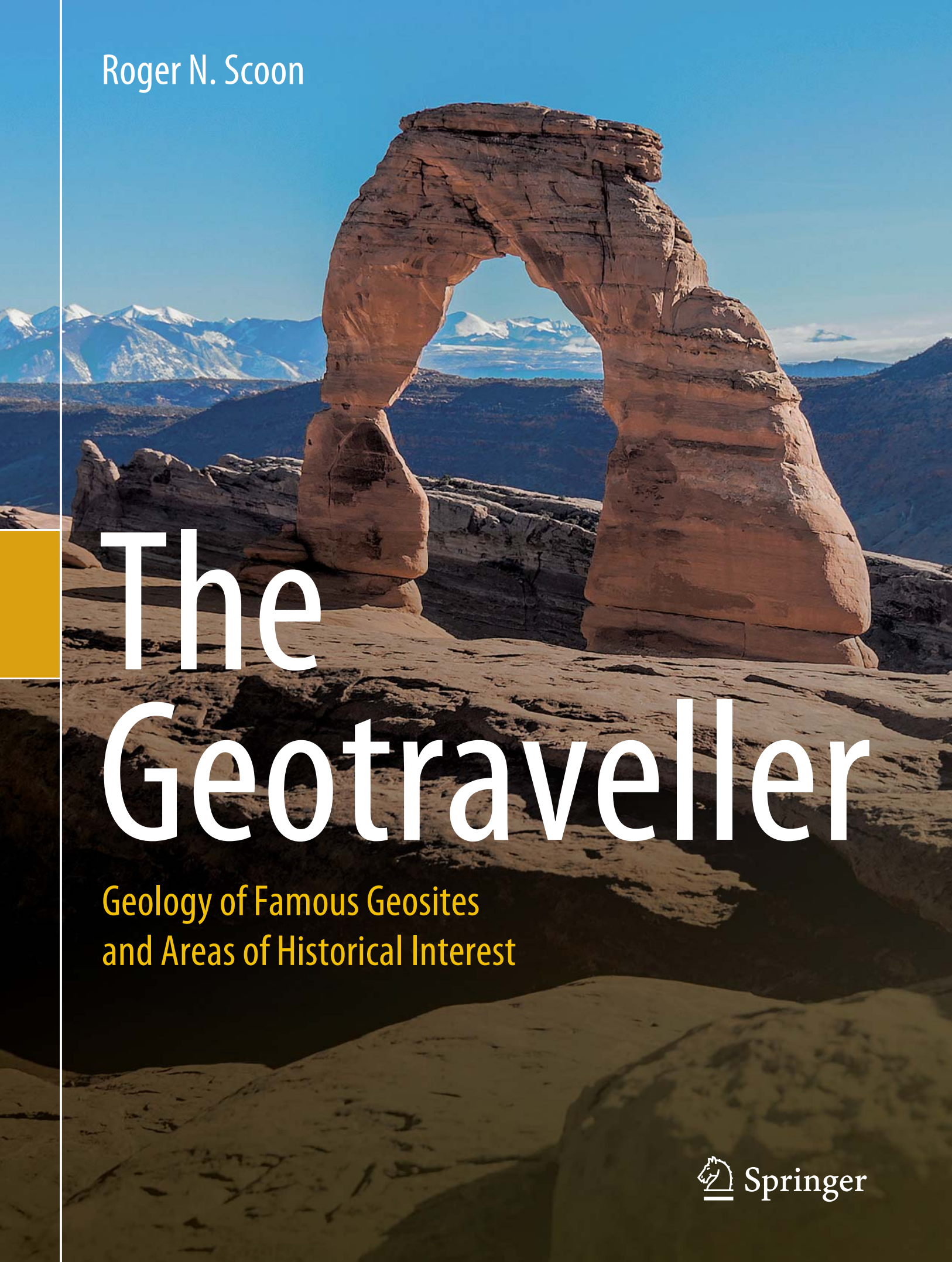
Roger N. Scoon



The Geotraveller

Geology of Famous Geosites and Areas of Historical Interest

Springer

The multi-coloured rocks in the walls of the Yellowstone Canyon illustrate the derivation of the name of the Yellowstone National Park. The brightest patches of colour are due to hot springs and fumaroles that have hydrothermally altered the thick sequences of rhyolitic volcanic ashes and pyroclastics erupted from the Yellowstone Volcano during the most recent of the caldera events. Thin basaltic flows (a subordinate component of the volcanism) that display prominent columnar jointing are intercalated with the rhyolitic ashes and pyroclastics. The hydrothermal features, including the famous geysers, are driven by heat associated with a shallow magma chamber located beneath the Yellowstone Caldera

Roger N. Scoon

The Geotraveller

Geology of Famous Geosites and Areas of Historical Interest

Springer

Roger N. Scoon
Department of Geology
Rhodes University
Grahamstown, South Africa

ISBN 978-3-030-54692-2 ISBN 978-3-030-54693-9 (eBook)
https://doi.org/10.1007/978-3-030-54693-9

Cover photograph: Delicate Arch is the most photogenic of the sandstone monoliths in the Arches National Park, northern Utah. Differential erosion of the gently-dipping Entrada sandstone (Middle Jurassic) is a key component in formation of arches

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The Geotraveller describes the geology of famous geosites and areas of archaeological and historical interest from the USA, Africa, and Europe. Geological descriptions are supported by simplified geological maps and colour photographs. Many of the geosites occur in national parks and reserves, some of which have been upgraded to world heritage sites, while others are located in newly formed geoparks. A Geopark is a unified area that advances the protection and use of geological heritage in a sustainable way and promotes the economic well-being of the people who live there (definition from Wikipedia). There are Global Geoparks and National Geoparks. Many of the geosites not located in parks or reserves could be protected as areas of special interest. The creation of geoparks in areas of outstanding natural landforms is indicative of a growing interest in geological heritage and geotourism.

The Geotraveller is largely based on published geological articles that are not readily accessible to the non-specialist. A short commentary on historical and archaeological features is provided where appropriate. The book is directed at both the professional geologist and the educated layperson. A short glossary is included to assist with the increasingly complex geological nomenclature. The geosites are located on a map (Map A) with the rock sequences indicated on a stratigraphic chart (Map B).

The first section of the book deals with geosites located in North America. Amongst these, the state of Utah in the southwestern USA contains some of the most spectacular landforms on Earth. Giant canyons, free-standing monoliths, and natural sandstone arches are associated with thick sequences of mostly flat-lying Mesozoic strata. Differential erosion of resistant sandstone formations that are interbedded with relatively soft shales and mudstones is a key process in development of landforms at the Canyonlands National Park, as well as at Monument Valley. The natural rock arches at the Arches National Park, possibly one of the most recognizable geological phenomena on Earth, have formed in thick sequences of jointed sandstones associated with the Jurassic-age Entrada Formation (Cover). The Dinosaur National Park contains a museum built over a quarry face where an unusual concentration of dinosaur fossils can be observed in situ within mudstones and shales of the Jurassic-age Morrison Formation. The landscapes of the Yosemite National Park in California have been carved out of Mesozoic granitic batholiths by the action of glaciers and ice sheets. The Late Pleistocene Ice Ages were a global phenomenon, and the deep valleys, waterfalls, and Alpine lakes of Yosemite offer an idealized version of a glaciated landscape. The Yellowstone National Park is not only the world's most well known national park but is also the oldest. The creation of Yellowstone to protect the world's greatest concentration of geothermal features provided the impetus to conserve wilderness areas throughout the world. The geysers, hot springs, and mud pots are driven by heat from an active magma chamber situated beneath the Yellowstone Caldera (Frontispiece). The Yellowstone National Park also offers the opportunity to examine the relationship between geology and large mammals that include bears and bison. The landforms and mountain scenery of the Canadian Rocky Mountains attract millions of tourists annually. The 232 km-long Icefields Parkway in the Banff and Jasper National Parks reveals captivating views of giant U-shaped valleys, snow-clad peaks, icefields and glaciers, and lakes and waterfalls. The Yoho National Park includes exposures of marine fossils associated with the "Cambrian Explosion of Life".

Descriptions of the spectacular geology of East Africa make up the second part of the book. Commentary is provided on the way the geology has influenced the evolution of life, including early hominids. Many of the national parks and reserves in southern Uganda are associated with the Albertine Rift, the western branch of the East African Rift System. The rifting severely impacted drainage patterns within the heart of the African continent, including the upper reaches of the Victoria Nile. The rifting and associated volcanism, a relatively recent phenomena, also impacted the speciation and distribution of fauna and flora, examples of which can be observed in the Murchison Falls and Queen Elizabeth National Parks. The endangered Mountain gorilla is postulated to have evolved in the relatively ancient Bwindi Forest (Uganda), spreading to the younger forests of the Virunga Mountains (Democratic Republic of the Congo, Rwanda, Uganda) in more recent times. The Nyiragongo Volcano in the southern part of the Virunga National Park, Democratic Republic of the Congo, includes a summit crater that contains probably the world's largest and most active lava lake. The Ngorongoro Conservation Area in northern Tanzania reveals a diverse range of landforms, including regional plateaus, volcanic uplands with giant calderas, alkaline lakes, and active and quiescent volcanoes. The biannual migration of grazers on the Serengeti Plains is in part related to nutrient-rich grasses which grow on ashes associated with the Oldoinyo Lengai Volcano. The coexistence of multiple hominid species is an intriguing feature of the palaeoanthropological sites of Oldupai Gorge and Laetoli, localities which have greatly influenced our understanding of human evolution. Initiation of new species by Darwinian evolution during the Pliocene and Pleistocene epochs (5.3 Ma-11,500 BP), including hominins, occurred in remarkably short time intervals. In East Africa, the two epochs were characterized by intense volcanism and extreme climatic cycles (e.g., the Ice Ages).

The third part of the book deals with the complex geology of the Mediterranean. Large parts of the central and eastern Mediterranean remain tectonically active and the volcanoes of southern Italy and the Italian Islands, including Etna and Stromboli, have helped shape the science of volcanology. Parts of southern Italy and eastern Sicily are subjected to severe, even catastrophic earthquakes related to crustal extension. The volcanoes, however, are driven by proximity to an active subduction zone related to collision of the African and Eurasian Plates. The geological features of this region may in part be associated with historical and classical sites, some of which are described in Greek mythology, including Homer's *Odyssey*. The region proximal to the Bay of Naples contains three active or dormant volcanoes, Campi Flegrei, Ischia, and Vesuvius. The historical eruption of Vesuvius in 79 AD affected the Roman cities of Herculaneum and Pompeii, which are of special interest to volcanologists and archaeologists. Many of the famous historical sites and antiquities of southeast Greece, including the Acropolis of Athens, Delphi, and Thermopylae, occur in regions subjected to active tectonism. Tectonism has in part reshaped landscapes, and recent geomorphological reconstructions generally substantiate the classical descriptions. Northwest Greece includes mountainous terrains related to the Alpine Orogeny, in which antiquities and monasteries, including the Meteora, occur in seemingly inaccessible locations. The ancient settlements of the Peloponnese, including Mycenae, typically occur in valleys created by grabens associated with the crustal extension which has followed the Alpine Orogeny. The juxtaposed Alpine tectonic zones are dominated by limestone mountains which supply groundwater to settlements in the valleys. Active and dormant volcanoes of the Hellenic Volcanic Arc include the Methana Volcanic Complex in the Peloponnese and the islands of Milos and Santorini in the Aegean Sea. Milos offers an unparalleled opportunity for geotourism and mining heritage, with geotrails accessing sites including deposits of pumice and agglomerate in spectacular sea cliffs. The Santorini archipelago reveals a large, partially submerged caldera, the formation of which is ascribed to one of the most explosive volcanic eruptions in the historical record. The eruption buried the Minoan city of Akrotiri and may have initiated Plato's legend of the lost continent of Atlantis.

The ancient city of Troy in western Turkey, which reveals nine levels, including the Homeric city of the *Iliad*, is similar to the Greco-Roman antiquities of Ephesus and Pergamum in being located in an active graben. The grabens are subjected to relatively rapid rates of sedimentation which adversely affected harbours in ancient times. The Hierapolis-Pamukkale archaeological and geosite in southwest Turkey includes one of the world's largest deposits of travertine. The travertine, which is a hard, compact variety of limestone, was deposited from hot springs or geothermal waters associated with active graben faults. The travertine has covered large sections of the Hierapolis antiquity. The Cappadocia region of central Turkey contains innumerable natural rock monoliths and pinnacles, together with the largest concentration of underground rock dwellings reported in the world. Many of the most remarkable landforms in this region, including the "fairy chimneys" in the Göreme Historical National Park, are related to differential erosion of recent volcanic deposits.

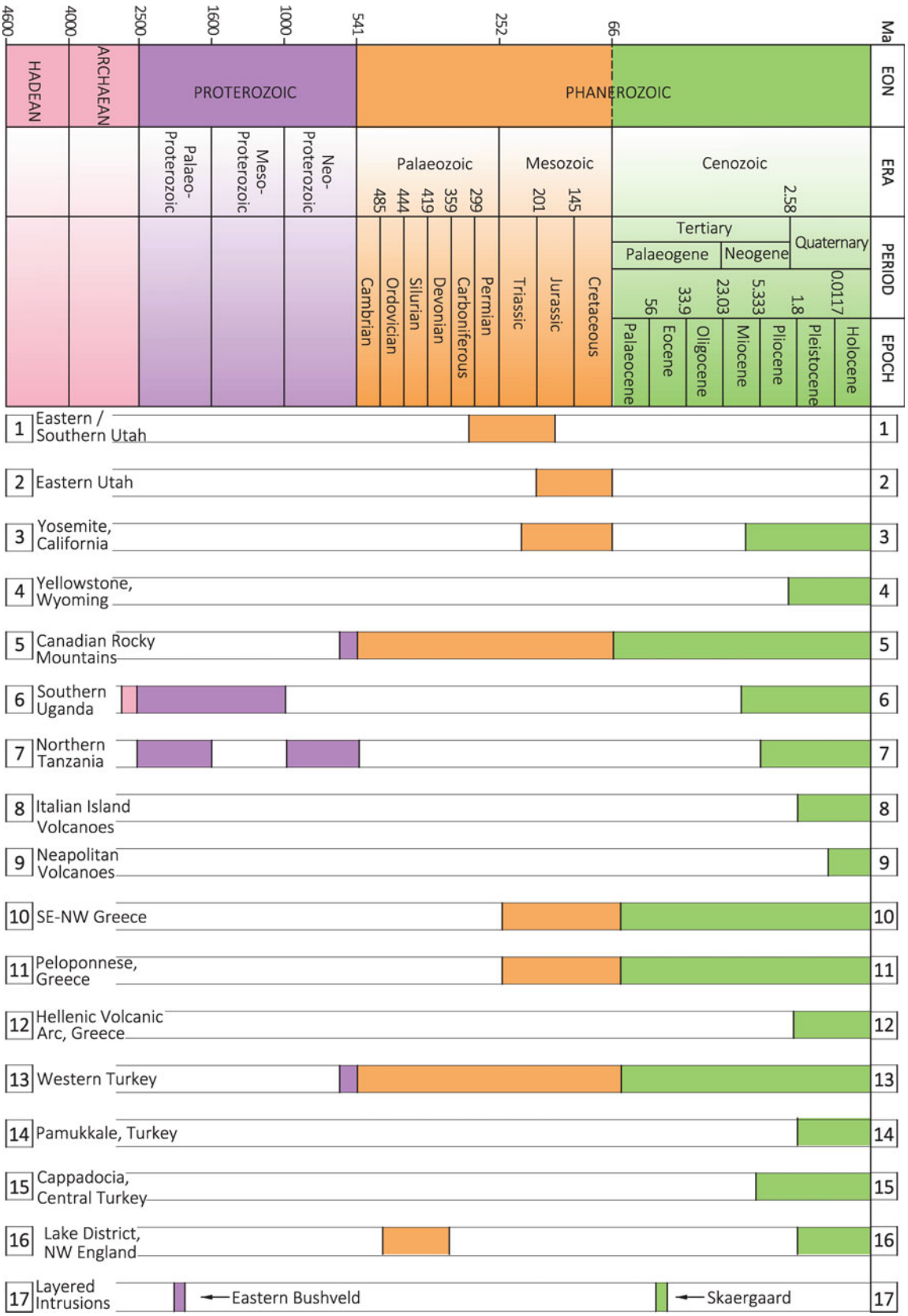
The Lake District National Park in northwest England is dealt with in the fourth section of the book. This is the most widely visited rural area in the British Isles, with tourists attracted by outdoor activities including a network of mountain footpaths. The national park includes rugged peaks associated with extinct volcanoes and ice-sculptured landforms made famous by painters and writers. The Lake District has a rich mining heritage with the opportunity to visit historical slate and copper mines.

Two examples of layered mafic igneous intrusions are described in the fifth and final part of the book. Layered mafic igneous intrusions are large plutons characterized by sub-horizontal rock layers. The first example is the Skaergaard Intrusion in Greenland, which, despite its relatively small size, has had a substantial influence on the development of conceptual thinking regarding layered intrusions. The other example of this category of geological phenomena is the giant Bushveld Igneous Complex in South Africa. There is no consensus on the formation of igneous layering, despite intensive studies. The Bushveld Igneous Complex includes important layered orebodies, or "reefs", including the platinum-rich Merensky Reef, together with layers of chromitite and vanadium-rich Ti-magnetite. The history of the discovery of the platinum in the Eastern Limb makes a fascinating read.

Grahamstown, South Africa Roger N. Scoon

The original version of the book was revised: Belated corrections have been incorporated. The corrections to the book are available at https://doi.org/10.1007/978-3-030-54693-9_18

Map A Location of geosites



Map B Stratigraphic chart. The Lower Carboniferous in North America is referred to as the Mississippian and the Upper Carboniferous is the Pennsylvanian period. The base of the Pleistocene is located at 1.8 Ma (older usage), rather than 2.58 Ma as is currently recommended to indicate the start of the Quaternary

Acknowledgements

This contribution would not have been possible without the detailed research of geologists, archaeologists, and historians. Maps produced by Geological Surveys and other government institutions are similarly essential. The simplified maps and diagrams were draughted by Lyn Whitfield and her patience in attending to the seemingly endless corrections is greatly appreciated. The satellite images were provided and processed by Philip Eales (Planetary Visions/DLR). Belinda Boyes-Varley is thanked for her assistance with labelling the photographs and also for the layouts of the original Geotraveller articles. Reviews by Prof. Carl Anhaeusser and Dr. Andrew Mitchell greatly improved the manuscript and scientific content. The support and encouragement of Springer Books was also invaluable, particularly the assistance of Margaret Deignan (Netherlands) and Ritu Chandwani (India), as was that of the Geological Society of South Africa. Steve Prevec as editor of the Geobulletin when the first of the series of articles was published is thanked for his encouragement. My wife, Amelia, accompanied me on almost all of the field excursions and geological hikes and has supported me whole-heartedly throughout the preparation of the manuscript. We both gratefully acknowledge the many guides and rangers who assisted us in our travels.

The Geotraveller

The Geotraveller started as a regular contributor of short articles on areas of geological interest to the Geobulletin, a quarterly publication of the Geological Society of South Africa. The first article was published in March 2010 and the most recent contribution was published in December 2020.

Contents

1 Canyonlands National Park and Monument Valley, Eastern and Southern Utah 1
1.1 Introduction 1
1.2 Colorado Plateau 3
1.3 Regional Geology 5
1.3.1 Upper Carboniferous 6
1.3.2 Lower Permian 6
1.3.3 Triassic 7
1.3.4 Jurassic 8
1.3.5 Mineral Resources 8
1.4 Canyonlands National Park 9
1.4.1 Stratigraphy 9
1.4.2 Salt Domes 10
1.4.3 Additional Features 11
1.4.4 Trails 11
1.5 Monument Valley 11
1.5.1 Navajo Tribal Park 11
1.5.2 Stratigraphy 12
1.5.3 Monuments 15
References 16

2 Arches National Park and Dinosaur National Monument, Eastern Utah 19
2.1 Introduction 19
2.2 Regional Geology 21
2.3 Moab Fault 22
2.4 Arches National Park 22
2.4.1 Geological Setting 23
2.4.2 Middle Jurassic Sandstone 26
2.4.3 Formation of Arches 27
2.4.4 Delicate Arch 29
2.4.5 Landscape Arch 29
2.4.6 Balanced Rocks 30
2.4.7 Trails 30
2.4.8 Stone Tools 31
2.5 Dinosaur National Monument 31
2.5.1 Geological Setting 32
2.5.2 Morrison Formation 33
2.5.3 Quarry Sandstone 34
References 36

3 Yosemite National Park, California . . . 37
3.1 Introduction . . . 37
3.2 History of the Park . . . 38
3.3 Ecosystems . . . 39
3.4 Park Entrances . . . 40
3.5 Geological Setting . . . 40
3.6 Glaciations . . . 42
3.7 Geosites . . . 43
3.7.1 Formation of Granitic Domes . . . 46
3.7.2 Alpine Lakes . . . 46
3.7.3 Waterfalls . . . 46
3.8 Giant Sequoia . . . 46
References . . . 50

4 Yellowstone National Park, Wyoming . . . 51
4.1 Introduction . . . 51
4.2 History and Physiography . . . 52
4.3 Fauna . . . 53
4.4 Rocky Mountains . . . 53
4.4.1 Grand Teton National Park . . . 53
4.5 Older Volcanism . . . 55
4.6 Yellowstone Volcano . . . 56
4.7 Late Pleistocene Ice Ages . . . 56
4.8 Yellowstone Caldera . . . 57
4.8.1 Yellowstone Tuff . . . 57
4.8.2 Plateau Rhyolite . . . 57
4.8.3 Obsidian . . . 57
4.8.4 Basalt Flows . . . 60
4.9 Geothermal Activity . . . 60
4.9.1 Circulation of Groundwater . . . 61
4.9.2 Hot Springs . . . 61
4.9.3 Mudpots and Fumaroles . . . 62
4.9.4 Geysers . . . 62
4.9.5 Travertine . . . 64
4.10 Yellowstone Lake and Canyon . . . 64
References . . . 66

5 National Parks of the Canadian Rocky Mountains . . . 69
5.1 Introduction . . . 70
5.2 Rocky Mountain Fold-and-Thrust Belt . . . 71
5.3 Erosion and Ice Ages . . . 72
5.4 Geological Setting . . . 73
5.5 Jasper National Park . . . 73
5.5.1 Lake Maligne . . . 73
5.5.2 Maligne Gorge . . . 73
5.5.3 Mounts Edith Cavell and Geraldine . . . 75
5.5.4 Waterfalls on the Athabasca River . . . 77
5.5.5 Columbia Icefield . . . 77
5.5.6 Athabasca Glacier . . . 77
5.6 Banff National Park . . . 80
5.6.1 Bow Valley . . . 82
5.6.2 Lake Louise . . . 82
5.6.3 Moraine Lake . . . 82

5.7 Yoho National Park . . . 85
5.7.1 Natural Bridge and Emerald Lake . . . 85
5.7.2 Cambrian Explosion of Life . . . 87
5.7.3 Burgess Shale . . . 87
References . . . 88

6 National Parks, Rivers and Lakes of Southern Uganda . . . 89
6.1 Introduction . . . 90
6.2 National Parks and Speciation Patterns . . . 91
6.3 Regional Geology . . . 92
6.3.1 Central African Craton . . . 95
6.3.2 Proterozoic Belts . . . 95
6.3.3 Regional Plateau . . . 95
6.3.4 East Africa Rift System . . . 95
6.4 Lakes and Rivers . . . 97
6.4.1 Lake Albert and Lake Edward . . . 99
6.4.2 Lake Victoria . . . 99
6.4.3 Victoria Nile . . . 99
6.5 Quaternary Climatic Regimes . . . 99
6.6 Lake Victoria and the Victoria Nile . . . 100
6.7 Murchison Falls National Park . . . 100
6.7.1 Lake Albert . . . 103
6.8 Queen Elizabeth National Park . . . 104
6.8.1 Lake Edward and Lake George . . . 104
6.9 Kibale National Park . . . 104
6.10 Crater Fields . . . 105
6.11 Rwenzori Mountain and Semliki National Parks . . . 105
6.12 Lake Mburo National Park . . . 105
6.13 Bwindi Impenetrable National Park . . . 107
6.14 Mgahinga National Park and the Virunga Mountains . . . 108
6.14.1 Virunga Volcanic Province . . . 108
6.14.2 Nyiragongo . . . 109
6.15 Evolution of Mountain Gorilla . . . 111
References . . . 115

7 Lake Natron and the Ngorongoro Conservation Area, Northern Tanzania . . . 117
7.1 Introduction . . . 117
7.2 Regional Geology . . . 119
7.3 Lake Natron . . . 120
7.3.1 Geological Setting of Lake Natron . . . 120
7.4 Oldoinyo Lengai . . . 121
7.5 Ngorongoro Conservation Area (NCA) . . . 122
7.5.1 Geological Setting . . . 122
7.5.2 Ngorongoro Caldera . . . 123
7.5.3 Other Volcanoes of the Ngorongoro Volcanic Complex . . . 126
7.5.4 Shifting Sands . . . 127
7.5.5 Serengeti Migration . . . 128
7.6 Oldupai Gorge . . . 128
7.6.1 Geological Setting . . . 128
7.6.2 Oldupai Group . . . 130
7.6.3 Discovery of the Hominin Fossils . . . 130

7.7 Laetoli . . . 133
7.8 Evolution of Hominins . . . 134
7.9 Treks . . . 135
References . . . 137

8 Mediterranean Basins and Italian Island Volcanoes . . . 139
8.1 Introduction . . . 140
8.2 Ancient Greeks and Romans . . . 140
8.3 Regional Geology . . . 141
8.3.1 Alpine Orogeny . . . 142
8.3.2 Accretionary Convergent Margin . . . 143
8.3.3 Apennine-Mahgreb Thrust . . . 143
8.4 Mediterranean Basins . . . 145
8.5 Earthquakes . . . 145
8.6 Volcanism . . . 146
8.6.1 Explosiveness of Eruptions . . . 146
8.6.2 Magma Compositions . . . 147
8.7 Aeolian Islands . . . 149
8.7.1 Volcanic Island Arc . . . 149
8.7.2 Stromboli . . . 150
8.7.3 Vulcano . . . 150
8.7.4 Fossa Cone . . . 150
8.8 Etna . . . 152
8.8.1 Early Volcanism . . . 153
8.8.2 Historical Activity . . . 153
8.8.3 Recent Activity . . . 157
8.9 Pantelleria . . . 158
8.10 Archaeological Sites of Magna Graecia . . . 158
8.11 The Odyssey . . . 160
References . . . 166

9 Neapolitan Volcanoes, Southern Italy . . . 169
9.1 Introduction . . . 170
9.2 Volcanology . . . 172
9.3 Regional Geology . . . 172
9.4 Neapolitan Volcanoes . . . 172
9.5 Campi Flegrei Volcano . . . 173
9.5.1 Historical Tectonism . . . 175
9.5.2 Magma Chamber . . . 176
9.6 Ischia Volcano . . . 176
9.6.1 Cliff Sections . . . 177
9.6.2 Recent Activity . . . 177
9.7 Somma-Vesuvius Massif . . . 177
9.7.1 Prehistoric Eruptions of Somma-Vesuvius . . . 180
9.7.2 Periodicity . . . 181
9.7.3 79 AD Event . . . 181
9.7.4 Roman Cities . . . 182
9.7.5 Roman Beach Resorts . . . 185
9.7.6 Details of the 79 AD Volcanic Deposits . . . 185
9.8 Vesuvius National Park . . . 188
References . . . 191

10 Antiquities and Archaeological Sites of Southeast and Northwest Greece . . . 193
10.1 Introduction . . . 193
10.2 Regional Geology . . . 194
10.2.1 Alpine Zones . . . 195
10.2.2 Basins and Grabens . . . 198
10.3 The Acropolis of Athens . . . 198
10.3.1 Tourkovounia Limestone . . . 199
10.3.2 Antiquities . . . 199
10.4 Plains of Marathon . . . 201
10.5 Delphi . . . 202
10.5.1 Regional Geology . . . 203
10.5.2 Delphic Landscape . . . 204
10.5.3 Antiquities . . . 204
10.5.4 Delphic Oracles . . . 204
10.6 The Pass of Thermopylae . . . 205
10.6.1 Modern Landscape . . . 207
10.6.2 Geomorphological Reconstruction . . . 207
10.7 Pindus Mountains . . . 208
10.7.1 Regional Geology . . . 208
10.7.2 South Pindus Mountains . . . 210
10.7.3 North Pindus Mountains . . . 211
10.8 Meteora . . . 214
10.8.1 Regional Geology . . . 214
10.8.2 Meteora Group . . . 214
References . . . 217

11 Antiquities and Archaeological Sites of the Peloponnese and Zakynthos, Greece . . . 219
11.1 Introduction . . . 220
11.2 Early Civilizations . . . 221
11.3 Regional Geology . . . 223
11.3.1 Alpine Zones . . . 223
11.3.2 Basins and Grabens . . . 224
11.4 The Argolid . . . 224
11.4.1 Ancient Humans . . . 225
11.4.2 Antiquities . . . 225
11.5 Corinthia and Achaea . . . 226
11.5.1 Corinth Basin . . . 226
11.5.2 Antiquities . . . 227
11.5.3 Corinth Canal . . . 229
11.5.4 Earthquakes and Tsunamis . . . 230
11.6 Elis . . . 230
11.6.1 Olympia . . . 231
11.7 Arcadia . . . 233
11.8 Laconia and Messenia . . . 235
11.8.1 Antiquities in Laconia . . . 235
11.8.2 Antiquities in Messenia . . . 237
11.9 Zakynthos . . . 240
11.9.1 Geological Framework . . . 240
11.9.2 Earthquake of 1953 . . . 241
11.9.3 Springs . . . 242
References . . . 243

12 Volcanoes of the Hellenic Volcanic Arc, Greece . . . 245
12.1 Introduction . . . 246
12.2 Regional Geology . . . 247
12.2.1 Aegean Basin . . . 248
12.2.2 Subduction Zone . . . 248
12.2.3 Island Arc Volcanism . . . 249
12.3 Methana Peninsula . . . 249
12.3.1 Geological Framework . . . 249
12.3.2 Methana Volcanic Complex . . . 250
12.3.3 Mavri Petra Volcano . . . 251
12.3.4 Pausanias Submarine Volcanism . . . 253
12.4 Milos . . . 253
12.4.1 Geological Framework . . . 254
12.4.2 Volcanism . . . 254
12.4.3 Geotrails . . . 255
12.4.4 Historical Mining . . . 255
12.4.5 Archaeological Sites . . . 257
12.4.6 Current Mining . . . 258
12.4.7 Geosites . . . 259
12.5 Santorini . . . 262
12.5.1 Geological Framework . . . 264
12.5.2 Explosive Cycles . . . 265
12.5.3 Minoan Event . . . 267
12.5.4 Historical and Archaeological Sites . . . 268
12.5.5 Kameni Islands . . . 269
12.5.6 Columbo Seamount . . . 270
12.5.7 Recent Activity . . . 271
References . . . 271

13 Antiquities and Archaeological Sites of Western Turkey . . . 273
13.1 Introduction . . . 274
13.2 First Century Christianity in Asia Minor . . . 275
13.3 Regional Geology . . . 276
13.3.1 Regional Sutures . . . 276
13.3.2 Southwest Migration of the Anatolian Microplate . . . 277
13.3.3 Basins and Grabens . . . 278
13.3.4 Geological Terrains . . . 278
13.3.5 Sea Level Changes . . . 278
13.3.6 Geomorphological Changes . . . 280
13.4 Troy . . . 280
13.4.1 Geological Setting . . . 281
13.4.2 Ancient Troy . . . 281
13.4.3 Historical Reconstruction . . . 283
13.5 Gallipoli Peninsula National Park . . . 284
13.6 Assos and Pergamum . . . 284
13.6.1 Geological Setting . . . 285
13.6.2 Assos . . . 285
13.6.3 Pergamum . . . 285
13.7 Ephesus . . . 288
13.7.1 Geological Setting . . . 288
13.7.2 Antiquities . . . 292
13.7.3 Geomorphological Reconstruction . . . 295

13.8 Antiquities in the Denizli Basin . . . 295
13.8.1 Geological Setting . . . 296
13.8.2 Aphrodisias . . . 296
13.8.3 Laodicea . . . 298
13.8.4 Colossae and Kibyra . . . 298
13.8.5 Marbles . . . 299
References . . . 299

14 The Hierapolis-Pamukkale Archaeological and Geosite, Southwest Turkey . . . 301
14.1 Introduction . . . 302
14.2 Travertine . . . 302
14.3 Geological Setting . . . 303
14.3.1 Denizli Basin . . . 303
14.3.2 Pamukkale Travertine Deposits . . . 304
14.3.3 Formation of the Travertine Deposits . . . 304
14.4 Pamukkale Geosite . . . 305
14.5 Hierapolis Archaeological Site . . . 307
14.6 Earthquakes . . . 310
References . . . 310

15 Cappadocia, Central Turkey . . . 313
15.1 Introduction . . . 313
15.2 Historical Activity . . . 315
15.3 Regional Geology . . . 315
15.4 Cappadocia Volcanic Province . . . 316
15.4.1 Petrogenesis and Volcanic Centres . . . 317
15.4.2 Ignimbrite Sheets and Ash-Fall Deposits . . . 317
15.5 Göreme Historical National Park . . . 318
15.6 Differential Erosion . . . 320
15.7 Human Settlement . . . 321
15.7.1 Üchisar Castle . . . 321
15.7.2 Ihlara Gorge . . . 322
15.7.3 Underground Cities . . . 322
15.8 Current Hazards . . . 325
References . . . 326

16 The Lake District, Northwest England . . . 327
16.1 Introduction . . . 328
16.2 Human Settlement and Literary Connections . . . 329
16.3 Topography . . . 330
16.4 Regional Geology . . . 331
16.4.1 British Caledonides . . . 331
16.4.2 Caledonian Orogeny . . . 333
16.4.3 Skiddaw Group . . . 335
16.4.4 Eycott Volcanic Group . . . 336
16.4.5 Borrowdale Volcanic Group . . . 336
16.4.6 Windermere Supergroup . . . 338
16.4.7 Ordovician Intrusions . . . 338
16.4.8 Devonian Granite . . . 338
16.5 Late Pleistocene Glaciation . . . 340
16.6 Finger Lakes . . . 340

16.7 Archaeology and Mining Heritage . . . 343
16.7.1 Lead Mines . . . 345
16.7.2 Coppermines Valley, Coniston . . . 345
16.7.3 Graphite . . . 345
16.7.4 Tungsten . . . 347
16.7.5 Slate . . . 347
References . . . 350

17 Skaergaard Intrusion, Greenland and Eastern Bushveld Complex, South Africa . . . 353
17.1 Introduction . . . 354
17.2 Skaergaard Intrusion . . . 355
17.2.1 Geological Research . . . 357
17.2.2 Geological Setting . . . 357
17.2.3 Igneous Layering . . . 357
17.3 Eastern Bushveld Complex . . . 358
17.3.1 Human Habitation and Mining . . . 361
17.3.2 Discovery of Platinum in the Eastern Limb . . . 364
17.3.3 Dunite Pipes . . . 364
17.3.4 Zones and Igneous Layering . . . 364
17.4 Origin of Igneous Layering . . . 369
References . . . 373

Correction to: The Geotraveller . . . C1

Glossary . . . 375

Index . . . 385

Abbreviations

BP	Years before present
BVG	Borrowdale Volcanic Group
DAD	Debris Avalanche Deposit
DRC	Democratic Republic of the Congo
EARS	East African Rift System
Ga	Billions of years
IAFZ	Izmir-Ankara Fault Zone
Ma	Millions of years
NAFZ	North Anatolian Fault Zone
NCA	Ngorongoro Conservation Area
PGE	Platinum Group Element
RAMSAR	Conservation on wetlands signed in Ramsar, Iran in 1971

List of Figures

Fig. 1.1 The heavily incised Colorado Canyon viewed from Dead Horse Point. The thick succession of flat-lying Upper Palaeozoic and Mesozoic strata include the distinctive bench developed on the White Rim Sandstone (Lower Permian). The mesa is capped by the Kayenta Sandstone (Lower Jurassic) 2

Fig. 1.2 Map showing location of some of the national parks in Utah, together with Monument Valley which overlaps the boundary with Arizona 3

Fig. 1.3 The dominant physiographic and geologic feature of southern and eastern Utah is the Colorado Plateau. The Colorado Plateau is bordered to the north and east by the Rocky Mountains and to the south and west by the Basin and Range terrain. *Source* Simplified after Baars (1993) 4

Fig. 1.4 Geological map of southern and eastern Utah showing location of the Canyonlands and Arches National Parks together with the Monument Valley. *Source* Simplified from regional map of Geological Survey of Utah (2005). 5

Fig. 1.5 Simplified stratigraphic sections for Canyonlands and Monument Valley. The thickness of the strata is entirely schematic as there is considerable regional variation. The relatively resistant nature of the different formations is shown schematically. *Source* Modified after Baker (1936) and Harris et al. (2004) 6

Fig. 1.6 Steeply-dipping Lower Permian strata on the flanks of the Monument Uplift, viewed from Highway 163 southern Utah 7

Fig. 1.7 The Petrified Forest Member constitutes the colourful rock layers exposed in the Painted Desert, Arizona. *Source* Wikipedia. 8

Fig. 1.8 The canyons and mesas at Canyonlands National Park reveal multiple beds of flat-lying, mostly red sandstones. 9

Fig. 1.9 Upheaval Dome, Canyonlands. The pale grey rocks in the core are the Organ Rock Mudstone (Lower Permian) and the red-brown rocks in the rim are the Wingate Sandstone (Lower Jurassic). 10

Fig. 1.10 **a** Chaotic cross-bedding indicative of wind-blown sands, Navajo Sandstone, Canyonlands; **b** Mud cracks consistent with a fluvial environment at the same locality. 11

Fig. 1.11 The desert landscape of the Monument Valley Navajo Tribal Park includes free-standing monoliths such as West Mitten Butte (left), East Mitten Butte, and Merrick Butte (right) 12

Fig. 1.12 Image showing location of the Monument Valley with some of the well known mesa and monoliths. Rain God Mesa is located just to the south of the image. The pediment is dominated by the Organ Rock Mudstone (light brown) and the highest mesas and monoliths are capped by the resistant Shinarump Conglomerate (pale green). *Source* Google Earth 13

Fig. 1.13 Idealized cross section of the regional plateau (left) and Monument Valley (right), the latter including mesas, buttes, pinnacles, and spires. The pediment is underlain by the relatively soft Organ Rock Mudstone. The near-vertical cliffs are associated with the resistant De Chelly Sandstone. The contact between the De Chelly Sandstone and the Moenkopi Sandstone is a major unconformity, although the Permian-Triassic boundary (the greatest mass extinction event known) is not found in Utah. The plateau, mesas and buttes are capped by the extraordinarily resistant Shinarump Conglomerate 13
Fig. 1.14 View looking south through the "North Window" at Monument Valley. The characteristic stratification of the Lower Permian and Triassic sediments can be observed in Cly Butte (left) and Elephant Butte (right). Pinnacles of the Rain God Mesa occur in the background with the Thunderbird Mesa in the far distance 14
Fig. 1.15 **a** The massive nature of the De Chelly Sandstone can be observed in the near-vertical rock faces at Monument Valley; **b** Pinnacles of De Chelly Sandstone form due to closely-spaced vertical jointing 15
Fig. 1.16 The West Mitten Butte at Monument Valley with its distinctive pinnacle. 16
Fig. 1.17 The pinnacles and spires grouped to the south of Spearhead Mesa include the 137 m-high "Totem Pole" (right) 16
Fig. 2.1 Delicate Arch, Arches National Park, is comprised of gently-dipping Entrada Sandstone (Middle Jurassic). The snow-capped La Sal Mountains are visible in the distance 20
Fig. 2.2 Map showing location of the Arches National Park and Dinosaur National Monument, eastern Utah. 21
Fig. 2.3 Simplified stratigraphic section for the Arches National Park and Dinosaur National Monument. The thickness of the strata is schematic. *Source* Modified after Baker (1936), Harris et al. (2004) and others. 22
Fig. 2.4 Monoliths of the Entrada Sandstone (Middle Jurassic) project from the pediment at Arches National Park. Localized areas of badlands erosion on the flanks of the Salt Valley (centre) reveal pale buff coloured cliffs of the Wingate Sandstone (Lower Jurassic). The snow-capped La Sal Mountains in the background are associated with intrusive igneous rocks 23
Fig. 2.5 **a** View looking south along Highway 191 from the entrance road to Arches National Park with Moab and the La Sal Mountains visible in the distance. The western escarpment is capped by the Wingate Sandstone and the eastern escarpment by the Entrada Sandstone; **b** Details of the Moab Fault in an information board at the Arches National Park with the up-faulted block to the left and the down-faulted block to the right (view looking north). Note the repetition of the Wingate Sandstone. 24
Fig. 2.6 Map of the Arches National Park showing the location of the Visitor Centre and selected geosites. The southern boundary of the park abuts against the Colorado River 25
Fig. 2.7 The high-altitude desert (grey and pale mauve) of the Arches National Park contrasts with the narrow vegetated strip (green) associated with the sinuous Colorado River. Salt Valley (brown) is a prominent physiographic feature in the centre of the park. The majority of arches occur on the flanks of this structure (dark mauve). Highway 191 follows a prominent NW-SE aligned valley (red) associated with the

Moab Fault: the national park is situated east of the fault. *Source* Google Earth 26
Fig. 2.8 Geological map and section of the Arches National Park. The area proximal to the Salt Valley contains numerous small faults which are not shown for reasons of scale. *Source* Simplified from maps of the Utah Geological Survey 27
Fig. 2.9 The three members of the Entrada Formation are exposed in cliff faces at Park Avenue, a small canyon at Arches National Park 28
Fig. 2.10 Formation of arches is initiated by erosion of broad sandstone fins (background) in the Slickrock Member, as seen in the Devils Garden, Arches National Park 29
Fig. 2.11 Holes develop in slightly softer sandstone beds of the Slickrock Member (lower and top) which may be separated by more resistant cross-bedded units (centre), as seen on the trail to Delicate Arch. 30
Fig. 2.12 A window located in a sandstone fin comprised of the Slickrock Member next to the trail to Delicate Arch. 31
Fig. 2.13 Landscape Arch is reported to have the longest span of any natural arch. The arch is developed on a prominent fin or buttress comprised of massive sandstones of the Slickrock Member 32
Fig. 2.14 Balanced Rock, Arches National Park, consists of the Slickrock Member perched on a relict of the Dewey Bridge Member (both Entrada Sandstone) resting on a pedestal of Navajo Sandstone 33
Fig. 2.15 The Quarry Museum, Dinosaur National Monument is constructed over the "Quarry Sandstone", a steeply-dipping and partially contorted rock face anomalously rich in dinosaur fossils 34
Fig. 2.16 The impure sandstone, shales and mudstones of the Morrison Formation are steeply-dipping in an exposure near the Dinosaur Museum. 35
Fig. 2.17 Geological map of Dinosaur National Monument. *Source* simplified from maps of the Geological Survey of Utah (2005) 35
Fig. 2.18 **a** The Quarry Museum exposes a bedding plane of the Quarry Sandstone with more than 1,600 dinosaur fossils in situ; **b** Fossils of sauropods in the Quarry Sandstone 36
Fig. 3.1 Half Dome is one of the most well known of the granitic monoliths at the Yosemite National Park. The 600 m-high, planar north face, which hangs above the upper sections of the Yosemite Canyon, is defined by a set of near-vertical joints. Exfoliated scree was removed by glacial activity and ice sheets scraped clean large sections of the granite plutons which dominate the Sierra Nevada in this region 38
Fig. 3.2 Map showing location of the Yosemite National Park relative to coastal ranges in the state of California 39
Fig. 3.3 Yosemite is well known for black bear which can be observed on granite pavements 40
Fig. 3.4 Image of the Yosemite National Park showing the mountainous terrain and entrance gates and geosites referred to in the text. *Source* Google Earth. 41
Fig. 3.5 Tenaya Lake, located between the Tuolumne and Yosemite Canyons is an example of a high-altitude or Alpine lake located in a hanging valley at an elevation of 2,484 m 42
Fig. 3.6 Graph showing estimated temperatures during the previous 20 centuries. The most pronounced cycles (with estimated durations) are the Medieval Warm Period (950–1250 AD) and the Little Ice Age (1300–1850 AD). The relatively rapid temperature changes during the Little Ice Age

promoted numerous advances and recessions of ice sheets at Yosemite. *Source* https://commons.wikimedia.org 43
Fig. 3.7 **a** The Yosemite Canyon is the principal feature of the national park. The U-shape is typical of ice-carved valleys although the canyon initially developed due to an older phase of erosion; **b** The view from Glacial Point includes pastures associated with nutrient-rich moraine deposits in the floor of the Yosemite Canyon 44
Fig. 3.8 El Capitan is the highest of the granitic domes with a near-vertical face of 1,095 m. Just visible are sections of younger granitic intrusives and cross-cutting granite pegmatite dykes and veins (darker) 45
Fig. 3.9 The near-vertical-face of Half Dome includes dark vertical lines associated with water seepage 47
Fig. 3.10 Many of the granite domes proximal to the Yosemite Canyon reveal prominent joints. The rock slabs have been swept clean by glacial activity 47
Fig. 3.11 The idyllic scenery of Mirror Lake occurs in a hanging valley perched hundreds of metres above the Yosemite Canyon 48
Fig. 3.12 **a** The upper section of the Yosemite Falls, a tributary of the Merced River, plunges 436 m over granitic cliffs into the Yosemite Canyon; **b** The Vernal Falls on the Merced River is associated with a glacial step cut into the basement granite by the Yosemite Glacier 49
Fig. 3.13 The stands of giant sequoia in the Mariposa Grove, Yosemite encouraged protection of the area 50
Fig. 3.14 Historical photograph of the Wawona Tree, a giant sequoia in the Mariposa Grove, which fell in 1969 (internet) 50
Fig. 4.1 The multi-coloured rocks in the walls of the Yellowstone Canyon illustrate the derivation of the name of the Yellowstone National Park. The brightest patches of colour are due to hot springs and fumaroles that have hydrothermally altered the thick sequences of rhyolitic volcanic ashes and pyroclastics erupted from the Yellowstone Volcano during the most recent of the caldera events. Thin basaltic flows (a subordinate component of the volcanism) that display prominent columnar jointing are intercalated with the rhyolitic ashes and pyroclastics. The hydrothermal features, including the famous geysers, are driven by heat associated with a shallow magma chamber located beneath the Yellowstone Caldera 52
Fig. 4.2 Map showing location of the Yellowstone National Park, in the states of Wyoming, Idaho and Montana, northwest USA 53
Fig. 4.3 Image showing the location of the Yellowstone National Park together with some of the mountain ranges, including the Tetons. *Source* Google Earth 54
Fig. 4.4 Views of wildlife, including bison, in association with active geothermal features is a unique feature of the Yellowstone National Park 54
Fig. 4.5 Deeply incised U-shaped valleys in the Beartooth Mountains formed during the Late Pleistocene Ice Ages 54
Fig. 4.6 View from Jenny Lake of the triangular-shaped and snow-capped peaks in the Grand Teton National Park 55
Fig. 4.7 Information board located close to the Teton Fault, looking west towards the uplifted Teton Range 55
Fig. 4.8 The volcanism of the Columbia River basalts and the Yellowstone Volcano is related to a single deep-seated hot spot which appears to have "migrated" eastward due to the westward drift of the North Atlantic Plate 56

Fig. 4.9 Geological map of the Yellowstone National Park showing extent of the youngest caldera, a scarp related to an older caldera, and the larger geyser basins. *Source* Simplified after Keefer (1975) 58
Fig. 4.10 View of the desolate landscapes typical of geyser basins at Yellowstone with the rim of the youngest caldera visible in the background 59
Fig. 4.11 Simplified cross-section of the Yellowstone Volcano illustrating a schematic magma chamber at depth. The position of the magma chamber relative to the caldera is offset to the east due to the apparent migration of the hot spot. 59
Fig. 4.12 Obsidian (black volcanic glass) occurs in pink-coloured banded rhyolite at Obsidian Cliff, Yellowstone 60
Fig. 4.13 Columnar jointing typical of basaltic lava flows at Yellowstone. 60
Fig. 4.14 The Norris Geyser Basin contains numerous geothermal features including geysers, fumaroles and hot springs 61
Fig. 4.15 Section showing how geothermal features work The geyserite (grey) is underlain by rhyolite depicted schematically as getting hotter with depth (pink, orange, and red). *Source* based entirely on White (1967) 62
Fig. 4.16 **a** Blue pools are relatively hot; **b** Brown pools are cooler; **c** Orange pools are rich in thermophiles; **d** Mud pools occur in areas where groundwater is sparse; and **e** A colour chart (from an information board in the park) illustrating the relationship between colour and temperature and/or the presence of thermophiles 63
Fig. 4.17 **a** The column of hot water associated with Old Faithful, the most famous of the geysers at Yellowstone, erupts on average every 92 min; **b** Castle Geyser in the Upper Geyser Field has built up a substantial mound of geyserite and includes a relatively long steam phase at the end of each eruptive cycle 65
Fig. 4.18 Terraces of travertine at the Mammoth Hot Springs reveal constantly changing forms as they are shaped by subtle changes in the springs' plumbing system 66
Fig. 4.19 The Yellowstone River includes several large waterfalls. 66
Fig. 5.1 View looking south along the Icefields Parkway in the U-shaped valley of the North Saskatchewan River, Banff National Park. The ice-scoured mountains of the Front Ranges consist of well-bedded, eastward-dipping Palaeozoic strata 70
Fig. 5.2 Map showing location of the three national parks in the Canadian Rockies, the continental divide, major rivers, and access routes 71
Fig. 5.3 Stratigraphy of the Canadian Rocky Mountains. *Source* Simplified after Leckie (2017) 72
Fig. 5.4 **a** Selected geosites in the Banff and Jasper National Parks accessed by the Icefields Parkway and sites in the Yoho National Park close to the Trans-Canadian Highway. Only icefields in the national parks are shown (slope glaciers are too small to show). The provincial boundary corresponds to the "Great Divide"; **b** Geological map of the area proximal to the Icefields Parkway. *Source* Simplified after Yorath and Gadd (1995); Leckie (2017), and maps of the Geological Survey of Alberta 74
Fig. 5.5 The northern part of the Icefields Parkway, Jasper National Park, follows the course of the Athabasca River with views of the Main Ranges 75
Fig. 5.6 The narrow gorge of the Maligne River carved into flat-lying limestone of the Palliser Formation (Devonian) 76
Fig. 5.7 **a** The upper section of the Maligne Canyon reveals evidence of a cave system in the sidewalls; **b** The lower sections of the Maligne River includes springs exiting the cave system. 77

Fig. 5.8 **a** Mount Edith Cavell is comprised almost entirely of resistant quartzite of the Gog Group (Lower Cambrian); **b** The crenulated face of Mount Geraldine includes cirques that contain small glaciers (foreground left and centre) 78
Fig. 5.9 **a** The gorge below the Athabasca Falls occurs in well-bedded quartzite of the Gog Group (Lower Cambrian); **b** Large potholes on the walls of the Sunwapta Gorge are relicts of higher water stands. The gorge cuts into limestone of the Cathedral Formation (Middle Cambrian) 79
Fig. 5.10 Terminal moraines left by the receding Athabasca and Saskatchewan Glaciers, part of the irregular-shaped Columbia Icefield, are visible on this satellite image. *Source* Modified Copernicus Sentinel data of August 2018 processed by Philip Eales, Planetary Visons/DLR 80
Fig. 5.11 **a** The Athabasca Glacier is located in a valley fed by the Columbia Icefield (vehicles on the glacier are specialized tour buses); **b** Recession of the Athabasca Glacier reveals extensive terminal and lateral moraines 81
Fig. 5.12 Geothermal deposits, Cave Spring, Banff. *Source* https:// www.google.com/ gonewiththewynns.com 82
Fig. 5.13 **a** View of Lake Louise looking southwest towards the high peaks of Mount Victoria. A barren rock face comprised of Cog Quartzite separates the two glaciers on the lower flanks; **b** View of Lake Louise from the trail to Lake Agnes shows the renowned turquoise colour with gently dipping quartzites of the Cog Group exposed in the mountain face 83
Fig. 5.14 **a** The turquoise-coloured Moraine Lake is one of the most scenic of the glacial lakes in the Canadian Rockies; **b** Cone-shaped scree deposits occur at the base of the cliffs above Moraine Lake 84
Fig. 5.15 Terminal moraine and landside deposit with large blocks of Cog Group quartzite dams Moraine Lake 85
Fig. 5.16 The debris fan associated with the unstable face of Cathedral Mountain, on the northern side of Kicking Horse Pass, Yoho National Park, affects the Canadian Pacific Railway and Trans-Canada Highway. *Source* Original photograph by Lukas Arenson and annotation of Leckie (2017) 86
Fig. 5.17 Natural Bridge, Yoho National Park, is associated with a knickpoint on the Kicking Horse River. The calcareous slate of the Chancellor Formation (Middle Cambrian) reveals prominent cleavage 87
Fig. 5.18 A slab of Burgess Shale in the interpretative centre at Field contains typical Middle Cambrian marine fossils, including a large trilobite, *Ogygopsis* (width of approximately 4 cm) 88
Fig. 6.1 The Nyinambuga Crater viewed from Ndali Lodge in the Ndali-Kasenda Crater Field, southern Uganda. 90
Fig. 6.2 Map showing location of national parks and major lakes in southern Uganda, together with the two components of the White Nile (Victoria Nile and Albert Nile) and parks in the DRC and Rwanda in the vicinity of the Virunga Mountains 91
Fig. 6.3 Image of southern Uganda showing the extensiveness of the wooded savannahs on the regional plateau (light green), the forested rift shoulders and areas of central Africa west of the Albertine Rift (dark green), and the rift valley with its finger-shaped lakes. Lake Victoria and Lake Kyoga are associated with shallow warps on the regional plateau. The Victoria Nile exits Lake Victoria at Jinja, flows northwest via Lake Kyoga, and exits Lake Albert as the Albert Nile. *Source* Google Earth . . . 92
Fig. 6.4 **a** African elephant are a common site in the Queen Elizabeth National Park and can be approached to within a few metres in the Kazinga

Channel; **b** Cape buffalo can be observed in swamps at the Murchison Falls National Park; **c** The Uganda kob is the most abundant grazer on grassy savannahs of the Queen Elizabeth National Park; **d** Chimpanzee are protected in forests of the Kibale National Park; **e** Mountain gorilla occur in Afromontane forests of the Virunga Mountains (Volcanoes NP, Rwanda); **f** Aquatic birds such as yellow-billed stork and little egret are a common site on the banks of the Kazinga Channel 93

Fig. 6.5 Simplified geological map of southern Uganda. Each of the finger-shaped lakes of the Albertine Rift occurs in a separate sedimentary basin. Five rift-related volcanic terrains are recognized in the Albertine Rift: **a** Fort Portal-Kasekere; **b** Ndali-Kasenda; **c** Katwe-Kikorongo; **d** Bunyaraguru; **e** Virunga. The Mount Elgon volcanic field is part of the Gregory Rift (inset). *Source* Simplified from the 1:1,500,000 scale map compiled by R. MacDonald and published by the Department of Geological Survey and Mines, Uganda (1966). 94

Fig. 6.6 Large sections of the regional plateau in southern Uganda are covered by thick palaeosols and recent deposits of gravels and alluvium, as seen in this quarry near Mbarara 95

Fig. 6.7 Simplified geological map of East Africa depicting the three branches of the EARS. Some rifts are truncated by older, Cretaceous-age rifts (e.g., Anza Graben). Volcanism associated with the Ethiopian and Gregory Rifts is notably extensive. The Albertine Rift is dominated by sedimentary basins. *Source* Compiled from the 1:1,000,000 Geological Map of Kenya, the 1:2,000,000 Geological Map of Tanzania, and the 1:1,500,000 Geological Map of Uganda 96

Fig. 6.8 The effects of the Late Cenozoic rifting on river systems and lakes in southern Uganda. **a** Pre-rifting; **b** Formation of a large palaeo-lake in the Albertine Rift; **c** Isolation of lake basins in the Albertine Rift; **d** Formation of the Albert Nile and Lake Victoria; **e** Upwarping between the Albertine Rift and Lake Victoria; **f** Development of the Victoria Nile. *Source* Compiled from Beadle (1981), Pickford et al. (1993), Talbot and Williams (2008) and others 98

Fig. 6.9 **a** The Victoria Nile exits Lake Victoria at Jinja; **b** View of the Owens Dam on the Victoria Nile with hills (background) comprised of the Buganda-Toro System; **c** View from Wildwaters Lodge, Kangulumira Island, showing resistant outcrops of the Uganda Gneiss Complex in a fast-flowing, wide section of the Victoria Nile. 100

Fig. 6.10 The Uganda Gneiss Complex is intruded by dark amphibolite dykes of the Buganda-Toro System, Kangulumira Island 100

Fig. 6.11 **a** The Victoria Nile at Murchison Falls is constricted from a wide channel to a narrow gorge as the river plunges into the Albertine Rift; **b** The gorge is carved out of resistant rocks of the Uganda Gneiss Complex 101

Fig. 6.12 **a** In the Murchison Falls National Park, the Victoria Nile is fringed by riverine forest with hardwoods, including African mahogany and borassus palms; **b** The Victoria Nile enters Lake Albert by a delta that includes a myriad of channels and small islands. The water hyacinths have survived the passage from Lake Victoria 102

Fig. 6.13 View looking south along the Albertine Rift. Lake Albert is constrained between two escarpments. *Source of Image* Christian Hormann 2012 (http://earth.imagico.de). 103

Fig. 6.14 **a** The tranquil setting of Lake Edward viewed from Uganda; **b** The sluggish, meandering Kazinga Channel which connects Lakes George and Edward is located in the Queen Elizabeth National Park 104
Fig. 6.15 **a** Kitagata Crater Lake and **b** Kikeronga Salt Pan. Both localities occur in the Katwe-Kikorongo Crater Field, Queen Elizabeth National Park 106
Fig. 6.16 Outcrops of amygdaloidal alkali lavas and agglomerate cap the walls of the Kyemengo Crater, Katwe-Kikorongo Crater Field 107
Fig. 6.17 Rwenzori Mountains. *Source* en.Wikipedia.org 107
Fig. 6.18 Monoliths of the Uganda Gneiss Complex are a feature of the Lake Mburo National Park. 108
Fig. 6.19 The Bwindi Impenetrable National Park is situated in an area of uplands (on the shoulders of the Albertine Rift) covered by dense Afromontane and lowland forest. 109
Fig. 6.20 The volcanic peak of the Sabinyo Volcano in the Virunga Mountains, viewed from the Volcanoes National Park, Rwanda 110
Fig. 6.21 Image of the Nyiragongo Volcano showing location in the southern part of the Virunga National Park (DRC) and proximity to Goma and Lake Kivu. The ascent of the cone starts at the Kibati gate and includes sections located on the 2002 lava. *Source* Google Earth 110
Fig. 6.22 The steep-sided and rugged Nyiragongo cone (foreground) as compared with the smoother and gentler slopes of Nyamulagira (background). Both volcanoes are more-or-less continuously active 111
Fig. 6.23 View of Goma airport, partly covered by the 2002 lava flow, looking south over the city which is situated next to Lake Kivu. *Source* Guido Potters (http://www.gnu.org/copyleft/ fdl.html. 112
Fig. 6.24 **a** The active summit crater of the Nyiragongo Volcano contains a lava lake (left) and an active spatter cone (right). Lava fountains associated with the spatter cone attain a height of approximately 50 m; **b** The rim of the near vertical-walled summit crater is capped by lava from the major eruption of 1977 113
Fig. 6.25 **a** The lava lake (left) and active vent (right) in the summit crater of the Nyiragongo Volcano are a spectacular sight in the twilight; **b** A night time view of the lava lake shows the occurrence of cracks and segments with magma flares. 114
Fig. 7.1 The Western Escarpment of the Gregory Rift near Lake Natron is constructed of multiple, near-horizontal layers of lava and tephra. 118
Fig. 7.2 Map showing location of selected national parks and wilderness areas in northern Tanzania 119
Fig. 7.3 Geological map of the northern Tanzanian divergence. The rifted terrains are dominated by volcanics (light green) and include the extinct volcanic complex associated with the Ngorongoro Highlands (dark green). Some of the larger cones and calderas are shown, but for reasons of scale the subordinate sedimentary basins are omitted. *Source* Simplified after Dawson (2008) 119
Fig. 7.4 The unusual colour of the northern and central parts of Lake Natron is due to the red photosynthesizing pigment in the cyanobacteria. The rugged terrain on either sides of the lake is associated with deeply-eroded Pleistocene volcanics. View looking north; width of lake in southern part of image is approximately 10 km. *Source* NASA Terra-ASTER image for 2003, processed by Philip Eales, Planetary Visions/DLR 121

Fig. 7.5 The symmetrical cone of the Oldoinyo Lengai Volcano rises abruptly from the floor of the rift valley near Lake Natron . . . 122
Fig. 7.6 The eastern part of the Ngorongoro Conservation Area (NCA) is constrained to the Eyasi Half-graben, a discrete structural block (located between the Rift Valley and Eastern Serengeti Plains) defined by prominent escarpments. The Rift Valley contains Lake Natron and Lake Manyara; Lake Eyasi is situated in the Eyasi Half-graben. The contrast between the lush Ngorongoro Highlands (dark green) and arid terrains of the Salei Plains, Gol Mountains, Rift Valley and Eastern Serengeti Plains (beige) is pronounced. The Ngorongoro Highlands is associated with the extinct Ngorongoro Volcanic Complex (EC: Empakaai Caldera; LE: Lemagrut; LO: Loolmalasin; NC: Ngorongoro Caldera; OC: Olmoti Caldera; OL: Oldeani; SA: Sadiman). Other components of the NCA are dominated by wind-blown ash from the active Oldoinyo Lengai Volcano. The palaeoanthropological sites of Oldupai and Laetoli are located in the Eastern Serengeti Plains. The Oldupai River peters out in the Olbalbal Swamps (OS). Approximate width of view is 150 km. *Source* NASA Landsat 7 ETM + image mosaic for the year 2000 sourced from the University of Maryland Global Land Cover Facility, processed by Philip Eales, Planetary Visions/DLR . . . 123
Fig. 7.7 The eastern approach to the NCA ascends the Western Escarpment near Lake Manyara (background, left). The escarpment is composed of multiple, near-horizontal volcanic layers of lavas and tephra associated with the Ngorongoro Volcanic Complex . . . 124
Fig. 7.8 Ngorongoro Caldera and Lake Magadi from the viewpoint on the southeast of the caldera during the wet season . . . 124
Fig. 7.9 Geological map of the Ngorongoro Conservation Area. Outcrop of the Oldupai and Laetoli Basins are not shown for reasons of scale. *Source* Simplified after Pickering (1958; 1964; 1965), Orridge (1965) and Dawson (2008) . . . 125
Fig. 7.10 Simplified geological section of the NCA and adjacent terrains. Section centred on the Ngorongoro Caldera (latitude 3^{o} $10^{'}$ South). Localities in brackets (e.g., Lake Ndutu, Oldupai Gorge, Kilimanjaro etc.) are located north of the section line. The thickness of the rift-related volcanics is schematic . . . 125
Fig. 7.11 Geological map of the Ngorongoro Caldera and part of the Olmoti Caldera. *Source* simplified from the Geological Survey of Tanzania 1:125,000 quarter degree sheet 53 by Pickering (1965) . . . 126
Fig. 7.12 The lush paradise of the Ngoitokitok Springs, Ngorongoro Caldera. The northern wall of the caldera is dwarfed by the flanks of the Olmoti Volcano . . . 127
Fig. 7.13 A Maasai herdsman on a trail leading to the Elanairobi Ridge. The background shows the thickly forested inner slopes and lake of the Empakaai Caldera . . . 127
Fig. 7.14 **a** Isolated, barchan-style dune of black volcanic ash at Shifting Sands with the western rampart of the Ngorongoro Highlands visible in the background; **b** The front of the dune (which is migrating towards the right of the photograph) reveals a steep slope and distinctive outer horns . . . 129
Fig. 7.15 Migration of wildebeest and zebra in the vicinity of Lake Ndutu on the Eastern Serengeti Plains . . . 130