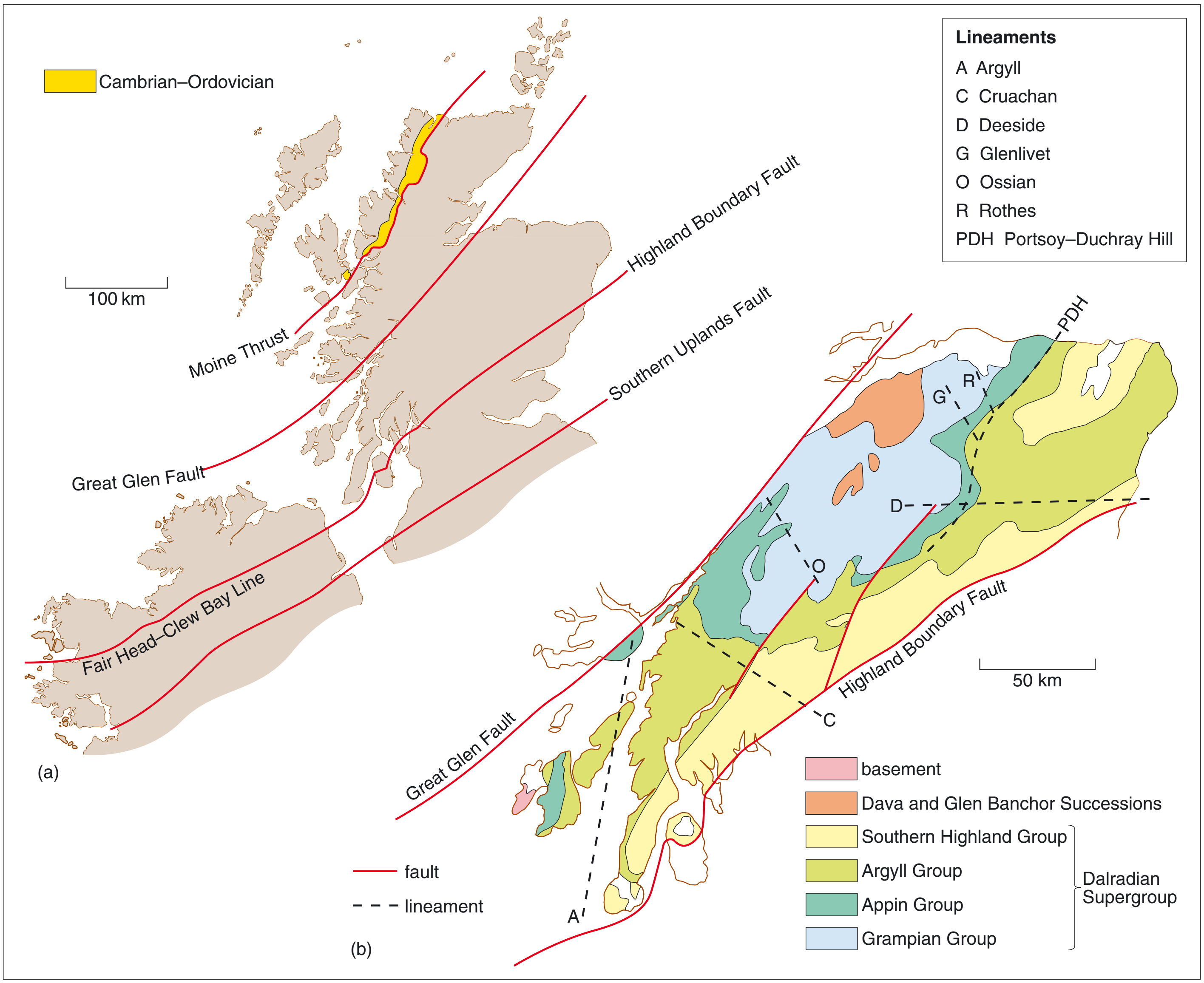
4 Continental break up and opening of the Iapetus Ocean

4.1 Introduction

In the period from *c*. 2500–750 Ma, plate collisions led to the formation of a series of supercontinents which periodically broke up to form large oceanic basins. By *c*. 750 Ma, the main continental blocks were once again amalgamated, forming the Vendian supercontinent. Subsequently, the Vendian supercontinent split apart into the smaller continental masses of Laurentia, Baltica and Gondwana, a process which led to the formation of the Iapetus Ocean (Figure 1.5). During this period, extensive sedimentary deposits accumulated on the passive continental margins until extension and rifting were brought to an end by the early Palaeozoic Caledonian Orogeny.

This Section presents the evidence for a prolonged period of extension, rifting and sedimentation along the margin of the continent of Laurentia that lasted from *c*. 800 Ma into early Ordovician times. Firstly, we describe the evolution of the Dalradian Supergroup, a late Neoproterozoic to early Ordovician sedimentary succession that was extensively metamorphosed during the Caledonian Orogeny and is now exposed in the Grampian Highlands. Secondly, we describe the Cambrian–Ordovician sedimentary succession that is exposed in the Hebridean Terrane.

Figure 4.1 (a) Outcrop distribution of Cambrian–Ordovician sedimentary rocks of the Caledonian Foreland. (b) Simplified outcrop map of the Dalradian rocks of Scotland. The lineaments are major structural features that were active during Dalradian sedimentation.



4.2 The Dalradian Supergroup

The Dalradian Supergroup is found between the Great Glen Fault and the Highland Boundary Fault. The main outcrop pattern is controlled by the location of major folds and ductile faults or shear zones, known as slides, and also by the amount of post-folding uplift that occurred near the end of the Caledonian Orogeny. Late post-orogenic brittle faults have displaced boundaries, often by tens of kilometres. In the central Grampian region, a series of NE–SW-trending faults with significant sinistral displacements offset the regional pattern, and significant vertical displacements occurred along several transverse NW–SE-trending faults. Fortuitously for geologists, this pattern reveals a wide range of exposure levels.

4.2.1 Dalradian sedimentary basins: seeing through metamorphism

Despite complex deformation and metamorphism during the Caledonian Orogeny, the sedimentary evolution and pre-Iapetan context of the Dalradian basin have been established. The intensity of Caledonian metamorphism and deformation varies across the Grampian Highlands, but in areas of low metamorphic grade, sedimentological studies have revealed much about the palaeogeography and the nature and origin of the sedimentary sequences. Furthermore, petrological and chemical studies of contemporaneous igneous rocks have provided additional constraints on tectonic settings. In areas of high metamorphic grade, the original sedimentary nature of the rocks has been more difficult to establish because recrystallization and deformation have partly destroyed the sedimentological evidence. Despite this, some rock types such as psammites (metamorphosed muddy sandstones) and quartzites retain evidence of primary sedimentary structures (Figure 4.2), whereas coarse recrystallization and mineral growth has eradicated all such evidence from pelitic and semipelitic lithologies (metamorphosed mudstones and sandy mudstones). As a result, studies of the evolution of the Dalradian Supergroup are based on large-scale approaches to sedimentation and basin evolution.

Figure 4.2 Grampian Group quartzites, in the A9 road cutting at Clunes, 20 km north-west of Pitlochry. The cross-stratification demonstrates that these sediments are the right way up.

4.2.2 Primary rock types and terminology

The Dalradian Supergroup is a metamorphosed succession of clastic sediments (marine sandstones, siltstones, and mudstones) and limestones with some volcanic rocks. The names used to describe individual units depend on metamorphic grade. To describe rocks of low metamorphic grade, many sedimentary rock terms are used (e.g. sandstone, siltstone) whereas, as metamorphic grade increases, metamorphic terms (e.g. pelite, semipelite, psammite and quartzite) are used to indicate the original composition of the sediment. To these, some textural terms have been added (e.g. slate, phyllite, schist or gneiss). The metamorphosed carbonate rocks are referred to as limestones, dolomites or dolostones. Metamorphosed igneous rocks are classified, where possible, on the basis of their non-metamorphosed equivalents (e.g. metabasalt, metagabbro). Where the non-metamorphosed equivalent cannot be identified, the term amphibolite, hornblende schist or gneiss is often used.

4.2.3 Lithostratigraphic subdivisions of the Dalradian Supergroup

The total thickness of the Dalradian succession is difficult to work out as it has been tectonically thickened and thinned by later orogenesis. There is also no continuous section. Piecing all the evidence together, it has been estimated that the Dalradian succession is at least 25 km thick. As with other major sedimentary successions, the Dalradian Supergroup is divided on the basis of a hierarchy of scales, which are, from largest to smallest, Group, Subgroup and Formation. Hence the Dalradian Supergroup is subdivided into the Grampian, Appin, Argyll and Southern Highland Groups (Figure 4.3).

In most parts of the Dalradian Supergroup a consistent stratigraphy has been established on the basis of distinctive lithologies and lithological associations cropping out in a consistent order, as determined from sedimentary and igneous way-up structures. However, problems arise where rapid lateral sedimentary facies changes and tectonic complexity occur, such as where very high tectonic strains excise or severely attenuate parts of the succession. Because of such difficulties, widespread correlation at Formation level across the Dalradian basin is not reliable. Correlation at Group level is based on distinctive and key lithologies that have been recognized and traced throughout the Grampian Highlands and into Ireland and Shetland, a distance of up to *c*. 700 km. These distinctive lithologies are thought to represent regionally significant changes in the evolution of the basin. Correlation at Subgroup level has been successful in some areas.

4.3 Dalradian sedimentation and tectonics

Reconstructing the geological evolution of the Dalradian basin depends on studies of the Dalradian sedimentary succession, so this Section provides an overview of the key stratigraphic observations upon which the synthesis given in Section 4.4 relies.

The Grampian Group is mainly composed of micaceous to quartzose psammites and semipelites (7–8 km thick). The lowermost Glenshirra Subgroup consists of psammites and metaconglomerates. Sedimentary structures in these rocks indicate deposition in shallow marine environments, and the progressive westward thickening and coarsening of strata indicate deposition possibly adjacent to the basin margin. The onset of widespread extension and rifting led to basin deepening and the influx of turbiditic sandstones of the Corrieyairick Subgroup. Lateral facies changes and thickness variations point to the existence of a series of NE–SW-trending major syn-sedimentary faults (Figure 4.4a,b).

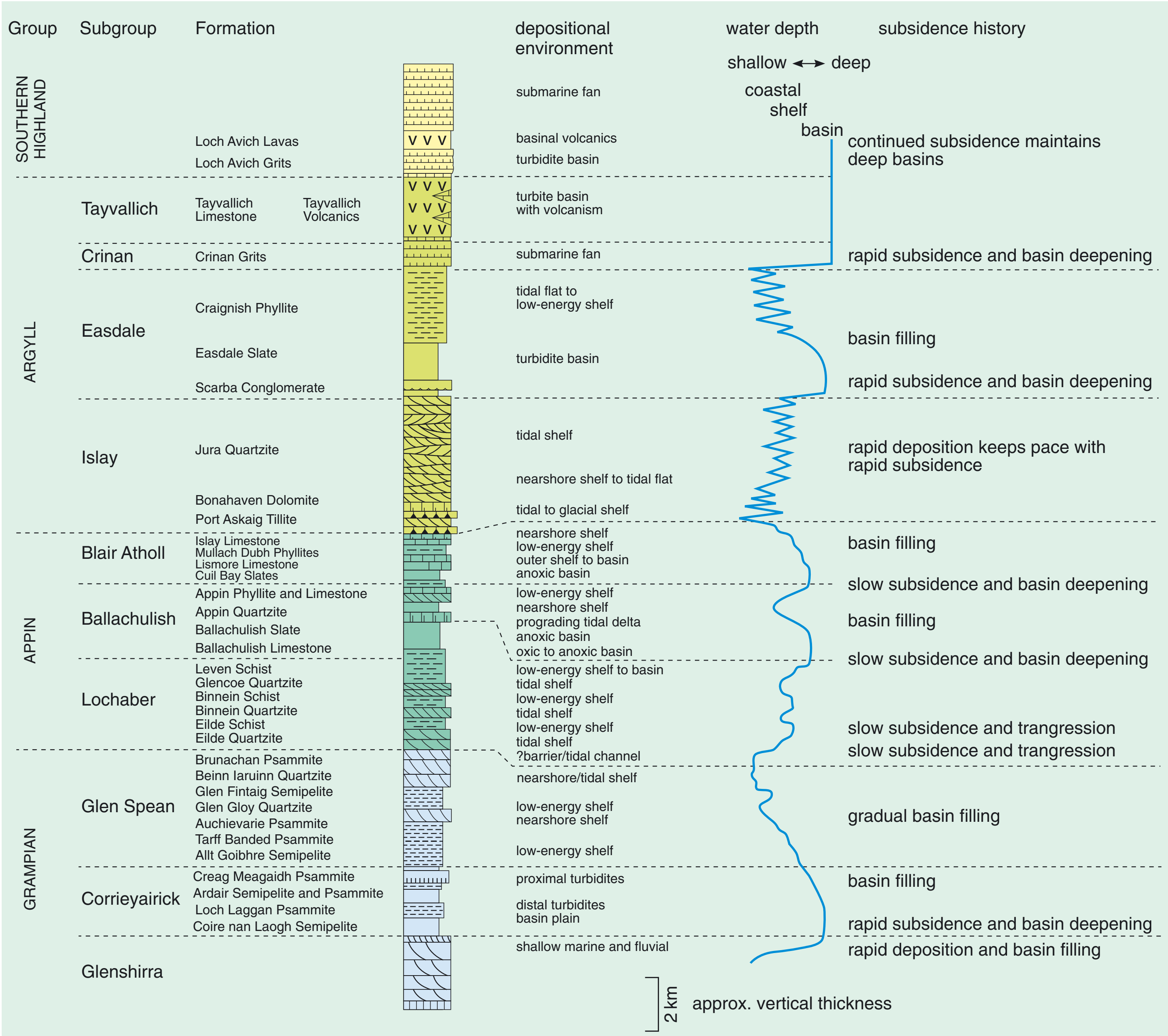


Figure 4.3 Dalradian stratigraphy and sedimentary evolution, based on successions from the western Central Highlands. Chronostratigraphic division of the Dalradian is discussed in Section 4.5.

The overlying semipelites, psammites and quartzites of the Glen Spean Subgroup are interpreted to represent SE-prograding deltaic and shallow marine tidal sequences (Figure 4.4b). The overstep onto older strata constrains the basin margins and is related to intrabasinal structural highs that were active and uplifting during Grampian and early Appin Group times (Figure 4.4c).

Quartzites, limestones, pelites and semipelites belonging to the Appin Group were deposited on a marine shelf. Sediments of the lowermost parts of the Lochaber Subgroup are interfingered with those of the Grampian Group as a result of renewed marine transgression, such that the Appin Group has a transitional base. Sedimentary structures indicate deposition on a periodically emergent tidal shelf, and SW to NE sedimentary influx. The upper parts of the Appin Group, the Ballachulish and Blair Atholl Subgroups, are dominated by extensive offshore carbonates and anoxic mudstones – sequences that point to a period of low sediment supply and basin widening. The top of the Appin Group, the Islay Limestone, indicates a return to shallow intertidal deposition, and sedimentary structures indicate a warm arid environment. Rapid lateral facies changes in the upper part of the Appin Group imply syn-depositional faulting

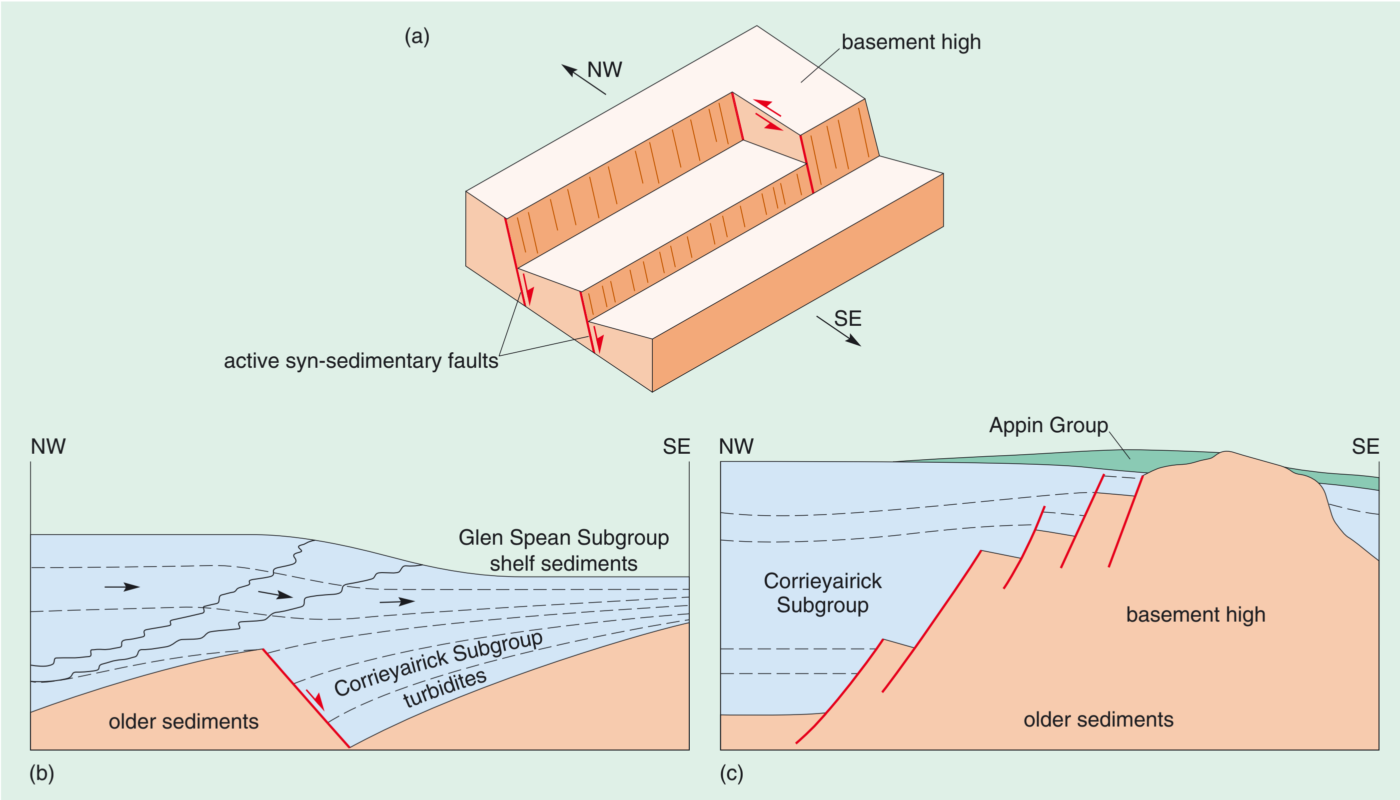


Figure 4.4 Schematic summary of basin evolution during deposition of the Grampian Group in Scotland. (a) Basement configuration as indicated by variations in facies thickness. (b) Syn-rift deposition of the Corrieyairick Subgroup produced thickness variations. Arrows show the progradation of post-rift deposits of the Glen Spean Subgroup. (c) Sedimentation against an intrabasinal structural high in Grampian times. The older sediments are those of the Dava and Glen Banchor Successions. Note that the faults on the margin of the high were active at different times during sedimentation.

and the development of half-graben basins that accommodated the deposition of these essentially shallow-water deposits (Figure 4.5). Palaeocurrent data and lateral thickness variations suggest SW to NE sedimentary influx into a series of NE–SW-trending basins during a phase of more active rifting.

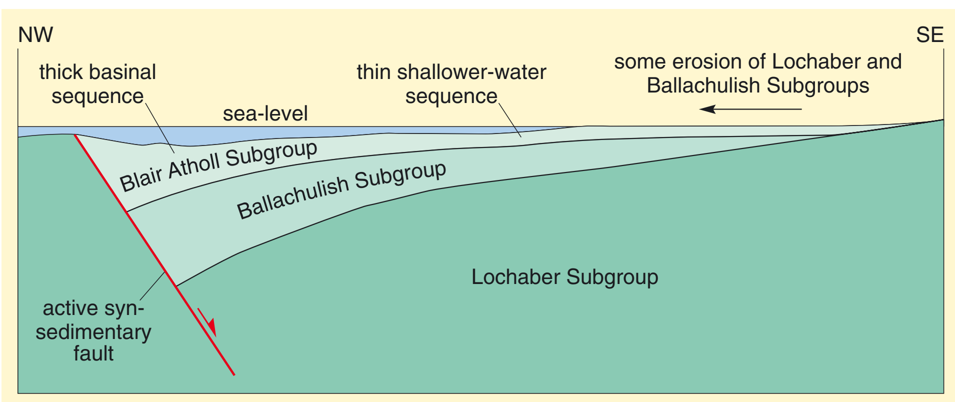


Figure 4.5 Syn-rift sedimentation and basin evolution during the deposition of the upper Appin Group. Note the thinning of facies and erosion of lower Subgroups on the rift shoulders indicating they were active and uplifting during deposition.

The base of the Argyll Group is marked by a marine tillite, or boulder bed deposit – the Port Askaig Tillite (correlated with the Schiehallion Boulder Bed in Perthshire). The sediments comprise *c*. 750 m thickness of sandstones, conglomerates, dolostones, siltstones and numerous boulder beds (diamictites).

The boulder beds were either deposited from grounded ice sheets, or, given the presence of dropstones, were derived from floating ice (Figure 4.6).

Figure 4.6 Diamictite from the Port Askaig Tillite, Garvellach Islands.

The overlying Bonahaven Dolomite indicates a return to warmer conditions. The Jura Quartzite represents a marine transgression heralded by the influx of thick (*c*. 5 km) tidal-shelf sands. Thick conglomerates, turbidites and muds of the Easdale Subgroup marked the initiation of shelf deepening, due to rapid crustal stretching. Sharp lateral thickness variations were caused by deposition of sediment in a series of fault-controlled NE–SW-trending basins. Intrabasinal structural highs are marked by local thinning, lateral facies changes and erosion or non-deposition of sediments. These highs correspond to long-lasting NW–SE- and NE–SW-trending lineaments. Regional crustal extension in the deep basins allowed seawater to penetrate down reactivated faults, leaching underlying sediments through the creation of hydrothermal convection cells and forming brines containing barium and base metals. Where the mineral-rich brines came to the surface and ponded on the sea-floor, barium and base-metal mineral deposits such as those found at Foss, near Aberfeldy, in Perthshire (a major source of the mineral barytes) were formed. The deep-water basins eventually filled, and shallower-water conditions returned. Renewed rapid subsidence is indicated by the turbidite fan deposits of the Crinan Grits. The uppermost part of the Argyll Group, the Tayvallich Subgroup, includes the Tayvallich Volcanics, which comprise pillow basalts and volcanic ashes interbedded with deep-water turbiditic limestones and pelites, and cross-cut by basic sills and dykes. Sedimentary structures indicate that the sediments were wet at the time of dyke intrusion. The Tayvallich Volcanics are mostly tholeiitic in composition and probably resulted from mantle melting during crustal rifting.

The north-eastern limit of abundant volcanism coincides with a major NW–SE-oriented structure known as the Cruachan lineament (for location, see Figure 4.1). The Cruachan lineament is thought to correspond to a major structure in the basement that is transverse to the main structural trend. On the basis that many of the basic dykes on Jura have a NW–SE trend, implying NE–SW extension, it has been suggested that the Cruachan lineament bounds a pull-apart basin that developed as a result of transtension (Figure 4.7).

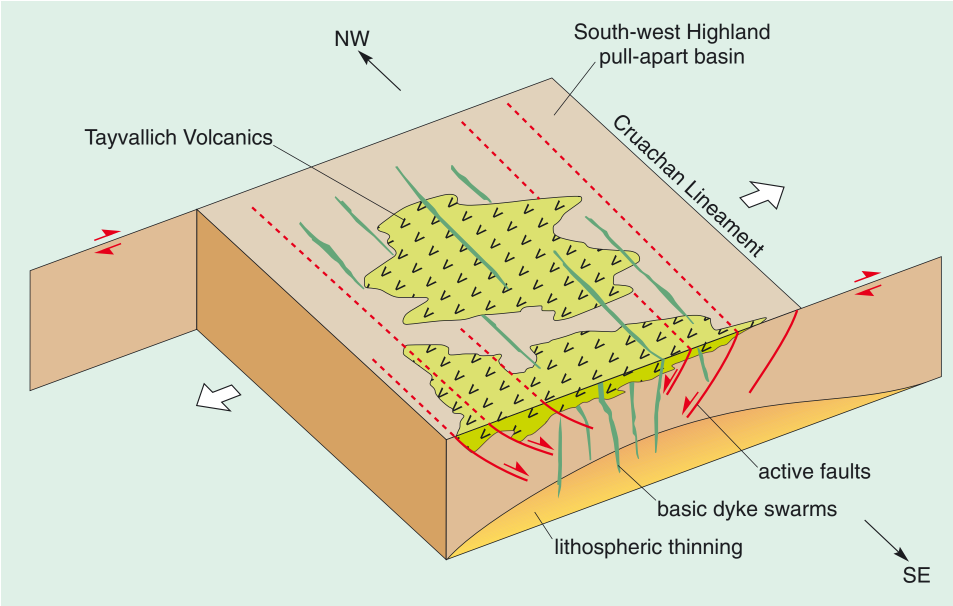


Figure 4.7 Schematic illustration of the South-west Highland pull-apart basin active during late Argyll times.

The Southern Highland Group marks the top of the exposed Dalradian succession and consists mainly of mudstones, sandstones and grits. These clastic sediments are interbedded with basic volcanics – in the form of pillow basalts and 'green beds' that are thought to represent volcaniclastic deposits – and deep-water trilobite-bearing limestones and mudstones. The clastic sediments are interpreted as submarine fans and indicate a return to rapid basin deepening. The Southern Highland Group sediments were deposited on an outer continental margin.

4.4 Dalradian basin evolution

The lithostratigraphic, sedimentological and tectonic studies described in the previous Section revealed periods of basin deepening and shallowing that corresponded to phases of lithospheric stretching, rifting and subsidence. Faulting related to lithospheric stretching has been recognized as the principal control on sedimentation. It is envisaged that a series of SE-dipping fault blocks, bounded by normal faults, delimited individual basins on the continental shelf, exerting a direct impact on the shape and form of the sedimentary pile. In addition, the transverse structures termed lineaments (Figure 4.1), which have been identified on the basis of geophysical, stratigraphic and structural data, are also thought to have played a significant role. Major changes in Dalradian stratigraphy across some of these structures indicate that they had an influential control on sedimentation, as well as forming a focus for later Caledonian deformation and magmatism. The interpretation of these transverse structures as representing the site of pull-apart basins indicates that rifting may not have been simply a response to NW–SE extension.

The Dalradian Supergroup represents a segment of a significantly more extensive continental shelf sedimentary succession (Figure 4.8). Sedimentation initiated in a broad rift, floored by continental crust, that propagated north-eastwards to form a marine gulf. The Grampian and Appin Groups were deposited on a passive continental shelf on the north-west side of the rift. Continued extension and widening deepened the rift during deposition of the Argyll Group. The appearance of large volumes of volcanic material towards the

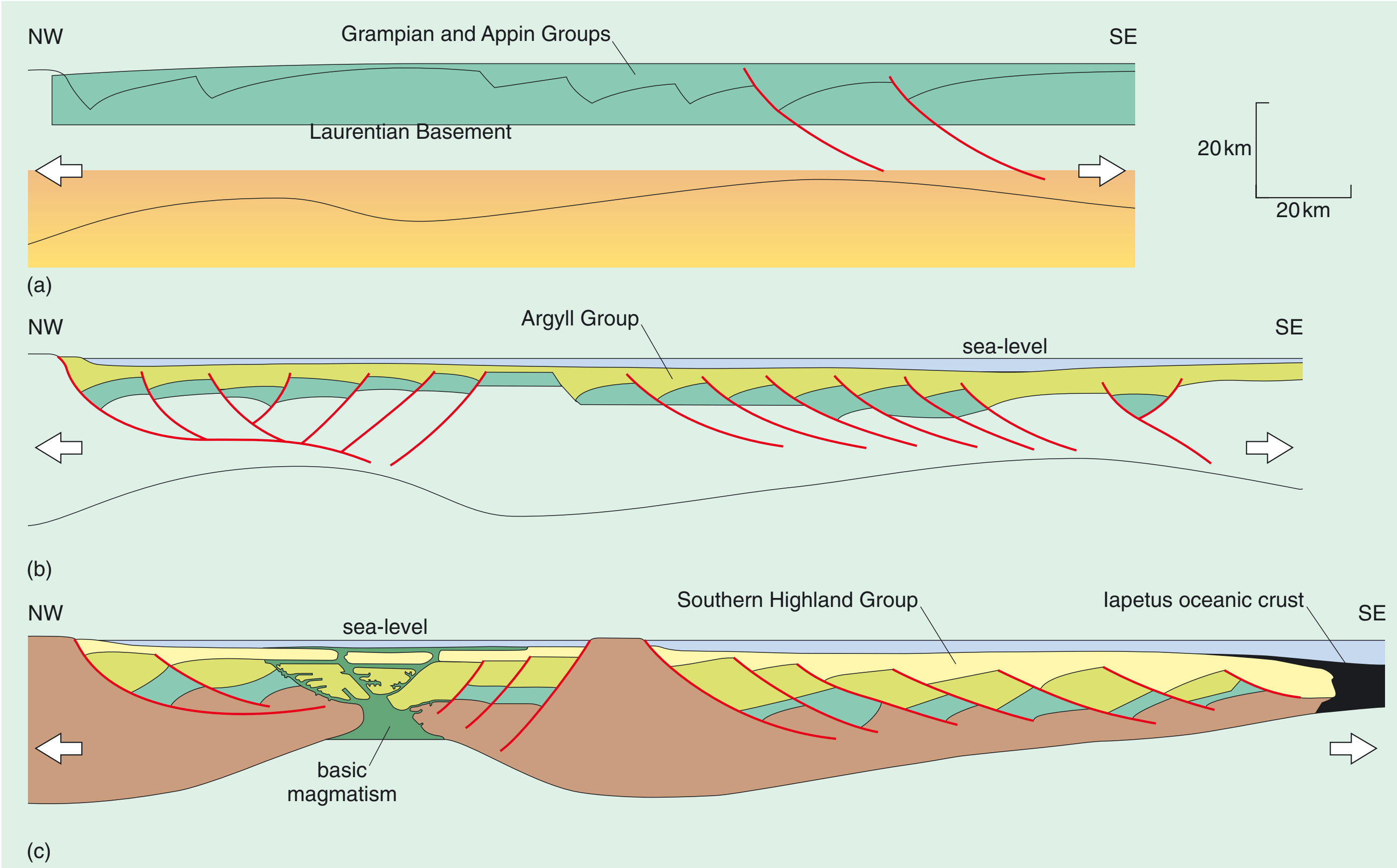


Figure 4.8 Schematic cross-sections showing the progressive development of the rifted Laurentian margin in Scotland in (a) late Appin Group times; (b) Argyll Group times; and (c) Southern Highland Group times.

top of the Argyll Group was associated with lithospheric thinning and rupturing of the continental crust. Volcanic activity continued during the deposition of the Southern Highland Group; this occurred on the rapidly subsiding continental margin which eventually broke up to form the Iapetus Ocean.

4.5 Age of the Dalradian Supergroup

The age of the Dalradian Supergroup is constrained by isotopic dating and occasional fossils, such that the essentially lithostratigraphic divisions of the Dalradian can be placed in a chronostratigraphic context as shown in Figure 4.9.

The lowermost part of the Dalradian is thought to onlap the older (>*c*. 840 Ma) metasediments of the Dava and Glen Banchor Successions. As we saw in Section 3.6.5, these metasediments were deformed and metamorphosed at *c*. 806 Ma, yet the Dalradian Supergroup shows no evidence of these events. These observations can only provide a maximum age of *c*. 806 Ma for deposition of the older parts of the Dalradian Supergroup (Grampian and Appin Groups).

The base of the Argyll Group is marked by the Port Askaig Tillite (Figure 4.9). A long-standing correlation of this important horizon with the *c*. 630–590 Ma Varangian tillites of Norway has recently been questioned, and on the basis of correlation with trends in global glaciations, a new age of *c*. 750–720 Ma (Sturtian) has been suggested. If this correlation is correct then the Loch na Cille Boulder Bed (Tayvallich Subgroup), which occurs near the top of the Argyll Group, must be significantly younger, and may therefore correlate with the *c*. 630–590 Ma Varangian tillites. Volcanics at the top of the Argyll Group (the Tayvallich Volcanics) provide better age constraints. An eruption age of

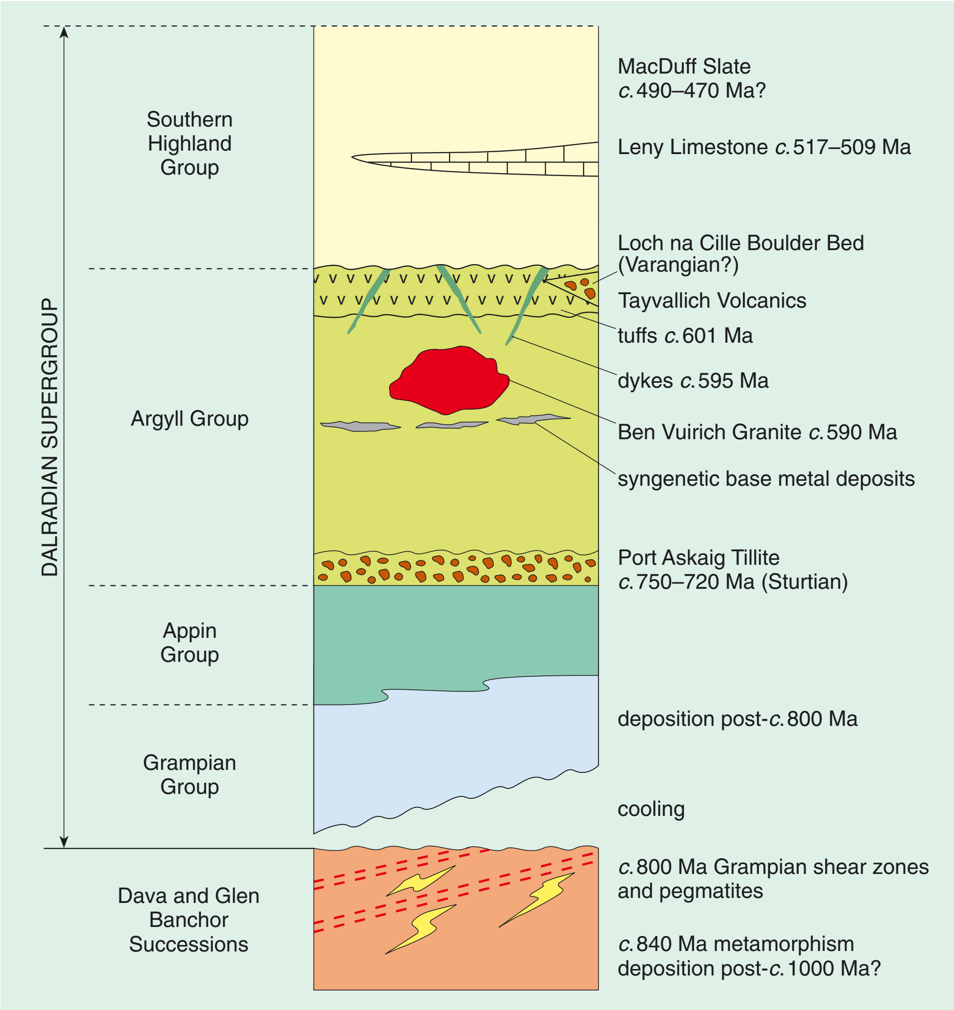


Figure 4.9 A simplified chronostratigraphy of the Dalradian Supergroup (not to scale).

c. 595 Ma has been obtained by dating zircons from a mafic dyke intrusive into the lavas, and a felsic tuff has yielded an age of *c*. 601 Ma. A further constraint is provided by the age of intrusion of the Ben Vuirich granite, dated by U–Pb methods on zircons at *c*. 590 Ma. The Ben Vuirich granite is one of several deformed and metamorphosed granites, collectively referred to as the Older Granites, which intrude Argyll Group sediments in the Pitlochry area. Structural studies of the Ben Vuirich granite have indicated that it was emplaced prior to regional orogenic (Grampian) deformation and metamorphism (described in Section 5). Given the overlap in the ages of the Older Granites and the Tayvallich Volcanics, it follows that granitic magmatism, basaltic volcanism and sedimentation must have been near-synchronous and occurred during continental rifting at *c*. 600–590 Ma. Taken together, these data indicate that the deposition of the Argyll Group spanned about 160 million years from *c*. 750–590 Ma.

Critical information on the biostratigraphic age of the highest preserved parts of the Southern Highland Group is provided by the presence of Early Cambrian trilobites, *c*. 517–509 Ma, within the Leny Limestone (found north of Callander). In north-east Scotland, in the Buchan area, the youngest sedimentary rocks of the Macduff Slate have yielded microfossils interpreted as Early Ordovician in age, although these identifications remain highly controversial and are not wholly accepted. If substantiated, these data would indicate that Dalradian sedimentation may have continued until *c*. 490–470 Ma.

Taking the available information at face value, it could be argued that the Dalradian Supergroup was deposited over a considerable time span (up to *c*. 330 million years) within the period from approximately 800 Ma to 470 Ma. However, a comparison of the Dalradian with well dated, better exposed and less deformed Neoproterozoic and Phanerozoic sedimentary basins, indicates that episodic rifting over such a considerable time span may be improbable. Moreover, it has been argued that the sedimentary facies represented in the lower part of the Dalradian (sub-Easdale Subgroup) are unlike those associated with extensional rifting, and are more akin to deposits formed in a convergent setting in foreland basins. It has also been suggested that several significant time gaps may exist in the succession, shedding some doubt on the validity of any model of continuous Dalradian deposition. Although at present controversial, the testing of these hypotheses and models, and the search for gaps in the Dalradian stratigraphy that may indicate major orogenic phases continues, and can only be achieved by detailed fieldwork in conjunction with integrated metamorphic and isotopic studies.

4.6 Cambrian–Ordovician shelf sedimentation in north-west Scotland

Cambrian–Ordovician sediments outcrop in a narrow belt immediately west of the Moine Thrust (Figure 4.1a). These rocks were deposited unconformably on the Lewisian Complex and Torridon Group; their present outcrop pattern is influenced by the effects of later deformation in the Moine Thrust Zone (Figure 4.10a). A restored cross-section indicates that the underlying Torridon Group lies in fault-bounded half-grabens that developed prior to deposition of the Cambrian succession (Figure 4.10b). The faults that bounded the half-grabens are thought to have developed in response to the late Neoproterozoic crustal extension which also generated the Dalradian sedimentary basins.

The Cambrian–Ordovician succession consists of a basal clastic sequence (250 m in thickness) that is overlain by over 1000 m of carbonates (Figure 4.11a). The succession overall records a marine transgression onto a stable shelf (Figure 4.11b).

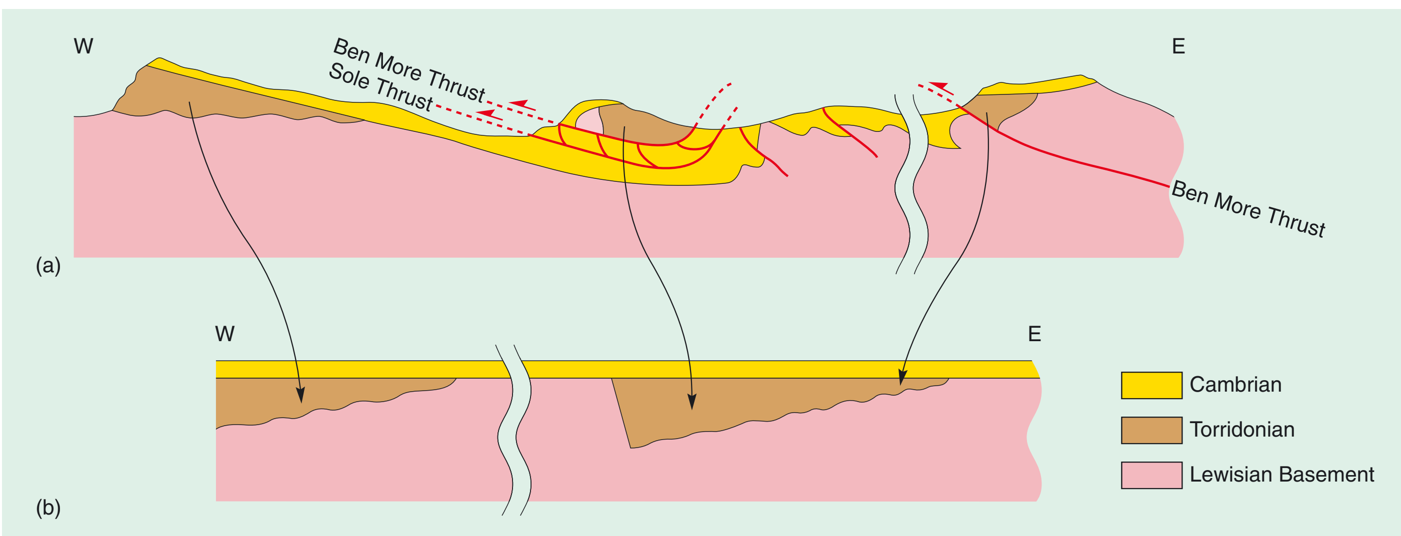


Figure 4.10 (a) Cross-section of the Caledonian Foreland and Moine Thrust Zone, from Canisp in the west to Ben More about 15 km to the east, in the Assynt area, north-west Scotland. (b) Restored cross-section showing Cambrian sediments deposited on a Lewisian and Torridonian surface.

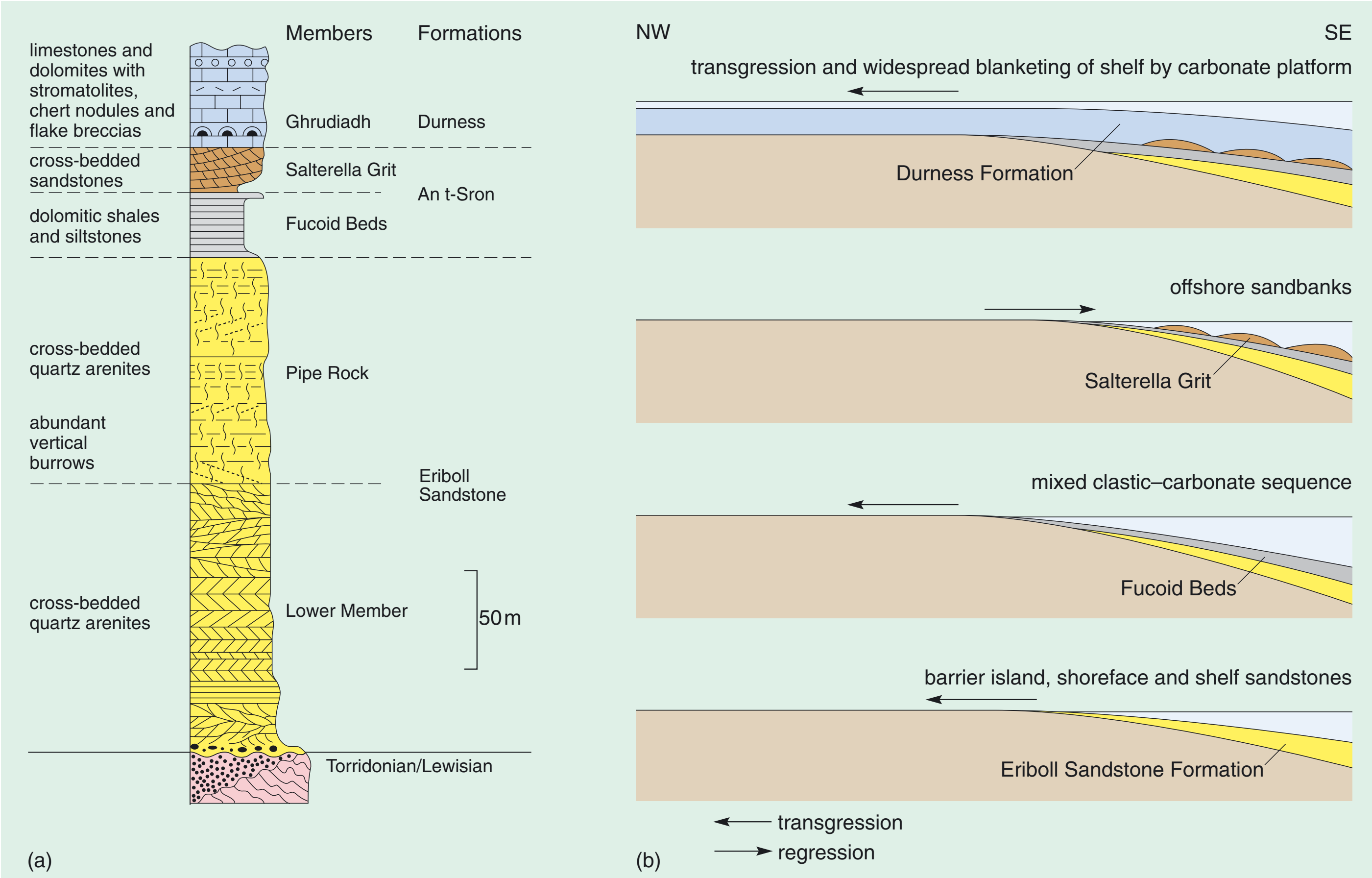


Figure 4.11 (a) Stratigraphy of the Cambrian–Ordovician of north-west Scotland. (b) Simplified sedimentary evolution of the Cambrian–Ordovician succession of north-west Scotland.

The lowermost part of the Eriboll Sandstone Formation comprises cross-bedded sandstones deposited in a barrier to tidal-shelf environment. The upper member, the Pipe Rock, gets its name from the abundant trace fossils formed as a result of pervasive burrowing of the sediment (*Skolithus* and *Monocraterion*) (Figure 4.12).

Figure 4.12 The upper member of the Eriboll Sandstone Formation, the Pipe Rock, showing distinctive burrows, Skaig Bridge, Loch Assynt shore. Scale indicated by coin.

The Eriboll Sandstone Formation is overlain by the An t-Sron Formation, comprising carbonate and clastic storm-dominated deposits (Fucoid Beds). Trilobites within this unit indicate an Early Cambrian age. The upper part (Salterella Grit) comprises coarse sandstones and grits that were probably deposited as offshore sandbanks during a short marine regression. Deposition of clastic sediments ceased and the platform was then swamped by a blanket of carbonates (the Durness Formation) that were deposited in a tidal flat to shallow subtidal environment. Rare fossils indicate an Early Ordovician age for these carbonates.

The shallow marine Cambrian–Ordovician succession of north-west Scotland developed contemporaneously with the deeper-water muds of the Southern Highland Group. It has been suggested that the shallow shelf conditions that existed in the early Dalradian trangressed north-westwards with time, as a result of continued rifting and a probable eustatic sea-level change.

4.7 Summary of Section 4

- Dalradian sedimentation occurred during a prolonged phase of lithospheric extension, lasting *c*. 330 million years (*c*. 800–470 Ma), which eventually led to formation of the Iapetus Ocean.
- The Grampian, Appin and Argyll Groups were deposited on a passive continental shelf. Progressive instability of the basin through time led to deposition of deeper-water facies. Sedimentation was controlled by the development of a series of NE–SW-oriented fault-bounded basins. Transverse structures may have controlled both sedimentation and the locus of volcanic activity.
- The emplacement of large volumes of basic magma resulted from the rupturing of the continental crust.
- Basic volcanics and glacial deposits (tillites) are potentially important stratigraphic markers and also provide critical constraints on the timing of Dalradian sedimentation.
- Cambrian–Ordovician shallow-water shelf sedimentation in north-west Scotland was contemporaneous with deposition of deep-water, outer-shelf, muds of the Southern Highland Group.