins ending at the margin; bases of leaves equal. 4
Secondary veins looping before the margin; bases of leaves oblique (not equal)

. . . . . ***Ziziphus mucronata***
4(3) Lenticels present on branchlets . . . . . ***Dombeya rotundifolia***
Lenticels absent from branchlets . . . . . ***Hibiscus calyphyllus***

Group 7B

1 Secondary veins with hairy pockets in axils; leaves hairy on both surfaces . . ***Dovyalis zeyheri***
Secondary veins without hairy pockets in axils; leaves glabrous on both surfaces
. . . . . ***Gymnosporia tenuispina***

Group 7C

1 Leaves not glaucous . . . . . ***Brachylaena rotundata***
Leaves markedly glaucous on lower surface . . . . . ***Maytenus undata***

Group 7D

1 Plants with pendant branches. . . . . ***Salix babylonica***
Plants with mainly upright branches 2
2(1) Leaves broadly elliptic or obovate; tips of leaves emarginate (notched), acuminate or apiculate . . . . . ***Maytenus undata***
Leaves narrowly ovate or elliptic; tips of leaves acute or aristate
. . . . . ***Salix mucronata* ssp. *capensis***

Group 7E

1 Midrib of leaves raised above upper surface . . . . . ***Acalypha glabrata***
Midrib of leaves channelled into upper surface . . . . . ***Brachylaena rotundata***

Group 7F

1 Bases of leaves decurrent . . . . . ***Brachylaena rotundata***
Bases of leaves cuneate 2
Bases of leaves rounded 3
2(1) Secondary veins with hairy pockets in axils. . . . . ***Dovyalis zeyheri***
Secondary veins without hairy pockets in axils. . . . . ***Brachylaena rotundata***
3(1) Midrib of leaves raised above or level with upper surface . . . . . ***Cassine burkeana***
Midrib of leaves channelled into upper surface . . . . . ***Brachylaena rotundata***

Group 7G

1 Midrib of leaves raised above or level with upper surface . . . . . ***Scolopia zeyheri***
Midrib of leaves channelled into upper surface . . . . . ***Ilex mitis***

Group 7H

1 Midrib of leaves raised above or level with upper surface 2
Midrib of leaves channelled into upper surface . . . . . ***Grewia flava***
2(1) Margin of leaves ciliate . . . . . ***Acalypha glabrata***
Margin of leaves glabrous 3
3(2) Petioles 1– 5 mm long . . . . . ***Grewia occidentalis***
Petioles longer than 6 mm. . . . . ***Acalypha glabrata***

Group 7I

1 Teeth of margin tipped with brown glands; young stems glabrous . . . . . ***Ziziphus mucronata***
Teeth of margin not tipped with brown glands; young stems with eglandular hairs
. . . . . ***Celtis africana***

Group 7J

1 Bases of leaves equal . . . . . ***Acalypha glabrata***
Bases of leaves oblique (not equal) 5
2(1) Teeth of margin tipped with brown glands; young stems glabrous . . . . . ***Ziziphus mucronata***
Teeth of margin not tipped with brown glands; young stems with eglandular hairs
. . . . . ***Celtis africana***

Appendix 3

*Checklist of **BIRDS** of the Vredefort Dome*
From: Anonymous. Proposal: Vredefort Dome World Heritage Site. Department of Tourism, Environment and Economic Affairs, Free State Province.
Kindly checked/updated to the list at http://web.uct.ac.za/depts/fitzpatrick/docs/roberts.html by Reneé Reddy.

Tachybaptus ruficollis	Little Grebe (= Dabchick)
Phalacrocorax lucidus	White-breasted Cormorant
P. africanus	Reed Cormorant
Anhinga rufa	African Darter
Ardea cinerea	Grey Heron
A. *melanocephala*	Black-headed Heron
A. *goliath*	Goliath Heron
Egretta alba	Great Egret
Egretta garzetta	Little Egret
E. intermedia	Yellow-billed Egret
Bubulcus ibis	Cattle Egret
Ardeola ralloides	Squacco Heron
Nycticorax nycticorax	Black-crowned Night-Heron
Ixobrychus minutus	Little Bittern
Scopus umbretta	Hamerkop
Ciconia ciconia	White Stork
C. *abdimii*	Abdim's Stork
Mycteria ibis	Yellow-billed Stork
Threskiornis aethiopicus	African Sacred Ibis
Bostrychia hagedash	Hadeda Ibis
Platalea alba	African Spoonbill
Dendrocygna viduata	White-faced Duck
D. bicolor	Fulvous Duck
Alopochen aegyptiaca	Egyptian Goose
Tadorna cana	South African Shelduck
Anas undulata	Yellow-billed Duck
A. *sparsa*	African Black Duck
A. *erythrorhyncha*	Red-billed Teal
A. *smithii*	Cape Shoveler
Netta erythrophthalma	Southern Pochard
Sarkidiornis melanotos	Comb Duck (= Knob-billed Duck*)*
Plectropterus gambensis	Spur-winged Goose
Sagittarius serpentarius	Secretarybird
Gyps coprotheres	Cape Vulture
G. *africanus*	White-backed Vulture
Milvus migrans	Black Kite (= Yellow-billed Kite)
Elanus caeruleus	Black-shouldered Kite
Aquila verreauxi	Verreaux's Eagle (= Black Eagle)
A. rapax	Tawny Eagle
Haliaeetus vocifer	African Fish-Eagle
Buteo vulpinus	Steppe Buzzard
Accipiter ovampensis	Ovambo Sparrowhawk
A. *minullus*	Little Sparrowhawk
Melierax gabar	Gabar Goshawk
Melierax canorus	Southern Pale Chanting Goshawk
Falco peregrinus	Peregrine Falcon

F. biarmicus	Lanner Falcon
F. amurensis	Amur Falcon (= Eastern Red-footed Kestrel)
F. rupicolus	Rock Kestrel
F. rupicoloides	Greater Kestrel
F. naumanni	Lesser Kestrel
Scleroptila levaillanthoides	Orange River Francolin
Pternistis natalensis	Natal Spurfowl
P. swainsonii	Swainson's Spurfowl
Coturnix coturnix	Common Quail
Numida meleagris	Helmeted Guineafowl
Amaurornis flavirostris	Black Crake
Porphyria madagascariensis	African Purple Swamphen *(*= Purple Gallinule*)*
Gallinula chloropus	Common Moorhen
Fulica cristata	Red-knobbed Coot
Actophilomis africanus	African Jacana
Charadrius tricollaris	Three-banded Plover
Vanellus coronatus	Crowned Lapwing (= Crowned Plover)
V. *armatus*	Blacksmith Lapwing (= Blacksmith Plover)
V. *senegallus*	African Wattled Lapwing (= Wattled Plover)
Actitus hypoleucos	Common Sandpiper
Tringa glareola	Wood Sandpiper
T. stagnatilis	Marsh Sandpiper
T. nebularia	Common Greenshank
Himantopus himantopus	Black-winged Stilt
Larus cirrocephalus	Grey-headed Gull
Chlidonias hybrida	Whiskered Tern
C. *leucopterus*	White-winged Tern
Columba guinea	Speckled Pigeon (= Rock Pigeon)
Streptopelia semitorquata	Red-eyed Dove
S. *capicola*	Cape Turtle-Dove
S. *senegalensis*	Laughing Dove
Gena capensis	Namaqua Dove
Cuculus gularis	African Cuckoo
C. *solitarius*	Red-chested Cuckoo
Clamator jacobinus	Jacobin Cuckoo
Chrysococcyx klaas	Klaas's Cuckoo
C. *caprius*	Diederik Cuckoo
Centropus burchellii	Burchell's Coucal
Tyto alba	Barn Owl
Bubo africanus	Spotted Eagle-Owl
Caprimulgus pectoralis	Fiery-necked Nightjar
C. *rufigena*	Rufous-cheeked Nightjar
C. *tristigma*	Freckled Nightjar
Apus apus	Common Swift (= Eurasian Swift)
A. *barbatus*	African Black Swift
A. *caffer*	White-rumped Swift
A. *horus*	Horus Swift
A. *affinis*	Little Swift
Cypsiurus parvus	African Palm Swift
Colius striatus	Speckled Mousebird
C. *colius*	White-backed Mousebird
Urocolius indicus	Red-faced Mousebird
Ceryle rudis	Pied Kingfisher
Megaceryle maximus	Giant Kingfisher

Alcedo semitorquata t	Half-collared Kingfisher
A. *cristata*	Malachite Kingfisher
Halcyon albiventris	Brown-hooded Kingfisher
Merops apiaster	European Bee-eater
M. *persicus*	Blue-cheecked Bee-eater
M. *hirudineus*	Swallow-tailed Bee-eater
Coracias garrulus	European Roller
C. *caudate*us	Lilac-breasted Roller
Upupa africana	African Hoopoe
Phoeniculus purpureus	Green Wood-Hoepoe (= Red-billed Wood-hoopoe)
Rhinopomastus cyanomelas	Common Scimitarbill (= Scimitar-billed Wood-hoopoe)
Lybius torquatus	Black-collared Barbet
Trichlaema leucomelas	Acacia Pied Barbet
Trachyphonus vaillantii	Crested Barbet
Indicator indicator	Greater Honeyguide
Indicator minor	Lesser Honeyguide
Prodotiscus regulus	Brown-backed Honeyguide (= Sharp-billed Honeyguide)
Campethera abingoni	Golden-tailed Woodpecker
Dendropicos fuscescens	Cardinal Woodpecker
D. namaquus	Bearded Woodpecker
Jynx ruficollis	Red-throated Wryneck
Mirafra africana	Rufous-naped Lark
Calendulauda sabota	Sabota Lark
Calandrella cinerea	Red-capped Lark
Hirundo rustica	Barn Swallow (= European Swallow)
H. albigularis	White-throated Swallow
H. semirufa	Red-breasted Swallow
H. cucullata	Greater Striped Swallow
H. spilodera	South African Cliff-Swallow
H. fuligula	Rock Martin
Delichon urbicum	Common House Martin
Riparia riparia	Sand Martin
R. paludicola	Brown-throated Martin
R. cincta	Banded Martin
Campephaga flava	Black Cuckooshrike
Dicrurus adsimilis	Fork-tailed Drongo
Oriolus larvatus	Black-headed Oriole
Corvus capensis	Cape Crow (= Black Crow)
C. *albus*	Pied Crow
Parus cinerascens	Ashy Tit
Pycnonotus nigricans	African Red-eyed Bulbul
Turdus olivaceus	Olive Thrush
Psophocichla litsipsirupa	Groundscraper Thrush
Oenanthe monticola	Mountain Wheateater (= Mountain Chat)
O. *pileata*	Capped Wheatear
Cercomela familiaris	Familiar Chat
Thamnolaea cinnamomeiventris	Mocking Cliff-Chat
Mymecocichla formicivora	Anteating Chat
Saxicola torquata	African Stonechat
Cossypha caffra	Cape Robin-Chat
C. *humeralis*	White-throated Robin-Chat
Cercotrichas paena	Kalahari Scrub-Robin

Sylvia borin	Garden Warbler
S. *communis*	Common Whitethroat
Parisoma subcaeruleum	Chestnut-vented Tit-babbler
Hippolais icterina	Icterine Warbler
H. olivetorum	Olive-tree Warbler
Acrocephalus arundinaceus	Great Reed-Warbler
A. *baeticatus*	African Reed-Warbler (= African Marsh Warbler)
A. *gracilirostris*	Lesser Swamp-Warbler (= Cape Reed Warbler)
Bradypterus baboecala	Little Rush-Warbler (= African Sedge Warbler)
Phylloscopus trochilus	Willow Warbler
Apalis thoracica	Bar-throated Apalis
Sylvietta rufescens	Long-billed Crombec
Eremomela icteropygialis	Yellow-bellied Eremomela
Cisticola juncidis	Zitting Cisticola (= Fan-tailed Cisticola)
C. *lais*	Wailing Cisticola
C. *chiniana*	Rattling Cisticola
C. *tinniens*	Levaillant's Cisticola
C. *fulvicapilla*	Neddicky
Prinia flavicans	Black-chested Prinia
Muscicapa striata	Spotted Flycatcher
Sigelus silens	Fiscal Flycatcher
Batis molitor	Chinspot Batis
Batis pririt	Pririt Batis
Terpsiphone viridis	African Paradise Flycatcher
Motacilla aguimp	African Pied Wagtail
M. *capensis*	Cape Wagtail
Anthus cinnamomeus	African Pipit (= Grassveld Pipit)
Macronyx capensis	Cape Longclaw (= Orange-throated Longclaw)
Lanius minor	Lesser Grey Shrike
L. collaris	Common Fiscal (= Fiscal Shrike)
L. collurio	Red-backed Shrike
Laniarius atrococcineus	Crimson-breasted Shrike
Dryoscopus cubla	Black-backed Puffback (= Puffback)
Nilaus afer	Brubru
Tchagra australis	Brown-crowned Tchagra (= Three- streaked Tchagra)
Telophorus zeylonus	Bokmakierie
Spreo bicolor	Pied Starling
Creatophora cinerea	Wattled Starling
Cinnyricinclus leucogaster	Violet-backed Starling (= Plum-coloured Starling)
Lamprotornis nitens	Cape Glossy Starling
Onychognathus morio	Red-winged Starling
Nectarinia famosa	Malachite Sunbird
Cinnyris afer	Greater Double-collared Sunbird
C. talatala	White-bellied Sunbird
Chalcomitra amethystina	Amethyst Sunbird (= Black Sunbird)
Zosterops capensis	Cape White-eye
Plocepasser mahali	White-browed Sparrow-weaver
Passer domesticus	House Sparrow
P. melanurus	Cape Sparrow
P. diffuses	Northern Grey-headed Sparrow
Petronia superciliaris	Yellow-throated Petronia (= Yellow-throated Sparrow)

Sporopipes squamifrons	Scaly-feathered Finch
Ploceus velatus	Southern Masked Weaver
Quelea quelea	Red-billed Quelea
Euplectes orix	Southern Red Bishop
E. *afer*	Yellow-crowned Bishop (= Golden Bishop)
E. *albonotatus*	White-winged Widowbird
E. *ardens*	Red-collared Widowbird
E. *progne*	Long-tailed Widowbird
Pytilia melba	Green-winged Pytila (= Melba Finch)
Lagonosticta rubricata	African Firefinch (= Bluebilled Firefinch)
L. rhodopareia	Jameson's Firefinch
L. senegala	Red-billed Firefinch
Uraeginthus angolensis	Blue Waxbill
Granatina granatina	Violet-eared Waxbill
Estrilda astrild	Common Waxbill
Ortygospiza atricollis	African Quail Finch
Sporaeginthus subflavus	Orange-breasted Waxbill
Amadina erythrocephala	Red-headed Finch
Spermestes cucullatus	Bronze Mannikin
Vidua macroura	Pin-tailed Whydah
V. *paradisaea*	Long-tailed Paradise-Whydah
V. *funerea*	Dusky Indigobird (= Black Widowfinch)
V. *chalybeata*	Village Indigobird (= Steelblue Widow-finch)
Crithagra atrogularis	Black-throated Canary
C. *flaviventris*	Yellow Canary
Emberiza flaviventris	Golden-breasted Bunting
E. *capensis*	Cape Bunting
E. *tahapisi*	Cinnamon-breasted Bunting (= Rock Bunting)

The following additional birds have been sighted at Habula Lodge by Susan Love:

Peliperdix coqui	Coqui Francolin
Coccopygia melanotis	Sweet Waxbill
Estrilda erythronotos	Black-faced Waxbill (= Black-cheeked Waxbill)
Crithagra mozambicus	Yellow-fronted Canary (= Yellow-eyed Canary)

The following additional birds have been sighted at Habula Lodge:

Turnix sylvatica	Small Buttonquail
Corythaixoides concolor	Grey Go-away-bird
Burhinus capensis	Spotted Thick-knee
Hieraaetus spilogaster	African Hawk-Eagle
Plegadis falcinellus	Glossy Ibis
Laniarius ferrugineus	Southern Boubou
Turdus smithii	Karoo Thrush
Acridotheres tristis	Common Myna
Hirundo dimidiata	Pearl-breasted Swallow
Hirundo abyssinica	Lesser Striped Swallow
Zosterops pallidus	Orange River White-eye
Acrocephalus palustris	Marsh Warbler
Ploceus capensis	Cape Weaver
Vidua regia	Shaft-tailed Whydah

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