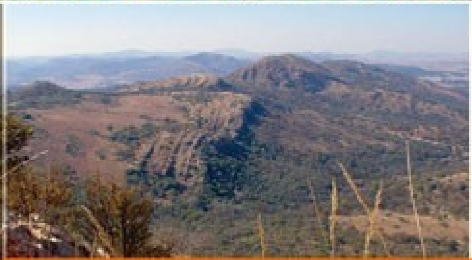
GEOPARKS OF THE WORLD



W. U. Reimold · R. L. Gibson

Meteorite Impact!

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

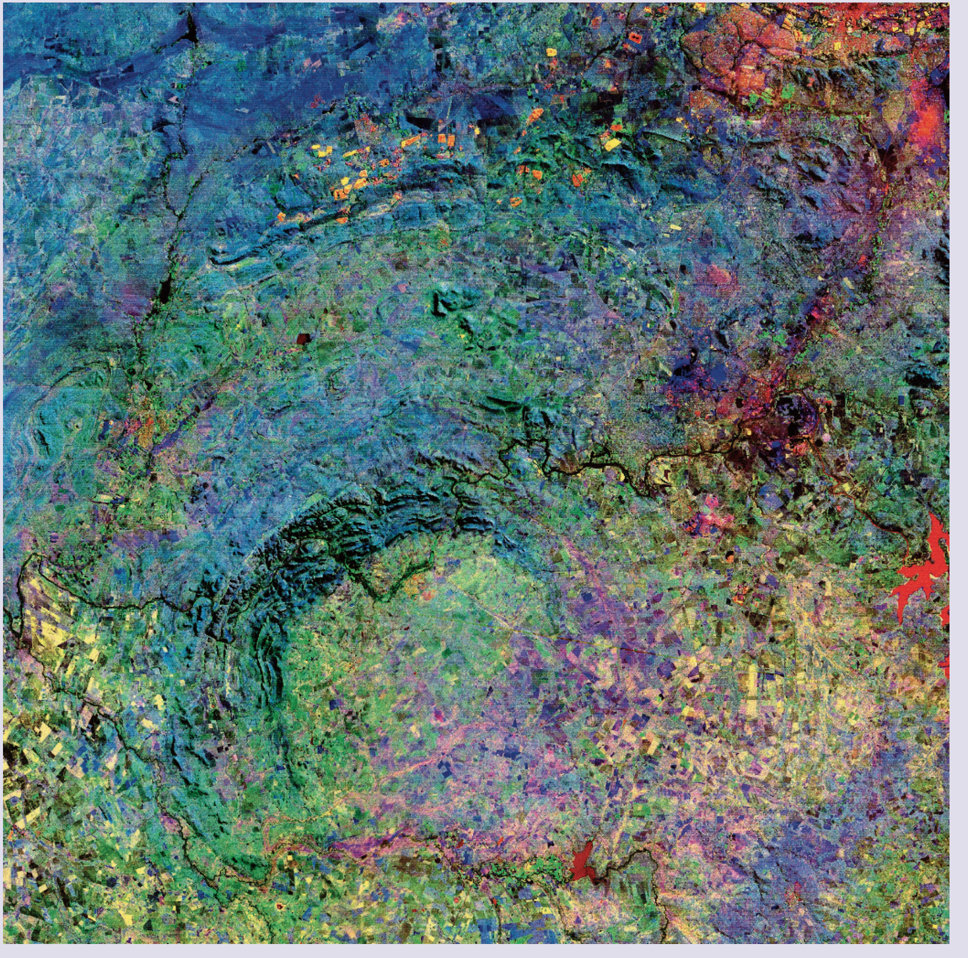
The Vredefort Structure

Springer

Council for Geoscience

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

Credited to: *Hugo von Hofmannsthal*



↑ **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

Geoparks of the World
Development and Management

Third Edition, completely revised.
Published by

Springer

Third Edition
2009

Council for Geoscience

Credits

Production Team

Editing and layout
Council for Geoscience

Illustrations redrafted by
Linette Cloete

Printers and Bookbinders

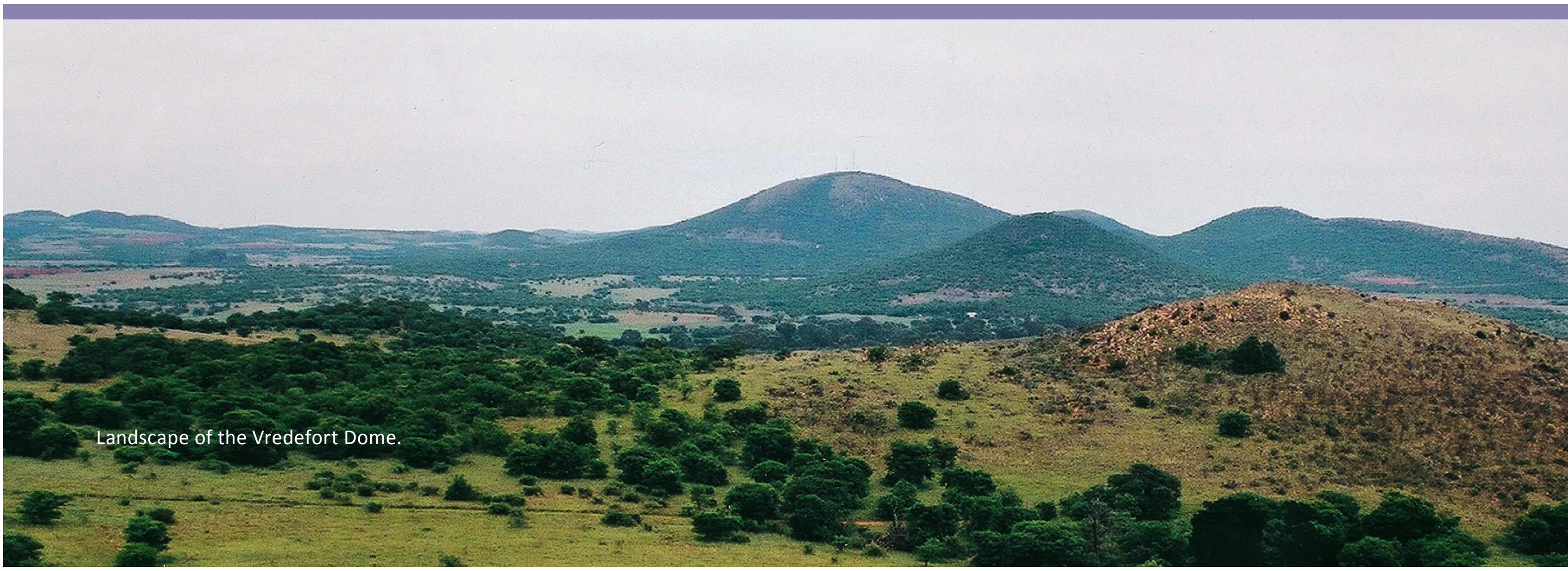
Copyright Reserved

Copyright

Publishers

ISBN 978-3-642-10463-3

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.

Vaal River at Schoemansdrift Bridge.

Contents

Chapter 4

Chapter 5

Chapter 6

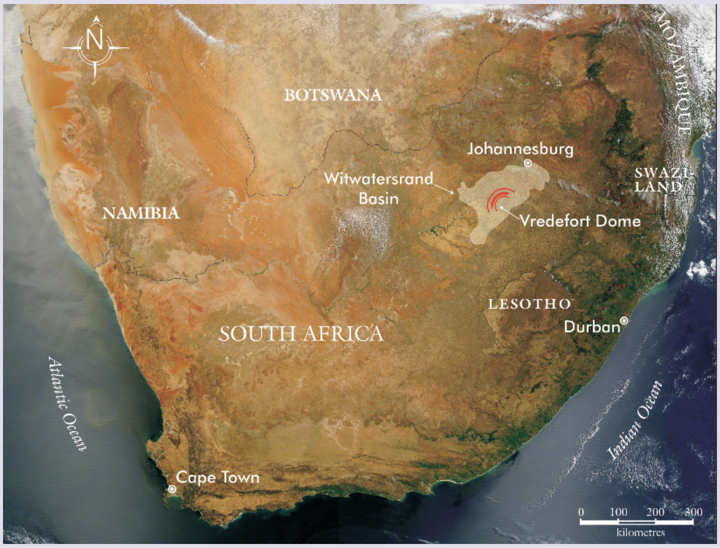
Chapter 7

Chapter 8

The phenomenal landscape of the Vredefort Dome area.

Part II

Tour guide through the Vredefort Dome



➔ **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.

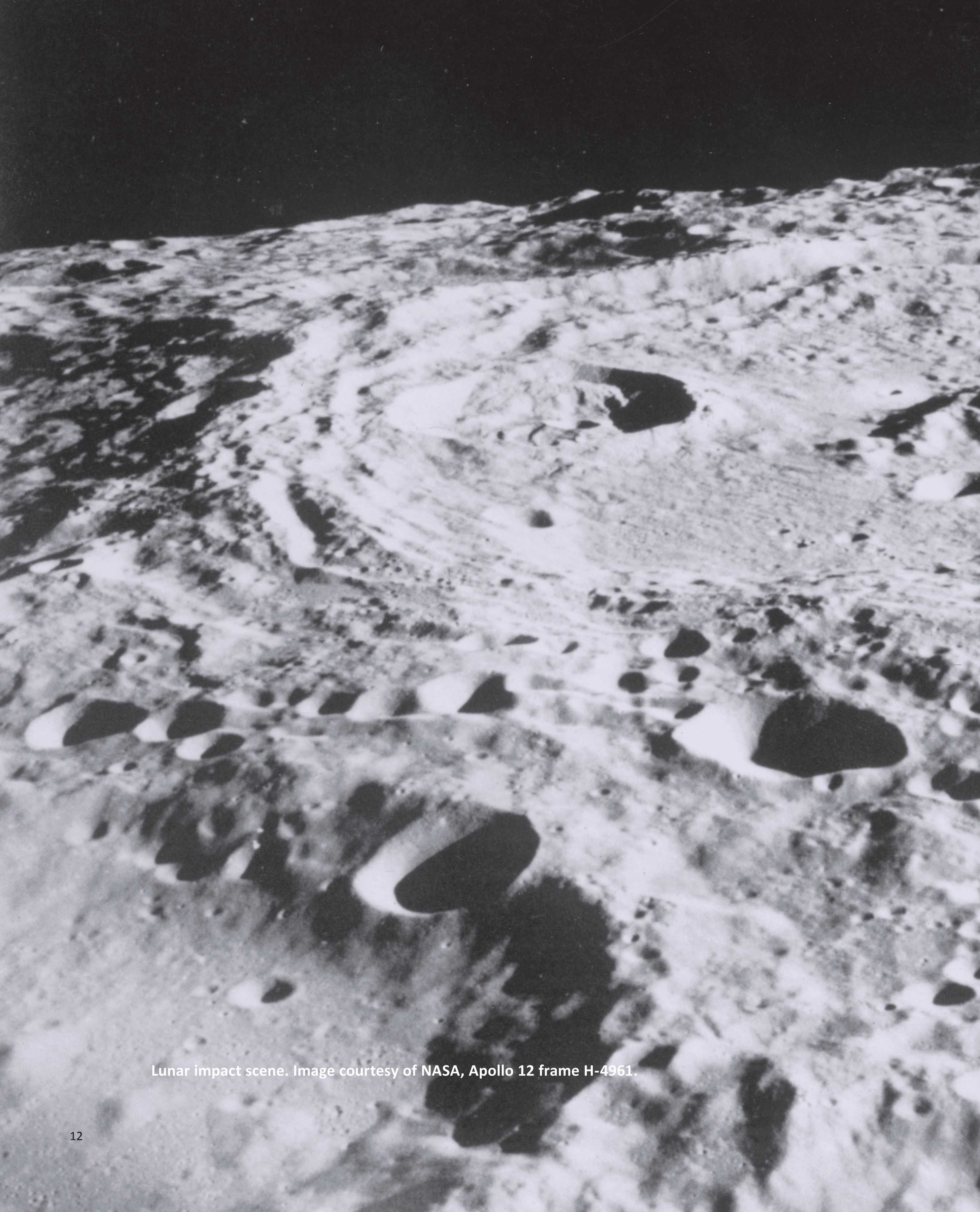
The first edition of *Meteorite Impact!* was published in July 2005 and coincided with the announcement in Durban by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) that the Vredefort Dome was to be listed as South Africa's seventh World Heritage Site. The UNESCO motivation 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

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.

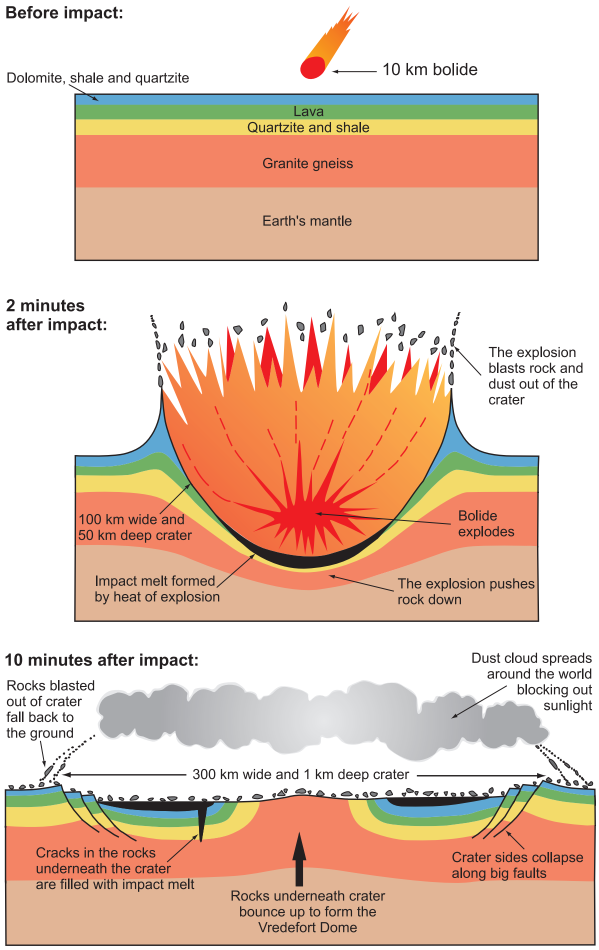
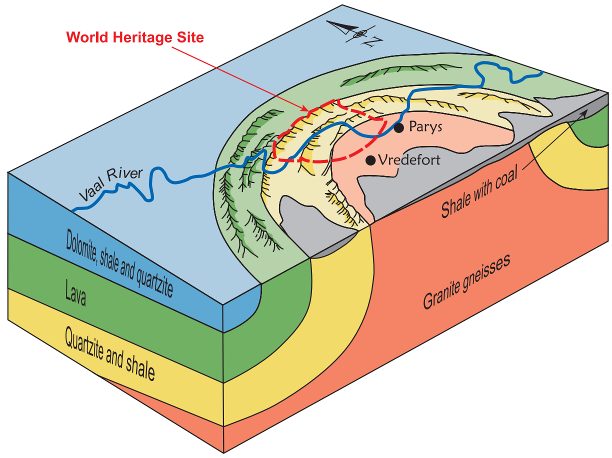


Figure 3a–c: A giant impact event 2 020 million years ago formed the Vredefort Dome.
← **a.** Cross-sections through the Earth's crust, showing how the Vredefort impact crater, with the Vredefort Dome at its centre, formed.
↓ **b.** Cutaway diagram of the Vredefort Dome today, showing how erosion of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

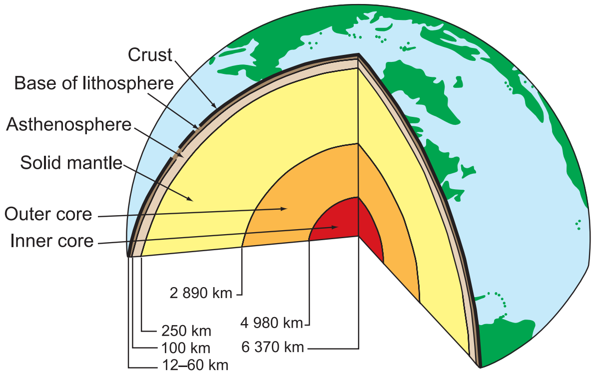
It has also become clear that long-term climatic change is a natural phenomenon. The Earth as a whole was significantly warmer during the Cretaceous period than it is today, and the planet has experienced quite a number of Ice Ages in the last couple of million years alone. By the latter part of the 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.

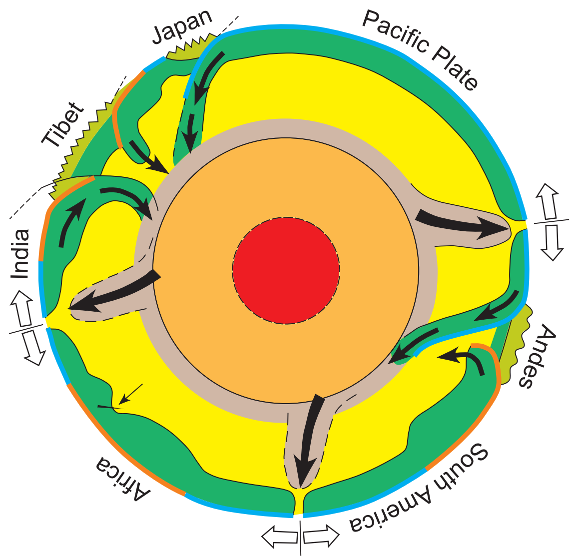
The Structure of Earth

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

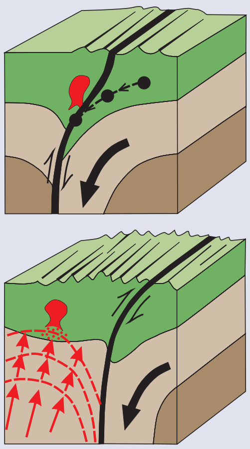
Individual plates are constantly 'on the move'. This slow movement of plates is a result of convection within the mantle of the Earth, driven by heat loss. As new crust is formed at some plate boundaries, crust is colliding at other plate boundaries, with some sinking back into the mantle to maintain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

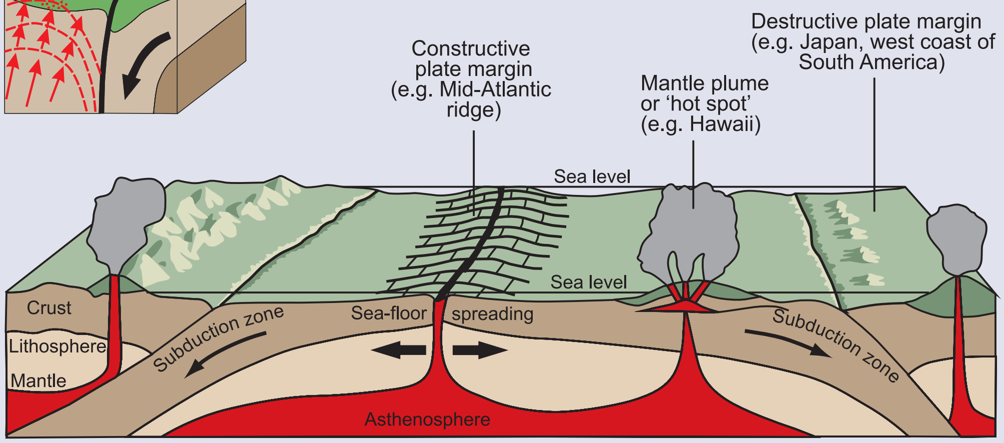
Plates are also shuffled obliquely past one another. These transverse movements lead to build-up of enormous stress in the lithosphere causing ruptures and earthquakes. An example of such grinding action between two plates is the well-known San Andreas Fault Zone in California (Fig. 37, page 55), a zone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

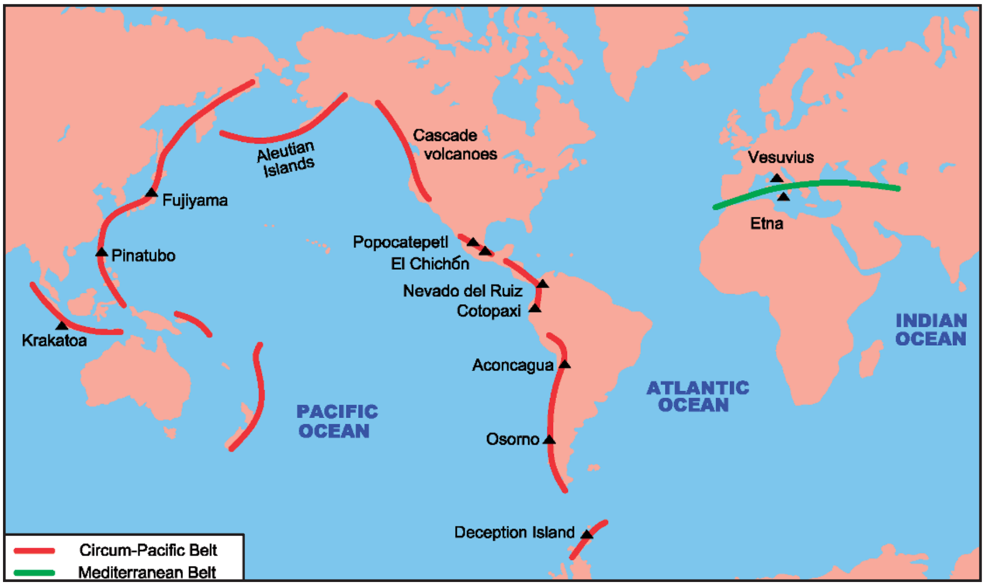
The second, often catastrophic, effect caused by plate tectonics is volcanism. This process allows heat to be lost from the interior of our planet. Volcanism occurs at mid-oceanic ridges, or at zones where plates converge on each other, when the subducting plate starts to heat up as it plunges to greater 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.

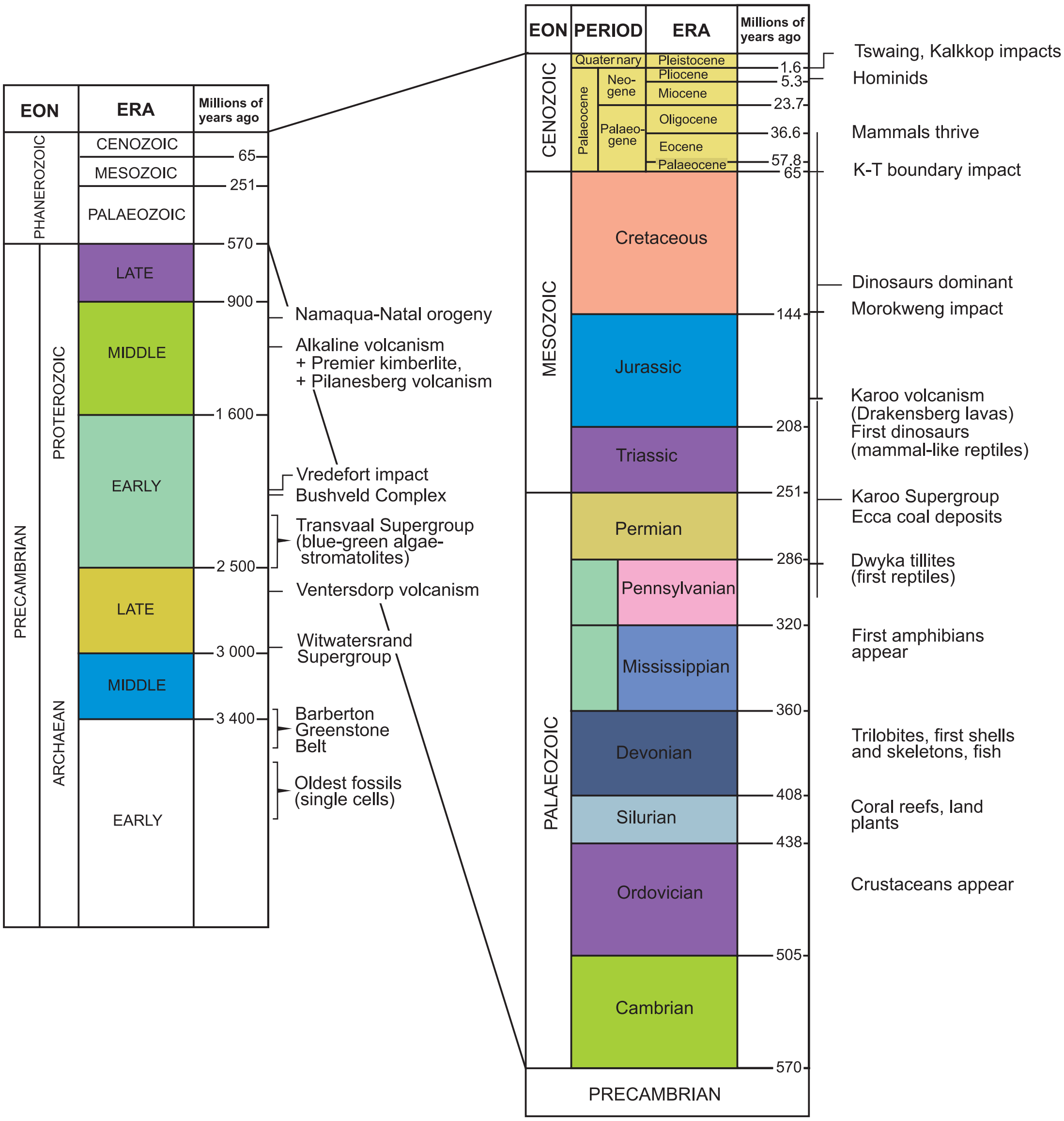
↓ **Figure 7:** The volcanic and earthquake regions of the World — the so-called 'Ring of Fire'. Active volcanoes and earthquake 'hot spots' are concentrated in a belt around the Pacific Ocean. A second belt that is frequently hit by volcanic and earthquake catastrophes is the Mediterranean belt, from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

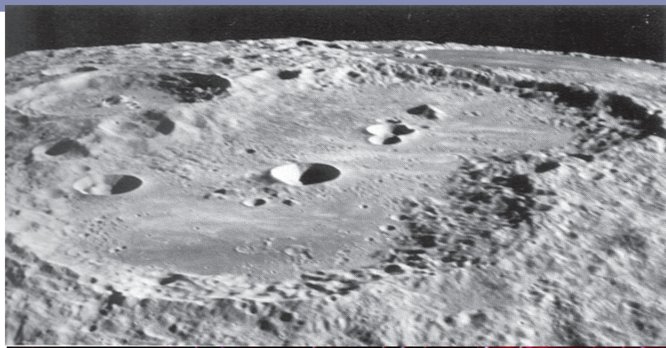
↓ **Figure 8:** Geological time scale, marking the most important geological time divisions and some important events in the geological history of southern Africa. The Tertiary period has been renamed the Palaeogene; however, the term 'K–T boundary' persists.



Man on the Moon

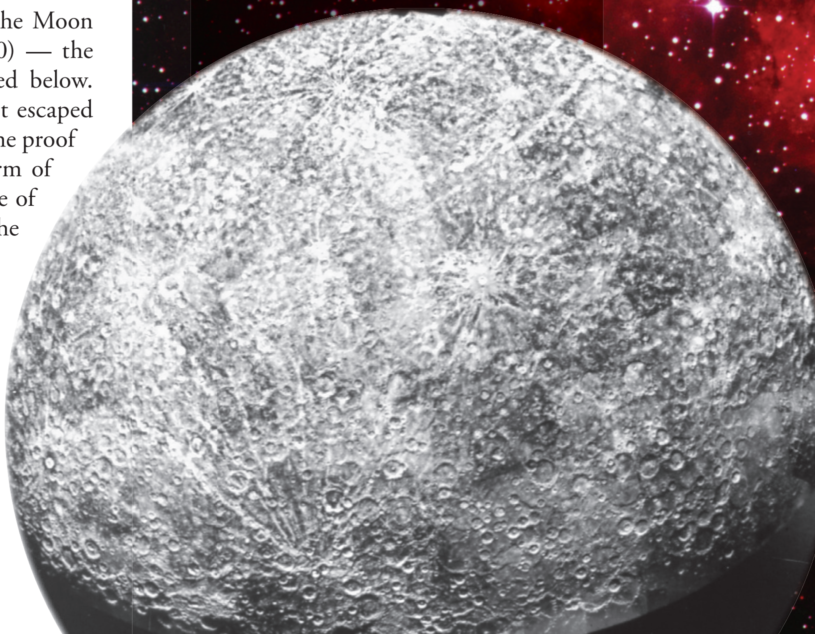
In the late 1960s, just as plate tectonics became firmly established in geological theory, humankind reached out beyond our planet, to the Moon. Craters on the Moon had been known since the first telescopes had been developed in the 16th Century. Galileo Galilei built his first telescope in 1609, and 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.

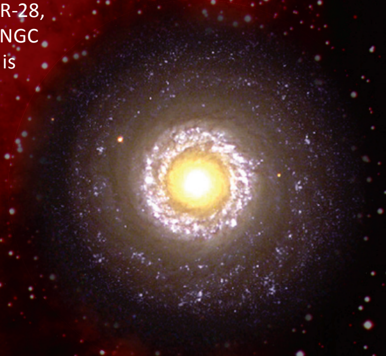
Impact cratering is now known as one of the fundamental processes taking place in the Solar System. Forty years of research have indicated that it has, without doubt,



↑ **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.

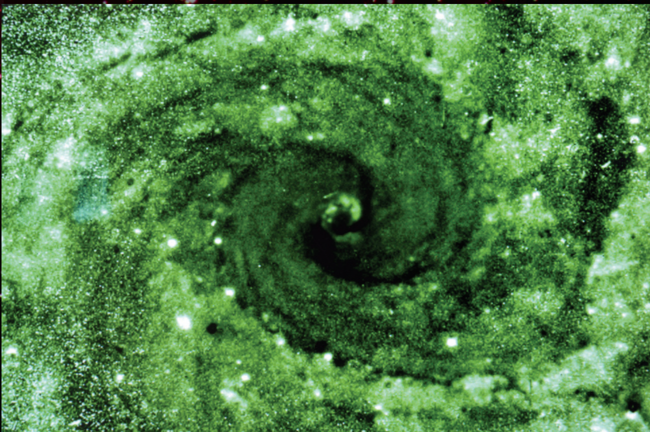




→ **Figure 11a:** NASA's Hubble space-telescope image (STScI-PR-28, October 1998) of Galaxy NGC 7742 — a spiral galaxy. It is thought that the 'lumpy, thick' ring around the core of the galaxy is an area of active star birth. The distance between the ring and the bright core is about 3 000 light years.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

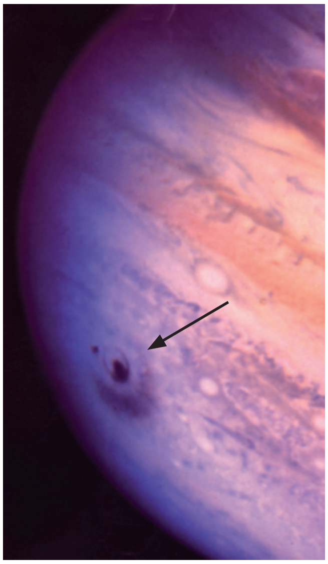
← **Figure 11b:** The Rosette Nebula in our Milky Way Galaxy, photographed from the European Southern Observatory in Chile. Photograph courtesy of David L. Block, University of the Witwatersrand, Johannesburg.

↓ **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.



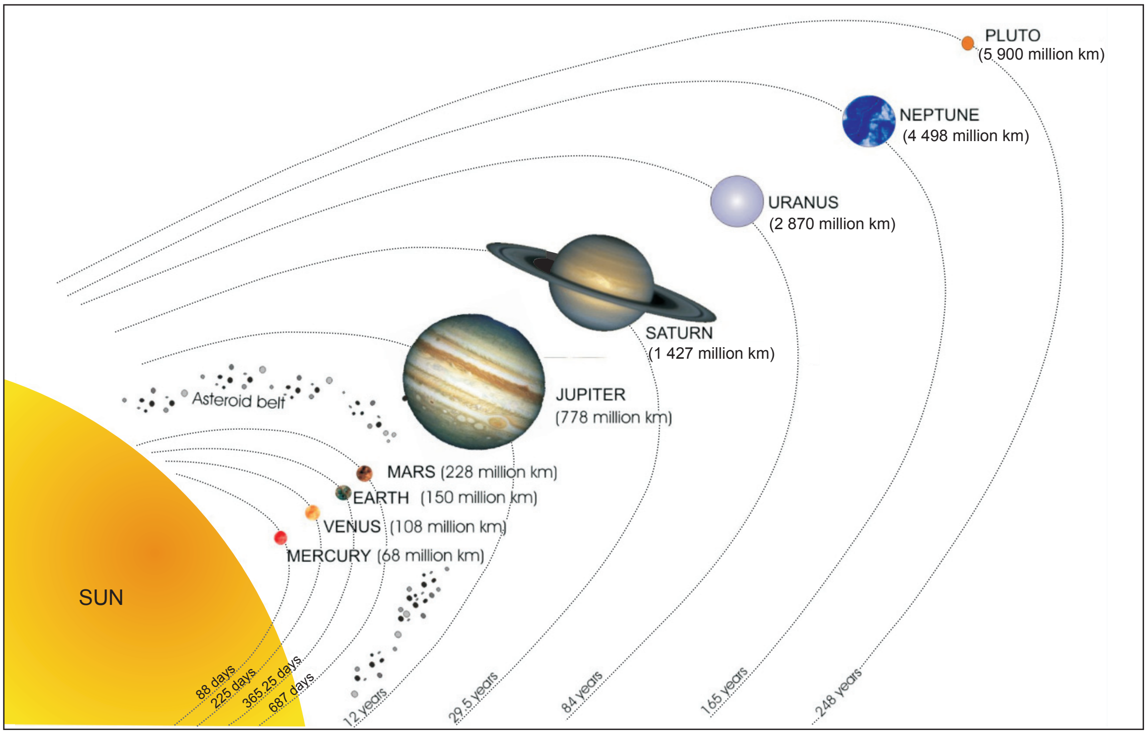
played a major role in the evolution of planet Earth and life on it. One can only speculate on what our species would be like if not for some major impacts that caused massive extinctions and terminated periods dominated by certain species, initiating proliferation of new ones. It is now clear that uniformitarianism 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

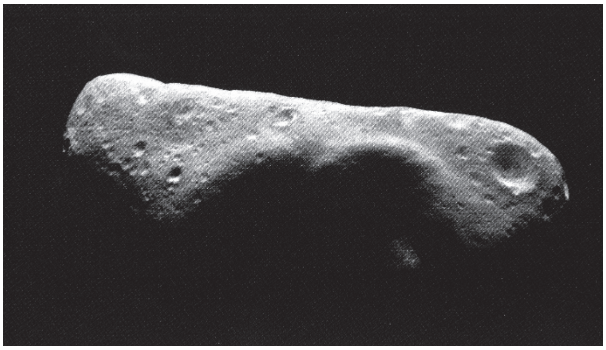
The arrangement of the Sun and the planets in our Solar System (Fig. 14) is similar to a giant rotating disk, with the Sun situated in the centre. All the planets move in the same direction around the Sun, and they lie in approximately the same plane. Most planets also spin on their own axes. There are 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).

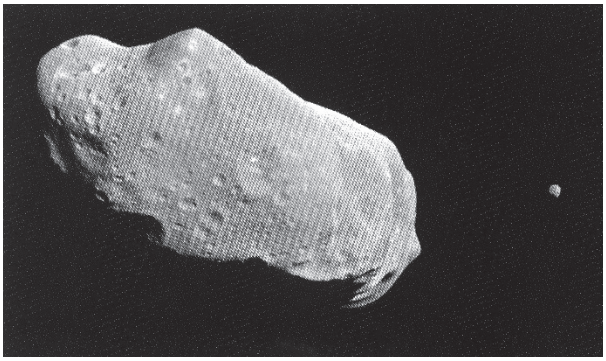
In addition to the planets and Pluto, there are countless so-called asteroids (Fig. 15) in the Solar System. The largest known asteroid is 1 Ceres, of 933 km diameter. Four thousand asteroids have been named to date, but it is estimated that tens of thousands of them exist, with most much smaller than 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.

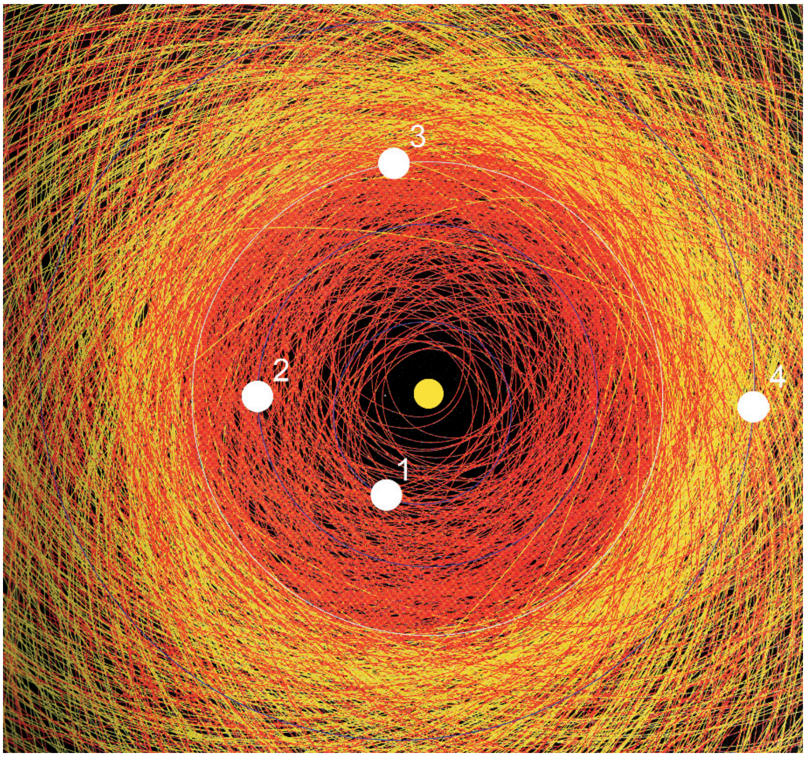
In addition, the Solar System is traversed by comets (Figs 17 and 18), comprising masses of loosely bound frozen water, ammonia, methane, carbon dioxide, and rock fragments and dust. Cores of comets may be up to 40 km in size. These bodies originate from beyond the orbit of Pluto, a vast region known 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.

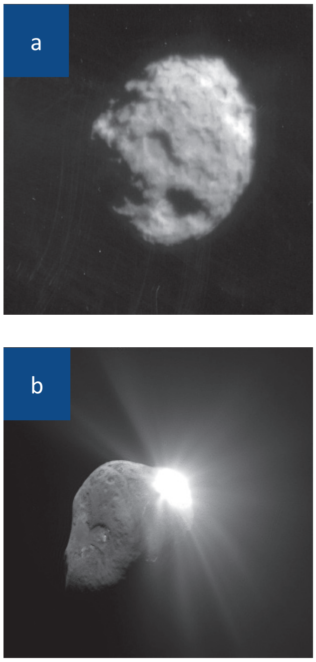




↑ **Figure 15b:** At 58 by 23 km, asteroid Ida is somewhat larger than Eros. Visible at right is Dactyl, Ida's own little moon, which is thought to represent a fragment that was blown out of Ida in an impact event, but failed to escape Ida's weak gravitational field. Image courtesy of NASA.



↑ **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 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.

• **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.

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