Lewisian, Torridonian and Moine Rocks of Scotland

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GCR Editor: **P.H. Banham**

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Chapter 4

Torridonian rocks of Great Britain

INTRODUCTION

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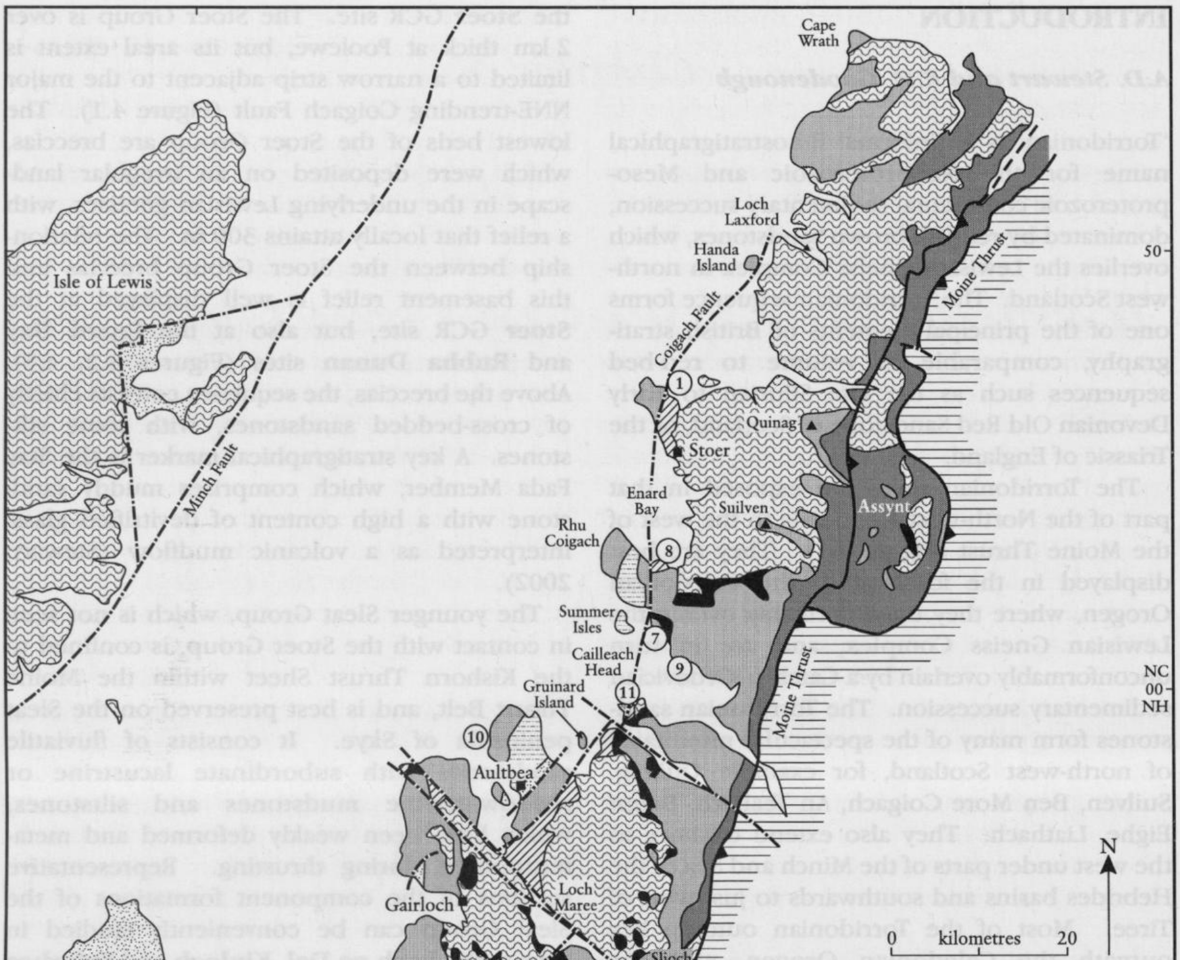
'Torridonian' is an informal lithostratigraphical name for the Neoproterozoic and Mesoproterozoic continental sedimentary succession, dominated by reddish-brown sandstones, which overlies the Lewisian Gneiss Complex in north-west Scotland. The Torridonian sequence forms one of the principal elements 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 (Figures 4.2, 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 (Figures 4.2, 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,



Cape Wrath
Loch Laxford
Handa Island
Moine Thrust
Coigach Fault
Isle of Lewis
Minch Fault
Quinag
Stoer
Enard Bay
Suilven
Assynt
Rhu Coigach
Summer Isles
Cailleach Head
Gruinard Island
Aultbea
Gairloch
Loch Maree
Slioch
Diabaig
Torridon
Applecross
Skye
Raasay
Scalpay
Kishorn Thrust
Sound of Sleat
N
0 kilometres 20
50
NC 00 NH
NH 00 NN
NM 00 NN
Mesozoic and Cainozoic rocks
Cambro-Ordovician rocks
Cailleach Head Formation
Aultbea Formation
Applecross Formation
Diabaig Formation
Torridon Group
Sleat Group
Stoer Group
Moine Supergroup
Lewisian Gneiss Complex
fault
thrust

◂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**.

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.

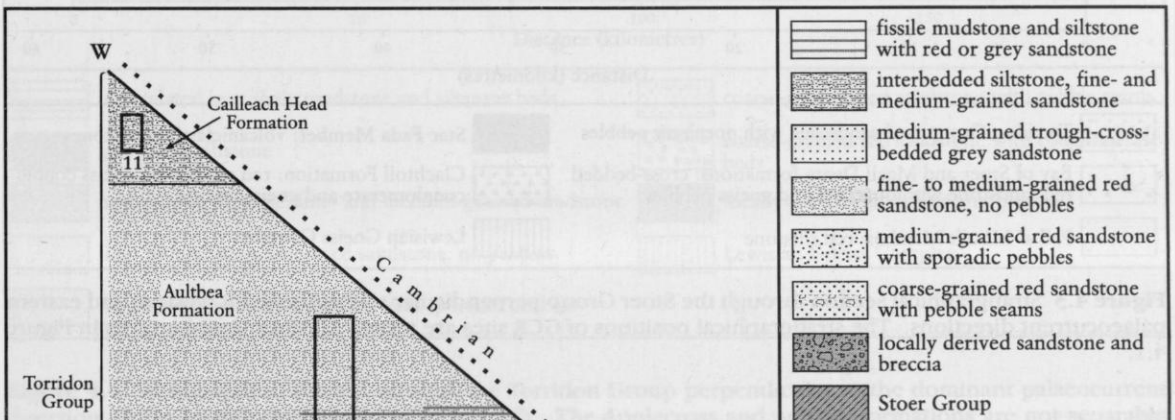


Figure 4.2 Diagrammatic section through the Torridonian, parallel to the dominant easterly palaeocurrent directions. The stratigraphical positions of GCR sites are shown as boxes, numbered as in Figure 4.1.

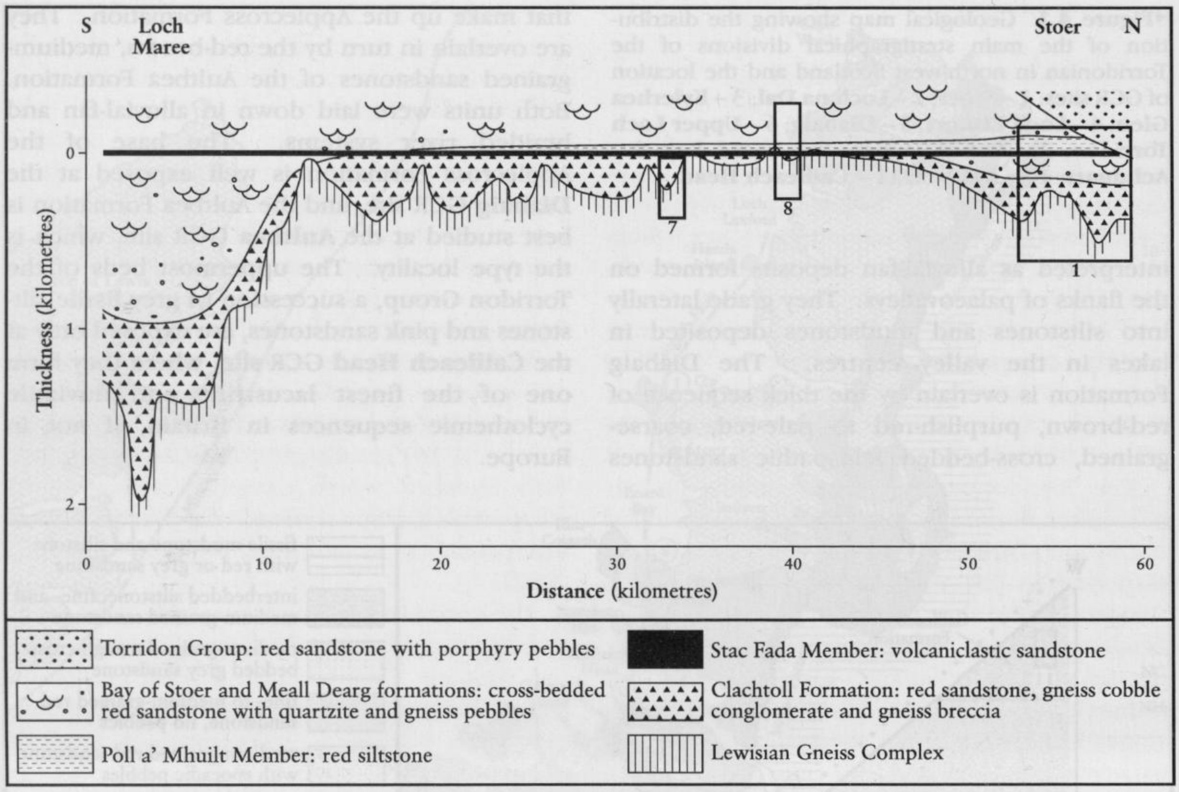


Figure 4.3 Stratigraphical section through the Stoer Group perpendicular to the dominant western and eastern palaeocurrent directions. The stratigraphical positions of GCR sites are shown as boxes, numbered as in Figure 4.1.

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 moutonnées', 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), re-affirmed 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

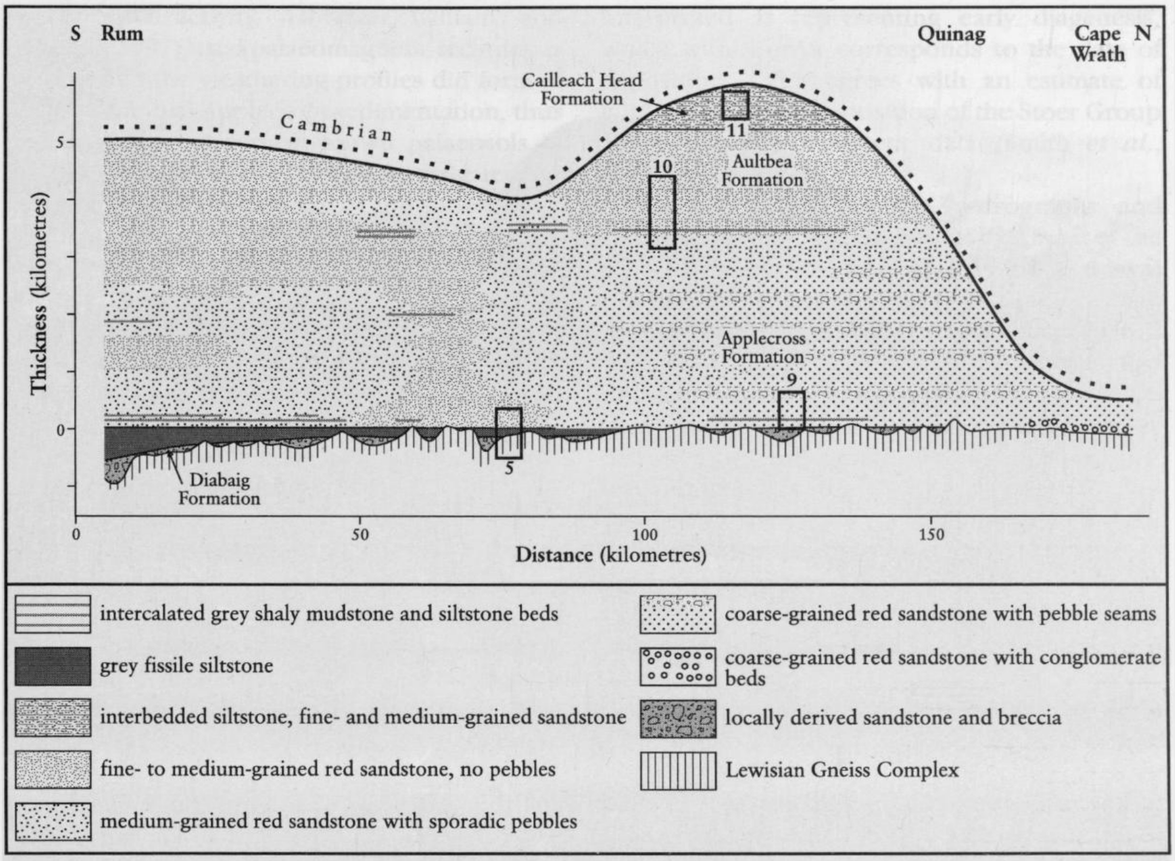


Figure 4.4 Stratigraphical section through the Torridon Group perpendicular to the dominant palaeocurrent direction of the Applecross Formation (θ = 123°). The Applecross and Aultbea formations are not separable over the southern half of the section. The stratigraphical positions of GCR sites are shown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

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

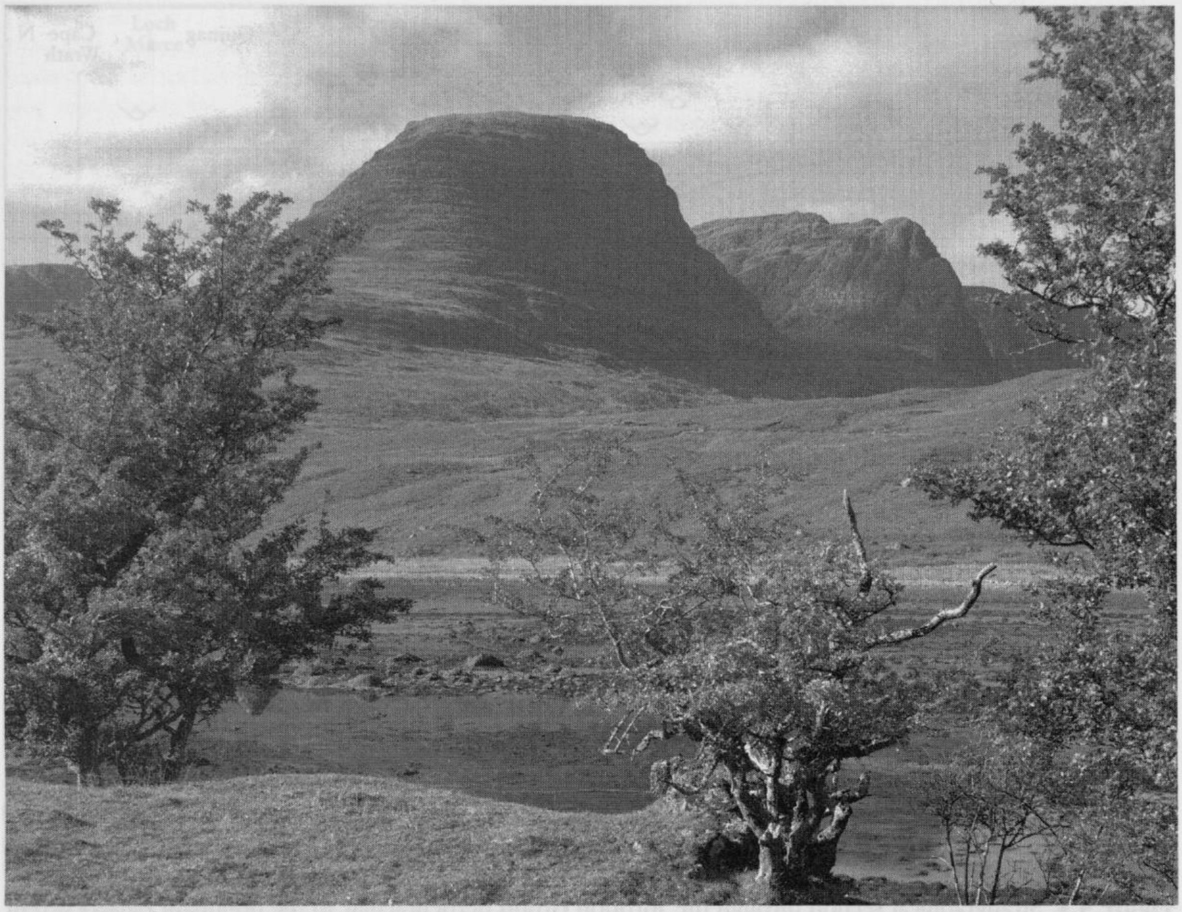


Figure 4.5 Spectacular cliffs composed of sandstones belonging to the Torridon Group, Sgurr a' Chaorachain, Kishorn, Ross-shire. (Photo: British Geological Survey, No. P002854, reproduced with the permission of the Director, British Geological Survey, © NERC.)

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 1250–1050 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 geochemical 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.

STOER (NC 041 283–NC 027 291, NC 041 266–NC 039 281, NC 045 328)

A.D. Stewart

Introduction

The Stoer GCR site, some 8 km north-west of Lochinver, represents the type area for the Stoer Group (Figure 4.6). The sequence is exposed in excellent coastal exposures, which clearly illustrate the sedimentology and structures of the group. The Stoer Group has an importance out of all proportion to its limited geographical extent (Figure 4.3), as it is the only non-metamorphosed Mesoproterozoic stratigraphical unit in Britain, having been formed about 1200 Ma, between the end of the Laxfordian orogeny at about 1750 Ma (Corfu *et al*., 1994) and the deposition of the Torridon Group at about 1000 Ma. The rocks were originally assigned by the Geological Survey to the Diabaig Formation of the Torridon Group (Peach *et al*., 1907), but were later recognized as an entirely distinct lithostratigraphical unit (Stewart, 1969) and given the name 'Stoer Group'. The Stoer Group has been described in detail by Stewart (1988a, 1990b, 1991b, 2002).

The Stoer Group rocks form a *c*. 2 km-wide belt on the Stoer peninsula lying between the basal unconformity and the NNE-trending Coigach Fault (Figure 4.6). They dip between 20° and 35° to the WNW, with dips locally increasing close to the Coigach Fault, which throws down Torridon Group rocks to the WNW. On the north coast of the peninsula, east of the Coigach Fault by Port Feadaig (NC 042 329), a basal conglomerate and up to 10 m of red siltstones of the Diabaig Formation unconformably overlie an irregular surface cut in the Stoer Group rocks. Coarse-grained pebbly sandstones of the Applecross Formation immediately overlie these basal Torridon Group siltstones and cut out the Diabaig Formation rocks to the north-west.

The sedimentary rocks of the Stoer Group include alluvial and aeolian sandstones, lacustrine mudrocks and carbonate rocks, and tuffaceous deposits. Palaeomagnetic measurements on the sandstones have established a well-defined magnetic pole (Smith *et al*., 1983;

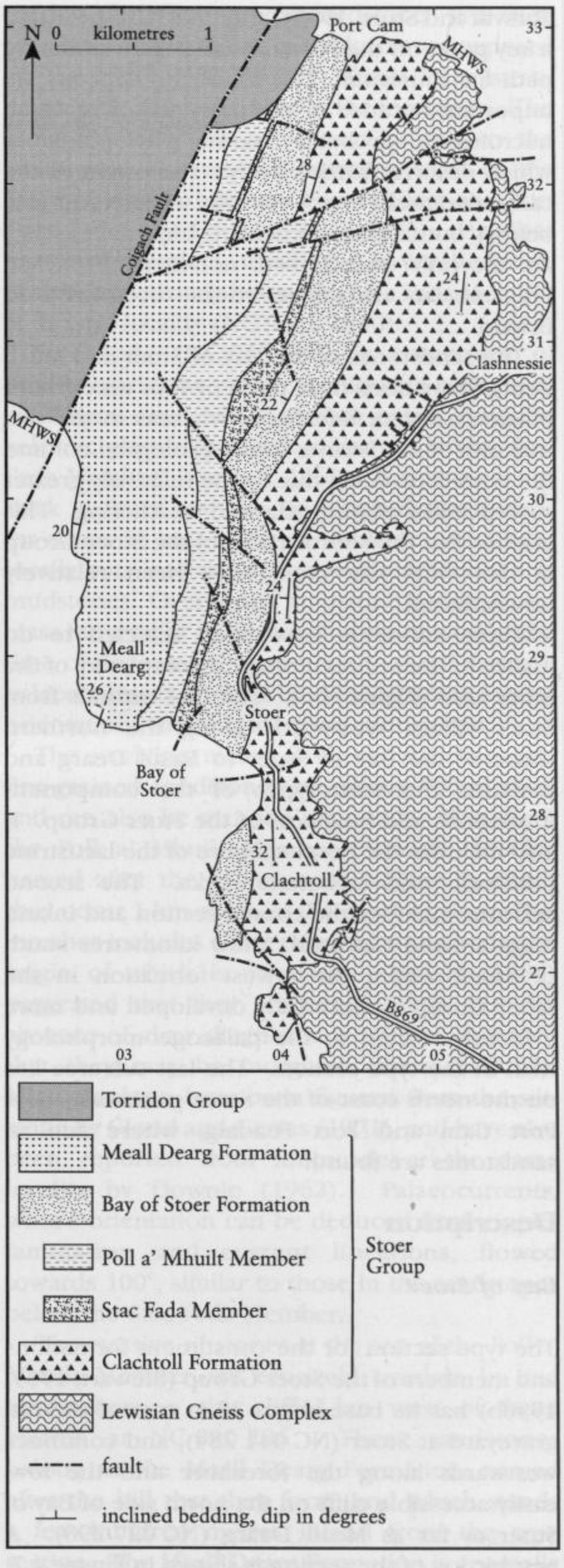


Figure 4.6 Geological map of the area around Stoer.

Torsvik and Sturt, 1987), and thus have provided a key point on the Precambrian polar wandering path for Laurentia. The lacustrine deposits are important because of the presence of acritarch microfossils, probably marine phytoplankton, which deserve further study. The origin of the carbonate rocks is not yet fully understood (see below), but they are particularly important as they are the only undeformed, non-metamorphosed Precambrian carbonate rocks recognized in Britain.

The sandstones of the Bay of Stoer and Meall Dearg formations have three or four times more plagioclase than K-feldspar, whereas in the vast majority of sandstones in the geological column the ratio is reversed due to the relatively greater susceptibility of plagioclase to weathering. This implies that the source rocks of the Stoer Group at this GCR site must have been relatively unweathered.

Three sub-areas have been selected to do justice to the sedimentological complexity of the Stoer area (Figure 4.6). The first extends from Stoer village westwards along the northern shore of the Bay of Stoer to Meall Dearg and contains the stratotypes of the component formations and members of the Stoer Group. It also includes the best exposure of the lacustrine mudrocks and carbonate rocks. The second sub-area includes the coastal section and inland crags around Clachtoll, a few kilometres south of Stoer, where the lowest formation in the Stoer Group is more fully developed and more evidently related to the palaeogeomorphology than in the type section. The last sub-area lies on the north coast of the Stoer peninsula, near Port Cam and Port Feadaig, where aeolian sandstones are found.

Description

Bay of Stoer

The type section for the constituent formations and members of the Stoer Group (Stewart, 1969, 1990b) has its base about 33 m east of the old graveyard at Stoer (NC 041 284), and continues westwards along the foreshore and the low, easily accessible cliffs on the north side of Bay of Stoer as far as Meall Dearg (NC 027 290). A graphic log of the section is shown in Figure 4.7.

The base of the oldest unit, the Clachtoll Formation, is formed of massive breccia derived from the immediately underlying Lewisian

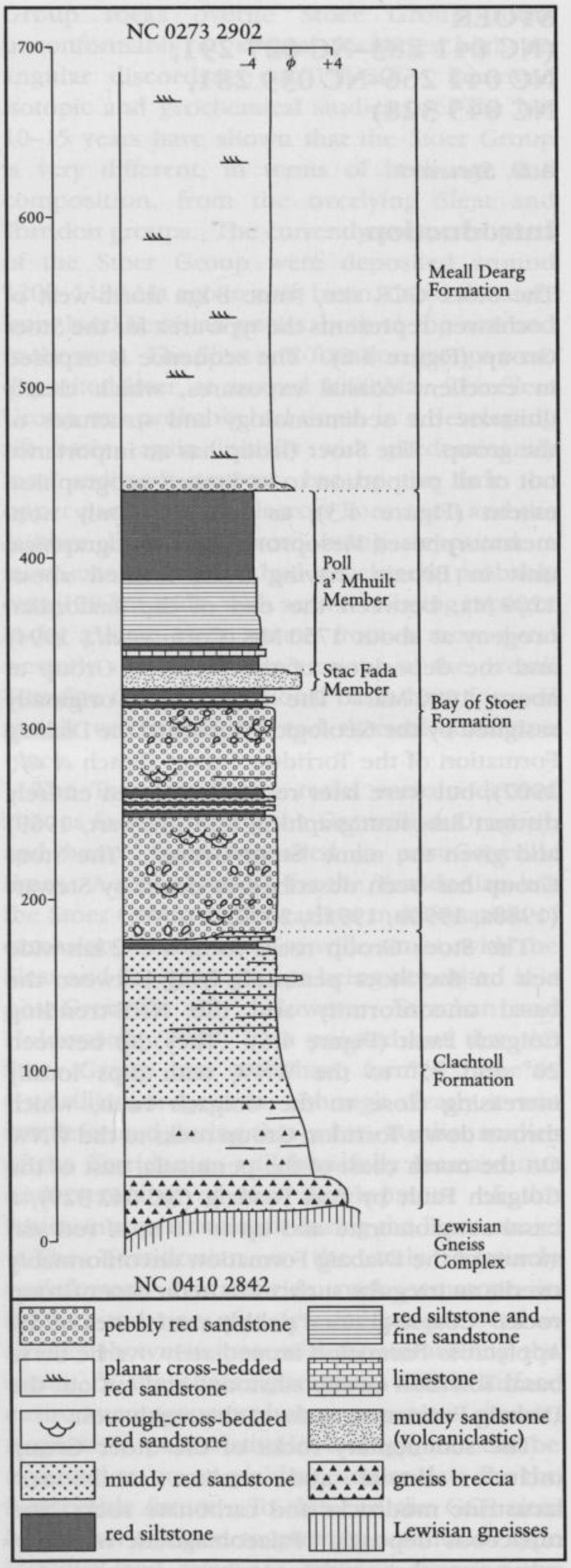


Figure 4.7 Stratigraphical log of the type section of the Stoer Group, along the north side of the Bay of Stoer, west of the old graveyard. Grain-size scale from +4Ø to –4Ø (0.06–16 mm).

gneisses. The breccia passes upwards into red tabular sandstone, well exposed in a small quarry near the north-east corner of the new graveyard (NC 0406 2832). Massive dark-red muddy sandstone overlies the tabular sandstone facies, but the contact here is concealed by sand. A 2 m-thick section of the muddy sandstone is exposed in a small quarry near the roadside (NC 0398 2837). The facies here is structureless but for a thin bed of very coarse sandstone, from which descend wispy, sand-filled veins. These appear to be relics of desiccation cracks in the muddy sediment, which have closed during a period of rewetting. Farther west, where the shore section starts (NC 0383 2832), there are good exposures of decimetre-scale bedded muddy sandstone with desiccation cracks and millimetre-sized holes, perhaps casts of former evaporite needles. Centimetre-thick beds of carbonate rock are common.

A 2 m-thick bed of very coarse sandstone interrupts the sequence, and forms a small promontory at NC 0378 2831. Small-scale trough-cross-bedding near the top of this sandstone shows that palaeocurrents flowed towards the south-west. The coarse sandstone can be traced south to Clachtoll and north to the coast at Port Cam, a distance of 6 km overall. A few metres above this sandstone marker bed a 5 m-thick sequence of fissile mudstone is exposed, grey in the lowest 0.5 m and red above. Ripple-bedded sandstones, which appear in the upper part of the mudstone unit indicate that palaeocurrents were directed towards the north-east. The uppermost sandstones, which are the highest beds in the Clachtoll Formation, contain pebbles of gneiss and quartz (but no quartzite) up to 1 cm across. The detritus in these rocks is solely derived from the local basement gneisses.

The top of the Clachtoll Formation is represented by an erosion surface, which is overlain by red sandstones containing rounded pebbles of gneiss and quartzite. These sandstones form a large promontory extending out into the Bay of Stoer at NC 0371 2834. The rocks above the erosion surface belong to the Bay of Stoer Formation, and are characterized by trough cross-bedding, soft-sediment contortions (Figure 4.8a), pebbles of gneiss and fine-grained metasedimentary quartzite, and millimetre-thick concentrations of opaque and other heavy minerals.

The sandstones of the Bay of Stoer Formation are punctuated by sharply defined couplets of muddy sandstone and red mudstone. Five such couplets totalling 17 m in thickness are exposed on the shore (NC 035 285) about 70 m stratigraphically above the base of the formation. The same five couplets occur at Clachtoll to the south, and also on the northern coast of the Stoer peninsula between Port Feadaig and Port Cam (NC 0429 3291–NC 0432 3293). Another group of couplets, totalling 8 m in thickness, occurs immediately below the Stac Fada Member at its type locality (NC 0332 2850).

Stac Fada (NC 033 284) is composed of muddy sandstone, which is unique in containing centimetre-sized lapilli of dark-green, vesicular volcanic glass. This unit is known as the 'Stac Fada Member' (Stewart, 1969). It is about 11 m thick at Stoer and can be mapped southwards for some 55 km, as far as Poolewe. The base locally cuts into the underlying sandstones and mudstones. Overfolded sandstone beds indicate mass movement to the south-west or west at the time of deposition, in contrast to the E-directed palaeocurrents implied by cross-bedding foreset orientations in the underlying sandstones.

The overlying, mainly fissile red siltstones and fine-grained sandstones are about 100 m thick and can also be mapped regionally. They form the Poll a' Mhuilt Member (Stewart, 1990b), named after the pronounced hollow in which they occur 1 km north of the coast section. This member includes some thin limestone beds, the origin of which is uncertain. Upfold (1984) suggested that they are stromatolitic, but the absence of clear diagnostic structures indicates that they may be inorganic (Stewart, 2002). Microplankton have been figured from the siltstone by Cloud and Germs (1971), and have also been reported from limestone at the same locality by Downie (1962). Palaeocurrents, whose orientation can be deduced from ripple-lamination and current lineations, flowed towards 100°, similar to those in the sandstones below the Stac Fada Member.

The massive siltstones at the top of the Poll a' Mhuilt Member are erosively overlain by red sandstones on the cliff 1 km west of Stoer church at NC 030 286. These sandstones belong to the Meall Dearg Formation, named after the hill that they form, and which stands a few hundred metres inland from the type section. The Meall Dearg Formation is generally characterized by planar cross-bedding in sets up to 1 m thick, laterally extensive intercalations of thinly bedded sandstone with wave ripples and

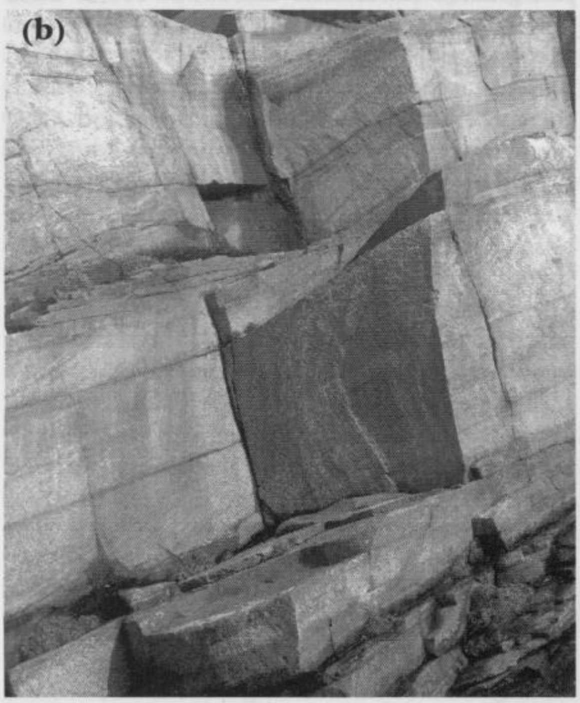


Figure 4.8 ▲(a) Trough-cross-bedded red sandstones of the Bay of Stoer Formation at Clachtoll (NC 0359 2728) in the Stoer GCR site. Contorted bedding is common in the formation; the crest of a water-escape cusp is marked by the ruler (20 cm long). ◄(b) Planar cross-bedded red sandstone of the Meall Dearg Formation at Meall Dearg (NC 0299 2855) in the Stoer GCR site. The two sets in the centre of the photograph are each about 25 cm thick. Contorted bedding is absent from this formation. (Photos: A.D. Stewart.)

desiccated mudstone drapes, but an absence of contorted bedding, pebbles or heavy-mineral bands. However, the lowest 7 m of the Meall Dearg Formation in the type section are anomalous in being trough cross-bedded and pebbly. The pebbles resemble those in the Bay of Stoer Formation, but material from the Stac Fada Member is not present. This pebbly interval is sharply overlain by the typical planar cross-bedded lithology (Figure 4.8b). Palaeocurrent directions in the pebbly interval and above are towards the west, counterposed to those in the Poll a' Mhuilt Member.

Clachtoll

At Clachtoll, south of the type section, the Clachtoll Formation infills a palaeovalley. The breccia facies is about 12 m thick near the centre of the palaeovalley (NC 043 273), while the overlying muddy sandstones are 200 m thick.

The lowest 120 m of the muddy sandstone are massive, and what appear to be bedding planes, for example in the roadside quarry at NC 0423 2727, are in fact joints. Joints with similar orientation are seen in bedded muddy sandstones stratigraphically higher in the Clachtoll Formation, where they make a small angle with bedding.

The muddy sandstone has a fine-grained ferruginous matrix, separating larger grains (mainly feldspar) that make up about 30–40% of the rock. The geochemistry suggests that most of the matrix was originally ash-fall tuff, whose composition would have formed smectite on decomposition (Stewart, 1990b). There is clear evidence of repeated desiccation of the sediment (Stewart, 1988a). The repeated shrinking and swelling of the smectite-rich sediment probably accounts for the destruction of bedding features in most of the muddy sandstone.

Towards the Bay of Clachtoll the basement rises rapidly so that the massive muddy sandstone is either directly in contact with Lewisian gneisses, or separated from them by a few metres of breccia, or by tabular sandstones with gneiss clasts. Outcrops of breccia mantle the gneiss slopes in many parts of this area, indicating that the hills represent an exhumed Proterozoic landscape (Figure 4.9). Good examples can be seen on the south-east side of the bay at NC 040 267, and on a hill of gneiss 350 m east of A' Clach Thuill at NC 041 267. At this latter locality dilatational veins transect the gneiss for at least 5 m below the unconformity. The vein fill is red siltstone, unlike the matrix of the overlying breccias, and the siltstone is typically laminated, parallel to the regional bedding. The origin of the breccias, and of the fractures in the rocks, is rather controversial, and is discussed below.

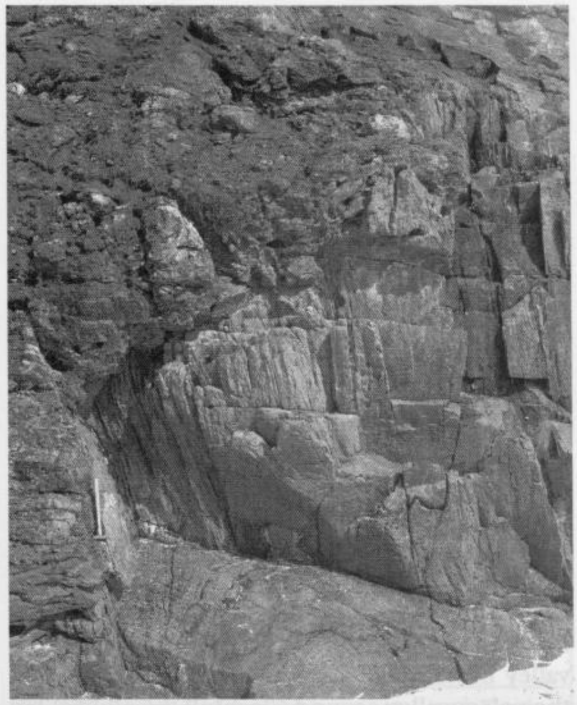


Figure 4.9 Breccia of the Clachtoll Formation resting on Lewisian gneisses at Clachtoll Bay in the Stoer GCR site. The hammer is 50 cm long. (Photo: British Geological Survey, No. P005850, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Port Cam

The northern coast of the Stoer peninsula, around Port Cam, provides excellent exposures of the laminated sandstone facies of the Clachtoll Formation, believed to be of aeolian origin. The sandstones have an average grain-size of 0.2 mm, ranging up to a maximum of 2 mm. They contain cross-beds which are generally only a few grains thick, forming sets mostly a few decimetres thick but in places up to as much as 10 m. The foresets dipped up to 25° to the east before tectonic tilting. The laminated sandstone facies contains numerous interbeds of relatively coarse-grained, pebbly sandstone with strongly erosive bases, and desiccated red siltstone laminae. The facies is bisected by a gneiss-cobble conglomerate unit, informally termed the 'Rienachait conglomerate', which reaches the sea about 200 m east of Port Cam at NC 0474 3293. The conglomerate is about 8 m thick and has a strongly erosional base.

Pebbly sandstones of the Bay of Stoer Formation erosively overlie laminated sandstone about 100 m west of Port Cam (NC 0435 3294). Farther west along the shore at Port Feadaig (NC 042 329) the Torridon Group unconformably overlies the Bay of Stoer Formation. Both groups have a westerly dip, the Stoer Group at 30° and the Torridon Group at about 20°. The lowest Torridon Group beds are red fissile mudstones and a basal conglomerate, both assigned to the Diabaig Formation, which are exposed only at low tide. Sandstones of the Applecross Formation in turn erosively overlie the thin Diabaig Formation units.

Interpretation

The earliest sediments, the Clachtoll Formation, were deposited on an irregular landscape, with a relief of up to *c.* 300 m; the eroded surface of the underlying Lewisian gneiss basement. The massive breccio-conglomerates, bedded breccias and tabular red sandstones seen in the Stoer area were probably deposited in alluvial fans. However, Davison and Hambrey (1996) suggested that some of the breccias around Clachtoll could represent glacial deposits, with infilled fractures in the gneiss having formed through hydro-fracturing beneath a glacier. Beacom *et al.* (1999) also interpreted the veins as dilational, but formed by tectonic hydro-fracturing. Stewart (1997) and Young (1999a) disagreed with the glacial hypothesis and considered that the weight of evidence still points to alluvial fans as a more likely depositional environment for the breccias. The fan deposits are thickest in the valley bottoms and absent from the ridges. In the palaeovalley around Clachtoll the alluvial-fan deposits pass laterally into muddy sandstones, which formed on ponded water mudflats (Stewart, 1988a). These muddy sandstones were rich in smectite group clay minerals, partly due to enrichment in Mg and Ca from basic rocks in the hinterland, but mainly supplied by ash-fall tuff (Stewart, 1990b). Seasonal wetting and drying subsequently destroyed any original bedding features.

Alluvial, trough-cross-bedded, red sandstones and gneiss-cobble conglomerates infill the northern palaeovalley around Port Cam, and near the northern coast they interdigitate with laminated red sandstones. The latter are believed to have been laid down on barchan sand dunes because of their grain size and cross-bedding and the presence of several tongues of evidently water-laid, massive, pebbly sands with erosive bases. A possible explanation for the contrast in the valley fill between Clachtoll and Port Cam is syn-depositional tectonic tilting of the area, which eliminated the longitudinal gradients of some palaeovalleys so that they became the sites of lakes or swamps, whereas other palaeovalleys retained vigorous streams.

The last event in the burial history of the basement relief was the formation of a lake over the whole area, represented by red mudstones near the top of the Clachtoll Formation. At this point the palaeoslope apparently changed abruptly through 180° from westerly to easterly, marking the start of a second phase of sedimentary history.

The lake sediments were covered by the pebbly alluvial sands of the Bay of Stoer Formation, which were deposited by braided rivers coming from the rift flanks (Stewart, 1988a). This fluvial sedimentation was frequently interrupted by down-warping of the alluvial plain, perhaps due to volcanic eruptions, allowing the formation of temporary lakes. The lake deposits are the muddy sandstone–red mudstone couplets described above, of which the most remarkable are those constituting the Stac Fada and Poll a' Mhuilt members. The volcanic association is demonstrated by the abundance of glassy lapilli in the Stac Fada Member, which differentiates this unit from the other muddy sandstones.

Lawson (1972) interpreted the Stac Fada Member as a hot pyroclastic flow, while Sanders and Johnston (1989) suggested that it represents an extrusion of fluidized peperite resulting from the injection of hot magma into wet sediment at depth. Most recently, Stewart (1990a,b) has studied the geochemistry of these rocks and interpreted them as having formed when ash-fall tuff was washed into temporary lakes together with more-typical sediments of the Bay of Stoer Formation.

The top of the Poll a' Mhuilt Member is marked by another abrupt change in palaeo-current direction, this time from easterly back to westerly. This last phase of sedimentation, represented by the Meall Dearg Formation, was again alluvial, but the channels were wider and the slopes more gentle than in Bay of Stoer Formation time. The cross-bedding was formed by transverse bars, rather than as dunes.

The reversals of palaeocurrent direction through 180° indicate that the sediments of the Stoer Group accumulated in an active rift-valley trending north–south (Stewart, 1982). Geochemical and detrital zircon studies on rocks from Stoer confirm that the main source for these sediments was the local Lewisian gneisses (Van de Kamp and Leake, 1997; Young, 1999a; Rainbird *et al.*, 2001). The volcanic glass in the Stac Fada Member has been shown to be silica-undersaturated and potassic, further supporting a rift setting (Stewart, 1990b).

The palaeoclimate during deposition of the Stoer Group was probably semi-arid. The palaeo-latitude, deduced from earlier palaeomagnetic studies (Torsvik and Sturt, 1987), was 10°–20° N, but the revised data of Buchan *et al.* (2000,

2001) and Darabi and Piper (2004) suggests that the area lay between 20° and 25° N. This corresponds today to climates ranging from tropical savannah to desert. The absence of significant chemical weathering of mineral grains in both the alluvial sandstones and the locally derived sedimentary rocks near the basal unconformity is consistent with a semi-arid climate over the whole area of the rift (Young, 1999a; Stewart, 2002).

Conclusions

The Stoer GCR site contains the type section of the Stoer Group, which consists of sedimentary breccias, sandstones and mudstones with minor carbonate rocks and volcanic rocks, interpreted as deposited in an evolving Mesoproterozoic rift. It provides the best exposures in Britain in which the complex interplay of fluvial, aeolian, lacustrine and volcanic processes within a rift sequence of this type can be studied. Because of their superb exposure and lack of metamorphism, the sedimentary rocks at Stoer have a significant potential for further geochemical, palaeontological and isotopic studies, which can be used to study palaeoenvironments during the Proterozoic. There are no comparable sedimentary rocks of similar age on the Laurentian shield, or in Europe, and the site is therefore of international importance.

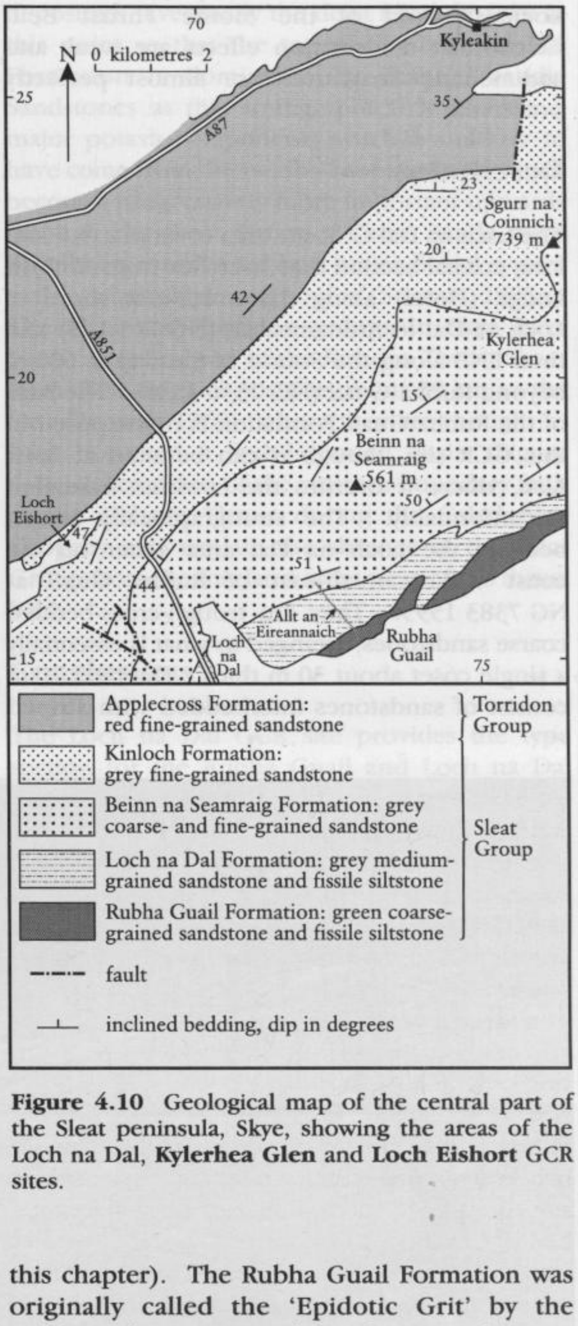


Figure 4.10 Geological map of the central part of the Sleat peninsula, Skye, showing the areas of the Loch na Dal, **Kylerhea Glen** and **Loch Eishort** GCR sites.

LOCH NA DAL (NG 703 160–NG 739 160)

A.D. Stewart

Introduction

The Sleat Group conformably underlies the Torridon Group in the Kishorn Thrust Sheet of Skye and is probably about the same age (*c.* 1000 Ma; Turnbull *et al.*, 1996). The lowest units of the Sleat Group, the Rubha Guail and Loch na Dal formations, are together about 1 km thick. The best and most easily accessible exposures of these formations are found on the Isle of Skye along the west coast of the Sound of Sleat and the east coast of Loch na Dal (Figure 4.10). This latter locality constitutes the type section (Peach *et al.*, 1907). It also exposes the immediately overlying Beinn na Seamraig Formation (see **Kylerhea Glen** GCR site report, this chapter). The Rubha Guail Formation was originally called the 'Epidotic Grit' by the Geological Survey (Peach *et al.*, 1907), but was renamed by Stewart (1975). The sequence dips north-west at angles ranging from 20° to 50° and lies on the lower right-way-up limb of the Lochalsh Syncline.

The Loch na Dal section shows interfingering alluvial-fan and lake deposits, the latter containing phosphatic laminae with acritarch microfossils. The rocks have been affected by very low-grade Caledonian metamorphism, which probably explains why they are grey rather than red. However, in spite of its structural position in the

Lochalsh Fold of the Moine Thrust Belt, Caledonian deformation effects are weak and sedimentary structures are almost perfectly preserved.

Description

The Loch na Dal GCR site area covers a *c.* 4.5 km-long coastal section that stretches from Kinloch Lodge (Hotel) along the north-east shore of Loch na Dal to Ardnameacan (NG 715 148) and then ENE along the Sound of Sleat to *c.* 600 m beyond Rubha Guail (NG 7336 1556). The base of the Rubha Guail Formation is not exposed in this GCR site, though it can be seen at Loch Alsh, where it overlies the Lewisian basement unconformably. The stratigraphically lowest beds in the Loch na Dal area occur on the coast 400 m north-east of Rubha Guail at NG 7383 1595. They are trough-cross-bedded coarse sandstones, arranged in what is essentially a single coset about 30 m thick. The next 70 m consist of sandstones interbedded with striped siltstones and mudstones (Stewart, 1962). The sandstone beds are trough cross-bedded and have erosional bases (Figure 4.11). Some of the striped beds have well-developed desiccation polygons. The rocks have been metamorphosed under greenschist-facies conditions and are all greyish-green in colour, due to the presence of chlorite in the mudstones and epidote in the sandstones.

South-westwards from Rubha Guail the coast section exposes grey and green, fine-grained sandstones and millimetre-laminated mudstones, which overlie the sandstones described above. Sedimentologically these belong to the Loch na Dal Formation, but were included in the Rubha Guail Formation by the Geological Survey, presumably because of their green tints. They are about 170 m thick. The palaeocurrent directions inferred from trough-cross-bed foresets in the sandstones are tightly clustered around 073° (Sutton and Watson, 1960), suggesting that they were deposited on an E-inclined palaeoslope.

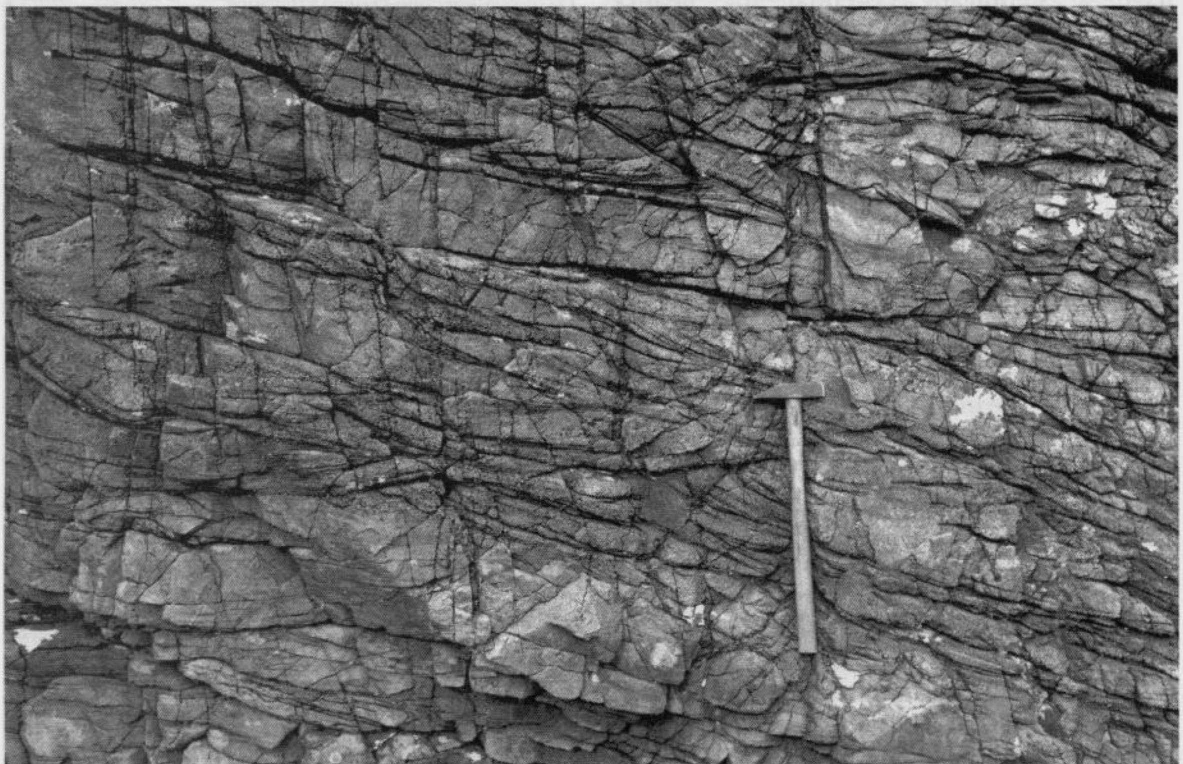


Figure 4.11 Trough-cross-bedded epidotic sandstone, typical of the lower part of the Rubha Guail Formation in Skye. The grain size of the sandstone is coarse to very coarse, with a maximum of 5 mm. The observer looks roughly eastwards, parallel to the palaeocurrent direction. The locality is near high-water mark 60 m north-east of the mouth of Allt an Eireannaich (NG 7296 1535). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

The overlying Loch na Dal Formation (800 m thick) consists of interbedded dark-grey mudstones and grey sandstones. The contact with the Rubha Guail Formation is concealed by a shingle beach at the mouth of the Allt na Teanga Odhair (NG 7220 1504). The sandstones of the Loch na Dal Formation are coarse grained, normally containing seams of quartz and K-feldspar grains up to 5 mm in size, and weather to a yellowish-grey colour. Grading is absent from the sandstones, but beds with ripple-drift lamination and rippled tops are common. Sorting is poor, so that many of the sandstones have textures similar to wackes, and wisps and fragments of mudstone are commonly incorporated. The mudstone units may be either massive or laminated on a millimetre-scale, and they contain rare phosphate laminae a few millimetres thick. W.L. Diver (pers. comm.) has reported acritarchs from the phosphate layers, but no details have been published.

The uppermost 200 m of the Loch na Dal Formation contains coarser-grained sandstone and less mudstone than the rest of the formation. The overlying Beinn na Seamraig Formation is not well exposed on the coast section, and its contact with the Loch na Dal Formation is concealed.

Interpretation

Substantial basement relief existed when deposition of the Sleat Group started. In Lochcarron, some 25 km north-east of Loch na Dal, both the Rubha Guail Formation and part of the Loch na Dal Formation are contained within palaeovalleys eroded into Lewisian gneisses (Peach *et al.*, 1907). Farther south, in Skye, the Rubha Guail Formation contains gneiss blocks up to 30 cm across (Bailey, 1955). The basal breccias and trough-cross-bedded sandstones of this formation are thus interpreted as alluvial fans, which fine upwards and pass laterally into mudstones deposited in lacustrine or shallow-marine conditions. This conclusion is confirmed by the normative mineralogy of the Rubha Guail sandstones, which is very similar to the local hornblende-biotite gneiss (Stewart, 1991a).

The coarse-grained nature of the sandstones in the Loch na Dal Formation indicates a nearby fluvial source. They are seen as having been deposited from the west by turbid underflows, close to a delta, which was building out into the lake or shallow sea in which the mudstones were deposited. Eventually the delta filled the lake at this point so that the top of the Loch na Dal Formation is dominated by channel sands. Sandstones at this stratigraphical level have a major potash component, which is unlikely to have come from the nearby basement and which becomes progressively more important upwards through the Sleat Group. These sands must have been contributed by a major fluvial system with a relatively distant source (Stewart, 1991a). The Sleat and Torridon groups in Skye have been carried as part of the Kishorn Thrust Sheet from their original position about 20 km to the east (Ramsay, 1969), where they are thought to have occupied a fault-bounded basin (Figure 4.2). Reactivation of the western boundary fault as the Kishorn Thrust during the Caledonian Orogeny may explain the absence of the Sleat Group from the foreland areas west of the thrust belt.

Conclusions

The Loch na Dal GCR site provides the type section for the Rubha Guail and Loch na Dal formations that make up the lower part of the Sleat Group. The sedimentary sequence in this site consists of alluvial sandstones and lacustrine or shallow-marine mudstones, deposited on an irregular surface of Lewisian gneisses during the initial subsidence of a rift-valley. The alluvial sands, supplied by streams coming from the west, gradually built out into a lake, generating a fining-upward sequence represented by the Rubha Guail and Loch na Dal formations. The site provides an important reference section through the older parts of the Torridon Group and is nationally important for teaching and research purposes.

KYLERHEA GLEN (NG 753 209)

A.D. Stewart

Introduction

This small site contains a representative and easily accessible reference section for the top part of the Beinn na Seamraig Formation, one of the component units of the Sleat Group. The formation consists of coarse-grained alluvial sandstones, with subordinate fissile grey mudstones, and is interpreted to have been deposited in a fault-bounded basin (Figure 4.2). The outcrops in Kylerhea Glen (Figure 4.10) display excellent examples of sedimentary structures in the sandstones, including current bedding, convolute bedding and slumping. The beds dip 22°–30° to the NNE and lie close to the hinge of the Lochalsh Syncline. Their structural position has probably accentuated the sedimentary features.

The rocks form extensive outcrops near the road at the head of Kylerhea Glen in the eastern part of the Sleat peninsula of Skye (Figure 4.10). The less-accessible type area for the formation, originally established by Peach *et al.* (1907), is at Beinn na Seamraig some 4 km to the south-west. Here, the formation is about 1100 m thick.

Description

The Kylerhea Glen GCR site consists primarily of craggy, etched sandstone outcrops of the Beinn na Seamraig Formation which lie some 1.5 km north of Bealach Udal. Figure 4.12 shows the greater part of a continuous 15 m section through the site, and illustrates the variety of sedimentary structures present. The rocks are mainly coarse-grained sandstones and are greenish-grey in colour. Both trough and planar cross-beds are common, and around half of the beds show convolute bedding, which developed while the sediment was still wet, prior to consolidation and diagenesis. The bases of the sandstone beds are commonly erosive, while the tops frequently show ripple-drift lamination due to waning flow. Finer-grained beds are comparatively rare in the formation, but one is included in the measured section. It contains laminated siltstones and current-rippled, fine-grained sandstones similar to those seen in the upper part of the Loch na Dal Formation.

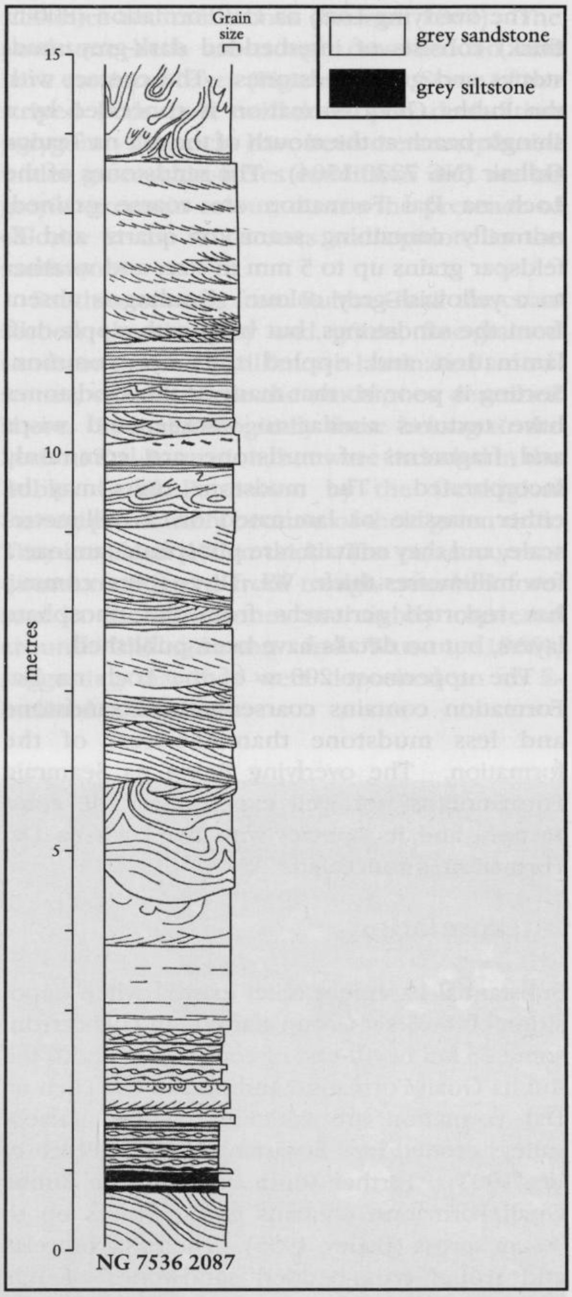


Figure 4.12 Graphic log of part of the Beinn na Seamraig Formation in Kylerhea Glen, about 150 m north-east of the road summit. The grain-size scale at the top of the log spans +4Ø to 0Ø units (0.06–1 mm). Sedimentary structures are illustrated schematically, but drawn as seen and to scale.

Interpretation

The coarse sandstones of the Beinn na Seamraig Formation were deposited in river and stream channels on a braided alluvial plain. The finer-grained beds, which in places form mappable units (Sutton and Watson, 1964), may represent the temporary advance of a lake margin across the area. Palaeocurrent directions derived from cross-bed and ripple-bedding orientations indicate a source area to the north (Sutton and Watson, 1964). However, Potts (1990) suggested that as the area lies within the Kishorn Thrust Sheet, it was possibly rotated *c.* 26° clockwise during Scandian deformation and thrusting.

Hence, the original palaeocurrent direction may have been from the NNW. The formation is interpreted as having been deposited in a NNE-trending fault-bounded trough (Figure 4.2) with coarser-grained sands supplied mostly from its north-western flank. The fine-grained sediment was deposited in an axial lacustrine or shallow-marine environment that prevailed periodically.

Conclusions

The Kylerhea Glen GCR site provides a coherent reference section for the Beinn na Seamraig Formation. This unit is restricted to Skye and Lochalsh, and except in Kylerhea Glen it is relatively inaccessible. The formation is over 1000 m thick and lies in the mid- to upper part of the Sleat Group, which formed in an early Neoproterozoic rift environment. It contains excellent examples of sedimentary structures, such as cross-bedding and convolute bedding, in sandstones deposited mainly from braided rivers. Subsidiary fine-grained sandstones and siltstones represent deposition in short-lived lakes or during shallow-marine incursions. The site is nationally important to the understanding of the geological history and palaeogeography of the Sleat Group.

LOCH EISHORT (NG 668 169, NG 677 161)

A.D. Stewart

Introduction

The Loch Eishort GCR site displays a reference section that is representative of the upper part of the Kinloch Formation, the youngest formation of the Sleat Group, which is well exposed in coastal exposures north-west of Drumfearn on the Sleat peninsula of Skye (Figure 4.10). Exposures of the formation near Kinloch, 3 km to the north-east, originally designated as the type area by Peach *et al.* (1907), are less suitable for the examination of sedimentary structures. The Kinloch Formation is about 1100 m thick and is composed of fine-grained grey sandstones and subordinate fissile mudstones of fluvial and lacustrine origin. The beds dip 40°–50° to the north-west and lie on the lower right-way-up limb of the Lochalsh Syncline.

Description

The GCR site stretches from the craggy summit of Mullach an Achaidh Mhòir (NG 6770 1618) down its north-western flank to the raised-beach and rock-platform outcrops around the 'neck' near the head of Loch Eishort. Exposures are best seen on the coastal section. The Kinloch Formation here comprises fining-upward sedimentary cycles, individually 25–35 m thick, with strongly contorted, cross-bedded sandstones at the bases of the cycles, passing upwards into interbedded sandstones and siltstones (Stewart, 1966a).

The sandstones at the base of the cycles are uniformly fine-grained and of medium-grey colour. Large-scale trough-cross-bedding can be identified, and ripple-drift lamination is very common. The darker-grey fine-grained siltstones that form the top parts of the cycles have been preferentially ground down by glaciation and are now covered by shingle. These concealed siltstones can be seen on Skye 500 m south-west of Ob Gauscavaig (NG 591 115). They consist of millimetre- and centimetre-thick beds of fissile, grey siltstone, commonly ripple-laminated (Stewart, 1966a). These correspond to the 'carbonaceous shales' that were searched unsuccessfully for fossils by the Geological Survey (Geikie, 1900).

Interpretation

The sedimentary cycles at Loch Eishort are interpreted as having originated as alluvial-fan sandstones interfingering with lake or shallow-marine sediments. They are analogous to the Rubha Dubh Ard and Achduart members, which occur at the base of the overlying Applecross Formation (Torridon Group) and are described in the **Achduart** GCR site report (this chapter; Stewart, 1966a). Palaeocurrents in the Kinloch Formation flowed eastwards (Sutton and Watson, 1964), towards a permanent water body that expanded westwards periodically across the alluvial fans. The formation is interpreted as having been deposited in a NNE-trending fault-bounded trough (Figure 4.2) in which fine-grained sediment was deposited in an axial lacustrine or shallow-marine environment, while coarser-grained alluvial sediment was supplied from the western flank.

Conclusions

The Loch Eishort GCR site provides a reference section for the sandstones of the Kinloch Formation of the Sleat Group, which are not particularly well exposed elsewhere. As such it complements the **Kylerhea Glen** GCR site, and together they provide a picture of the depositional environment and palaeogeography of the upper part of the Sleat Group. The sandstones at the Loch Eishort GCR site show excellent examples of sedimentary structures that include trough cross-bedding, convolute bedding and ripple-lamination. They are interpreted as having been laid down on alluvial fans and in ephemeral lakes in an early Neoproterozoic rift environment. The site provides a useful teaching and reference section, suitable for further study, and is of national importance.

DIABAIG (NG 785 604–NG 798 600, NG 820 622– NG 821 598)

A.D. Stewart

Introduction

The coastal section and inland outcrops around Diabaig, on the north side of Loch Torridon, constitute the type area for the Diabaig Formation, the lowest unit in the Torridon Group. The basal parts of the overlying Applecross Formation are also well exposed (Peach *et al.*, 1907). The beds mainly dip between 10° and 18° to the west and locally to the south-west and north-west. A geological map of the area is shown in Figure 4.13. The Diabaig Formation was deposited in deep palaeovalleys eroded in the basement gneisses, reaching a maximum thickness at Diabaig of about 130 m. Breccias, which formed on the valley flanks, grade laterally into grey siltstones in the valley centres. Diabaig is renowned for the exceptional clarity with which this facies change can be demonstrated, and for its shore section, which displays a thick sequence of desiccated grey siltstones. Phosphate concretions in the siltstones contain well-preserved algal filaments and spheroidal microfossils (Downie, 1962; Peat and Diver, 1982). The earliest sedimentological study of the Diabaig Formation was the subject of a brief essay by Allen *et al.* (1960). Later work has concerned the boron content of illites in the siltstones (Stewart and Parker, 1979), the sedimentology and geochemistry (Rodd and Stewart, 1992), and the source of the sediments (Stewart, 1995b; Van de Kamp and Leake, 1997). Phosphorite samples from Diabaig have been dated by Rb-Sr methods to give an age of diagenesis for the Diabaig Formation of 994 ± 48 Ma (Turnbull *et al.*, 1996).

Description

The Diabaig GCR site area includes the well-exposed 1.5 km-long coastal section on the north shore of Loch Diabaig extending west from the jetty at Sgeir Ghlas (NG 7968 5982) and including its backing cliffs. The site extends north-east through Lower Diabaig to the rocky plateau above. It also includes a rocky inland area that stretches north from the eastern end of Loch Diabaigas Airde via Loch Roag to Loch na h-Uamhaig. The site adjoins the **Alligin** GCR site, which displays notable features in the Lewisian Gneiss Complex (see Chapter 3).

The Diabaig Formation was deposited on an irregular landscape cut into the Lewisian basement, with a relief of about 250 m at Diabaig. All the sediments of the formation accumulated in the lower parts of the palaeovalleys, and laterally abut the basement gneisses that supplied the coarser detritus. The sediments nearest the gneiss, termed the 'breccia facies', are the coarsest at any given stratigraphical level of the Torridonian, consisting mostly of either massive breccias, or interbedded breccia and red sandstone. The clasts are mostly centimetre- or decimetre-size and only rarely exceed 1 m across. Reddened rims are common, and the clasts are more angular than those in the Stoer Group breccias. Away from the unconformity, clast-size diminishes and the proportion of sandstone increases. The breccias pass laterally into tabular sandstones, the transition being defined where the clast content falls below 50% (by volume). At Diabaig, this transition from breccias to tabular sandstones is always less than 400 m along a bedding plane from the unconformity.

The tabular sandstones owe their well-defined bedding to relatively fine-grained laminae, normally micaceous. They are ornamented by straight-crested, symmetrical ripples and small scours are common. Liquefaction of some of the tabular sandstone

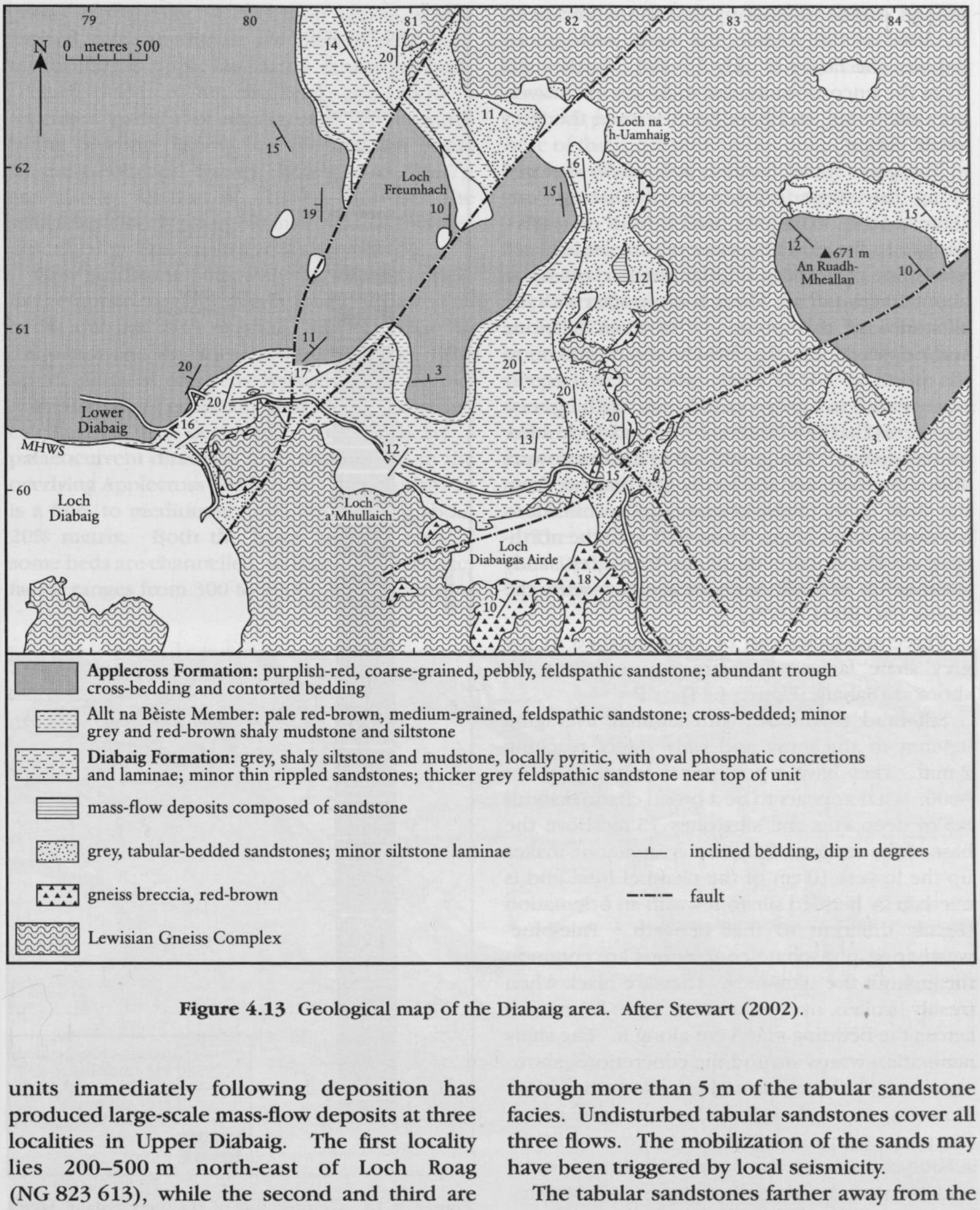


Figure 4.13 Geological map of the Diabaig area. After Stewart (2002).

units immediately following deposition has produced large-scale mass-flow deposits at three localities in Upper Diabaig. The first locality lies 200–500 m north-east of Loch Roag (NG 823 613), while the second and third are about 1 km south-east of the loch at NG 825 603 and NG 825 600. The mass-flow deposit nearest the loch is 20 m thick and its basal contact is sharp, with signs of injection and disruption. Wispy asymmetrical folds within the deposit indicate movement towards the south-west, down the local palaeoslope. At the third locality the base of the massive deposit cuts down through more than 5 m of the tabular sandstone facies. Undisturbed tabular sandstones cover all three flows. The mobilization of the sands may have been triggered by local seismicity.

The tabular sandstones farther away from the unconformity are interbedded with fine-grained micaceous sandstones and siltstones, in parts red but more generally grey. Those seen by the roadside near Upper Diabaig at NG 8195 6016 have abundant W-migrating climbing ripples and are situated about 400 m down the palaeoslope from the gneisses. The thinnest and finest-grained sandstone beds have a persistency factor (lateral extent divided by maximum thickness) of 1000–10 000, while for beds with gneiss pebbles the factor is only 50–100. Farther still from the unconformity, the rocks are exclusively grey siltstones, and have been termed the 'grey 'shale' facies'.

The grey 'shale' facies is splendidly exposed along the shore north-west of Diabaig jetty (Figure 4.14). The jetty itself is built on gneiss, flanked to the north by some tabular beds of red sandstone containing angular gneiss clasts up to about 10 cm across. There is no contact with the siltstones at this point. The main siltstone section starts on the beach about 300 m to the north at NG 797 601, where it is laterally equivalent to grey sandstone with gneiss fragments that can be seen by the roadside a few metres distant. The gneiss hill of An Torr towers above the road, and the horizontal distance from the shale facies to the Lewisian gneiss hillside is here only about 30 m. Some 520 m to the north-east, on the north side of An Torr, grey sandy siltstone is actually seen in contact with the gneiss (NG 8004 6057).

Three sub-facies can be distinguished in the grey 'shale' facies, which are exposed along the shore at Diabaig (Figure 4.14):

Silt–mud rhythmite, with laminae averaging 0.3 mm in thickness and only rarely reaching 2 mm. They have a persistency factor of about 3000. What appears to be a broad channel about 0.5 m deep cuts the siltstones 75 m above the base of the section. Calcareous sandstone makes up the lowest 10 cm of the channel infill and is overlain by bedded siltstones with an orientation slightly different to that beneath. Pale-blue-weathering phosphate concretions are common throughout the siltstones. They are black when freshly broken, oval, measuring up to 1 cm thick across the bedding and 5 cm along it. The shaly lamination wraps around the concretions, showing clearly that they formed prior to compaction. More-extensive phosphate laminae also occur. Organic-walled microfossils are common in the siltstones but are best preserved and quite undeformed in the phosphate concretions. They have never been described in detail.

Ripple-laminated sandstone beds of millimetre- to centimetre-thickness are interlayered with the siltstones. The ripple foresets have no consistent dip direction, and although the crests are fairly constant in orientation in any given stratigraphical interval, they gradually swing from east–west at the base of the section to north–south at the top. They do not indicate palaeocurrent directions and are interpreted as reflecting wave patterns related to the emergent

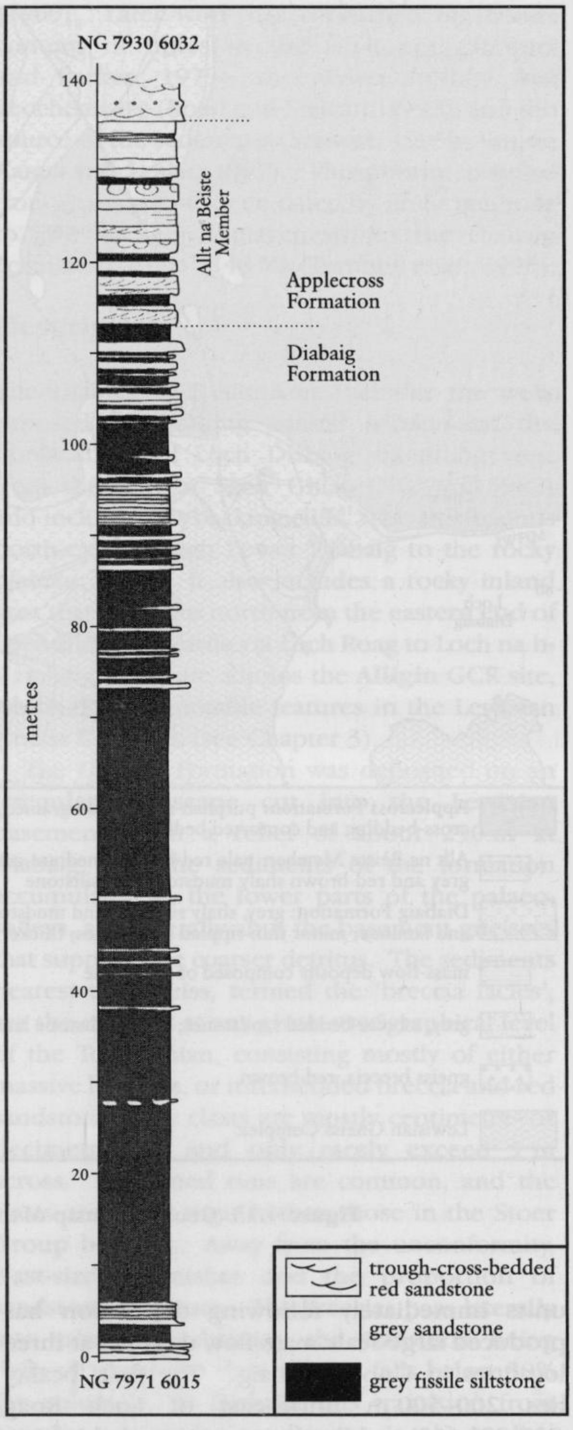


Figure 4.14 Graphic log of the grey 'shale' facies (Diabaig Formation) and Allt na Bèiste Member (Applecross Formation), exposed along the coast west of Diabaig jetty.

gneiss topography. Desiccation cracks, which formed in the rhythmite, are filled by sand from the overlying ripple-laminated sandstone beds (Figure 4.15). The siltstones also show a reticulate pattern of small ridges on upward-facing bedding planes, described as rain prints by the Geological Survey (Peach *et al.*, 1907), and also by Allen *et al.* (1960). However, the structures closely resemble micro-load structures described by Dzulynski and Walton (1965).

Grey sandstone beds with sharp bases appear in the upper part of the grey 'shale' facies. The beds are up to 1 m thick and increase in frequency and thickness towards the top. The upper parts of the beds typically show ripple-drift lamination, especially clear where secondary calcification has occurred. They indicate a palaeocurrent direction from the west, as in the overlying Applecross Formation. The 'sandstone' is a fine- to medium-grained wacke, with about 20% matrix. Both the bases and the tops of some beds are channelled, so that the persistency factor ranges from 300 to 1000. The uppermost 25 m of the section contains abundant rippled sandstones (Figure 4.16), which are much coarser than those at lower levels, but the siltstones still show evidence of desiccation.

Small pyrite cubes have been noted near the base of the shore section but not at higher levels. There is no trace of either primary carbonate or evaporite minerals in the Diabaig Formation.

Facies inter-relationships in the Diabaig Formation are conveniently studied along the roadside north-east of Loch Diabaigas Airde. Exposures begin just above the bend in the road at NG 8214 6008 where massive breccia is in contact with gneiss. Stratigraphically higher and progressively finer-grained beds crop out to the west, the last seen being red, micaceous, ripple-laminated beds at NG 8187 6008. The up-dip breccia equivalents of the micaceous beds can be seen to the NNE above the recent screes, with the Lewisian basement beyond.

The contact between the grey 'shale' facies of the Diabaig Formation and the overlying Applecross Formation is defined at the western

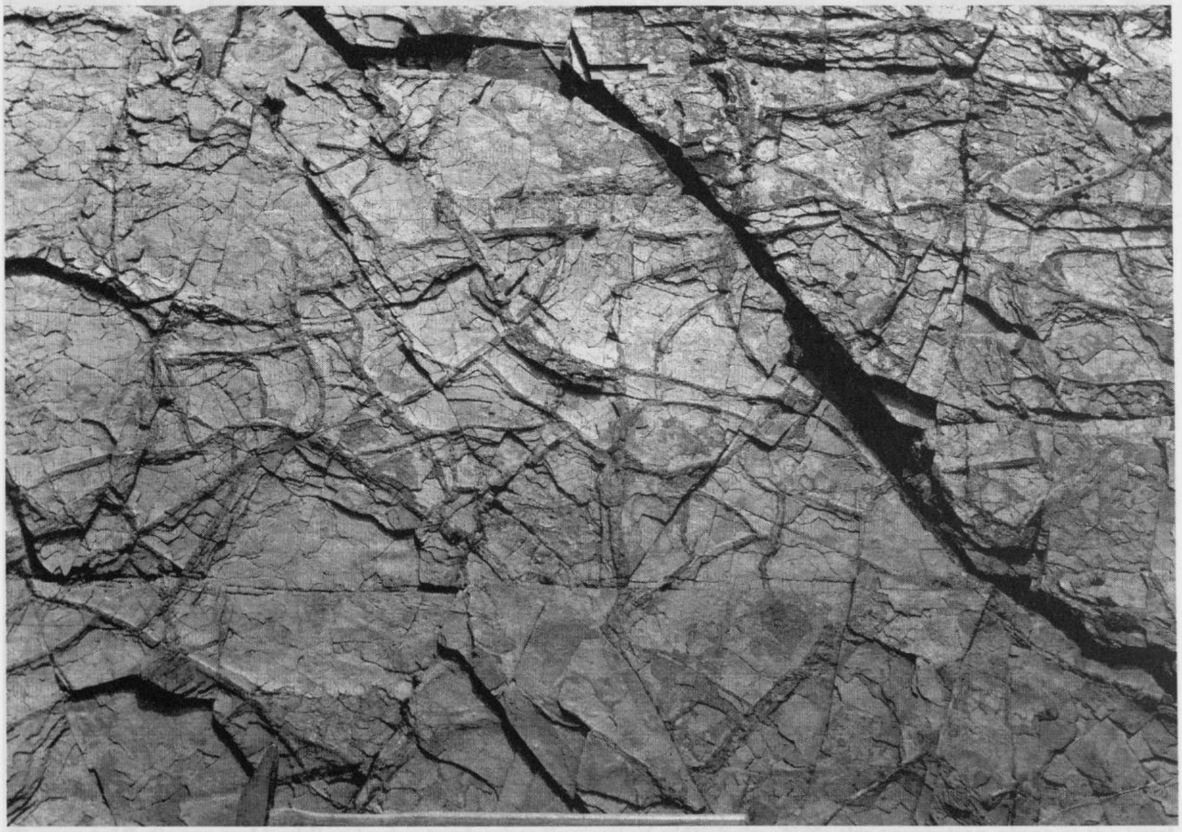


Figure 4.15 Desiccation cracks in the grey 'shale' facies of the Diabaig Formation at Diabaig. The exposure is on the shore about 400 m north-west of Diabaig jetty (NG 7964 6017). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

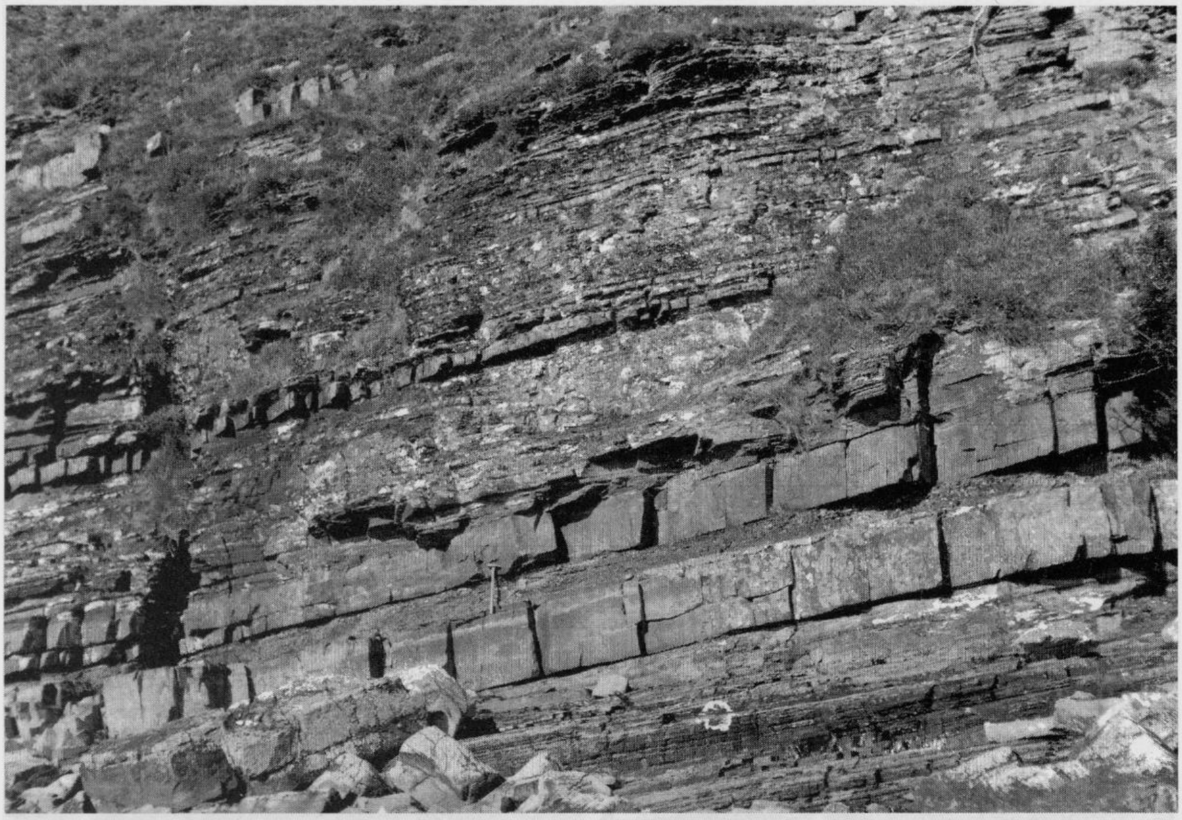


Figure 4.16 Grey sandstone beds in the upper part of the grey 'shale' facies at Diabaig. The two prominent beds touching the hammer are at 96–97 m on the section in Figure 4.14. The location is just above high-water mark at the mouth of Allt na Bèiste (NG 7927 6027). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

end of the shore section by the abrupt appearance of trough-cross-bedded red sandstone. The lowest 20 m of the Applecross Formation form a mappable member, exposed in the burn section of the Allt na Bèiste where it dashes down through the wooded scarp to the sea (NG 7929 6028). This is the type section of the Allt na Bèiste Member. The Geological Survey described the unit as 'massive bright-red sandstones with shale partings' (Peach *et al.*, 1907) and included it in the Diabaig Formation, doubtless because it lacked large durable pebbles. However, the sandstones of the Allt na Bèiste Member, though finer grained than much of the Applecross Formation, have trough cross-bedding, contorted in places, which is similar to that seen elsewhere in the formation. The modal mineralogy is also very similar to that of the Applecross Formation, but is unlike that of the sandstones in the Diabaig Formation (see below). The Allt na Bèiste Member also contains 'porphyry' and black chert pebbles, typical of the Applecross Formation. These are most easily found on the low cliffs about 500 m west of the type section at NG 7877 6029, where the exposures are fresher than in Allt na Bèiste.

The sandstone of the Allt na Bèiste Member weathers to a pale reddish-brown, but when fresh is pale red to greyish red. These colours largely reflect the K-feldspar content, which forms about 25% of the rock. This contrasts with the tabular sandstones of the Diabaig Formation, which contain about 40% detrital feldspar, mostly plagioclase derived from the local basement gneisses. The siltstones in the Allt na Bèiste Member are generally grey, becoming red toward the top of the succession. Palaeocurrents flowed eastwards, as in the underlying rocks of the Diabaig Formation and the higher parts of the Applecross Formation.

The top of the Allt na Bèiste Member in the type section is marked by the highest red siltstone, above which the sandstone is noticeably different to that below. The colour of this sandstone is reddish purple and the grain size is coarse to very coarse. About 50% of the beds are contorted as compared to only about 5% in the Allt na Bèiste Member. Half-centimetre-sized durable pebbles appear about 2 m above the top of the Allt na Bèiste Member, and pebbles over 1 cm across become common about 10 m higher.

Magnificent exposures of these coarse-grained beds of the Applecross Formation can be studied about 200 m west of the Diabaig township wall, at NG 786 603, *c.* 45 m above sea level. More than half the beds show soft-sediment deformation features like those described by Owen (1995) from the Torridon area, including isolated structures, discrete units, chaotic units and multi-layer complexes (Figure 4.17), although the reported contorted heavy-mineral laminae are not present at Diabaig.

Interpretation

The palaeovalleys in the gneisses beneath the Torridon Group were initially half-filled by the breccias, sandstones and siltstones of the Diabaig Formation (Stewart, 1972). The clasts in the breccias accurately reflect the composition of the adjacent gneiss and represent fan-head deposits, grading laterally into the tabular sandstones, which were formed in the more-distal parts of the alluvial fans. The grey 'shale' facies, which occupies the centres of the palaeovalleys, represents lake deposits. The boron content of illite in the shale facies is low and does not suggest permanent marine conditions (Stewart and Parker, 1979). The breccia clasts and the sands were derived from the local gneiss palaeohills, but the geochemistry of the siltstones shows that about a quarter of the finest sediment was extraneous biotite. This biotite was probably supplied by the rivers that later deposited the Applecross Formation (Rodd and Stewart, 1992).

The size of the Diabaig lake is indicated by the dimensions of the grey 'shale' facies, which extends southwards from Diabaig for at least 70 km, and attains some 400 m in thickness on Rum (Figure 4.4). The lack of evaporites and primary carbonates suggests that the lake had an outlet and that solute concentrations were

Figure 4.17 Contorted bedding in the Applecross Formation at Diabaig. Note the truncation plane at the level of the hammer head. Water-escape structures like this affect over half the Applecross Formation and the whole of the Aultbea Formation. The exposure is about 170 m west of Diabaig township (NG 7867 6037). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

consequently low (Rodd and Stewart, 1992). Diabaig was near the lake margin, and episodic variations in lake level may have caused temporary emergence and desiccation of the lake sediment. Assuming a typical sedimentation rate of around 500 m/Ma (Baltzer, 1991) and one desiccated surface every 6 cm (see above), there must have been an average of one desiccation event each century. This could easily have been caused by changes either in climate or in the height of the outlet. Such changes produce variations of a few metres in the water level of African rift lakes in a century (Beadle, 1981) and suggest that the lake at Diabaig was only a few metres deep.

The grey sandstone sub-facies are interpreted as turbid underflows, fed by the 'Applecross' rivers advancing from the highlands to the west (Stewart, 1988b). These too seem to have formed in shallow water, as shown by the presence of desiccation cracks in the intervening siltstones and the evidence of scouring of the tops of some beds. The sandstones of the Allt na Bèiste Member represent the first true alluvial sediments, deposited in shallow channels by braided streams.

The Applecross Formation was deposited on the Diabaig Formation, and the remaining basement hilltops by braided rivers flowing from a mountainous source some distance to the west (Nicholson, 1993; Van de Kamp and Leake, 1997; Rainbird *et al.*, 2001; Stewart, 2002).

Conclusions

The Diabaig area provides the type locality for the basal units of the Diabaig Formation, the oldest formation of the Torridon Group. It is an exceptional site for demonstrating the progressive burial of Precambrian topography by lake silts and river sands accumulating in a rift-valley environment. The microfossils, excellently preserved in phosphate concretions in the grey lacustrine siltstones, have yet to be described in detail. Their stratigraphical value and relationship to the contemporaneous sedimentary environment are promising subjects for future research. The sedimentary rocks are so little altered that they appear to be quite recent, whereas in fact they date from about 1000 million years ago. The site demonstrates the facies variations that prevailed at the base of the Torridon Group and is of national, possibly international, significance.

UPPER LOCH TORRIDON (NG 826 538–NG 869 553)

A.D. Stewart

Introduction

The southern shore of Upper Loch Torridon intersects a series of palaeovalleys in Lewisian gneisses, which are infilled by sedimentary rocks of the Diabaig and Applecross formations of the Torridon Group. The sea has invaded the softer sedimentary rocks so that the bays coincide with the ancient valleys, and are separated by hills of gneiss. From west to east these bays are Loch Shieldaig, Ob Mheallaidh, Balgy Bay, Ob Gorm Beag and Ob Gorm Mòr (Figure 4.18). Topographical relief just prior to deposition of the Torridon Group was about 250 m, as shown by the section in Figure 4.19. The A896 road follows the coast so the area is readily accessible.

The sedimentary sequences of the Diabaig Formation and the basal Applecross Formation are described in detail in the **Diabaig** GCR site report (this chapter). The Diabaig Formation consists of four component facies. The breccia facies, composed of angular clasts of local basement rocks in a matrix of red sandstone, is found mantling gneiss palaeoslopes and in the lower parts of the palaeovalleys. Moving away from the unconformity the breccias pass upwards and laterally into tabular red sandstones. At still farther distances from the unconformity, the tabular sandstones interfinger with rocks of the grey 'shale' facies. This facies consists of graded units of grey siltstone, interbedded with fine sandstones, which fill the central parts of the palaeovalleys. Towards the top of the Diabaig Formation, the sandstone beds are more prominent (the grey sandstone sub-facies). These are overlain in turn by red fluvial sandstones of the Applecross Formation. The dips of bedding in the Diabaig Formation rocks range from 2° to 30°, but are typically gentle and locally variable in direction. Bedding in the immediately overlying Applecross Formation sandstones mainly dips gently to the west, but farther south the regional bedding dips to the south and south-west at angles between 7° and 15°.

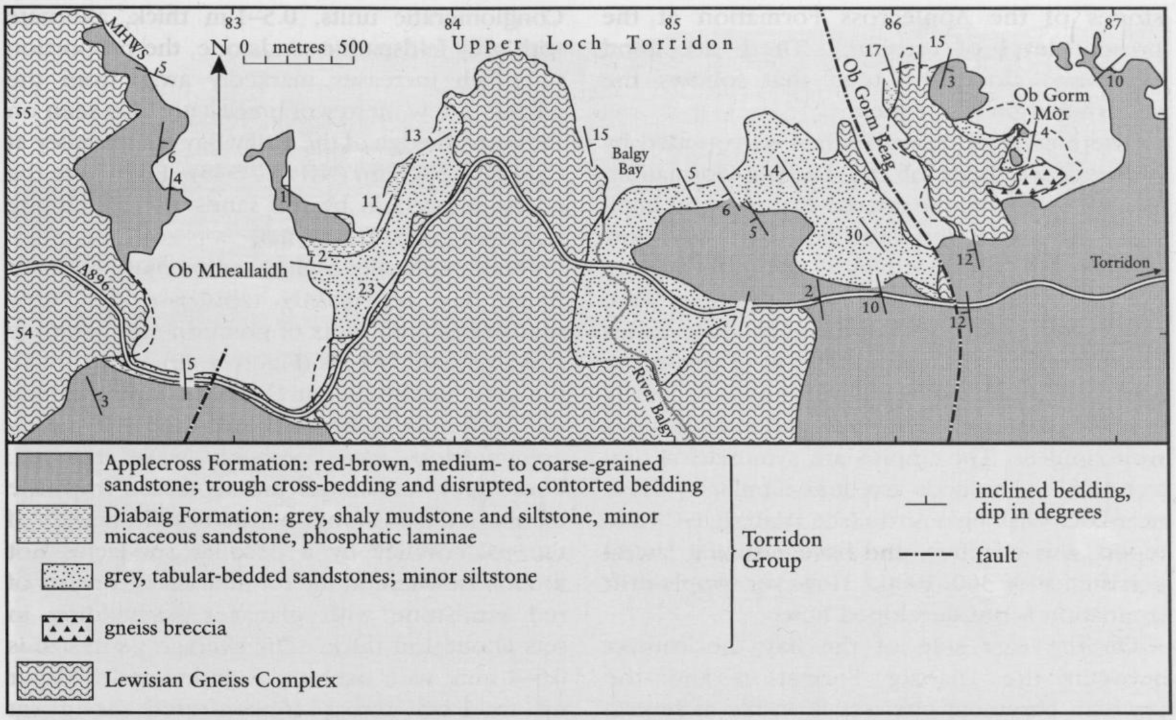


Figure 4.18 Geological map of the Upper Loch Torridon area. After Stewart (2002).

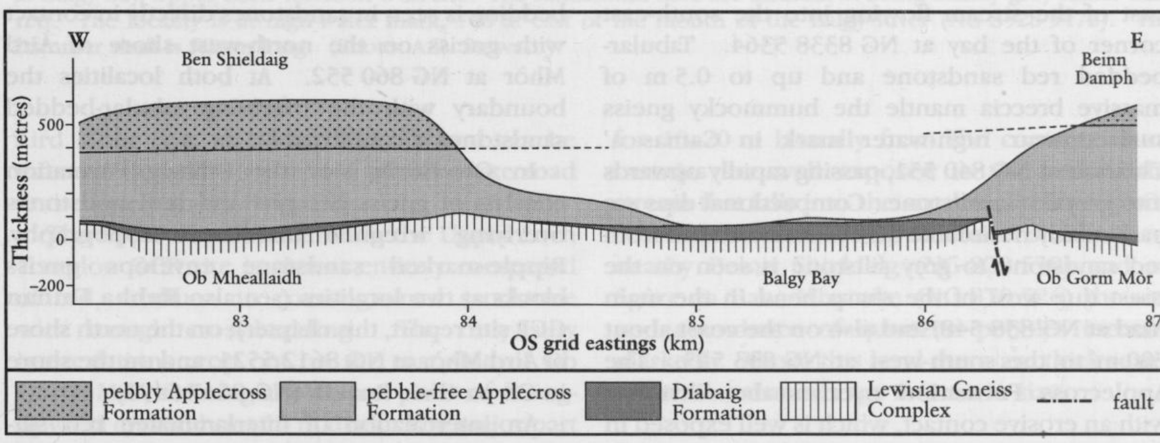


Figure 4.19 True-scale cross-section along the south side of Upper Loch Torridon, showing undulating topography developed in the basement gneisses, buried by Torridon Group sedimentary rocks. The section follows grid-line northing 542. Kilometre eastings are shown.

Description

The Upper Loch Torridon GCR site extends from the sheltered bay of Ob Mheallaidh eastwards to include the bays of Ob Gorm Beag and Ob Gorm Mòr. It includes the intervening headlands of Rubha na Feòla, Rubha Molach Beag and Àird Mhòr that all expose Lewisian gneisses and were areas of higher relief during deposition of the Torridon Group rocks. The coastal exposures are generally good, and glacially scoured and rounded rocky hills and crags are present inland. The various Diabaig Formation facies along the section are described from west to east.

The palaeovalley presently occupied by Loch Shieldaig to the west is infilled by red sandstones of the Applecross Formation at the present level of erosion. There are good exposures along the road that follows the eastern margin of the loch.

The bay of Ob Mheallaidh is surrounded by well-exposed beds of the Diabaig Formation, that dip gently off the gneiss. Exposures at high-water mark along the south side of the bay show the grey 'shale' facies typical of the formation, but also some red micaceous sandstones. Wave ripples in the siltstones of the grey 'shale' facies trend roughly south-east. The road section at about 15 m above sea level exposes locally pebbly red coarse sandstones, and red siltstones with ripples. The ripples are symmetrical and trend SSE. The beds are quite similar to those near Loch Diabaigas Airde (see **Diabaig** GCR site report, this chapter), and have a similar lateral persistency of 300–1000. However, ripple-drift lamination is not developed here.

On the east side of the bay the contact between the Diabaig Formation and the Lewisian basement gneisses is visible at several points. Red sandstone rests unconformably upon a gneiss crag by the roadside 87 m north-east of the stream flowing into the south-east corner of the bay at NG 8338 5364. Tabular-bedded red sandstone and up to 0.5 m of massive breccia mantle the hummocky gneiss surface near high-water mark in Camas a' Chlarsair at NG 840 551, passing rapidly upwards into grey fissile siltstone. Compactional dips are particularly noticeable here. The transition from red sandstone to grey siltstone is seen on the coast due west of the sharp bend in the main road at NG 838 548, and also on the coast about 700 m to the south-west at NG 833 543. The Applecross Formation overlies the siltstones with an erosive contact, which is well exposed in the wooded bluff (NG 835 545) overlooking Camas a' Chlarsair, and also under low-tide conditions about 300 m to the WNW. The grey siltstones closely resemble those in the lower part of the type section at Diabaig and, like them, contain phosphatic laminae. However, they lack the grey sandstone beds found in the upper part of the type section.

Diabaig Formation breccias are well exposed on the coast 300 m north of the river mouth at Balgy Bay (NG 845 549). The clasts are derived from the immediately adjacent gneisses and are predominantly mafic in composition. Blocks are well rounded and average about 10 cm in size, though in places they reach up to 1 m. Conglomeratic units, 0.5–1 m thick, alternate with grey feldspathic sandstone, the proportion of which increases markedly away from the gneiss. A few metres of breccia are also seen on the eastern edge of the Balgy Bay palaeovalley at Camas na Nighinn (NG 857 548). Elsewhere the gneiss is overlain by red sandstone containing scattered gneiss fragments.

Stratigraphically higher sedimentary rocks at Balgy Bay are mainly tabular-bedded grey sandstones with films of greenish-grey siltstone and abundant ripples (Figure 4.20), quite unlike the grey sandstones at Diabaig. Ripple trends are uniformly south-east and, though typically asymmetrical, were probably wave induced. These grey sandstones are separated from the tabular red sandstones on the eastern margin of the palaeovalley by a peculiar sub-facies not found elsewhere in the formation. It consists of red sandstone with planar cross-bedding in sets about 1 m thick. The average grain-size is 0.5–1 mm, with pebbles of quartz and feldspar up to 1 cm across concentrated along set boundaries. In thin section lithic grains of volcanic origin are detectable. Similar cross-bedding is seen in sandstones directly in contact with gneiss on the north-west shore of Àird Mhòr at NG 860 552. At both localities the boundary with the overlying tabular-bedded sandstones is conformable.

In Ob Gorm Mòr the Diabaig Formation consists of gneiss breccias and red sandstones overlying irregular basement topography. Ripple-marked sandstone envelops gneiss blocks at two localities (see also **Rubha Dunan** GCR site report, this chapter); on the north shore of Àird Mhòr at NG 8612 5521, and on the shore in Ob na Glaic Ruaidh (NG 8647 5491).

An intercalation of interlaminated red siltstone and pale-grey sandstone about 65 cm thick can be seen in the breccia in the south-east corner of Ob Gorm Mòr at NG 867 547. The intercalation can be traced for about 100 m along the low cliff. Bull (1972) attributed this feature to playa-lake deposition within a fanglomerate sequence.

The contact between the Applecross and Diabaig formations along the south side of Upper Loch Torridon is sharp and locally erosive. It cuts down over 1 m into breccia on the west side of Ob Gorm Mòr at NG 8663 5492, suggesting a degree of pre-Applecross Formation cementation. Sharp, planar contacts are seen on the north shore of the peninsula of

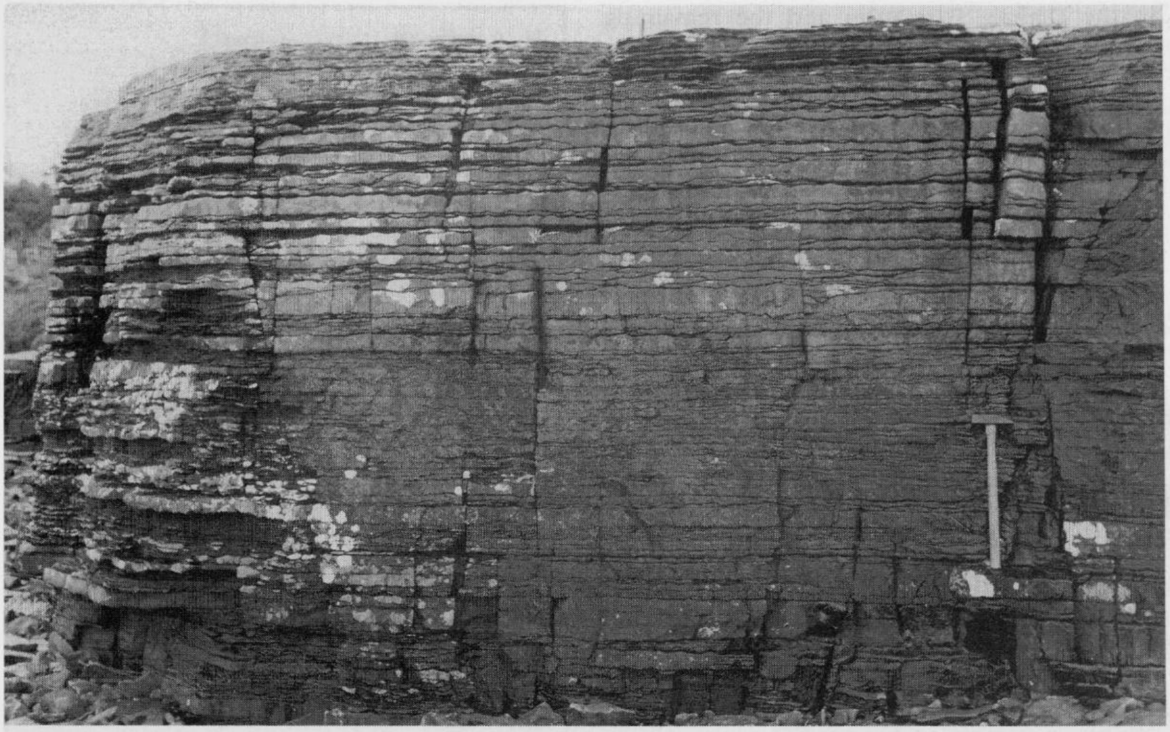


Figure 4.20 Tabular ripple-marked sandstones of the Diabaig Formation filling the centre of the palaeovalley at Balgy Bay, Upper Loch Torridon GCR site. The sandstones here are unusual in being mainly grey rather than red. The locality is at high-water mark, 700 m east of the mouth of the Balgy River (NG 8528 5472). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

Àird Mhòr (e.g. at NG 8620 5523), and can be inferred along the south side of the estate road immediately above Balgy Bay.

The Applecross Formation in the Upper Loch Torridon GCR site is almost entirely composed of red, medium- to coarse-grained sandstone with trough cross-bedding. The only silty intercalations crop out on the east side of Ob Gorm Mòr, forming the upper parts of fining-upward cycles about 10 m thick. The major part of each cycle is made up of the normal Applecross Formation lithology, with an erosional base. The upper part is formed of centimetre- to decimetre-thick tabular red sandstone beds with rippled surfaces and beds of interlaminated red siltstone and pale-grey sandstone. Siltstone dominates towards the cycle tops, although in places it has been removed by erosion. The orientations of trough axes imply that the palaeocurrents flowed south-eastwards.

Quartzite and chert pebbles up to about 1 cm in size are only rarely found in the lower part of the Applecross Formation in this area. However, where the formation rests on gneiss it contains trails of decimetre-sized, angular gneiss blocks for 10–20 m laterally from the contact. Such breccias are well exposed in the bed of the stream that falls into the south-east corner of Ob Mheallaidh. About 350 m above sea level on nearby Beinn Shieldaig (NG 829 530) and on Sgùrr na Bana-Mhoraire (NG 870 526) the size and abundance of quartzite pebbles increase markedly. Above this level there are thick seams of pebbles that average 2–3 cm in size.

Interpretation

The bays along the south side of Upper Loch Torridon represent palaeovalleys excavated in the gneisses beneath the Torridon Group, which were initially filled by the breccias, sandstones and siltstones of the Diabaig Formation (Stewart, 1972). The breccia clasts reflect the composition of the adjacent gneiss and represent fan-head deposits, grading laterally into the tabular sandstones, which were formed in the more-distal parts of the alluvial fans. The grey siltstones, which occupy the centres of the palaeovalleys, represent lake deposits. The sandstones of the overlying Applecross Formation were deposited on the Diabaig Formation and the remaining protruding basement hilltops by braided rivers flowing from the north-west.

Conclusions

A combination of uplift and erosion during more-recent geological times has exhumed spectacular exposures of the sub-Torridon Group unconformity and the overlying Torridonian sedimentary sequence in the Upper Loch Torridon GCR site. Ancient valleys in the Lewisian gneisses, which were infilled with Torridon Group sedimentary rocks, have been exploited by recent glacial and marine erosion so that they now form bays on the southern shores of the loch. Breccias and sandstones of the Diabaig Formation, which were deposited from ancient alluvial-fans around 1000 million years ago, mantle the gneisses on the slopes of these valleys. These fan deposits pass laterally and upwards into grey siltstones and sandstones, deposited in lakes in the centres of the valleys. Above the Diabaig Formation rocks are exposures of red sandstones belonging to the Applecross Formation, which were deposited from braided rivers carrying sediments from a mountainous source to the north-west. Although the Diabaig site describes similar Lewisian–Torridonian relationships, the Upper Loch Torridon GCR site illustrates the three-dimensional nature of the Lewisian–Torridonian unconformity and local facies variations in the Diabaig and Applecross formations. The site is ideal for teaching and further research and is of national importance.

RUBHA DUNAN (NC 018 069–NC 030 069)

A.D. Stewart

Introduction

The headland of Rubha Dunan, near Achiltibuie (Figures 4.1 and 4.21), is essentially a palaeohill formed of Lewisian gneisses and Stoer Group sandstones that have resisted recent erosion more effectively than the overlying gently dipping sedimentary rocks of the younger Torridon Group. The Stoer Group beds belong to the Clachtoll Formation and dip between 5° and 20° to the WNW. The steeply dipping unconformity between the Stoer and Torridon groups, which represents a Precambrian hill-slope, is beautifully exposed in low cliffs on the south side of the headland (Figure 4.22). The overlying Torridon Group beds belong to the Diabaig Formation and consist of red sandstones containing breccia units, succeeded by grey siltstones. The beds dip 20°–25° to the south-east initially but dips decrease away from the unconformity to between 5° and 10°.

The sedimentary rocks above the unconformity were thought to be Triassic when they were first mapped by the Geological Survey in 1888, but Lawson (1965) pointed out that several supposed Triassic conglomerates in north-west Scotland were, in fact, intra-Torridonian.

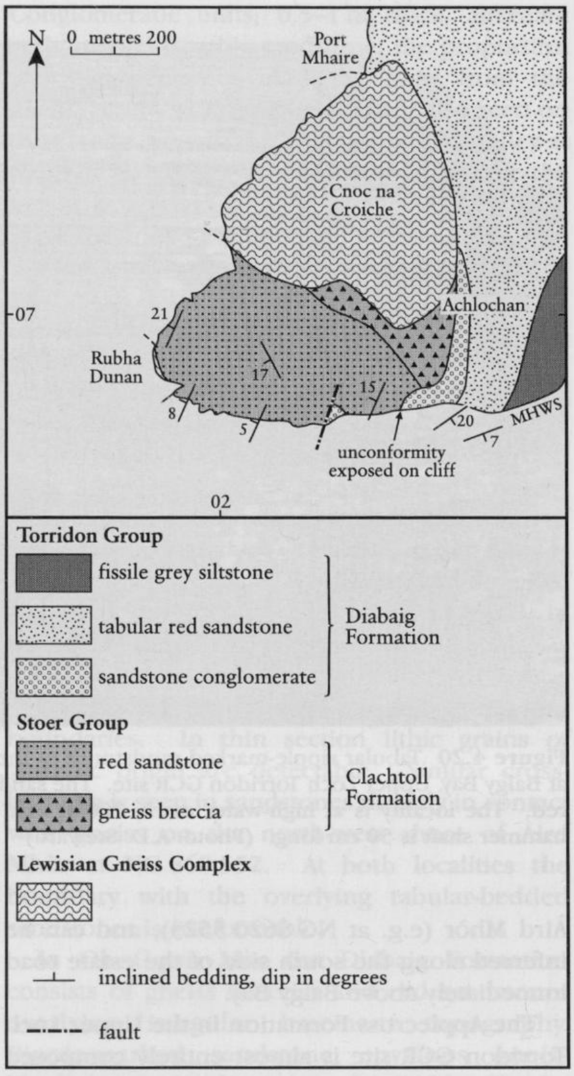


Figure 4.21 Geological map of the Rubha Dunan headland, near Achiltibuie.

Figure 4.22 The unconformity between the Stoer Group (dipping to the left) and the Torridon Group (dipping right) just above high-water mark on the south side of Rubha Dunan. The cliff section is 15 m high. (Photo: A.D. Stewart.)

Palaeomagnetic measurements by Irving and Runcorn (1957) showed a major shift in direction of magnetization between the red sandstones (Stoer Group) forming the headland of Rubha Dunan and the Torridon Group rocks about 200 m to the south-east. This led to the suggestion that the intra-Torridonian conglomerates detected by Lawson overlay a major angular unconformity, corresponding to the magnetic break at Rubha Dunan (Stewart, 1966b). Later palaeomagnetic and stratigraphical studies have confirmed this hypothesis.

Description

Rubha Dunan is a 10–30 m-high grassy and rocky promontory that lies some 1.5 km southwest of Achiltibuie, and the GCR site principally encompasses the 15–20 m-high cliff-section along its southern edge. The lowest Torridonian beds are massive conglomerates of the Stoer Group, composed exclusively of local gneiss debris, which fringe the gneiss palaeohill to the south of Achlochan House at NC 024 069. The overlying 70 m are tabular red sandstones exposed along the southern shore of the peninsula (Figure 4.21). These sandstones contain centimetre-sized angular gneiss fragments, and channels up to about 40 cm deep, filled by lateral accretion deposits. In the highest beds exposed, west of the fault at NC 0225 0674, grain size decreases and bedding surfaces commonly show symmetrical ripples and desiccation cracks. About 300 m ESE from the headland of Rubha Dunan, at NC 0210 0677, the sequence contains a bed of red siltstone 0.9 m thick, above which the sandstones are finely laminated with an average grain-size of about 0.2 mm and a maximum of 0.5 mm. The millimetre-scale laminations commonly form low-angle cross-beds. Within the laminated sequence are poorly laminated to massive beds, which, however, are of similar grain-size and virtually indistinguishable in thin section. These thicker-bedded units have erosional bases and contain gneiss pebbles up to 3 cm in size. Rarely, small blocks of the laminated facies can be found incorporated in the more-massive beds. A contact between the two sub-facies is particularly well seen in the low cliffs 200 m south-east of the headland at NC 0199 0678, where the pebbly sandstone is trough cross-bedded. The stratigraphical level here is estimated to be about 50 m beneath the Stac Fada Member of the Bay of Stoer Formation, which crops out on the coast about 1 km to the north. The summit of a gneiss hill forms a small inlier at the headland Rubha Dunan (NC 018 068) where the stratigraphical level is roughly 100 m above the local base of the sequence seen near Achlochan. Hence, palaeo-relief at the time of Stoer Group deposition must have been at least 100 m.

The most spectacular exposures of the breccias at the base of the Torridon Group are found in the eastern part of the Rubha Dunan section. At NC 0242 0678 the low sea cliff exposes a palaeohill slope dipping at 15°–25° to the west, formed in sandstone of the Clachtoll Formation (Stoer Group) (Figure 4.22). Tabular-bedded, red sandstones belonging to the Diabaig Formation (Torridon Group), onlap the hill and partially bury it. These overlying sandstones dip 20°–25° to the south and enclose red sandstone blocks up to 4 m across that can be matched petrographically with the nearby Clachtoll Formation sandstones (Figure 4.23). The resultant boulder bed is about 6 m thick and forms a fringe no more than 25 m wide marginal to the basement hill. It is overlain by sandstones and fissile red siltstones that are locally rippled and desiccated. About 20 m stratigraphically above the base of the Torridon Group sequence the red sandstones are succeeded by poorly exposed grey fissile siltstones (Diabaig Formation) with similar dip. The grey siltstones can be matched with those of the same formation exposed farther south along the coast, and elsewhere (see **Diabaig** GCR site report, this chapter). Thus, the boulder bed described above is Precambrian and not Triassic in age. The steeply dipping unconformity between the

Figure 4.23 Red sandstone block in the Diabaig Formation (basal Torridon Group), derived from the Stoer Group, which forms the hill-slope behind. High-water mark on the south side of Rubha Dunan (NC 0244 0678). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

Stoer Group and Torridon Group rocks can be traced westwards along the present coastline for about 150 m.

Palaeomagnetic studies by Stewart and Irving (1974) and Torsvik and Sturt (1987) have shown that the unconformity at Rubha Dunan corresponds to a major shift in palaeomagnetic direction, implying that the area drifted from a palaeolatitude of about 10° N in Stoer Group time to 30° or 40° S when the Torridon Group was deposited. Stewart (2002) provides a wider summary and discussion of the existing palaeomagnetic data.

Interpretation

The Rubha Dunan GCR site contains excellent exposures of the unconformity between the Stoer Group and the Lewisian basement, and the younger unconformity between the Stoer Group and the overlying Torridon Group. The south side of the headland of Rubha Dunan offers a splendid section through the Clachtoll Formation, which constitutes the lower part of the Stoer Group. The lowest beds are breccias with clasts derived from local Lewisian gneiss basement, which are interpreted as laid down by alluvial fans in a rift-valley around 1100–1200 Ma. Above the breccias are sandstones and siltstones, representing an alternation of finely laminated wind-blown sands and texturally massive flood deposits.

The Stoer Group sediments were lithified, tilted westwards and eroded between *c.* 1150 Ma and 1000 Ma to form the hill-slopes that are exposed around Rubha Dunan. This uplift and erosion may well relate to the Grenville Orogeny whose main effects were focused in eastern Canada (Gower and Krogh, 2002; Stewart, 2002). During the evolution of the rift environment in which the later Torridon Group sediments were initially laid down, sandstone boulders up to 4 m across (Figure 4.22) tumbled down the steep hillside and plunged into shallow lakes where they were gradually covered by wave-rippled sands belonging to the basal Diabaig Formation.

The nature of the sub-Torridon Group unconformity at Rubha Dunan, together with the large shift in palaeomagnetic direction described above, indicates the presence of a significant time-gap between the deposition of the Stoer and Torridon groups. This has been confirmed by recent radiometric dating (Turnbull *et al.*, 1996), which shows that at least 100 million years elapsed between the two periods of deposition. These data suggest that the Stoer Group rocks were deposited around 1150 Ma and Torridon Group rocks around 1000 Ma (see Stewart, 2002).

Conclusions

The Rubha Dunan GCR site provides excellent exposures of both sub-Torridonian and intra-Torridonian unconformities. Breccias and overlying sandstones of the Stoer Group, deposited against an ancient hill formed of Lewisian gneisses, are exposed on the south coast of the Rubha Dunan peninsula. The Lewisian gneisses and the gently WNW-dipping Stoer Group rocks are unconformably overlain by later breccias, sandstones and siltstones of the younger Torridon Group that dip gently south-east. The Stoer Group–Torridon Group unconformity is superbly exposed in the south-east part of the site. This site is also of historical interest, for it was here that Irving and Runcorn (1957) first detected a major change in the relict palaeomagnetic direction within the Torridonian succession, later correlated with a major unconformity and time-gap. The Rubha Dunan site is ideal for teaching and further research work and is of national importance.

ENARD BAY (NC 021 140–NC 039 140)

A.D. Stewart

Introduction

The Enard Bay GCR site covers little more than a square kilometre in total but displays an excellent and accessible coastal section on the south side of Enard Bay, south-west of Lochinver (Figure 4.24). Its importance comes from the easily demonstrable superposition of typical Torridon Group sedimentary rocks on the Stoer Group, the latter represented by the Stac Fada Member. In this respect it is unique and constitutes a cardinal point in Scottish Precambrian stratigraphy. Both Torridonian groups lie unconformably on an irregular erosion surface cut in the basement Lewisian Gneiss Complex, which shows significant topographical relief. The Geological Survey

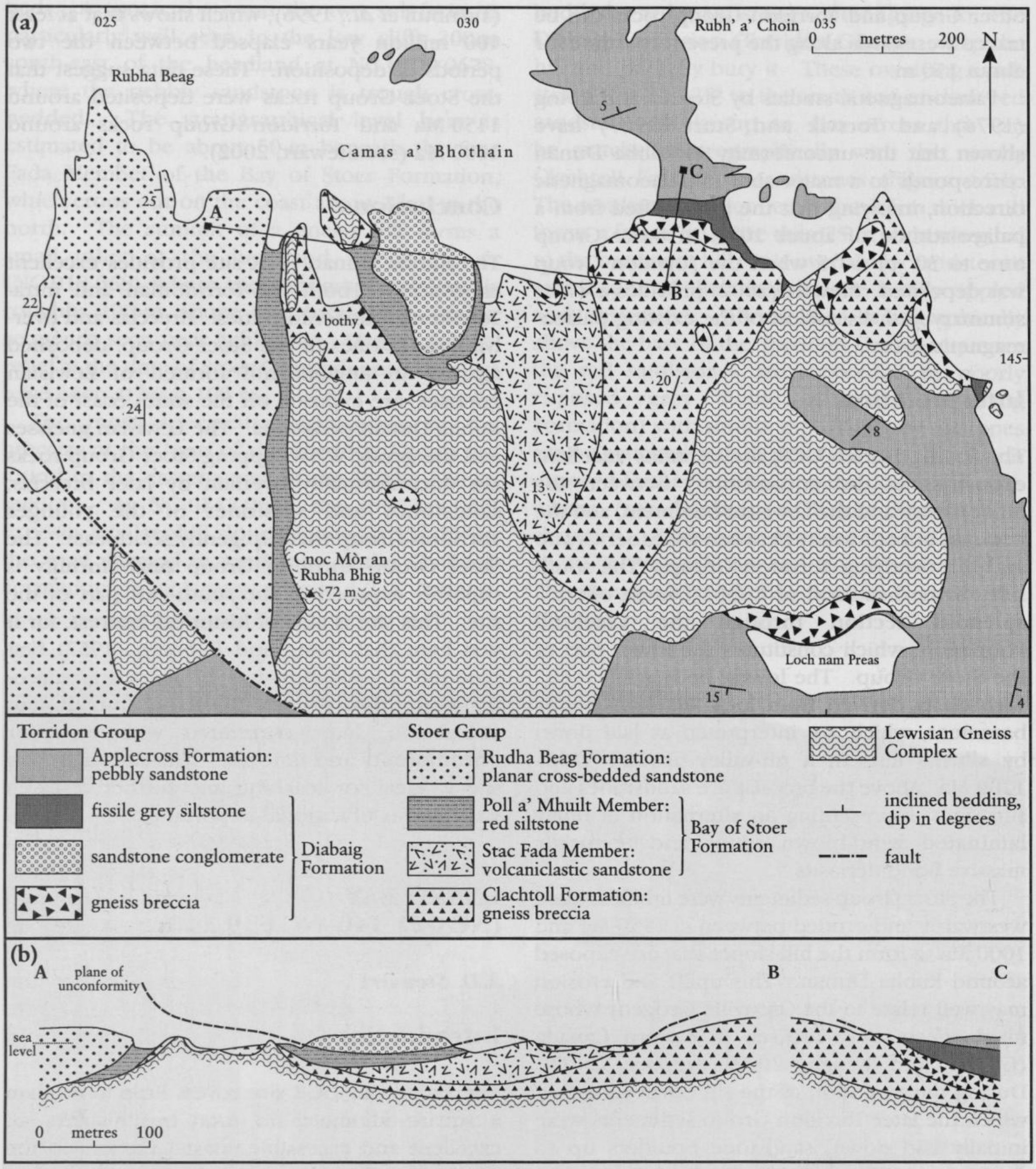


Figure 4.24 Geological map and true-scale cross-section of the Enard Bay area.

mapped the area in 1888, prior to the establishment of any formal Torridonian stratigraphy, and consequently the importance of this site was overlooked. Gracie and Stewart (1967) first described the detailed geology and recognized its wider significance. It is extraordinarily complex due to the fact that both the Stoer and Torridon groups rest on landscape unconformities, with the younger Torridon Group unconformity cutting across the older Stoer Group unconformity. Breccias, sandstones and siltstones overlie each unconformity, and care is needed to distinguish the basal rocks of one group from those of the other. The most important criterion is the composition of the clasts, which are of Lewisian gneiss in the Stoer

Group, but include reworked sedimentary rocks in the Torridon Group.

Palaeomagnetic investigations by Stewart and Irving (1974) showed quite different palaeomagnetic directions in the sedimentary rocks immediately above and below the unconformity separating the Stoer and Torridon groups at Enard Bay, similar to the directions found at Rubha Dunan and elsewhere. Subsequent work on the Stac Fada Member and Rudha Beag Sandstone at Enard Bay by Smith *et al.* (1983) confirmed this conclusion and suggested ages of *c.* 1100 Ma for the Stoer Group and *c.* 1040 Ma for the Torridon Group, based on comparison of the palaeomagnetic data with the apparent polar wander path for the Proterozoic. Recent radiometric dating of a limestone from the Stoer Group at Enard Bay has given a Pb-Pb isochron age of 1199 ± 70 Ma and a Rb-Sr whole-rock age of 1009 ± 130 Ma on the Poll a' Mhuilt Member at Stoer (Turnbull *et al.*, 1996). The same study produced an Rb-Sr whole-rock date of 994 ± 48 Ma for Diabaig Formation phosphate nodules from Diabaig. These dates are compatible with the palaeomagnetic estimates, and confirm that a considerable period of time (over 100 million years) elapsed between the deposition of the Stoer and Torridon groups.

Controversy has developed recently regarding the deposition of the basal Stoer Group sediments at Enard Bay, which have been variably interpreted as alluvial (Gracie and Stewart, 1967; Stewart, 1997; Young, 1999b), and as glacial (Davison and Hambrey, 1996). Samples from Enard Bay have also been used in recent provenance studies based on U-Pb isotopic ages of detrital zircons (Rainbird *et al.*, 2001).

Description

The GCR site comprises a continuous rocky shoreline section some 3.7 km long from Achnahaird Bay in the west around the promontories of Rubha Beag and Rubh' a' Choin to Garvie Bay in the east. It also includes the immediate rocky hinterland areas on the northern slopes of Cnoc Mòr an Rubha Bhig. Much of the inland area to the south is now planted with conifers. A geological map and section are shown in Figure 4.24. The Stoer Group in the area of the map rests unconformably on hills of Lewisian gneiss. It totals 350 m thick, of which the lowest 200 m belong to the Clachtoll Formation. Small Lewisian inliers (hilltops) appear just south of the map area (NC 022 134), near the stratigraphical top of the section, showing that basement relief at the time of Stoer Group deposition was similar to the stratigraphical thickness preserved today, i.e. several hundred metres.

The lowest sedimentary rocks in the area are massive breccias, which are well exposed on the headland (NC 035 147) about 450 m south-east of Rubh' a' Choin. Blocks of weathered felsic gneiss in the breccia here are commonly coloured pale-green by pumpellyite, and Hay *et al.* (1988) recorded pumpellyite alteration and veining of the underlying gneiss. The massive breccia is sharply overlain by bedded breccia with thin red sandstone interbeds. The contact between the two types of breccia is well exposed on the headland (Figure 4.25), only a few metres below a prominent outlier of the Applecross Formation sandstones at NC 0359 1470. At one point the contact is clearly erosional.

Rocks of the bedded breccia facies are also exposed at NC 0278 1463, about 100 m northwest of the ruined bothy on the southern shore of Camas a' Bhothain, where gently dipping brownish-grey interlaminated sandstones and mudstones contain blocks of gneiss, varying in size up to 2 m across (Figure 4.26). The laminae below the clasts have been depressed, whilst those above drape over the tops of the blocks. This led Davison and Hambrey (1996) to interpret the clasts as dropstones, deposited in moderately deep water from melting glacial ice. However, laterally equivalent sandstone bedding surfaces are covered by symmetrical ripple marks and well-developed desiccation polygons, which suggest a shallow-water environment (Stewart, 1997; Young, 1999a). The blocks are lithologically and geochemically similar to the Lewisian gneisses that underlie the succession and form the ridge against which the sandstones onlap to the west. Hence, the blocks are unlikely to have been transported far from their source. These bedded breccias, and the underlying massive gneiss breccia, can be traced westwards round the headland into the next bay, where they can be seen to underlie red siltstones which belong to the Poll a' Mhuilt Member of the Bay of Stoer Formation.

To the south of Rubh' a' Choin, the bedded breccia facies grades upwards into a volcaniclastic sandstone, which can be identified from

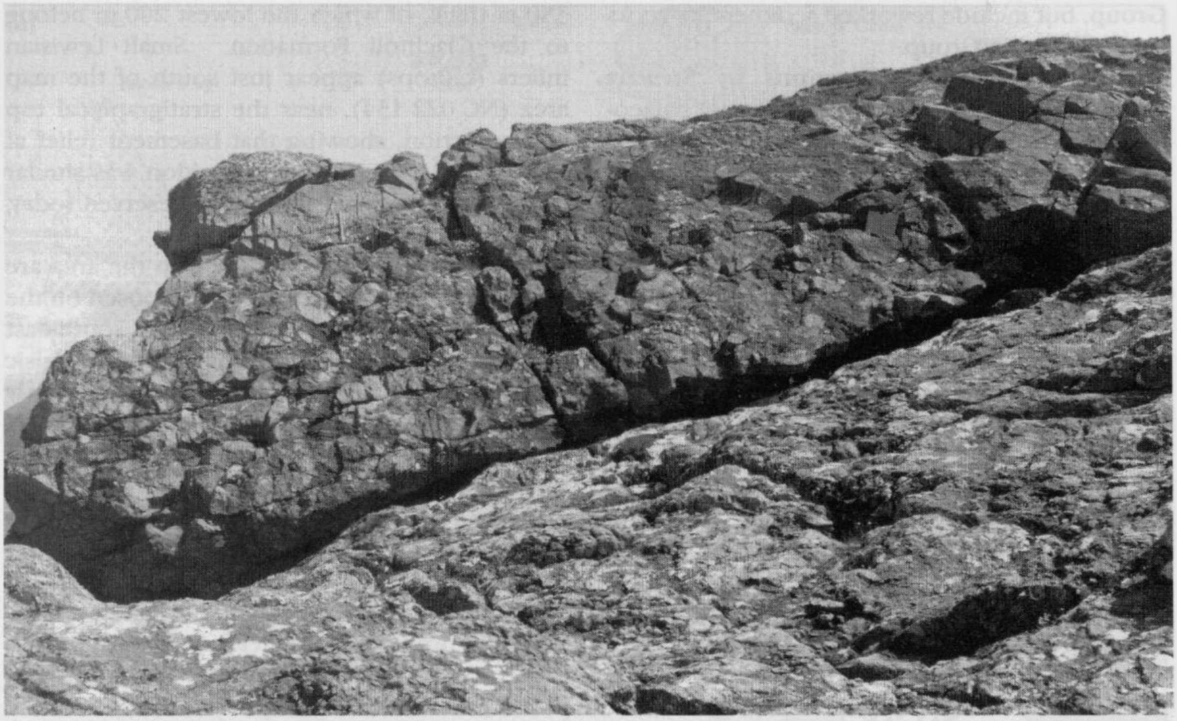


Figure 4.25 Massive breccio-conglomerate at the base of the Stoer Group at Enard Bay. The breccia passes upwards, to the right, into brown tabular-bedded coarse sandstone. The hammer, which is 53 cm long, marks the base of a small outlier of Applecross Formation unconformably overlying the breccia. The locality is to the south-east of Rubh' a' Choin at NC 0359 1470. (Photo: A.D. Stewart.)

its distinctive lithology, and from its stratigraphical relationships, as the Stac Fada Member (Figure 4.24). This member is 32 m thick here, three times the thickness found elsewhere. The lowest 20 m is massive and is relatively rich in gneiss clasts, suggesting that underlying breccias and sandstones were reworked during the deposition of these rocks. By contrast, the uppermost 12 m of the member contain conspicuous accretionary lapilli. Extensive erosion surfaces are also present, and it is clear that the topmost 4–5 m of the member has been strongly reworked.

The Stac Fada Member passes up into massive red siltstones of the Poll a' Mhuilt Member, which includes thin limestone beds that appear discontinuous owing to decalcification along joint planes. To the west, about 120 m north of the bothy at NC 0235 1468, limestone encrusts gneiss breccia. Farther west still, in the floor of a small bay at NC 0272 1467, 175 m north-west of the bothy, about 25 m of siltstone are exposed. The siltstone rests on massive gneiss breccia partly cemented by limestone, and is overlain by the Rudha Beag Sandstone that here forms a scarp feature. The Rudha Beag Sandstone probably correlates with the Meall Dearg Formation at Stoer but the old name is retained here with informal status.

The Rudha Beag Sandstone consists of about 150 m of fine- to medium-grained reddish-grey sandstone with interbeds of horizontally laminated sandstone up to 2 m thick. Grain size is invariably less than 1 mm, and contortions, ripples, silty interbeds or drapes are absent from this unit. However, tabular planar cross-bedding is common, with set thickness ranging from a few decimetres up to 5 m. Individual foresets are only a few millimetres thick and are asymptotic to the basal erosion surface, which is generally planar but locally has a relief of up to 10 cm. Foresets generally dip at an angle of 16°–20° to truncation surfaces, and had a mean dip direction towards 244° before tectonic tilting.

Torridon Group rocks, which unconformably overlie the Stoer Group rocks in this area, are exposed on the peninsula of Rubh' a' Choin and also immediately to the north-east of the bothy. They closely resemble the rocks of the Diabaig Formation in its type area (see **Diabaig** GCR site

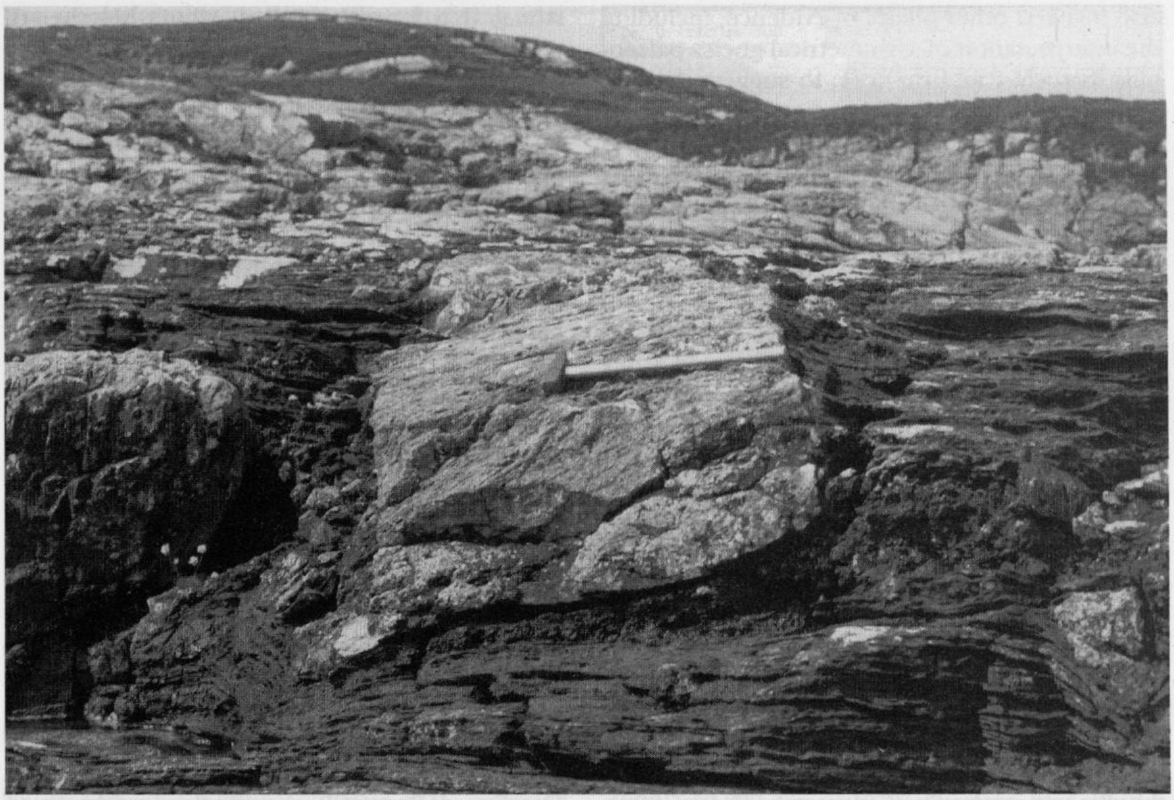


Figure 4.26 Gneiss blocks in the bedded breccia facies of the Stoer Group at Enard Bay, interpreted by Davison and Hambrey (1996) as glacial dropstones. The dark-brown sandstones between the boulders range in grain size from fine to very coarse. Lewisian basement is seen in the background above the block with the hammer. The locality is at high-water mark about 250 m north-west of the ruined bothy (NC 0278 1463). The hammer shaft is 50 cm long. (Photo: A.D. Stewart.)

report, this chapter), and like them are overlain by pebbly sandstones typical of the Applecross Formation. The basal breccio-conglomerate, which can be seen on the coast about 200 m north-east of the bothy, contains blocks exclusively derived from the Rudha Beag Sandstone, some as much as 11 m in size. Elsewhere, by contrast, it contains both gneiss and sandstone clasts derived from the immediately underlying basement. On the coast, 400–500 m south-east of Rubh' a' Choin at NC 035 146 and NC 036 146, both the matrix and the clasts contain green pumpellyite (Hay *et al.*, 1988).

A few metres of mainly grey fissile siltstones and tabular sandstones belonging to the Diabaig Formation are developed south and south-east of Rubh' a' Choin (NC 034 146). The topmost metre is red and contains a thin bed packed with centimetre-sized clasts of gneiss, fine-grained red sandstone (probably derived from the Stoer Group) and orthoquartzite. Fissile siltstone and beds beneath the Applecross Formation on the coast at NC 037 145 are all red. 'Channels', several metres across and reaching a depth of 80 cm, have been reported in these siltstones (Gracie and Stewart, 1967). They are infilled by fine-grained, laminated sandstones and siltstones essentially concordant with the 'channel' sides and floor, and are now believed to have formed by penecontemporaneous extension and attenuation of the beds, rather than by erosion. On both Rubh' a' Choin and on the coast to the south-east, red, pebbly coarse sandstones of the Applecross Formation overlie the siltstones. These are the highest rocks in the Torridon Group sequence at Enard Bay.

Interpretation

As mentioned above, Davison and Hambrey (1996, 1997) have interpreted the large gneiss clasts in the laminated sandstones in the basal part of the Stoer Group at Enard Bay as dropstones, deposited from melting ice. They also invoked other pieces of evidence, including the interpretation of asymmetrical gneiss palaeohills as roches moutonnées, to suggest that the basal Stoer Group sediments were deposited under glacial conditions. Stewart (1997, 2002) and Young (1999a) strongly disputed this interpretation and contended that the observed features are compatible with deposition in alluvial fans. Preliminary oxygen isotope data (Davison and Hambrey, 1996; Turnbull *et al.*, 1996) for Stoer Group limestones from Enard Bay do indicate the possibility of a cold-water non-marine environment, but the restricted δO^{18} values could equally be interpreted as a diagenetic signature. At present, it seems more probable that the Stoer Group breccias and siltstones were deposited in alluvial fans and lakes, whereas the Rudha Beag Sandstone was probably laid down as straight-crested transverse dunes in river channels.

The sandstone–boulder conglomerate unit at the base of the Torridon Group, exposed just to the north-east of the bothy, is unusual in showing features typical of a rotational landslide or slumped mass. The original eastern margin of the deposit can be fixed accurately, about 300 m from the present Rudha Beag Sandstone scarp, whereas farther to the east the basal breccia of the Torridon Group was derived from underlying rock-types. The sandstone conglomerate must have originally extended westwards to the foot of the scarp, but has been eroded from the intervening zone in recent times. The original slip, using the equations of Anderson and Dunham (1966), was probably about 100 m high, the upper 75 m consisting of Rudha Beag Sandstone. The sandstone moved on the underlying, water-saturated siltstone, which is about 25 m thick near the existing Rudha Beag Sandstone scarp. By comparison with recent landslips it may be deduced that, when movement occurred, the Rudha Beag Sandstone and the partly compacted siltstone beneath it were porous, rain-soaked and consequently weak. The collapse of the sandstone scarp may also account for the shearing and disruption in the uppermost metre of the underlying siltstone, exposed 120 m north of the bothy at NC 0286 1463.

The rest of the Torridon Group sequence at Enard Bay mirrors that of the underlying Stoer Group in comprising alluvial-fan breccias and sandstones grading up into silty lake deposits. In both cases sandstones deposited in braided rivers overlie these sequences. The red mudstones that form the Poll a' Mhuilt Member of the Bay of Stoer Formation, and the fissile grey siltstones in the Diabaig Formation of the Torridon Group, are believed to be lake deposits on account of the low boron content in the illite (Stewart and Parker, 1979).

Recent provenance work on samples from Enard Bay (Young, 1999a; Rainbird *et al.*, 2001) has confirmed that, whilst the Stoer Group sediments were originally derived from local basement rocks, the Applecross Formation sandstones (Torridon Group) were derived from a more-distal source. Although Rainbird *et al.* (2001) showed that only 16% of the detrital zircons in these sandstones are Grenvillian in age (*c.* 1100–1200 Ma), the Grenvillian Orogeny was a complex continent–continent collisional event during which older rocks were undoubtedly reworked and uplifted (Gower and Krogh, 2002). Hence, a Grenvillian mountain range may well have supplied sediment to the large-scale rivers that fed the Torridonian basin.

Conclusions

The Enard Bay GCR site displays evidence of two phases of Precambrian landscape formation and burial by Torridonian sediments. Alluvial breccias, lake sediments and volcaniclastic sands belonging to the Stoer Group covered the earlier landscape, with several hundred metres of relief cut in the underlying Archaean and Palaeoproterozoic Lewisian gneisses. The sediments and volcaniclastic unit were deposited about 1200 million years ago. The second landscape was formed in both the Lewisian gneisses and the older, now lithified Stoer Group. Alluvial breccias and lake sediments of the Torridon Group, deposited about 1000 million years ago covered this later landscape. Unusually, at the base of the Torridon Group sequence is a large landslip or slumped mass, originally some 100 m high, that contains blocks of Stoer Group sandstone up to 11 m across.

The site is of prime stratigraphical importance because it is the only place where the unconformable relationship between the Stoer Group and the overlying Torridon Group can be proved unequivocally. The Stoer Group is uniquely identified by the presence of the volcaniclastic Stac Fada Member, and the Torridon Group by the Applecross Formation with its diagnostic suite of durable pebbles. At other sites where the unconformity has been identified (e.g. the **Rubha Dunan** GCR site), the Stac Fada Member is lacking and palaeomagnetic studies have been needed to prove that the Stoer and Torridon groups formed at different palaeolatitudes. At Enard Bay several of the elements have been isotopically dated, and their provenance and palaeomagnetic declination and inclination are known. Student parties regularly visit the site because it condenses much of the sedimentary history of the Torridonian into a small and accessible area. The Enard Bay GCR site is thus of international importance for teaching purposes and for continued research into Proterozoic depositional environments.

ACHDUART (NC 046 044–NC 055 034)

A.D. Stewart

Introduction

The Achduart GCR site, which lies about 5 km south-east of Achiltibuie (Figure 4.1), contains the type sections of the two upward-fining sandstone units that here form the lowermost part of the Applecross Formation – the Rubha Dubh Ard Member (40 m thick) and the Achduart Member (100 m thick). The bedding dips consistently at around 9° to the east and south-east, and the contact with the underlying Diabaig Formation is exposed. The Rubha Dubh Ard Member has been mapped across country from Loch Broom in the south, through Achduart, north to Loch Veyatie in Assynt, a distance of 25 km. The depositional history of these members is readily interpreted, but it gives a valuable insight into the processes responsible for the deposition of the Applecross Formation. Nicholson (1993) has studied the detailed sedimentology of the Rubha Dubh Ard Member.

Description

The GCR site consists of a *c.* 2 km-long section, mostly of low, easily accessible coastal cliffs (2–20 m high), on the S- and W-facing sides of Rubha Dubh Ard (Figure 4.27). A cairn near the cliff top at NC 0427 0380 is a useful landmark. Just south of the cairn, slightly above high-water mark, the basal erosion surface of the Applecross Formation rests on reddened grey siltstones of the Diabaig Formation that crop out on the W-facing cliffs north of the Rubha Dubh Ard.

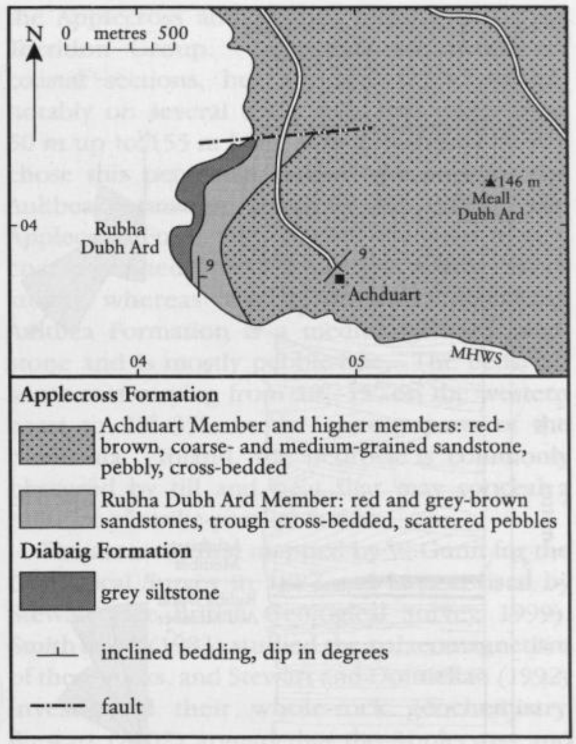


Figure 4.27 Geological map of the Achduart area. After 1:50 000 Sheet 101W, Summer Isles (British Geological Survey, 1998).

The sandstones of the Applecross Formation at this locality belong to the Rubha Dubh Ard Member, the type section of which is seen in the cliffs between NC 0426 0374 and NC 0449 0355. The lowest 20 m of this member consist of trough-cross-bedded, contorted coarse-grained reddish-brown sandstone with scattered durable pebbles, including red porphyry, up to 1.5 cm in size. The upper half of the member is much finer-grained, consisting of medium- to fine-grained brownish-grey tabular sandstone (Figure 4.28). Small-scale trough-cross-bedding, ripple-lamination, flat bedding with current lineations and shallow scours are common, and durable pebbles are present but generally less than 0.5 cm across. Palaeocurrents changed direction during deposition of the Rubha Dubh Ard Member, flowing towards the SSE in the lower part, south-east through most of the upper part, and north-east in the very top part (Nicholson, 1993; Stewart, 2002).

The base of the Achduart Member is seen immediately to the east at NC 0449 0355. The

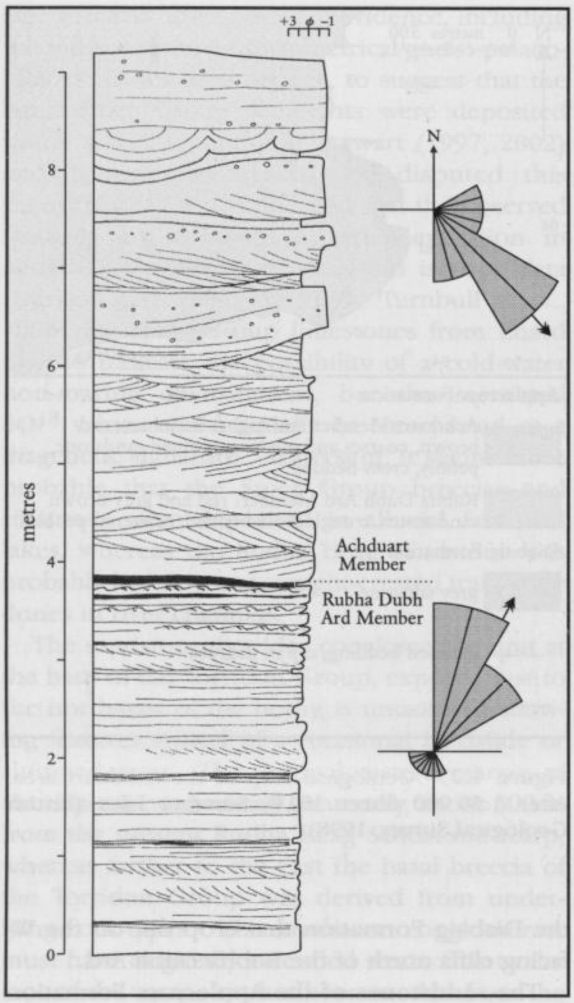


Figure 4.28 Graphic log of the contact between the Rubha Dubh Ard Member and the Achduart Member in the type section about 500 m west of Achduart (NC 0449 0355). The grain-size scale at the top of the log spans +3 Ø to −1 Ø units (0.12–2 mm). Fissile red siltstone is black on the log, and red sandstone is white. Sedimentary structures are illustrated schematically, but drawn as seen in the section. Pebbles over 1 cm across are shown. Rose diagrams, each based on 13 measurements of foresets, show palaeocurrent directions in the two members.

top of the Achduart Member is exposed on the coast south-east of Achduart at NC 0526 0347, and the coast section between these two points constitutes the stratotype for this unit. The Achduart Member, which is about 100 m thick, is formed of very coarse-grained red sandstone with durable pebbles up to 2 cm in diameter. Grain size diminishes upwards, so that at the top the sandstone is medium-grained and only sparsely pebbly. Trough cross-bedding shows that palaeocurrents flowed towards the south-east, significantly different to the current directions in the Rubha Dubh Ard Member beneath, and in the undifferentiated Applecross Formation above, where the palaeocurrents flowed to the north-east. Nicholson (1993) has shown that cross-beds in the lowest 9 m of the Achduart Member are arranged in cosets 1–2 m thick, dipping to the SSE. The Applecross Formation above the Achduart Member is a uniformly coarse-grained sandstone with durable pebbles up to 3 cm in diameter, normally arranged in seams. Fining-upward units like the Rubha Dubh Ard and Achduart members have not been found at higher levels in the Applecross Formation.

Interpretation

The Rubha Dubh Ard and Achduart members were originally interpreted as the deposits of alluvial fans with their apices on or near the Minch Fault, *c.* 85 km north-west of Achduart (Stewart, 1982). The lowest sediments in each member are thought to have been channel sands, formed following uplift of Lewisian gneisses west of the fault. Subsequent tectonic quiescence led to progressive retreat of the fan heads westwards, with a consequent reduction in discharge, channel cross-section and grain size at any point on the fans. Fan-head retreat is also the probable cause of the progressive upward changes in palaeocurrent directions noted above, as Williams (1969a, 2001) showed in the Applecross Formation at Cape Wrath. Repeated reactivation of the fault scarp led to the re-establishment of fans and thus the repeat of fining-upward sequences (Stewart, 1982). Stewart (2002) and Stewart and Donnellan (1992) noted that the tentative correlation of the Rubha Dubh Ard Member and the Cape Wrath Member, as suggested by Williams (1969a), was untenable on geochemical grounds. Williams (2001) noted that the Cape Wrath Member only extends southwards as far as the Coigach area, and that the southern parts of the Applecross Formation correlate with the higher parts of the sequence farther north. He argued that Torridon Group deposition commenced first in the northern area with formation of a rift basin corresponding roughly to the present-day Minch.

Nicholson (1993) has put forward a different hypothesis, interpreting the cosets of cross-bedded sandstone at the base of each member as having formed in large transverse bars in channels 3–9 m deep. The tabular sandstones forming the upper part of the Rubha Dubh Ard Member were interpreted as deposits of sheet floods and waning-phase flows on a floodplain. Nicholson noted that the tabular sandstones and the cross-bedded sandstones interdigitate over a 2 m stratigraphical interval at one point, indicating the lateral equivalence of the two environments during sedimentation. These features were interpreted to suggest that the Applecross Formation sandstones were deposited on a large-scale braided alluvial plain. However, this hypothesis does not explain the wide regional extent of the two members, nor the fining-upward structure of the Rubha Dubh Ard Member that is present through most of its outcrop. The environment of formation of the lower units of the Applecross Formation is thus still a matter for debate.

Stratigraphically higher beds of the Applecross Formation can be seen east of Achduart, and Stewart (2002) has estimated that the total thickness of the formation is *c.* 1350 m between Rubha Dubh Ard and Strath Kanaird, where it is unconformably overlain by the Cambrian quartzites.

Conclusions

The Achduart GCR site contains the type sections for the lower units of the Applecross Formation, termed the Rubha Dubh Ard and Achduart members. It is the best site for examination of two extensive, fining-upward Torridon Group sandstone units. The units have been variably interpreted as sections through large alluvial-fans (Stewart, 1982), or as deposits from a large-scale braided river system (Nicholson, 1993). The site is thus likely to be of continued national importance as it furnishes excellent sections in which the environments of deposition of the Torridon Group rocks can be studied.

AULTBEA (NG 852 920, NG 880 978–NG 892 960)

A.D. Stewart

Introduction

The peninsula of Rubha Mòr, between Loch Ewe and Gruinard Bay (Figures 4.1, 4.29), exposes about 2500 m of red sandstones belonging to the Applecross and Aultbea formations of the Torridon Group. Exposures are mainly in coastal sections, but are also found inland, notably on several rocky hills that range from 50 m up to 155 m high. The Geological Survey chose this peninsula as the type area for the Aultbea Formation (Peach *et al.*, 1907). The Applecross Formation consists of coarse- to very coarse-grained, reddish-brown pebbly sandstone, whereas the conformably overlying Aultbea Formation is a medium-grained sandstone and is mostly pebble-free. The beds dip south-east varying from 10°–15° on the western coast to 25°–35° on the eastern parts of the peninsula. Inland, the bedrock is commonly obscured by till and peat that may conceal a number of strike-parallel faults.

The area was first mapped by W. Gunn for the Geological Survey in 1887 and later revised by Stewart (see British Geological Survey, 1999). Smith *et al.* (1983) studied the palaeomagnetism of these rocks, and Stewart and Donnellan (1992) investigated their whole-rock geochemistry. Stewart (2002) argued that the Applecross and Aultbea formations merely represent facies variations of a coherent package of Torridon Group red fluvial sandstones. He suggested that the two formations are only recognized sensibly in the Aultbea–Rubha Mòr area.

Description

The Aultbea GCR site is divided into two sub-areas. The first, a rocky inland area around Creag an Fhithich Mòr (124 m) (NG 851 920), contains the stratotype for the boundary between the Applecross and Aultbea formations. The second, a 3.5 m-long coastal section from Camas Rainich (NG 880 978), south-east around Creag an Eilean and Leac an Fhaobhair to Camas a' Charraig (NG 8926 9596), which lies roughly 8 km NNE of Aultbea, contains the stratotype for the Aultbea Formation itself.

The upper part of the Applecross Formation, exposed in the north-west part of the Rubha Mòr, is about 500 m thick. It consists of reddish-brown pebbly sandstones, which are typically trough cross-bedded. About half the beds have soft-sediment contortions, generally taking the form of open synclines 0.5–2 m wide, normally linked by sharp anticlinal cusps. Pebbles on the coast section north-west of Slaggan reach 5 cm in size, but elsewhere they do not exceed 3–4 cm. The pebbles are durable types, mainly

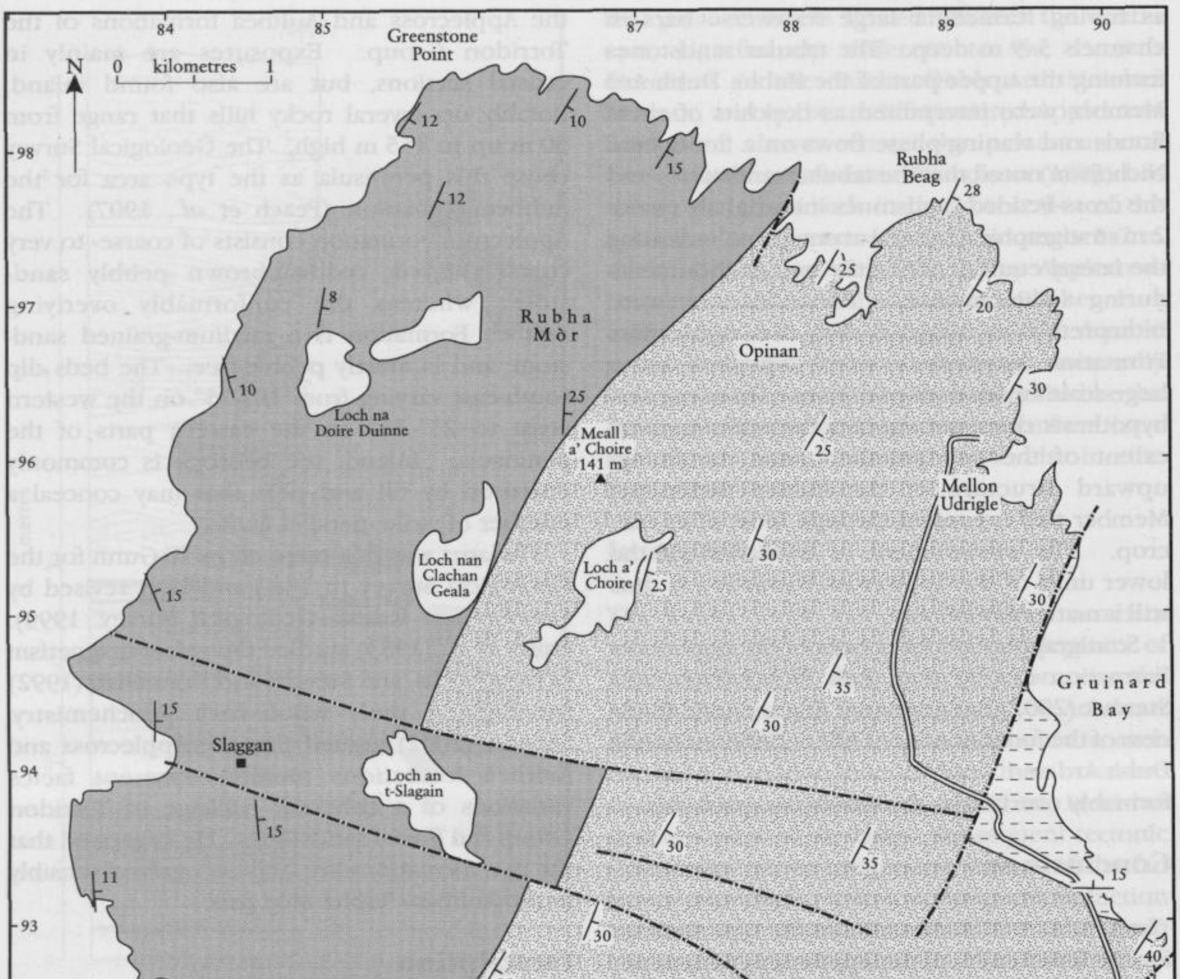


Figure 4.29 Geological map of the Rubha Mòr peninsula. After 1:50 000 Sheet 91, Gairloch (British Geological Survey, 1999).

quartzite, chert and red 'porphyry' (porphyritic rhyolite or rhyodacite) (Williams, 1969b; Anderton, 1980; Stewart, 2002). They are either scattered through the sandstone or concentrated into seams one pebble thick. On the east side of the sandy bay at Mellon Charles (NG 845 908) a medium-grained sandstone unit, 14 m thick, contains a discontinuous grey micaceous siltstone bed a few centimetres thick that shows partial phosphatization. This lies some 15 cm below the upper contact of the sandstones with a *c*. 1.5 m-thick bed of mid-grey, millimetre-laminated, coarse siltstone to fine sandstone, with traces of ripple-lamination. Coarse-grained sandstones of the Applecross Formation with pebbles of red 'porphyry', white quartz and quartzite, green chert and pink quartz-feldspar rock, immediately overlie the coarse siltstone bed. The pebbles reach 3 cm in size just above the siltstone, but decrease in size and abundance at higher levels in the stratigraphy.

The *c*. 1.5 m-thick coarse siltstone bed can be traced along strike inland to Creag an Fhithich Mòr at NG 8500 9194, where it is again overlain by pebbly sandstones. The sandstone grain-size diminishes stratigraphically upwards, i.e. to mthe south-east. The contact with the Aultbea Formation, about 165 m stratigraphically above the grey siltstone, is exposed 160 m south-west of the south end of Loch Beinn Dearg at NG 8542 9200. Coarser-grained sandstones are defined as belonging to the Applecross Formation and finer-grained ones to the Aultbea Formation. However, the finer- and coarser-grained sandstones show metre-scale interbedding in this area. The transitional contact is defined in the centre of a 10 m-thick sandstone interval, where the maximum grain-size first drops below 0.5 mm. This section, from Creag an Fhithich Mòr to the outlet of Loch Beinn Dearg, is the stratotype for the Applecross Formation–Aultbea Formation boundary. Palaeocurrents, measured from trough cross-bedding and linguoid ripples, are directed consistently towards the east or north-east. No change of palaeocurrent direction is observed at the contact between the Applecross and Aultbea formations.

Using the same definition, the Applecross Formation–Aultbea Formation boundary occurs on the coast about 2.5 km north-west of Aultbea (NG 852 907), at a point about 280 m stratigraphically above the grey siltstone bed. The apparently different stratigraphical intervals between the siltstone and the top of the Applecross Formation in the coastal and inland sections are attributed to faulting. Normal faults parallel to the strike are present in the inland section.

One or more grey siltstones similar to that described above are found at about the same stratigraphical level, *c*. 3.5 km above the base of the Applecross Formation, at localities spread over a distance of nearly 100 km. In the Summer Isles, about 20 km north-east of Aultbea, siltstones at this stratigraphical level have yielded abundant sphaeromorphic acritarch microfossils and filaments (Zhang *et al*., 1981; Zhang, 1982), including the new genus *Torridoniphycus*, a cyanobacterium. However, the environment in which they lived remains uncertain.

The north-east coast of the Rubha Mòr peninsula (Rubha Beag) exposes some 2000 m of the Aultbea Formation, with the top concealed beneath Triassic sandstone and the base cut out by several strike faults north of Opinan. The type section for this formation is the continuous coastal section, which stretches from Camas Rainich, north of the hamlet of Opinan, to Camas a' Charraig, close to Mellon Udrigle. This section exposes 800 m of mainly pale-red medium-grained sandstones. Contorted bedding and heavy-mineral layers, containing mainly hematite and ilmenite, are typical and are notably abundant on the coast by Rubha Beag at NG 889 975.

The coast section north of Mellon Udrigle also has a few coarser-grained sandstones, some of which are sparsely pebbly, and some intercalations of fine-grained red sandstones, which are planar bedded and display linguoid ripples.

Interpretation

The Applecross and Aultbea formations consist of sandstones that were laid down in a fluvial system during late Proterozoic times. The exact environment of formation is still the matter of some debate; Stewart (1982) has proposed deposition in a wide, active rift-valley, whilst Nicholson (1993) has suggested that the depositional environment may have been a large-scale braided river system in a thermal relaxation basin formed at a late stage in the rifting process. A recent study of detrital zircons from near Aultbea (Rainbird *et al*., 2001) showed that their source was probably a significant distance to the west on the Laurentian Shield, suggesting input from a large river system. On the other hand, the palaeocurrent data of Williams (2001) clearly indicate a much closer source area for most of the sandstone detritus.

The Applecross and Aultbea formations around Aultbea show abundant soft-sediment contortions, as is common elsewhere in these two formations. Contortions affect about half the beds in the Applecross Formation and almost the entire Aultbea Formation. Such abundance appears to be unusual in the geological record, even among sandstones deposited in rifts. Although such contortions are indicative of dewatering following rapid sedimentation, their precise origin remains unclear, despite substantial research, most recently by Owen (1995, 1996). The structures result from the upward movement of water derived from liquefaction of the underlying bed or beds. Liquefaction is known to result from seismic shaking, but the abundance of the structures in the Aultbea Formation implies that shaking occurred very frequently, which seems improbable. Liquefaction due to abrupt changes in groundwater level has been suggested as a mechanism, but has not been demonstrated experimentally. As all the contortions involve gravitational instability, it follows that they would be more abundant if gravity were stronger. However, there is no independent evidence that the Earth's gravity field in the past was significantly different to that prevailing today (Stewart, 1977).

Conclusions

The Aultbea GCR site contains the type section for the Aultbea Formation of the Torridon Group, and its contact with the underlying Applecross Formation. These two formations, which consist mainly of medium- and coarse-grained sandstones respectively, were probably laid down in an extensive braided river system. They have an aggregate thickness of about 5 km and extend for at least 150 km along the north-west coast of Scotland, making them volumetrically one of the most important rock sequences in Britain. Provenance work (Williams, 1969b; Van de Kamp and Leake, 1997; Rainbird *et al.*, 2001) has suggested that the source for at least some of these sediments was not local, and that they were derived from a source located far to the west, now part of the Canadian shield.

The ubiquitous, large-scale, soft-sediment contortions, that are particularly spectacular in the Aultbea Formation, appear to be unique. Their origin, despite substantial research, remains obscure. The Aultbea GCR site remains an important study area for the sedimentology of the Torridon Group sandstones and merits national importance.

CAILLEACH HEAD (NG 986 979–NG 987 988)

A.D. Stewart

Introduction

Cailleach Head, between Loch Broom and Little Loch Broom (Figure 4.1), is the type area for the Cailleach Head Formation, the youngest part of the Torridon Group (*c.* 1000 million years old). Unlike other parts of the Torridonian sequence this formation is composed entirely of the coarsening-upward siltstone–sandstone cyclothems. Each cyclothem has grey fissile siltstone at the base and cross-bedded sandstone at the top, recording the gradual advance of deltaic sediments into a lake or shallow sea. The lowest 15 cyclothems, totalling 320 m, are very well exposed and readily accessible in the cliffs south of the lighthouse at Cailleach Head. The bedding dips 30°–40° to the south-east. Although this is one of the finest cyclothemic sequences in Europe it has never received more than passing mention in the literature (Stewart, 1988b). The fining-upward sequences found at the base of the group, for example at the **Achduart** GCR site, have a different origin.

The Cailleach Head Formation is only preserved to the west of the Coigach Fault, which cuts across the peninsula 1.2 km south-east of Cailleach Head (Figure 4.30), and throws down to the west some 6 km (Stewart, 1993). A small sliver of the Cambrian Eriboll Sandstone Formation is present immediately west of the fault at NG 9908 9733 where it lies unconformably on the Cailleach Head Formation. Stewart (2002) records that the Cambrian quartzites strike 110° and dip 16° S. The adjacent Cailleach Head Formation beds strike 085° and dip 40° S, implying that the Cambrian unconformity cuts down through the Torridonian succession to the west. In contrast,

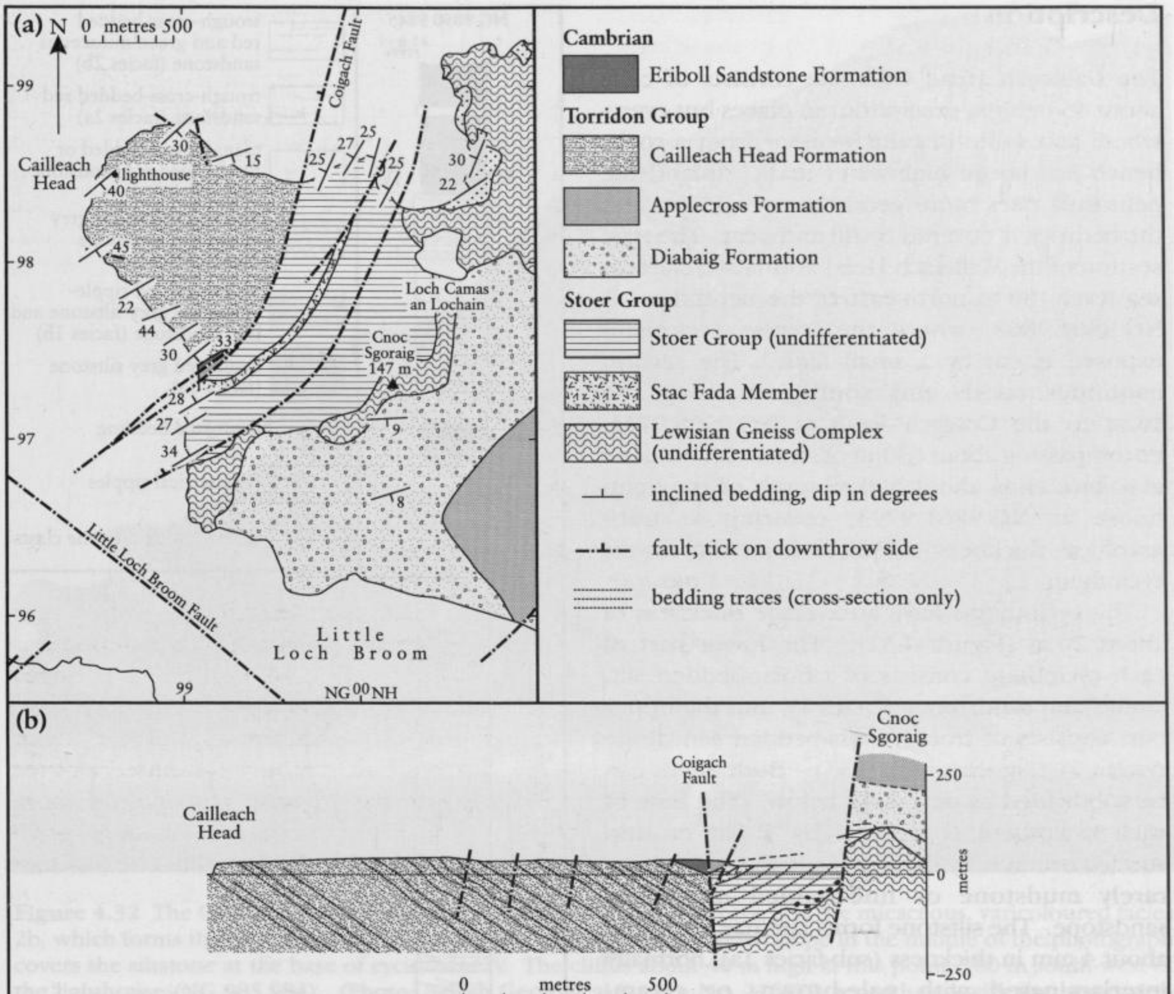


Figure 4.30 (a) Geological map of the Cailleach Head peninsula (compiled by A.D. Stewart, 1994). (b) Projected true-scale cross-section of the Cailleach Head Formation. After Stewart (2002).

in the vicinity of the Moine Thrust Belt the Cambrian unconformity cuts down to the east. The base of the Cailleach Head Formation lies below sea level at Cailleach Head, but it is exposed on Gruinard Island, 6 km to the south-west. Here it is conformable with the underlying sandstones of the Aultbea Formation. This implies that there could be about another 500 m of the formation below that exposed at Cailleach Head, giving an estimated total thickness of *c.* 1130 m.

Cailleach Head is also of historical interest, in that the first Precambrian microfossils found in Britain were obtained here. John Horne, who mapped the area for the Geological Survey in 1885, collected the phosphatic concretions in which J.J.H. Teall found clusters of unicellular microfossils and fibres (Geikie, 1903, p. 56; Peach *et al.*, 1907, pp. 287–8 and plate 52). Gregory (1917) stated that the sampled locality is on the shore 265 m north-west of the Coigach Fault, but phosphatic concretions are found sporadically throughout the Cailleach Head Formation. Downie (1962) reported 'spore-like bodies, isolated and in clusters, cellular sheets of tissue, and filaments' from the siltstones containing the phosphatic nodules. He assigned them tentatively to the middle Riphean, but no further details have been published. Palaeomagnetic data from the Cailleach Head Formation are compatible with other parts of the Torridon Group (Irving and Runcorn, 1957). Van de Kamp and Leake (1997) briefly considered the geochemistry of these rocks as part of their overall Torridonian study.

Description

The Cailleach Head GCR site consists of cliffs about 45 m high, precipitous in places but everywhere accessible in calm weather from a rocky bench just above high-water mark. Inland the peninsula rises more gently to over 110 m and the bedrock is covered by till and peat. The type section of the Cailleach Head Formation starts at sea level 180 m north-east of the lighthouse at NG 9864 9868, where the lowest cyclothem exposed is cut by a small fault. The section continues south and south-east along the coast to the Coigach Fault at NG 9908 9733, encompassing about 630 m of strata. Continuous exposure ends about 500 m south of the lighthouse at NG 9861 9793, covering a stratigraphical thickness of 326 m from the lowest cyclothem.

The cyclothems have an average thickness of about 20 m (Figure 4.31). The lower part of each cyclothem consists of tabular-bedded siltstones and sandstones (facies 1), and the upper part consists of trough-cross-bedded sandstone (facies 2) (Figures 4.32, 4.33). Both facies can be subdivided as described below. The base of each cyclothem is defined by a flat erosion surface overlain by dark-grey siltstones, or more rarely mudstone or fine-grained micaceous sandstone. The siltstone forms laminae averaging about 4 mm in thickness (sub-facies 1a), normally interlaminated with pale-brown- or cream-weathering ripple-laminated sandstone, from which sedimentary veins penetrate downwards into the siltstone. The lateral persistency (lateral extent divided by maximum thickness) of siltstone laminae in sub-facies 1a is over 10 000. Where the sandstones form more than 50% of a sequence, it is considered to belong to a separate sub-facies, 1b. Sub-facies 1c consists of tabular beds of light-red-weathering, fine-grained sandstone. The lateral persistency of beds in sub-facies 1c is in the range 300–5000. Typical sedimentary structures are flat bedding with current lineation, and repeated sets of tabular, planar cross-beds. The bases of the sandstones commonly show drag and brush marks and isolated, compacted shrinkage cracks. These resemble trace fossils and it is not surprising that they were recorded as such by the Geological Survey (Geikie, 1900). The tops of the sandstones have symmetrical ripples, commonly in interfering sets. In two of the

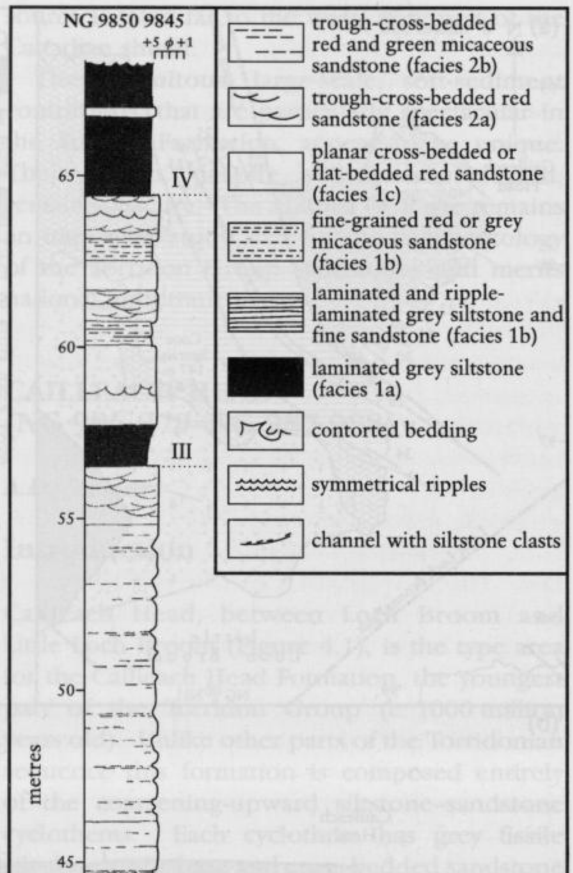


Figure 4.31 Graphic logs of cyclothems II, III and part of IV in the Cailleach Head Formation at Cailleach Head. The grain-size scale near the top of the log spans +5 Ø to +1 Ø units (0.03–0.5 mm).

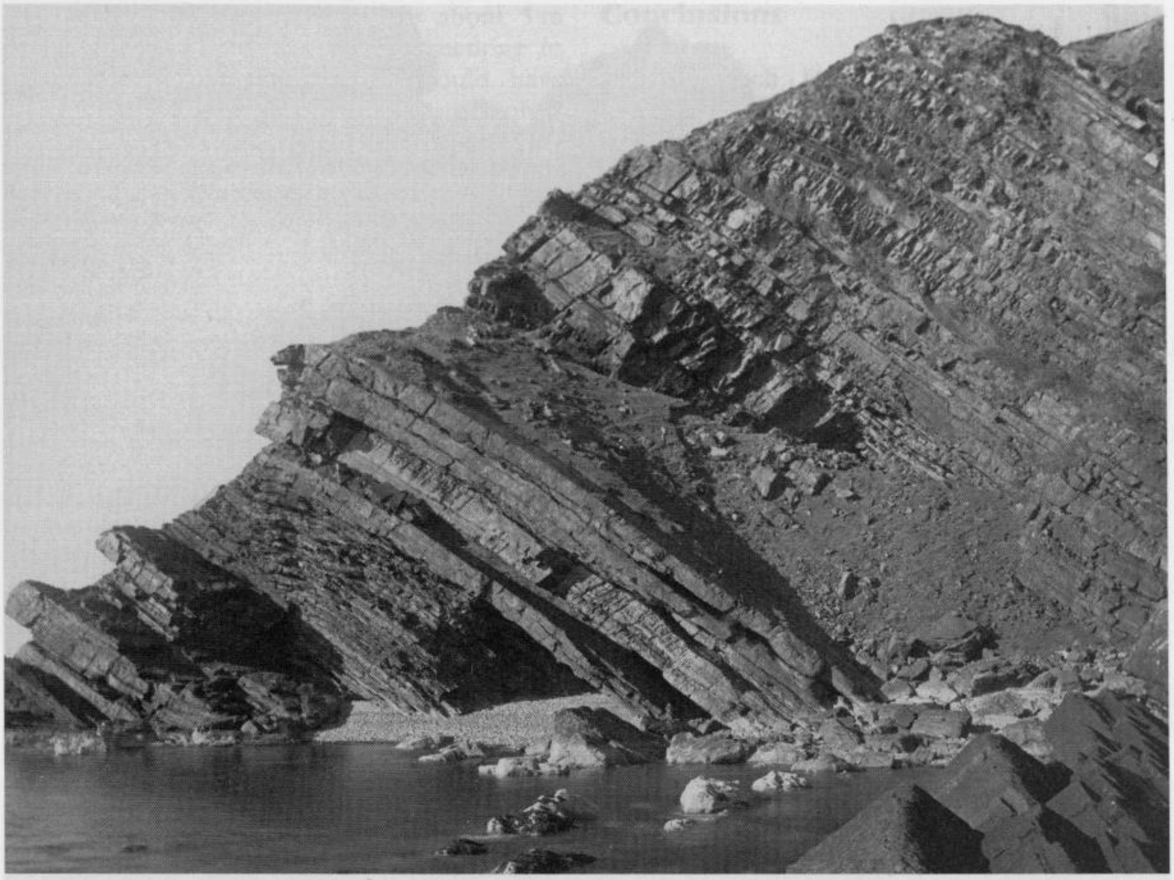


Figure 4.32 The Cailleach Head Formation at Cailleach Head. The cave is in the micaceous, varicoloured facies 2b, which forms the top half of cyclothem II. The grassy, boulder-strewn slope in the middle of the photograph covers the siltstone at the base of cyclothem IV. The cliff is about 40 m high at this point, 100 m south-west of the lighthouse (NG 985 984). (Photo: British Geological Survey, No. 216879, reproduced with the permission of the Director, British Geological Survey, © NERC.)

cyclothems large desiccation polygons cut the intervening grey siltstones of sub-facies 1a or 1b.

In the upper part of each cyclothem (facies 2), the sandstones are slightly coarser-grained than those of facies 1 (but only rarely reach medium grain-size), and trough cross-bedding is the typical sedimentary structure. There are two dominant sub-facies, 2a and 2b. The first weathers to a moderate pink colour and locally contains intercalations of the grey sandstone and siltstone (sub-facies 1b). Such intercalations are impersistent due to erosion at the base of the sandstone beds. The second sub-facies (2b) consists of greyish-red-weathering sandstone in which the iron minerals are concentrated in small spots. The sandstone typically shows abrupt lateral passage into yellowish-green and greyish-red micaceous sandstone and siltstone. The lateral persistency of units in facies 2 is in the range 10–100.

Siltstone fragments, up to 40 cm long, and channel features are present sporadically throughout facies 2. The largest channel is seen 15 m above the base of cyclothem IV and is well exposed halfway up the cliff beneath the lighthouse (NG 9851 9850). Here, sandstone of sub-facies 2a fills a channel 5 m wide and about 0.5 m deep in the underlying sub-facies 1b. The boundary between facies 1 and 2 is easily located in the sections by the appearance of trough cross-bedding, and by the abrupt change in the persistency factor. The average palaeocurrent direction from cross-bedding, cross-lamination and current lineation in the cyclothems is towards the north-east, with vector mean of 037° (52 observations).

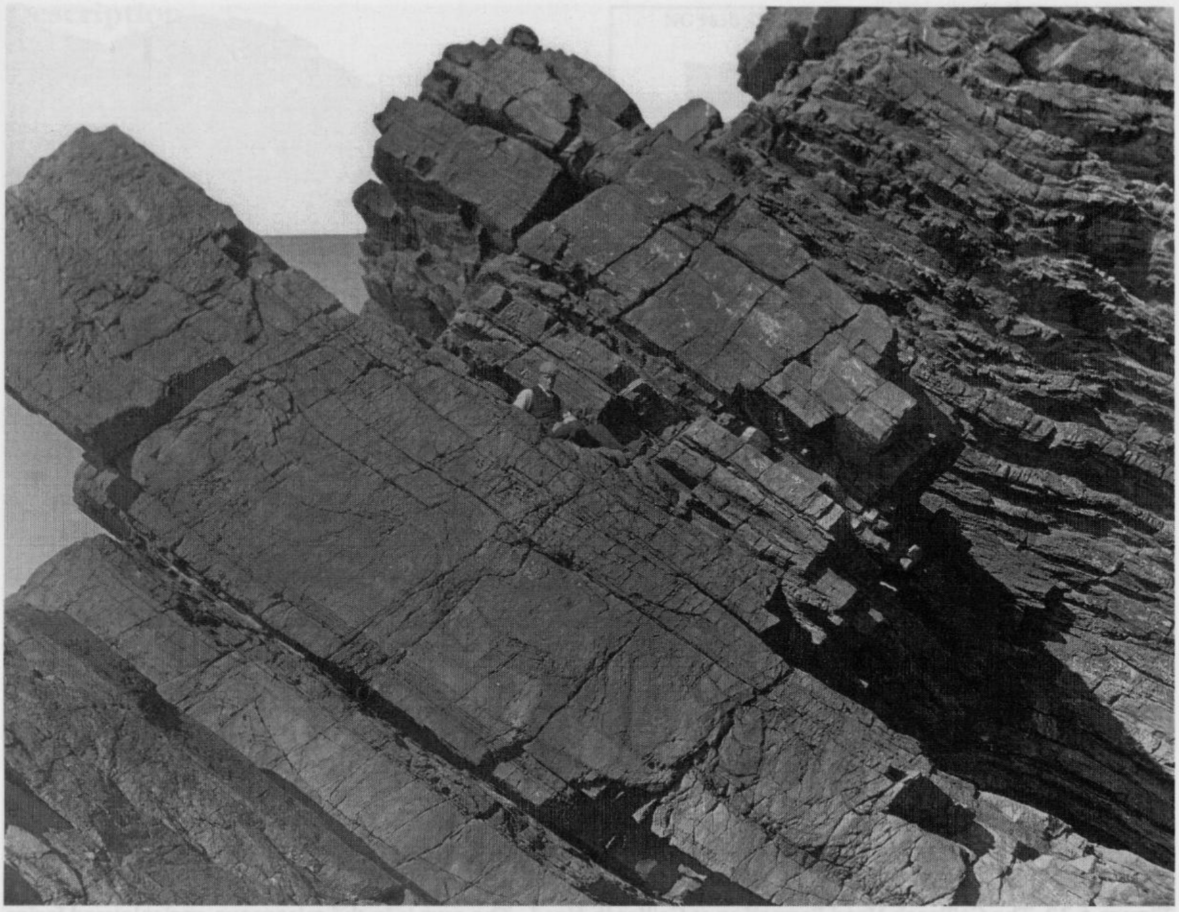


Figure 4.33 Cyclothem II in the Cailleach Head Formation at Cailleach Head. The sandstones below the man in the photograph belong to facies 1, those above belong to facies 2. The location is the left hand extremity of the cliff shown in Figure 4.32, which corresponds to the 32–44 m interval on the stratigraphical log, Figure 4.31. (Photo: British Geological Survey, No. P216884, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Interpretation

The lowest sediments in each cyclothem (sub-facies 1a) were deposited from suspension into a body of water, below wave base, where bottom currents rarely penetrated. However, progressively more sandy sediment was introduced upwards through the sub-facies. The absence of carbonate, or macroscopic pyrite, suggests that the water body above the sediment was well circulated, oxygenated and dilute, probably a lake whose level was controlled by overflow rather than evaporation.

The flat-bedded tabular sandstones of sub-facies 1c may have been deposited from fast-flowing, shallow floodwaters, crossing sandflats bordering the lake. When the lake level rose and temporarily covered the sandflats, the floodwaters decelerated on entering the lake and deposited sediment as straight-crested sand waves. Some of the sediment was carried beyond the sandflat and across the lake floor, thus accounting for the ripple-laminated sandstone bands in sub-facies 1b. After the floods had ended, waves reworked the sediment top into symmetrical ripples. No beach deposits have been identified.

Upstream from the sandflat the floodwaters crossed a braided fluviatile plain. The currents were swifter than on the sandflat and formed the dunes responsible for the trough cross-bedding seen in facies 2.

If the hypothesis of a hydrologically open lake environment for the Cailleach Head Formation is accepted then the cyclothems must reflect periodic variations in water depth. The minimum water depth is given by the combined thickness of sub-facies 1a and 1b, which is about 5 m (10 m when decompacted). Fluctuations in water depth over about 10 m would have allowed deposition and occasional desiccation of the interbedded sub-facies 1b and 1c. At longer intervals the lake appears to have deepened abruptly by 15–25 m, resulting in deposition of sub-facies 1a and 1b directly on top of facies 2. Variations in lake water levels consistent with this hypothesis are well known from rift-valley lakes (Beadle, 1981) and are recorded in Mesozoic rift sequences in eastern North America (see Stewart, 2002, p. 35). The Cailleach Head Formation overlies some 5 km of fluviatile red sandstones, and was probably deposited in a NNE-trending rift basin. Van de Kamp and Leake (1997) considered the geochemistry of the Cailleach Head Formation and concluded that the detritus was derived from a local 'Hebridean' source. They suggested that at that time there had been renewed local uplift, leading to the formation of a highland area, which diverted the rivers that had deposited the Applecross and Aultbea formations, allowing deposition of local sediment in lakes in the rift basin.

Conclusions

The Cailleach Head GCR site displays a beautifully exposed set of Precambrian sedimentary cyclothems from the uppermost part of the Torridon Group (about 1000 million years old). They form the type section of the Cailleach Head Formation. The cyclothems average 20 m in thickness and show an upward-coarsening sequence from siltstone to fine and coarse sandstone, representing the gradual advance of sandy braided streams into a shallow lake. The grey siltstones at the base of each cyclothem are the former lake bottom sediments, while the cross-bedded red sandstones above are the stream deposits. The sequence is interpreted to have been deposited in a large lake in a NNE-trending rift basin, which underwent periodic phases of deepening. Unicellular microfossils, the first Precambrian fossils found in Britain, were also obtained from phosphatic concretions at this locality. The GCR site provides the most complete set of Precambrian cyclothems in Europe and hence should be regarded as of international importance.