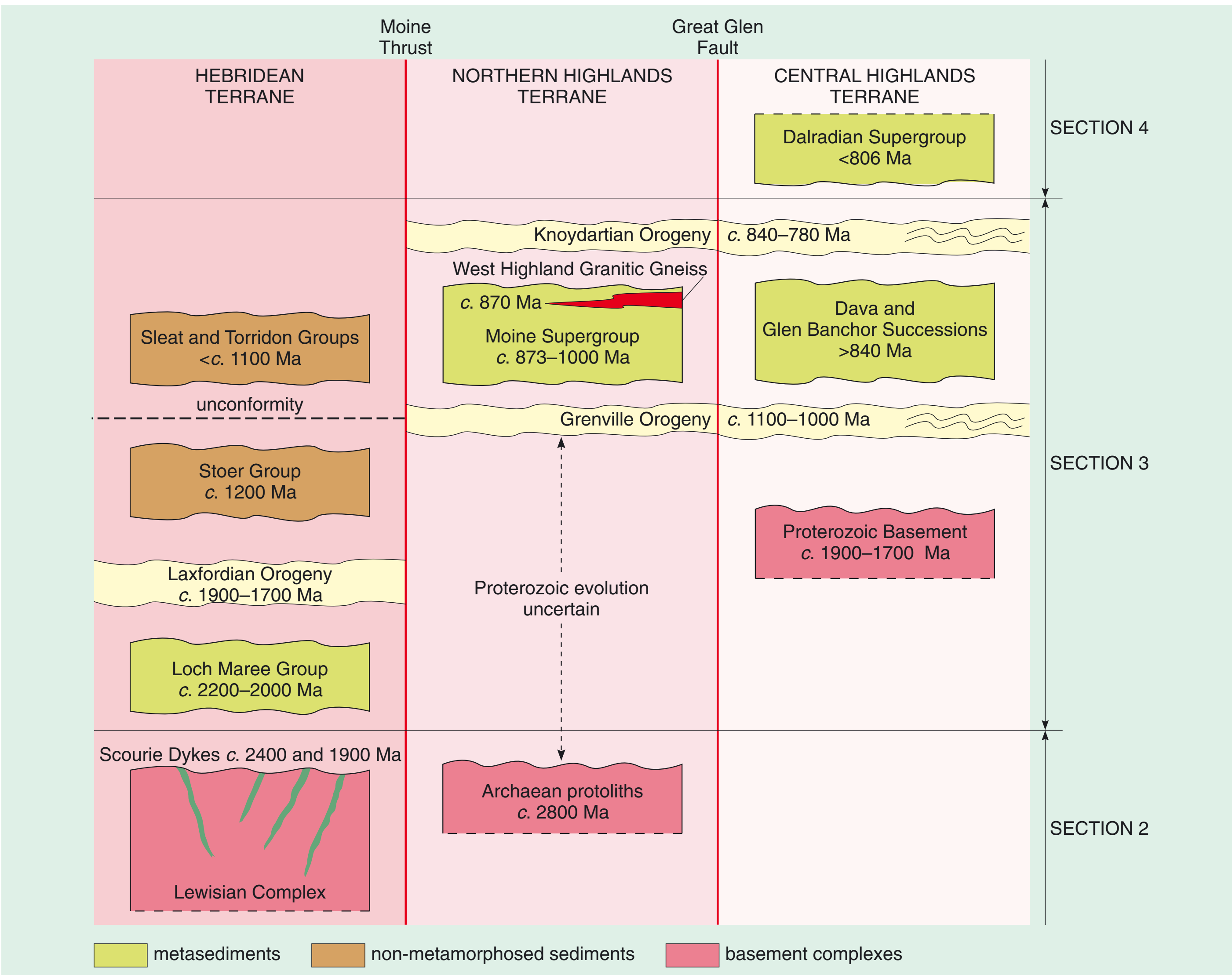
3 Orogenies in the Proterozoic

3.1 Introduction

Orogenies in the Proterozoic are thought to have resulted from the collision of large continental blocks and the closure of intervening oceans. These orogenic episodes are often recognized by the presence of three geological features: 1) calc-alkaline igneous rocks formed during subduction; 2) discrete suture zones containing ophiolites; and 3) remnants of high-pressure regional metamorphism that indicate periods of crustal thickening. The amalgamation of continental blocks or fragments led to the formation of large individual continental masses known as supercontinents. The periodic break-up of supercontinents led to the formation of extensive passive margins where thick sedimentary sequences accumulated. Subsequent collisions of continental fragments formed extensive linear mountain belts.

Although Britain and Ireland only represent a small area of crust, the various basement complexes and sedimentary sequences of Proterozoic age provide a record of plate reorganizations that occurred during the time period from *c.* 2500 Ma to *c.* 750 Ma. The major rock units and geological events that date from this time are summarized in Figure 3.1 and discussed in this Section,

Figure 3.1 A summary of the geographical and time relationships of Late Archaean to Late Proterozoic rocks and events discussed in Sections 2, 3 and 4 of this book.



from which the following points will emerge:

- Proterozoic rocks outcrop in three fault-bounded terranes.
- The boundaries between the various rock units in each terrane are regionally important unconformities; in other words, they are gaps in the geological record that identify periods of crustal shortening, uplift and erosion.
- Metamorphism and magmatism were associated with the orogenic episodes.
- Between these orogenic episodes there were major periods of sediment accumulation, often associated with crustal extension.
- Basement orthogneiss complexes identify major periods of primary crustal growth, some evidence for which was discussed in Section 2.

3.2 Palaeoproterozoic rifting, sedimentation and magmatism

We have already seen that continental growth in the Archaean was achieved by magma addition and that these rocks were involved in collision-related events that continued into the early Palaeoproterozoic. In the Lewisian Complex, and in particular in the Assynt Terrane, a terrane that largely escaped Proterozoic deformation (see Section 3.3.1), the structures and fabrics formed during granulite-facies metamorphism and the subsequent amphibolite-facies metamorphism are cross-cut by mafic dyke swarms, collectively known as the Scourie dykes (Figure 3.2). In areas of low strain, these dykes contain primary igneous textures and mineralogies, and often retain chilled margins against the surrounding gneisses.

Figure 3.2 A Scourie dyke (left of the contact marked in white) intruding Lewision gneiss containing an earlier, near-horizontal foliation, Balgey, Loch Torridon, north-west Scotland. Note that the margin of the dyke is slightly foliated as a result of later deformation.

The dykes were emplaced into crust for which ambient temperature and pressure conditions were 450–550 °C and 400–500 MPa. Isotopic dating of these dykes has identified two discrete swarms that were emplaced at *c.* 2420 Ma and *c.* 1990 Ma. The occurrence of mafic dyke swarms is usually linked to wholesale crustal thinning or rifting and signifies periods of lithospheric extension. The interpretation of the dyke swarms in the Lewisian Complex is no exception. Mafic dyke swarms have also been identified within the other terranes of the Lewisian Complex and all are thought to be linked to phases of crustal extension and rifting.

The record of sedimentation in the Palaeoproterozoic is limited to the Loch Maree Group, which occurs within the Gruinard Terrane of the Lewisian Complex (Figure 3.3). The Loch Maree Group comprises two components: one is oceanic and includes shallow marine plateau basalts and abyssal sediments, the other is continental and consists of greywackes and deltaic sediments. Dating of detrital minerals from the continental sediments indicates a provenance (see Box 3.1) from both Archaean and Palaeoproterozoic sources and indicates a maximum age of deposition for the Loch Maree Group of *c.* 2200–2000 Ma.

- What is the style of tectonism implied by the timing of dyke emplacement and sedimentation?

- The widespread occurrence of mafic dyke swarms at *c.* 2420 Ma and *c.* 1990 Ma that are broadly correlated with sedimentation at *c.* 2200–2000 Ma is considered to reflect the break-up by rifting of the Archaean to Early Proterozoic crust into smaller continental fragments separated by oceanic tracts. The occurrence of rocks of oceanic affinity within the Loch Maree Group indicates that rifting eventually led to rupture of the crust and formation of oceanic lithosphere.

Box 3.1 Provenance studies

Provenance studies involve the petrographical, chemical and isotopic analysis of the rock and mineral fragments within sediments to provide important information on the sediment source regions, which were usually mountain belts that were undergoing erosion at the time of sedimentation. These types of data, along with palaeocurrent information, can be used to identify the existence of ancient mountain belts. Furthermore, in the absence of palaeontological data, the timing of sedimentation in (meta)sedimentary rocks can normally be bracketed by dating pre- and post-depositional orogenic events, e.g. magmatism, deformation and metamorphism, or by the isotopic dating of syn-sedimentary volcanic deposits. In recent years advances in the chemical fingerprinting and isotopic dating of mineral grains has improved our understanding of the provenance of older (meta)sediments and the timing of their deposition.

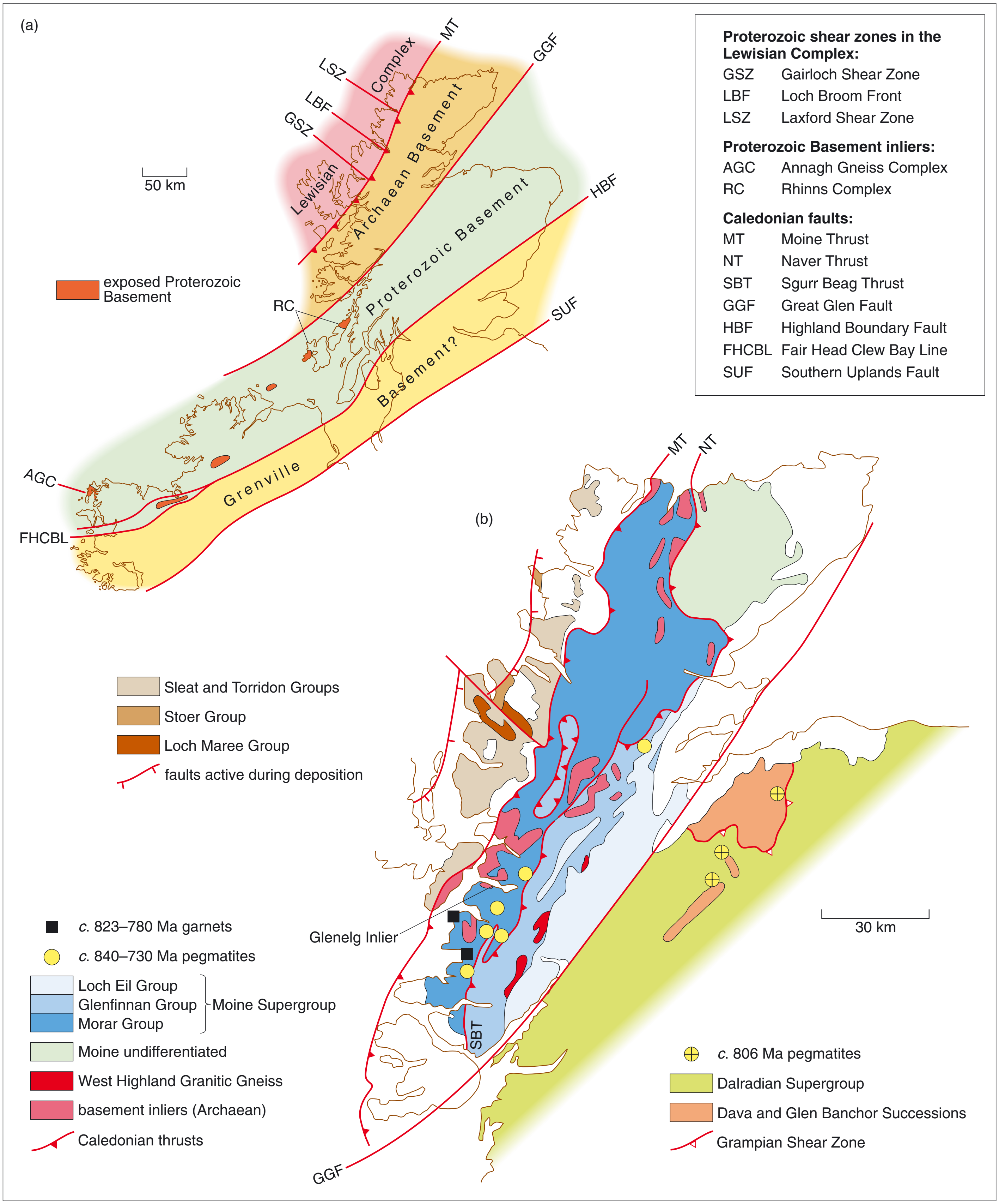


Figure 3.3 (a) Tectonic subdivision of the Caledonides. Areas thought to be underlain by various basement types and the location of Proterozoic shear zones in the Lewisian Complex are indicated. (b) Location of Proterozoic rocks.

3.3 The Palaeoproterozoic Laxfordian Orogeny

The sequence of tectonic events spanning *c.* 2000–1600 Ma provides a record of the convergence of continental blocks and the subsequent development of an active plate margin. The Palaeoproterozoic *c.* 1900–1750 Ma Laxfordian orogenic event records the closure of minor oceanic basins and the progressive accretion of terranes that eventually amalgamated to form a larger continental mass. The emplacement of mantle-derived magmas at *c.* 1900–1780 Ma suggests the formation of a subduction zone along the margin of this continental mass. Evidence for these events is preserved in the Lewisian Complex of north-west Scotland, the Rhinns Complex of the Inner Hebrides, and the Annagh Gneiss Complex of north-west Ireland (Figure 3.3a).

3.3.1 Assembly of the Lewisian Complex

Widespread deformation and metamorphism of the Lewisian Complex between *c.* 2000–1750 Ma resulted from the progressive amalgamation of the Rhiconich, Assynt, Gruinard and Southern Region Terranes. In the Gruinard Terrane, deformation, metamorphism and magmatism in the Loch Maree Group record an early phase of the Laxfordian deformation and are related to the accretion of oceanic and volcanic arc components to the upper plate of a subduction zone formed between two converging continental blocks (Figure 3.4).

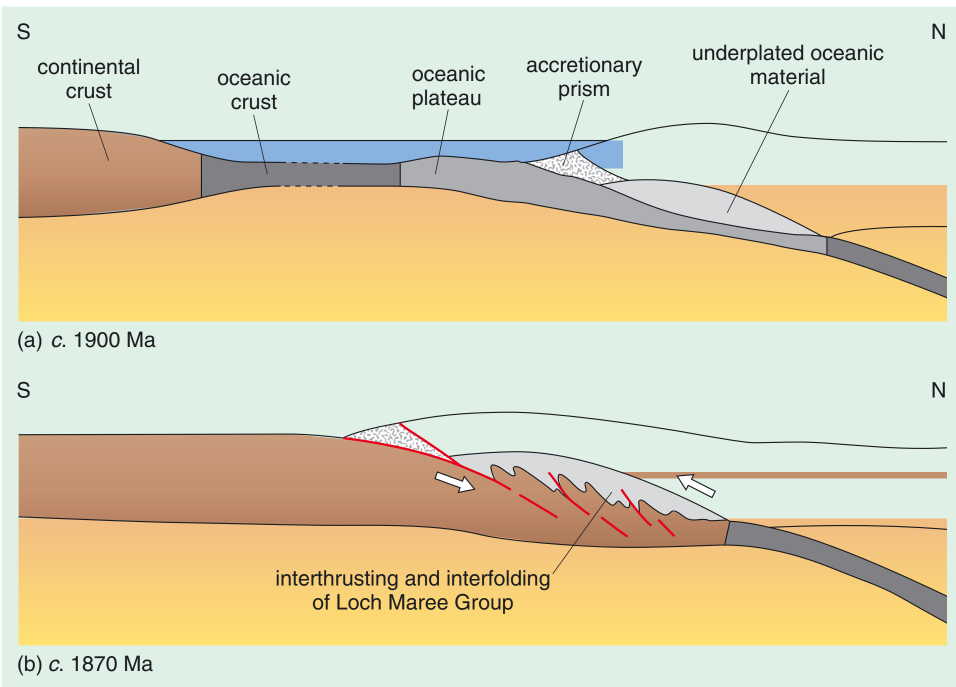


Figure 3.4 Cartoon illustrating the possible structural development of the Loch Maree Group. (a) Accretionary prism and underplated oceanic material represent the protoliths of the Loch Maree Group. (b) Interthrusting and interfolding of the Loch Maree Group as a result of subduction and plate collision.

Melting of the subducted oceanic crust led to granodioritic magmas that were emplaced into the complex at *c.* 1900 Ma. Metamorphic conditions reached amphibolite facies (*c.* 530–630 °C) and suggest that the crust was being thickened at this time. A later sequence of deformation events (*c.* 1700 Ma) led to the formation of upright folds and shear zones that probably record continued or renewed convergence.

Elsewhere in the Lewisian Complex, Laxfordian deformation and metamorphism are associated with regional-scale folding and formation of major ductile shear zones (Figure 3.5). Several of these shear zones are interpreted as terrane-bounding structures: the Laxford Shear Zone, the Loch Broom Front and the Gairloch Shear Zone (Figure 2.3). Figure 3.6 is a simplified cross-section illustrating the complex geological relationships across the Laxford Shear Zone, a structure that marks the boundary between the Rhiconich and Assynt Terranes.

Figure 3.5 Laxfordian deformation of Archaean gneisses of the Rhiconich Terrane at Rispond Beach, north coast of Scotland. The steep, near-vertical fabric is a shear zone formed during intense Laxfordian deformation. The dark inclusions in the paler gneisses are interpreted as boudins of intensely deformed mafic dykes. Width of view *c*. 25 m.

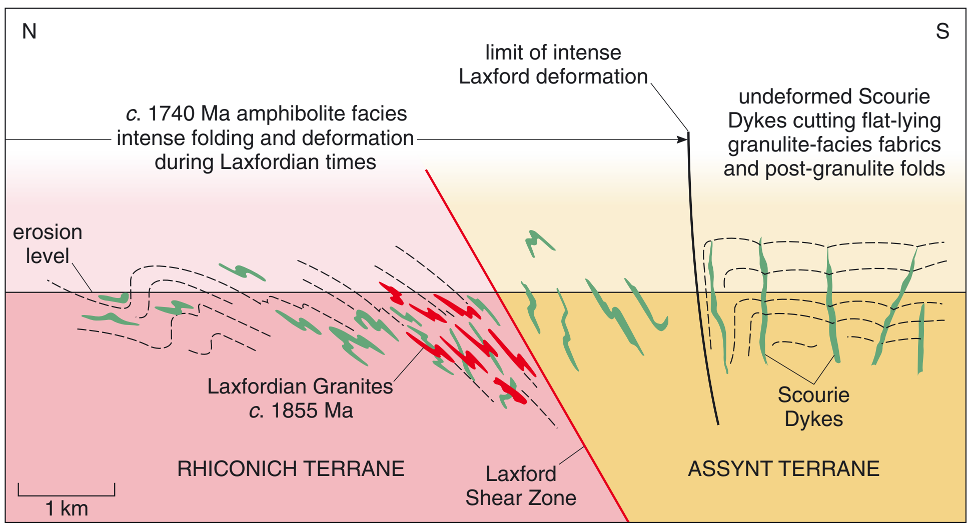


Figure 3.6 Simplified cross-section showing Laxfordian deformation across the Rhiconich–Assynt Terrane boundary and the Laxford Shear Zone.

Only the Assynt Terrane escaped this major period of crustal reworking, and so near pristine granulite-facies rocks and structures are still preserved (Figure 3.6). Here deformation is weak and non-pervasive and is concentrated along previously formed steeply-dipping shear zones and the margins of the Scourie dykes. In these shear zones, the early granulite-facies fabrics are reoriented and the magmatic fabrics of the dykes are strongly foliated and brought into parallelism with the dyke margins; a transformation that can be observed by comparing Figures 3.2 and 3.7.

Figure 3.7 Laxfordian deformation showing parallel foliation (yellow lines) in a Scourie dyke and its surrounding gneisses, Loch Tritlean, north-west Scotland.

Along the northern edge of the Laxford Shear Zone, early Laxfordian granitic sheets (*c*. 1855 Ma) are strongly deformed under amphibolite-facies conditions (Figure 3.8). These granites are not observed in the Assynt Terrane (Figure. 3.6).

Figure 3.8 Laxfordian deformation at Loch na Fiacail (for location see Figure 2.3). On the section the Archaean gneisses (gn) are cut by mafic dykes (md) and both are cross-cut by granitic pegmatites (gp). The oldest dated mineral in Britain (Figure 2.5) came from a sample of the gneiss from this locality. The regularly spaced, near vertical lines were formed during construction of the road cutting.

Radiometric dating of amphibolite-facies metamorphism in the Rhiconich and Assynt Terranes gives ages of *c.* 1740 Ma.

- What are the tectonic implications of the similar ages recorded from these two terranes?
- Whereas the absence of Laxfordian granites in the Assynt Terrane indicates that the two terranes must have been juxtaposed after *c.* 1855 Ma (the intrusion age of the granitic sheets), the common metamorphic ages of *c.* 1740 Ma suggest that the two terranes probably amalgamated at *c.* 1740 Ma or somewhat earlier.
- The proposed tectonic boundary between the Assynt and Gruinard Terranes, the Loch Broom Front, is located on Figure 2.3. Given the data presented in Figure 2.3, determine a maximum age for terrrane accretion along this boundary.
- The Assynt and Gruinard Terranes were accreted along the Loch Broom Front after *c.* 2490 Ma. We know this because *c.* 2490 Ma is the age of the youngest granulite-facies event to have affected the Assynt Terrane but not the Gruinard Terrane.

3.3.2 Formation of Proterozoic crust

Basement rocks of Palaeoproterozoic age are exposed in small fault-bounded inliers – the Annagh Gneiss Complex of north-west Ireland and a series of inliers collectively termed the Rhinns Complex of the Inner Hebrides (Figure 3.3a). The Rhinns Complex comprises weakly deformed and metamorphosed alkaline igneous rocks, syenites and gabbros, which have geochemical signatures consistent with formation in a subduction-related magmatic arc. The syenites have been dated at *c.* 1782 Ma and *c.* 1779 Ma. Amphiboles from the Rhinns Complex have given ages of *c.* 1710 Ma, and these younger ages are interpreted as recording cooling of the complexes following metamorphism. Isotopic studies indicate that the rocks of the Rhinns Complex formed as newly differentiated (juvenile) mantle-derived materials. The Annagh Gneiss Complex of north-west Ireland consists of a series of orthogneisses cut by granites and metabasic dykes (Figure 3.9). The igneous protoliths of some of the rocks have yielded radiometric ages of *c.* 1900 Ma.

The Rhinns and Annagh Gneiss Complexes, although small in area, provide an important record of Palaeoproterozic events. Several indirect lines of evidence indicate that this Palaeoproterozoic basement has a much greater extent (Figure 3.3a). Its existence at depth has been inferred from the isotopic signatures of Caledonian granites and Tertiary dykes that have incorporated older, so-called inherited, components from deeper crustal levels. These inherited basement components have given an age range of *c.* 1960–1850 Ma. Furthermore, regional gravity and magnetic data indicate that low-density, highly magnetic basement, which is unlike the Lewisian Complex, lies beneath both the Midland Valley and much of the Central Highlands Terrane. Provenance studies of locally-derived granitic boulders in younger sediments (Neoproterozoic glacial tillites within the Dalradian Supergroup) show them to be petrographically and chemically similar to components of the Rhinns Complex. These data suggest that rocks found in the Rhinns Complex were once much more widespread.

Figure 3.9 Palaeoproterozoic orthogneisses of the Annagh Gneiss Complex cross-cut by later granite sheets (of Grenville age, *c.* 1100–1000 Ma).

3.4 Synthesis: the broader view of Palaeoproterozoic events

Reconstructing the palaeocontinental blocks in the North Atlantic region indicates that the Lewisian Complex formed part of a continuous Palaeoproterozoic orogenic belt linking the Canadian Shield (Labrador Belt) with Greenland (Nagssugtoqidian and Ammassalik Belts) and Scandinavia (Lapland–Kola Belt) (Figure 3.10).

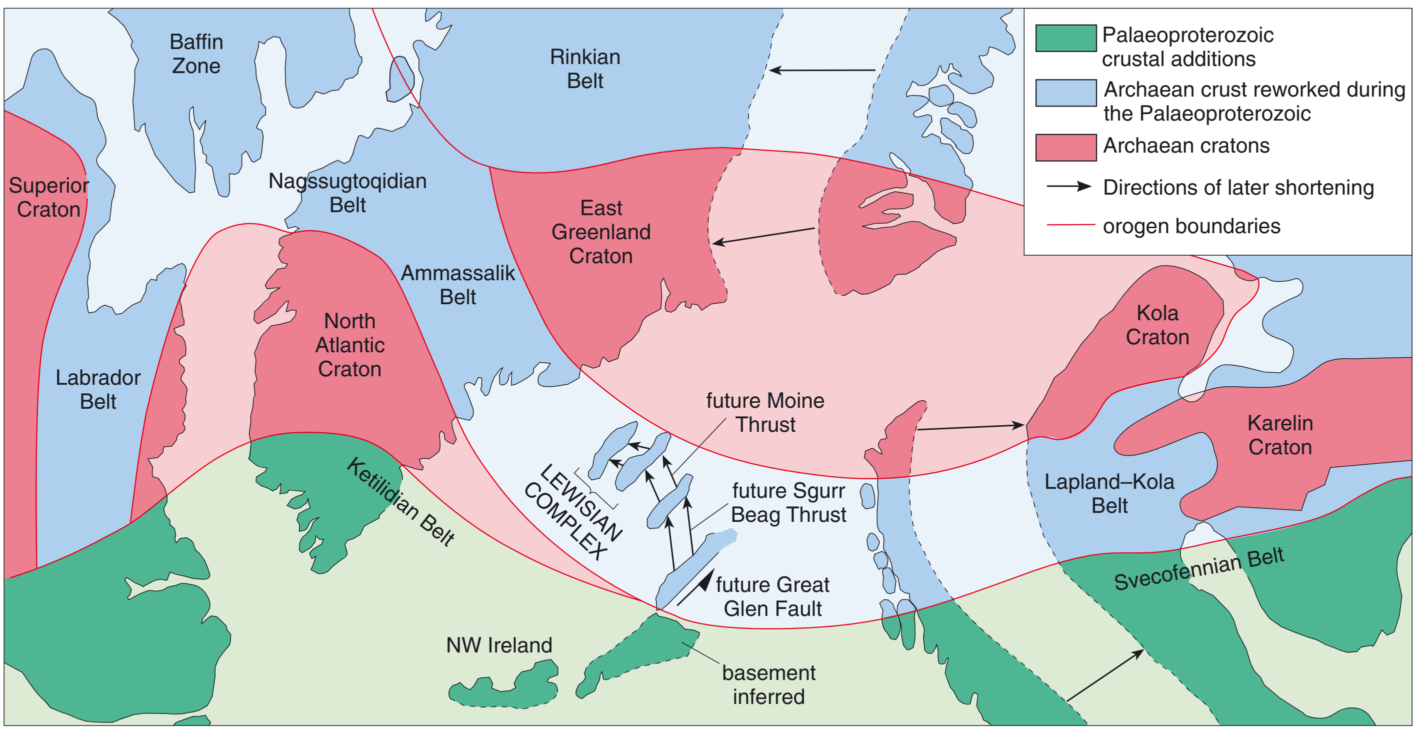


Figure 3.10 Reconstruction of the Palaeoproterozoic orogenic belts and Archaean cratons of the North Atlantic region.

This belt comprises mainly Archaean rocks that were deformed and metamorphosed at *c.* 1900–1800 Ma. Crustal thickening and metamorphism are thought to have resulted from the collision of the various continental blocks, which followed oceanic closure by subduction. The convergence of continental blocks between *c.* 1900 Ma and *c.* 1600 Ma resulted in the formation of a broadly continuous continent that included Laurentia and Baltica. A major subduction zone developed along the southern margin of this supercontinent and led to the formation of juvenile Palaeoproterozoic materials between *c.* 1900 and *c.* 1600 Ma. This event is correlated with the Ketilidian Belt of Greenland and the Svecofennian Belt of Scandinavia (Figure 3.10).

3.5 Mesoproterozoic events

In the British Isles there is only rather isolated evidence for Mesoproterozoic events. The supercontinent that was assembled in the Palaeoproterozoic by the amalgamation of Archaean terranes is thought to have existed until *c.* 1400–1300 Ma. A limited record of Mesoproterozoic sedimentation provides evidence of extension and rifting, whereas basement inliers of metamorphic rocks give glimpses of the late Mesoproterozoic Grenville Orogeny *c.* 1100–1000 Ma.

3.5.1 Mesoproterozoic rifting: deposition of the Stoer Group

The Stoer Group outcrops in north-west Scotland (Figure 3.3b) and is a sequence of continental sedimentary rocks comprising aeolian, fluvial and deltaic deposits. They rest unconformably on the Lewisian Complex and fill an eroded Lewisian landscape (Figure 3.11).

Figure 3.11 Basal unconformity (white line) of the Stoer Group with breccio-conglomerates resting on Lewisian gneisses (lower left), Clachtoll graveyard, north-west Scotland.

Basal conglomerates with Lewisian-derived clasts pass upwards into cross-bedded sandstones which are intercalated with aeolian sandstones. Palaeocurrents indicate both an easterly and westerly derivation of these sediments, and an age for diagenesis of *c.* 1199 Ma has been obtained on limestones within the sequence. The presence of normal faults in the Lewisian basement, which were active at the time of sedimentation, suggest that deposition of the Stoer Group was linked to major rifting during crustal stretching. On a broader scale, it has been suggested that these events may be linked to a major phase of crustal extension that led to rifting apart of Baltica from Laurentia at this time.

3.5.2 The Grenville Orogeny

On a global scale, the Mesoproterozoic Grenville Orogeny resulted from plate convergence associated with the formation of a major Mesoproterozoic supercontinent called Rodinia. Evidence for the Grenville Orogeny, most of which is preserved in Canada, is provided by exposures from the basement rocks in the Glenelg inlier of north-west Scotland and the Annagh Gneiss Complex of north-west Ireland. Rocks of the Glenelg inlier (for location see Figure 3.3b) occur in fault-bounded contact with rocks of the Neoproterozoic Moine Supergroup (described in Section 3.6.2). The basement gneisses and mafic inclusions, thought to have been dykes or sills, contain relicts of high-pressure eclogite-facies mineral assemblages metamorphosed at 750 ± 25 °C and *c.* 1600 MPa. These conditions correspond to depths of *c.* 55 km (Figure 2.6) and can only have been achieved as a result of considerable crustal thickening during collisional orogeny resulting from plate convergence. Isotopic dating of metamorphic minerals has given an age of *c.* 1110–1082 Ma for this event, corresponding to the Mesoproterozoic Grenville Orogeny. Additional evidence for Grenvillian events is provided by ages of *c.* 1100–1000 Ma obtained from syn-tectonic granites that intrude the Annagh Gneiss Complex (Figure 3.9). Indirect evidence for the extent of possible Grenville-age rocks south-east of the Highland Boundary Fault (Figure 3.3a) comes from fragments of deep crustal rocks that were brought to the surface by Carboniferous volcanic activity in the Midland Valley. Certain of the volcanic vents contain granulite-facies blocks that have given ages of *c.* 1100–1000 Ma, coincident with the timing of Grenville orogenic crustal thickening

3.6 Neoproterozoic events

The period from *c.* 1000 Ma to *c.* 800 Ma was dominated by the accumulation of thick sedimentary sequences (the Sleat and Torridon Groups) in extensive basins. The sediments were derived from the erosion of the Grenville mountain belt. In the Northern and Central Highlands, crustal or lithospheric extension at this time culminated in the emplacement of bimodal (mafic and felsic) magmatic suites at *c.* 870 Ma, and was brought to an end by the Knoydartian Orogeny at *c.* 840–780 Ma.

3.6.1 Early Neoproterozoic continental sedimentation: the Sleat and Torridon Groups

Early Neoproterozoic continental sedimentation is represented by the Sleat and Torridon Groups (sometimes referred to informally as the Torridonian), which outcrop along the north-western seaboard of Scotland (Figure 3.3b). The oldest rocks belong to the Sleat Group and comprise *c.* 3.5 km of coarse-grained fluvial and deltaic sandstones with minor marine and lacustrine deposits. Although the base is unexposed, the Sleat Group is thought to lie unconformably on the Lewisian basement. The Sleat Group passes transitionally upwards into the overlying red arkosic sandstones of the Torridon Group.

The Torridon Group overlaps the underlying Stoer Group and in places rests unconformably on an eroded Lewisian landscape with *c.* 600 m of topography. The lowest formation, the Diabeg, is a succession of red breccias, grey sandstones and shales, deposited in an alluvial fan environment. The uppermost Torridon formations (the Applecross and Aultbea Formations) comprise coarse clastic sandstones and were deposited from major alluvial braided-river systems that prograded eastwards. The petrology of the clasts within the Torridon Group suggests that they were derived from the erosion of Lewisian gneisses and supracrustal rocks. The youngest date obtained from detrital zircons from the

Applecross Formation is *c.* 1060 Ma, so this constrains the maximum depositional age of this Formation. Furthermore, Rb–Sr ages from the Diabeg and Applecross Formations are interpreted to date diagenesis at *c.* 994 Ma and *c.* 977 Ma respectively. Data from detrital minerals also indicate a distal source that comprised remnants of Archaean to Mesoproterozic basement rocks that had been affected by high-grade Grenvillian metamorphism. These data confirm a post-*c.* 1100 Ma depositional age for the Torridon Group.

3.6.2 Early Neoproterozoic marine sedimentation: the Moine Supergroup

The Moine Supergroup is a thick succession of strongly deformed and metamorphosed siltstones, mudstones and sandstones that outcrop extensively between the Moine Thrust and the Great Glen Fault (Figure 3.3b). The Moine Supergroup was deposited unconformably on *c.* 2800 Ma Archaean basement gneisses, which occur as infolded and tectonically interleaved inliers within Moine rocks as a result of extensive Caledonian tectonism (Figure. 3.3b). An upper age limit for deposition (*c.* 1000 Ma) is provided by the age of the youngest detrital minerals dated so far. A lower age limit is provided by the age of the oldest igneous rocks that intrude the sediments (*c.* 873 Ma, see Section 3.6.4).

The Moine Supergroup is subdivided into the Morar, Glenfinnan and Loch Eil Groups. The Morar and Loch Eil Groups are shallow marine sediments that were probably deposited in NNE–SSW-trending half grabens that were bounded by major ESE-dipping faults (Figure 3.12).

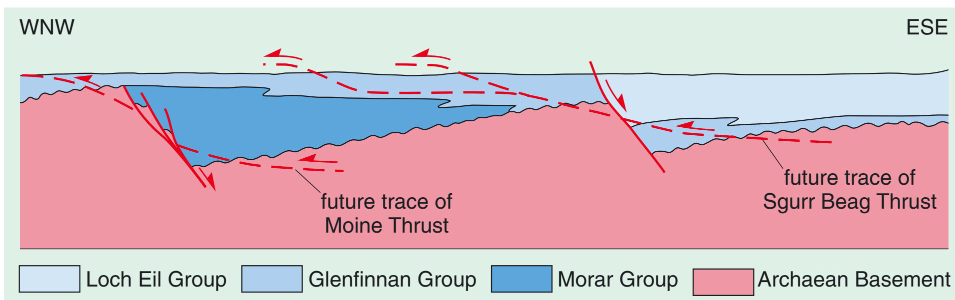


Figure 3.12 Schematic illustration of the original stratigraphic relationship of the Moine Supergroup basins. The positions of the major Caledonian thrusts that subsequently dissected the basins are shown.

Palaeocurrent data suggest that the basins were sourced from the south. Early rift sedimentation in the Morar Group may have been followed by transgressive deposition of the Glenfinnan Group. The Loch Eil Group conformably overlies the Glenfinnan Group and its asymmetric facies distribution and westward thickening of sediments in half grabens suggests a return to more active rifting. Amphibolites in the Loch Eil and Glenfinnan Groups are thought to represent basic igneous rocks intruded during rifting.

Provenance studies reveal that detrital zircons from Moine metasediments have ages ranging from *c.* 1900 Ma to *c.* 1000 Ma, precluding derivation from the Archaean Lewisian Complex. Taking the age data together with sedimentary structures in the Moine metasediments that indicate sediment transport from the south, the Palaeo- and Mesoproterozoic rocks of the Rhinns and Annagh Complexes are one possible source.

There has been much debate over whether or not the Torridonian and Moine rocks were deposited as continental and marine sequences in the same basin. Although isotopic constraints on the Sleat and Torridon Groups and the Moine Supergroup indicate that they are time equivalent (Figure 3.1), the rather different source regions, as indicated by the detrital mineral suites, suggest that they may have been deposited in separate basins.

3.6.3 The Dava and Glen Banchor Successions

The Dava and Glen Banchor Successions (formerly the Central Highland Migmatite Complex) are a sequence of psammites and pelites that outcrop south-east of the Great Glen Fault (Figure 3.3b). The rocks strongly resemble part of the Moine Supergroup and have been correlated by some workers. The detrital zircon ages are similar to those from the Moine Supergroup, which suggests that the sediments were derived from a similar source region. A radiometric age of *c.* 840 Ma obtained from the migmatitic gneisses is interpreted as dating metamorphism (discussed in Section 3.6.5), so it only provides a minimum age of deposition. These rocks are therefore probably Neoproterozoic in age, and as such may be a possible time equivalent of the Moine Supergroup (Figure 3.1).

3.6.4 Extension-related magmatism

A suite of deformed and metamorphosed granitic bodies, collectively termed the West Highland Granitic Gneisses, intrude the Moine Supergroup (Figure. 3.3b). These granites are thought to have been formed as a result of partial melting of Moine rocks at a deeper crustal level, and recent isotopic dating of several of these bodies indicates an age of *c.* 873 Ma for their emplacement. The granites are cut by a series of metagabbros which have yielded similar ages (*c.* 873 Ma). The metagabbros are spatially related to a regional suite of MORB-type metadolerites, and these basaltic rocks were thought to have been emplaced during regional extension. The mafic magmas may have provided the heat source necessary to melt the Moine rocks and generate the granitic gneisses.

3.6.5 Evidence for a Neoproterozoic (Knoydartian) Orogeny?

A growing body of isotopic-dating evidence now points to the existence of a major orogenic episode in the Neoproterozoic, an event referred to as the Knoydartian Orogeny. The Moine Supergroup is widely veined by pegmatites (Figure 3.13), with isotopic dating yielding an age range of *c.* 827–780 Ma. Field relations indicate that these pegmatites were emplaced during regional ductile deformation and metamorphism.

Figure 3.13 Deformed and folded granitic pegmatite within Moine metasediments, Morar Peninsula, north-west Scotland.

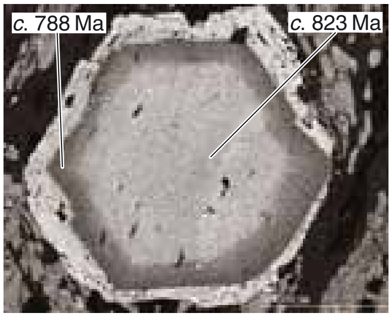


Figure 3.14 Chemical zoning of garnet from the Morar Peninsula, Scotland, is shown in this X-ray map obtained using a scanning electron microscope. Calcium concentration is depicted on a grey scale: pale denotes high concentration, dark denotes low concentration. The garnet shows three chemical zones which clearly indicate a well-formed garnet that is overgrown by a later high-Ca ragged rim. The high-Ca inner cores have given ages of *c.* 823 Ma whereas the low-Ca outer cores gave *c.* 788 Ma. The high-Ca garnet overgrowth is probably related to a later phase of garnet growth during the Caledonian Orogeny. Width of image *c.* 1 cm.

In addition, garnets from Morar Group metasediments have been dated by isotopic methods. Radiometric dating of the cores of garnet crystals that show multiple growth phases indicated initial growth at *c.* 823 Ma, whereas the rims yielded *c.* 788 Ma (Figure 3.14), implying that garnet growth lasted some 35 million years. Conditions of metamorphism at the time of garnet rim growth have been estimated at 1000–1200 MPa and 575–625 °C. These metamorphic conditions could not have been produced by crustal extension and are therefore linked to a significant crustal thickening event, the Knoydartian Orogeny.

To the south-east of the Great Glen Fault, in the Dava and Glen Banchor Successions, radiometric ages obtained on zircons from the metasediments are interpreted as dating partial melting and migmatite formation at *c.* 840 Ma. The migmatites were subsequently deformed in a series of ductile shear zones collectively known as the Grampian Shear Zone (Figure 3.3b). Some of the shear zones incorporate syn-tectonic granitic pegmatites and veins; the ages of the shear zones are considered to be *c.* 806 Ma, based on the dating of monazite that crystallized during metamorphism. These ages therefore record pegmatite crystallization and metamorphic mineral growth. The Dava and Glen Banchor Successions are unconformably overlain by rocks of the Dalradian Supergroup (the subject of Section 4) which show no evidence of having been affected by the deformation and metamorphic events that are assigned to the Knoydartian event.

From the available evidence it is concluded that the Moine Supergroup and Dava and Glen Banchor Successions were deformed and metamorphosed during the Knoydartian Orogeny at *c.* 840–780 Ma. Although there is mounting evidence for the Knoydartian Orogeny, it is a good example of an orogenic episode for which there is only fragmentary evidence. As such, its broader geological significance is uncertain at present.

3.7 Summary of Section 3

- The Proterozoic *c.* 2500–750 Ma evolution of Britain and Ireland was characterized by periods of rifting and extension, and episodes of plate convergence and collision.
- Periodic crustal extension led to the accumulation of thick sedimentary successions in rift-related basins. On a larger scale, extreme extension led to rupturing of the crust, the intrusion of dyke swarms and formation of oceanic crust. These periods are linked to separation and eventual break-up of major continental masses (supercontinents).
- Plate convergence and collision led to the closure of ocean basins, the assembly of continental masses by terrane accretion and crustal growth by magma addition at subduction zones.
- During collision, rock units were subjected to intense deformation and the resulting crustal thickening led to regional metamorphism.