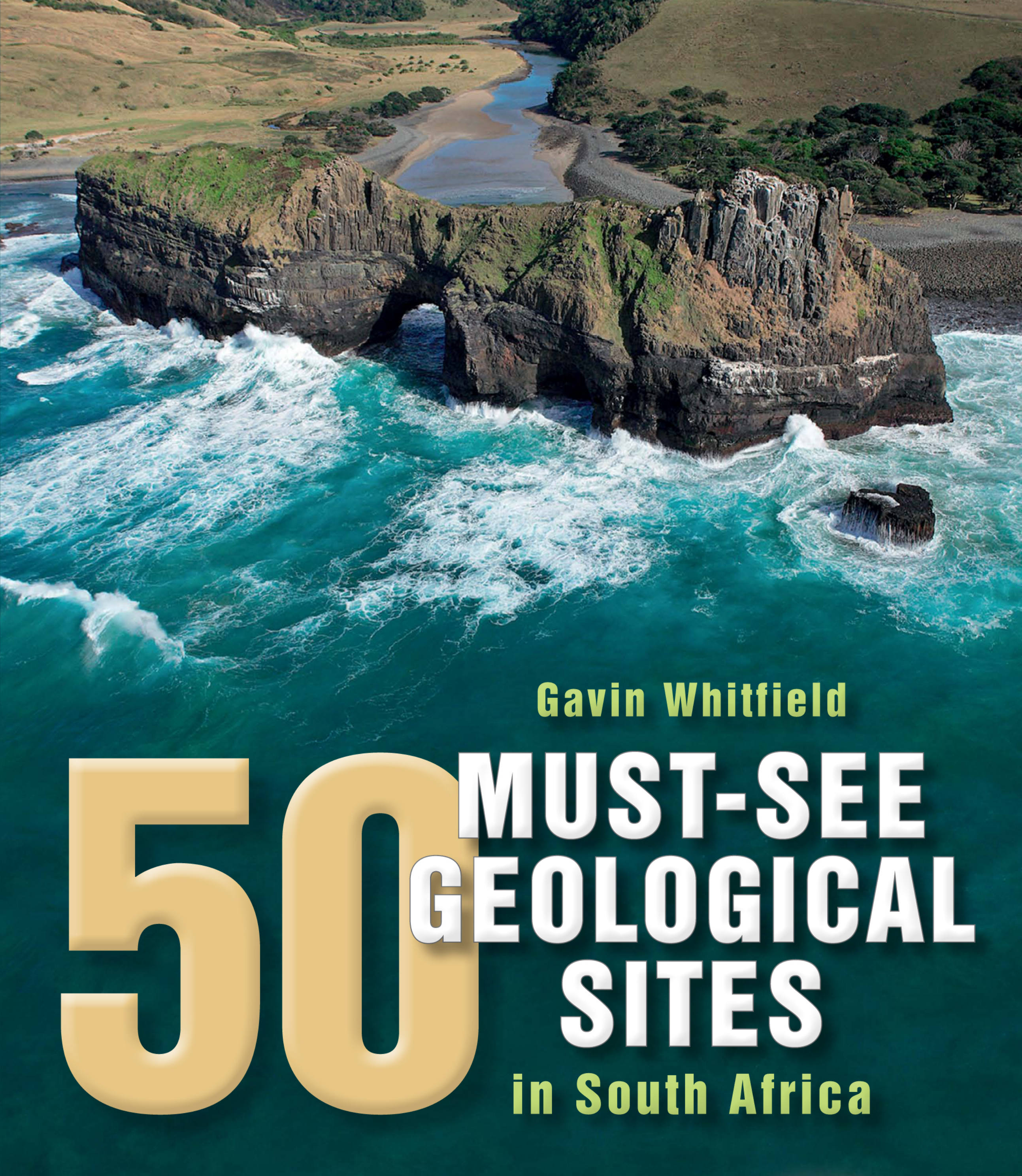
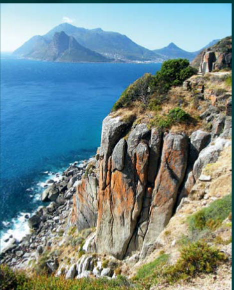
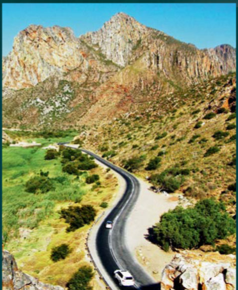


Gavin Whitfield

50 MUST-SEE GEOLOGICAL SITES

in South Africa




Key to the regional geological maps

NB: NOT TO SCALE

ERA Present			
CENOZOIC	🟨	Recent and Tertiary deposits (including Sandveld Group)	
66MY	🟧	Kalahari Group	
MESOZOIC	🟨	Uitenhage Group	
	🟪	Karoo Dolerite	KAROO SUPERGROUP
	🟪	Lebombo Group	
	🟪	Drakensberg Group	
	🟧	Stormsberg Group (Molteno, Elliot and Clarens Formations)	
252MY	🟩	Beaufort Group	
PALAEOZOIC	🟩	Ecca Group	
	🟫	Ecca Group (southern part)	
	🟩	Dwyka Group	
	🟦	Witteberg Group	CAPE SUPERGROUP
	⬜	Bokkeveld Group	
	⬜	Table Mountain Group	
	⬜	Natal Group and Msikaba Formation	
	🟨	Klipheuwel Group	
541MY	🟪	CAPE GRANITE SUITE	
LATE PROTE-ROZOIC 1,000MY	🟪	Malmesbury, Cango Caves and Gamtoos Groups	
MIDDLE PROTEROZOIC	⬜	NATAL METAMORPHIC PROVINCE	
	🟩	Alkaline Intrusions	
1,600MY	🟩	Timbavati Gabbro	
EARLY PROTEROZOIC	🟦	Soutpansberg and Waterberg Groups	
	⬜	Lebowa Granite and Granophyre Suites	BUSHVELD COMPLEX
	🟦	Rustenburg Layered Suite	
	🟩	Rooiberg Group	TRANSVAAL SUPERGROUP
	🟩	Pretoria Group	
2,500MY	⬜	Chuniespoort Group (including Malmani Dolomite)	
LATE ARCHAEAN	⬜	Black Reef Formation and Wolkberg Group	
2,800MY	⬜	VENTERSDORP SUPERGROUP	
MIDDLE ARCHAEAN	⬜	Central Rand Group	WITWATERSRAND SUPERGROUP
	🟥	West Rand Group (including Dominion Group)	
3,200MY	🟪	Archaean Granite and Gneiss (various ages)	BASEMENT COMPLEX
EARLY ARCHAEAN	🟩	Greenstone Belts (including part of the Limpopo Complex)	
3,600MY	⬜	Beit Bridge Complex (part of the Limpopo Complex)	

GAVIN WHITFIELD

50

MUST-SEE GEOLOGICAL SITES

in South Africa


Rod MacLeod

GSSA
Geological Society of South Africa

E. Oppenheimer & Son
South Africa

Council for Geoscience

Contents

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It is a reality that a book such as this needs sponsorship to get beyond the conceptual stage, so my appreciation must go first to several major benefactors. My thanks go to Ernest Oppenheimer & Son who at the start believed in the concept and who provided a generous donation to get the book going; and a special thank you goes to Duncan MacFadyen, their Manager of Research and Conservation.

No book on a geological topic can be successful without good quality maps, as were supplied by the Council for Geoscience (CGS), at no cost to the author or publisher. My considerable gratitude goes to this organisation and, in particular, to the Spatial Data Management Unit, headed by Ken Wilkinson and Magda Roos, and assisted by Belinda Fourie: they provided excellent geological and digital elevation model maps.

The Geological Society of South Africa also contributed financially, through substantial donations from their Research, Education and Investment Fund, to assist with the field work that was required across the country. Thank you for your support and assistance, which is now bearing fruit, and for helping with the cost of illustrations.

The team at Struik Nature, led by Publishing Manager Pippa Parker, must take full credit for yet another very professional popular science publication. I owe a great deal to the editing skill and patience of Helen de Villiers, and the vision and design ability of Janice Evans. Thank you as well to others in the team, including Colette Stott, who assisted with many photographs, Emsie du Plessis, who undertook the proofreading and indexing, Craig Smith who checked the book for technical accuracy, and others who contributed to the success of the book.

Photographs and illustrations form an essential part of this book; a number of people provided images of geological sites, and are gratefully acknowledged in photo credits alongside their photographs. Most of the illustrations were done independently by James Berrangé who, with considerable enthusiasm, produced attractive pictures with a minimum of supervision. The illustration of palaeo-Karoo life came from the Albany Museum. Illustrations of the Premier kimberlite pipe at Cullinan came from renowned geological artist Maggie Newman. Robert Reisz from the University of Toronto generously made available an exceptional photograph and illustrated reconstruction of an unhatched dinosaur embryo from Golden Gate.

Most of the information provided in this book is available from a wide variety of published literature, much of which is listed in the section marked ‘Further reading’, and wherein many of the authors are indicated. Nevertheless, special thanks are due to a number of persons who, during the course of the field work, provided either additional information, usually informal, or access to geological sites. These include Pippa Haarhoff, Manager of the West Coast Fossil Park; Doug Cole, Paul Macey, Coenie de Beer and Dave Roberts from the Bellville

office of the CGS; and Greg Botha and Nigel Hicks from the Pietermaritzburg office of the CGS. Wild Coast authority John Costello kindly reviewed the Hole in the Wall geosite. Roger Gibson provided insight into the status of the Vredefort Dome. Assistance on the Barberton Makhonjwa Mountains was given by local scientists Tony Ferrar and Chris Rippon. Stefa Estebeth, the Manager at Sudwala Caves, supplied an unpublished report by speleologist Pedro Boshoff. Greater geological insight into the distribution of the Black Reef came from George Henry. Sian Tiley-Nel, Curator of the Mapungubwe Collection, made available numerous images and Emese Bordy and Adam Bumby supplied geological information on the Mapungubwe area. Richard Wadley and Pat Ericson provided background to the geology of the Waterberg. Access to Makapans Valley came from Mark Howitt at the National Game Breeding Centre in Mokopane.
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DEDICATION
This book is a tribute to all of South Africa's superb geologists, both past and present, who made the fascinating geology of the country understandable; without this invaluable input an explanation of the geological sites would have been impossible.
It is also dedicated to my wife Ann, my partner for over 45 years, who supported and encouraged me throughout the process.

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Foreword

South Africa is world renowned for its geology and mineral wealth, with mining playing a huge role in the economy of the country. There are many geological wonders such as numerous diamond-bearing kimberlite pipes; the extraordinary Witwatersrand goldfield, the world's greatest producer of gold; and the platinum-rich Bushveld Complex – all are geological superlatives that have attracted the attention of generations of geologists and world-class mining companies formed to exploit their contained mineral wealth. The importance of South Africa's lesser known geological and landscape treasures, however, which are generally not associated with minerals of economic value, but which are often of outstanding scenic, cultural and scientific value, is frequently overlooked.

In this beautifully illustrated and meticulously researched publication, Gavin Whitfield, a real champion of the geological heritage of South Africa, has highlighted 50 of these outstanding sites throughout the country, and in so doing has made them accessible to the broader public, tourists and geoscientists alike. The geology that has been highlighted covers 3.5 billion years of Earth history and provides an almost continuous record of the development of Earth and of the life it supported. Each site within each of the seven regions of the country has been chosen with care, and photographs of panoramic views, details of interesting rock formations, together with simplified geological maps, geological cross-sections and descriptions make for easy reading and will assist in the understanding of many of our landscapes and geology. A useful adjunct to the geological descriptions of individual sites are lists of things to see and do, including hiking trails, and associated historical and cultural attractions.

The appearance of *50 Must-see Geological Sites* is timeous as it will be of great value for delegates to the 35th International Geological Conference (to be held in Cape Town in 2016) wishing to see some of our outstanding geological attractions before or after the conference. The Board of the 35th IGC Foundation and the Local Organizing Committee for the conference are proud to be associated with this publication, a fitting celebration of South Africa's rich geological heritage.

PROF. RICHARD VILJOEN

Co-President of the 35th International Geological Conference Local Organizing Committee

Preface

This book was conceived several years ago during a 'brain-storming' session between Pippa Parker of Struik Nature and Craig Smith of the Geological Society of South Africa on future geoheritage publications and the idea was passed on to me. The concept of documenting a large number of important geological sites in South Africa was appealing and I agreed to author this guidebook.

But this is part of a trend to bring geology to the greater public, and since the late 1990s a number of earth science publications have emerged in South Africa, and have done well in the bookshops. Pointing the way was *An Introduction to South Africa's Geological and Mining Heritage* (1999) by Morris Viljoen and Uwe Reimold; followed by the highly commended *The Story of Earth and Life* (2005) by Terence McCarthy and Bruce Rubidge, which tells a complex yet fascinating tale of southern Africa's development; *How on Earth?* authored by Terence McCarthy in 2009; and the popular travel guide *Geological Journeys* (2006) authored by Nick Norman and me, which has sold remarkably well, far exceeding the publisher's original expectation. Such successes show that at the popular level there is considerable and growing interest about the nature of the Earth beneath our feet. This is not surprising, bearing in mind numerous recent rumblings of the Earth such as earthquakes, volcanoes and landslides, our increasing environmental awareness and the threat of climate change. Geoscientists are increasingly being asked to present their knowledge to the public and this involves the challenging task of communicating to people with no or little prior knowledge of how the Earth works. One of the main outcomes of this book is that it provides a guide to geological processes and South Africa's geological past.

My travels around South Africa during the course of preparing this book made me very aware that an explanation of the geology is generally missing at almost all sites of natural interest: it is rare to find a magnificent landscape, a spectacular landform or a fold mountain that has an adequate description, be it on-site or in the tourist literature. How many times have you looked at a particular geological feature, such as a mountain range, or a canyon, or a major escarpment, or even a cave, and wondered how it was formed or what it means? This was another spur to write this book.

I have tried to provide information on a large selection of South Africa's best-known geological sites and landscapes, placed in their regional geological context, and to give the observer a good idea of what they are seeing. The book takes in a wide variety of geological and land-forming processes, both large and small. It has been compiled with the interested lay person and visitor in mind and, as far as possible, geological jargon has been kept to a minimum, or at least explained. The book provides illustrated descriptions of geological sites (geosites) that have been selected from a much longer list, based on their geo-educational credentials and accessibility to the public. No-one who has used this book should be able to say that they don't understand how specific geological features were formed.

While effort has also been made to cover as much of South Africa as possible, please remember that there is still a lot more to see and experience!

GAVIN WHITFIELD
Johannesburg, South Africa

Introduction

South Africa's geological heritage

The geological sites (or geosites) described in this book are part of South Africa's incomparable geological heritage. The definition of 'geological sites' has been taken as broadly as possible in order to illustrate specific rock types, geological or structural processes, palaeo-environments, spectacular landscapes or specific landforms; and certain mines are included. Many of the sites are located within protected areas, including World Heritage Sites. Importantly, they are accessible to the public, are relatively easy to visit and can be appreciated by all without undue effort.

The science of geology is commonly defined as 'the study of the origin and nature of the Earth'. Geology includes a wide variety of separate disciplines, including broad-scale mapping of geological strata to create geological maps, computer-assisted interpretation of aerial photos and satellite images, prospecting and exploration for valuable resources, environmental and mining studies, the study of fossils, and detailed microscopic and chemical investigations of rocks and minerals. Geomorphology is the study of the surface forms of the Earth or of landscapes, in particular the processes that relate to the origin and evolution of landforms. There is a fundamental relationship between the underlying geology and the landscape, and the landforms that have been created at all levels.

Southern Africa's vast span of geological time provides an opportunity to see the country's unique geological record, from nearly 3,600 million years ago to 'Recent' times, and to get insight into how the Earth and its infinite variety of life forms evolved over the immensity of geological time. Some of southern Africa's most impressive large-scale geoheritage attractions, from oldest to youngest, include:

- **Barberton Mountain Land:** One of the best preserved volcanic, sedimentary and granitic micro-continents that grew and eventually united to form the Kaapvaal Craton. Some of the Barberton rocks provide evidence of very primitive, single-cell microbes that lived around 3,400 million years ago in a primordial sea.

Site BM7 on the new Barberton Makhonjwa Geotrail provides representative mounted specimens of all rock formations seen on the 37km-long road trail.

- **Witwatersrand Basin:** A little less than 3,000 million years ago, after the Kaapvaal Craton had enlarged and stabilised, down-warping of the craton took place and a large inland sea formed. The resulting basin began to fill with sedimentary material, including the gold-bearing quartz pebble conglomerate reefs of the Witwatersrand goldfield.
- **Transvaal Basin:** Around 2,650 million years ago this large sedimentary depository started forming on top of and alongside the earlier cratonic basins, which by now had become hard rock formations; and vast marine beds of photosynthesising cyanobacteria developed, which produced

copious algal-generated oxygen that was released into the sea water, resulting in the deposition of South Africa's immense sedimentary iron and, later, manganese deposits. Life on Earth, albeit marine, had never before existed on such a grand scale. These fossil algae are now preserved as thick layers of dolostone, also called 'dolomite'.

- **Bushveld Complex:** Over a relatively short period of geological time, around 2,060 million years ago, the Kaapvaal Craton was massively intruded by magmas of deep-seated origin to create what is by far the world's largest layered igneous intrusion. South Africa thus became host to the world's biggest resources of platinum, chromium and vanadium, and the pre-eminent producer of these commodities for the foreseeable future.
- **Vredefort meteorite impact:** Not long after this, Earth was struck by an enormous meteorite, now leaving only its roots as the central uplift – caused by the rebound of the underlying rock – of the once-enigmatic Vredefort Dome. This has now been identified as the world's largest and oldest known meteorite impact structure, dating from 2,020 million years ago, and the impact is considered to have resulted in the Earth's largest single release of energy. This catastrophic event significantly influenced the distribution of the rich Witwatersrand gold reefs that became, for a time, the backbone of South Africa's economy. These conglomerates were to yield the largest gold haul of all time: more than 50,000 tons of gold has already been mined, and a lot is still unmined.

And, at the opposite end of the time-scale, only around 200,000 years ago, another much smaller meteorite struck, creating the Tswaing Crater – one of the youngest, best preserved and most accessible bowl-shaped meteorite impact craters on Earth.

- **Waterberg and Soutpansberg Basins:** In these basins, the world's earliest red beds formed. Rich in iron oxide, they reveal that, by at least around 1,900 million years ago, oxygen was freely present in the atmosphere, a situation that eventually enabled life to exist on land and changed the Earth's future forever.
- **Cape Fold Belt:** The magnificent mountain ranges of the southern and Western Cape owe their existence to the movement of crustal plates far south of the Gondwana supercontinent around 300 million years ago. A subduction zone developed along the southern margin of Gondwana as oceanic crust moved under the continent. Sedimentary rocks previously deposited in the Cape Basin became compressed and formed the elongated fold belt. The result was a mountain range of Himalayan proportions and, although it's now considerably worn down, the passes and poorts provide a marvellous geological spectacle.

More than 500 million years ago, and prior to deposition of the Cape sedimentary rocks, an earlier mountain-building event caused large-scale crustal deformation and resulted in the intrusion of numerous batholiths and plutons of Cape granite.

Folded Table Mountain quartzitic sandstone in the little-known Seweweekspoort, which cuts through the Great Swartberg near Ladismith. In the distance is the 2,325m-high Seweweeksberg, the highest peak in the range.

- **Karoo Basin:** The rising mountain ranges along the southern Cape coast resulted in a vast sedimentary basin developing further to the north. Some primitive life

Coloured Beaufort shales of the Karoo Basin in Teekloof Pass, an area well known for its reptile fossils and intruded by many Karoo dolerite sills, one seen capping the sedimentary strata at the top left.

that had evolved under water gradually moved onto the land, plants flourished and around 250 million years ago the great alluvial flood plains saw the progressive development of a variety of prehistoric reptiles and, eventually, the ancestors of early mammals. But by about 190 million years ago the basin was reduced to a sandy desert, seen today as the Clarens sandstone.

- **Karoo Igneous Province:** As a forerunner to the break-up of Gondwana, the Earth's crust started to crack and, around 180 million years ago, basalt magma rose up and flooded across most of southern Africa, making one of the world's great continental basalt provinces. At the same time, basalt magma intruded existing Karoo sedimentary formations to form dolerite sills and dykes, ultimately giving rise to the region's iconic Karoo scenery.
- **Kimberlites:** At various times during the geological past there were explosive eruptions from kimberlite volcanoes, the primary source of all natural diamonds. Kimberlite was first discovered in South Africa in 1871 and the country was for many years the world's largest producer of diamonds. In 1905 the Premier kimberlite pipe produced the famous Cullinan Diamond, the largest gem diamond ever found, and the same pipe is still producing world-class gems.
- **Great Escarpment:** South Africa is renowned for its magnificent landscapes, and much of the spectacular scenery can be traced back to the break-up of the Gondwana supercontinent, which started more than 140 million years ago. This resulted in large-scale rifting of the continental margins, the creation of new oceans, uplift of southern Africa, down-cutting by coastal rivers and massive denudation.

Part of the Blyde River Canyon, viewed looking west, showing the Great Eastern Escarpment being cut back by erosion. Capping the high flat ground in the distance on the right is the thin blanket of Black Reef quartzite.

- **Human evolution:** The widespread Transvaal dolostone beds mentioned above are riddled with cave systems that developed very much later, and it is a strange coincidence that these caves witnessed and protected the evolutionary path of mankind, starting with our distant apeman ancestors around 3 million years ago. Many renowned fossils from this time have been recovered from numerous cave sites associated with the world-famous Cradle of Humankind World Heritage Site.

About this book

- This book showcases 50 of the best geological sites in South Africa: some are diamond mines, others fossil sites and many are landscapes that will be known to you in passing. Their locations are shown on the maps on pp.12 and 13 (and see note alongside).
- Naturally, the selection of geological sites has been somewhat subjective and is by no means inclusive; many other interesting sites, tucked away in remote and rugged places, are omitted.
- While the main aim of this book is to describe and interpret places of geological interest across South Africa, the 'Introduction' offers readers an overview of the geology and its companion science of geomorphology.
- A Glossary (pp.312–314) provides explanations of many technical terms.
- 'Further reading' (p.315) provides a list of recommended publications, giving access to more detailed information.

TIP Most geological and landscape information can best be seen from above. Google Earth allows you to 'fly' anywhere on the planet to view combined satellite imagery and aerial photography in amazing topographic detail. All geosites presented here can be viewed on-line at various scales – a highly recommended tool for the 'arm-chair' geoscientist.

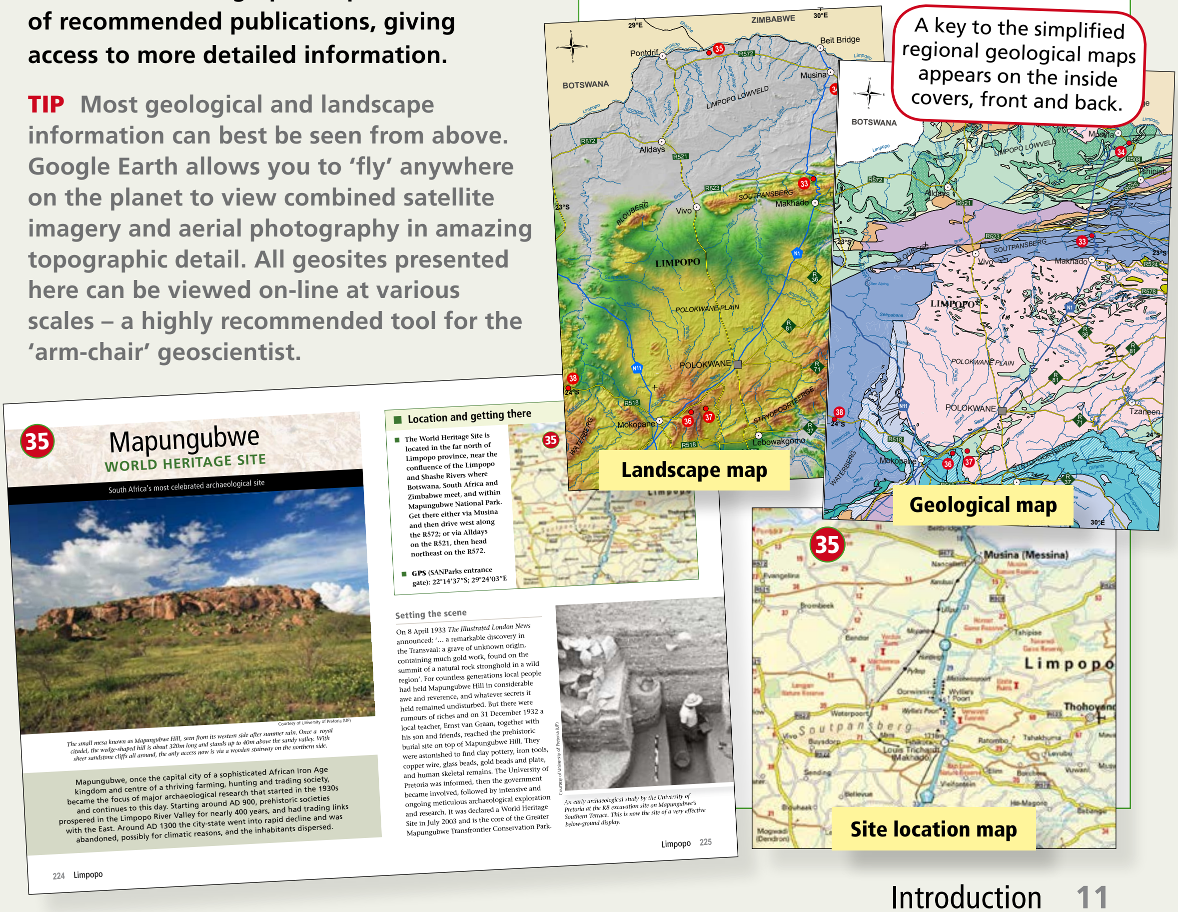
A note about maps

Country-wide landscape and geological maps (pp.12–13), compiled using digital terrain technology and simplified geology, show the entire region and indicate the distribution of all featured geosites (numbered **1–50**).

Six of the regions (all except Northern Cape, where the geosites are too widely distributed) have larger-scale, more detailed landscape and geological maps that also locate more precisely the featured sites. In each instance, the twinned maps emphasise the strong connection between the underlying geology and the formation landscape.

A location map shows key routes and towns in the vicinity of each site: GPS co-ordinates pin-point the feature, or closest vehicular approach.

The Council for Geoscience (CGS) is able to supply detailed information and more comprehensive regional maps.



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Mapungubwe

WORLD HERITAGE SITE

South Africa's most celebrated archaeological site

Courtesy of University of Pretoria (UP)

The small mesa known as Mapungubwe Hill, seen from its western side after summer rain. Once a royal citadel, the wedge-shaped hill is about 320m long and stands up to 40m above the sandy valley. With sheer sandstone cliffs all around, the only access now is via a wooden stairway on the northern side.

Mapungubwe, once the capital city of a sophisticated African Iron Age kingdom and centre of a thriving farming, hunting and trading society, became the focus of major archaeological research that started in the 1930s and continues to this day. Starting around AD 900, prehistoric societies prospered in the Limpopo River Valley for nearly 400 years, and had trading links with the East. Around AD 1300 the city-state went into rapid decline and was abandoned, possibly for climatic reasons, and the inhabitants dispersed.

224 Limpopo

Location and getting there

- The World Heritage Site is located in the far north of Limpopo province, near the confluence of the Limpopo and Shashe Rivers where Botswana, South Africa and Zimbabwe meet, and within Mapungubwe National Park. Get there either via Musina and then drive west along the R572; or via Alldays on the R521, then head northeast on the R572.
- **GPS** (SANParks entrance gate): 22°14'37"S; 29°24'03"E

Setting the scene

On 8 April 1933 *The Illustrated London News* announced: '… a remarkable discovery in the Transvaal: a grave of unknown origin, containing much gold work, found on the summit of a natural rock stronghold in a wild region'. For countless generations local people had held Mapungubwe Hill in considerable awe and reverence, and whatever secrets it held remained undisturbed. But there were rumours of riches and on 31 December 1932 a local teacher, Ernst van Graan, together with his son and friends, reached the prehistoric burial site on top of Mapungubwe Hill. They were astonished to find clay pottery, iron tools, copper wire, glass beads, gold beads and plate, and human skeletal remains. The University of Pretoria was informed, then the government became involved, followed by intensive and ongoing meticulous archaeological exploration and research. It was declared a World Heritage Site in July 2003 and is the core of the Greater Mapungubwe Transfrontier Conservation Park.

Courtesy of University of Pretoria (UP)

An early archaeological study by the University of Pretoria at the K8 excavation site on Mapungubwe's Southern Terrace. This is now the site of a very effective below-ground display.

Limpopo 225

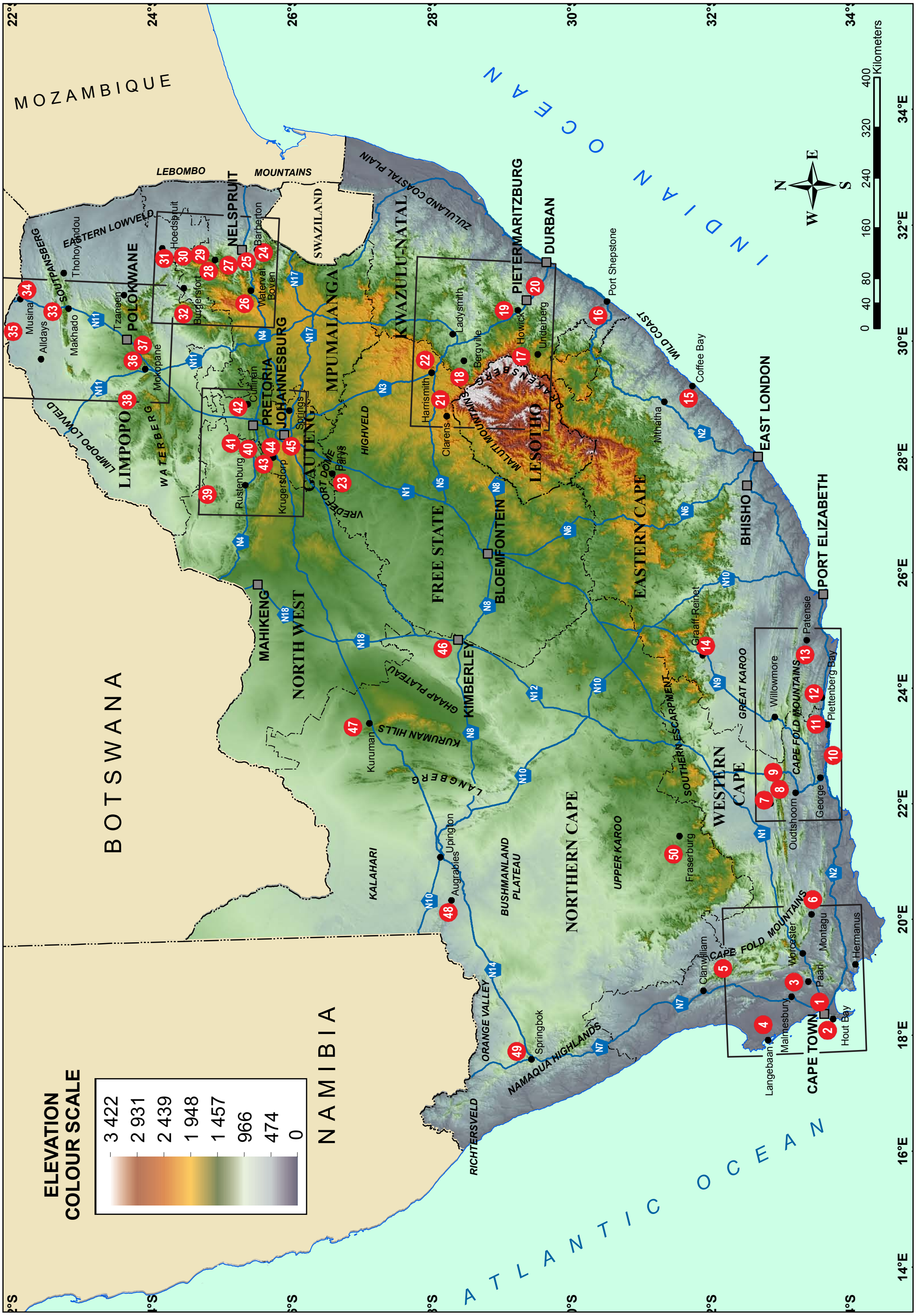
Landscape map

Geological map

Site location map

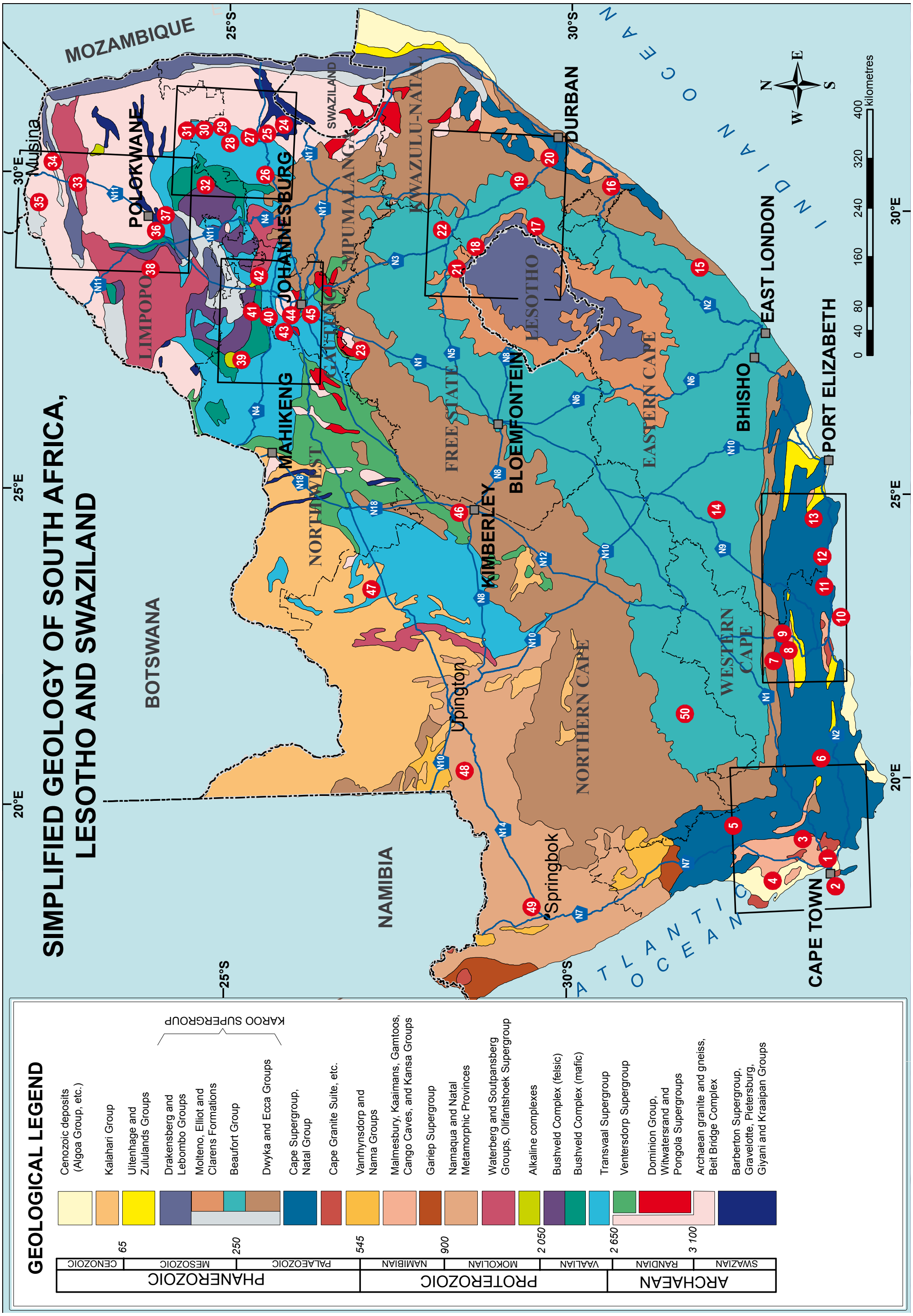
A key to the simplified regional geological maps appears on the inside covers, front and back.

Figure 1: Landscape map of South Africa and Lesotho, derived using digital elevation technology and showing the locations of all featured geological sites.



Council for Geoscience

Figure 2: Simplified geological map of South Africa, Lesotho and Swaziland. Boxes delineate six of the seven regions discussed, although some geosites fall outside of the more detailed regional maps at the start of sections, and Northern Cape is without a regional map as the sites are too widely dispersed.



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What rocks are made of

Rocks are aggregates of one or several common minerals, and are defined by these varying mineral proportions and by grain size. Minerals are naturally occurring inorganic compounds and often have complex chemical compositions. They have characteristic physical properties and crystal structures, and all minerals have approved names. There are about 4,000 of them, but the majority are uncommon to rare. The most common rock-forming and accessory minerals are listed in **Table 1** below.

Table 1

ROCK-FORMING MINERALS			
Name and varieties	**Occurrence**	**Essential chemistry***	**Colour**
Quartz and other silica varieties Also found as **rock crystal, agate, chalcedony, chert** and **jasper**	Found in igneous and metamorphic rocks of granitic composition; in quartz veins; and in most sedimentary rocks; the main component of sandstone	SiO_2 (also called 'silica') and the building block of all silicate minerals	Colourless to white, many coloured varieties
Alkali Feldspar Group Ranges from **albite** (sodium-rich) to **orthoclase** or **microcline** (potassium-rich)	Alkali feldspars are among the most common minerals; a major constituent of igneous and metamorphic rocks	SiO_2 (silica) and Al_2O_3 (alumina) with variable Na and K	White to pinkish, even reddish
Plagioclase Feldspar Group From **albite** (sodium-rich) to **anorthite** (calcium-rich)	Plagioclase feldspars are common in intermediate and mafic igneous rocks and in many metamorphic rocks	SiO_2 (silica) and Al_2O_3 (alumina) with variable Ca and Na	Whitish to pinkish
Mica Group Ranges from **muscovite** (potassium-rich) to **biotite** (magnesium- and iron-rich)	Primary minerals in igneous and metamorphic rocks. Muscovite is found as flakes in sedimentary rocks. Common in pegmatites	Series of very platy hydrated K-, Mg- and Fe-bearing alumino-silicate minerals	Almost colourless to golden or dark brown
Pyroxene Group Includes **augite** (common) and **enstatite** (magnesium-rich) and **diopside** (calcium-rich)	Common in high-temperature gabbros and dolerite, and ultramafic rocks of mantle origin	Complex alumino-silicate series with variable Ca, Mg, Fe and Na	Dark brown, green or yellowish crystals
Amphibole Group Includes **hornblende** (common), **tremolite** and fibrous **riebeckite** (blue asbestos)	Common in intermediate and mafic igneous rocks and alkaline rocks. Very common in metamorphic amphibolite	Complex hydrated alumino-silicate series with variable Ca, Mg, Fe and Na	Dark brown or green; often altered to chlorite
Olivine Series End-members are **fosterite** and **fayalite**; gem quality is called '**peridot**'	Common in high-temperature ultramafic rocks (peridotite, komatiite) and in some mafic and metamorphic rocks	Series ranging from magnesium-rich Mg_2SiO_4 to iron-rich Fe_2SiO_4	Green to brownish; alters to serpentine.

Name and varieties	Occurrence	Essential chemistry*	Colour
Epidote Group Includes **zoisite**; the rare blue-mauve form is called '**tanzanite**'	Widespread metamorphic and hydrothermal mineral found mostly in altered igneous rocks and in veins	Complex hydrated alumino-silicate series with variable Ca and Fe	Pistachio or dark green, also orange to reddish
Garnet Group Numerous species including **almandine, andradite, grossular** and **pyrope**	Widespread in high-grade metamorphic schist, gneiss and marble; pyrope is found in kimberlite	Complex alumino-silicate series with variable Fe, Ca and Mg	Dark red to brown to blackish, or yellowish to orange
Chlorite Group A general name for several mineral species, the most common being **clinochlore**	Widespread and formed by breakdown of primary alumino-silicates. Also a low-grade metamorphic mineral and found in fine-grained sedimentary rocks	Clay-like, complex hydrated alumino-silicate series with variable Fe and Mg	Usually greenish, fine-grained and earthy
Kaolinite Common in a group of secondary clay minerals, often massive; used to make pottery	Formed from breakdown of feldspar minerals by weathering or alteration, and in fine-grained sedimentary rocks	Complex hydrated K-rich alumino-silicate	Usually whitish or creamish, fine-grained and earthy
Calcite and Dolomite Common carbonate mineral species, found as discrete grains, as mineral cement and as rock-making minerals	Sedimentary limestone and dolostone, found as matrix cement, as secondary calcrete, and as travertine. Also in metamorphic marble	Carbonate minerals, $CaCO_3$ or $CaMg(CO_3)_2$	Usually whitish (calcite) to greyish (dolomite)
Iron ores Includes **magnetite, hematite** and **limonite** (iron-rich); **ilmenite** (titanium-rich) and **chromite** (chromium-rich)	Most within mafic igneous rocks, either as concentrated layers or accessory minerals. Hematite and limonite are more oxidised forms, usually secondary in nature	All Fe-oxide minerals, which may also contain Ti, V and Cr	Black to grey metallic minerals; hematite is reddish; limonite is 'rusty'
Sulphide minerals Carriers of economic metals such as copper, zinc, lead, nickel plus gold and platinum metals	In many rock types as accessory or rare minerals. They form under reducing conditions, and oxidise rapidly near surface	Commonly include **pyrite** and **marcasite** (both FeS_2) and **pyrrhotite** ($Fe_{1-x}S$)	Brassy or bronzy, metallic appearance

*Elements mentioned in Table 1

Ca – calcium
Cr – chromium
Fe – iron
K – potassium
Mg – magnesium
Na – sodium
O – oxygen
S – sulphur

Al_2O_3 – alumina molecule
CO_2 – carbon dioxide
Si – silicon
SiO_2 – silica molecule
Ti – titanium
V – vanadium
Hydrated – contains water, H_2O

Rock types and their classification

Over the years geologists have delighted in giving names to different types of rock, often naming them after the place where they were first found. The result is that there are hundreds of rock names, but these can be resolved to fewer than 50, and divided into three fundamental rock groups: **igneous, sedimentary** and **metamorphic**.

Igneous rocks

Deep within the Earth, magma (molten rock) is generated and rises through the crust. Before reaching the surface, and sometimes at great depth, it may slowly cool and crystallise into solid rock; rocks formed in this way are known as intrusions, and form plutons (igneous rock bodies), dykes and sills (vertical and horizontal sheets). If magma reaches the Earth's surface, the red-hot molten lava erupts into the atmosphere, or sometimes under water, cools very quickly and forms extrusions. Volcanic eruptions form rocks of this igneous type. Igneous rocks were the first to form on primordial Earth more than 4,000 million years ago, and many different types of such rock have evolved over geological time. As shown in **Table 2**, the classification of igneous rocks depends on both rock chemistry (shown by mineral composition) and grain size, which is linked to the depth at which it solidified.

Grain size: Igneous rocks are described as being coarse-grained, medium-grained or fine-grained to glassy, and the size of mineral crystals that form depends on the time it took the magma to crystallise. The rate of cooling depends on their depth within the crust: deep, slow-cooling magma results in a coarse-grained rock (e.g. granite plutons); at a shallow depth the rocks formed have cooled somewhat faster and are medium-grained (e.g. dolerite sills); and magma that reaches the surface cools quickly and results in fine-grained rocks (e.g. basalt lava).

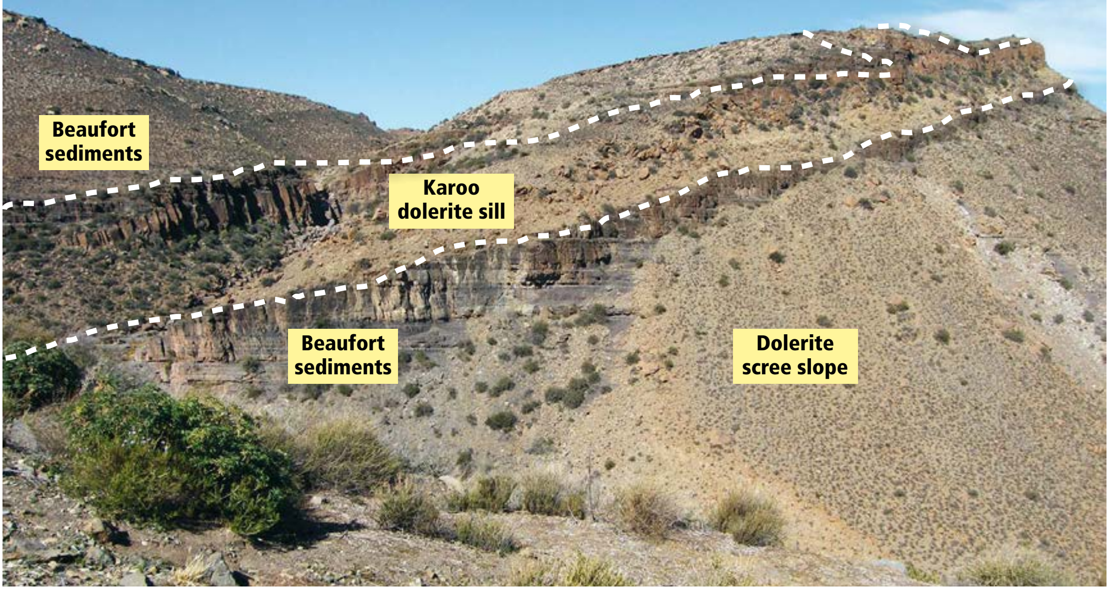
Mineral composition: Depending on the chemical composition of the magma, a range of different minerals will form, resulting in

Table 2

CLASSIFICATION OF COMMON IGNEOUS ROCKS

Igneous rocks are classified into three categories according to grain size (average size of crystals) and four classes depending on mineral composition, mainly silica content.

	Felsic High silica, light-coloured	**Intermediate** Moderate silica, medium-coloured	**Mafic** Low silica, dark-coloured	**Ultramafic** Very low silica, dark-coloured
Common rock-forming minerals	Quartz, alkali feldspar and micas	Alkali feldspar, amphiboles	Plagioclase feldspar, amphiboles and pyroxenes	Olivine, pyroxenes and serpentine
Volcanic Fine-grained to glassy (<1mm)	Rhyolite, Felsite and Trachyte	Andesite	Basalt	Komatiite (rare)
Hypabyssal Medium-grained (1–5mm)	Microgranite and Granophyre	Microdiorite	Dolerite and Diabase	Kimberlite and Carbonatite – also as volcanic phases
Plutonic Coarse-grained (>5mm)	Granite, Granodiorite and Pegmatite	Diorite, Syenite and Foyaite (rare)	Gabbro, Norite and Anorthosite	Pyroxenite, Peridotite and Dunite



Shown here in the Teekloof Pass is a thick, northward-dipping sill of Karoo dolerite, intruded into horizontal blueish-grey shales of the Beaufort Group. These extensive sills form the most resistant part of the Great Escarpment in the Nuweveld Mountains south of Fraserburg. Notice the columnar jointing on the upper left side.

A much younger mafic (dolerite) dyke several metres thick cuts cleanly across very much older highly deformed gneiss in the valley of the dry Sand River near Musina.

different rock types, and these minerals will also start to crystallise at different temperatures. Rocks with high silica content are called 'felsic' (rich in feldspar and quartz), those with less silica are called 'intermediate', those with lower silica are called 'mafic' (rich in magnesium and iron) and those with very low silica are termed 'ultramafic' rocks.

Sedimentary rocks

The Earth's crust is unstable and dynamic, and erosion of the early igneous rocks, transport of detritus by streams and rivers, and deposition of resulting sediment into the oceans led to the formation of the first sedimentary rocks. Gradually, thick deposits of sedimentary material that accumulated on continental shelves, in ocean basins or troughs became consolidated into hard rock. Over geological time deposited sediment became buried, compacted and cemented, and eventually formed hard rock through a process called 'lithification', which takes millions of years.

Not all sediment is deposited in deep water; for example, much of the sediment deposited in the slowly sinking Karoo Basin is alluvial – deposited by periodic flooding of major rivers that crossed vast flood plains. In the same way that the deposits in ocean basins became lithified, so did the thickly accumulated alluvial sediment.

Classes of sedimentary rock: Three different classes of sedimentary rock are formed: clastic, chemical and organic, and these are classified primarily by grain size and their mineral composition.

Clastic rocks (**Table 3**) are formed from sedimentary detritus deposited as thick or thin beds or strata, under a wide variety of conditions: on the floor of seas and oceans, on growing river deltas entering the sea (deltaic sediments), along river flood plains (fluvial sediments), on offshore bars and beaches (shallow marine sediments) and in lakes and estuaries (lacustrine and estuarine sediments). Volcanic eruptions can also produce sedimentary deposits, called 'agglomerates' (coarse, and found near the volcanic source) or 'tuffs' (fine volcanic ash) resulting from atmospheric fall-out, either into water or on land. Tillite (also called 'diamictite') forms unsorted beds derived from rock debris deposited by glaciers and ice sheets. Strong wind also forms fine-grained aeolian sedimentary deposits that are essentially ancient sand dunes.

Less common are sedimentary rocks of chemical or organic origin, formed by chemical deposition under more restrictive environmental conditions, e.g. limestone, banded iron formation or chert, while organic-rich rocks are represented by oil shale, coal or some types of biogenic limestone (**Table 4**).

Table 3

CLASSIFICATION OF SEDIMENTARY ROCKS OF CLASTIC ORIGIN

Clastic rocks are categorised according to grain size, a feature of how deposition took place, ranging from extremely coarse-grained to very fine-grained.

Rock type	Consists of	Grain or particle size	General rock description
Conglomerate	Rock fragments, boulders and pebbles	Very coarse, >2.5mm	Very coarse and heterogeneous forming a concrete-like mixture. The gold-bearing Witwatersrand conglomerates are well known
Sandstone and grit	Sand, usually quartz-rich, also feldspar	Coarse to medium, 2.5–0.05mm	Generally made of quartz sand but may contain other resistant minerals. Usually shows bedding and cross-bedding
Siltstone	Silt, usually quartz-rich, also feldspar	Fine, 0.05–0.005mm	Transitional grain size between sandstone and mudstone, may be quartz-rich and contain less clay
Mudstone and shale	Mud and clay	Very fine, <0.005mm	Deposited in either deep water or as river 'overbank' deposits. Shale is well layered, mudstone is more massive
Agglomerate and tuff	Erupted volcanic debris and ash	Variable, very coarse to very fine	Made from volcanic debris that was explosively ejected. May have been deposited on land or in water
Tillite (diamictite)	Unsorted rock debris moved by ice sheets and glaciers	Very variable	Essentially a type of conglomerate formed by clastic deposition from melting ice

Table 4

CLASSIFICATION OF SEDIMENTARY ROCKS OF CHEMICAL AND ORGANIC ORIGIN

Chemical sediments are usually very finely layered as a result of slow deposition under very calm conditions; organic rocks, such as coal beds or limestone, are variable.

Rock type	Consists of	Grain or particle size	General rock description
Limestone and dolostone	Carbonate mud, algal layers or stromatolites; or compacted coral	Fine to medium; some may contain shells	Usually thick deposits of organically derived carbonate. Dolostone is formed by partial replacement by $CaMg(CO_3)_2$. Some limestones are from coral reefs
Chert	Precipitated or replaced crypto-crystalline silica	Very hard, flinty rock, extremely fine-grained	Usually associated with beds of dolostone and banded ironstone. It is dense and resists weathering
Banded ironstone	Precipitated iron oxides, carbonate and silica	Very fine unless later recrystallised	Extremely well banded, usually with alternating layers of iron oxides, chert and jasper
Coal and peat	Carbonised plant material	Fine, semi-crystalline in part	Plant debris, often with minor impurities, accumulated under swampy, oxygen-free conditions
Black shale and oil shale	Accumulated fine organic matter and other fine sediment	Fine-grained, may contain carbon-rich layers	Very dark-coloured, shale-like, consists of fine organic material deposited under oxygen-free conditions
Calcrete and silcrete	Re-deposited carbonate or silica found near surface	Variable, from hard, fine to crumbly	'Younger' deposits of secondary origin capping older land surfaces. Cementing material is derived from underlying rocks

The rock formations at Brenton Beach near Knysna were originally sand dunes deposited by strong coastal wind and later consolidated into hard dune rock. The rugged outcrops are now again being worn down into sand by wind and sea erosion.

Grain size: The grain size of clastic sediment (much more common than rocks of chemical or organic origin) depends on the energy of the water that transported it or reworked it, and ranges from very coarse gravels to fine muds. Coarse gravels that form pebble beds, and ultimately conglomerates, are deposited by fast-flowing rivers and streams, usually when in flood, and often reworked along beaches. Sand is carried further out to sea, coarser sand and grit being deposited first, the finer sand being deposited in deeper water. Strong currents along the coast and advancing or retreating sea levels that result in prograding or retrograding conditions constantly rework the deposits. Silt-size particles are deposited still further away in deeper water, eventually forming siltstone, followed even further away by clay-size particles that ultimately form shale.

Metamorphic rocks

Metamorphic rocks (**Table 5**) are either igneous or sedimentary rocks that have been transformed, physically and/or chemically, under extreme conditions. In a region that is geologically as old and complex as southern Africa it is not surprising that metamorphic rocks make up an important part of the geology. These rocks have formed in places where large-scale crustal processes related to plate tectonics have involved the deep burial and compression of rock formations, or where heat and pressure within the Earth's crust (lithosphere) have radically changed the original rock formations. The metamorphic process takes several different forms: rocks can be transformed by being subjected to intense heat from an igneous intrusion (thermal or contact metamorphism); by being compressed by strong folding on a large scale (dynamic metamorphism); or by being buried deeply (burial or regional metamorphism).

Table 5

CLASSIFICATION OF ROCKS OF METAMORPHIC ORIGIN			
Metamorphic rocks originate from earlier rock types that have been substantially altered and changed. Metamorphic intensity results in rocks varying from low-grade to high-grade (not shown here), characterised by new metamorphic minerals and/or new textures.			
Metamorphic rock	**Original rock**	**Texture and grain size**	**Produced by**
Amphibolite	Mafic lava and intrusive, or some sedimentary rocks	Medium-grained, usually foliated or gneissic	Alteration of pre-existing mafic rocks or some iron- and lime-rich sediments, under high-grade metamorphism
Gneiss	Granite or granodiorite	Streaky, banded and coarse-grained	Regional metamorphism of granitic rocks, or highly altered sedimentary formations
Hornfels	Mudstone or shale	Hard, fine-grained and locally baked	Contact (heat) metamorphism of fine-grained sedimentary rock, usually of local occurrence
Marble	Limestone	Usually massive to granular	Metamorphic recrystallisation of pre-existing rock, usually made of calcite grains plus impurities
Migmatite	Gneiss and granite	Strongly veined, coarse-grained and streaky	Large-scale partial melting of banded gneiss and invasion by granitic veins, at high temperature
Phyllite and schist	Fine-grained clastic or volcanic rock	Medium- to fine-grained, platy texture	Low- to medium-grade metamorphism under strong folding, typically contains flaky micas or talc
Quartzite	Sandstone	Medium-grained, granular, usually shows bedding	Regional metamorphism of clean sandstone beds; original quartz grains have become recrystallised
Slate	Shale or mudstone	Fine-grained, very good platy cleavage	Strong folding and low-grade metamorphism of shale, to form very well-foliated rock, with platy layers

How sedimentary geological formations are made

‘Supergroups’ generally cover a large area, while ‘groups’ may cover a more limited area. Each is formed under unique sedimentary (or sometimes volcanic) depositional conditions and can be dated to a particular geological period. The nature of the geological sequence that forms is a reflection of the type and size of basin or trough into which eroded rock or volcanic material has accumulated over an extended period of geological time.

At some stage crustal conditions around basins change, ending the deposition of sediments; and if sedimentary deposits in a basin are buried deep enough, they will eventually harden to form sedimentary rock by a process called ‘lithification’ – and so make up new formations that may ultimately become part of a new group or even supergroup.

Later, other forces in the crust may come into action: over time, the now lithified sedimentary basin may be slightly tilted, or involved in a major episode of folding or thrusting, or become faulted or rifted, or be intruded by igneous rocks, and the original formations may become metamorphosed and perhaps extremely deformed. After the elapse of considerable geological time, and possible crustal uplift, erosion and planation, conditions may result in another sedimentary basin being formed, and a new group or supergroup being deposited on top of the older one. It is the task of geologists to recognise these differences and categorise rocks in their correct stratigraphic and structural framework.

Geological formations

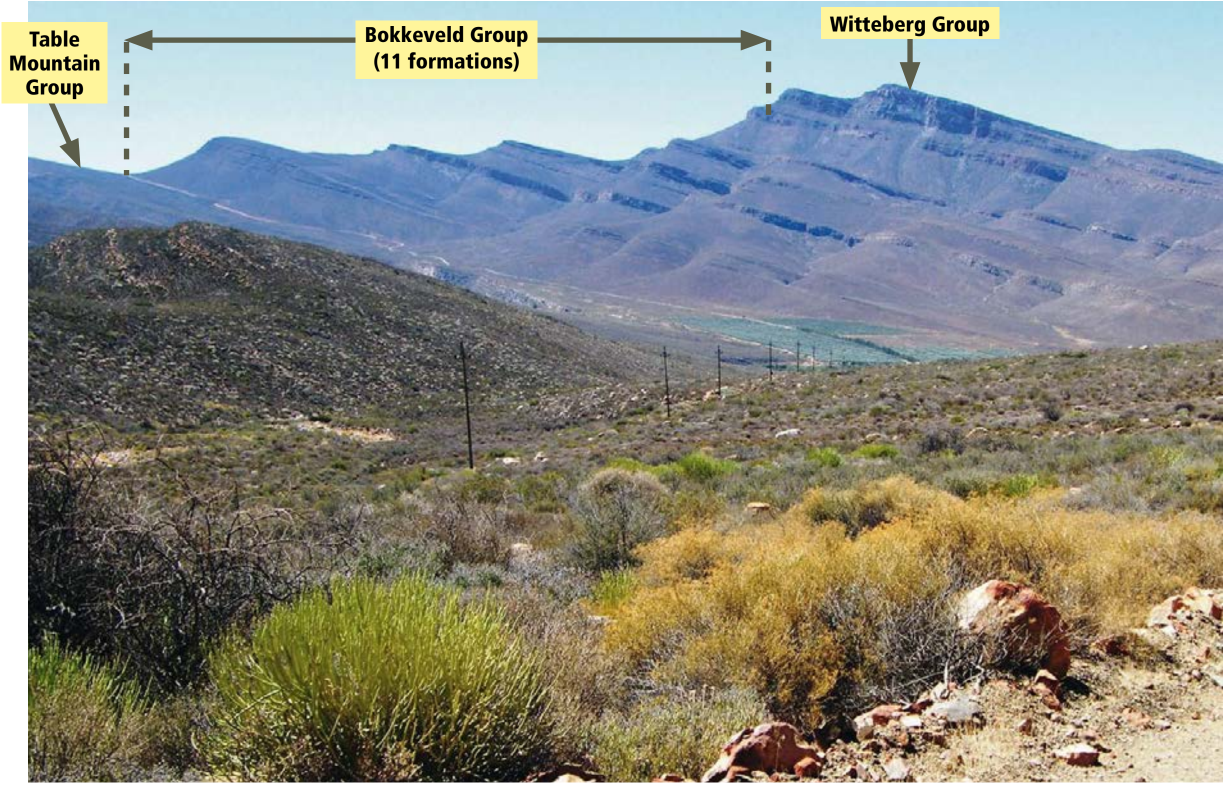
The recording and mapping of geological formations follows a standard, internationally accepted system of classification based on their geological characteristics. For all sedimentary and most metamorphic rocks this hierarchical system starts at the level of the supergroup and cascades downwards into groups (and sometimes subgroups), formations, members and finally beds. The system is underpinned by the Geological Timescale (**Table 6**, see p.24), which puts each geological sequence into its correct time context. This branch of geology is known as stratigraphy and in South Africa is managed by the South African Committee for Stratigraphy. All geological formations in South Africa have their place within a country-wide and well-documented scheme of classification, and are relatively fixed in geological time.

It is easiest to understand the naming process by means of a South African example that is familiar to most. The **Karoo Supergroup**, which covers about 65% of the country, is made up of six major ‘groups’, which are, from the bottom upwards, known as the **Dwyka**, **Ecca**, **Beaufort**, **Stormberg**, **Drakensberg** and **Lebombo Groups**, the latter two being of volcanic origin. These six groups were deposited within the enormous Karoo Basin over a period of about 120 million years, during which time the basin slowly subsided and shrank in area. Each group is made up of several distinct ‘formations’; for example, the **Stormberg Group** comprises the **Molteno**, **Elliot** and **Clarens Formations**, which overlie each other and were formed in the same shrinking basin under different depositional conditions, and are locally subdivided even further.

This same principle is followed for all geological sequences in South Africa, from supergroup downwards, and they are usually named according to geographic place names or areas where the geology is representative of a particular group or formation. For example, the picturesque village of Clarens lends its name to the surrounding very characteristic sandstone, the **Clarens Formation**, and the same name is used for the identical formation that may be hundreds of kilometres away.

Intrusive igneous rocks, such as the well-known intrusion of the Bushveld, are collectively referred to as a 'complex', or in part as a 'suite', for example the **Rustenburg Layered Suite**. Similarly, the numerous granitic plutons in the Western Cape are collectively referred to as the **Cape Granite Suite**. A large number of intrusive dykes may be called a 'swarm', usually with a descriptive name such as the **Pilanesberg Dyke Swarm**; and in the case of numerous related intrusives, a 'province' – for example, the **Karoo Igneous Province**. Large areas of strongly metamorphosed and deformed rocks are also referred to as 'provinces', such as the **Namaqualand Metamorphic Province**; or if there are substantial differences in parts, as 'terrains', for example the **Bushmanland Terrain** of Namaqualand.

The simplified geology of South Africa is illustrated in **Figure 2** on p.13, showing the geology down to group level – generally good enough to get an understanding of the regional picture. This is to be read with the Stratigraphic Key on the inside back cover, which lists all the major groups in order of age, ranging from the oldest rocks of the greenstone belts, at about 3,570 million years, to Recent formations that are less than 1 million years old.



The entire east-dipping Bokkeveld Group is displayed in this classic view taken in the eastern Cederberg near Grootrivier-hoogte. The group forms a continuous sedimentary depositional sequence of 11 distinct and alternating formations, six of mudstone and siltstone, and five thinner layers of sandstone. These units where deposited within the same ocean basin but under a variety of conditions, and over a long period of time within the Devonian. The base (far left) is the underlying Table Mountain Group and the top-most sandstone ridge is the start of the overlying Witteberg Group.

Geological time

One of the most challenging geological concepts is understanding the immensity of ‘geological time’, as well as mastering the confusing and unfamiliar terminology that portrays it. We can perhaps appreciate events that took place thousands, or even tens of thousands of years ago, and maybe even a million years does not stretch our imagination too far. But to think in terms of many millions – or even billions – of years is incredibly challenging. Nevertheless ‘geological time’ is an unalterable fact of science and one we have to accept.

Today, geological time (also called ‘deep time’) starts with the Hadean Eon, lasting from the creation of the Earth around 4,600 million years ago to the start of the Archaean Eon 4,000 million years ago. Geoscientists continue to push that number back towards a time when the Earth was still a slowly cooling molten mass. At present the oldest dated rock formations come from Canada, either the Acasta gneiss of North West Territory (dated at 4,031 million years) or the Nuvvuagittug greenstone of northern Quebec (4,280 million years), but the latter is still being debated. The oldest measured geological sample (not a rock) is a minute zircon crystal that comes from the Yilgarn Craton in Western Australia; it has been dated at 4,404 million years, and is thought to represent the probable age of the Earth’s first crust.

Over the years earth scientists have constructed a workable, albeit extremely detailed Geological Timescale, which is regularly updated and refined by the International Commission on Stratigraphy. This timescale is divided into four Eons, 10 Eras, 12 post-Cambrian Periods and numerous Epochs and Ages, but only those intimately involved are able to comprehend the system fully. In the geological site descriptions that follow, only Periods (for example Cretaceous or Jurassic) will generally be used for Cambrian

Dating and naming of rock formations

In the early 19th century scientists in Europe began systematically to study the nature and order of geological sequences. Age differences began to be recorded of the different layers of fossil-bearing sedimentary rocks, keeping in mind the Law of Superposition – that sedimentary layers are deposited in a time sequence, with the oldest layer at the bottom and the youngest layer at the top. At that stage geological time could only be measured in relative terms, i.e. one rock formation was seen to be older than another. Periodic changes in the type and number of fossils in the various strata resulted in different geological formations being identified and named, the names being derived from local places, and these are generally still in use today. For example, the name of the Cambrian Period comes from ‘Cumbria’, the ancient name for Wales, where rocks of this age were first studied; similarly, the name for the Jurassic Period comes from the Jura Mountains that lie between France and Switzerland. At that stage fossils were the most important and reliable indicator of geological age and correlation, but in South Africa this does not work for Proterozoic rocks, formed at a time before hard-shelled life existed.

It was only in the early 20th century that the discovery of radioactive dating methods changed the way rocks could be dated. This method uses the principle of naturally occurring radio-isotopes that decay at known, fixed rates over geological time. Provided that the right minerals exist in a rock, and that later geological events have not re-set its internal geological clock, it is possible to measure absolute ages with great precision.

and younger time, while Eons (for example the Proterozoic or Archaean) will be used for the much more distant Proterozoic time. The most up-to-date information on the Geological Timescale, considerably simplified, is shown in **Table 6**. Also shown in the context of geological time are major events that have affected South Africa's geology, including five major extinctions, and a probable sixth now in progress.

Table 6

NB: NOT TO SCALE

GEOLOGICAL TIMESCALE AND MAJOR EARTH EVENTS IN SOUTHERN AFRICA'S PAST

EON	ERA	PERIOD		EPOCH	LOWER AGE (MY)	SOME MAJOR EARTH EVENTS IN SOUTHERN AFRICA – MILLIONS OF YEARS AGO (MY)
PHANEROZOIC	CENOZOIC	QUATERNARY		HOLOCENE	RECENT	6th MASS EXTINCTION NOW IN PROGRESS
				PLEISTOCENE	2.6	TSWAING METEORITE ~200KY
		NEOGENE	TERTIARY PERIOD	PLIOCENE	5.3	HOMINIDS APPEAR ~3MY
				MIOCENE	23	MAMMALS GREATLY DIVERSIFY DURING THE TERTIARY
		PALAEOGENE		OLIGOCENE	34	
				EOCENE	56	
				PALAEOCENE	66	
	MESOZOIC	CRETACEOUS			145	5th MASS EXTINCTION ~65MY MOROKWENG METEORITE IMPACT ~145MY
		JURASSIC			201	KAROO VOLCANISM ~183MY
		TRIASSIC			252	4th MASS EXTINCTION ~210MY FIRST MAMMALS DEVELOP
	PALAEOZOIC	PERMIAN			299	3rd MASS EXTINCTION ~252MY
		CARBONIFEROUS			359	FIRST REPTILES DEVELOP
		DEVONIAN			419	2nd MASS EXTINCTION ~354MY
		SILURIAN			443	FIRST LAND PLANTS DEVELOP
		ORDOVICIAN			485	1st MASS EXTINCTION ~440MY
		CAMBRIAN			541	CAMBRIAN EXPLOSION OF LIFE
PROTEROZOIC	NAMIBIAN*	1,000	PRECAMBRIAN	LATE PROTEROZOIC	1,000	EDIACARAN FAUNA ~560MY SNOWBALL EARTH ~700MY
	NAMAQUAN*	1,600		MIDDLE PROTEROZOIC	1,600	PILANESBERG COMPLEX ~1,200MY
	KHEISIAN*	2,057		EARLY PROTEROZOIC	2,500	OXYGENATION OF ATMOSPHERE ~1,900MY VREDEFORT IMPACT ~2,020MY BUSHVELD COMPLEX ~2,060MY
ARCHAEAN	VAALIAN*	2,650		LATE ARCHAEAN	2,800	VENTERSDORP VOLCANISM ~2700MY
	RANDIAN*	3,200		MIDDLE ARCHAEAN	3,200	1st MICRO-CONTINENT FORMS ~3,200MY
	SWAZIAN*	3,600		EARLY ARCHAEAN	3,600	1st BACTERIAL LIFE FORMS ~3,400MY EARLIEST OCEANIC CRUST ~3,500MY
				VERY EARLY ARCHAEAN	4,000	
			HADEAN		4,600	CREATION OF EARTH ~4,560MY

*The older South African-named Eras are now obsolete, and have been replaced by Epochs of the International timescale, as shown.

Adapted from the *International Chronostratigraphic Chart*

The Rock Cycle

It is useful to understand why and how there are continual changes within the rocks of the Earth's crust, albeit over geological time. The Earth is a dynamic planet and is in constant motion, a never-ending cycle of rock creation, modification, destruction and re-creation. The original theory is attributed to James Hutton, one of the early founders of modern geology, who in his famous 1788 treatise, *Theory of the Earth,* wrote: 'The result therefore of our present enquiry is that we find no vestige of a beginning and no prospect of an end.' This idea was popularised in Charles Lyell's *Principles of Geology* first published in 1830, which significantly influenced both Charles Darwin and road-builder and amateur geologist Andrew Geddes Bain, who lived and worked in South Africa. The essential point is that, over geological time, the rocks that make up the Earth are continually changing from one type to another by geological processes; put simply, the Earth is a great recycling machine. This is the concept of the Rock Cycle, as illustrated in **Figure 3** below.

The process starts with the creation of magma, which then cools and solidifies to form igneous rock. Exposed to the elements, this igneous rock becomes weathered and eroded, creating sediment, which is transported by wind and water and eventually deposited in a sedimentary basin, where it becomes compacted and cemented to form sedimentary rock formations. Under conditions of heat and pressure these sedimentary rocks may eventually become modified to produce metamorphic rock, which could become re-melted to produce magma, and thus the cycle is repeated.

This idealised cycle can be 'short-circuited': for example, under suitable conditions igneous rock can change directly into metamorphic

Figure 3: The fundamental Rock Cycle in which new rocks are constantly created as old ones are destroyed.

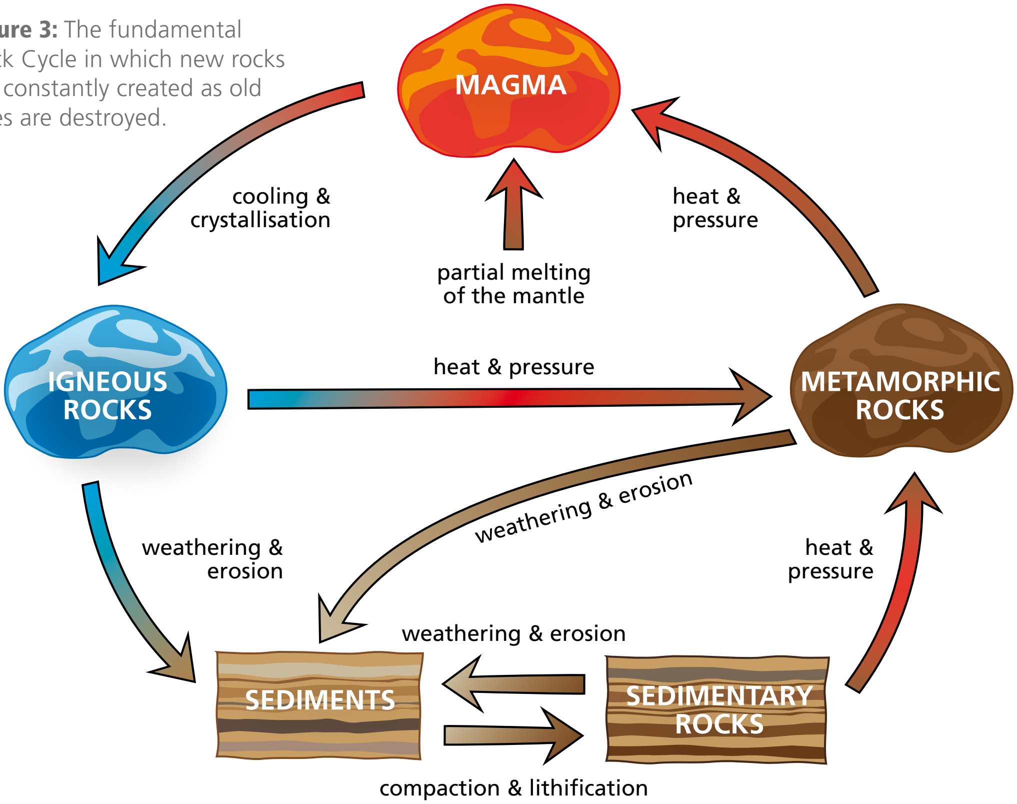


Plate tectonics – the movement of crustal plates

The Earth's rigid outer shell (the lithosphere) is composed of about 18 major plates and sub-plates that are able to move, albeit very slowly, on the underlying plastic upper mantle. These semi-rigid plates that make up the Earth's surface are constantly moving slowly relative to each other; they are said to 'jostle', an indication that Earth is a dynamic planet. Both oceanic crust (~7km thick) and continental crust (~35km thick) are extremely thin in comparison to the diameter of the Earth (~6,370km). It is at the boundaries or margins of plates that may be moving apart (divergent), or moving together (convergent) or moving past each other (transcurrent) that the dynamic interaction takes place, causing rifting, faulting, folding, thrusting, earthquakes and new igneous activity. Some of the overwhelming evidence includes:

- Sea-floor spreading (creating new oceanic crust) along the Mid-Atlantic Ridge where the African and South American Plates are moving apart at a rate of about 4cm per year (40km in a million years).
- The devastating earthquakes, tsunamis and regular volcanic activity around Indonesia, where the Indian-Australian and Eurasian Plates are converging and subduction is taking place (old crust being destroyed).
- Massive mountain building, deep crustal melting and volcanic activity in the Andes fold mountain chain along the west coast of South America, where the oceanic Nazca Plate is being forced under the continental South American Plate.

rock; or metamorphic rock can be weathered and eroded to produce sediment; or, as is often the case, old sedimentary rock can be recycled into new sedimentary rock.

The entire process is driven by the ongoing movement of crustal plates, known as the Theory of Plate Tectonics (see text box above). Plate tectonics explains the creation and closing of ocean basins, the thinning and thickening of the Earth's crust, and the creation of rising plumes of magma. The realisation that the Earth's crustal plates move relative to each other and that oceanic crust is much younger than continental crust was the key to understanding and explaining many fundamental geological phenomena.

The African plate has been almost stationary for the past 30 million years, and the surrounding plates are moving away from it. Thus Africa is the most stable of all the continents, although it is not entirely free of plate tectonic movement: the impressive and tectonically active African Rift Valley is a continental rift zone that extends the entire length of eastern Africa from the Red Sea to Mozambique. It displays a divergent plate boundary in the early stages of break-up, in which the Somali Subplate is in the process of splitting off from the rest of the African Plate. Centred in the Afar Depression, there is a classic triple-point meeting of the Gulf of Aden, the Red Sea and the Ethiopian Rift Valley, which continues southwest into East Africa. It is theorised to have been caused by a rising column of hot mantle material (also called a 'mantle plume') that formed deep beneath the crust, causing massive updoming. This resulted in the development of three rift arms at 120° to each other and considerable magma generation that caused the eruption of flood basalts. It is known as a mantle 'hot-spot'. There was once a similar but failed triple-point development in northeastern southern Africa that resulted in the formation of extensive Drakensberg and Lebombo lavas and Karoo dolerites.

Geological structures

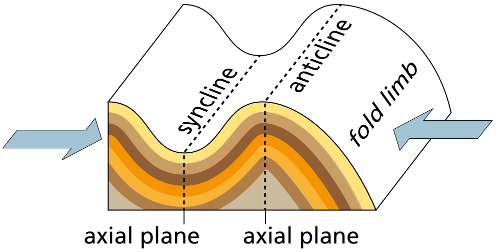
Having looked at the broad picture, it's time to see what happens at a more local scale. Geology is not only about rocks and minerals but includes a variety of geological structures that affect the rock formations, sometimes in a major way. These include folds, faults, thrusts and joints, and landscapes and landforms are usually strongly controlled by these post-formational structures. Many geological exposures owe their spectacular appearance to preferential erosion along bedding layers, fault planes and joint surfaces.

Folds and folding

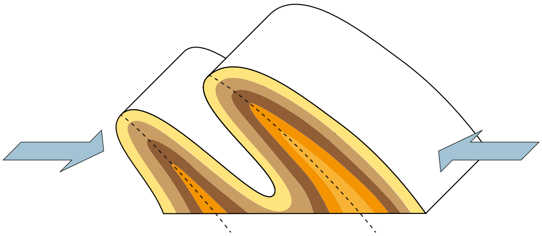
Folds are bends or undulations in sedimentary rocks that start off as being more or less horizontally layered. Folding is seen most clearly in layered, alternating sandstone-shale sequences, where the shaly beds assist with the differential movement of the stronger rock units that takes place during folding. Folding can result in conspicuous structural changes that happen at a wide range of scales, and it invariably involves changes in the nature of the original rocks.

Although often of random appearance, folding invariably follows a systematic and predictable pattern. Beds are initially folded into 'open folds' to produce anticlines and synclines, and with increasing tightness into steeply dipping isoclinal folds (**Figure 4**). Increased compression may result in the formation of overturned folds and eventually recumbent folds. Continued compression may result in low-angle thrust structures. In low-intensity, monoclinal folding only one fold limb is affected. Large-scale folding results in composite and complex fold structures called 'anticlinoria' and the complementary 'synclinoria'.

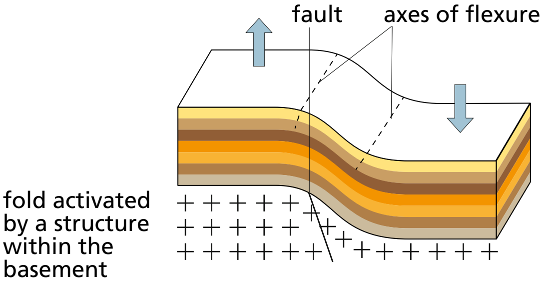
Figure 4: Diagrammatic geological fold structures produced by compression within the upper crust and, in places, by vertical movement within the basement.



Open fold showing simple syncline and anticline



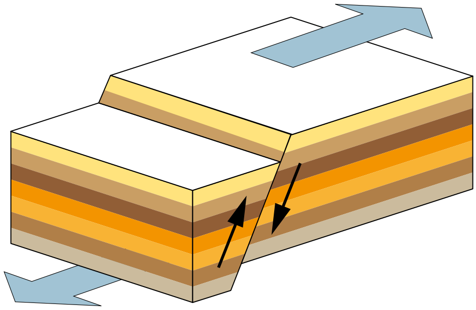
Overturned isoclinal fold – strata have similar dip



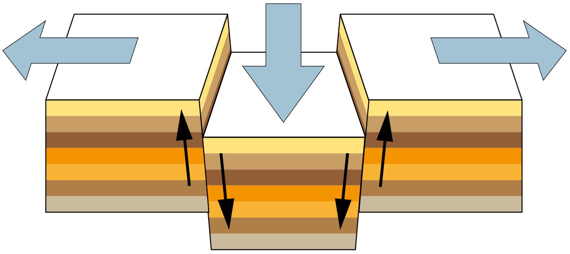
Monoclinal fold

Folding results from horizontal compression exerted during a time of crustal 'closing' (e.g. when two crustal plates move together); the amount of folding varies considerably, depending on the degree of compression, depth of burial and the nature of the rock formations. When rock formations are deeply buried and strongly heated, folding is accompanied by a degree of recrystallisation, or even strong metamorphism. The Cape Fold Mountains of the Western and Eastern Cape show spectacular examples, and different styles of folding are evident in the same area, in some places the rocks apparently having experienced compression of very high intensity.

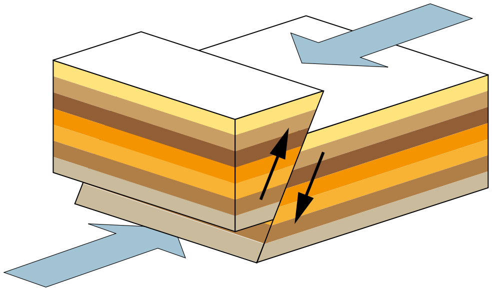
Figure 5: Diagrammatic geological fault structures produced by different stress directions in the crust.



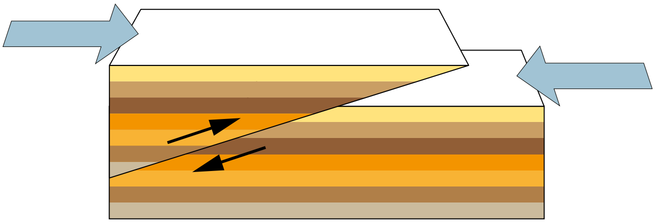
Normal or dip-slip fault



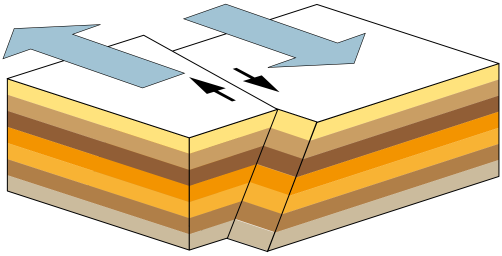
Parallel rift fault and graben structure



Reverse fault



Thrust fault



Wrench or strike-slip fault

Faults and thrusts

Faulting of most geological formations is very common and varies from small-scale to macro-scale, from mere centimetres to many kilometres in length, and of variable movement. A fault is generally a plane-like or slightly curved structure or discontinuity that forms where forces have caused a relative displacement of rocks on either side of the fault plane. If faulting occurs over a wide distance and comprises many smaller, individual faults, the combined effect is called a ‘fault zone’. Depending on its location within the crust, the fault plane will show either brittle fracturing in the upper crust or ductile shearing in the lower crust. On a geological map, a fault will usually be seen as a line that represents where the fault plane projects to the surface. There are several types of faults, depending on the direction of displacement, and whether from tensional or compressive forces (**Figure 5**):

- **Normal or dip-slip faults** are most common, and are due to tension in the crust and include parallel **rift faults**. In South Africa, major normal faults include the Montagu and Worcester Faults, and the step-like faulting in the Soutpansberg seen at Wyllie’s Poort (pp.214–218).

- **Reverse faults** result from compressive forces in the crust. Subduction zones form the largest of this type. An example of this is under the west coast of South America, where large-scale subduction has formed the Andes Mountain chain.
- **Wrench or strike-slip faults** are due to transform (sideways) movement. The San Andreas Fault in California is a major strike-slip fault zone.
- **Thrust faults** are similar to reverse faults but occur at a lower angle, when blocks slide over each other, as seen in Meiringspoort, for example (pp.86–89).
- **Ring faults** (not illustrated) can occur around collapsed calderas and may become filled by magma to form ring intrusions, as seen in the Pilanesberg (pp.248–253).

Fractures and joints

Joints in rocks are planes of brittle fracture that show preferred directions and regular spacing without movement. They are present in almost all surface outcrops and near surface rocks, and they play a major role in weathering and erosion. Almost any vertical rock surface or quarry face will reveal many joints that form a well-defined pattern of preferred joint directions. Joints generally occur as subparallel sets at more or less right angles, or as a strong parallel pattern. Close to the surface, joints are very susceptible to agents of weathering such as water, frost, wind and roots; they become the loci of erosion and play an important role in the development of landscape and landforms, notably controlling weathering in limestone that leads to the formation of caves. Regional scale jointing that is not easily recognised on the ground because we're too close to it often shows up well on Google Earth images. Several distinct types of joints exist and they include:

- **Tectonic joints** formed by subtle rock deformation resulting from minor regional stresses, probably due to earth movement.
- **Unloading joints** formed by release of the overlying compressive load due to erosion, allowing the rock mass to expand.
- **Exfoliation joints** that are similar to unloading joints, typically forming semi-horizontal sheeted layers in partly weathered granitic rocks.
- **Cooling joints** formed by contraction of hot rock masses, including polygonal columnar jointing in basalt or dolerite.

Cooling joints (or columnar jointing) formed within a thick, slowly cooling dolerite sill, seen here at the Valley of Desolation near Graaff-Reinet. Weathering has preferentially exploited the vertical joint planes between the solidified dolerite columns to produce this unusual but not uncommon dolerite landform (see pp.106–109).

Curved exfoliation joints are well developed in places on Paarl Rock and are common to many generally unbroken granite and gneissic bodies around South Africa (see Moon Rocks at Augrabies, p.299). This is the main mechanism for the peeling off of sheet-like granitic layers.

How landforms and landscapes are made

Landforms are natural physical features on the Earth's surface, while landscapes comprise the visible features of an area of land, in particular its natural scenery. The study of geomorphology focuses on the origin, evolution and processes involved in the making of landforms and the creation of landscapes, in which the role of geology is fundamental. Geomorphology is also of importance in disciplines such as agriculture, engineering, environmental studies, archaeology and even warfare.

The Earth's surface is in a continuous process of being worn down by forces of nature – part of the ceaseless Rock Cycle – although the process is almost undiscernible over a human lifetime. In simple terms, landscapes evolve over considerable time, starting with juvenile streams and steep valleys, moving to mature valleys and rounded terrain, and then to lowlands, senile rivers and flood plains. Eventually, this is followed by renewed crustal uplift – and the process starts again.

Geomorphological processes can be divided into four categories: the production of material by weathering; the removal of weathered detritus by erosion; the mass transport of the eroded material; and the deposition of the transported material. Weathering and erosion are geological processes that work closely together to shape the Earth's surface. The term denudation is often used to describe the lowering of a land surface.

Weathering

Rocks are slowly broken down into smaller mineral grains or to secondary minerals by chemical, physical or biological processes, often in combination; and the process is invariably accompanied by distinct changes in colour due to oxidation.

● **Chemical weathering:** This is the decomposition of some or all of the components by natural chemical reactions – a process of natural decay. Breakdown occurs by alteration of primary rock-forming minerals to secondary, softer minerals. For example, alkali feldspar, which decomposes

Deeply weathered and eroding Cape granite, seen on Chapman's Peak Drive near Hout Bay. Feldspar grains have been completely weathered to creamish clay minerals and the quartz is released as sand.

Weathering of the Msikaba Formation sandstone in the Oribi Gorge Nature Reserve is being assisted by a covering of lichen. This is a widespread, slow but potent mechanism for the biochemical breakdown of hard, quartz-rich rocks.

Along the Barberton Makhonjwa Geotrail, deeply weathered dolerite containing remnant boulders shows typical 'onion-skin' (small-scale exfoliation) weathering.

Weathered debris from the eroding high ground of Table Mountain has accumulated in lower areas to produce a soil-covered scree made largely of angular sandstone fragments, seen here in Diepsloot Reserve near Kloof Nek, Cape Town. This is largely a gravitational process.

to form clay minerals, particularly under wet, oxidising conditions. Very mildly acidic rainwater is especially effective in dissolving limestone and forming caves.

- **Mechanical weathering:** Such weathering involves the disintegration of rock by various physical means, including thermal expansion and contraction of minerals, freezing and thawing along fractures, abrasion by wind, grinding by glaciers, and attrition by wave and current action.
- **Biological weathering:** This describes actions such as those of lichens (see p.202) and mosses, of invasive roots causing expansion, of animals burrowing, digging and trampling, and of humans having an impact on the environment.

Erosion

The physical removal of decomposed or disintegrated rock material is very closely associated with weathering. Processes include transport of loose rock fragments of all sizes down mountain slopes (by gravity), along stream beds, in river courses, across plains and along coastlines, always to lower elevations. The main erosional agents are water, wind and ice.

- **Fluvial erosion:** Water run-off is by far the most important erosion agent, carrying away weathered rock debris by means of sheet-flow, and down gullies, streams and rivers. Eventually the transported material reaches a base level at a flood plain or sea, where the load is deposited. Major waterfalls are knickpoints created by changes in geological conditions. River terraces are evidence of slightly lowered base levels, and drowned valleys indicate major changes in sea level.
- **Aeolian erosion:** The sustained action of wind is an effective agent of erosion and sediment transport; it has given rise to today's sandy deserts and huge coastal sand dunes; and windblown deposits of the past were responsible for deposition of the extensive Clarens sandstone. Erosion of rock by wind is commonly seen in the Cederberg's 'sand-blasted' sandstones.