Chapter 1 Lewisian, Torridonian and Moine rocks of Scotland: an introduction

Introduction

M. Krabbendam, K.M. Goodenough and J.R. Mendum

This volume describes the Precambrian rocks of northern Scotland, including Archaean to Palaeoproterozoic basement (the Lewisian Gneiss Complex) and later Proterozoic sedimentary and metasedimentary rocks (the Torridonian and Moine successions). The volume also contains detailed descriptions of structures within the Moine Thrust Belt and the northern part of the Caledonian Orogen. The Moine Thrust Belt is the orogenic front of the Silurian-age Scandian Event in the British Isles, and extends from Loch Eriboll on the north coast of Scotland to the Isle of Skye. The area covered in this volume includes most of mainland Scotland north of the Great Glen, together with the Outer Hebrides and parts of Shetland (Figure 1.1).

The Lewisian Gneiss Complex is exposed on the Outer Hebrides and also along the northwest coast of the mainland. It is composed of a variety of gneisses, including the oldest rocks in the British Isles, dated to just over 3000 Ma. Altogether, the Lewisian Gneiss Complex contains a record of igneous, depositional and orogenic events that occurred over a period of 1400 million years — almost one-third of the history of the Earth itself (Figure 1.2).

The Torridonian and Moine sequences represent at least two phases of sedimentation that occurred from late Mesoproterozoic to early Neoproterozoic times. The Torridonian rocks are exposed in the foreland to the Moine Thrust Belt, where they rest unconformably on gneisses of the Lewisian Gneiss Complex. Both the Lewisian and Torridonian rocks also occur within the thrust belt. The informal name 'Torridonian' actually refers to two separate rock sequences; the Mesoproterozoic Stoer Group, and the Neoproterozoic Torridon Group. A third group, the Sleat Group, is only exposed on the Isle of Skye and is rather more enigmatic.

The Moine Supergroup was also deposited during the early Neoproterozoic, and is now exposed to the east of the Moine Thrust Belt. Rocks considered to correlate with the Moine are also exposed on the Shetland Isles. Whereas the rocks to the west of the thrust belt have remained relatively undeformed, the Moine succession contains evidence of at least four distinct tectonothermal events. The GCR sites illustrate that evidence, tantalizing and complex as it may be in some cases.

A Cambro-Ordovician sedimentary sequence occurs within the Moine Thrust Belt and in its immediate foreland. The character of these rocks is only briefly described in this volume, as they are fully covered in GCR Volume 18, *British Cambrian to Ordovician Stratigraphy* (Rushton *et al.,* 2000). Numerous Ordovician to Devonian igneous rocks also occur within the area of this GCR volume: many of these are described in detail in GCR Volume 17, *Caledonian Igneous Rocks of Great Britain* (Stephenson *et al.,* 1999).

The contribution of the Northern Highlands to the understanding of tectonic processes

KM. Goodenough, J.R. Mendum and M. Krabbendam

Over the last two centuries, generations of geologists have used the Northern Highlands as a natural laboratory for the understanding of tectonic processes. The juxtaposition of readily accessible exposures of an Archaean basement gneiss complex, deformed and undeformed Proterozoic sedimentary successions, and a classic example of a thrust belt, has ensured the importance of the area for both research and teaching. The Northern Highlands have been the focus for the development of many modern geological concepts, varying from the processes of thrust tectonics to the use of isotopic dating to unravel tectonic histories. Despite two hundred years of research, many major geological problems remain to be resolved in the Lewisian, Torridonian and Moine rocks. They continue to be the subject of international scientific research, and of great interest to the geological community.

During the 19th century, the North-west Highlands attracted great attention in geological circles as a result of the 'Highlands Controversy', the story of which has been described in detail by Oldroyd (1990) and is only summarized briefly here. The earliest significant study of the Northern Highlands was that of MacCulloch, who produced a geological map of Scotland (MacCulloch, 1836). He did not separate the Lewisian and the Moine, but he did pick out the red Torridonian sandstones and the Cambrian quartzites.

For the next 20 years, only a few geologists ventured into the Northern Highlands (e.g. Cunningham, 1841; Miller, 1841). Then, in 1855, a visit to the Northern Highlands was made by Roderick Murchison, Director General of the Geological Survey, and James Nicol, Professor of Natural History in Aberdeen. This visit was to be the beginning of the 'Highlands Controversy'. In subsequent years, Murchison and Nicol visited the area separately, and developed their own theories to explain the structures that they observed. Murchison believed that the rocks of the Northern Highlands represented a simple stratigraphical sequence, with the basement gneisses in the west overlain eastwards by 'Cambrian' sandstones (the Torridonian), and then by quartzites, limestones and Moine schists, all of which were considered to be Silurian. The Old Red Sandstones of the north-east were recognized as Devonian, and considered to be the uppermost part of this sequence (Murchison, 1858). Nicol, in contrast, considered the Moine schists to be separated from the rocks to the west by a major (high-angle) fault-line (Nicol, 1860).

With relatively few geologists visiting the Northern Highlands to investigate the evidence for themselves, Murchison's higher standing in the geological world allowed his views to become more widely accepted through the 1860s and 1870s. He was supported by Archibald Geikie, a rising star in Scottish geology, who had visited the Northern Highlands with Murchison, and collaborated with him on a new geological map of Scotland (Geikie, 1865).

After Murchison's death, the issue of the 'Highlands Controversy' was re-opened towards the end of the 1870s (Hicks, 1878), and a number of geologists became interested (see Oldroyd, 1990, for a full review). The most important work of this time was that of Charles Lapworth, who was well aware of ongoing work in the Alps and in North America that showed the existence of low-angle 'thrust' faults in mountain belts. Working east of Loch Eriboll he recognized the complexity of the Moine schists, and showed that they had been deformed and metamorphosed within an ancient mountain range, and were separated from the underlying sedimentary rocks by a major low-angle fault (Lapworth, 1883). He was also the first person to appreciate that the finely layered rocks immediately above this fault were formed by high tectonic strain, rather than being well-layered sedimentary rocks. He coined the term 'mylonite', derived from the Greek *mylon* (mill), for these rocks (Lapworth, 1885); the term is still part of our modern geological vocabulary.

As soon as Lapworth's work was publicised, Geikie (by now Director General of the Geological Survey) ordered some of his most able surveyors — including Benjamin Peach and John Horne — to begin work in the North-west Highlands. They rapidly came to agree with Lapworth, recognizing the existence of low-angle thrust faults that had carried metamorphic rocks westwards over the underlying sedimentary rocks (Peach and Horne, 1884). The maps and memoir that were eventually produced to describe the geology of the North-west Highlands (Peach *et* at, 1907) were ahead of their time as detailed depictions of a thrust belt. These maps have been used for a hundred years by generations of geologists studying the classic example of the Moine Thrust Belt, and are only now being revised.

Following the production of the 1907 memoir, the geology of the North-west Highlands was largely considered to be 'solved'. In the first half of the 20th century, the attention of the Geological Survey, and of many academics, focused largely on the mapping of the broad, and in some areas rather featureless, tract of Moine schists; this work is discussed in more detail in the 'Introductions' to Chapters 6, 7 and 8. Some initial work was also carried out during this time in both the Shetland Isles and the Outer Hebrides.

One of the major features of this period was the first use of microscopic techniques in the interpretation of structural history, building on detailed early petrographical work such as that of Jethro Teall (Peach *et al.,* 1907). Analysis of the crystallographic preferred orientations of minerals was pioneered by Frank Coles Phillips, who was the first to apply this type of systematic analysis to Highlands rocks (Phillips, 1937). Phillips studied the Moine rocks under a microscope that was mounted with a 'universal stage' that allowed the sample to be freely rotated around three axes. In this way he gathered a large amount of petrofabric data, mainly on the orientation of quartz and mica crystals. He linked these crystallographic orientations to the lineations and fold axes that had been measured in the field in the same rocks. The kinematic interpretation (i.e. in which way the rocks had deformed to produce the structures) was to be the subject of intense debate for several decades to come (see Howarth and Leake, 2002, for a review). Phillips followed the theory of Sander (1930), which stated that fold axes were perpendicular to the 'tectonic transport direction'. As lineations were commonly orientated parallel to the fold axes, the transport direction was thus interpreted to be perpendicular to the lineation. Hence, Phillips interpreted the lineations in the Moine succession to be formed by tectonic transport in a north-east–south-west direction. As this direction was at right angles to the transport direction of the Moine Thrust, and to the strike of the Moine succession, it was thought that these lineations were formed by an earlier, pre-Caledonian orogeny (Phillips, 1945). Not all structural geologists agreed with Phillips' ideas, and even researchers as far away as the United States used plots of the structural data from the original Geological Survey maps to argue that lineations could be independent from fold axes (Cloos, 1946). This debate was to last until the 1960s; for instance Christie (1963) argued that thrusting in the Moine Thrust Belt was locally directed towards the south-west — at right angles to the stretching lineations — but this was contradicted by Johnson (1965). A solution came from the work of Derek Flinn, who carried out detailed work on the deformed Lower Palaeozoic Funzie Conglomerate in Shetland (Flinn, 1956), and later showed that neither fold axes nor axial planes necessarily bore any particular relationship to movement directions (Flinn, 1962), and hence that the theories of Sander (1930) were not universally applicable.

Another aspect of interest to geologists in the middle of the 20th century was the Great Glen, one of the main landscape features of the Highlands. This deep valley formed by erosion along the Great Glen Fault, which is now known to have experienced a long and complex history (Harris, 1995; Stewart *et* ed., 1999, 2001). It is clear from the subvertical nature of the fault, and the lack of continuity across the fault trace, that it is a product of large-scale transcurrent movement. Silurian and mid-Devonian sinistral movements, and Mesozoic dextral movements, can be readily demonstrated, but the earlier history and age of the structure remain unclear. Kennedy (1946) postulated that the Strontian and Foyers granitic plutons had originally been linked across the Great Glen Fault, implying an overall sinistral displacement of approximately 100 km. Although this idea has been discounted after modern studies of the two plutons, it did provide the impetus for similar studies of transcurrent (strike-slip) faults in other parts of the world.

Early in the 1950s, interest in the Northern Highlands was raised by the publication of a seminal paper on the rocks of the Lewisian Gneiss Complex (Sutton and Watson, 1951). Sutton and Watson recognized two orogenic cycles within the Lewisian; an older Scourian event and a younger Laxfordian event, separated by the intrusion of a major dyke-swarm known as the 'Scourie dykes'. This work, which drew on previous research in Scandinavia and Greenland, has since been viewed as a benchmark in the use of field relationships to separate tectonic events in high-grade metamorphic areas.

Sutton and Watson's work stimulated a renewed interest in the Lewisian Gneiss Complex, and also generated significant controversy. Some of the new work was readily accepted; for instance, the identification of a third metamorphic event, termed the Inverian' (Evans, 1965), which occurred just prior to the intrusion of the Scourie dykes. Dearnley (1962a, 1963) applied the Sutton and Watson chronology to the Outer Hebrides, and described a post-dyke granulite-facies event ('Early Laxfordian'). Much of the debate about Lewisian chronology was generated by the suggestion that there was more than one episode of Scourie dyke intrusion, and that some of the Scourie dykes cut Laxfordian structures (Bowes and Khoury, 1965; Bowes, 1968a,b, 1969). However, although most workers in the Lewisian at the time accepted that the Scourie dykes were intruded over a significant period of time, they did not accept that phases of dyke intrusion were separated by significant orogenic events (Tarney, 1963; Park, 1970).

Much of this early controversy was clarified as the developing techniques of isotopic dating began to be applied to the Lewisian gneisses.

The earliest isotopic dating of this area was that of Holmes *et al.* (1955); they used the potassium-argon technique to date feldspars from Lewisian pegmatites, producing an age of 1090 Ma that was taken as a minimum age for the gneisses. However, the first systematic isotopic study aimed at dating events in the Northern Highlands was carried out by Giletti *et al.* (1961), and was the first major paper to come out of the new age-dating laboratories in Oxford. They used Rb-Sr methods to study a variety of samples from the Lewisian Gneiss Complex, chiefly pegmatites, and showed that the Scourian metamorphism was older than 2460 Ma, whereas the Laxfordian metamorphism occurred at about 1600 Ma. This work was followed by that of Evans and Tarney (1964), who dated the Scourie dykes at roughly 2200 Ma, and

Evans (1965), who gave an age for the Scourian episode of approximately 2600 Ma.

Following this, the Oxford group also pioneered the use of lead isotopes to study the history of basement gneiss complexes, choosing the Lewisian Gneiss Complex for their first investigations (Moorbath *et al.,* 1969). They showed that the protoliths of the Lewisian gneisses were largely in existence by about 2900 Ma.

Over the last 40 years, a wide variety of isotopic systems have been used to date metamorphic and igneous events in the Lewisian Gneiss Complex, and have refined the detail of the timescale considerably; nonetheless, the basic chronology established in these earliest papers has largely stood the test of time. The Lewisian Gneiss Complex continues to be a testing ground for ever more-sophisticated methods of isotopic dating, including use of the Re-Os system (Burton *et* at, 2000), and dating of a variety of accessory minerals such as monazite (Zhu *et al.,* 1997a,b). However, controversies over the detailed relationships of the various elements of the Lewisian Gneiss Complex still continue (e.g. Kinny *et* ed., 2005; Mason and Brewer, 2005; Park, 2005).

The paper by Giletti *et al.* (1961) also included some of the earliest age dates on samples from the Moine. They postulated that the main (Caledonian) metamorphism occurred at around 420 Ma. However, pegmatites from Knoydart and Morar, including some from the Knoydart Mica Mine GCR site, were shown to have formed before 740 Ma, and this led to the first suggestion of a Neoproterozoic metamorphic event in the Moine. The nature and timing of this event continues to be a source of debate, as discussed in more detail in the chapters dealing with the Moine Supergroup.

At around the time of this dating work, evidence for early deformation in the Moine was also being produced by field studies. Although the geometry of deformed rocks had interested geologists from the earliest days of mapping (e.g. Sorby, 1908), it was not until the 1950s that geologists began to make use of more-rigorous mathematically based analyses to try to define the overall three-dimensional nature of folding and related cleavages. Gilbert Wilson pioneered such methods (Wilson, 1961), but it was his students, encouraged by John Sutton, who combined geometrical analysis with detailed field mapping in the North-west Highlands and took such studies to new levels. John Ramsay was the most notable exponent of this approach and he published a number of landmark papers (Ramsay, 1957a,b, 1960, 1962), in which he described two major episodes of folding in the Moine in Glen Strathfarrar and in the Glenelg–Arnisdale area. Later papers discussed the more-theoretical aspects of strain and folding and culminated in his classic book describing methods to assess and quantify the folding and fracturing of rocks (Ramsay, 1967). Similar work was being carried out elsewhere, but it was in the Northern Highlands that many of the theoretical models and methods were tested.

During the 1970s, the use of modern analytical techniques in the Appalachians and the Canadian Rockies greatly advanced the international understanding of the development of thrust belts (e.g. Dahlstrom, 1970; Boyer and Elliott, 1982). In a classic paper, Elliott and Johnson (1980) applied some of these new ideas to try to define thrust geometry and quantify displacements in the northern part of the Moine Thrust Belt. This area was considered to be an important example of a thrust belt where basement is involved in the thrusting. They constructed new balanced cross-sections, which gave estimates of the slip on the Moine Thrust of the order of 100 km, and also stated that the movement in the thrust belt was foreland-propagating. This work stimulated an increased amount of research in the Moine Thrust Belt, which continues to the present day. A major body of work was that of Coward (1980, 1982, 1983, 1985), who emphasized the importance of extensional faults within the Moine Thrust Belt. He suggested that gravity spreading was an important feature of the later stages of movement on the Moine Thrust Belt, with the reactivation of some existing thrust features as extensional faults. Coward (1985) recognized that the classic example of the Moine Thrust at Knockan Crag, in southern Assynt, was actually a late extensional fault. Continuing work (e.g. Butler and Coward, 1984; Butler, 1987, 2004a) illustrated the complexity of the Moine Thrust Belt, with the recognition of breaching and back-thrust systems. This work emphasized the importance of the thrust belt as a well-exposed, easily accessible testing ground for new theories, as well as a classic locality for teaching.

In tandem with the work on major structures in the field, the microscopic study of rock fabrics was also being used to investigate microstructures. From the 1950s onwards, more and more rock deformation experiments were performed in laboratories around the world (e.g. Griggs and Handin, 1960). What was required was a real rock that was highly strained but with a simple mineralogy, so that the natural microstructures could be compared with those obtained by experiments in the lab. Wilkinson *et al.* (1975) used the deformed *Skolithos* pipes in the Pipe Rock as strain markers to enable them to determine the finite strain in the sheared quartzites. Such rock was ideal for detailed crystallographic studies: it was highly strained and composed dominantly of quartz, which could be used for the measurement of quartz c-axes. These measurements could then be correlated with independent determinations of strain obtained from the deformed pipes. Numerous publications followed in which the microfabrics and the microtextures of the quartz mylonites in the Moine Thrust Belt were determined (e.g. White *et al.,* 1982; Law *et al.,* 1986; Law, 1987). This work was compared to computer-simulations of the development of microfabrics by workers in Europe and Australia (e.g. Lister and Hobbs, 1980), and led to a thorough understanding of the deformation mechanisms involved in high-strain zones. The main conclusions of these studies still stand today (e.g. review by Law, 1990).

This section has discussed some of the most internationally significant pieces of work that have been published on the Northern Highlands. However, much of our understanding of the area has come from our gradual build-up of knowledge over 150 years of detailed fieldwork and analysis by many different geologists. Work of this type is drawn on heavily in this volume, and includes the detailed studies of the sedimentology and tectonic setting of the 'Torridonian' rocks by Sandy Stewart (e.g. Stewart, 1969, 1975, 1982, 1988a,b, and this volume); work on the Lewisian Gneiss Complex by Graham Park (e.g. Park, 1964, 1966, 1970, 2002, and this volume; Park *et al.,* 1994, 2001); and investigations across the Shetland Isles by Derek Flinn (e.g. Flinn, 1967, 1985, 1988, 1994, and this volume). Full details of much of this work are given in the relevant chapter introductions.

At the time of writing, debate about many geological questions in the Northern Highlands is as lively and as international as ever, and some of the ongoing controversies are discussed in the next section.

Tectonic setting and evolution of the Northern Highlands

M. Krabbendam, J.R. Mendum and K.M. Goodenough

For much of Precambrian time, northern Scotland was part of a continental block that also incorporated parts of present-day North America and Greenland. At various times within the Precambrian, this block was included within larger supercontinents; but towards the end of the Precambrian, it became a separate continent known as 'Laurentia'. As a result of this common history, many rock units and events in Scotland can be correlated with parts of the geological record in Greenland and north-eastern North America (Figure 1.3). Some correlations are also possible with the palaeocontinent of Baltica, which was composed of parts of present-day Scandinavia and Russia. For the purposes of this review, the terms 'Laurentia' and 'Baltica' are used to refer to these blocks of continental crust, even prior to their development as separate continents.

The Archaean tectonic history of the basement of northern Scotland is complex and still the source of debate, as discussed below. During much of the Proterozoic, Laurentia and Baltica formed part of a single supercontinent, although there were episodes of extension and rifting such as that recorded by the Mesoproterozoic Stoer Group. Eventually, both Laurentia and Baltica became part of the supercontinent of Rodinia, which was assembled during the Grenville Orogeny at around 1100 Ma.

At around 600 Ma, a major rifting event began to split Rodinia into several separate blocks. A major ocean, known as 'Iapetus' (named after the father of Atlas in Greek mythology), developed at about 570–580 Ma. This ocean separated Laurentia from two major continental masses, Gondwana to the south and Baltica to the east. The Iapetus Ocean reached its greatest extent — about 2000 km in width — at around 500 Ma, but then began to close rapidly. During the Silurian Period, Laurentia and Baltica collided again, resulting in the formation of the Moine Thrust Belt. The Iapetus Ocean was finally closed during the Silurian by the docking of a continent called Avalonia — containing England and Wales — with Laurentia. Scotland remained part of Laurentia until the opening of the North Atlantic during the Palaeogene around 53 Ma.

Thus, it is clear that most of the rock units described in this volume can be better correlated with parts of North America and Greenland than with other parts of Great Britain. Large parts of the Lewisian Gneiss Complex have been matched with gneisses of the Nagssugtoqidian Belt in southern and central Greenland, whilst the Moine Supergroup has been tentatively correlated with similar sequences of metamorphosed sedimentary rocks in south-east Greenland.

The Northern Highlands were situated close to the margin of Laurentia, where they experienced several collisional events, and thus they preserve a unique record of Neoproterozoic and Palaeozoic orogenic activity. Even the Mesoproterozoic Grenville Orogeny has been recorded, in the Glenelg–Attadale Inlier, despite the fact that younger deposits probably obscure most of the evidence for Grenvillian orogenesis in Scotland. As a result, the Grenville Front in North America can be linked, through Scotland, to the Sveconorwegian Front in Scandinavia. Similarly, the Moine Thrust Belt provides a key link in the western front of the Caledonian Orogeny. This western Caledonian Front can be followed from east Greenland, through Scotland to Newfoundland, whilst the eastern Caledonian Front runs through Norway and Sweden.

The major events in the tectonic history of northern Scotland are discussed in more detail below. Good, recent overviews of the tectonic setting and evolution of this area are also given in Woodcock and Strachan (2000) and Trewin (2002).

Archaean

Most of the gneisses of the Lewisian Gneiss Complex formed during the Late Archaean as typical 'TTG' (tonalite–'Vondjhemite'–granodiorite; see glossary) plutonic suites intruded into lower levels of the crust. 'TTG' suites characterize much of the Earth's Archaean crust, but modern analogues are rare. However, the rare-earth-element and trace-element geochemistry of the quartzofeldspathic Lewisian gneisses is broadly similar to that of plutonic rocks formed above modern-day subduction zones. It is thus likely that the protoliths of the gneisses formed at active plate margins, although possibly with melting at rather shallower depths than in modern subduction zones (Park and Tarney, 1987; Rollinson, 1996). The later reworking of the Lewisian Gneiss Complex was so pervasive and varied that it is now difficult to unravel the original relationships of these igneous protoliths.

Traditionally, the whole of the Lewisian Gneiss Complex was thought to be part of the same block of crust. The mainland Lewisian can be divided into Northern, Central and Southern regions, each with different deformation histories (Peach *et al.,* 1907; Sutton and Watson, 1951), and the Lewisian Gneiss Complex in the Outer Hebrides has generally been considered to have a comparable history to parts of the mainland Lewisian (Fettes and Mendum, 1987).

However, recent use of isotopic dating techniques — notably U-Pb dating of zircon and other accessory minerals — has resulted in the recognition of a number of discrete intrusive events, which occurred in different areas of the Lewisian Gneiss Complex between 3100 Ma and 2650 Ma (Kinny and Friend, 1997; Whitehouse *et al.,* 1997a; Corfu *et al.,* 1998; Friend and Kinny, 2001; Love *et al.,* 2004). On this basis, it has been proposed that the Lewisian basement consists of several separate terranes (Figure 1.4), which are characterized by protoliths of different ages, and by different Archaean and Palaeoproterozoic histories (Kinny *et al.,* 2005). However, the nature of these Archaean and later events, and the precise location and significance of the terrane boundaries, remain the subject of ongoing debate (e.g. Mason and Brewer, 2005; Park, 2005).

The oldest gneisses include those on Lewis and North Harris, and also the southernmost outcrops of the mainland, with protolith ages between 3125 Ma and 2800 Ma. On the mainland, the gneisses in the northern part of the Central Region (the Assynt Terrane of Kinny *et al.,* 2005) also have protolith ages around *c.* 3000 Ma, whilst those in the Northern Region (the Rhiconich Terrane) have protolith ages that range between 2840 Ma and 2680 Ma. The gneisses of the Northern Region are known to have distinctly higher K, Rb, U and Th contents than those of the Central Region (Sheraton *et al.,* 1973), although it is difficult to ascertain whether this is a primary feature (Tarney and Weaver, 1987a). The gneisses of the southern part of the Central Region (the Gruinard Terrane) have similar protolith ages to gneisses on eastern Barra, around 2840 Ma. Friend and Kinny (2001) suggested that the gneiss terranes of the western Outer Hebrides can be correlated reasonably well with gneiss terranes in east Greenland (Figure 1.4) on the basis of their composition, protolith and reworking ages.

However, basement gneisses occur extensively offshore on the Hebrides Shelf, and probably form the foundation of the Rockall Plateau, and therefore correlations between the Outer Hebrides and Greenland remain somewhat speculative.

During latest Archaean and earliest Palaeoproterozoic times, parts of the Lewisian Gneiss Complex were affected by granulite-facies metamorphism. This metamorphic event was originally recognized by Sutton and Watson (1951) in the

Central Region of the mainland Lewisian, and termed the 'Scourian' event; it was later renamed 'Badcallian' by Park (1970). The most recent work (Zhu *et al.,* 1997a,b; Love *et al.,* 2004; Kinny *et al.,* 2005) has identified two different high-grade events, one at approximately 2730 Ma that has been recognized in the gneisses of Barra and of the Gruinard Terrane, and a second at 2490 Ma recognized in the Assynt Terrane. However, the tectonic setting of these events is unclear. A subsequent amphibolite-facies deformation event, the Inverian event, has been recognized across the Central Region (i.e. in both the Assynt and Gruinard terranes). This event had largely ended by the time of emplacement of the major Scourie Dyke Suite, and thus occurred between 2490 Ma and 2400 Ma (Friend and Kinny, 2001; Park *et al.,* 2001; Kinny *et al.,* 2005).

Palaeoproterozoic

Following the Badcallian and Inverian tectono-thermal events, there was a period of significant crustal extension, possibly related to rifting across an Archaean continental mass. The main evidence for this comes from the presence of major swarms of mafic and ultramafic dykes across Laurentia and Baltica, such as the 2480–2450 Ma Matachewan Dyke Swarm in Ontario (Heaman, 1997). On the Scottish mainland, the Palaeoproterozoic dykes are known as the 'Scourie Dyke Suite', and they have been correlated with a similar swarm of mafic dykes in the Outer Hebrides (the 'Younger Basics' of Fettes and Mendum (1987)). Dykes from the swarm have only been dated in the Assynt area, where two phases of intrusion were recognized: the first at *c.* 2400 Ma and a second at *c.* 2000 Ma (Heaman and Tarney, 1989; Waters *et al.,* 1990). The rifting episode was also recorded by the development of extensional rift basins, in which voluminous volcanic and sedimentary sequences were formed. In the Lapland-Kola Belt of Baltica, with which the Lewisian Gneiss Complex is commonly correlated (see Buchan *et al.,* 2000), the Sumi-Sariola Group includes volcanic sequences, mafic intrusions and dykes that were formed at this time (Amelin *et al.,* 1995; Hanski *et al.,* 2001).

From about 2000 Ma, the extensional tectonic regime was replaced by the development of subduction zones and the onset of convergent tectonics. Within the mainland Lewisian, the major evidence for this tectonic regime comes from the Loch Maree Group. This unit comprises metamorphosed mafic volcanic rocks and a range of associated metasedimentary rocks. Detrital zircon ages show that the metasedimentary rocks of the Loch Maree Group are younger than approximately 2000 Ma, and they are intruded by the *c.* 1905 Ma Ard Gneisses, which define the younger age limit of deposition (Park *et al.,* 2001; Park, 2002). The geochemistry of the Ard Gneisses indicates that they were formed above a subduction zone. Park *et al.* (2001) interpreted the Loch Maree Group as a juvenile subduction-accretion complex, suggesting that the volcanic and sedimentary units were formed in an oceanic setting and then tectonically juxtaposed in a collisional suture zone between two blocks of Archaean continental crust. The Ard Gneisses were intruded following the accretion of the volcano-sedimentary succession.

As well as the Loch Maree Group, two main belts of Palaeoproterozoic, mainly arc-related rocks occur on the Outer Hebrides. In the far north of Lewis is the Ness gabbro-anorthosite complex, dated at *c.* 1860 Ma (Whitehouse, 1990b; Whitehouse and Bridgwater, 2001). In South Harris, the South Harris Igneous Complex (SHIC) is flanked by the metasedimentary Langavat and Leverburgh belts to the north and south respectively; together these make up the Roineabhal Terrane of Friend and Kinny (2001). The SHIC comprises a gabbro-anorthosite unit and bodies of mafic tonalite and diorite; the latter intruded at *c.* 1890 Ma (Friend and Kinny, 2001; Mason *et al.,* 2004a). The metasedimentary rocks contain abundant detrital zircons that have similar ages to the intrusions. Thus, the sediments may have been derived from the high-level volcanic equivalent of the SHIC (Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001). The tonalitic and dioritic igneous rocks have a calc-alkaline character (Fettes *et al.,* 1992) and the Roineabhal Terrane is considered to represent a magmatic-accretionary arc complex, developing into a collisional arc system, similar to, but slightly younger than the Loch Maree arc system (Baba, 1998).

Subduction and formation of magmatic arcs was rapidly followed by a period of collisional tectonics with associated magmatism and metamorphism. The sedimentary and igneous rocks of the Roineabhal Terrane were subjected to very high-pressure granulite-facies metamorphism at *c.* 1870–1830 Ma, followed by rapid uplift (Cliff *et al.,* 1998; Baba, 1999a; Whitehouse and Bridgwater, 2001). In the northern part of the mainland Lewisian, a major thermal event caused localized melting, approximately coeval with the intrusion of a series of granite and pegmatitic granite sheets (the Rubha Ruadh granites) at *c.* 1855 Ma (Friend and Kinny, 2001).

More-widespread reworking occurred on the mainland at *c.* 1740 Ma, during the Laxfordian event (Corfu *et al.,* 1994; Kinny and Friend, 1997). The Laxfordian event included widespread retrogressive amphibolite- to greenschist-facies metamorphism, folding and shearing. It affected most of the gneisses of the mainland, from the north coast southward to the Loch Maree Group. A second reworking event, including migmatization and granite veining, occurred on the Outer Hebrides and across much of the mainland at *c.* 1675 Ma (Corfu *et al.,* 1994; Mason *et al.,* 2004b). Low-strain areas that have not been affected by these reworking events occur within the Lewisian Gneiss Complex, and in places these preserve earlier, unmodified Archaean and Palaeoproterozoic features and structures.

The Palaeoproterozoic sedimentation and arc-related magmatism, and the subsequent reworking event, also have their correlatives in Baltica and Laurentia (Figure 1.3). In both Baltica and Laurentia, large amounts of juvenile crust were generated by arc magmatism to the south of the major Archaean cratons. Examples include the Svecofennian Province (19001850 Ma) in Baltica, and the Penokean, Ketilidian and Makkovik belts (1900–1800 Ma) and the Yavapai Province (1800–1700 Ma) in Laurentia (e.g. Hoffman, 1988). The Lewisian gneisses are generally considered to correlate with the Nagssugtoqidian Belt of Greenland and the Lapland–Kola Belt of Scandinavia (e.g. Park, 1994; Buchan *et* ed., 2000). The Nagssugtoqidian Belt consists of Archaean gneisses that were intensely reworked in the Palaeoproterozoic, together with Palaeoproterozoic arc-related intrusions dating from 1920 Ma to 1760 Ma (Whitehouse *et al.,* 1998). Similarly, the Lapland–Kola Belt contains reworked Archaean crust and Palaeoproterozoic arc-related intrusions.

Mesoproterozoic

Following the Palaeoproterozoic orogenesis described above, there was a period of relative tectonic quiescence, during which the Lewisian gneisses were uplifted and exhumed. Around 1300 million years ago, extension and rifting commenced once again (Figure 1.5)a,b. The onset of rifting was marked by intrusion of large-scale mafic dyke-swarms across parts of Laurentia and Baltica, including the *c.* 1270 Ma Mackenzie Dyke Swarm in Canada (Le Cheminant and Heaman, 1989), and the 1350–1140 Ma Gardar Province in southern Greenland (Upton *et al.,* 2003).

In Scotland, the Mesoproterozoic rifting was marked by the deposition of the Stoer Group, a sedimentary sequence of which some 2 km in thickness is preserved around the Bay of Stoer. It is largely composed of fluvial breccias, conglomerates, sandstones, and siltstones, with a single volcaniclastic member. The succession is interpreted as having been deposited in a fault-bounded rift basin (Stewart, 1982, 2002; Rainbird *et al.,* 2001) at around 1200 Ma (Turnbull *et al.,* 1996).

Towards the end of the Mesoproterozoic, extensional tectonics again gave way to a collisional regime, and a series of mountain belts was formed around the globe from 1100 Ma to 950 Ma (Figure 1.5)c. This mountain-building event, generally referred to as the 'Grenvillian' after its type area in North America, led to amalgamation of the supercontinent of Rodinia. Reconstructions of this supercontinent, based on palaeomagnetic work, generally place Baltica, Laurentia and Amazonia adjacent to each other (Figure 1.5)c, with northern Scotland positioned close to the triple junction (e.g. Torsvik *et al.,* 1996; Dalziel, 1997; Holdsworth *et al.,* 2000). In eastern Canada, the Grenvillian Orogen is well exposed, and there is a clearly defined Grenville Front (e.g. Rivers, 1997; Gower and Krogh, 2002). However, in Scotland, evidence for Grenvillian orogenesis is sparse and it is not possible to map out the Grenville Front, mainly because of the extensive cover of post-Grenville metasedimentary rocks. The Outer Hebrides Fault Zone appears to have been initiated during the Grenvillian, with ductile thrusting at approximately 1100 Ma (Fettes *et al.,* 1992; Imber *et ed.,* 2002). Further evidence for the Grenvillian in Scotland comes from the Archaean and Palaeoproterozoic gneisses of the Glenelg–Attadale Inlier, which are surrounded by rocks of the Moine Supergroup. In the inlier, eclogite-facies metamorphism and subsequent amphibolite-facies retrogression has been dated at approximately 1000 Ma (Sanders *et al.,* 1984; Brewer *et al.,* 2003; Storey *et al.,* 2004). Eclogite-facies rocks of similar age also occur in the eastern Grenville Province in Canada (e.g. Indares and Dunning, 1997) and in the Sveconorwegian Orogen in south-west Sweden (Moller, 1998), confirming on the one hand the pcisition of northern Scotland on the margin of Laurentia, and on the other hand the continuity of the Grenvillian–Sveconorwegian Orogen.

Neoproterozoic sedimentation

Towards the end of the Grenvillian Orogeny, thick sedimentary successions were deposited widely across the North Atlantic region (Figure1.5d). In northern Scotland, two main Neoproterozoic sedimentary sequences are recognized, the Torridon Group and the Moine Supergroup. The Torridon Group is up to 7 km thick and dominated by fluviatile, cross-bedded red sandstones. These sediments were deposited by braided river systems, with palaeocurrent indicators suggesting transport from the west. The age of the Torridon Group is constrained by detrital zircon studies as younger than approximately 1060 Ma (Rainbird *et al.,* 2001). Diagenesis has been dated at roughly 1000–970 Ma (Turnbull *et al.,* 1996), ages considered to be close to the time of deposition. Deposition of the Torridon Group was thus approximately coeval with the waning stages of the Grenvillian Orogeny.

Stewart (1982, 2002) and Williams (2001) argued for deposition of the Torridon Group in a half-graben rift system, with a bounding fault situated close to the present-day Minch Fault, just to the east of the Outer Hebrides. This interpretation was contested by Nicholson (1993) who argued that the river systems depositing the sandstones must have been much larger and longer — of the order of 1000 km. Moreover, detrital zircon data for the Torridon Group include very few Archaean zircons (Rainbird *et al.,* 2001); the majority of zircons are dated at around 1650 Ma, suggesting a source outside the Lewisian Gneiss Complex. Rainbird *et al.* (2001) and Prave *et al.* (2002) suggested that the Torridon Group may represent a foreland basin to the Grenvillian mountain belt, with a significant amount of sedimentary material derived from the Labrador segment of the orogen.

The Moine Supergroup comprises a thick and extensive sequence of siliciclastic metasedimentary rocks, dominated by psammites and with subordinate pelites. It is divided into three groups; the Morar, Glenfinnan and Loch Eil groups (Johnstone *et al.,* 1969). Sedimentary evidence that indicates deposition in a shallow-marine environment, including cross-bedding, is present in much of the sequence. It has been suggested that Moine sedimentation occurred in two major rift basins, each forming a half-graben (Soper *et al.,* 1998). However, an alternative possibility has been raised by Cawood *et al.* (2004), who suggested deposition in a single slowly subsiding, regionally extensive basin.

The nature of its basal contact has been the subject of much discussion, but it is now generally accepted that the Moine Supergroup was unconformably deposited upon a crystalline 'Lewisianoid' basement, with locally preserved basal conglomerates (Peach *et al.,* 1907; Ramsay, 1957b; Holdsworth, 1989a). The Lewisianoid basement is exposed in a series of inliers, either as thrust slices or as antiformal keels.

The maximum age of Moine deposition is constrained by the youngest detrital zircons at *c.* 950 Ma (Kinny *et al.,* 1999; Friend *et al.,* 2003), and the minimum age by the intrusion of the West Highland Granite Gneiss Suite at *c.* 870 Ma (Friend *et al.,* 1997). From these constraints, the Moine Supergroup appears to be broadly coeval with, or slightly younger than, the Torridon Group. Indeed, a correlation between the Moine and Torridon sequence was first made by Geikie (1893), and favoured by Peach (Peach and Horne, 1930). However, the Moine and Torridonian detrital zircon patterns are rather different from each other, indicating that deposition in the two sedimentary basins was probably separated, either temporally or spatially (Friend *et al*., 2003; Cawood *et al.,* 2004). Krabbendam *et al.* (2008) recently argued that the upper parts of the Torrridonian succession (Torridon Group) are directly equivalent to the lower parts of the Moine Supergroup (Morar Group) in Sutherland.

Archaean detrital zircons are virtually absent from the Moine psammites, except for some basal units, and thus the Moine sediments are unlikely to have been derived from a source in the Lewisian Gneiss Complex (Friend *et al.,* 2003). It is most likely that they were derived, at least in part, from erosion of the Grenvillian mountain belt (Cawood *et al.,* 2007; Krabbendam *et al.,* 2008). The Moine Supergroup shows some similarities in lithology and detrital zircon content to the Krummedal sequence in east Greenland (Leslie and Nutman, 2003; Cawood *et al.,* 2004). Thus, the basin in which the Moine siliciclastic sediments were deposited was probably considerably larger than the Moine outcrop as preserved today.

Neoproterozoic tectonothermal events

Evidence for a number of magmatic and metamorphic events during the Neoproterozoic is preserved within the Moine Supergroup. Although it is clear that this part of Laurentia has a complex tectonic history, the detail of individual orogenic events has proved difficult to unravel and is still the subject of considerable academic debate. At the time of writing, the following summary can be made.

At *c.* 870 Ma, the Moine Supergroup was intruded by granitic sheets that were derived from melting of metasedimentary rocks (the West Highland Granite Gneiss Suite). These were preferentially emplaced around the Glenfinnan Group–Loch Eil Group boundary (Friend *et al*., 1997; Rogers *et al*., 2001). Associated metabasic intrusions, with tholeiitic, MORB-like chemistry, have yielded the same intrusive age (Millar, 1999). This type of bimodal igneous event is typical of an intra-continental rift setting. Although the formation of the West Highland Granite Gneiss Suite has previously been attributed to a contractional, orogenic event (Friend *et al*., 1997), an extensional rifting hypothesis for the *c.* 870 Ma event is now generally accepted (e.g. Ryan and Soper, 2001). It is likely that this event represents the development of a failed rift between Baltica and Laurentia (Figure 1.5)d.

Numerous dates on pegmatites and, more recently, on metamorphic minerals have shown that the Moine rocks experienced tectono-thermal events in the periods 820–780 Ma and 750–730 Ma (Giletti *et al.,* 1961; Long and Lambert, 1963; van Breemen *et al.,* 1974, 1978; Powell *et al.,* 1983; Piasecki and van Breemen, 1983; Rogers *et al.,* 1998; Vance *et al.,* 1998; Zeh and Millar, 2001; Tanner and Evans, 2003). These events have been variously termed 'Knoydartian' (Bowes, 1968a) and 'Morarian' (Lambert, 1969), with Knoydartian now generally being used for the 820–780 Ma period and Morarian for the later events. The dates and their interpretation have been the source of a long-standing controversy. Soper and England (1995) envisaged that the Neoproterozoic evolution of the Scottish part of the Laurentian margin was dominated by rifting and extension, without any contractional orogenic events. However, by linking isotopic age dating with metamorphic P-T data, recent work has shown that at least some of the Knoydartian events are contractional (Vance *et al.,* 1998; Zeh and Millar, 2001; Tanner and Evans, 2003). It has generally been difficult to assign specific structures within the Moine to the Neoproterozoic orogenic events, although initiation of the major Sgurr Beag Thrust is now interpreted as being of Neoproterozoic age (Tanner and Evans, 2003).

On a larger scale, Neoproterozoic orogens are problematical in the sense that palaeogeographical reconstructions show Scotland positioned within a Rodinian supercontinent at that time (Figure 1.6)a, and there is no evidence of similar-aged orogenesis in North America (Cawood *et al.,* 2004). As well as in northern Scotland, evidence of Neoproterozoic (840800 Ma) compressional tectonics has been found in the Dava-Glen Banchor Succession (formerly Central Highlands Complex or Division) south of the Great Glen (e.g. Noble *et al.,* 1996; Highton *et al.,* 1999). Farther afield, *c.* 840–800 Ma igneous activity in northernmost Norway has been attributed to a 'Porsanger orogeny' (Daly *et al.,* 1991; Kirkland and Daly, 2004), which may have been associated with the events in Scotland. Park (1992) suggested that at *c.* 800–750 Ma sinistral strike-slip motion occurred between Baltica and Laurentia. Nevertheless, the extent, nature, evolution and tectonic setting of the Knoydartian/Morarian orogenic events in Scotland remain largely unresolved.

Towards the end of the Neoproterozoic, the supercontinent of Rodinia again began to rift and eventually broke up (Figure 1.6)b. The Iapetus Ocean started to open between Laurentia and Baltica after *c.* 600 Ma, although rifting and extensionally related sedimentation may have started much earlier. Clear evidence for rifting at *c.* 600 Ma is preserved in the Dalradian Supergroup of the Grampian Highlands. This thick metasedimentary unit represents a rift-drift transition and contains mafic and felsic igneous rocks dated between 595 Ma and 600 Ma (Halliday *et al.,* 1989; G. Rogers *et al.,* 1989; Dempster *et al.,* 2002). Details of these events are described in the *Dalradian Rocks of Scotland* GCR Volume (in prep.).

North-west of the Great Glen, the main evidence for the onset of Iapetan opening lies in a variety of igneous rocks intruded into the Moine Supergroup. The Berriedale and Braeval augen granites, within the Moine Supergroup of Caithness, have been dated at 590–600 Ma (Kinny *et al.,* 2003b). The Carn Chuinneag-Inchbae Igneous Complex contains deformed mafic and granitic intrusions, and includes some alkaline rocks (Harker, 1962; Wilson and Shepherd, 1979), which provide evidence for a continental rift setting. The complex has been dated at approximately 610 Ma (Kinny *et al.,* 2003b). Amphibolites with alkaline chemistry (the Loch a' Mhoid Metadolerite Suite; Moorhouse and Moorhouse, 1979) are found as intrusions in the Moine of Sutherland, and preliminary data suggests that these also have a late Neoproterozoic age (P Kinny and R.A. Strachan, pers. comm.).

Cambrian-Early Ordovician

At the start of the Cambrian, the Iapetus Ocean had opened to a width of around 2000 km (Figure 1.6)c. A thick marine sedimentary succession — the Dalradian Supergroup — had been deposited in the area now occupied by the Grampian Highlands. The upper part of this sequence was deposited between 600 Ma and 520 Ma, during which time a rift-drift succession formed. Farther inland, deposition only started with a significant marine transgression in the Cambrian, and sediments were deposited on a wide, shallow shelf These sediments formed the Cambro-Ordovician sequence of the Northwest Highlands, comprising quartzite at the base and a carbonate sequence at the top. The sequence is described in detail in GCR Volume 18 (Rushton *et al.,* 2000). The basal unconformity of the sequence is remarkably planar, showing that the tilted Torridonian rocks had been eroded to a near-level peneplain, which was flooded during the Cambrian transgression. The Cambro-Ordovician sequence in Scotland can be wholly or partially correlated with sequences in Newfoundland, east Greenland and Svalbard (Swett and Smit, 1972; Cowie, 1974; Wright and Knight, 1995; Smith *et al.,* 2004) showing that a continuous passive margin existed along the Laurentian margin, from north Greenland through Scotland to Newfoundland.

Early Ordovician to Silurian: the Caledonian Orogeny

From about 520 Ma, the Iapetus Ocean began to narrow again. The early Ordovician Grampian Event was the first collisional event to affect the Scottish part of the Laurentian margin, and was the first phase of the Caledonian Orogeny. This event is regarded as having been caused by the collision of an arc terrane against the Laurentian passive margin (Van Staal *et al.,* 1998; Oliver, 2001; see (Figure 1.6)d. Remnants of the arc are difficult to pinpoint, but may occur at depth in the Midland Valley or beneath part of the Southern Highlands. It is clear that this collisional event was relatively short-lived, and its culmination is constrained in both western Ireland and Scotland to between 475 Ma and 465 Ma (Dewey and Mange, 1999; Soper *et al.,* 1999; Oliver, 2001). Most Grampian deformation and metamorphism in Scotland occurred south-east of the Great Glen, in the Grampian Highlands. North of the Great Glen, most deformation appears to be Scandian (see below) or Knoydartian (see above), but some significant Grampian tectonic and metamorphic effects have also been proven.

The Sgurr Beag Thrust, which carries the Glenfinnan Group of the Moine over the Morar Group, has been generally attributed to the Grampian Event (e.g. Powell *et al.,* 1981; Harris, 1995). However, Tanner and Evans (2003) demonstrated that the first movement of this thrust could be related to Knoydartian deformation, although it was reactivated during the Grampian Event. Migmatization in thrust sheets to the east of, and structurally above, the Sgurr Beag Thrust is now considered to be Ordovician in age and related to the Grampian Event (Kinny *et al.,* 1999). Farther to the east, a *c.* 470 Ma age for titanite in the West Highland Granite Gneiss Suite near Fort Augustus has been interpreted as dating a regional amphibolite-facies metamorphism (Rogers *et al.,* 2001). The onset of the Grampian Event may also have led to minor uplift in the foreland areas of north-west Scotland, resulting in the cessation of Cambro-Ordovician sedimentation (e.g. Soper *et al.,* 1999).

The Scandian Event (the second main phase of the Caledonian Orogeny) occurred between *c.* 438 Ma and 425 Ma. It coincided with the final closure of the Iapetus Ocean, and the docking of Avalonia, but mainly results from the collision of Baltica with Laurentia (Figure 1.6)e,f. The most prominent structure ascribed to the Scandian Event in Britain is the Moine Thrust Belt, which effectively represents the front of the Caledonian Orogeny in Scotland. The exact age of the thrust belt is the source of some debate. Thrusts within the Moine Thrust Belt are cut by the Loch Borralan Syenitic Pluton (Parsons and McKirdy, 1983), which have been dated at 430 ± 4 Ma (van Breemen *et al.,* 1979a). However, dating of micas in Moine schists and mylonites has indicated that ductile deformation may have occurred along at least some parts of the Moine Thrust Belt as late as *c.* 410 Ma (Kelley, 1988; Freeman *et al.,* 1998; Dallmeyer *et al.,* 2001). Ductile deformation also occurred farther to the east within the Moine rocks, with a number of ductile thrusts (e.g. the Sgurr Beag and Naver thrusts) thought to have operated or been reactivated during the Scandian Event (Strachan *et al.,* 2002a). To the west of the Moine Thrust Belt, the Scandian Event had little effect on the rocks of the foreland, except for movements along the Outer Hebrides Fault Zone (Kelley *et al.,* 1994; Imber *et al.,* 2002).

Displacement along the Moine Thrust was dominantly to the WNW, but farther to the east in the Moine succession lineations swing to a more north–south trend, possibly reflecting earlier movements (Phillips, 1937; Strachan *et al.,* 2002a). The amount of displacement taken up within the imbricates of the Moine Thrust Belt has been estimated at between 50 km and 100 km (Elliott and Johnson, 1980; Butler and Coward, 1984). Similar amounts of displacement may have occurred in the mylonites that directly overlie the Moine Thrust. Farther east, significant shortening occurred across the more-ductile thrusts such as the Ben Hope, Naver and Swordly thrusts in Sutherland (Barr *et al.,* 1986; Strachan *et al.,* 2002a). In its entirety, the Scandian Event resulted in significant crustal shortening, probably in excess of 150 km. Farther north, in east Greenland, a fold-and-thrust belt showing similar characteristics also developed. In Scandinavia a fold-and-thrust belt with the opposite, easterly vergence developed, and is characterized by the presence of several large discrete thrust sheets.

Towards the end of the Scandian Event, sinistral strike-slip displacements occurred along an array of NE-trending, steep faults, which in northern Scotland include the Great Glen Fault, the Strathconon Fault and the Strathglass Fault. These fault movements marked the start of a period of widespread orogenic uplift and intrusion of granitic plutons. The Great Glen Fault, which has been linked with the Walls Boundary Fault in Shetland (Flinn, 1961), is a major landscape feature and forms the southern boundary of the area described in this volume. The timing and displacement of movement along the Great Glen Fault are important for reconstructing some of the tectonic events described above. Although little is known about its pre-Silurian history, sinistral movement occurred along the Great Glen Fault at *c.* 428 Ma, at the time of intrusion of the Clunes Tonalite (Stewart *et al.,* 2001). It was reactivated around 400–393 Ma, as shown by evidence of sinistral transpression affecting the *c.* 400 Ma Rosemarkie Inlier leucogranite intrusions (Mendum and Noble, 2003). Similarly, the Ratagain Dioritic-syenitic Pluton was intruded during a period of sinistral shear along the Strathconon Fault, dated at *c.* 425 Ma (Hutton and McErlean, 1991; Rogers and Dunning, 1991).

Thus, lateral movement along the Great Glen and associated faults overlapped with, and outlasted, the Scandian Event. During Early Devonian times, conglomerates and sandstones were deposited on alluvial fans along the active fault scarps. Although the timing of strike-slip movement is well known, amounts of displacement are not as well constrained. Most estimates indicate that it was of the order of *c.* 200 km (e.g. Briden *et al.,* 1984). However, Dewey and Strachan (2003) suggested that at least 700 km of sinistral displacement must have occurred along the Great Glen Fault, as no evidence for Scandian deformation has been found in the Grampian Highlands. Quantifying the amount of displacement along the Great Glen Fault has significant implications for reconstructions of the Scandian Event in northern Scotland.

GCR site selection

K.M. Goodenough and D. Stephenson

The majority of the sites described in this volume were selected in the 1980s for the Geological Conservation Review (GCR), a project which began in 1977. The GCR aims to identify the most important sites for a comprehensive series of categories representing the range and diversity of British geology and geomorphology, and provides the scientific case for site protection and conservation through documentation as a public record. Some sites were added to the list at a later date, notably several sites along the Moine Thrust Belt that were needed to fully represent this internationally famous structure. The ultimate aim is that GCR sites will be formally notified as Sites of Special Scientific Interest (SSSIs). Notification of SSSIs under the National Parks and Access to the Countryside Act 1949, and subsequently under the Wildlife and Countryside Act 1981, is the main mechanism of legal protection for GCR sites in Britain. Most of the sites described in this volume have now been notified as SSSIs. The origin, aims and ongoing operation of the GCR project, together with comments on the law and practical considerations of Earth science conservation, are explained fully in Volume 1 of the GCR series, An *Introduction to the Geological Conservation Review* (Ellis *et al.,* 1996).

Features, events and processes that are fundamental to the understanding of the geological history, structure and composition of Britain are arranged for GCR purposes into subject 'blocks'. This volume covers three blocks, *Lewisian, Torridonian* and *Moine.* Within each block, sites fall into thematic groupings, termed 'networks'. The eight networks described in this volume, each represented by a single chapter, mainly represent broad geographical divisions of the three blocks. In total, 116 sites are described; these are listed in (Table 1.1), together with their principal reasons for selection. The GCR invokes three fundamental site-selection criteria; *international importance, presence of exceptional features,* and *representativeness.* Each site must satisfy at least one of these criteria, many of them satisfy two, and some fall into all three categories (Table 1.1).

The *international importance* of the Lewisian, Torridonian and Moine GCR sites has already been discussed above. Many of the Moine sites that satisfy this criterion have been fundamental in the understanding of processes occurring in collisional tectonic belts — these include the Eriboll, Glencoul, Knockan Crag and Loch Monar sites. Lewisian and Torridonian sites such as Roineabhal, Badcall, An Fharaid Mhòr–Clachtoll and Stoer have features that are important to the understanding of worldwide Precambrian crustal development.

Sites that contain *exceptional features* are commonly of great importance for research and teaching. Many Lewisian and Moine sites have internationally known examples of structures formed within compressional mountain belts. These include the folds of the North Uist Coast, Farr Bay, Beinn a' Chapuill and Loch Monar GCR sites; the mullions of the Coldbackie Bay and Oykel Bridge GCR sites; and the thrusts in many of the GCR sites in the Moine Thrust Belt. Some Torridonian sites have exceptional examples of sedimentary structures, for instance the dramatic basal unconformity seen at the Diabaig and Upper Loch Torridon GCR sites and the unique cyclothemic sequence of the Cailleach Head GCR site. There are also exceptional examples of certain rock-types that are relatively rare in Britain, including anorthosite in the Roineabhal GCR site, granulite-facies gneisses at the Badcall GCR site, Mesoproterozoic sedimentary rocks at the Stoer GCR site, and eclogites at the Totaig GCR site.

The criterion of *representativeness* aims to ensure that all the major stratigraphical and tectonic features of the Lewisian, Torridonian and Moine rocks, and of the Moine Thrust Belt, are featured in the GCR lists. It is, of course, difficult to do this whilst keeping the number of sites to a manageable level, and so there are some groups of rocks and types of structure of more-regional importance that are not well represented. There are no sites wholly within the Northern Region of the mainland Lewisian, on the Isle of Lewis, or within the Outer Hebrides Fault Zone; only one site representing the voluminous Applecross Formation of the Torridonian; and no sites to exclusively represent the Loch Eil Group of the Moine Supergroup. In general this is because there are many places at which these rock groups can be studied, but there are no localities that stand out from the others or show any exceptional features. Within this volume, rock groups that are not specifically represented by GCR sites are described in the appropriate chapter introductions, so that the volume does constitute a complete review of all Lewisian, Torridonian and Moine rocks, and associated structures, in Scotland.

Some of the sites described here contain localities that are also important for other reasons. Many of the sites include Caledonian igneous intrusions; of particular note are the alkaline intrusions of Assynt (Ben More Assynt–Conival–Na Tuadhan, Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel, and Skiag Bridge GCR sites), the Rogart Quartz-monzodiorite–granite Pluton (Creag na Croiche, Brora Gorge, and Aberscross Burn–Kinnauld GCR sites), and the Ross of Mull Granite Pluton (Ardalanish Bay GCR site). These intrusions are described in more detail in GCR Volume 17, *Caledonian Igneous Rocks of Great Britain* (Stephenson *et al.,* 1999). The Eriboll, Meall a' Ghiubhais and Ord GCR sites contain areas of interest for their Cambro–Ordovician sedimentary rocks, and these are included in GCR Volume 18, *British Cambrian to Ordovician Stratigraphy* (Rushton *et al.,* 2000). The Coldbackie Bay, Sgeir Ruadh (Portskerra) and Dirlot Castle GCR sites all show the unconformity between Moine rocks and the overlying Devonian sedimentary rocks. Many of the sites described in this volume are also of scientific interest for their Quaternary and coastal geomorphology, and some contain important cave features.

Table 1.1 GCR site selection criteria — Lewisian, Moine and Torridonian

Site name	GCR selection criteria
Lewisian Block	
Lewisian of the Outer Hebrides Network Chapter 2	
Roineabhal, South Harris	Representative of the Palaeoproterozoic South Harris Igneous Complex. Exceptional example of a metamorphosed layered gabbro-anorthosite intrusion, the largest in the British Isles. Internationally important for the understanding of Palaeoproterozoic magmatism and tectonics.

Na Buirgh (Borve), South Harris	Representative of Palaeoproterozoic elements of the Lewisian Gneiss Complex of the Outer Hebrides, including the South Harris Igneous Complex, the metasedimentary and metavolcanic rocks of the Langavat Belt and the Uig Hills–Harris Granite Vein-Complex.
North Pabbay, Sound of Harris	Representative of the variation in intensity of Laxfordian deformation and metamorphism across a lithological boundary in the Lewisian Gneiss Complex.
North Uist Coast	Representative of Laxfordian structures in the Lewisian Gneiss Complex. Exceptional examples of fold and boudinage structures on a variety of scales, mainly affecting intrusions of the 'Younger Basic' Suite.
Gearraidh Siar (Garry-a-siar) and Baile a' Mhanaich (Balivanich), Benbecula	Representative of the variation in intensity of Laxfordian deformation and metamorphism across areas of contrasting lithology. Also representative of the structural relationships of the 'Younger Basic' Suite. Internationally important for the understanding of the scale and processes of Laxfordian reworking in the Lewisian Gneiss Complex.
Rhughasinish, South Uist	Representative of the Palaeoproterozoic 'Younger Basic' Suite. Exceptional example of a composite mafic–ultramafic intrusion.
Loch Sgioport (Skipport), South Uist	Representative of Scourian meta-igneous and metasedimentary gneisses, and members of the 'Older Basic' and 'Younger Basic' suites, which have been relatively unaffected by Laxfordian reworking.
Cnoca Breac (Rubh' Aird-mhicheil), South Uist	Representative of the mafic and ultramafic intrusive rocks of the 'Older Basic' Suite. Exceptional example of an Archaean layered mafic–ultramafic body.
Leinis (Leanish), Barra	Representative of early Scourian gneisses, a variety of late-Scourian intrusions, and dykes of the 'Younger Basic' Suite, which are exceptional in that they have not suffered significant Laxfordian reworking.
Cnoc an Fhithich (Aird Grèin)	Representative of features related to the Outer Hebrides Fault Zone. Exceptional examples of pseudotachylite veins and breccias.
Lewisian of the Scottish mainland Network — Chapter 3	
Badcall	Representative of the Scourian features of the mainland Lewisian Gneiss Complex, including exceptional examples of gabbroic and tonalitic granulite-facies gneisses. Representative of the Scourie Dyke Suite. Internationally important as the type locality for the Badcallian event, and also as one of the first localities in the world to be studied in detail using isotopic dating techniques.
Scourie Mor	Representative of the Scourian features of the mainland Lewisian Gneiss Complex, including exceptional examples of mafic and ultramafic bodies that have undergone granulite-facies metamorphism.
Sìthean Mòr	Representative of metasedimentary gneisses of the mainland Lewisian Gneiss Complex that have been metamorphosed to granulite facies.
Scourie Bay	Representative of the Scourie Dyke Suite.

Tarbet to Rubha Ruadh	Representative of the Laxford Front, illustrating the transition from Scourian gneisses of the Central Region to those affected by Inverian and Laxfordian reworking to the north. Internationally important as one of the first locations at which an episode of mafic dyke emplacement was used to separate tectonic events, creating a type of 'pseudo-stratigraphy'.

Site name	GCR selection criteria
Loch Drumbeg	Representative of the mafic–ultramafic bodies that are believed to be the oldest parts of the Lewisian Gneiss Complex.
An Fharaid Mhòr to Clachtoll	Representative of the Inverian event in the mainland Lewisian Gneiss Complex, including the Canisp Shear Zone, an exceptional example of an Inverian shear-zone reworked during the Laxfordian event. Internationally important as the type locality for the Inverian event.
Gruinard River	Representative of the transition from Scourian gneisses of the Central Region to those affected by Inverian reworking to the south.
Creag Mhòr Thollaidh	Representative of the Laxfordian Gairloch Shear Zone and of the large scale Tollie Antiform. Exceptional example of a Laxfordian shear-zone, recognizable by the increasing intensity of deformation of Scourie dykes across the area.
Kerrysdale	Representative of the Kerrysdale unit of the Loch Maree Group, and of shear zones within the Loch Maree Group.
Flowerdale	Representative of the Flowerdale marble belt of the Loch Maree Group.
An Ard	Representative of the Ard Gneisses, the only known Palaeoproterozoic granites to intrude the Loch Maree Group.
Loch Braigh Horrisdale to Sidhean Mòr	Representative of the Laxfordian Gairloch Shear Zone, and an exceptional locality for the demonstration of the sequence of Palaeoproterozoic metamorphic events in the Southern Region of the Lewisian Gneiss Complex.
Alligin (Diabaig)	Representative of the transition from Scourian gneisses of the Central Region to those affected by Inverian and Laxfordian reworking to the south. Exceptional examples of Laxfordian ductile shear-zones.
Torridonian Block — Chapter 4	
Stoer	Representative of the internationally important Stoer Group, the only unmetamorphosed Mesoproterozoic stratigraphical group in Britain, and an exceptional example of a sedimentary and volcanic sequence formed in a rift environment.
Loch na Dal	Representative of the lower part of the Sleat Group.
Kylerhea Glen	Representative of the middle to upper part of the Sleat Group.
Loch Eishort	Representative of the upper part of the Sleat Group.

Diabaig	Representative of the Diabaig Formation of the Torridon Group and of the Torridonian/Lewisian unconformity. Exceptional locality for demonstrating the progressive burial of an exhumed Precambrian topography by river sands and lake silts accumulating in a Neoproterozoic rift-valley. Exceptional examples of microfossils in the lake silts that deserve further research.
Upper Loch Torridon	Representative of the Diabaig Formation of the Torridon Group and of the Torridonian/Lewisian unconformity. Exceptional locality for demonstrating the progressive burial of an exhumed Precambrian topography by river sands and lake silts accumulating in a Neoproterozoic rift-valley.
Rubha Dunan Enard Bay	Representative of the unconformities between the Stoer and Torridon groups, and between the Lewisian gneisses and the Stoer Group. Exceptional as the only locality at which the unconformable relationship between the Mesoproterozoic Stoer Group and the Neoproterozoic Torridon Group can be proved unequivocally. Also representative of the unconformity between the Lewisian gneisses and the Stoer Group.
Achduart	Representative of the basal members of the Applecross Formation of the Torridon Group.
Aultbea	Representative of the Aultbea Formation of the Torridon Group.
Cailleach Head	Representative of the Cailleach Head Formation of the Torridon Group. Exceptional example of a Precambrian cyclothemic sequence.
The Moine Thrust Belt Network — Chapter 5 Moine Block	
Eriboll	Representative of the northern part of the Moine Thrust Belt. Exceptional examples of thrust structures, associated folds, and mylonites. Internationally important for historical reasons, as a key locality for the understanding of concepts of compressional tectonics.
Cleit an t-Seabhaig	Representative of mylonitic rocks from the uppermost part of the Moine Thrust Belt and the lowermost part of the Moine Thrust Sheet. Internationally important as the location at which the structure considered to be the Moine Thrust was first directly observed.
Faraid Head	Representative of mylonitic rocks from the uppermost part of the Moine Thrust Belt and the lowermost part of the Moine Thrust Sheet. Exceptional example of a klippe of the Moine Thrust Sheet. Internationally important as one of the first localities where the kilometre-scale displacement of a major thrust sheet was recognized.
Sango Bay	Exceptional examples of post-Caledonian normal faults that have downthrown Moine Thrust Belt mylonites of the Faraid Head klippe.
Foinaven	Exceptional examples of thrust structures, including classic examples of a duplex, within Cambrian quartzites of the Moine Thrust Belt.

Glencoul	Representative of the northern part of the Assynt Culmination in the Moine Thrust Belt. Exceptional examples of thrust exposures. Internationally important as a world-famous view of large-scale thrust sheets.
Skiag Bridge	Representative of the foreland succession, Sole Thrust, and lowest imbricate systems in the Assynt Culmination. Exceptional examples of stratigraphical repetition due to thrusting. Internationally important as a teaching site for basic thrust concepts.
Stronchrubie Cliff	Representative of imbricate thrusts within the Sole Thrust Sheet in the Assynt Culmination. Exceptional examples of sections that can be used to study the three-dimensional geometry of an imbricate system.
Traligill Burn	Representative of thrusting within the Sole Thrust Sheet in the Assynt Culmination. Exceptional exposures of a thrust plane.
Ben More Assynt–Conival–Na Tuadhan	Representative of the central part of the Assynt Culmination, including the Ben More Thrust. Exceptional large-scale exposures of thrusts and related folds. Internationally important as a classic location for the demonstration of thrust structures.
Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel	Representative of the Ben More Thrust and associated fold and thrust structures in the Assynt Culmination. Also representative of the relationships between Lewisian and Torridonian units in the Ben More Thrust Sheet.
Cam Loch	Representative of thrust klippen and thrust-propagation folding in the Assynt Culmination.
Knockan Crag	Representative of the Moine Thrust and of the Moine mylonites. Exceptional example of a well-exposed, accessible thrust plane. Internationally important as one of the first locations at which the Moine Thrust was observed and as a world-famous locality for the study of thrust structures.
Dundonnell	Representative locality at which a 'piggy-back' thrust sequence was first demonstrated in the Moine Thrust Belt. Exceptional and internationally important as the type example of an antiformal-stack duplex.
Càrn na Canaich	Representative of those parts of the Moine Thrust Belt that show little or no deformation in the footwall to the Moine Thrust.
Slioch–Heights of Kinlochewe	Representative of the Moine Thrust Belt and the foreland succession in the Kinlochewe area. Of historical importance as one of the key localities of the 'Highlands Controversy'.
Meall a' Ghiubhais	Exceptional views of major thrust sheets and klippen in the Moine Thrust Belt, including the Kishorn Thrust Sheet.
Beinn Liath Mhor	Representative of the Moine Thrust Belt in the Achnashellach area. Exceptional examples of large-scale imbricate systems that can be clearly seen from distant viewpoints.
Cnoc nam Broc, Kishorn	Representative of a major fold–thrust complex termed the 'Kishorn Thrust Sheet', one of the major structures of the southern Moine Thrust Belt.

Slumbay Island, Loch Carron	Exceptional examples of mylonites in the Moine Thrust Belt.
Carn a' Bhealaich Mhoir	Representative of the Lewisianaorridonian unconformity within the Moine Thrust Belt.
Hangman's Bridge	Representative of the Moine Thrust, being one of the few localities where the thrust plane is actually exposed.
Ard Hill	Representative of the Balmacara Thrust and associated structures of the Moine Thrust Belt in the Lochalsh area.
Ord	Representative of the Ord Window, one of the major structures in the Moine Thrust Belt whose origin is not yet fully understood.
Tarskavaig	Representative of the Tarskavaig thrust sheets, and the metasedimentary rocks of the enigmatic Tarskavaig Group.
Ard Thurinish–Port na Long	Representative of the Moine Thrust, being its southernmost exposure.
Moine (North) Network — Chapter 6	
Ben Hutig	Representative of the lower parts of the Moine Supergroup. Exceptional examples of deformed pebbles and quartz veins that have been used to study deformation mechanisms.
Port Vasgo–Strathan Bay	Representative of the basal Moine metasedimentary rocks, including conglomerate units, the underlying Lewisianoid basement, and the Talmine Imbricate Zone. Exceptional examples of outcrop-scale sedimentary and tectonic structures that have been used to interpret the regional structural history.
Melness	Representative of the basal Moine metasedimentary rocks and the underlying Lewisianoid basement, and of the Talmine Imbricate Zone.
Allt na Caillich	Representative of the Ben Hope Thrust and Ben Hope Sill. Exceptional example of an intra-Moine thrust.
Allt an Dherue	Representative of the basal Moine metasedimentary rocks and the underlying Lewisianoid basement. Representative of the Loch a' Mhoid Metadolerite Suite.
Coldbackie Bay	Representative of the unconformity between the Moine psammites and the overlying sandstones and conglomerates, which are probably Devonian in age.
Strathan Skerray to Skerray Bay	Representative of the Borgie Lewisianoid Inlier.
Aird Torrisdale	Representative of the Naver Thrust Zone. Exceptional exposures of ductile thrust contacts between Moine rocks and Lewisianoid gneisses and within the Moine sequence.
Ard Mor (Bettyhill)	Representative of the migmatitic Moine rocks of the Bettyhill Banded Formation, and of the amphibolite intrusions of the Bettyhill Suite.
Farr Bay (Bettyhill)	Representative of the Farr Lewisianoid inlier and associated Moine rocks of the Bettyhill Banded Formation. Exceptional examples of refolded folds.
Glaisgeo to Farr Point	Representative of the appinitic, dioritic and amphibolitic Clerkhill Intrusion, and the Moine rocks of the Bettyhill Banded Formation.

Sgeir Ruadh (Portskerra)	Representative of the migmatitic Moine rocks known as the Portskerra gneisses, and their relationships with mafic intrusions of the Bettyhill Suite and with the Strath Halladale Granite Complex. Also shows the unconformity between the Moine rocks and the overlying Middle Devonian sandstones.
Dirlot Castle	Representative of the unconformity between the Moine rocks and the overlying Devonian carbonate-cemented breccias and sandstones.
Ben Klibreck	Representative of the Naver Thrust. Exceptional examples of migmatites, first studied in the 1920s and still the subject of research.
Oykel Bridge	Exceptional examples of mullions in the Moine rocks. Historically important in the development of ideas relating small-scale structures to regional tectonics.
The Airde of Shin	Representative of the lithologically diverse Shin Lewisianoid Inlier, which includes amphibolitic and quartzofeldspathic gneisses, metalimestones and schistose calc-silicate rocks.
Allt Doir' a' Chatha	Representative of finely banded amphibolitic rocks of the Shin Lewisianoid Inlier, originally interpreted as metavolcanic units within the Moine.
Creag na Croiche	Representative of the outer contact and the migmatitic envelope of the Rogart Pluton.
Aberscross Burn-Kinnauld	Representative of the transition from unmigmatized Moine rocks into the migmatitic envelope of the Rogart Pluton.
Brora Gorge	Representative of the outer contact and the migmatitic envelope of the Rogart Pluton.
Carn Gorm	Representative of the Carn Gorm 'Knoydartian' pegmatite, which has been dated by Rb-Sr methods and provides evidence for a Precambrian metamorphic event affecting the Moine rocks.
Comrie	Representative of Neoproterozoic-age mafic meta-igneous rocks in the Moine succession.
Cromarty and Rosemarkie Inners	Representative of the Moine and Lewisianoid rocks of the Cromarty and Rosemarkie inliers within the Devonian basins of the Moray Firth.
Moine (Central) Network — Chapter 7	
Fannich	Representative of the Morar and Glenfinnan groups, together with associated Lewisianoid inliers. Also representative of the ductile Sgurr Beag Thrust, which separates the two groups.
Mean an t-Sithe and Creag Rainich	Representative of the Sgurr Beag Thrust, demonstrating the chronological relationships between the period of ductile thrusting within the Moine Supergroup and the later movement focused on the Moine Thrust Belt.
Loch Monar	Representative of the Glenfinnan Group. Exceptional examples of fold interference patterns. Internationally important for the study of the geometry and formation mechanisms of complex fold structures in metasedimentary rocks.
Abhainn Gleann nam Fiadh	Representative of the Glenfinnan Group. Exceptional examples of well-preserved sedimentary structures, including cross-bedding and slump structures.

Attadale	Representative of the unconformity between the Moine rocks and the underlying Lewisianoid basement. Exceptional example of the basal conglomerate of the Moine succession.
Dornie–Inverinate Road Section	Representative cross-section across the Glenelg–Attadale Lewisianoid Inlier, including quartzofeldspathic gneisses, ultramafic bodies, metasedimentary rocks and eclogites, and also the zone of deformation separating the eastern and western parts of the inlier.
Avernish	Representative of the Glenelg–Attadale Lewisianoid Inlier, showing the original unconformable relationship between the inlier and the overlying Moine rocks.
Totaig	Representative of the variety of rocks in the eastern part of the Glenelg–Attadale Lewisianoid hiller, including metalimestones, kyanite-bearing gneisses, eulysite, graphitic schists, and exceptional examples of eclogites.
Allt Cracaig Coast	Representative of the Glenelg–Attadale Lewisianoid Inlier, showing the original unconformable relationship between the inlier and the Moine rocks. Exceptional example of the tectonized basal conglomerate of the Moine succession.
Druim Iosal	Representative of the variety of rocks in the eastern part of the Glenelg–Attadale Lewisianoid Inlier, including metalimestones, calc-silicate rocks, graphitic schists and exceptional examples of kyanite-bearing pelitic gneisses.
Beinn a' Chapuill	Representative of the Glenelg–Attadale Lewisianoid Inlier, showing the relationships between the inlier and the overlying Moine rocks. Exceptional example of a kilometre-scale refolded fold.
Eilean Chlaraail–Camas nan Ceann	Representative of the western part of the Glenelg–Attadale Lewisianoid Inlier.
Rubha Camas na Cailinn	Representative of the Glenelg–Attadale Lewisianoid Inlier, and showing Moine rocks interleaved and folded together with rocks of the inlier.
Ard Ghunel	Exceptional examples of zoned ultramafic pods within the Lewisianoid gneisses of the Moine Nappe.
Moine (South) Network — Chapter 8	
Glen Doe	Representative of metagabbroic intrusive rocks associated with the West Highland Granite Gneiss Suite.
Kinloch Hourn	Representative of the Sgurr Beag Thrust, an exceptional example of a major ductile thrust within the Moine succession.
Quoich Spillway	Representative of the West Highland Granite Gneiss Suite.
Knoydart Mica Mine	Representative of the 'Knoydartian' pegmatite suite, dating of which provides evidence for a Precambrian metamorphic event affecting the Moine rocks. Exceptional examples of large mica and beryl crystals.
North Morar	Representative of the Morar Group of the Moine and of associated Lewisianoid inliers. Also representative of the change from low-grade, moderately deformed Moine rocks in the west, to higher-grade, complex thrust and folded Moine rocks in the east.
Drulmindarroch	Representative of the Lower Morar Psammite Formation.

Fassfern to Lochailort Road Cuttings	Representative section across the whole Moine Supergroup in Inverness-shire.
Lochailort	Representative of the southern outcrop of the Sgurr Beag Thrust.
Eas Chia-Aig Waterfalls	Representative of an inlier of migmatitic gneisses correlated with the Glenfinnan Group, lying within the Loch Ed Group of the Moine.
Loch Moidart Road Cuttings	Representative of the Upper Morar Psammite Formation, showing good examples of sedimentary structures such as cross-bedding and slumps.
Eilean Mòr and Camas Choire Mhuilinn	Representative of the Upper Morar Psammite Formation. Exceptional examples of sedimentary structures such as cross-bedding and de-watering structures.
Ardalanish Bay, Mull	Representative of the most westerly known outcrop of the Moine succession and its contact with the late Caledonian Ross of Mull Pluton. Exceptional examples of aluminosilicate minerals within the metamorphic aureole.
Lewisian and Moine of Shetland Network — Chapter 9	
Uyea to North Roe Coast	Representative of the Caledonian Front in Shetland, including rocks correlated with the Lewisian gneisses, and the Moine and Dalradian supergroups. Internationally important for correlation along the length of the Caledonide Belt.
Gutcher	Representative of psammites and microcline augen gneisses of the Yell Sound Division, which is considered to correlate with the Moine Supergroup.
North Sandwick	Representative of psammites, pelites and quartzites of the Yell Sound Division, which is considered to correlate with the Moine Supergroup, and also of metamorphosed mafic sheets intruding the metasedimentary rocks.
Hascosay	Representative of the mylonitic gneisses of the Hascosay Slide Zone.
Calliyoe	Representative of the mylonitic gneisses of the Hascosay Slide Zone. Exceptional examples of fold structures within the mylonitic rocks.
Voxter Voe and Valayre Quarry	Representative of the Valayre Gneiss, a microcline-megacryst augen gneiss that forms the western edge of the Boundary Zone between the Moine and Dalradian rocks of Shetland.

Site selection is inevitably subjective, and some readers may feel that important localities have been omitted, whereas some features may seem over-represented. In the twenty years or more since the initial GCR lists for Lewisian, Torridonian and Moine rocks were drawn up, much new research has been carried out in the Northern Highlands, and so the list of sites given here will need to be updated in the future to embrace the changes in sites and new discoveries. However, the declared aim of the GCR was to identify *the minimum number and area of sites needed to demonstrate the current understanding* of the diversity and range of features within each GCR block. Since not all GCR sites have yet been afforded the legal protection of SSSI notification, it seems more appropriate to concentrate on describing and protecting the sites identified to date.

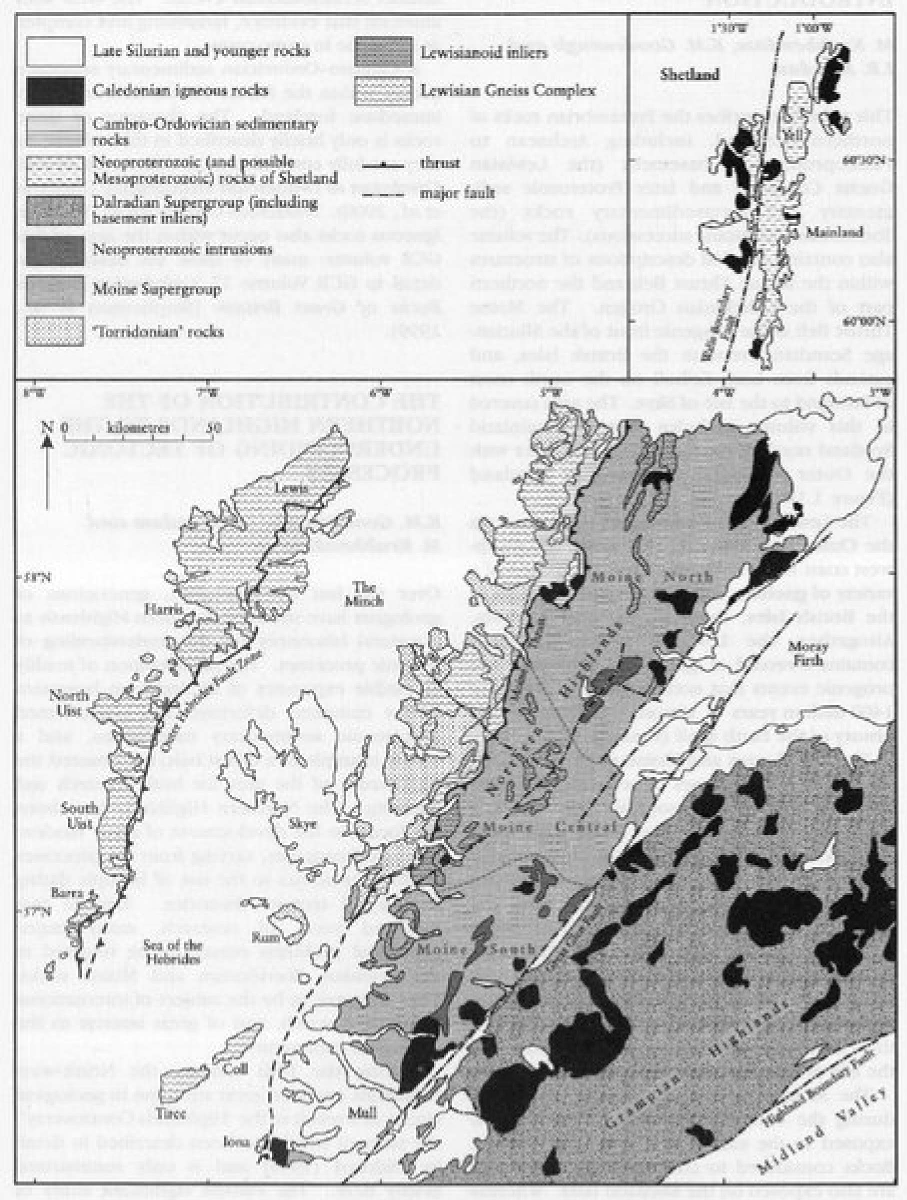
The Lewisian, Torridonian and Moine GCR sites described in this book are many and varied, ranging from some of Britain's wildest mountain and coastal areas to exposures along busy roads. However, even the remotest sites may be vulnerable to damage, as typified by the case of Roineabhal on South Harris. This GCR site, which contains the largest anorthosite body in Britain, also lies within a National Scenic Area. In 1991 a planning application was lodged to develop a superquarry and remove much of the anorthosite for use as aggregate. A lengthy public inquiry followed, before rejection of the planning application by the Scottish Executive in 2000. This decision is currently the subject of an appeal. Were this site not formally protected by a variety of designations, it is possible that much of the anorthosite body would have already been quarried.

Although quarrying on a large scale may damage features of geological interest by removing them entirely, small-scale quarrying may in some situations improve the condition of a site through the opening of new exposures, as for example at the Voxter Voe and Valayre Quarry GCR site. The appropriateness of quarrying or rock removal needs to be assessed on a site-by-site basis; at some localities even a small amount of rock removal can destroy much of the interest of the site, as has happened at the Ard Ghunel GCR site. However, many of the GCR sites in this volume include man-made rock faces that are extremely useful in areas with poor natural exposure; these sites include road cuttings such as those in the Fassfern to Lochailort Road Cuttings and Dornie–Inverinate Road Section GCR sites, and other, more-unusual cuttings such as those at the Quoich Spillway GCR site. Of course, these man-made sites are vulnerable to further change; for instance, at the Attadale GCR site, the rock exposures that were originally created as road cuttings have now become unstable and as a consequence have been covered with wire netting, making access to the outcrop extremely difficult.

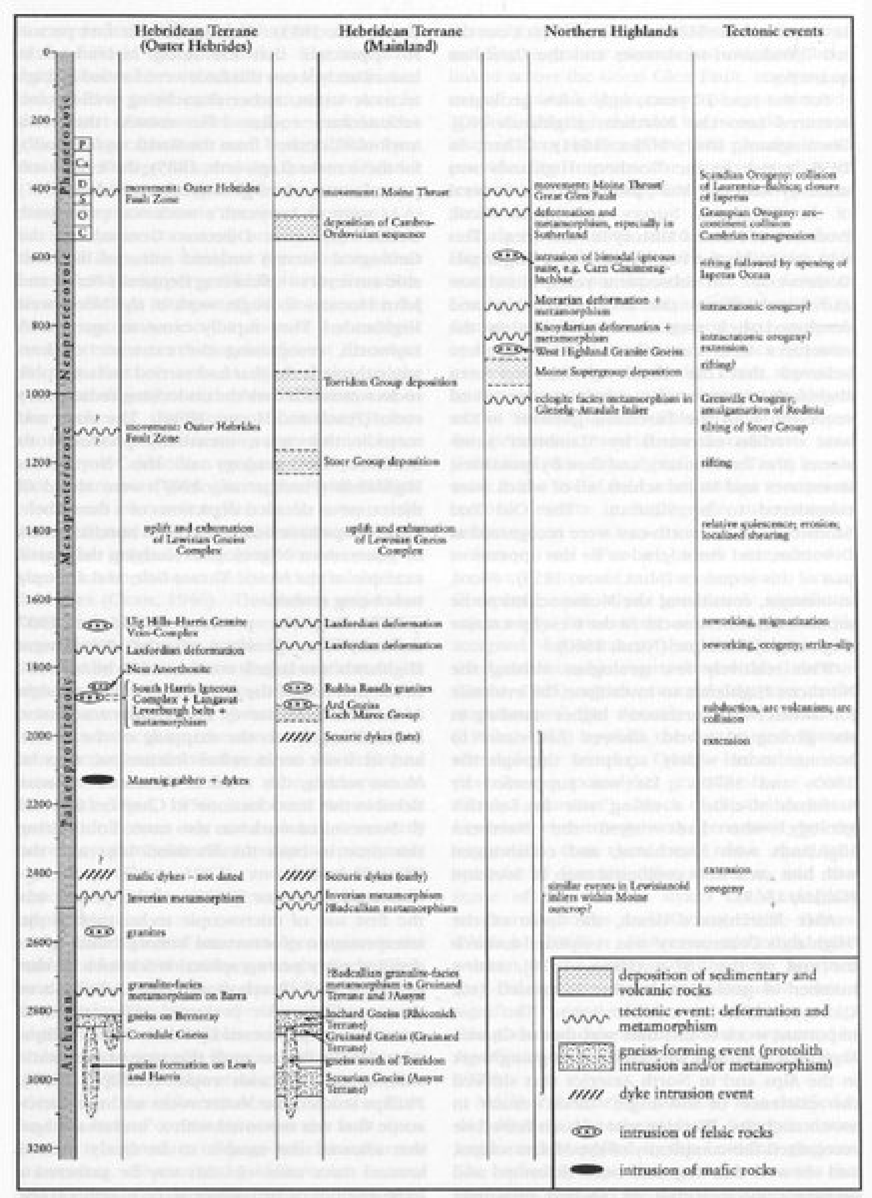
Many of the sites described in this volume are coastal or upland sites that have been relatively unaffected by human activities. One of the main threats to these sites is that their geological features might be obscured, perhaps by thick forestry or by hydro-electric schemes. Although this does not destroy the geological interest of the sites, it effectively renders them inaccessible for research and education purposes, hence removing the main reasons for the selection of the GCR site. The encroachment of forestry has greatly increased the difficulty of access to sites such as the Allt Cracaig Coast GCR site. However dialogue between landowners and conservation bodies such as Scottish Natural Heritage has successfully ensured that developments have not damaged or obscured the key geological features.

The wealth of sites of geological interest in the Northern Highlands has made this area one of the foremost in Britain in the development of geotourism. This is exemplified by the recent recognition of part of the Northwest Highlands as Scotland's first UNESCO Geopark. It is clear that conservation of geological sites is important not only for research and education, but also for the interest of all those who appreciate the development of our natural landscapes.

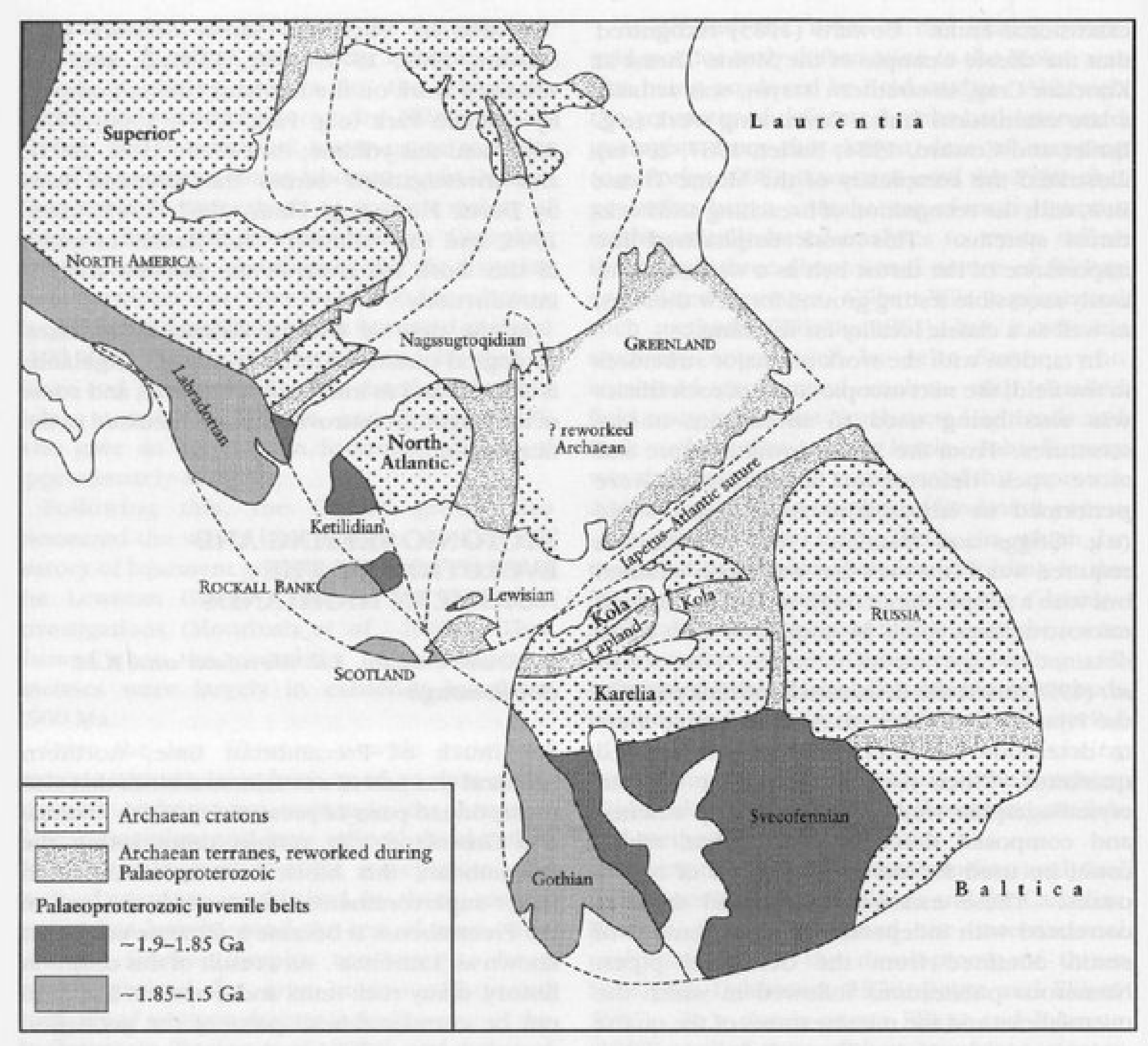
References



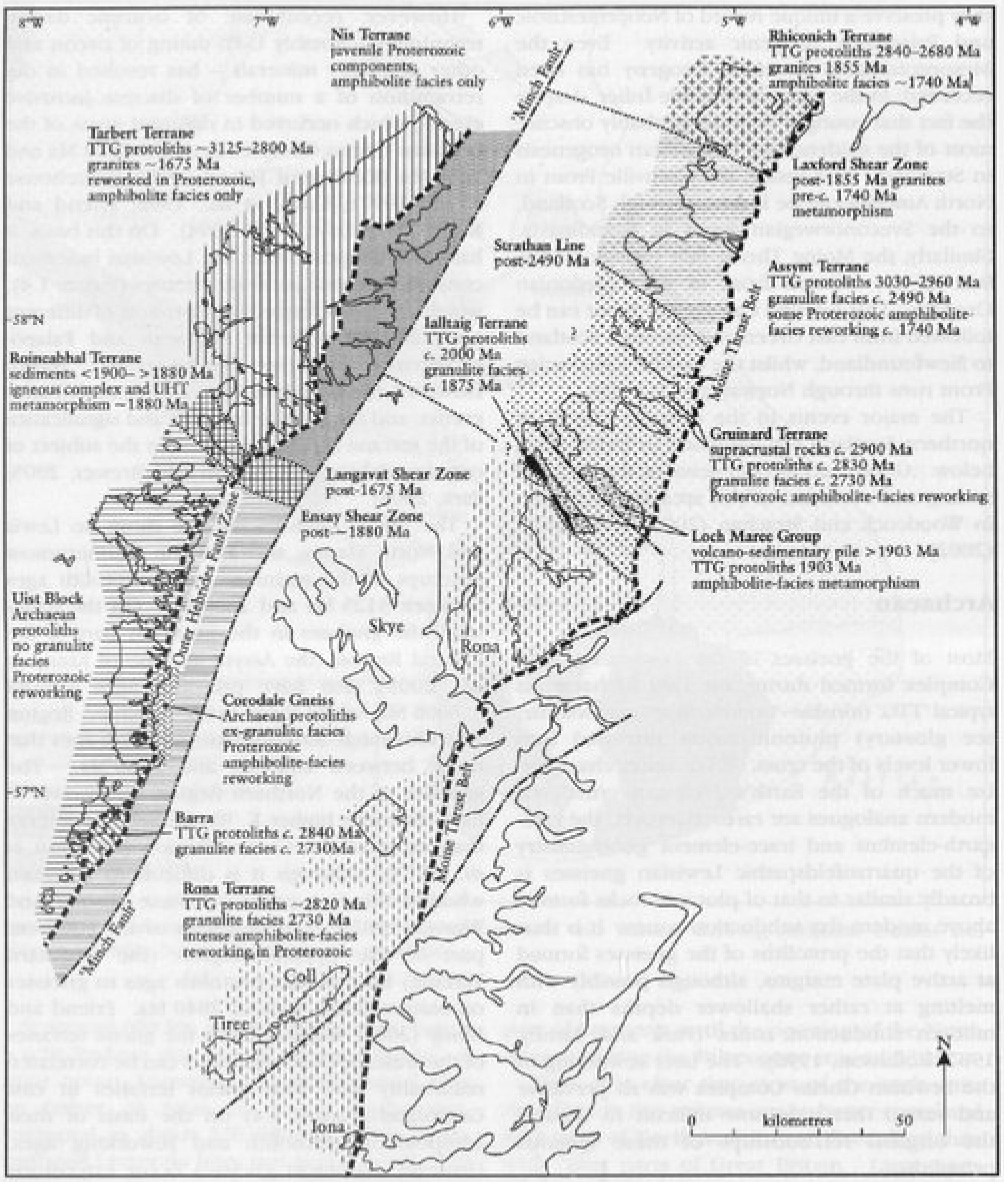
(Figure 1.1) Simplified geology of northern Scotland, showing the extent of the area described in this volume. Modified after British Geological Survey original.



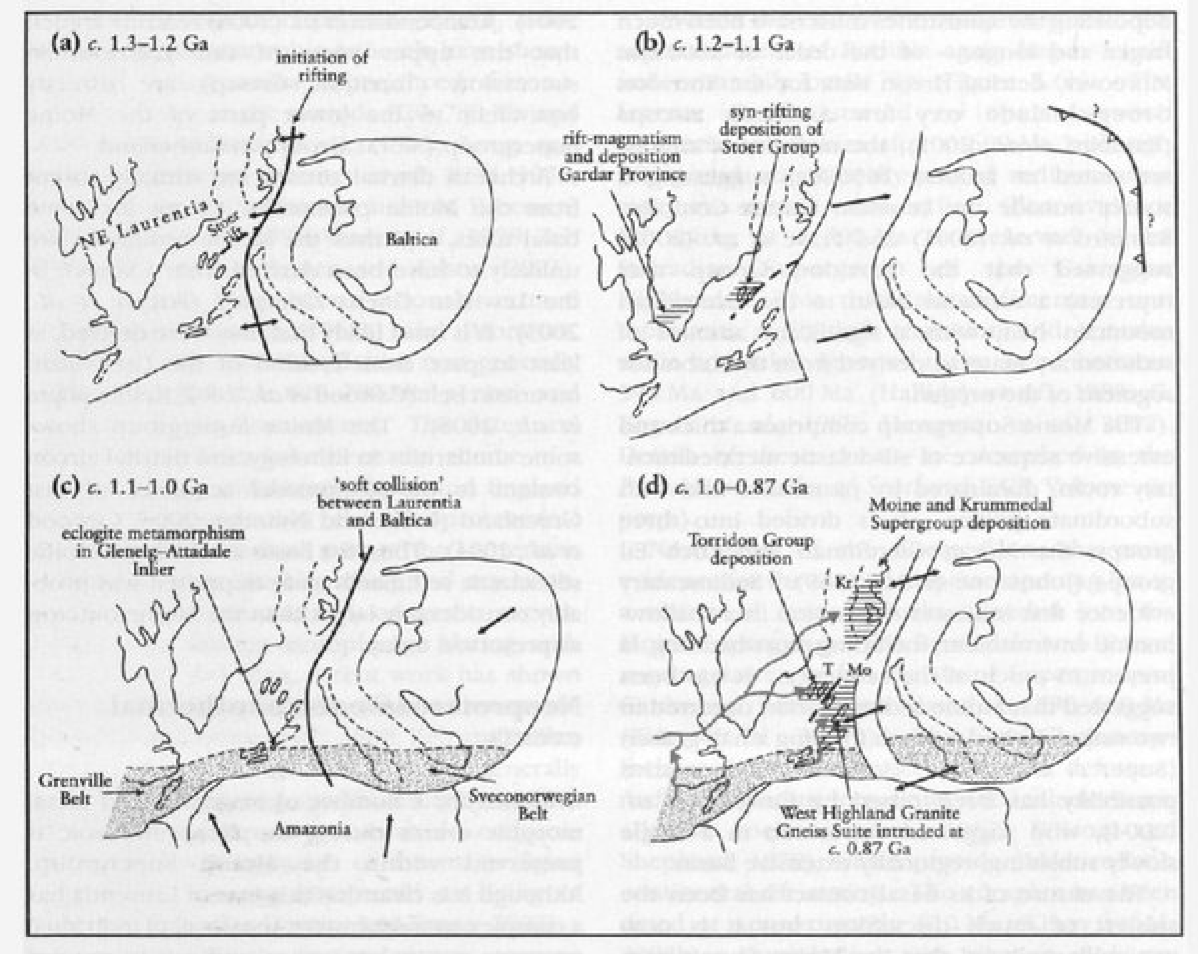
(Figure 1.2) Table of geological events in northern Scotland. Abbreviations for periods within the Phanerozoic are: P — Permian; Ca — Carboniferous; D — Devonian; S — Silurian; O — Ordovician; C — Cambrian. Based on Harris (1991), Trewin (2002) and Kinny et al. (2005).



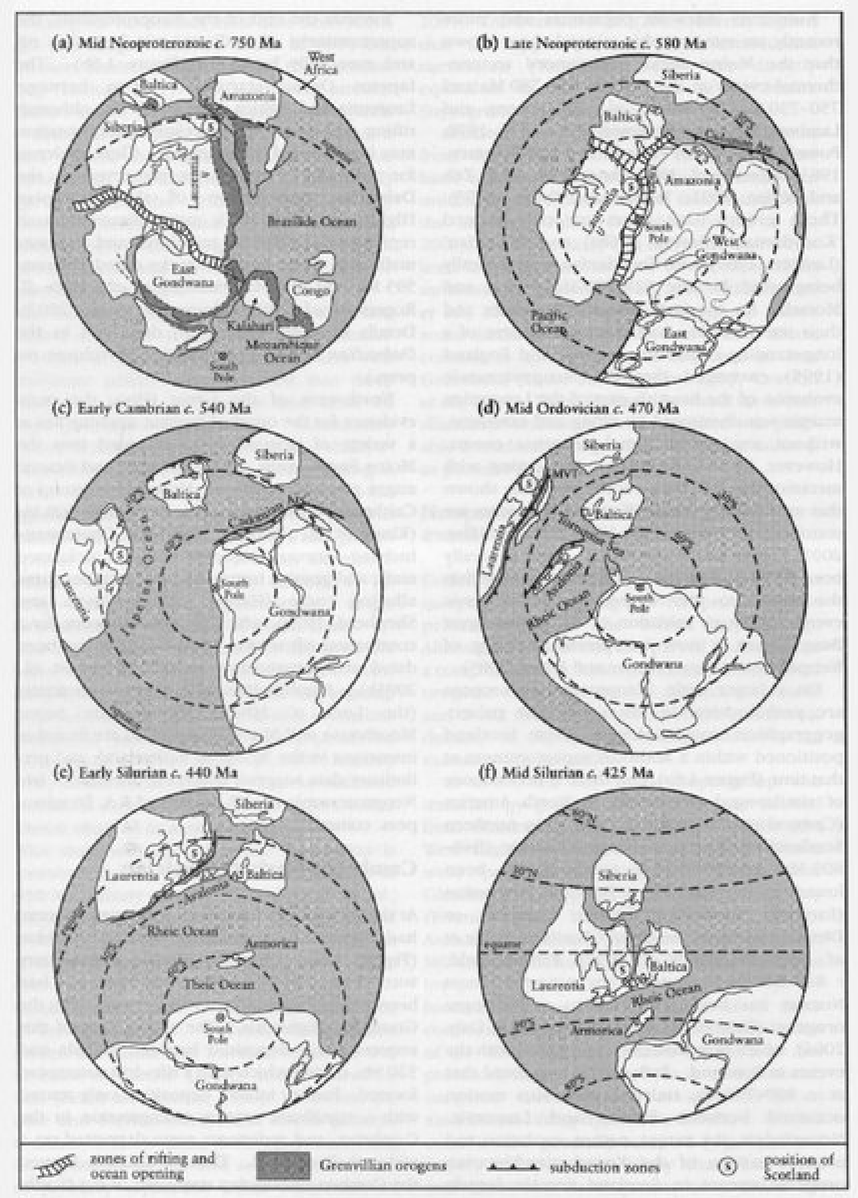
(Figure 1.3) Palaeogeographical reconstruction of Laurentia and Baltica, showing Archaean cratons and Palaeoproterozoic belts. After Buchan et al. (2000).



(Figure 1.4) Map of suggested terranes in the Lewisian Gneiss Complex of the Outer Hebrides and mainland Scotland, with a summary of isotopic dates. Based on Friend and Kinny (2001) and Kinny et al. (2005).



(Figure 1.5) Generalized palaeogeography of Laurentia and Baltica during the period 1300–870 Ma, showing the setting of deposition of the Stoer, Torridon and Moine sequences. Hatched areas show locations of sedimentary deposition. T — Torridon Group; Mo — Moine Supergroup; Kr — Krummedal sequence. After Strachan and Holdsworth (2000).



(Figure 1.6) Palaeogeographical reconstructions from the Neoproterozoic to the Silurian. (a) The supercontinent Rodinia at c. 750 Ma. The Grenvillian orogenic belts that welded the Rodinia continent together are indicated. Rifting has commenced between Laurentia and East Gondwana. (b) Mid-Neoproterozoic, c. 600–580 Ma. Rifting between the continents of Laurentia, Baltica and Amazonia. (c) Neoproterozoic—Cambrian, c. 550–540 Ma. The Iapetus Ocean is at its widest. Clastic and carbonate deposition occurs along the southern margin of Laurentia. (d) Ordovician, c. 470 Ma. The Iapetus Ocean is in the process of closing. Collision of oceanic and microcontinental arcs with Laurentia (e.g. the Midland Valley Terrane), results in the Grampian Event in Scotland and the Taconic Event in North America. (e) Early Silurian, c. 440 Ma. Collision of peri-Gondwanan continental terranes, notably Avalonia, with Laurentia as the Iapetus Ocean closes and the Rheic Ocean widens. The start of the Scandian Event. (t) Silurian, c. 425 Ma. Final closure of Iapetus and Tornquist oceans. Collision of Baltica and Greenland (Laurentia) gives rise to the main Scandian Event (438–425 Ma). MVT — Midland Valley Terrane. Based on Torsvik et al. (1996) and Holdsworth et al. (2000).