Chapter 4 Torridonian rocks of Great Britain

Introduction

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'Torridonian' is an informal lithostratigraphical name for the Neoproterozoic and Meso-proterozoic continental sedimentary succession, dominated by reddish-brown sandstones, which overlies the Lewisian Gneiss Complex in northwest Scotland. The Torridonian sequence forms one of the principal elements of British stratigraphy, comparable in volume to red-bed sequences such as the late Silurian to Early Devonian Old Red Sandstone of Scotland, or the Triassic of England.

The Torridonian rocks are exposed in that part of the North-west Highlands to the west of the Moine Thrust (Figure 4.1). They are best displayed in the foreland to the Caledonian Orogen, where they unconformably overlie the Lewisian Gneiss Complex, and are in turn unconformably overlain by a Cambro-Ordovician sedimentary succession. The Torridonian sandstones form many of the spectacular mountains of north-west Scotland, for example Quinag, Suilven, Ben More Coigach, An Teallach, Beinn Eighe, Liathach. They also extend offshore to the west under parts of the Minch and Sea of the Hebrides basins and southwards to just west of Tiree. Most of the Torridonian outcrop lies outwith the Caledonian Orogen, and has consequently escaped appreciable deformation, but more-deformed Torridonian rocks are found within the Moine Thrust Belt. Dips in the foreland sequence are generally low, reflecting gentle warping about NW-trending axes, which developed prior to deposition of the Cambrian sediments. The thermal history reflects burial and little more, giving ample scope for studies of palaeoclimate, palaeomagnetism and palaeontology. University and other field parties regularly visit some Torridonian localities, such as Enard Bay and Stoer, as they demonstrate the richly complex Mesoproterozoic and Neoproterozoic sedimentary geology in a small area.

The Torridonian sequence is readily divided into the Stoer, Sleat and Torridon groups (Stewart, 1969) and has assumed the status of a supergroup, although this has yet to be formalized. The oldest is the Stoer Group, which comprises fluviatile red sandstones and lake deposits, superbly exposed on the coast at the Stoer GCR site. The Stoer Group is over 2 km thick at Poolewe, but its areal extent is limited to a narrow strip adjacent to the major NNE-trending Coigach Fault (Figure 4.1). The lowest beds of the Stoer Group are breccias, which were deposited on an irregular landscape in the underlying Lewisian gneisses, with a relief that locally attains 300 m. The relationship between the Stoer Group breccias and this basement relief is well displayed at the Stoer GCR site, but also at the Enard Bay and Rubha Dunan. sites (Figure 4.2), (Figure 4.3). Above the breccias, the sequence consists chiefly of cross-bedded sandstones, with some siltstones. A key stratigraphical marker is the Stac Fada Member, which comprises muddy sandstone with a high content of devitrified glass, interpreted as a volcanic mudflow (Stewart, 2002).

The younger Sleat Group, which is not seen in contact with the Stoer Group, is confined to the Kishorn Thrust Sheet within the Moine Thrust Belt, and is best preserved on the Sleat peninsula of Skye. It consists of fluviatile sandstones with subordinate lacustrine or shallow-marine mudstones and siltstones, which have been weakly deformed and metamorphosed during thrusting. Representative sections of the component formations of the Sleat Group can be conveniently studied in Skye at the Loch na Dal, Kinloch and Kylerhea Glen GCR sites (Figure 4.2).

The youngest part of the Torridonian and by far the most important volumetrically is the Torridon Group (Figure 4.2), (Figure 4.4). This consists mainly of red-brown to purple, coarse-grained, fluviatile sandstones, which reach about 5 km in thickness. It is this rock type that forms almost all of the prominent, purplish- to red-brown, precipitous, tiered mountains of the foreland area of the North-west Highlands (Figure 4.5).

In Skye the Torridon Group conformably overlies the Sleat Group. Elsewhere it covers an ancient land surface, with relief locally reaching 500 m, eroded mainly in either the underlying Lewisian gneisses or more rarely in the Stoer Group sequence. Uplift has brought this palaeorelief to the surface again, for example at the Diabaig GCR site, at Slioch, and along the southern shore of the Upper Loch Torridon GCR site. The lowest rocks in the Torridon Group, the Diabaig

Formation, comprise breccias, sandstones, siltstones and conglomerates, interpreted as alluvial-fan deposits formed on the flanks of palaeovalleys. They grade laterally into siltstones and mudstones deposited in lakes in the valley centres. The Diabaig Formation is overlain by the thick sequence of red-brown, purplish-red to pale-red, coarse-grained, cross-bedded feldspathic sandstones that make up the Applecross Formation. They are overlain in turn by the red-brown, medium-grained sandstones of the Aultbea Formation. Both units were laid down in alluvial-fan and braided river systems. The base of the Applecross Formation is well exposed at the Diabaig GCR site, and the Aultbea Formation is best studied at the Aultbea GCR site, which is the type locality. The uppermost beds of the Torridon Group, a succession of grey fissile siltstones and pink sandstones, are exposed only at the Cailleach Head GCR site, where they form one of the finest lacustrine and fluviatile cyclothemic sequences in Britain, if not in Europe.

Tectonic environments of deposition

The three groups of the Torridonian are all believed to have accumulated in rift environments within the Proterozoic supercontinent of Rodinia and its precursors. In the type section of the Stoer Group at Stoer, palaeocurrent directions show 180° reversals at two points in the sedimentary sequence, demonstrating abrupt changes of palaeoslope. Stewart (1982) interpreted these reversals as indicating that the Stoer Group was deposited in a rift with sediments derived from areas uplifted on intermittently active marginal faults. The volcanic unit within the Stoer Group provides further evidence for a rift setting.

There has been significant recent debate about the palaeoclimatic conditions under which the basal breccias of the Stoer Group were deposited. The generally accepted model is that the breccias formed on alluvial fans in a rift-valley, in a subtropical climate with around 300–1200 mm/year rainfall and a long dry season (Stewart, 2002) at a palaeolatitude of *c.* 10°–30° N (Torsvik and Sturt, 1987; Piper and Poppleton, 1991; Darabi and Piper, 2004). However, Davison and Hambrey (1996) reviewed the basal units and recognized possible 'roches moutonnees', diamictite deposits apparently similar to glacial sediments, and large clasts in fine-grained sedimentary rocks that they interpreted as possible dropstones. They suggested that these basal Stoer Group lithologies could have been laid down under glacial conditions. In reply, Stewart (1997) and Young (1999b), reaffirmed the original model, showing that these features could have been formed equally well on alluvial fans and in shallow ephemeral lakes, in a warm and relatively arid environment. The sandstones and mudstones that make up the main part of the Stoer Group were laid down in a system of braided rivers and lakes.

The tectonic environment of the younger Sleat Group is more problematic; there is neither evidence for counterposed palaeocurrents nor of any contemporaneous volcanism. Stewart (1988b) suggested that the grey and grey-green, coarse-grained sandstones and dark-grey mudstones were derived from the west and deposited as alluvial fans and in lakes in a rift-valley environment. The interpretation of a rift is based mainly on the sheer thickness of the succession; *c.* 3.5 km in Skye, or *c.* 8.5 km if the conformably overlying Torridon Group is included. Stewart (1991b) showed that the geochemistry of sandstones from the Sleat Group and Torridon Group successions was compatible initially with local weathered detritus supplying the basin, but a more-distant input was detectable at higher stratigraphical levels.

Stewart (1982) suggested that the fluviatile sandstones and subsidiary conglomerates of the Torridon Group were deposited in a *c.* 70–80 km-wide rift, bounded by normal faults. Palaeomagnetic studies suggest that Scotland lay at *c.* 15°–20° S at this time (Smith *et al.,* 1983; Piper and Darabi, 2005). The average palaeocurrent direction in the Torridon Group is towards the east and south-east, near-perpendicular to the hypothetical bounding faults. The fan-wise arrangement of the palaeocurrents in the lowest few hundred metres of the group around Cape Wrath (Williams, 1969b, 2001) has also been taken to imply that the western margin of the basin coincided with the Minch Fault (Stewart, 2002). It has been suggested that the western boundary fracture was reactivated in the Mesozoic as the present-day Minch Fault (Stein, 1988; Stewart, 1993), and fractures forming the eastern margin of the rift were reactivated during development of the Moine Thrust Belt in Silurian time (Stewart, 1982).

More recently, it has been suggested that the very thick Applecross and Aultbea formations were formed in an extensive braided river system in a post-rift thermal relaxation basin (Nicholson, 1993). A comparison of estimated Applecross river discharges, obtained from measured channel cross-sections, with those of modern perennial rivers, implies a drainage basin of about 100 000 km^2; interpreted as too large for a rift setting. However, Nicholson noted that there are problems with this type of comparison, such as the lack of vegetation during the Precambrian, which would have resulted in greater sediment loads and discharge capabilities. In addition, the overall thickness of the Torridon Group (> 5 km) is about three times that expected from thermal relaxation alone (Einsele, 1992, figs 8.10 and 8.11). Recent geochemical and detrital zircon provenance studies (Young, 1999b; Rainbird *et al.,* 2001) broadly supported Nicholson's hypothesis of distant sediment derivation (see below), but Williams (2001) has re-emphasized the existence of alluvial-fan deposits in the northern part of the Applecross Formation, implying that active rifting was continuing when these rocks were deposited.

Williams (1968), and Retallack and Mindszenty (1994) reported weathering of Lewisian gneiss immediately below the Torridon Group rocks from the Cape Wrath area. They interpreted these surfaces and deposits as palaeosols formed through weathering at the time of Applecross Formation deposition, in a temperate to tropical, sub-humid palaeoclimate. Stewart (1995a) questioned these interpretations, noting that the mineralogy of the weathered zone shows little sign of the deep burial that would have been expected, and suggesting that either the weathering had occurred much later (during the Cainozoic) or that the weathered zone has been modified by subsequent hydrothermal activity. However, Williams and Schmidt (1997) used palaeomagnetic techniques to infer that the weathering profiles did form at the same time as Applecross sedimentation, thus making them the earliest-known palaeosols in the British Isles. Young (1999a) investigated the geochemistry of the palaeosols and showed that they had undergone metasomatism by potassium-bearing fluids, a characteristic feature of many ancient weathering profiles. Study of the palaeosols provides us with some indication of the nature of the climate during the deposition of the Torridon Group, and also shows that by that time in the Proterozoic, oxygen was already a substantial component of the atmosphere (Retallack and Mindszenty, 1994).

Age and provenance of the Torridonian

Proterozoic microfossils and algal remains have been found in mudstones of the Stoer and Torridon groups (Cloud and Germs, 1971; Peat and Diver, 1982; Zhang, 1982), but these do not provide accurate age constraints. However, evidence for the age and provenance of the Torridonian rocks has been obtained using a variety of isotopic, geochemical and palaeomagnetic techniques. The dearth of volcanic rocks suitable for direct isotopic dating has led to the use of less-precise techniques to constrain dates of deposition. Provenance and age studies are intertwined, as the age of the source rocks provides a constraint for the maximum age of the sedimentary rocks. From the regional stratigraphy, we know that the Torridonian sedimentary rocks were laid down after the Laxfordian event in the underlying Lewisian Gneiss Complex (1750–1670 Ma; Kinny and Friend, 1997) and before deposition of Cambrian sediments began at about 545 Ma (Tucker and McKerrow, 1995).

Early dating of chloritized biotite from a locally derived Lewisian boulder in the Stoer Group gave a K-Ar age of 1187 ± 35 Ma (Moorbath *et al.,* 1967), which was taken to provide an upper constraint on Stoer Group deposition. A Rb-Sr whole-rock isochron from mudstones of the Stoer Group gave an age of 940 ± 40 Ma (Moorbath, 1969), which was originally interpreted as the age of diagenesis, but the age is now regarded as unsound. More recently, Turnbull *et al.* (1996) obtained a Pb-Pb age of 1199 ± 70 Ma on limestones from the Stoer Group. This age is interpreted as representing early diagenesis, which within error corresponds to the date of deposition. This agrees with an estimate of *c.* 1100 Ma for the deposition of the Stoer Group based on palaeomagnetic data (Smith *et al.,* 1983).

Studies of geochemistry, petrography and clast distribution have indicated that most of the Stoer Group sediments were derived from local basement of the Lewisian Gneiss Complex (Van de Kamp and Leake, 1997). Recent provenance work by Rainbird *et al.* (2001) has shown that detrital zircons in the Stoer Group mostly range in age from 2930 Ma to 2480 Ma, and thus were derived from Archaean protoliths. The zoning, replacement textures, and overgrowth rims on the zircons all indicate a local Lewisian source and support the model of deposition in a fault-bounded rift-valley.

There are no age data for the Sleat Group, but they are reported to be conformable with, and thus only slightly older than, the Torridon Group. The first isotopic dates for the Torridon Group were obtained from muscovite flakes in the Diabaig Formation, which gave ages of 1168 ± 30 Ma (K-Ar) and 1190 ± 40 Ma (Rb-Sr) (Moorbath *et al.,* 1967). Subsequent Rb-Sr dating of mudstones from the Torridon Group gave an age of 788 ± 29 Ma (Moorbath, 1969). More recently, whole-rock Rb-Sr dates of 994 ± 48 Ma and 977 ± 39 Ma have been obtained for the Diabaig Formation and Applecross Formation respectively (Turnbull *et al.,* 1996). These dates are believed to record the time of albitization, which probably corresponds within error to the date of deposition. Again, the dates agree well with the palaeomagnetic data of Smith *et al.* (1983).

Detrital zircons from the Torridon Group show a wide spectrum of ages, with peaks at 1840–1777 Ma, 1679–1623 Ma, and 12501050 Ma (Rogers *et al.*, 1990; Rainbird *et al*., 2001). These peaks were interpreted as representing material sourced from the Ketilidian, Labradorian and Grenvillian orogenic belts respectively. All these belts lie to the west of the Scottish Torridonian outcrop, within the postulated supercontinent of Rodinia. All the data fit well with the palaeocurrent information, which suggests a source to the west. A few zircons of Archaean age have been found in the

Torridon Group, but, surprisingly, the Lewisian does not appear to have been an important source for Torridon Group sediments. The youngest recorded detrital zircon from the Applecross Formation gave an age of 1060 ± 18 Ma, indicating a maximum depositional age for the Torridon Group.

Stewart and Donnellan (1992) used geo-chemical data to show that the Applecross and Aultbea formations of the Torridon Group could be derived from Lewisian gneisses such as those of the Outer Hebrides. However, the detrital zircon data (Rainbird *et al.,* 2001) supported geochemical studies by Van de Kamp and Leake (1997) and Young (1999b), which suggested that that the source for the Applecross and Aultbea formations was not the local Lewisian gneisses, but younger gneissose rocks from Labrador and the Canadian shield farther to the west. This recent work supported the hypothesis of Nicholson (1993) for distal derivation of material that was transported eastwards and deposited in a large-scale thermal relaxation basin, rather than in a restricted rift-valley setting. All workers agree that the Diabaig Formation appears to have been more locally derived. Nicholson's model for the derivation of the Sleat Group and Torridon Group rocks involves an initial rifting stage of basin formation. This was followed by a second stage of extension, attributed to thermal relaxation processes, which resulted in a larger sedimentary basin in which most of the sandstones of the Torridon Group were deposited. The lower parts of the Applecross Formation were laid down on alluvial fans (Williams, 2001), but the upper parts of the Applecross Formation and the Aultbea Formation were deposited from a large-scale river system that transported detritus from an extensive upland catchment area to the west. However, it should be remembered that the Torridonian 'basin' must have lain close to the Grenville orogenic belt and other tectonic settings are also feasible. Intracratonic rift basins are the longest lived basin types and may relate to a wide range of both local and distant tectonic causes (McCann and Saintot, 2003).

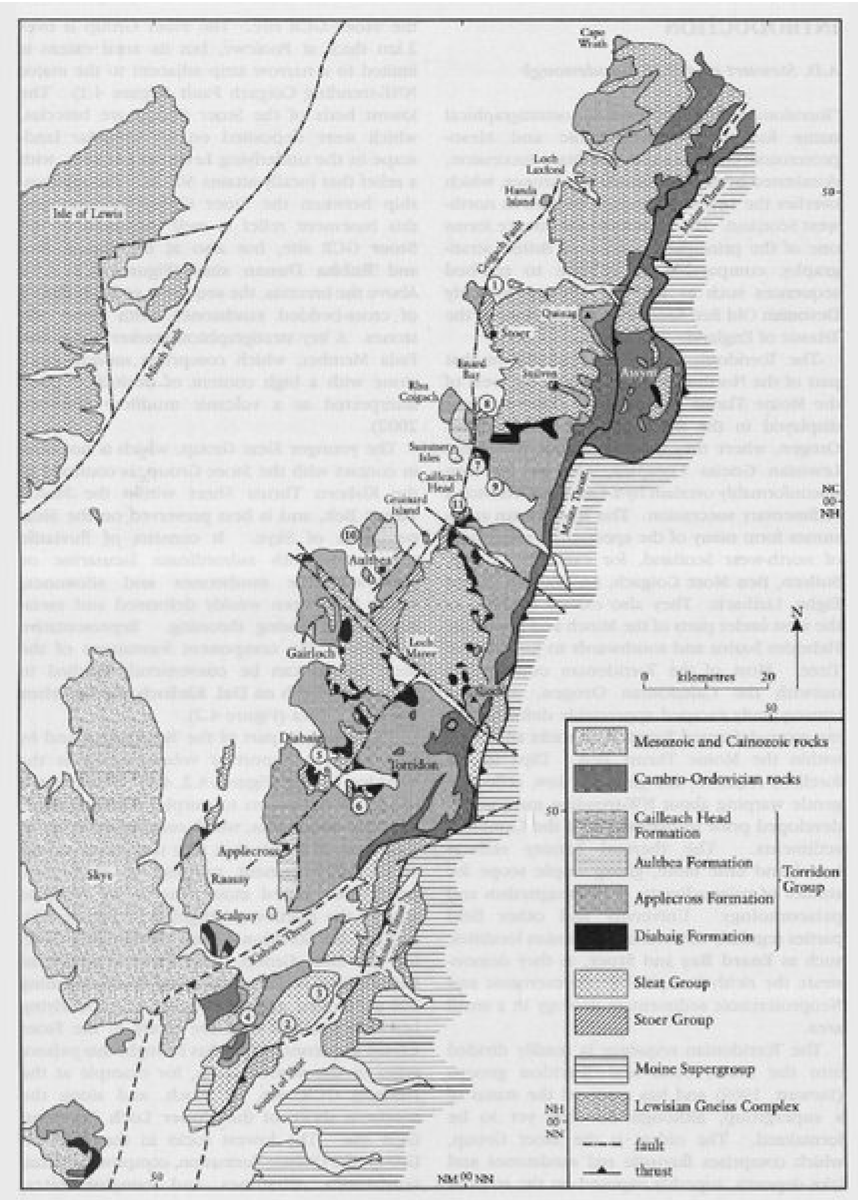
Summary

For many years, the Torridonian has been described as a thick, rift-related sedimentary sequence with a period of non-deposition between the top of the Stoer Group and the base of the Sleat and Torridon groups. Torridon Group rocks overlie Stoer Group rocks unconformably at several localities with an angular discordance of 15°–30°. Renewed isotopic and geochemical studies over the last 10–15 years have shown that the Stoer Group is very different, in terms of both age and composition, from the overlying Sleat and Torridon groups. The currently preserved parts of the Stoer Group were deposited around 1200–1100 Ma ago in a rift basin, derived mainly from local Lewisian gneiss, both to the east and to the west. The Sleat and Torridon groups were deposited later, at around 1000 Ma. The Sleat Group was probably laid down in a developing rift basin, again initially with predominantly local sediment sources; but by the time the upper part of the Applecross Formation and the Aultbea Formation were being deposited, a more-extensive basin had developed, probably over 100 km wide, with sediment being brought in by a large river system from a more-distal westerly source. Interpretations of the overall Torridon Group extensional basin have focused mainly on faulted rift and thermal relaxation types.

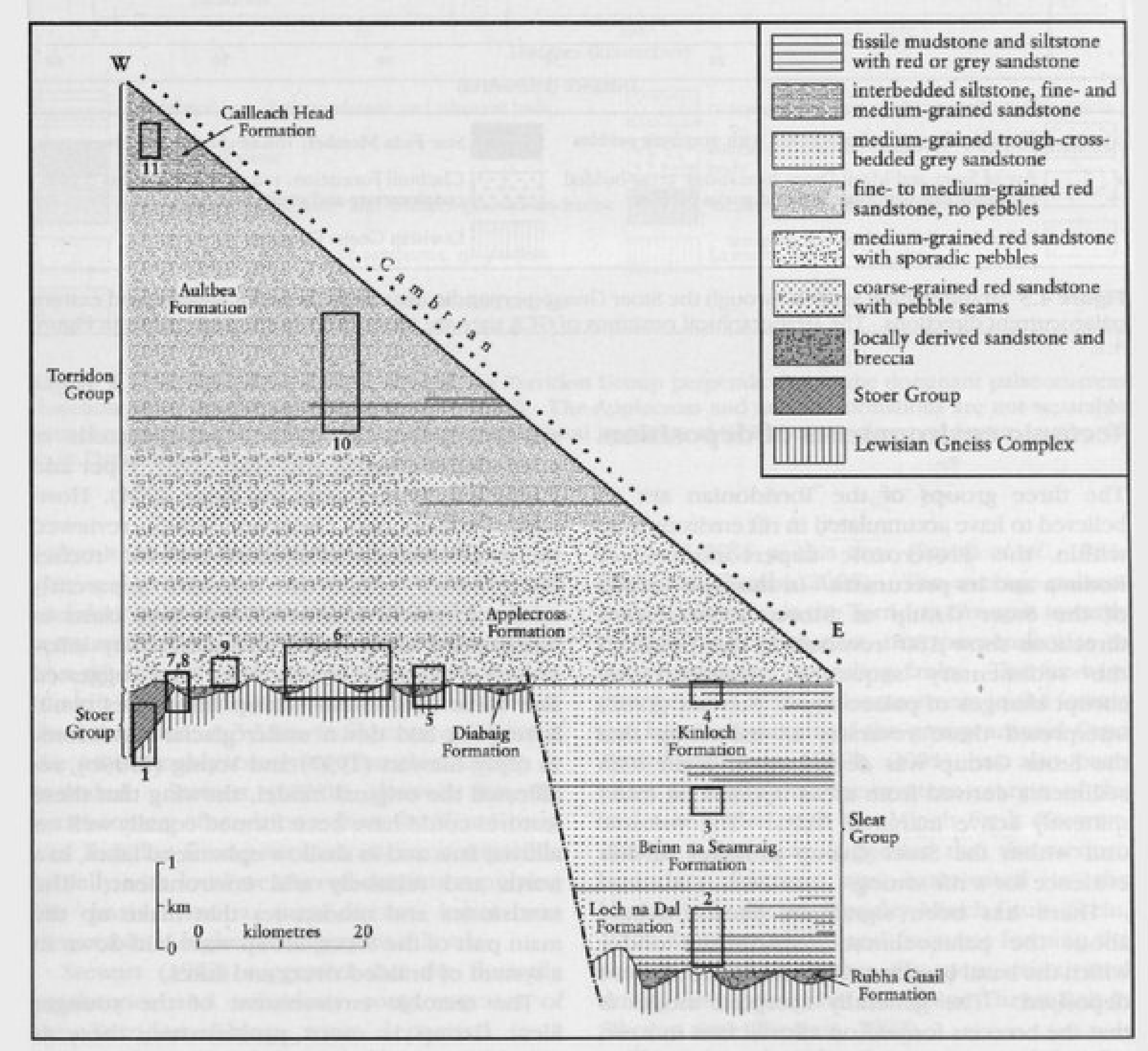
The Torridon Group rocks contain detrital zircons formed during the Grenvillian Orogeny, and hence were deposited in post-Grenville times. A typical model for the Torridonian has the Stoer Group as the earliest manifestation of extension during late Grenville times, with the Sleat and Torridon groups being deposited in a post-Grenville rift. However, Strachan and Holdsworth (2000) have pointed out that the Stoer Group may well have formed prior to Grenvillian orogenesis, although clearly it was not deformed during that event. Further studies of the Torridonian will hopefully increase our understanding of the development of the Rodinian supercontinent during the Proterozoic.

The Torridonian is the only relatively undeformed Precambrian rock sequence in Britain, and one of a few in Europe. It has already shown its potential for unravelling the nature of the contemporaneous Earth surface environment (geomorphology, tectonism, climate, magnetism, palaeolatitude, biology) and can be expected to go on yielding similar data for the foreseeable future. To this end the GCR sites have been selected to provide a series of type localities and reference sections covering the complete succession.

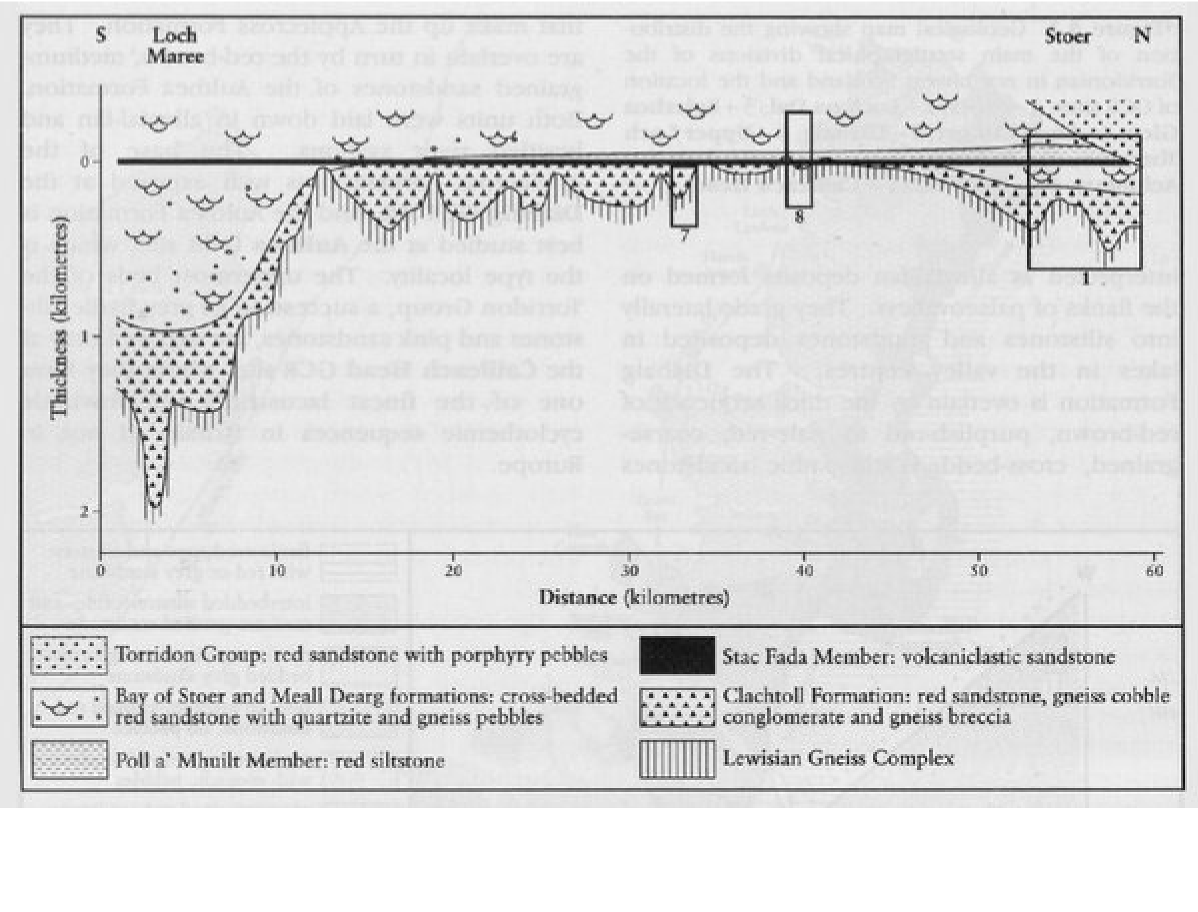
[References](#)



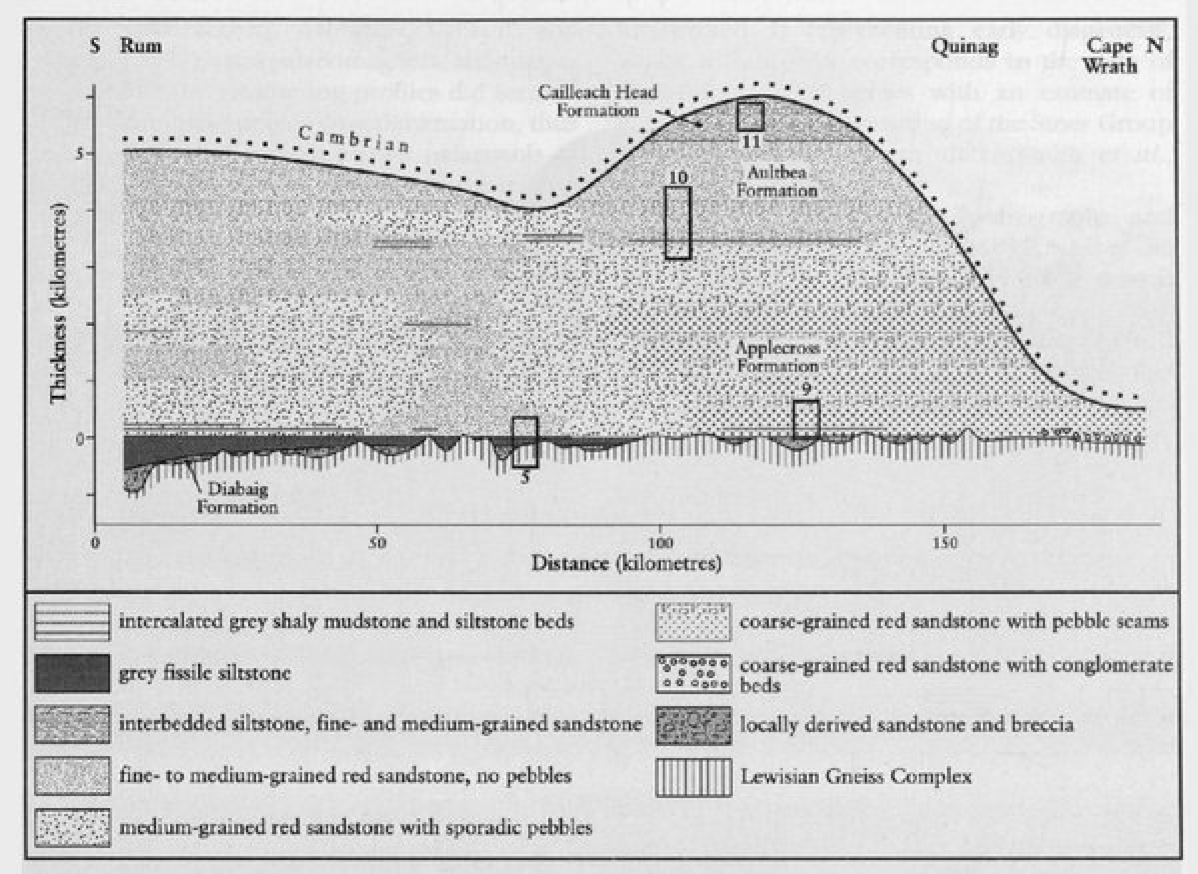
(Figure 4.1) Geological map showing the distribution of the main stratigraphical divisions of the Torridonian in north-west Scotland and the location of GCR sites: 1— Stoer; 2 — Loch na Dal; 3 — Kylerhea Glen; 4 — Loch Eishort; 5 — Diabaig; 6 — Upper Loch Torridon; 7 — Rubha Dunan; 8 — Enard Bay; 9 — Achduart; 10 — Aultbea; 11 — Cailleach Head.



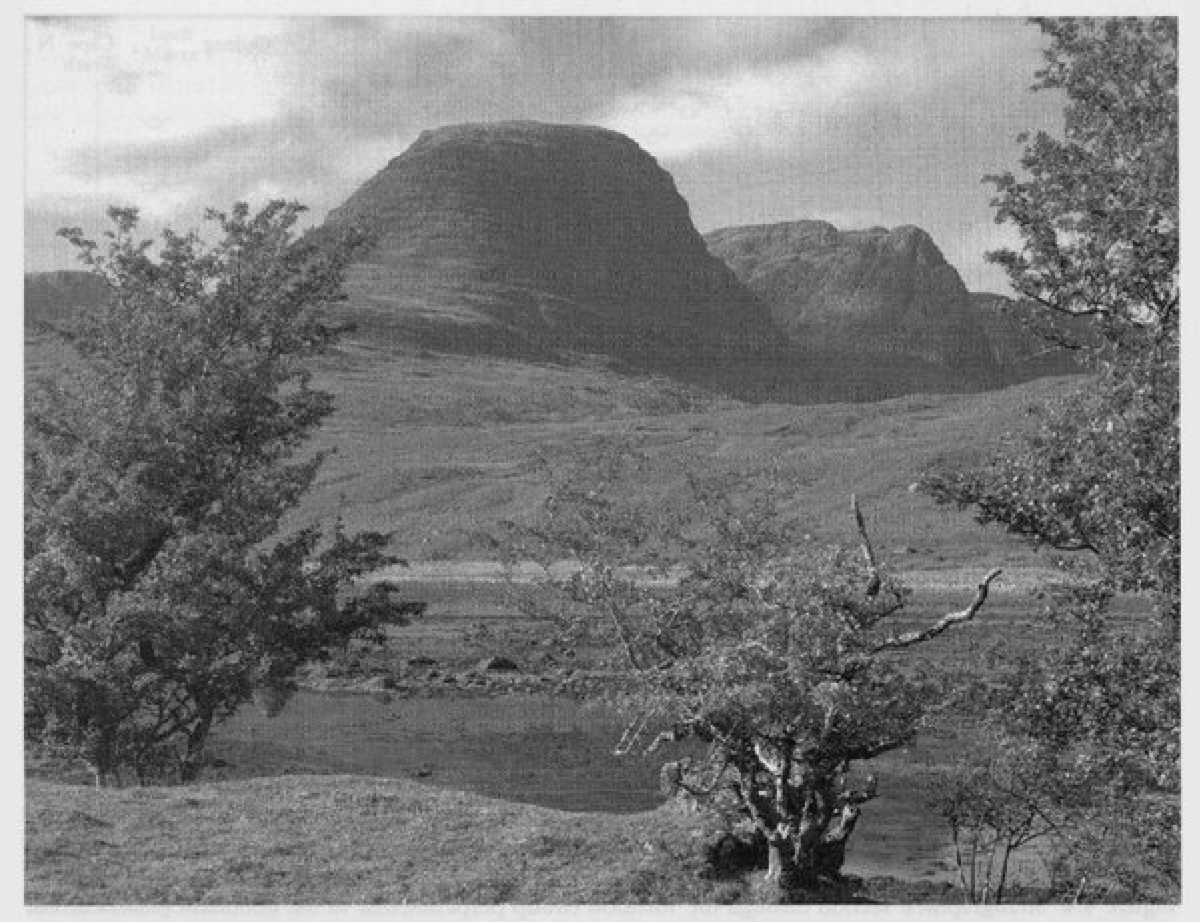
(Figure 4.2) Diagrammatic section through the Torridonian, parallel to the dominant easterly palaeocurrent directions. The stratigraphical positions of GCR sites are shown as boxes, numbered as in Figure 4.1.



(Figure 4.3) Stratigraphical section through the Stoer Group perpendicular to the dominant western and eastern palaeocurrent directions. The stratigraphical positions of GCR sites are shown as boxes, numbered as in Figure 4.1.



(Figure 4.4) Stratigraphical section through the Torridon Group perpendicular to the dominant palaeocurrent direction of the Applecross Formation (A = 123°). The Applecross and Aultbea formations are not separable over the southern half of the section. The stratigraphical positions of GCR sites are shown as boxes, numbered as in Figure 4.1.



(Figure 4.5) Spectacular cliffs composed of sandstones belonging to the Torridon Group, Sgurr a' Chaorachain, Kishorn, Ross-shire. (Photo: British Geological Survey, No. P002854, reproduced with the permission of the Director, British Geological Survey, © NERC.)