Science: a level 3 course

Mountain Building in Scotland

Prepared for the Course Team by Kevin Jones and Stephen Blake

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Front cover: Gearr Aonach (left) and Aonach Dubh (right) from the Meeting of the Three Waters, Glen Coe. *(David W. Wright, Open University)*

Back cover: The view westwards from Strath Fionan, near Schiehallion, central Perthshire, to Loch Rannoch. *(Nigel Harris, Open University)*

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1.1

1 Introduction

1.1 Setting the scene

Some of Britain's most dramatic scenery is to be found in the Scottish Highlands. The sight of mighty Ben Nevis, the desolate plateau of the Cairngorms, or the imposing landscapes of Glen Coe (pictured on the front cover) can unleash the call of the wild in all of us. Although these landforms were largely carved by glacial activity that ended some 10 000 years ago, the rocks themselves tell of a much older history. The Scottish Highlands, defined as lying north of the Highland Boundary Fault (Figure 1.1), are primarily composed of metamorphosed sedimentary and igneous rocks intruded by somewhat younger igneous bodies and cut by faults. The metamorphic rocks and igneous intrusions exposed at the surface must have formed within the Earth's crust, and this simple fact indicates that the Highlands are merely eroded stumps of a much higher range of ancient mountains. This book is an account of the origin and demise of that ancient mountain range, based on the geological evidence laid before us in rock exposures.

For well over a century, geologists have braved the rain, sun and midges to study the Highlands. Indeed, it was nineteenth-century field geologists working in northern Scotland who established several of the fundamental geological principles that are today almost taken for granted. Notable Victorian scientists such as Ben Peach, John Horne, George Barrow, Edward Bailey, Archibald Geikie, Charles Lapworth and Roderick Murchison were among those who made their names by observing and debating the significance of the rocks of the Highlands. For example, Peach and Horne, with others from the Geological Survey, mapped the rocks of north-west Scotland, recognizing an enormous low-angle fault in which ancient metamorphic rocks had been thrust tens of kilometres westwards over younger sedimentary rocks. This fault is now familiar to geologists across the world as the Moine Thrust (Figure 1.1). Working in the south-eastern Highlands around Glen Clova (Figure 1.1), George Barrow founded the concepts of metamorphic zones and index minerals, which are now universally used to map belts of regional metamorphic rocks. Another example, albeit from further south, is James Hutton's recognition, in 1788, of an unconformity at Siccar Point (Figure 1.1), where red sandstones (of Devonian age) had been deposited on upturned older (Silurian) strata. This and similar observations nearby led him to the revelation that sedimentary deposition had been interrupted by significant earth movements and erosion, requiring a truly dynamic Earth and eons of time.

Now, in the era of sophisticated geochemical, geochronological and geophysical methods, geologists are still working to make further sense of the region's dramatic geology in terms of plate tectonics and continental drift. So, the 'prodigious terrestrial displacements', recognized by Geikie to have formed the Moine Thrust, are now attributed to plate-tectonic collisions that happened almost half a billion years ago. To appreciate the classic geology of the Highlands, the basic geological field relationships remain fundamental, so this book has been written with field evidence very much to the fore.

In any story, the events that took place and the order in which they did so are critical. In the story of how the Highlands were built (and then eroded), the nature and relative timing of sedimentation, metamorphism, tectonism (folding and faulting), igneous activity and erosion are all revealed by the rocks. The evidence may come from field relationships, such as those that are pictured throughout this book, or from any one of a number of radiometric dating methods requiring high-precision laboratory instrumentation. Among the latter,

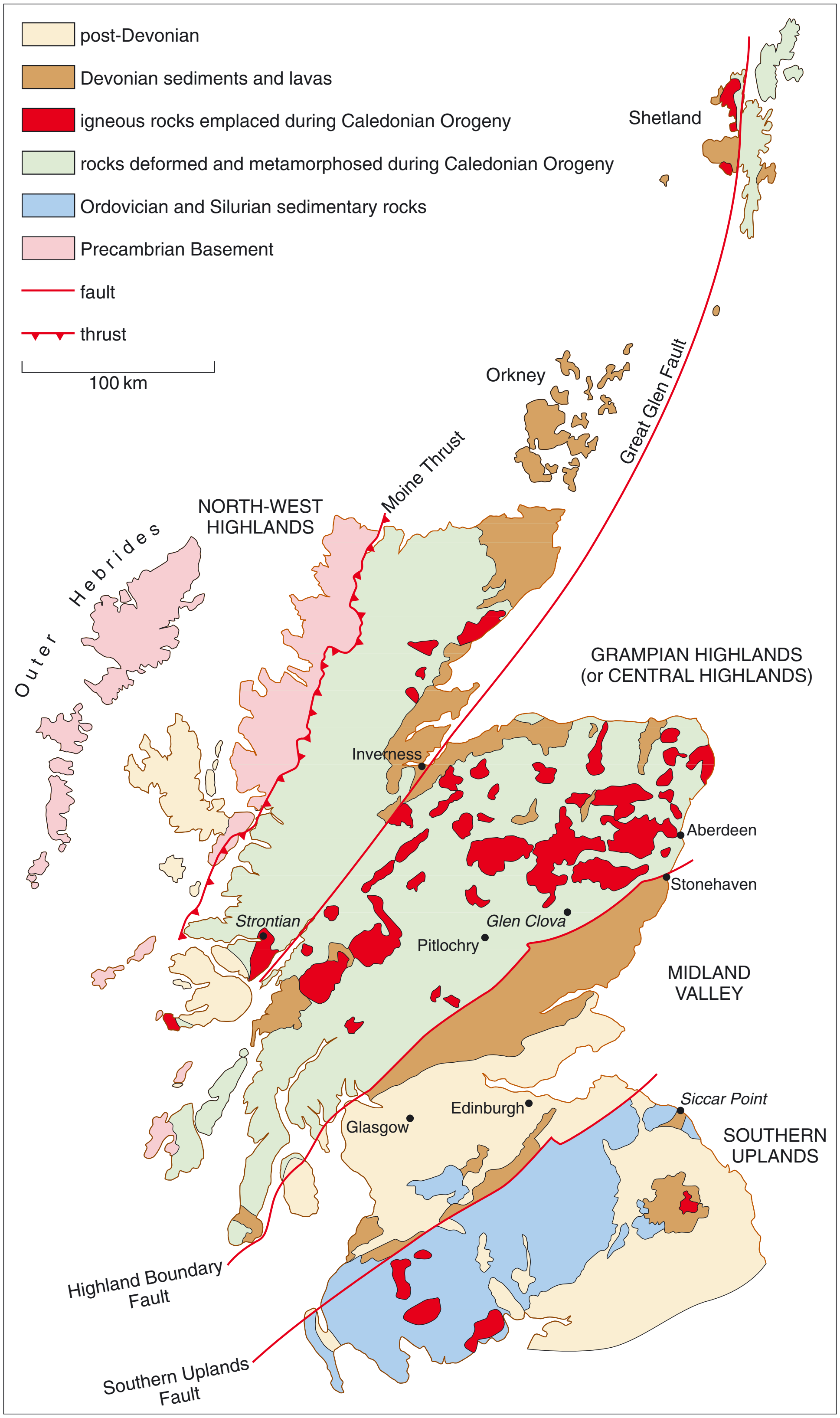

Figure 1.1 The physical geography and geology of Scotland are dominated by the products of mountain-building events, known collectively as the Caledonian Orogeny, that took place during the Palaeozoic. Some important localities in the historical development of the geological sciences (Glen Clova, Siccar Point and Strontian) are shown in italics.

incidentally, is the rubidium–strontium method. This relies on the radiogenic isotope of strontium, an element whose name derives from the village of Strontian in Argyllshire (Figure 1.1), where the element was first discovered in the mineral strontianite.

1.2 Recognizing ancient mountains

The great modern mountain ranges of the world, such as the Himalaya, have been built over millions of years, and act as natural laboratories where Earth scientists can study the complex interplay of processes that are active during mountain building. The formation of these great mountains ranges, a process called orogeny, is inextricably linked to the forces generated by the collision of lithospheric plates at destructive plate margins. In these collision zones the crust is thickened by deformation, folding and faulting, and/or by the addition of large quantities of magma. A major consequence of tectonic crustal thickening is that rocks that were once at the surface are buried to great depths and undergo substantial modification during deformation and metamorphism (Figure 1.2).

Figure 1.2 Highly deformed and metamorphosed igneous rocks from the Borgie inlier, north coast of Scotland.

The uplift of deeply buried rocks is achieved either by erosion or by a combination of erosion and tectonic movements such as faulting, and occurs in response to the isostatic readjustment of the overthickened crust – this process is called exhumation. Eventually, over millions of years, exhumation reveals the deeper levels, or roots, of the mountain belt. It follows, therefore, that the existence of ancient mountains can be recognized by the identification of zones of highly deformed and metamorphosed rocks – these zones are called orogens or orogenic belts. The study of these ancient mountain roots provides us with a record of the processes that were active in the deep crust during collision.

1.3 Orogeny through geological time

1.3.1 Geological time: a brief note

Geological time can be divided into Eons, Eras and Periods, with further subdivisions into Epochs and Ages (Figure 1.3). The order of rock units determined from the principles of superposition and faunal succession produces the lithostratigraphic column, which is based simply on the relative ages of rocks, e.g. Llandovery is younger than Ashgill but older than Wenlock. A second aspect of the stratigraphic column relates to the chronostratigraphic dating of rock units, which allows geologists to apply absolute ages to rock successions, e.g. the Llandovery ranges from 443–428 Ma.

Eon	Era	Period	Epoch	Age	Ma
					248
PHANEROZOIC	PALAEOZOIC	Permian	Late	Zechstein	256
			Early	Rotliegendes	290
		Carboniferous	Silesian	Stephanian	305
				Westphalian	315
				Namurian	327
			Dinantian	Viséan	342
				Tournaisian	362
		Devonian	Late	Famennian	377
				Frasnian	383
			Mid	Givetian	388
				Eifelian	394
			Early	Emsian	410
				Pragian	414
				Lochkovian	418
		Silurian	Late	Pridoli	419
				Ludlow	423
			Early	Wenlock	428
				Llandovery	443
		Ordovician	Late	Ashgill	449
				Caradoc	462
			Mid	Llanvirn	470
			Early	Arenig	485
				Tremadoc	495
		Cambrian	Late		505
			Mid		518
			Early		545
CRYPTOZOIC or PRECAMBRIAN	PROTEROZOIC	Neoproterozoic			1000
		Mesoproterozoic			1600
		Palaeoproterozoic			2500
	ARCHAEAN	Late Archaean			3000
		Middle Archaean			3500
		Early Archaean			4000
	HADEAN				4560

Figure 1.3 Part of the geological time-scale, showing chronostratigraphic subdivisions. Note that formally defined divisions start with an upper case letter (e.g. Mid-Ordovician), whereas informally defined divisions (e.g. mid-Silurian) start with a lower case letter. Accordingly, Early Devonian has a specific meaning or definition, whereas early Devonian is less specific.

1.3.2 Disentangling the continents

The dating of crystalline rocks using radiogenic isotopes has become a prerequisite to understanding and unravelling regions of complexly deformed and metamorphosed rocks. For several decades, radiogenic isotope systems have been used to date events such as the crystallization of metamorphic and igneous rocks. With the advent of new analytical methods it is now possible to date the crystallization of individual minerals (or even parts of minerals) such as zircon or garnet, to a precision of one or two million years, even in the oldest Precambrian rocks. Our knowledge of continental geology owes much to these methods. For instance, we now know that the succession of collisions or orogenies that have built the present-day continents occurred over long expanses of geological time.

Orogenic belts can be made up of several displaced crustal fragments, called terranes, which may have travelled thousands of kilometres across the Earth's surface before colliding with and accreting to an existing continental margin. These terranes can be oceanic crust, island arcs, or pieces of continental crust carried by subducting plates and plastered to continental margins when the plates collided. The collision 'scar' or suture zone may preserve relicts of the oceanic crust that once separated the crustal fragments – these relicts are called ophiolites.

The rocks that preserve a record of the oldest or most ancient orogenic episodes usually form the core or interior parts of continents – these are known as shield areas or cratons. These regions are often surrounded by a series of younger, more recently active mountain belts, which form long, relatively narrow topographic features such as the Alpine–Himalayan chain of southern Europe and Asia. As successively younger orogenic belts develop around the margins of the continents, the older orogenic belts that are exposed to these events become incorporated within the younger orogenies, and as a result are progressively reworked. During this process of reworking, the record of the earlier periods of orogeny becomes progressively overprinted by younger events, and so an incomplete record of orogeny is preserved.

Several factors may lead to problems in reconstructing the history of ancient orogens. Remnants of older orogens are often obscured and lie beneath younger sedimentary rocks. The older rocks may have complex histories resulting from multiple episodes of deformation, metamorphism and magmatism, which in many cases cannot be resolved even by conventional isotopic methods. The diachronous nature of the successive collisions and accretion of crustal fragments to continental margins during orogeny causes problems of correlation along the belt. In addition, details of early collisions are often obscured by later accretion events. For example, plate boundary histories are difficult to unravel if large-scale strike–slip fault systems have been active at different times.

1.4 The collage of ancient orogenic belts in the North Atlantic region

The geology of the Scottish Highlands is dominated by the effects of the last great mountain building event to have affected the region – the Caledonian Orogeny. However, the Highlands represents only a small fragment of an orogenic belt that was once of much greater extent. Fragments of this early Palaeozoic orogenic belt are scattered across the North Atlantic region as a result

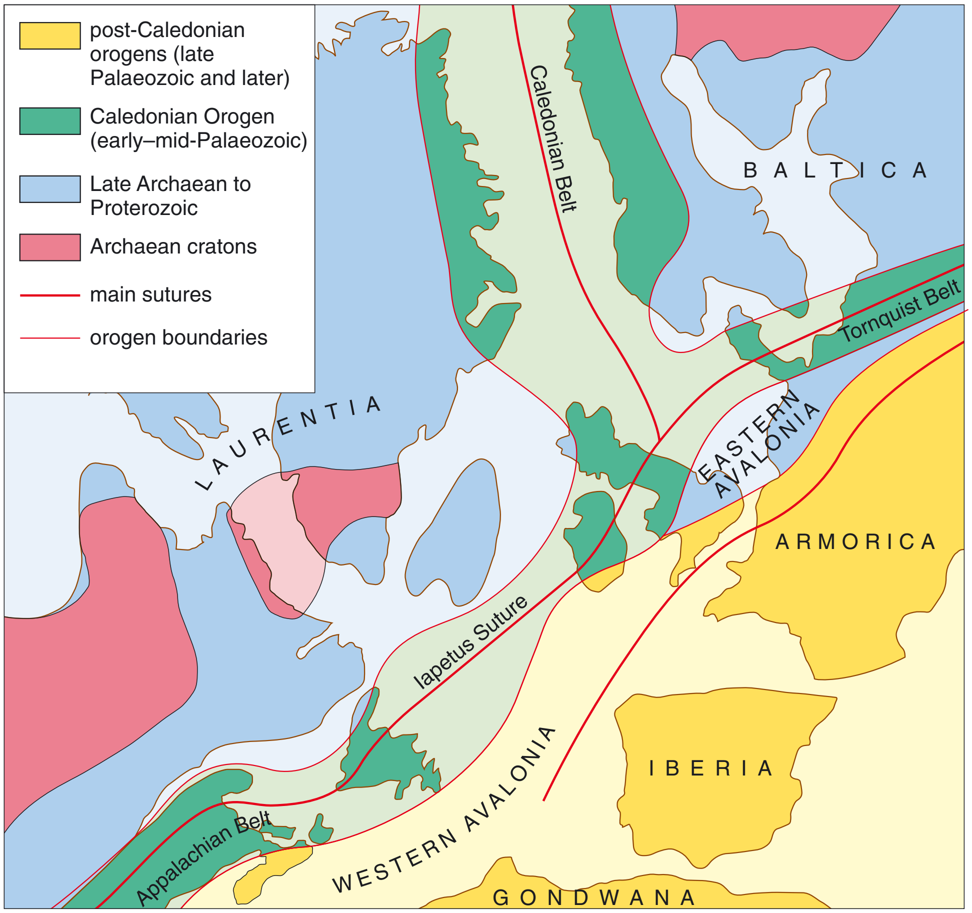

Figure 1.4 Map showing the distribution of ancient continental fragments around Britain and Ireland prior to the opening of the present-day Atlantic Ocean. The age assigned to different continental fragments is that of the most dominant period of orogeny. The younger orogenic belts are built on reworked older orogenic belts. Light shades indicate areas where the geological reconstruction is inferred.

of the opening of the present-day Atlantic Ocean. A reconstruction of the position of the continents prior to this opening clearly demonstrates the extent of the Caledonian Orogenic Belt (Figure 1.4).

Examination of Figure 1.4 reveals that the Caledonian Orogenic Belt (the Caledonides) has three distinct arms: a northern Caledonian Belt, a western Appalachian Belt and an eastern Tornquist Belt. These belts or branches separate parts of three major palaeocontinents that preserve records of much older orogenic episodes, e.g. the palaeocontinent of Laurentia is composed of rock units that were subjected to major periods of orogeny in both the Archaean and the Proterozoic. The three palaeocontinents of Laurentia (North America and Greenland), Baltica (Scandinavia and the Baltic) and Avalonia (southern Ireland and Britain) drifted together in the early Palaeozoic, colliding to form the Caledonian Orogenic Belt. Britain and Ireland hold a special position in this orogenic system as they straddle the Caledonian Orogen, adjacent to the three palaeocontinents.

1.5 What caused the Caledonian Orogeny?

The tectonics that led to the construction of the Caledonian Orogenic Belt were associated with the closure of a major ocean called Iapetus. The Caledonian Orogeny was not a simple continent–continent collision, it encompassed a series of more localized arc–arc, arc–continent and continent–continent collisions. The sequence of events that led to the collision of Laurentia, Baltica and Avalonia, and to the formation of the Caledonian Orogenic Belt, can be traced as far back in time as *c.* 600 Ma, to the break-up of a major palaeocontinental landmass referred to as the Vendian Supercontinent, named after the Vendian Period (*c.* 680–545 Ma). This sequence of events is illustrated on Figure 1.5 and can be summarized as follows:

- The initial break-up of the Vendian Supercontinent began *c.* 600–580 Ma ago with Baltica rifting from eastern Laurentia along the Greenland margin, and Gondwana rifting from North America, thus forming the Iapetus Ocean (Figures 1.5a,b).
- The initial stages of ocean destruction began in Cambrian to Early Ordovician times with the formation of subduction zones and the localized collision of volcanic arcs along the margins of the continents that surrounded Iapetus (Figures 1.5c,d). The phase of arc–continent collisions along the southern margin of Laurentia is referred to as the Grampian orogenic phase, evidence for which can be seen in the rocks of Scotland and Ireland.
- Also at this time the continent of Gondwana began to break up, and continental fragments, including Avalonia, which incorporated southern Britain, rifted and migrated northwards, narrowing the intervening Iapetus Ocean and opening another, the Rheic Ocean, in its wake (Figure 1.5d).
- The initial collision of Avalonian fragments with the Laurentian margin (Figure 1.5e) occurred between *c.* 470 Ma and *c.* 440 Ma. The final closure of Iapetus was in the Silurian (*c.* 425 Ma), with Baltica and parts of Avalonia converging obliquely with the Laurentian margin (Figure 1.5f), resulting in the Scandian orogenic phase. At this time, significant strike–slip displacements associated with oblique collision disrupted the Laurentian margin and the Iapetus Suture Zone.

1.6 The tectonic map of Britain and Ireland

The Caledonian Orogeny was primarily responsible for the consolidation of the British Isles into its present pattern of fault-bounded crustal blocks. These crustal blocks are terranes that represent displaced fragments of continents, volcanic arcs or ocean basins accreted to the continental margins by combinations of subduction, collision and strike–slip displacement. Each of these terranes has its own individual and distinct history. The terranes and major terrane-bounding faults of Britain and Ireland are illustrated in Figure 1.6.

These terranes are subdivided into three main groups:

- *Laurentian Terranes*: those to the north of the Highland Boundary Fault – Fair Head–Clew Bay Line, which have evolved as part of Laurentia (Hebridean, Northern Highlands and Central Highlands Terranes).
- *Gondwanan Terranes*: those to the south of the Solway Line, which are thought to have evolved as part of Gondwana (Leinster–Lakesman, Monian, Welsh Basin and Midland Platform Terranes).
- *Intermediate Accreted Terranes*: an intervening zone consisting of slivers of continental margin, island arc and oceanic rocks (Midland Valley and Southern Uplands Terranes) that form a complex suture zone separating Laurentia and the Gondwanan Terranes.

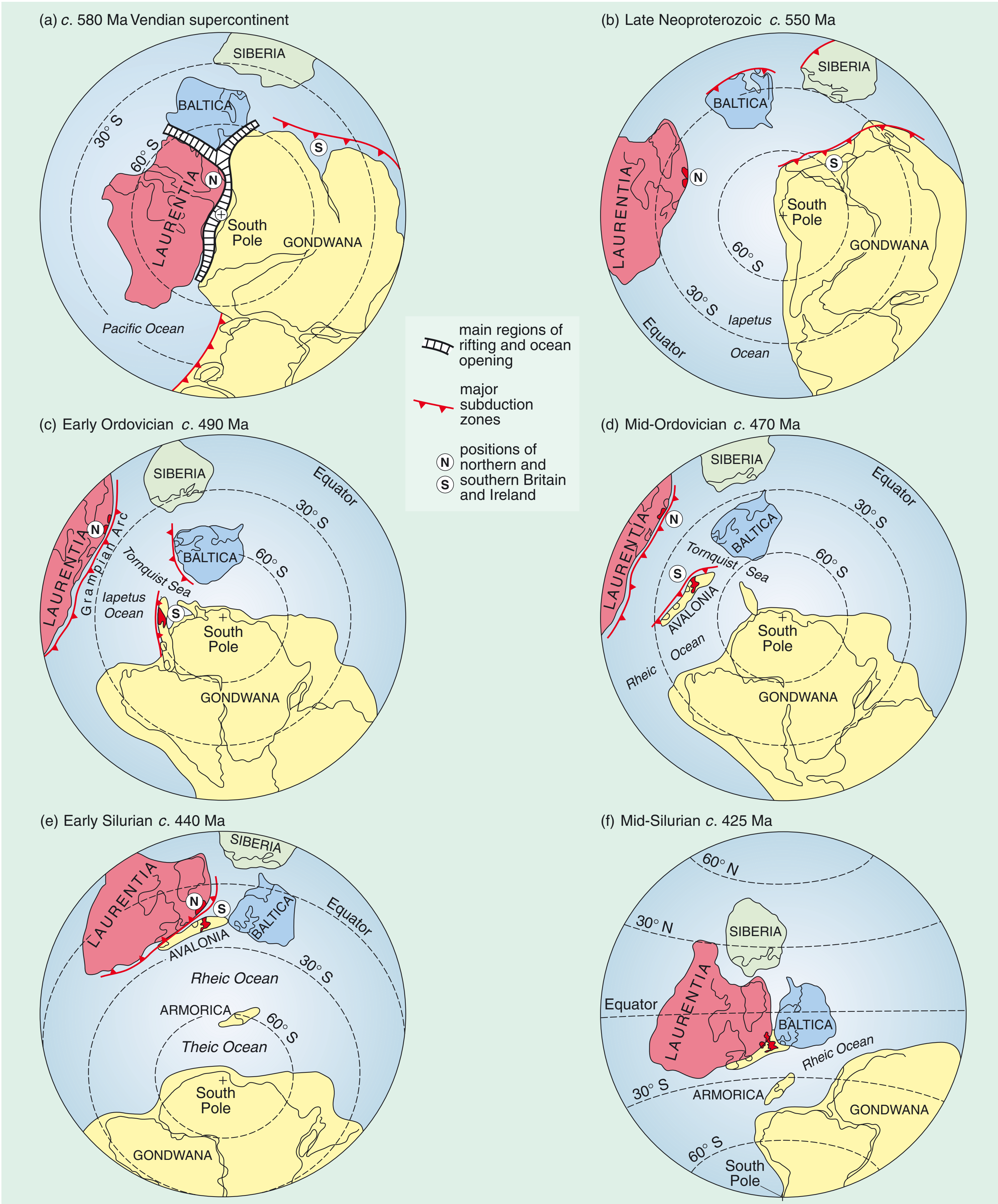

Figure 1.5 Global palaeocontinental reconstructions for the late Neoproterozoic and Palaeozoic: (a) *c.* 580 Ma; (b) *c.* 550 Ma; (c) *c.* 490 Ma; (d) *c.* 470 Ma; (e) *c.* 440 Ma; (f) *c.* 425 Ma.

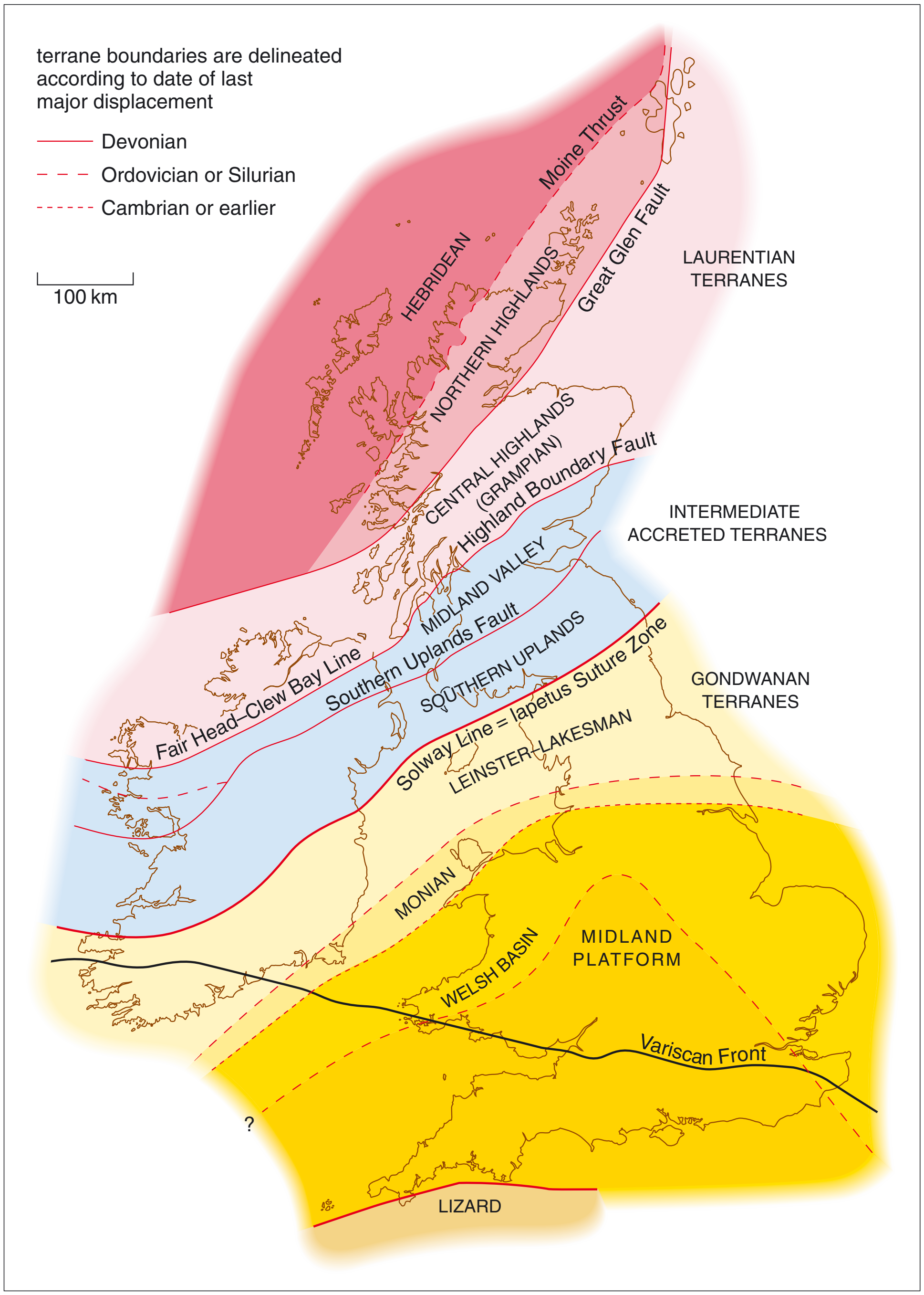

Figure 1.6 Simplified Palaeozoic terrane map of Britain and Ireland.

1.7 The scope of this book

The Scottish Highlands contains some of the most extensively studied areas of geology in the world. Given the fact that the region is of relatively small size, it is perhaps surprising that the rocks of the Scottish Highlands preserve a record of at least six periods of mountain building, which occurred over considerable geological time. In this book we will examine the nature of the evidence and the methods employed by geologists to unravel the complex history of this particular region. As mentioned in Section 1.4, the Caledonian Orogeny was the last major mountain-building event to have left an imprint on this region. In Sections 2 and 3 we will see glimpses of several older orogenic episodes from the Archaean and Proterozoic Eras. These serve to outline the basic concepts and principles of orogenesis, from which a more detailed study of the Caledonian Orogeny can be undertaken. Sections 4 to 9 focus on unravelling what happened during and after the Caledonian Orogeny.