Geology and landscapes of Scotland

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Preface

Scotland has been a Mecca for geologists for over 200 years. Indeed, the subject of geology was born here, with the pioneering work of the great James Hutton in the 1780s, and ever since, Scotland has played a key role in the development of geology. And with good reason, for Scotland boasts the most varied geological tapestry of any country of its size in the world.

This book has been designed for non-expert readers, and has been written in such a way that all the key concepts in geology are explained as plainly as possible. Here is an up-to-date account of each of Scotland's unique geological regions, from Shetland and Orkney, through the Western Isles to the Highlands, Central Lowlands and Southern Uplands. We trace movements across the globe from the dawn of time – how Scotland moved from southern ice-bound seas across the Equator into warm and humid coal-forming swamps, to be confronted eventually by icy conditions, this time near the North Pole. The book deals with not just the wide variety of rocks (and the minerals and fossil remains they contain), but also the landforms and types of scenery that owe their origin to the structure and composition of the bedrock. We explore how these landforms developed through time, to be used to great advantage by Scotland's first settlers, and how the mineral riches have been exploited, from iron ores and building stones to coal, oil and gas.

Many of the fundamental ideas in geology were developed on the basis of rocks and structures seen in Scotland. Indeed, Scotland could justifiably be called the cradle of modern geology. For its relatively small size, the country boasts a truly amazing variety of rocks and structures. At first sight, this may appear daunting and even confusing to the novice, but *Geology and landscapes of Scotland* will put you at your ease and allow you to grapple with the most complex of notions, as you travel on a journey, following Scotland's fortunes in time and space.

Con Gillen, Edinburgh, January 2003

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I wish to express my gratitude to Roger Jones of Terra Publishing for his unstinting support, professional advice and expertise shown at every stage of production, from the initial idea to the finished work. Secondly, I thank my students who, with their stimulating questions and bubbling enthusiasm inspired me to write down my explanations for the fascinating geological history of Scotland. In order to make the book as readable as possible, direct citations of individual published works – e.g. "(Smith & Jones 1999)" – have been omitted, because many readers may not be comfortable with this academic habit. However, I do wish to acknowledge the contribution of the many geologists whose work has made the writing of this book possible; they are listed in full in the Bibliography. I am extremely grateful to them. I also thank my colleagues for their support. Finally, for their patience and support, I wish to thank my family, to whom this book is dedicated – Patricia, Ann-Marie and Kathleen.

Introduction

This book is about the landscape you will see around you as you travel throughout Scotland. What makes up the natural landscape? Its components are part of the natural environment: rocks, soils, relief, climate and vegetation. This natural or physical environment in turn consists of closely interrelated systems working in harmony within cycles of varying duration. The landscape itself is not static, but has been evolving constantly throughout the history of the Earth by the interaction of animals, plants and physical processes, sometimes gradual, often abrupt or catastrophic. And, for at least the past 5000 years, humans have played an important part in changing the landscape, at an ever-accelerating pace. Recent climatic change as a result of the enhanced greenhouse effect is thought to be mainly induced by humans, and the future effects on the landscape could turn out to be profound and possibly irreversible in the scale of our lifetime.

Scotland is famous for its varied and attractive scenery, and for the sharp contrasts between different parts of the country. These scenic differences derive from natural forces acting on bedrock geology that is extremely varied, given the relatively small size of the country (less than 80000 km^2). We now embark on a journey of exploration through Scotland, looking at the variety of landscapes, and discovering the reasons for the patterns we see at the surface. In human terms, the landscape may seem never changing, save for seacliff collapses, or rockfalls down mountainsides, but over millions of years, it has been changed profoundly by the action of rain, ice, waves and wind. In the more distant past, the rocks of Scotland were formed by processes that originated in the Earth's interior: mountain building, folding of rocks, faulting, earthquakes, volcanic eruptions and deep underground intrusions of molten rock. The Scottish landscape is an intricate set of different landform elements of different ages and origins, resulting from a complex geological fabric and combining to produce an attractive patchwork, characterized by sharp contrasts in the various parts of the country, particularly between the east and the west.

Why do we see such marked contrasts, between high rugged mountains in the northwest, flat, high table lands in the northeast, lowlands in Central Scotland, and rolling hills in the Southern Uplands? The answer, as we shall soon see, lies in the nature of the bedrock that was sculpted by the forces of erosion. In very general terms, Scotland is an upland country, with the oldest rocks in the northwest and a land surface that slopes to the east and southeast, towards the North Sea, and is the direction of flow of most of the main rivers. The fabric of the rocks has strongly influenced the development of the landscape, since some rocks are relatively weak and can be easily sculpted by erosion, whereas others are much tougher and more resistant to erosion, so they can form prominent landscape features. In some parts of the country, such as the Northwest Highlands, the variety of rock types over a small area is considerable, and the result is a complex pattern of landform features that endows the region with a scenic beauty scarcely rivalled in the rest of Britain or Europe.

The rock fabric of Scotland

The Earth is made of three concentric shells: the crust, mantle and core. For our purposes, the crust and the upper part of the mantle are the most important. We live on the crust, the thin, outermost shell, which is 35 km thick on average in the continents and 7 km under the oceans. Continental mountain chains have thicker crust; for example, the crust beneath the Himalayas is 85 km thick. The centre of the Earth lies 6371 km beneath the surface.

The three main rock types that make up the Earth's crust are referred to as:

- igneous, formed by the cooling of molten material from below the crust
- metamorphic, formed when heat and pressure alter rocks that have already been formed
- sedimentary, formed on the surface by the deposition of material carried by wind, water or ice.

In very broad terms, igneous and metamorphic rocks, being crystalline, are harder and more resistant than sedimentary rocks, and so tend to form the higher ground and more rugged landscapes in the highland areas. Most of Central Scotland is made of sedimentary rocks and the land is generally low lying. Higher ground in the central belt is underlain by igneous rocks, such as the lava flows that make up the

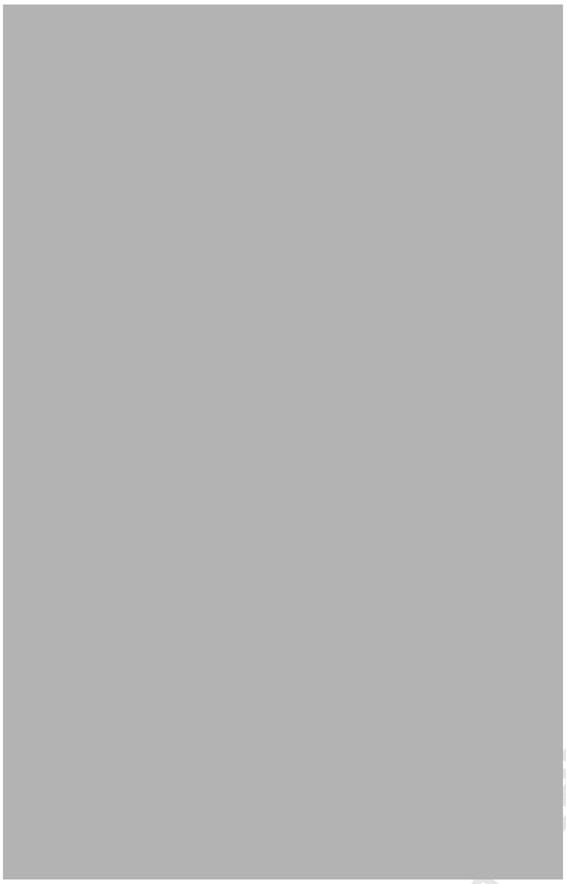

Figure 1.1 Sketch map of Scotland, showing distribution of the main rock types.

Campsie Fells north of Glasgow. The map of Scotland (Fig. 1.1) shows that the greater part of the country is made up of igneous and metamorphic rocks. Rocks are very varied in terms of their colour, the shape and size of crystals and grains, and their texture (how the grains interrelate), and this has given rise to a profusion of names. However, do not be daunted by this, for there are no more than a couple of dozen important rock names, and even fewer are used in this book.

Minerals – the building blocks of rocks

Rocks are made of minerals, which are naturally occurring chemical compounds that grow as crystals in igneous and metamorphic rocks, or exist as fragments in most sedimentary rocks, except limestones and salt deposits which are also crystalline. Individual minerals can be recognized on the basis of their composition, crystal shape and physical properties (i.e. colour, hardness, lustre, cleavage, density, etc.). Talc is the softest mineral and diamond the hardest. There are about 3700 known minerals, and more are being found all the time. Half of them are named after the individuals who discovered them, and a quarter are named after the place where they were found. Because they are chemical compounds, minerals are divided into groups on the basis of their chemical composition. Very few natural elements are able to exist in a pure state, gold, silver and platinum being well known examples of these. As far as the rocks of Scotland are concerned, they are mostly made of silicate minerals. Important non-silicate minerals include the metal ores that were once mined.

Igneous rocks

Igneous rocks are produced when molten magma (hot silicate melt with dissolved gases) cools and solidifies. Interlocking crystals of mainly silicate minerals grow freely together in all directions and in random fashion to create a solid rock. If magma penetrates other rocks underground, the igneous rocks that form are referred to as intrusive. When liquid magma escapes at the surface through fissures and cracks in the crust, or from volcanoes, the resulting lava flows that pour across the landscape are known as extrusive igneous rocks. Depending on the cooling rate, crystals of different sizes can grow, the relationship usually being that slow cooling underground (over possibly up to a million years) results in coarse-grain rocks; rapid cooling, as in surface lavas flows, produces fine-grain rocks. Sometimes cooling from a melt at a temperature of 1000°C or more is so rapid that no crystals have a chance to grow, and instead a dark volcanic glass forms. Large and small crystals can occur side by side in an igneous rock, which normally indicates a two-stage cooling history, larger crystals forming deep within the crust and finer crystals enclosing these as a groundmass or matrix when the rock finally cools at a faster rate on or close to the surface. Differences in mineral composition, related to magma chemistry, result in a great variety of igneous rocks, made all the more complicated by differences in crystal sizes.

Depending mainly on the amount of silica present, igneous rocks are traditionally classified as acidic,

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Although a small country, Scotland has an unrivalled diversity of rocks and landscapes. Most periods in the long history of the Earth are represented here, from the oldest hard crystalline rocks of the Outer Hebrides and Northwest Highlands to the younger and softer sedimentary rocks of central and southern Scotland. It is thanks to the underlying geology and the varying impact of different external processes that we have such varied landscapes, and the rocks have had a profound influence on the development of soils, land use, industry, transport and economic development.

Scotland owes the great diversity of its geology to the fact that it has always been at a sort of "geological crossroads", at the edge of a large continent. We now know that continents have been continually moving across the surface of the Earth, colliding together to form great mountain chains, or being split apart as new oceans are born. These processes have been taking place throughout billions of years, all over the Earth, but in different regions at different times. Once the activity ceased at any one place, the forces of erosion immediately began to erode the newly formed mountains to produce thick layers of sediment on low ground (or in "basins"), which sank slowly to accommodate the increased mass of material transported. Scotland's most recent mountain-building period took place 400–500 million years ago, to produce the Caledonian Highlands that stretch from Argyll to Shetland. What we have here, though, is only a small part of a much more extensive chain of mountains that runs from the Appalachians in North America, through Ireland, Wales and Scotland, then on northwards to eastern Greenland and western Norway (see Fig. 4.1). This mountain chain, although mostly worn down by erosion, forms the backbone of Scotland and is responsible for the northeast–southwest "grain" of the country. Almost the last event in the formation of these mountains was the faulting created when smaller portions of the land were forced against one another. Like the mountain chain, the faults also run roughly northeast–southwest, and now they divide Scotland into geological regions. From north to south the faults are the Outer Isles Thrust, the Moine Thrust, the Great Glen Fault (and the Walls Boundary Fault, its extension in Shetland), the Highland Boundary Fault, the Southern Uplands Fault, and the Solway Fault, which more or less coincides with the Scotland/England boundary (Fig. 2.1). We shall shortly see that Scotland and England used to be parts of two quite separate continents. The union came about 420 million years ago during a collision that produced the Caledonian Mountains. Once welded together, they have remained in that position; so the political boundary is really a geological one too. Figure 2.1 shows how these large faults have controlled the coastline, particularly the eastern seaboard of the Outer Hebrides, the east coast of Caithness and Sutherland, the long inlet of Loch Linnhe off Mull, and the Solway Firth. Most of the industrial development took place in Central Scotland, between the Highland Boundary Fault and the Southern Uplands Fault. The Highlands were once almost impenetrable north of the Highland Boundary Fault, and the Great Glen Fault has always acted as the main transport route in northern Scotland.

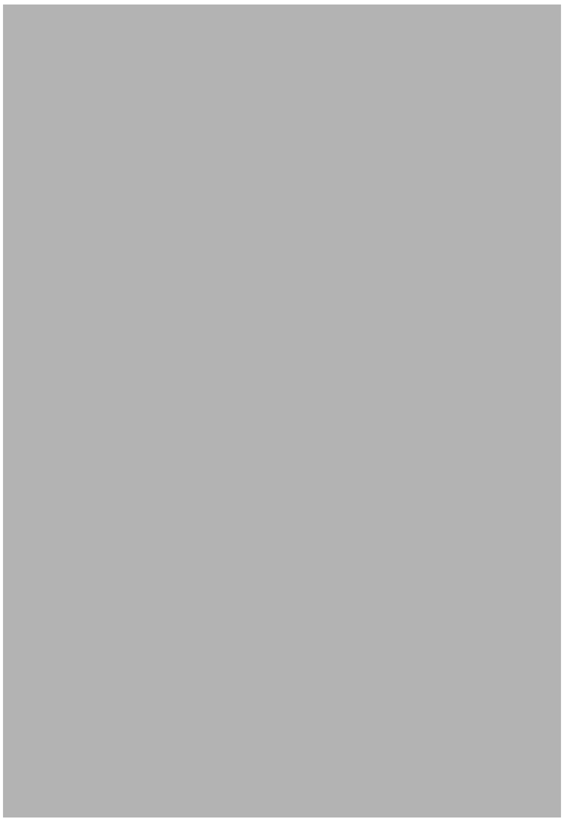

Figure 2.1 Sketch map of geological regions of Scotland.

Introduction

Our journey starts way back in time, with Europe's oldest rocks, 3 billion years old, which are found in a narrow strip of the Northwest Highlands and in the Outer Hebrides (Fig. 3.1). Taken together, the Outer Hebrides and Northwest Highlands comprise the Hebridean Terrane, one of five such blocks of crust that make up Scotland. These ancient rocks are known as the Lewisian, after the Isle of Lewis. Except for some Triassic sandstone and conglomerate around Stornoway, all the islands of the Outer Hebrides are made of Lewisian rocks, from the Butt of Lewis to Barra Head, and they are wonderfully exposed, particularly in the southern isles and in South Harris (Fig. 3.2). On the mainland, Lewisian rocks are found along the coast of Sutherland and Wester Ross, from Cape Wrath, through Assynt and Gairloch, towards Rona, northern Raasay and southeastern Skye, passing Dornie and Glenelg, and finally via Rum on to Coll, Tiree and Iona (Fig. 3.3). As in the Western Isles, on the mainland you will see the bare rocky knolls and lochans or peat bogs between (Fig. 3.4), or occasionally soaring cliffs, as at Cape Wrath (Fig. 3.5). Lewisian rocks occur almost exclusively to the west of the Moine Thrust zone, which really represents the western margin of the Caledonian mountain belt. For this reason, the old rocks of the Northwest Highlands are sometimes referred to as belonging to the foreland or basement, that is, a stable segment of the crust that was largely unaffected by the later events of the Caledonian orogeny. At the end of this orogeny, the now-folded metamorphic rocks of the Northern Highlands were pushed many kilometres to the west, over the top of the old basement rocks. This movement took place along a series of low-angle faults, known as thrusts, including the Moine Thrust zone (Fig. 3.6). Imagine pushing a stack of cards across a table top: the cards separate and are moved away from you, each one a little more than the ones below. If you add up all the small amounts of movement, you end up with quite a significant total, or displacement – at least 80 km, and possibly much more. And so it is in the Northwest Highlands, the Moine Thrust zone is just

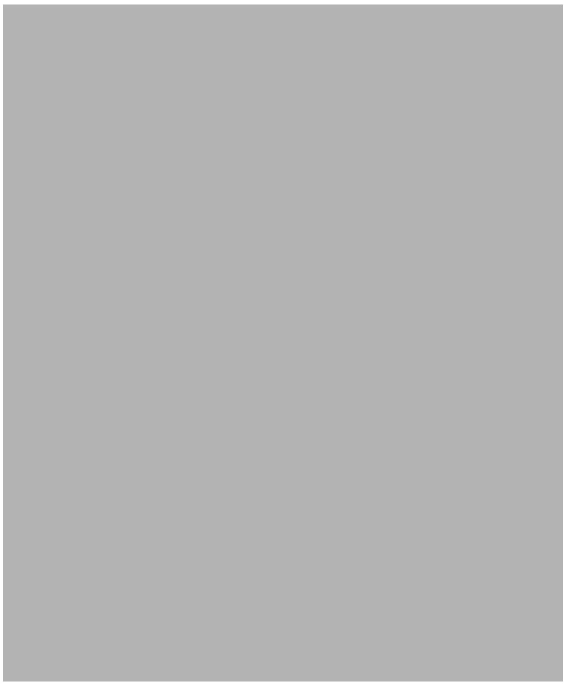

Figure 3.1 The Northwest Highlands and Outer Hebrides.

Figure 3.2 South Harris Igneous Complex: high rounded hills of resistant rock.

Introduction

The Caledonian Mountains form a narrow belt that extends all the way from Svalbard in the Arctic, through eastern Greenland and western Norway, to Shetland, the Scottish Highlands and Southern Uplands, Wales and Ireland, and then on to the Appalachians in eastern North America (Fig. 4.1). In Scotland we see only a small section of this 7500 km-long mountain chain, now deeply eroded. Despite the fact that the segment of the Caledonian Mountains in Scotland is at most 200 km across, this narrow zone, like the Northwest Highlands (Ch. 3), has for over a century provided incredibly fertile ground for the growth and development of new ideas and techniques relating to the origin of mountain belts. Major advances in our understanding of how rocks deform and respond to changes in pressure and temperature inside the Earth were made in the Caledonian belt of the Highlands. Thrusting was first demonstrated here: Peach & Horne revealed the effects of the Moine Thrust in Northwest Scotland in 1907 (see Ch. 3); and, in 1893, George Barrow was the first to introduce the concept of regional metamorphic zones in the Southwest Highlands (see p. 50). In 1930, Sir Edward Bailey used sedimentary structures in metamorphic rocks for the first time, to deduce the correct way-up of folded rocks. And as early as 1897, C. T. Clough demonstrated that, in mountain chains, rocks could be folded and re-folded several times over: the concept of polyphase deformation, which is fundamental to our understanding of the evolution of all mountain chains. These concepts and techniques are today used routinely throughout the world. The Scottish segment of the Caledonian mountain belt is one of the most intensively studied mountain chains anywhere in the world. Despite this, it has remained full of enigmas and controversies, relating to when the sedimentary units were deposited, when and how often they have been subjected to major mountain-building phases, and where the various segments of crust came from that were brought together to complete the geological jigsaw. In 1860, at the very beginning of serious study of the Caledonian belt, a major controversy arose, dubbed the "Highlands controversy", between survey geologists and academics (see box on p. 69).

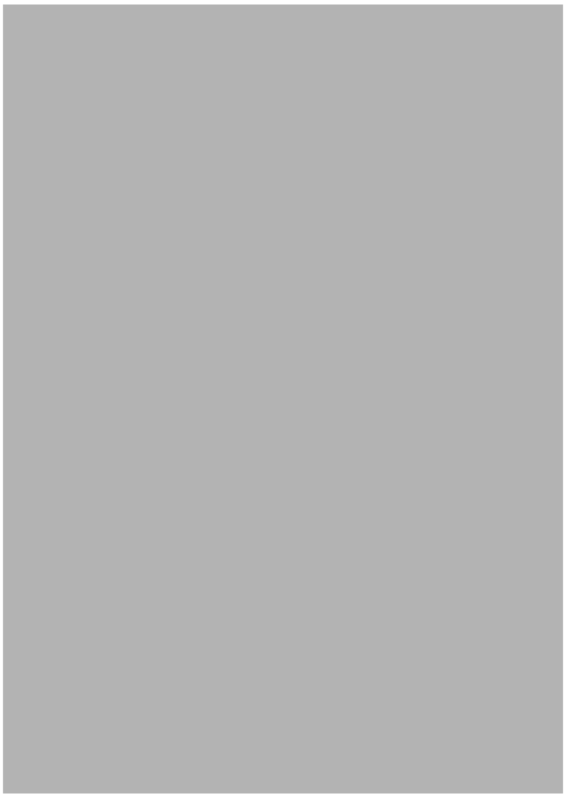

Figure 4.1 The extent of the Caledonian fold belt, prior to the opening of the North Atlantic Ocean.

The rocks forming the Caledonian mountain belt account for the largest terrane in Scotland, and the growth of the belt was a highly complex set of events, starting with the break-up of a large supercontinent, Rodinia, 750–600 million years ago, and ending with the closure of the Iapetus Ocean 420 million years ago. This chapter follows the development of the Caledonian orogenic belt in terms of plate-tectonic theory, and shows how the various crustal segments or terranes were finally assembled together in the concluding stages of the orogeny, by 400 million years ago.

The Caledonian belt was formed when the Iapetus Ocean that separated Laurentia (to which Scotland was attached) from Avalonia (to which England and Wales were attached) closed 420 million years ago. Closure of the ocean resulted in continental collision: the ocean disappeared and the sediments that had formed on the ocean floor and shelf became folded and metamorphosed. Melting of the deep thick crust led to the formation of granites, which forced their

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The Caledonian Mountains of Scotland, Ireland, Wales and Scandinavia arose 410 million years ago as a response to the collision of three continents to form a much larger supercontinent (see Fig. 4.2). At the time, Scotland lay in the interior of this continent, about 20° south of the Equator. An ocean existed some way to the south, in the area now occupied by the extreme southwest of Ireland and southwest England. Most of Scotland was mountainous, with several valleys and lowlands that were to become sedimentary basins: areas of crust that received the deposits washed down from the Scottish and Scandinavian mountains. Rapid downcutting of the young high mountains resulted in the root of the thickened crust rebounding to compensate for what was removed by gravity, torrential flood waters, and wind. Plant life during the Devonian period (418–362 million years ago) was very sparse on land, being restricted initially to lichens, ferns, reeds and mosses. With no tree or grass cover, the bare stony mountainous terrain was subjected to rapid erosion. Because Scotland was far from the effects of wet winds, rainfall would have been intermittent and probably torrential, so that large amounts of scree and boulders were washed down off the mountain tops and spread out across valley floors as alluvial fans during flash floods. A thickness of 20–25 km of material was removed and redistributed in this way, filling up the valleys with boulder conglomerates and sandstones. The latitude of 20° south is in the zone where desert conditions exist, and the continental deposits formed in such an environment are frequently stained red with hæmatite (iron oxide). For this reason, the rocks that accumulated in the sedimentary basins, which emerged after the Caledonian orogeny, are called the Old Red Sandstone. The Devonian period of geological time was named after Devon (by Sir Roderick Murchison, from Tarradale in Easter Ross, in 1839), which at the time was at the edge of a young ocean, while the rest of the British Isles area was a continental landmass.

The terms Old Red Sandstone and Devonian are often confused, but they are not interchangeable. The sedimentary rocks (conglomerates and sandstones) that make up the Old Red Sandstone sequences were deposited under arid and semi-arid conditions, which began and ended and ended at different times in different places, from near the end of the Silurian period until the early part of the Carboniferous period.*

At present, the main outcrops of Old Red Sandstone sedimentary rocks are found in the Midland Valley and in Caithness, Orkney and Shetland. Smaller amounts can also be seen in the Southern Uplands and at a few locations in the Highlands. Because the rocks formed in the Caledonian orogeny are intensely folded, Old Red Sandstone deposits generally lie unconformably on top of the older rocks. One of the best-known examples world wide of an unconformity is the famous section at Siccar Point, known as Hutton's unconformity (see Fig. 4.25). The sequence of events giving rise to an unconformity is illustrated in Figure 1.11.

During the late Silurian and early Devonian, the Midland Valley began to develop as a basin because of crustal tension that caused the Highland Boundary Fault and Southern Uplands Fault to act as a pair of parallel normal faults, allowing the crust in between the faults to sink and form a rift valley or graben (German: furrow or trench). Within this valley, northeast–southwest-trending basins developed as sediment accumulated. From northeast to southwest these are the Crawton, Strathmore and Lanark basins. As sediment was brought into the basins, faulting continued to allow the base to sink and accept more and more material. Old Red Sandstone rocks are found north of the Highland Boundary Fault and south of the Southern Uplands Fault, so the two main faults did not themselves actually control the deposition. Gravels were transported by large rivers flowing off the Highlands, Southern Uplands and the Scandinavian mountains to the northeast, and they were deposited in the basins that were developing along the faults bounding the Midland Valley. Scotland then was closer to Scandinavia, because the North Sea Basin had not yet opened up. Volcanoes existed in the region of the Ochil and Sidlaw Hills, and many of the

* Rock successions are subdivided into Lower, Middle and Upper, whereas time periods are subdivided into Early, Mid- and Late. Further subdivisions of time are used, and are based on internationally agreed type sections, usually of marine sedimentary rocks containing characteristic fossils. For example, the Late Devonian is divided into the Frasnian and above it the Famennian, named after Frasnes and Famenne in Belgium, where the European type sections were defined, in 1862 and 1885 respectively.

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Since the deposition of the Carboniferous sediments in lagoons, shallow seas, river deltas and swamps, most of the Scottish mainland has remained a land area for the past 250 million years. The collision between the northern and southern continents led to the formation of the Hercynian (or Variscan) orogeny and to the creation of the supercontinent of Pangaea, consisting of all the continents in one giant structure. Pangaea was arranged almost symmetrically as a north–south landmass across the Equator, but did not stretch as far as the poles. Glaciers in the southern hemisphere towards the end of the Carboniferous period began to melt, and the poles became free of ice. On the eastern side of Pangaea was an embayment of the worldwide ocean or Panthalassa (Greek: the whole sea). This broad inlet was called the Tethys Sea, and its final remnant today is the Mediterranean, which now has no connection with the Pacific Ocean.

The creation of Pangaea had profound effects on life, and the reasons are not hard to find. First, the shelf seas, which contain many important habitats for life, were reduced in number and area, once all the separate continents had collided. Secondly, the sharp reduction in plate-tectonic activity meant that sea levels were lowered because there were very few mid-ocean ridges rising up as broad structures from the ocean floor. Finally, the configuration of Pangaea and the absence of polar icecaps would have had an impact on global climate, because ocean currents and wind patterns would have been very different from those of today.

During the Permian period, Scotland lay just north of the Equator, in the middle of a large continent, and the climate was hot and dry. By the start of the Triassic period, 250 million years ago, the country lay at 15° north, and by the end of the period, 40 million years later, continental drift brought Scotland to a latitude of 30° north.

New Red Sandstone

Because the sea was never present in Scotland during the Permian and Triassic, and rainfall was low and sporadic, fossils are generally lacking in the rocks formed in that time interval, most fossils being found in marine sedimentary rocks. The few deposits are mostly bright red dune-bedded sandstones, laid down in valleys at the foot of the Caledonian Mountains. Occasional sedimentary breccias with angular rock fragments represent the deposits of flash floods that carried scree down steep mountain slopes into and along desert valleys or wadis, a situation found today in the Middle East. Dating of unfossiliferous rocks is very difficult; in Scotland the Permian and Triassic are usually grouped together as the New Red Sandstone, since a definite Permian or Triassic age often cannot be deduced. Outcrops are found in Southwest Scotland in the Solway Firth, Dumfries, Stranraer, Lochmaben, Annandale, Thornhill, Mauchline and Arran basins (see Fig. 2.7), on Mull and near Stornoway, and as a narrow strip on the south side of the Moray Firth near Elgin (Figs 6.1, 6.2). The Hopeman Sandstone (as it is known in Moray) has been widely used as for building in northeast Scotland (e.g. the cloisters at Elphinstone Hall, University of Aberdeen), and for the Museum of Scotland in Edinburgh (Fig. 6.3). The Moray Firth contains very thick New Red Sandstone deposits. In the North Sea, the Hopeman Sandstone is an important oil reservoir rock.

On the Moray Firth coast, the Old Red Sandstone and New Red Sandstone rocks are in close proximity, although separated in time by 150 million years. In adjacent quarries, the rocks can look identical, and it was only the discovery of fossil reptiles at Hopeman in 1893 that finally proved that the Hopeman Sandstone was New Red Sandstone (Permian) and not Old Red Sandstone (Devonian). During the period when the Clashach quarries near Hopeman were reopened to provide stone for the museum (Fig. 6.3), new finds were made of reptile skeletal remains, including a skull, and trails of footprints across the fossil sand dunes. Large-scale bedding structures are an indication of these dunes (Fig. 6.4). Well rounded sand grains and wind-sculpted pebbles also indicate desert conditions on land. To the east of Scotland during this time, an arm of a shallow sea originating from the site of present-day Germany encroached on what is now the North Sea. During the Permian, the North Sea was a subsiding basin, partially filled with a shallow sea.

High temperatures meant that the water in this sea was constantly being evaporated, and therefore thick

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Scotland's most recent volcanic rocks, and indeed youngest solid rocks, formed 60–55 million years ago on the west-coast Inner Hebridean islands, principally Skye, Mull, Rum, Canna, Eigg, Muck and Arran, as well as on the Ardnamurchan Peninsula and, west of Lewis, the St Kilda archipelago. These localities form part of the extensive North Atlantic Tertiary Igneous Province, which stretches for some 2000 km from the west coast of Greenland to the British Isles. Many volcanic centres have also been found during oil exploration in offshore areas to the west and north of Scotland (Fig. 7.1). Ailsa Craig is the southernmost outcrop of rocks of this age in Scotland, but the province also includes the Antrim lavas, the Mourne Mountains and Slieve Gullion in Ireland, and Lundy Island in the Bristol Channel.

Volcanic activity in Scotland at this time was related to the opening of the North Atlantic Ocean by seafloor spreading. Rifting of the Pangaea supercontinent moved into its final stages, and North America, Greenland, Britain and Scandinavia separated during this break-up. At the same time, Scotland drifted from a latitude of 45°N at the end of the Cretaceous period to 50°N then 55°N through the Tertiary (65–2 million years ago), eventually reaching its present position. During the early part of this period, the climate in Scotland was considerably warmer and wetter than it is today, and much rock was removed by erosion following intense periods of deep chemical and physical weathering. Some of the results of this episode still remain, such as the tor formations on the granite summits of Bennachie (near Aberdeen), the Cairngorm Plateau (see Fig. 8.2) and the extensive planation surfaces of the Highlands. These rare landforms are now protected as Sites of Special Scientific Interest. The ice later removed most other tors and remnants of

Figure 7.1 The Tertiary volcanic district of western Scotland.

Figure 7.2 Tertiary lava flows and trap topography: the Ardmeanach Peninsula on the west coast of Mull. The Ben More Central Volcanic Complex is visible in the background (right).

Introduction

Two million years ago, Scotland had arrived at its present northerly latitude. Simultaneously, there was a marked deterioration in the world's climate, especially in the North Atlantic region: Scotland had entered the Ice Age. The most recent period of Earth history is the Quaternary (Latin: fourth; a reference to a previous subdivision of geological time into four units). The boundary between the Quaternary and the preceding Tertiary period is put at 1.8 million years ago; the Quaternary is further subdivided into the Pleistocene, which includes the glaciations, and the Holocene, from 10000 years ago, when the ice finally melted from Scotland, up to and including the present. Investigations of past climates in the Quaternary clearly indicate that the present warm stage is merely the most recent of relatively shortlived interglacials between glacial stages (or full ice ages) and that, if the pattern continues, we are heading for another ice age within the next few thousand years. The present global warming is related to burning of fossil fuels (wood, peat, coal, oil and gas) and intensive agricultural practices: much carbon dioxide and methane are produced, which enhance the natural greenhouse effect, and this may delay the onset of the forecast ice age. On the other hand, we may be in for a surprise, since it is not yet fully understood how all the components of the climatic system interact, and disturbing the system may well produce quite unforeseen effects that could not be predicted.

For human beings, the Quaternary is the most significant period in Earth history, since that is when modern humans first emerged. The most recent ice sheets put the finishing touches to the landscape of Scotland, and the soils developed only after the ice melted. It is also the best-understood period, since nearly all the animals and plants found as fossils in the Quaternary exist today, and geological events in the Quaternary can be dated with remarkable accuracy.

In the annals of geology, Scotland is well known as being the first place where the existence of former glaciers was deduced, following on the observations of the Swiss geographer Louis Agassiz (1807–1873), who visited Scotland in 1840 and studied various localities, notably Edinburgh, where he observed scratch marks on rocks in the Braid Burn, and Glen Roy, where he interpreted the Parallel Roads as the signs of water levels in a former ice-dammed lake. (Incidentally, Agassiz was a palaeontologist who specialized in studying fossil fish, and he was influenced by Hugh Miller's collection from the Black Isle.) Many of the landforms produced during and after the most recent ice age are important internationally, including in particular the suite of landforms in the Cairngorms. Here we find remnants of the pre-Quaternary landscape still preserved, as well as superb examples of glacial-erosion features, such as corries and U-shape valleys, glacial deposition related to deglaciation (moraines, meltwater features), and more recent changes associated with permafrost activities and the establishment of plant communities and environmental changes over the past 10000 years.

The worsening climate

We have already seen in previous chapters that the basic outlines of Scotland were established many millions of years ago, long before the ice sheets blanketed the land. Already at the end of the Caledonian orogeny 400 million years ago, the Highlands, Central Lowlands and Southern Uplands had formed as basic features, and so too had the main features of the coastline, as dictated by the major faults. Apart from a relatively brief incursion of the sea in the early Carboniferous (340 million years ago), when coral limestone was deposited, most of the period since the uplift of the Caledonian Mountains has been characterized by erosion from the land and deposition in sedimentary basins around Scotland, particularly in the North Sea graben structures and in the Minches. Additionally, continental deposits were laid down in river valleys and at the foot of the mountains during the Devonian (Old Red Sandstone) and Permo-Triassic (New Red Sandstone) periods. Subsequently, the next important event (and the last time solid rocks were formed) was the volcanic and intrusive activity of the early Tertiary period (60–55 million years ago), when the central complexes formed off the west coast. As a consequence of the intrusion of a mantle plume that gave rise to this volcanism, the land was elevated in the west, and the eastern part was tilted towards the North Sea. The river system that became established

Thanks to the variety of rock types formed in different plate-tectonic settings over 3 billion years of Earth history, Scotland has a wide range of natural materials with economic potential. The most significant, which are currently being commercially exploited, are North Sea oil and gas, coal and limestone from the Midland Valley, and baryte from Aberfeldy in Perthshire. Bulk materials in the form of crushed rock, and sand and gravel for use in the construction industry, are also of importance and are rather widely distributed in Scotland. Their bulk and low price make transport costs the most significant factor in their exploitation, so that most of these materials are used locally, close to where they are extracted. Other minerals exist, including metal ores, but they are generally in small deposits, and economic considerations have resulted in the closure of most such mines.

Mineral resources have been dealt with in the context of the regional geology. The details will not be repeated here, but instead this chapter presents an outline of how useful minerals form and why they occur in particular geological settings. It is such knowledge that allows new discoveries to be made, driving exploration forwards.

Introduction – what is a natural resource?

At its simplest, a natural resource is any material that could in principle be removed from the Earth and put to some practical use for the benefit of people. However, in practical terms it is more usual to consider reserves, which is the amount of a particular resource that could be extracted at a profit. For example, the total amount of coal in the United Kingdom has been estimated to be 200 billion tonnes, but only 4 billion tonnes of this could be mined at a profit. Hence the stock of coal, the resource, is 200 billion tonnes, and the lower figure constitutes the reserve. Economic factors could change the situation. If more efficient and cheaper ways could be found to mine coal, then some more of the 200 billion tonnes could become part of the reserves. One other term worth defining clearly is "mineral". In the economics of commodities, Earth resources are frequently referred to as "minerals" or "mineral resources", where the term can mean oil and gas, coal, metal ores, stone, crushed rock and other materials used ultimately in construction, agriculture and the chemical industry. However, the term "mineral" is used here for a naturally occurring solid with a crystalline structure, such as quartz, feldspar or calcite. "Natural resources" is therefore used in preference to "mineral resources"; "fuel minerals" are fossil fuels (peat, coal, oil and gas); and "bulk minerals" or "industrial minerals" are referred to here as aggregates or industrial materials.

Natural resources of geological origin (i.e. not including water, soil, wood or other organic materials) are grouped according to the type of material, under the following headings:

- Metal ores: these are minerals in the geological sense, and include oxides, carbonates, sulphides, and so on, of metallic elements, usually with other unwanted minerals (termed "gangue", e.g. quartz or calcite).
- Fossil fuels: peat, coal, oil, oil shale, bitumen, natural gas, which are extracted and burned; they are therefore non-renewable and cannot be replaced once used up.
- Industrial materials: a wide range including building stones, slate, polished stone, crushed rock for roads, and concrete aggregate, cement, brick clay, glass sand, agricultural and chemical raw materials (fertilizers, salt, sulphur, etc.).

Examples of all these categories occur in Scotland, and here we examine how the workings of the rock cycle and plate-tectonic movements have created conditions necessary for their formation in specific geological environments at distinct periods in time.

Metal ore deposits

Scotland has a wide variety of mineral deposits in rocks ranging in age from the Precambrian Lewisian gneiss to the Tertiary igneous intrusions. However, the distribution of the main ore mineralization is related to events surrounding the formation of the Caledonian Mountains. Ore deposits are found in igneous, metamorphic and sedimentary rocks, and result from processes in the rock cycle that concentrate small amounts of widely dispersed metals into potentially useful deposits.

The oldest deposits are found in the Loch Maree

Appendix

Taking it further

Textbooks, websites and excursion guides will get you so far, but if you want to make significant progress in the study of geology, it is best to enrol in an evening class at a local university, college or community centre, or enrol in a course with the Open University (website www.open.ac.uk). It would also be a good idea to join a local geological society (in Scotland these are in Aberdeen, Edinburgh, Glasgow and Inverness; see the Bibliography for their website addresses). Winter lectures and summer field trips are organized, and members of the Edinburgh and Glasgow societies receive the *Scottish Journal of Geology* twice a year. Local museums may have a geology curator who can be approached for assistance with the identification of minerals, rocks and fossils. Every other year (in odd years), there is a national Scottish Geology Week, held in August, with events throughout the country; check details on the special website www.scottishgeology.com; this also has brief outlines of the geology of the main regions of Scotland and links to geological societies.

Fieldwork

This book deals with the broad features of Scotland's geology and landscape, and does not offer help with describing and identifying rocks. That is best done under the guidance of a trained specialist tutor, as is fieldwork, where different skills are required, and particularly in geological mapping where expert guidance is essential. Training in field techniques is a slow and painstaking process. However, it is worth remembering that all the major advances in our understanding of the geology of Scotland were done on the basis of the rocks and structures seen in the field. All available excursion guides to localities in Scotland are listed in the Bibliography, although the less experienced reader may find some of them challenging. If you undertake any fieldwork, it is essential to follow the Country Code and to take extra precautions when visiting working quarries (permission must be sought in advance, and protective headgear has to be worn). Disused quarries and mine shafts are full of hidden dangers (flooding, roof collapse, unstable faces, etc.) and are best avoided completely. Do not remove mineral and fossil specimens from rockfaces at outcrops, only from loose scree. At SSSIs, samples may be collected only with the prior permission of Scottish Natural Heritage (check their website for details, www.snh.org.uk; this site also gives details of the 2002 Natural Heritage Futures initiative, covering all aspects of geology, landscape, wildlife and conservation, with huge resources available on line).

In general, it is best to follow the countryside lover's advice: take nothing but photographs, leave nothing but footprints. Enjoy looking at Scotland's varied landscapes, which are the result of a billion years of geological evolution; they have inspired scientists for 250 years and more.

Geological maps

Geological maps at various scales are published by the British Geological Survey (www.bgs.ac.uk), and may

Glossary of technical terms

accretion Growth of continents by collision; or movement together of wedges of rock; or theory of the origin of planets by capture of matter in space.
accretionary prism A wedge-shape pile of sediments scraped off a subducting plate at a destructive plate boundary (subduction zone) and interleaved by overthrusting, resulting in strata being repeated.
acidic Igneous rock with over 65% silica, e.g. granite.
agate Colour-banded form of silica found lining cavities in lava.
agglomerate Mixture of ash and broken lava in volcanic neck.
aggregate Crushed rock, used as road stone and in concrete manufacture.
albedo effect Reflection of Sun's heat by ice and snow back into space.
alluvial deposits River sediments.
alluvial fan River deposits laid down at the mouth of a valley that opens out onto a flat plain at the edge of a steep mountain slope; fan shape spreads outwards and sediments thin away from the valley mouth.
alluvium Sand and gravel in river beds.
ammonite Extinct fossil mollusc with coiled shell; important zone fossil, used for dating Jurassic rocks.
amphibole Silicate of calcium, iron and magnesium (a ferromagnesian mineral); dark green to black; elongate crystals, double chain structure.
amphibolite Hornblende–feldspar– biotite gneiss, often with garnet; formed from high-grade metamorphism of basic lavas.
amygdale Almond-shape cavity in lavas, filled with minerals, e.g. agate, zeolite, calcite, quartz (rock crystal).
anaerobic Environments in which oxygen is excluded, e.g. in deep oceans or in stagnant lakes.
andalusite Aluminium silicate found in some schists.
andesite Igneous rock, lava of intermediate composition; named after the Andes mountains.
anhydrite Calcium sulphate, an evaporite mineral; similar to gypsum, but without water in its crystal structure.
anhydrous Lacking in water.
anorthosite Coarse-grain layered igneous rock containing mostly anorthite, a calcium-rich plagioclase feldspar.
anthracite High-ranking coal, i.e. high in carbon and heat value, low in ash and volatiles; found in deeply buried Carboniferous coal fields.
anticline Fold shape with limbs dipping away from axis; oldest rocks in centre or core of fold.
Archaean Precambrian rocks older than 2500 million years.
arête Glacial landform, a sharp ridge where two corries meet back to back.
arkose Type of coarse sandstone with over 20% feldspar fragments; red or brown in colour; e.g. Torridonian Sandstone.
Armorican orogeny Mountain-building episode in central Europe, Carboniferous to Permian, 360–290 million years ago; Gondwana collided with Laurussia and created the supercontinent of Pangaea; also known as Hercynian or Variscan orogeny.
arthropods Invertebrate animals, with jointed limbs and a hard outer skeleton; group includes crustaceans and extinct trilobites.
asbestos Fibrous silicate mineral found in metamorphosed ultrabasic igneous rocks.
ash Fine volcanic material from explosive eruptions.
asthenosphere Weak layer in upper mantle, beneath lithosphere, plastic, able to flow slowly.
augen gneiss Gneiss with large eye-shape feldspar crystals surrounded by mica; a type of metamorphosed granite.
augite Calcium–iron–magnesium silicate, in pyroxene group, found in basic igneous rocks (gabbro, basalt); black, stumpy crystals, single-chain structure.
aureole Zone of country rock around an igneous intrusion, affected by heat and fluids.
Avalonia Precambrian continent containing southern Britain, Ireland and western Europe; collided with Laurentia and Baltica to create the Caledonian mountain belt.

Baltica Precambrian continent containing Scandinavia; collided with Laurentia and Avalonia to create the Caledonian mountain belt.
banding Layering of different minerals in metamorphic rocks, usually gneisses.
banded ironstone (banded iron formation) Precambrian sedimentary rock made of iron ore and chert.
Barrovian metamorphism Type of regional metamorphism found in the Grampian Highlands, showing progressive grades from slate (originally shale) through schist to gneiss with increasing pressure and temperature.
Barrow's metamorphic zones Progressive sequence of minerals in regional metamorphic rocks, from chlorite to biotite, then garnet, kyanite and sillimanite.
baryte (barytes, barite; heavy spar) Barium sulphate, dense, white, creamy or pinkish mineral used in oil drilling (heavy mud).
basalt Dark fine-grain basic volcanic lava; contains olivine, pyroxene, calcium-rich plagioclase feldspar, iron ore.
basement Older rocks on which sediments have been deposited; usually refers to a Precambrian craton, e.g. Lewisian Gneiss basement of the Northwest Highlands.
basic igneous rock Rock with 44–52% silica; rich in ferromagnesian minerals (olivine, pyroxene) and calcium-rich plagioclase feldspar, no free quartz crystals.
basin Broad area of slowly subsiding continental crust into which sediment has been transported by rivers; some basins are rift valleys or graben structures when bounded by two parallel normal faults.
batholith Very large (over 100 km^2 exposed at the surface) plutonic igneous intrusion, usually granite.
bed A stratum or layer of sediment or sedimentary rock.
bedding plane Flat surface between two beds of sediment or sedimentary rock.
bedrock Solid, firm rock on which other, younger, unconsolidated materials may be deposited, e.g. soil, peat, sand and gravel; boulders and scree are not bedrock, but instead are described as superficial materials.
bentonite Light coloured, soft clay rock

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