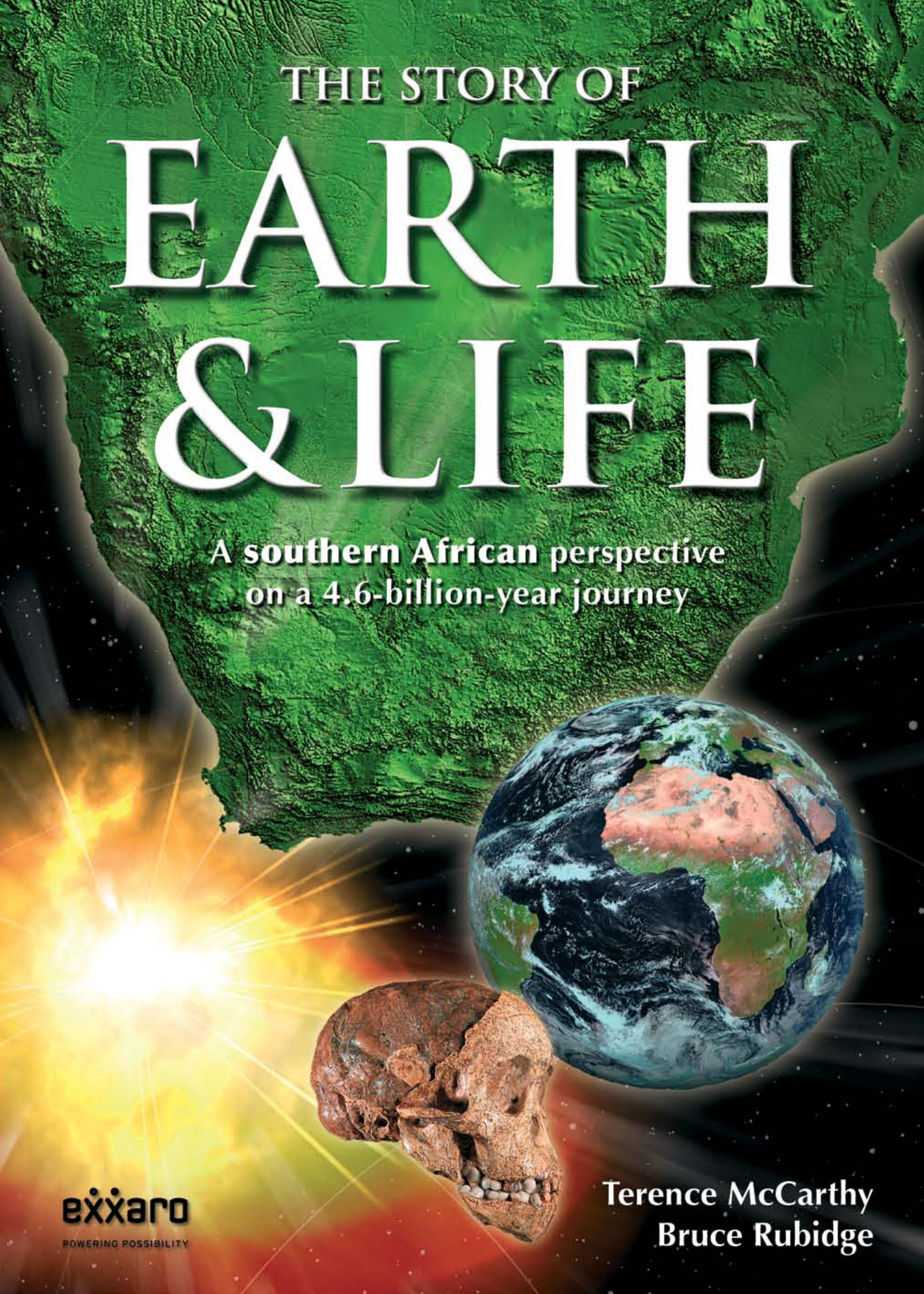

THE STORY OF EARTH & LIFE

A **southern African** perspective
on a 4.6-billion-year journey

Terence McCarthy
Bruce Rubidge

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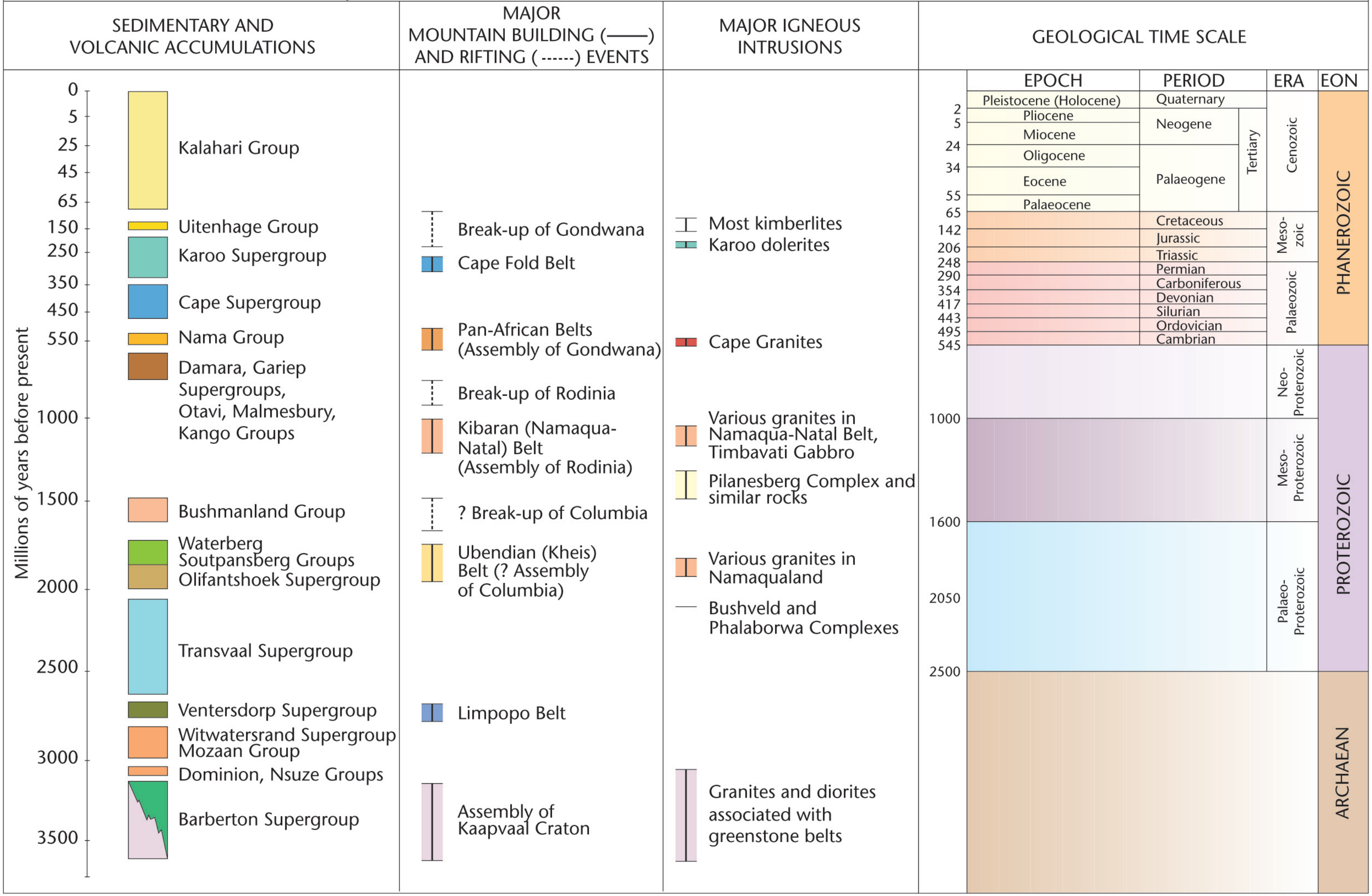
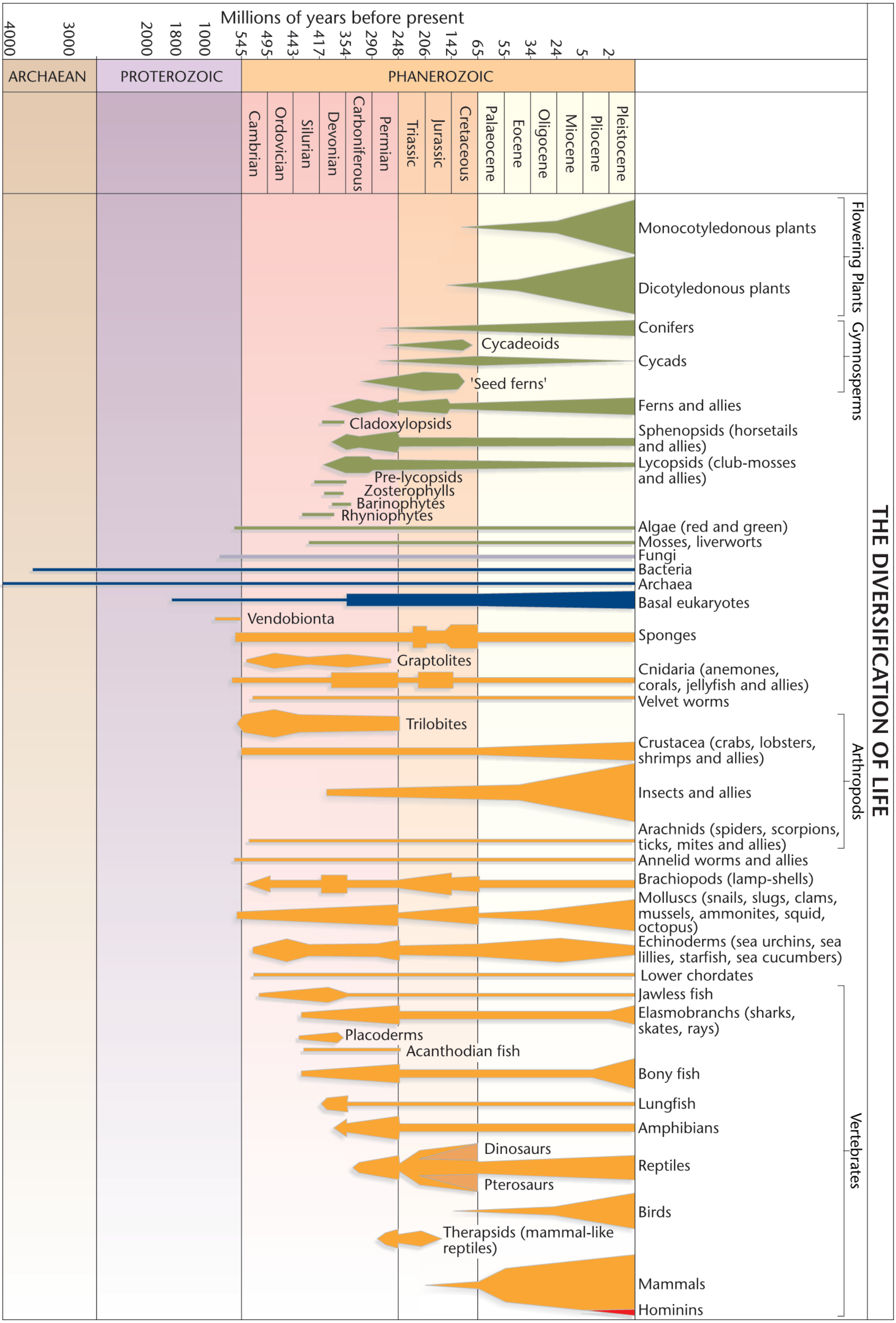
POWERING POSSIBILITY

MAJOR EVENTS IN THE GEOLOGICAL HISTORY OF SOUTHERN AFRICA





THE DIVERSIFICATION OF LIFE

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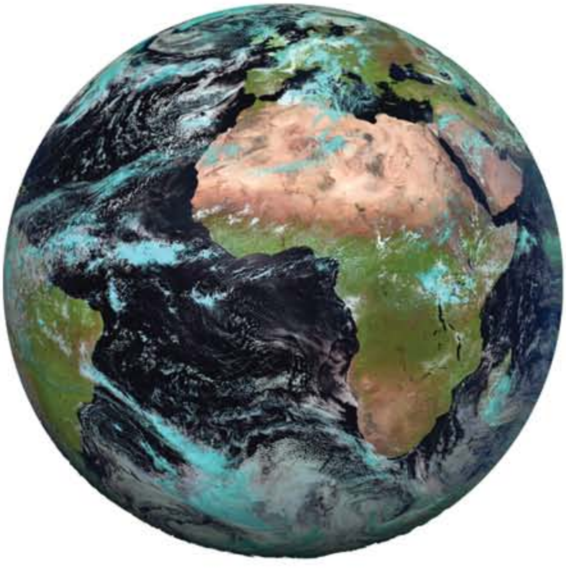

Terence McCarthy
Bruce Rubidge

POWERING POSSIBILITY

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Sponsor's Foreword

Although the mineral wealth of southern Africa has been exploited to some degree for well over 1 000 years, the transformation of the subcontinent from an agrarian to an increasingly industrialised economy was triggered by the discovery of diamonds along the Orange River in the 1860s. This was followed during the succeeding decades by the discoveries of gold in Limpopo, Mpumalanga and Zimbabwe, and then, in 1886, by what was to become the world's richest gold repository, the Witwatersrand. Next came the delineation of some of the world's largest deposits of platinum, chrome, manganese, iron ore, uranium, coal, titanium, vanadium and fluorspar, creating the platform for a burgeoning mining sector that would underpin southern Africa's industrialisation throughout the last century.

This astonishing concentration of mineral resources, unequalled by any other region in the world, is the result of a unique combination of diverse geological environments, an immense history of geological stability and generally excellent exposure. As if this were not sufficient, the region also hosts a strikingly comprehensive palaeontological record – from among the oldest multicellular organisms yet identified, to the remains of some of our earliest ancestors at the Cradle of Humankind, a World Heritage Site.

Given this legacy of enormous mineral wealth, great geological diversity and an extensive evolutionary record, it is surprising that, until now, there has not been a publication that could offer both the interested lay reader and the entry-level tertiary student a concise, yet comprehensive, accurate, topical and readable account of our geological and palaeontological past.

This book aims to address this shortcoming: in clear language, accompanied by lavish illustrations, innovative vignettes and chronological 'route maps', it introduces the reader to the processes and events that led to the fascinating accumulation of strata that lie beneath our feet and to which we owe the rich diversity of our natural environment.

Kumba Resources (now Exxaro Resources) is a leading South African-domiciled company that has been involved in the extraction and beneficiation of various minerals for almost 80 years. At the same time, we are committed both to the protection of the fragile environment in which we live, as well as to the education of our fellow citizens about our business and the context in which it operates.

It is therefore with great pleasure that we have had the privilege of becoming associated with the highly esteemed group of contributors and editors responsible for the publication of this much-needed volume. We hope that this book will be widely read and that it will become an essential reference text in the libraries of businesses, colleges, schools and homes across the country.

Con Fauconnier

Con Fauconnier
Chief Executive,
Kumba Resources Limited (now Exxaro Resources Limited)
(and President of the Chamber of Mines of South Africa, 2004/2005)

exxaro
POWERING POSSIBILITY

Preface

Southern Africa is a mineral-producing region of global importance and has been so for more than a century. It has a record of life preserved in its fossils that is more extensive than any other region in the world, a record that preserves not only the evolution of plants and animals, but humans too.

There is a growing awareness of the natural environment and in order to understand the landscape and ecosystems, a good grasp of local geology and geological history is essential because the basis of ecosystems is ultimately geological. Yet, ironically, information on the geological formations that host the region's mineral and fossil wealth, the story of life that the fossils tell, and the geological history of southern Africa are largely stashed away in technical publications that are accessible only to the specialist. With this book we hope to rectify this situation and share with non-specialists the exciting story of how southern Africa, and to some extent the world, came to be the way it is – how its mineral deposits formed, how its life evolved, and how the landscape of southern Africa was shaped.

Writing a book such as this requires a team effort, and we would like to express our appreciation to all of our contributing authors for their enthusiasm in the project, their on-time delivery and their good grace in the face of editorial reworking of their material. We would also like to thank our many colleagues who willingly provided illustrative material, as well as Robin Cox, Stanley Duncan, Andrew Terhorst, Philip Frost, Neil McKenna, Hein Pienaar, Glen McGavigan, Lew Ashwal and Marina Rubidge for assistance in sourcing images.

The subject matter of the book is extremely wide ranging, and as far as possible we wished to ensure that the content is accurate, or at least as accurate as such a work can be, given the divergent opinions that often exist in the earth sciences. We also wanted to ensure accessibility of the writing and clarity in the general approach to this vast subject. Many colleagues and associates assisted towards these ends: we thank Fernando Abdala, Carl Anhaeusser, John Begg, Bob Brain, Grant Cawthorn, Fred Daniel, Mike and Maarten De Wit, Doug Erwin, Nok Frick, Rob Gess, Roger Gibson, James Hersov, Judith Kinnaird, Pieter Kotze, Rodrigo Lacruz, Judy Maguire, Erna McCarthy, Jennifer Oppenheimer, Rose Prevec, Mike Raath, Uwe Reimold, Chris Sidor, Peter Tyson, Rob Veal, Richard Viljoen, Lyn Wadley, Lilith Wynne and Adam Yates. We nevertheless accept full responsibility for errors or omissions in the text and illustrations.

On the production end, we thank Pippa Parker (publishing manager), Robin Cox (designer) and especially Roxanne Reid for her editorial skills; Lynda Whitfield and Diane du Toit for the pioneering illustrative material, and Rose Prévec and Colin Bleach for the finished product. Henia Czekanowska undertook specialist photography for the book and Jacqui Thobois provided invaluable secretarial support.

Finally, we thank Kumba Resources, especially Richard Wadley and Trevor Arran, for supporting our book financially, thereby subsidising the price and increasing its accessibility.

Terence McCarthy

Terence McCarthy

Bruce

Bruce Rubidge

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Tugela Falls, Royal Natal National Park, KwaZulu-Natal.

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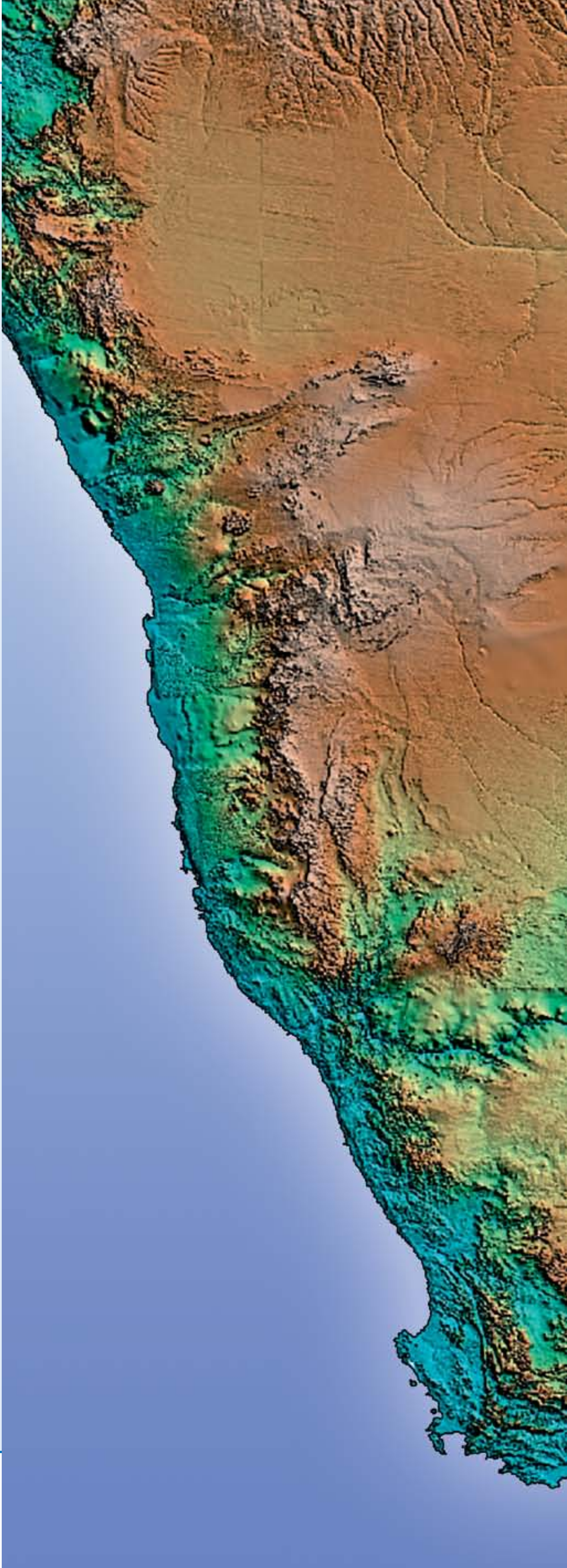
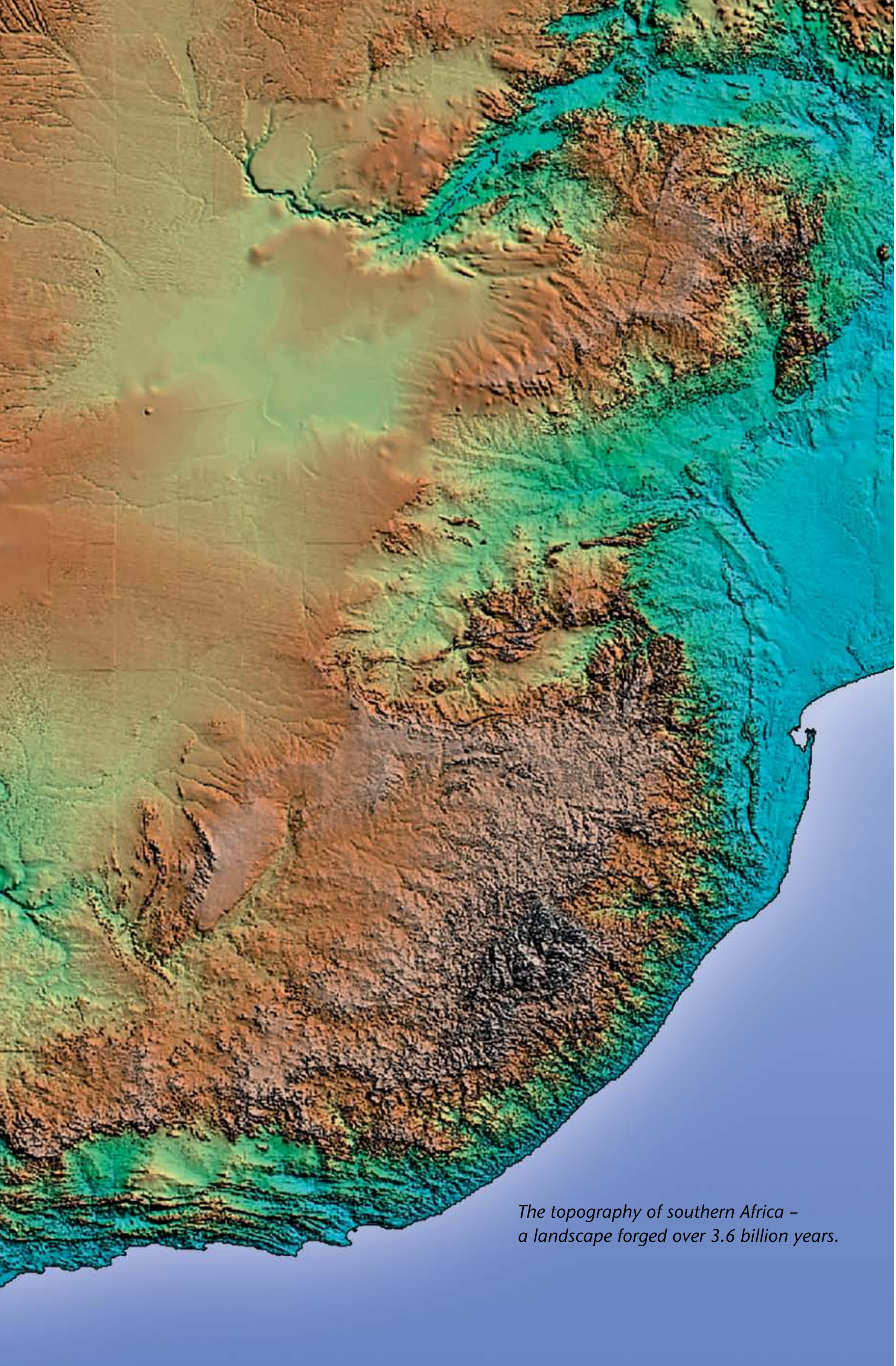
INTRODUCTION



Ian Haddon



The topography of southern Africa –
a landscape forged over 3.6 billion years.

The ability to reason, to understand cause and effect, is a uniquely human trait. Evidence for its beginnings extends back more than one and a half million years in the form of carefully selected digging tools found in cave deposits containing hominin (human ancestors) remains, such as at Sterkfontein and adjacent sites in Gauteng. Slightly younger deposits contain primitive stone tools.

In later deposits dating from just over a million years ago, we see evidence of the ability to design and manufacture tools to order, in the form of uniform, beautifully fashioned, symmetrical hand axes of the Acheulian period (**figure 1.1**). Whether these ancient tool makers possessed a true culture is not known, and the earliest evidence of what might be called culture – the use of decorative symbolism and of ochre paint (**figure 1.2**) and shell beads – comes from deposits in Blombos cave in the Western Cape, which are about 70 000 years old.

By about 40 000 years ago, these cultural practices had become commonplace and sophisticated both in Africa and Europe. They included elaborate paintings on cave walls, the use of decorative jewellery and even musical instruments. Many of the cave paintings created by these people are shamanistic (spiritualistic) and indicate that human thought extended well beyond the simple needs of daily living; the human mind had begun to probe spiritual questions. It is likely that these people had developed some form of mythology, perhaps seeking explanations for common events such as the rising and setting of the Sun and Moon, the passing of the seasons, and even of death. Probably later, deeper questions related to the origin of the world began to be probed. We have no idea when these appeared, but all cultures possess some form of creation mythology, usually intimately intertwined with religious beliefs.

In Judaeo-Christian philosophy, the Creation is specifically described in the opening chapter of the Book of Genesis. So specific is this description and the subsequent narrative that in 1654 the Bishop of Armagh, James Ussher, was able to use the biblical lineages to calculate the date and time of the Creation: 09h00 on 23 October, 4004 BC.

Understanding of the world throughout the Dark Ages was based on a combination of the Bible and the writings of Greek natural philosophers and astronomers, especially Ptolemy and Aristotle. The Renaissance brought with it not only a revival of art and literature, but a more enquiring approach to the natural world, initially in the area of astronomy, and later in physics and chemistry. Serious geological enquiry that addressed the question of Earth history, however, only arose in the late 1700s.


Kathy Kuman

Figure 1.1 *Examples of hand axes from the Acheulian period illustrate an ability to produce a standardised tool form of varying size and from different types of rock. These tools may be more than 500 000 years old.*

PROBING EARTH'S HISTORY

While matters related to the origin of the Earth fell into the realm of religious mythology, the more practical aspects of rocks and minerals received considerable attention. Stone was used since the earliest times, initially for tool manufacture and later for building. Minerals were mined and processed to extract metals such as iron, copper, lead, tin, silver and gold. Practical knowledge about mining and metallurgy was passed from generation to generation, and much of this accumulated knowledge was recorded in a famous book, *De Re Metallica* by Georg Agricola, published in 1556. Fossils, which are common in rocks over large parts of Europe, attracted considerable attention and were the subject of speculation since the earliest times. Greek and Roman scholars such as Pythagoras, Herodotus, Aristotle, Theophrastus, Strabo and Pliny developed ideas on their origins and their implications: they attributed the occurrence of fossil marine shells and fish at high altitude to alternate depression and uplift of the land.

Following the Dark Ages, writings again began to appear on geological topics. Fossils attracted the attention of theologians in particular, as they were considered to provide proof of the biblical flood. The rocks hosting fossils also began to attract attention, and their regularity was noticed – so much so that in 1684 Martin Lister proposed the concept of a geological map.

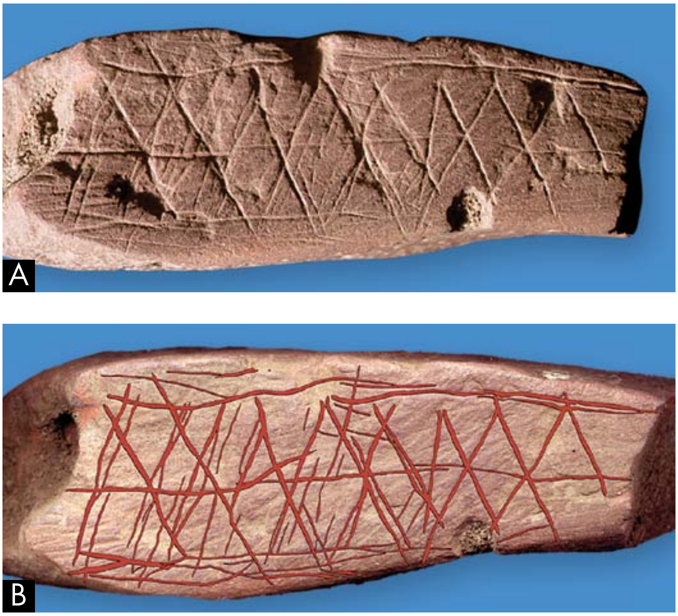
During the 1700s, the study of rocks and fossils began to grow in popularity among gentleman scientists. The French made important contributions. In his 1749 book on natural history, Georges Louis Buffon proposed that the Earth was of great antiquity and that its surface had experienced slow and gradual changes, but he was severely censured at the Sorbonne and the Faculty of Theology in Paris, and forced to withdraw his views. The study of rocks continued unabated, and in 1751 Jean Etienne Guettard published possibly the earliest geological map, showing the distributions of minerals and rocks in France. The term geology was coined in 1778 by JA de Luc.

In Germany, AG Werner, Professor of Mining at Freiburg, recognised the ordering of strata and the fact that rock strata could be characterised by the fossils they contained. His ideas were published in 1796. Similar observations were made in the United Kingdom by William Smith, whose geological maps began to make their appearance in the 1790s. Smith went further to produce the first geological column for the United Kingdom, which characterised and described the sequences of rocks and their fossils. His great work, a geological map of England, Wales and parts of Scotland, was published in 1815.

Meanwhile, in 1785, James Hutton published his extremely influential work *A Theory of the Earth*, which became a milestone in geological thought. Hutton argued that sediment accumulation that we can see taking place today, such as on mud flats and at river mouths, is very slow. Great thicknesses of sedimentary layers had been mapped by Hutton, Smith and others, and Hutton argued that these deposits must have taken immense periods of time to accumulate. The implication was that the Earth is very much older than suggested by the Old Testament. These arguments were expanded by Charles Lyell in his three-volume treatise *Principles of Geology* (1833).

Jean Baptiste Lamarck, a French biologist regared as the father of invertebrate palaeontology, rekindled the ideas of Buffon regarding the great antiquity of the Earth in a series of books published between 1801 and 1822. From his knowledge of the changing fossil forms in successive rock layers, he developed the notion of the evolution of life. His idea was that life forms evolved as a consequence of changing environmental factors and that characteristics or adaptations acquired by an organism during life could be inherited by succeeding generations.

Charles Darwin and Alfred Wallace, who were both keen naturalists with an interest in geology, also made the connection between changing fossil forms, the probable immense time involved, and



Chris Henshilwood

Figure 1.2 *Engraved red ochre from Blombos cave on the southern Cape coast. The specimen is 77 000 years old, and provides the earliest evidence of cognitive abilities central to modern human behaviour.* **A** *shows the clay tablet as it appears to the camera, while* **B** *emphasises the red ochre scratches.*

South Africa’s mineral reserves and production in a global context

Reserves are minerals or metals known to exist but not yet mined; **production** is the actual amount extracted annually. Percentages refer to South Africa’s share of the world’s reserves or production. The units are: t = tonnes; mt = million tonnes; bt = billion tonnes; mc = million carats. PGM denotes Platinum Group Metals (platinum, palladium, ruthenium, rhodium, osmium and iridium). The value of mineral production in 2001 was approximately R100 billion (b = billion; m = million).

Commodity	Reserves		World Rank	Production		World Rank	Rand Value
	%	Units		%	Units		
Manganese	80	4 bt	1	20	3.6 mt	1	3 b
Chrome	76	5.5 bt	1	45	6.6 bt	1	7 b
PGM	56	63 000 t	1	46	207 t	1	25 b
Gold	52	40 000 t	1	17	428 t	1	30 b
Vanadium	44	12 mt	1	57	18 000 t	1	780 m
Vermiculite	40	80 mt	2	45	210 000 t	1	132 m
Refractories				36	183 000 t	1	118 m
Zirconium	22	14 mt	2	28	0.25 mt	2	7 m
Titanium	20	146 mt	2	23	1 mt	2	600 m
Fluorspar	10	36 mt	3	5	213 000 t	3	1 000 m
Diamonds					11 mc	5	
Uranium	9	0.2 bt	4	2	860 t	9	215 m
Nickel	8	12 mt	6	3	37 000 t	9	2 b
Antimony	6	8 mt	4	3	3 700 t	4	29 m
Phosphate	7	2.5 bt	3	2	2.8 mt	9	900 m
Copper	2	13 mt	14	1	0.14 mt	13	1.6 b
Zinc	3	15 mt	5	1	63 000 t	18	310 m
Lead	2	3 mt	5	2	75 000 t	9	109 m
Iron	1	1.5 bt	9	4	34 mt	8	3 b
Coal	11	55 bt	5	6	224 mt	6	20 b

the diversity of life we see on the planet today, and simultaneously proposed their Theory of Evolution in 1858. They differed from Lamarck in that they noted there is always a range of characteristics (e.g. shorter or taller stature) within any individual species, and that environmental pressures can favour particular variants over others, allowing some variants to breed more successfully and therefore drive evolutionary change – a process Darwin termed natural selection.

Thus, in a brief period spanning the late 18th and early 19th centuries, the foundations of our present understanding of the Earth and its life were laid.

HOW CAN WE KNOW THE PAST?

We are a unique species. We possess the ability to manipulate natural materials to suit our purposes. We are capable of abstract thought and can communicate these thoughts to others. We can work in teams, executing complex plans. We can pass accumulated knowledge from one generation to the next. We alone among species can pose fundamental questions, including questions about our own origins and the origins of the world around us.

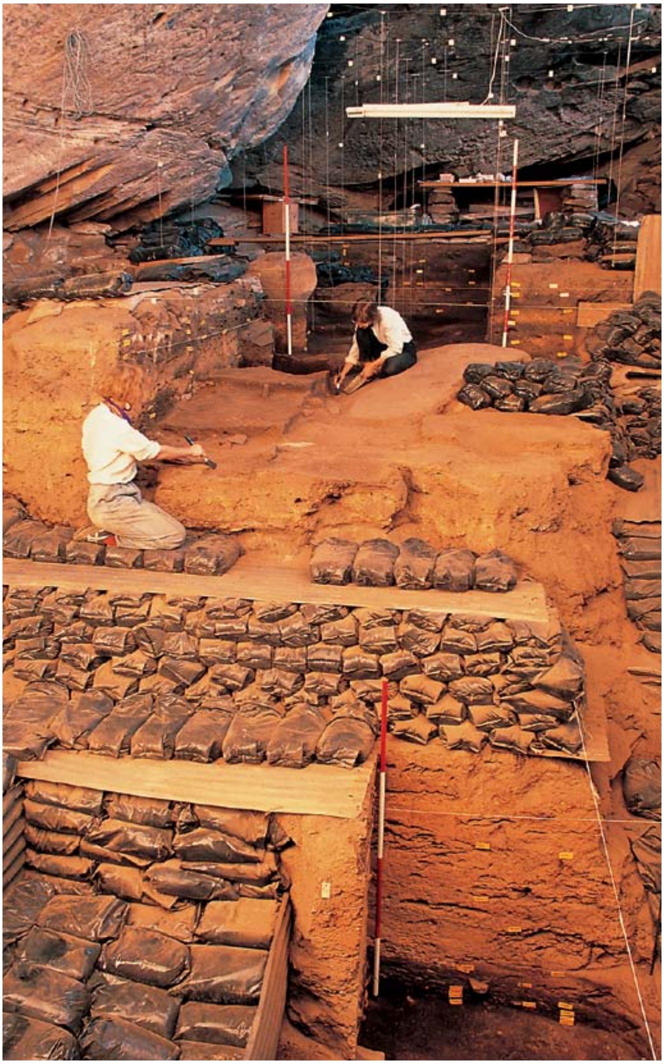
But posing such questions is one thing; providing the answers is quite another. How can we see back into the past, to a time before written records, before our species walked on this planet, or perhaps even to the time when our planet was born? There are some who turn to religious texts for answers, but there are others, scientists, who seek answers in the world around them, using the considerable mental abilities with which our species is endowed.

We are all familiar with archaeological methods, at least in general terms. Archaeologists dig at a site and recover artefacts (**figure 1.3**). These artefacts have an origin – they were made by early people. The deeper the archaeologists dig, the older the artefacts must be. Archaeologists can deduce what an artefact was used for by characteristics such as shape and wear patterns. They can also tell much about the lifestyle of its makers from the context of the artefact – how and where it was positioned in the site and what other artefacts and remains were associated with it. They can even measure its age by dating the object itself, or suitable material associated with it, using the radioactive decay of a kind of carbon atom present in organic matter, carbon 14 (^{14}C).

Archaeological sites are time capsules, having frozen during some event or succession of events in the past. By excavating and studying them archaeologists can reconstruct these past events. They have been very successful in piecing together the history of mankind, especially our more recent history. But as they go further back in time, the record becomes increasingly fragmentary and more difficult to interpret: fragmentary because of subsequent partial destruction by natural agencies such as erosion and decay; and more difficult to interpret because the artefacts become increasingly removed from our own experience.

We now understand that rocks are perfectly analogous to the ancient artefacts excavated by archaeologists. Rocks, too, are time capsules. All rocks are not of the same age, but formed at different times and in different ways. Some rocks, for example, were formed by solidification from the molten state – from lava erupted from volcanoes. Others were formed by accumulation of sediment, such as gravel in a riverbed, sand on a beach, or silt and mud on a river delta. Yet others may have been transformed by heat and pressure during deep burial to produce new kinds of rocks.

From the nature of a rock we can tell how it formed; from its context – the rocks with which it is



Lyn Wadley

Figure 1.3 *An archaeological excavation at Rose Cottage Cave in the Free State, where the deepest layers provide information about the earliest occupants of the cave. The 6 m of cave floor deposits encapsulate a record of 100 000 years of habitation.*

associated – we can deduce the environment in which it formed. In this way we can reconstruct geographic environments and geological events of the past. And in the same way as archaeologists date their artefacts using ^{14}C, geologists can date rocks using not carbon but other radioactive elements.

Rocks are much more common than archaeological sites; they are everywhere beneath our feet. By mapping their distribution and establishing how they formed and in what type of environment, geologists can reconstruct the changing environmental history of a particular region. Every region has had a unique history and each must be individually determined, just as each country has its own, unique social and political history. As we go further back in time, the record becomes increasingly fragmentary, evidence having been obliterated by erosion or later geological events that often overprint the earlier record. Very ancient rocks are therefore extremely rare and difficult to interpret.

Dion Brandt

Terence McCarthy

Figure 1.4 *Rocks deposited in southern Africa in ancient times are remarkably well preserved.* **A** *shows sand and gravel deposited by rivers a few thousand years ago (Rooisloot, Mokopane, Limpopo Province).* **B** *shows sand and gravel deposited 2 900 million years ago (Witwatersrand Supergroup, Gauteng).*

ABOUT THIS BOOK

South Africa is, geologically speaking, a very diverse and in many ways unique place, without equal on the globe. There are several factors that contribute to this uniqueness. South Africa is a treasure house of valuable minerals. Despite occupying only 1% of the Earth's land surface, the country is or once was (before some of the mines were exhausted) the world's largest producer of gold, chromium, diamonds, vanadium, manganese and platinum. It possesses very large reserves and is a world-class producer of iron, titanium, zinc, coal, fluorspar, refractory minerals and phosphorus, and also produces copper and lead. It has been said that hectare for hectare, the northern half of South Africa is the richest piece of real estate on earth. The table on page 12 shows just how spectacular the country's mineral wealth is.

South Africa has a very long geological history, its oldest rocks dating back some 3 600 million years. Rock-forming events extend from this ancient dawn virtually to the present, providing a long, albeit punctuated, geological history. The preservation of these ancient rocks is quite remarkable and many look lit-tle different today from the equivalents formed in very recent times (**figure 1.4**). The rocks record events during many crucial periods in Earth's history.

They also provide insight into globally important changes that took place in the past, such as the changing composition of Earth's atmosphere and the assembly and fragmentation of the supercontinents.

Finally, South Africa's rocks contain a very special and long record of life. The very earliest life forms are preserved as fossils in the rocks; the evolution of land plants and animals, and especially the origin of mammals and dinosaurs, are well preserved (**figure 1.5**). South Africa also has probably the best record of the origin of hominins. Truly an amazing record of Earth and its life.

In this book we will journey through time and examine the unfolding of that remarkable history. Although the logical place to start an historical account is at the beginning, we will begin our story at the end because it is not just an account of consecutive events, of seas that came and went, volcanoes that erupted and then became extinct. We also want to address the questions of how and why these events occurred. In other words, we want to put our geological history in context.

To do this, it is necessary to understand how the Earth works. In the last few decades, earth scientists have made remarkable strides in understanding the Earth, and it is believed that many processes we see operating today have oper-ated since the earliest times. This knowledge has radically improved our understanding of past events, as it provides a context for these events. So our story begins with the modern Earth, and describes how the Earth works. Armed with this knowledge, we will be able to journey back in time to the birth of the Earth.

Readers unfamiliar with geology will be faced with many new concepts and terms, introducing essentially a new discipline that – like all disciplines – has its own special jargon. While we have made every effort to reduce jargon to a minimum, there are essential concepts and terms you need to know to appreciate South Africa's geological history.

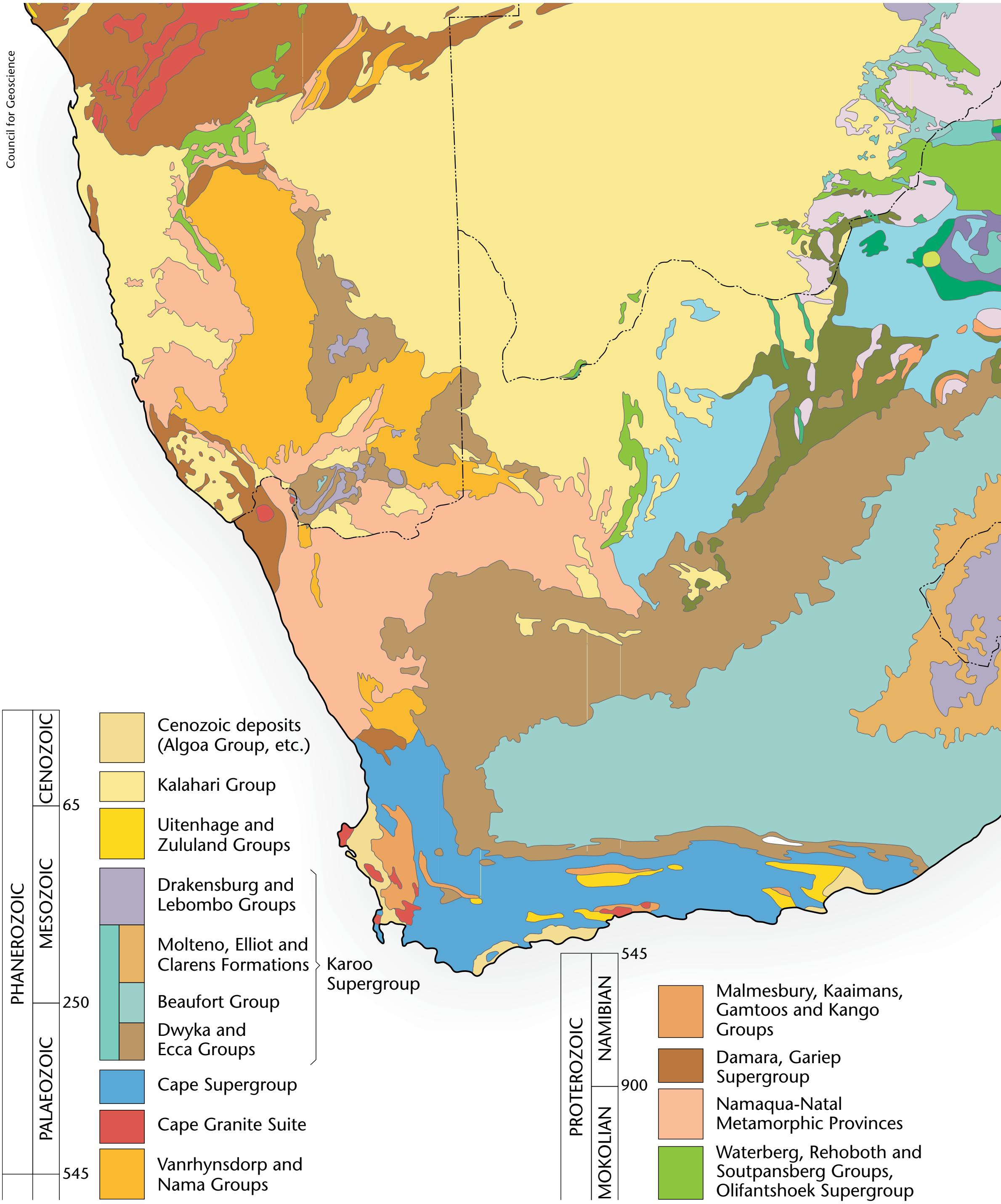
For some, this may have the unfortunate effect of making what is basically a fairly simple story seem quite complicated. If you tend to forget the meanings of terms, it can be a source of immense frustration. Just as a map helps you recall place names when travelling in a foreign country, we have included route maps in our journey through time to help recall the meanings and significance of names and terms used in the text. In addition, we have included a glossary for quick reference to the meaning of these terms (*see* page 318).

We live in a four-dimensional space-time world, and our minds are attuned to certain natural scales in both space and time. Time we measure in seconds, minutes and hours, and we are familiar with scales of seasons and years. As we age, we begin to appreciate time scales of a generation or two. But that is where our experience and familiarity with time ends. In the same way, we measure distance in centimetres, metres and even kilometres. We can gaze on and appreciate mountains many hundreds of metres high. We think of local places in terms of their distance from where we live. But we have no appreciation for really great distances, distances on a global scale. We travel globally, but we express global distances not in terms of kilometres, but in terms of the travel time by jet airliner, because the time is more comprehensible.

Our natural, in-built space-time reference frame is too limited to cope meaningfully with Earth history; time and distances are simply too vast. There is no easy solution to this problem. In their training, earth scientists develop a familiarity with the numbers involved, a familiarity that makes them feel comfortable with very old or very large things. But like everyone else, earth scientists cannot really comprehend the vast time expanses or huge distances in and on

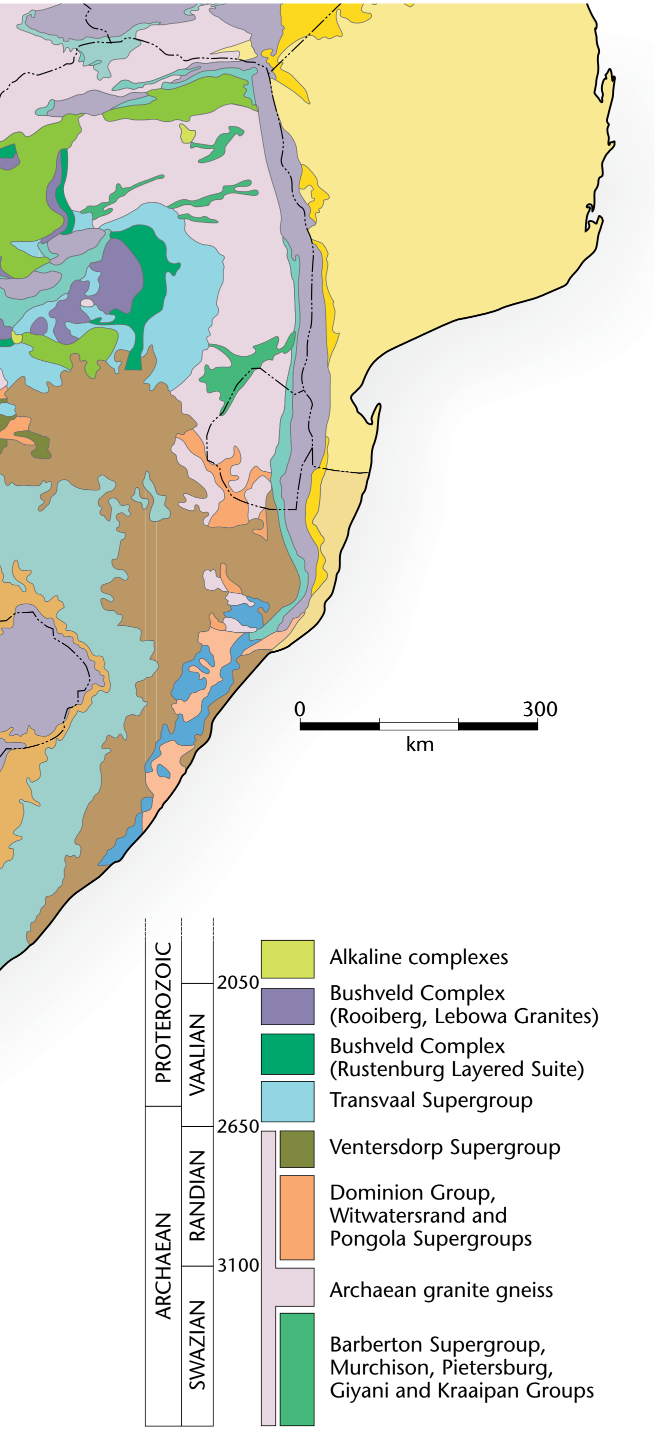
Bruce Rubidge

Figure 1.5 *Well-preserved fossils from southern Africa, such as this skull of a reptile that lived in the Karoo region, provide insight into the origins of dinosaurs and mammals.*



Council for Geoscience

Figure 1.6 *In this geological map of southern Africa each of the colours represents a group of rocks formed during a specific period. These rocks record the geological history of the region, a history recounted in this book.*



Earth. To really appreciate the story told in this book, you too need to develop a feeling for big numbers. Another useful skill is sensitivity to the Earth's three-dimensionality. Like architects, earth scientists operate in a world where the third dimension assumes a far greater importance than is required in everyday life. The ability to visualise a three-dimensional object from a two-dimensional sketch is therefore very useful.

It is inordinately difficult for most people to relate past events described by earth scientists to the world we see around us today. Reason and logic are strained when they describe mountains that were once seas, or seas where there were once mountains. It is hoped that this book will go some way to alleviating this kind of difficulty.

This book is about the rocks of southern Africa, shown in the geological map in **figure 1.6**, and the physiographic map on page 9, as well as the fossils they contain. Rocks are all around us, and they create the scenery we cherish – the Drakensberg, the Waterberg, the Cape mountains, the Karoo. When you gaze on these vistas, what are you seeing? Beautiful scenes to be sure, but there is another dimension to your view. Whether you realise it or not, you are looking back in time. This book is about that other dimension. How did the rocks form? And when? How did they get to be as we see them today? How did the mountains, valleys and rivers we see around us form, and how old are they? What animals and plants lived there in the past?.

Rocks in themselves are uninteresting to most people, and understandably so. But rocks are also time capsules because they encapsulate information about their surroundings when they form and preserve it. They have a story to tell. The story, however, is in code. Earth scientists are breaking the code and are steadily deciphering Earth's history. Study of the rocks of southern Africa has revealed the origins of the region's great mineral wealth. The most ancient rocks tell of a world very different from today, one with a crushing, toxic atmosphere and bacterial slime as its most advanced life. Rocks and their fossils also reveal the story of Earth's slow, at times life-threatening, journey to the present, and how southern Africa came to be the way it is.

THE STORY OF
EARTH & LIFE

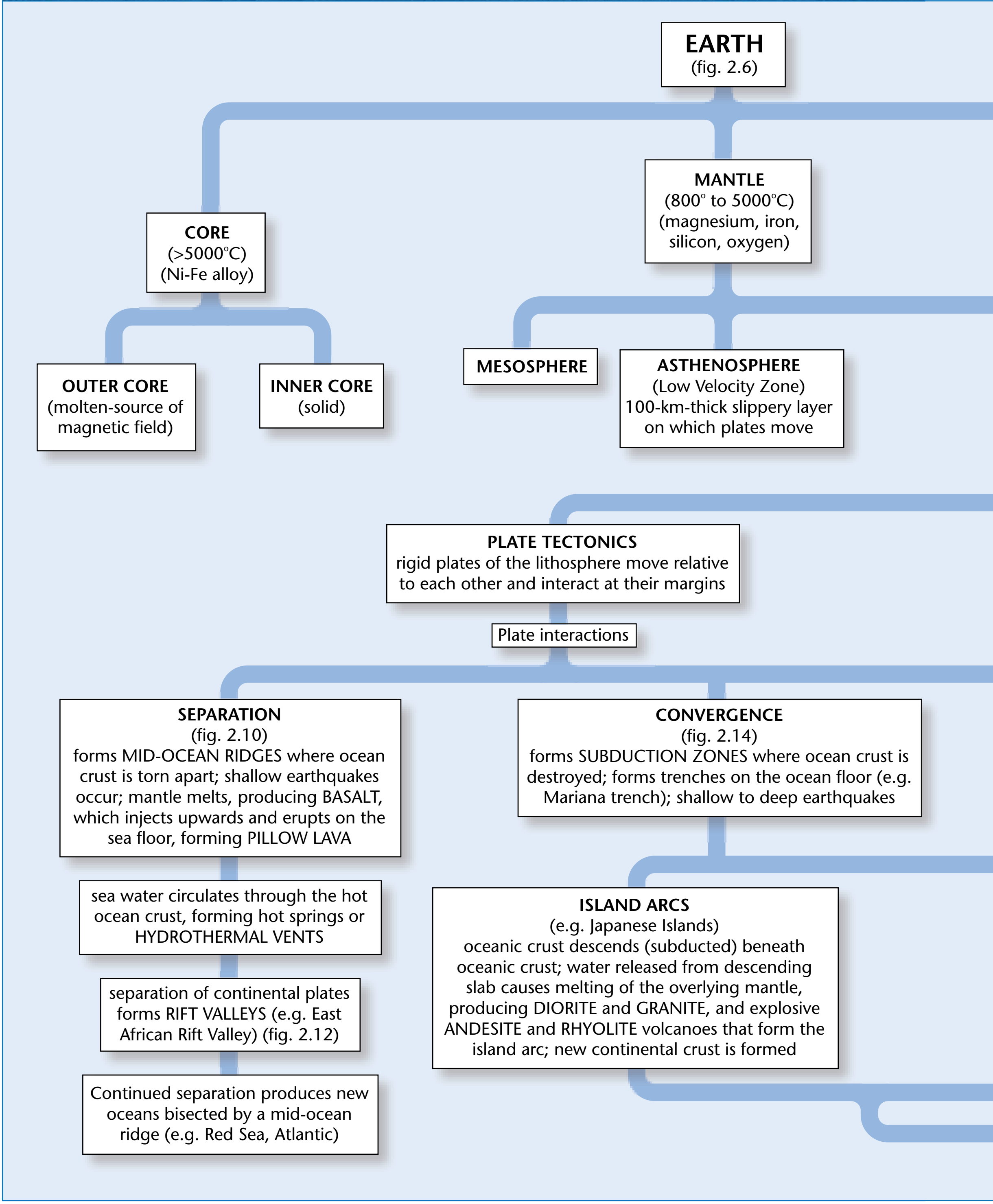
2

HOW THE EARTH WORKS

Lava flowing from the Kitazungurwla volcano in Central Africa during the 1986 eruption.

Judith Kinnaird

ROUTE MAP TO CHAPTER 2



EARTH
(fig. 2.6)

CORE
(>5000°C)
(Ni-Fe alloy)

OUTER CORE
(molten-source of magnetic field)

INNER CORE
(solid)

MANTLE
(800° to 5000°C)
(magnesium, iron, silicon, oxygen)

MESOSPHERE

ASTHENOSPHERE
(Low Velocity Zone)
100-km-thick slippery layer on which plates move

PLATE TECTONICS
rigid plates of the lithosphere move relative to each other and interact at their margins

Plate interactions

SEPARATION
(fig. 2.10)
forms MID-OCEAN RIDGES where ocean crust is torn apart; shallow earthquakes occur; mantle melts, producing BASALT, which injects upwards and erupts on the sea floor, forming PILLOW LAVA

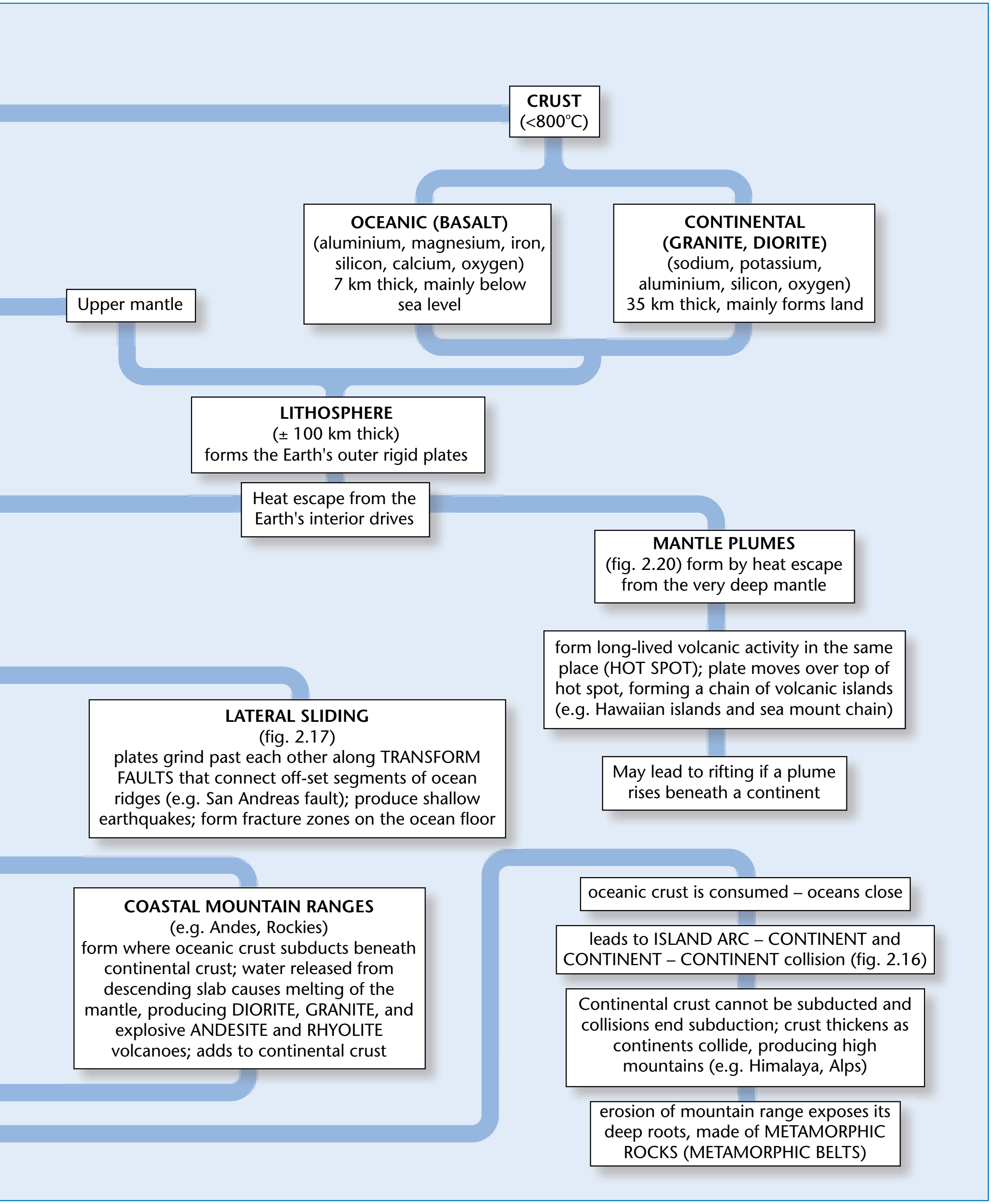
sea water circulates through the hot ocean crust, forming hot springs or HYDROTHERMAL VENTS

separation of continental plates forms RIFT VALLEYS (e.g. East African Rift Valley) (fig. 2.12)

Continued separation produces new oceans bisected by a mid-ocean ridge (e.g. Red Sea, Atlantic)

CONVERGENCE
(fig. 2.14)
forms SUBDUCTION ZONES where ocean crust is destroyed; forms trenches on the ocean floor (e.g. Mariana trench); shallow to deep earthquakes

ISLAND ARCS
(e.g. Japanese Islands)
oceanic crust descends (subducted) beneath oceanic crust; water released from descending slab causes melting of the overlying mantle, producing DIORITE and GRANITE, and explosive ANDESITE and RHYOLITE volcanoes that form the island arc; new continental crust is formed



CRUST
(<800°C)

OCEANIC (BASALT)
(aluminium, magnesium, iron, silicon, calcium, oxygen)
7 km thick, mainly below sea level

CONTINENTAL (GRANITE, DIORITE)
(sodium, potassium, aluminium, silicon, oxygen)
35 km thick, mainly forms land

Upper mantle

LITHOSPHERE
(± 100 km thick)
forms the Earth's outer rigid plates

Heat escape from the Earth's interior drives

MANTLE PLUMES
(fig. 2.20) form by heat escape from the very deep mantle

form long-lived volcanic activity in the same place (HOT SPOT); plate moves over top of hot spot, forming a chain of volcanic islands (e.g. Hawaiian islands and sea mount chain)

May lead to rifting if a plume rises beneath a continent

LATERAL SLIDING
(fig. 2.17)
plates grind past each other along TRANSFORM FAULTS that connect off-set segments of ocean ridges (e.g. San Andreas fault); produce shallow earthquakes; form fracture zones on the ocean floor

COASTAL MOUNTAIN RANGES
(e.g. Andes, Rockies)
form where oceanic crust subducts beneath continental crust; water released from descending slab causes melting of the mantle, producing DIORITE, GRANITE, and explosive ANDESITE and RHYOLITE volcanoes; adds to continental crust

oceanic crust is consumed – oceans close

leads to ISLAND ARC – CONTINENT and CONTINENT – CONTINENT collision (fig. 2.16)

Continental crust cannot be subducted and collisions end subduction; crust thickens as continents collide, producing high mountains (e.g. Himalaya, Alps)

erosion of mountain range exposes its deep roots, made of METAMORPHIC ROCKS (METAMORPHIC BELTS)

RESTLESS EARTH

We tend to think of the Earth as constant, solid and unchanging, a notion that is enshrined in our language in expressions such as *terra firma*, or *solid as a rock*. But every now and then we are reminded that the Earth is not just a lump of dead, inert rock – reminders that come in the form of devastating earthquakes or volcanic eruptions.

Such things generally do not happen in South Africa, but other countries are less fortunate: the Japanese islands, home to about 150 million people, are prone to severe earthquakes and violent volcanic eruptions, while many Californians live in constant fear of earthquakes. This chapter examines why these forms of geological activity are unevenly spread around the globe. There is reason to believe the processes responsible have been operating throughout most of Earth history and have shaped the world we live in today. An understanding of how the Earth works is therefore essential background for appreciating South Africa's long geological history. The essential concepts you will encounter in this chapter are summarised in the route map.

Geology is a young discipline compared to, say, physics, mathematics or chemistry, and only began to emerge as a serious science in the late 18th century. Early geologists focused their attention on trying to understand the origins of different rock types, their relative ages and distribution. Nevertheless, even in those early years, there were individuals who thought on a global scale. As early as the 16th century, Elizabethan philosopher Sir Francis Bacon pointed out the complementary shapes of Africa and South America, while Dutch scientist Ortelius suggested in 1596 that these two continents were once joined, and subsequently became separated.

Shape alone is insufficient evidence on which to postulate movement of the continents. Most of the important early geological work was, however, confined to local studies, particularly the making of geological maps and the documentation and description of rocks and fossils. It was these data that were to provide a basis for examining global geology in a more scientific manner in later years.

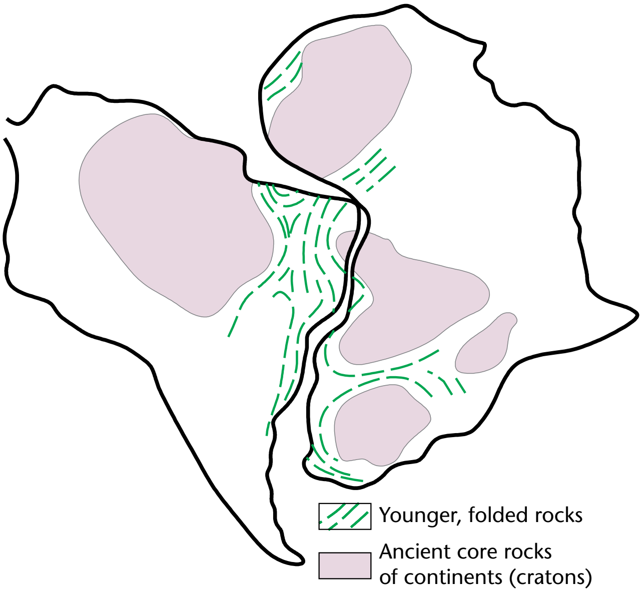


Figure 2.1 *If South America and Africa are placed alongside each other there is a good fit between the coastlines (the edges of the continental shelves give an even better fit). The rock formations along the boundary match, suggesting that they were once joined.*

DRIFTING CONTINENTS OR AN EXPANDING EARTH?

The notion that the continents, particularly Africa and South America, were once joined continued to haunt the discipline. One of the first attempts to reassemble the continents using scientific evidence was made by Antonio Snider-Pelligrini in 1859, based on fossil evidence from Europe and North America. Other attempts followed, but it was Alfred Wegener, the German meteorologist, who in 1915 proposed the most significant hypothesis concerning the former unity of the continental landmasses, based on extensive field observations. He suggested that all the present-day continents were once assembled into a single landmass he called **Pangaea**, meaning all land. This landmass had split and the various continental fragments had drifted to their present positions.

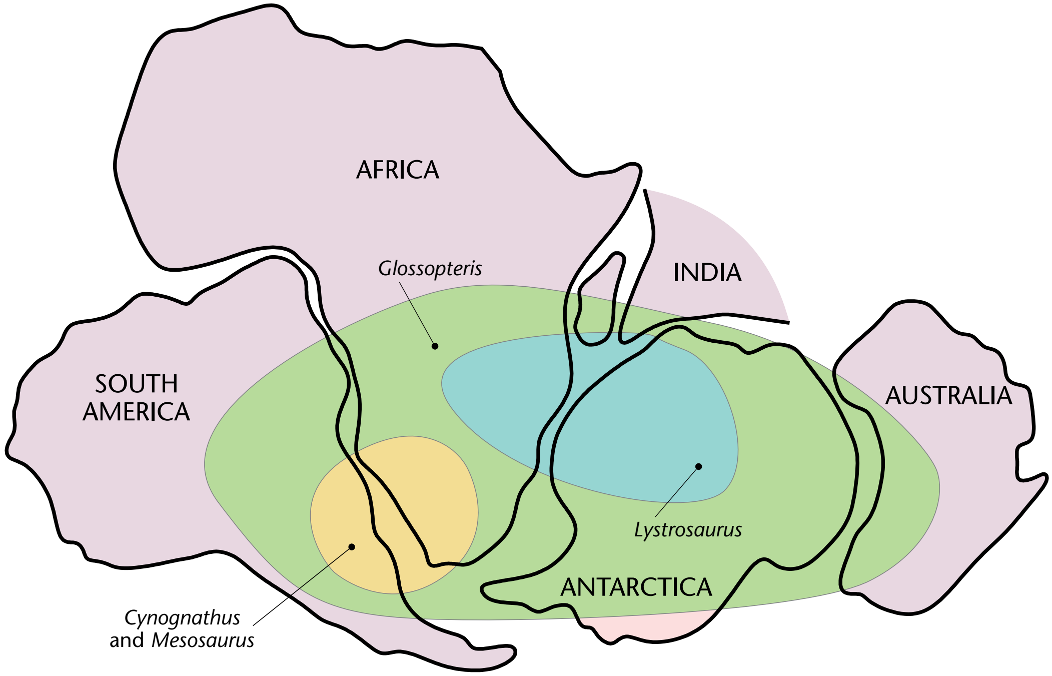


Figure 2.2 *The distribution of fossils of land-dwelling reptiles, such as* **Lystrosaurus**, *found in Africa, India and Antarctica,* **Cynognathus** *from Africa and South America, and the estuarine reptile* **Mesosaurus** *from Africa and South America – as well as the plant* **Glossopteris**, *which occurs on all of the southern continents and India – is inexplicable with the present arrangement of continents. But it makes sense if these continents were once joined together.*

Wegener's hypothesis of **Continental Drift** was supported by many geologists, among them prominent South African Alex du Toit in his work *Our Wandering Continents*, published in 1937.

The geological evidence that the continents were once joined is strong, particularly for the continents of the southern hemisphere. Old mountain belts and rocks of similar age in adjacent continents link up when the continents are reassembled like a picture on a jigsaw puzzle (**figure 2.1**). The reassembly of continents also explains the distribution of fossils of certain land-dwelling reptiles, as well as the fossil remains of a distinctive plant (**figure 2.2**). How could these terrestrial organisms have crossed the oceans if the continents had always occupied their present positions?

Other evidence is based on climatic conditions. Coal beds, which form in equatorial or temperate conditions, occur in Antarctica, indicating that Antarctica formerly occupied a position much closer to the equator. Glacial deposits, which formed about 300 million years ago, occur on all the landmasses of the southern continents, as well as India (**figure 2.3**). These glacial deposits can be observed in the Karoo region and in KwaZulu-Natal, and are discussed later (*see* page 195). The distribution of the deposits can best be explained if the southern continents had assembled as a large landmass or **supercontinent** centred on the South Pole some 300 million years ago. This supercontinent became known as **Gondwanaland**, subsequently shortened to **Gondwana** (Gondwana means land of the Gonds, a tribe in India, so to say Gondwanaland is tautology).

Although the hypothesis of Continental Drift had supporters, many earth scientists, especially from the northern hemisphere, were sceptical, because there was no acceptable mechanism to account for the splitting of large continents and their subsequent movement. After all, what conceivable force could be so powerful as to drive massive continents across the globe, especially

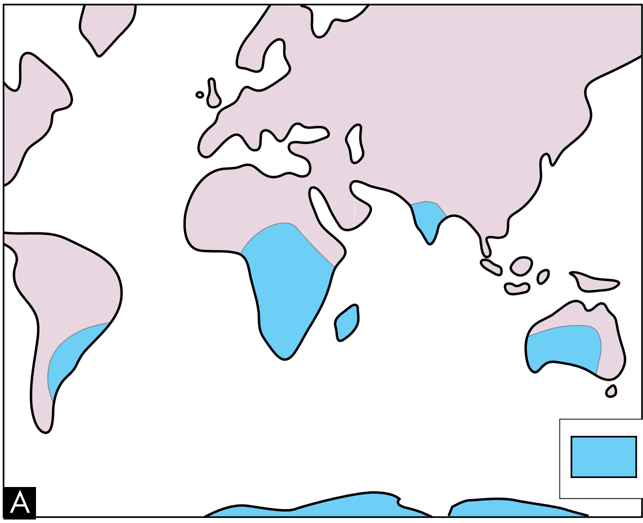


Figure 2.3A *Glacial deposits of the same age occur on the southern hemisphere continents.*

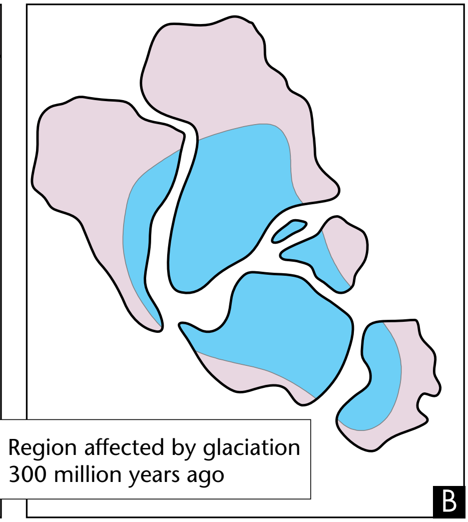


Figure 2.3B *If the southern hemisphere continents and India are united, the glacial deposits combine into a single entity, which could have formed when the combined continent lay over the South Pole.*

against the resistance provided by the rocks of the ocean floor? Sir David Attenborough, well known broadcaster and author, was a student during the 1940s when this debate was raging, and he provides an account of the attitudes of academics towards this new theory:

> *The Regius Professor of Geology in the University of Cambridge read our petition with care. We were a group of geology students. It was 1946. We demanded (in that way students are prone to do) that our lectures should examine the theory of continental drift. Our professor explained firmly that when someone could demonstrate to him the existence of the unimaginable forces in the earth that would be needed to make a continent move over the surface of the globe, he would lecture about it. But until then, the proposition was moonshine. So we went back to our lectures in this and other departments, and tried to make sense of the convoluted explanations we were being given of how, for example, dinosaurs managed to get across the oceans from North America to Australia, and why Australia's spectacular Banksia plants should be so extraordinarily similar to the beautiful Proteas of South Africa. And we were not allowed to dream about Gondwana.*

A rival hypothesis to explain the separation of the continents invoked expansion of the Earth. The **Expanding Earth Hypothesis**, championed by Australian Warren Carey, proposed that the present continents once covered the entire Earth. Expansion of the Earth resulted in the formation of the ocean basins, which separated the continental fragments. A simple analogy would be inflating a balloon covered with wet tissue paper. But this theory also suffered from the lack of a plausible mechanism to account for the expansion. The notions of Continental Drift and the Expanding Earth remained geological curiosities, and geologists continued their data gathering – mapping, collecting, describing and classifying rocks and fossils. The collection and classification of basic data has its place in science, and ultimately began to bear unexpected fruits.

A NEW VIEW OF THE EARTH

Since the start of space programmes in the late 1950s and early 1960s, views of Earth from space have become commonplace and have given us a completely new perspective of the Earth. Commonly referred to as the Blue Planet, some 70% of Earth's surface is covered by water, and satellite images (**figure 2.4**) typically show white swirls of clouds of the **atmosphere** and dark blue areas that are the ocean waters of the **hydrosphere**. The landmasses stand out in stark contrast to the oceans.

Extensive surveying and mapping of the topography of the ocean floor has been carried out since the 1950s, using sonar, seismic reflection and other techniques, ironically as a necessity for submarine warfare during the Cold War period. In addition, systematic geological investigation of the ocean floors commenced in the late 1960s. Knowledge of the ocean floor has had a profound impact on our understanding of the nature of the Earth's crust, the processes operating on it, and its evolution.

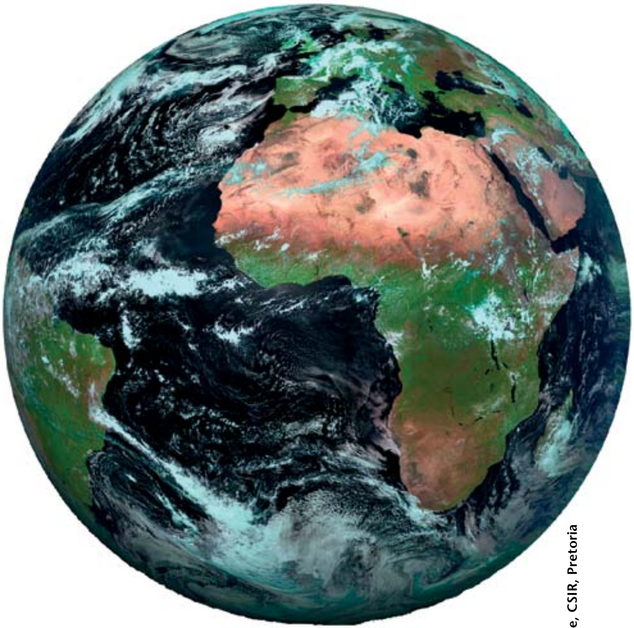
Maps of the ocean floor, created mainly by the military, combined with conventional maps of the continents, have enabled us metaphorically to peel off the atmosphere and the hydrosphere, providing a view of a naked Earth (**figure 2.5**). The two principal features on its surface are the **continents**, including the submerged **continental shelves**, and the **ocean basins**. Systematic surveys of the ocean basins over the past 40 years have revealed that the difference between continents and ocean floors is not just a matter of elevation – there are fundamental geological differences.

THE EARTH'S NAKED FACE

The Earth's radius is about 6 400 km, while the vertical distance between the deepest point on the ocean floor and the top of Mt Everest, Earth's maximum topographic relief, is about 20 km. To put this in an everyday context, suppose the Earth were shrunk to a ball 10 cm in diameter. The maximum relief would be just more than a tenth of a millimetre, whereas the average relief would be a tiny fraction of a millimetre. So the Earth is fairly smooth, but for us living on its surface, its relief is extremely important. For one thing, water occupies the lower ground, forming the oceans, while the higher ground forms the continents, providing habitat for terrestrial animals such as us.

Although really quite minor, the topography of the Earth nevertheless raises some fundamental questions. Why is the Earth divided into high and low areas – continents and ocean basins? Continents consist mostly of extensive flat areas, whereas the major mountains of the world form long, narrow belts such as the Cordillera of the Americas, extending from Alaska to the tip of South America, and the mountain chain of southern Europe and Asia, extending from the Pyrenees to the Himalaya (**figure 2.5**). Forces of erosion relentlessly attack and sculpt these mountainous regions, but why have they not been reduced to flat plains over geological time? And why do mountains occur in belts at all?

The topography of the ocean floor is in many ways even more remarkable than that of the continents. Perhaps the most striking feature is an almost continuous mountain chain (**figure 2.5**) that can be traced around almost the entire globe from the Pacific Ocean, through the Indian Ocean and across the Atlantic, a mountain chain about 70 000 km long, like the seam on a tennis ball. This is known as the **mid-ocean ridge** system, and it is approximately 1 500 km wide. It rises gently from the surrounding **abyssal plain** to reach heights of as much as 3 km in places, with a pronounced central valley.



Satellite Application Centre, CSIR, Pretoria

Figure 2.4 *A false-colour satellite image of the Earth, received from a weather satellite positioned at an altitude of 36 000 km on the Greenwich meridian above the equator.*

National Geographic Society, World Ocean Floor Map, 1981

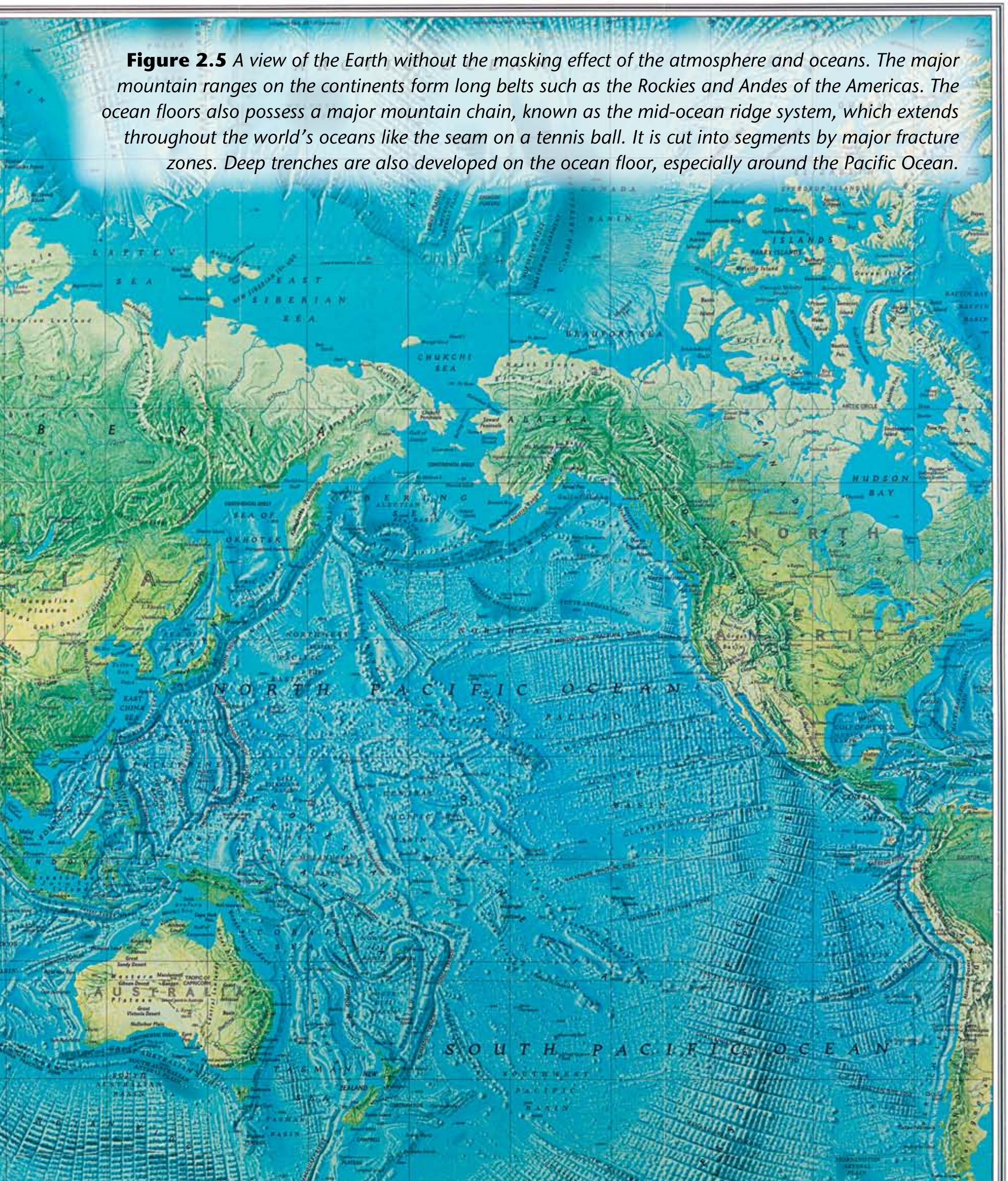


Figure 2.5 *A view of the Earth without the masking effect of the atmosphere and oceans. The major mountain ranges on the continents form long belts such as the Rockies and Andes of the Americas. The ocean floors also possess a major mountain chain, known as the mid-ocean ridge system, which extends throughout the world's oceans like the seam on a tennis ball. It is cut into segments by major fracture zones. Deep trenches are also developed on the ocean floor, especially around the Pacific Ocean.*

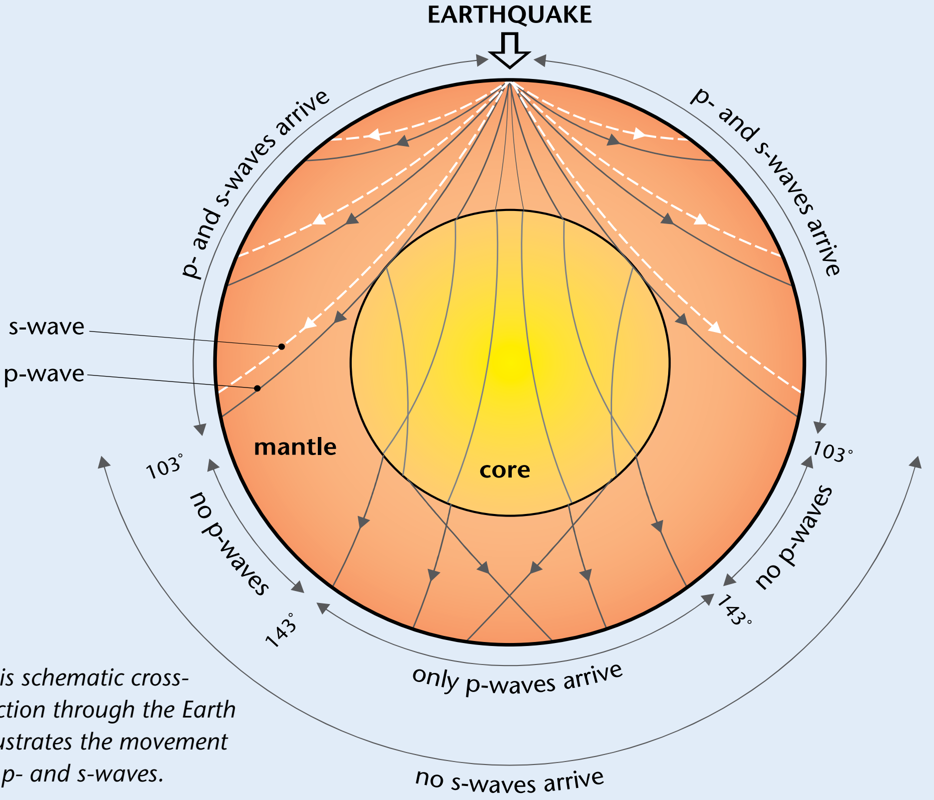
EARTHQUAKES

Earthquakes occur when rocks that have been subjected to sufficiently high stresses, fracture and in the process rebound and release energy in the form of seismic waves, much like the release of sound waves when a dry twig breaks. These seismic waves radiate outwards in all directions. Seismic waves behave in a similar way to light waves and can bend (refract) and reflect at boundaries between different rock layers.

The waves that travel through the interior of the Earth are called body waves, whereas those that travel along the Earth's surface are called surface waves. It is the body wave that is particularly useful in understanding the Earth's interior.

There are two main types of body waves, namely p-waves and s-waves. P-waves are compressional waves in that they compress and expand the material through which they pass. They can be transmitted through solids, liquids and gases. These waves are the fastest and arrive first at any measuring station. S-waves are shear waves and move particles from side to side at right angles to the direction in which the wave travels, like shaking a rope from side to side. S-waves are only transmitted through solids (liquids are unable to transmit shear) and travel slower than p-waves.

The time difference between the arrival of p- and s-waves is a measure of the distance to the source of an earthquake. The speed of seismic waves depends on the density and the rigidity or stiffness of the rock through which the waves travel. The speed at which the waves travel through the Earth gives an indication of the rock density and composition. The distribution of p- and s-waves received from distant earthquakes provides a view of Earth's interior (see diagram below).



This schematic cross-section through the Earth illustrates the movement of p- and s-waves.

The range is cut into segments by **fracture zones** thousands of kilometres long. Virtually the entire length of this mountain range lies below sea level. Also hidden beneath the oceans are deep **trenches**, particularly around the Pacific Ocean, where the greatest ocean depths are attained, such as the 11-km-deep Mariana trench east of the Philippines. Also visible on the ocean floor are chains of **sea mounts**, or submerged islands. The most impressive is the chain extending northwards from Hawaii, via Midway Island, to the trench that borders the Aleutian Islands.

Erosion sculpts the mountain ranges of the continents, but there is no erosion on the sea floor. So how does this topographic variability on the ocean floor arise?

Before these questions about the topography of the Earth can be answered, we need to take a closer look at the Earth's deep interior.

INSIDE THE EARTH

Rocks on the Earth's surface are easily accessible for examination and we know a lot about them. We can also get a certain amount of information on rocks near the surface from deep boreholes (generally less than 5 km deep). Some indications of rock compositions down to depths of about 100 km in certain regions can be obtained by examining rock fragments transported to the surface in volcanoes.

But how do we know what materials occur at greater depths, towards the centre of the Earth 6 400 km below us?

The density of rocks at the Earth's surface averages about 2.8 g/cm^3, but the density of the Earth as a whole is 5.5 g/cm^3. This implies that there has to be much denser material in the Earth's interior, but we have no way of sampling it. In fact, our knowledge of the deep interior of the planet is largely derived indirectly, from the study of seismic waves generated by earthquakes. The way these seismic waves travel through the Earth gives an indication of the composition and internal structure of the planet – much like a CAT (or CT) scan used in medical examinations (*see* 'Earthquakes', left).

The study of the interior of the Earth using seismic waves has revealed that the Earth is a **differentiated** planet, consisting of concentric shells with different compositions and varying physical properties. The primary layers are called the **crust**, **mantle** and **core** (**figure 2.6**). The boundaries between these layers affect the velocity of seismic waves due to sudden density changes, and are known as **seismic discontinuities**.

The Earth's crust varies from about 7 km to 35 km thick. (Some notable exceptions will be dealt with later, *see* page 47). The boundary that separates the base of the crust from the underlying mantle is the **Mohorovičić Discontinuity**, or simply the **Moho**, where a substantial increase in density occurs due to a change in chemical composition. The mantle is solid, made up of rocky material consisting mainly of magnesium, iron, silicon and oxygen. The velocity of seismic waves increases with increasing depth as they pass through the mantle, a consequence of the rising pressure.

Near the top of the mantle, over a depth range from 100–200 km, the waves slow down by about 7% in a region called the **Low Velocity Zone (LVZ)**. In this zone, the rocks display more plastic behaviour because they are close to their melting point. At a distance of 2 900 km below surface is a major boundary, which is known as the **Gutenberg Discontinuity**, and which marks the mantle-core boundary. Seismic evidence indicates that the outer core is a very dense liquid; by analogy with certain meteorites, it is believed to be molten nickel and iron. The inner core is solid, but it is also thought to be composed of a nickel-iron alloy. The density of the core is about 10.8 g/cm^3, whereas the density of the mantle ranges from 3.3 g/cm^3 at its top to 5.5 g/cm^3 at its base. These higher density materials in the interior are responsible for the Earth's high overall density.

The region above the LVZ, consisting of the upper part of the mantle and the crust, is referred to as the **lithosphere**, which forms a fairly rigid outer carapace to the Earth. The LVZ, also known as the **asthenosphere**, is plastic. The mantle below the asthenosphere, termed the **mesosphere**, is more rigid than the asthenosphere, but less rigid than the lithosphere.

This second subdivision of the Earth into layers may seem confusing, especially as the lithosphere includes the upper part of the mantle, as well as the crust. The two subdivisions arise because different criteria are used: the crust-mantle-core subdivision is based on differences in chemical composition

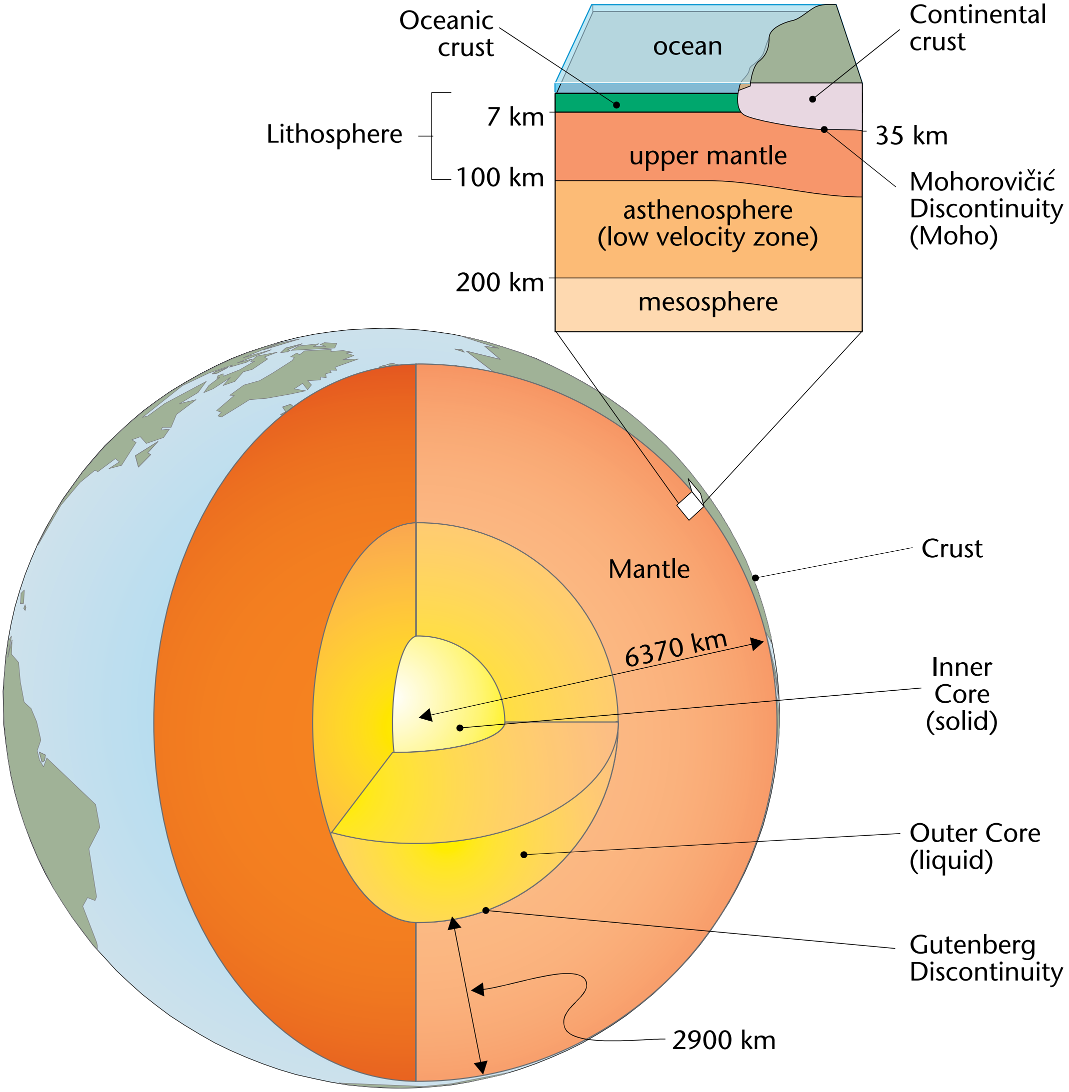


Figure 2.6 *A cut-away section through the Earth showing its component parts. The primary layers, which arise from major differences in chemical composition, are the crust, mantle and core. There are two kinds of crust, one forming the continents and continental shelves, and the other the ocean floors. These have different chemical compositions. The Earth can also be subdivided on a basis of the rheology of the rocks. The upper part of the mantle and the crust are rigid, and this combined layer is known as the lithosphere. Below it lies the 100-km-thick asthenosphere, which is very plastic. This layer is also known as the Low Velocity Zone because seismic waves slow down as they pass through it. Below the asthenosphere is the mesosphere, which is more rigid than the asthenosphere, but less so than the lithosphere.*