Totaig

[NG 872 255]–[NG 866 233]

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Introduction

The Totaig GCR site, in the Eastern Unit of the Glenelg–Attadale Lewisianoid Inlier, includes the most extensive outcrops of eclogite in Britain, and it was from here that the rock type was first described in the British Isles (Teall, 1891). Eclogites form by metamorphism of original basalts, dolerites or gabbros under high-pressure conditions, equivalent to a crustal depth of 50 km or more. They have a high density and consist essentially of green omphacitic pyroxene and red-brown pyrope garnet. As in many other eclogite-bearing terranes (e.g. Heinrich, 1982), the eclogites in the Glenelg–Attadale Inlier are partially retrogressed to amphibolites (Alderman, 1936). In the Totaig area, eclogite and amphibolite layers are closely associated with outcrops of forsterite-bearing metadolostones ('marbles'), garnetiferous kyanite-biotite gneissose pelite, and hornblende- and biotite-bearing felsic gneiss. In addition, small outcrops of other unusual rock-types, such as iron-rich eulysite and schistose graphitic pelite are present. The distinctive assemblage is a complex admixture of Archaean or Palaeoproterozoic sedimentary and igneous rocks, which have been subject to high-pressure, eclogite-facies metamorphism.

High-grade metamorphic rocks within the Lewisianoid Glenelg–Attadale Inlier were used to draw a comparison with the Scourian gneisses of the Lewisian Gneiss Complex of the foreland, west of the Moine Thrust (Peach *et al.,* 1910). However, Sm-Nd and U-Pb dating of eclogite from the Totaig area showed that the eclogite-facies metamorphism occurred at *c.* 1080 Ma and its subsequent retrogression at *c.* 995 Ma (Sanders *et al.,* 1984; Storey, 2002; Brewer *et al.,* 2003; Storey *et al.,* 2005) and provided evidence of Grenvillian orogenesis. To date, the Glenelg–Attadale Inlier is the only significant area in Britain that shows any record of Grenvillian orogenesis.

Teall (1891) reported the occurrence of eclogite in the area around Totaig, but C.T. Clough first mapped the area for the Geological Survey in 1897 (Geological Survey of Scotland, 1909; Peach *et al.,* 1910). Sutton and Watson (1958) carried out further structural mapping. The mineralogy and petrology of some of the unusual rock-types in the Totaig area have attracted the attention of various authors; these include eclogite (Alderman, 1936), kyanite-eclogite (Tilley, 1937a; Sanders, 1988), websterite (Mercy and O'Hara, 1965; Rawson *et al.,* 2001), clinopyroxenite (Sanders, 1978), forsterite 'marble' (Read and Double, 1935) and eulysite (Tilley, 1936, 1937b).

Description

The Totaig GCR site covers an extensive area of heather moorland and vegetated and tree-clad hill-slopes inland from the rocky coastal section along Loch Alsh and Loch Duich, near Totaig in the central part of the Glenelg Inlier (Figure 7.2). Exposure is almost continuous along the shore, but poor on the hill-slopes above. More-extensive outcrops occur on the higher NE- trending ridges that lead up to Beinn Fhada (445 m), and in the steep cliffs facing Loch Alsh.

The geology of the Totaig area is shown in (Figure 7.19). The rock units in the Eastern Unit strike north-east-south-west, with the foliation dipping gently to steeply to the south-east. A layer of hornblende- and biotite-bearing felsic gneiss interlayered with eclogite and amphibolite occurs in the northern part of the area, along the shore of Loch Alsh. To the south-east a major layer of forsterite-bearing metacarbonate rock and calc-silicate rock (together termed 'marble') extends down to the shore at Totaig pier. A thin mylonite zone separates the metacarbonate rocks from a 500 m-wide layer of gneissose garnetiferous kyanite-biotite pelite, which is exposed on Beinn Fhada, and in road cuttings and on the shore section between Totaig and Druidaig Lodge. A major zone of eclogitic rocks strikes south-west from Druidaig Lodge, although it passes into metalimestone to the south-west. Farther to the south-east is a wide area of felsic gneisses that contains thin intercalated layers of metacarbonate rock and eclogite, well seen in the shore section near Letterfearn. South of Fern Villa, the gneisses of the Eastern Unit dip beneath the Moine metasedimentary cover (Figure

7.19).

The Totaig area contains abundant outcrops of eclogite, which are composed of reddish-brown garnet (pyrope), pale- or grass-green pyroxene (omphacite), with accessory rutile, quartz, ilmenite, amphibole and feldspar (Teall, 1891; Alderman, 1936; Sanders, 1989). Kyanite-and orthopyroxene-bearing eclogite also occur (Sanders, 1988, 1989). The eclogite is normally associated with extensive outcrops of gneissose or schistose amphibolite (Figure 7.18). Alderman (1936) made a comprehensive study of the various stages in the retrogression of eclogites into amphibolitic rocks as seen in thin section. Omphacite is first replaced by a symplectitic intergrowth of pyroxene and plagioclase, with the pyroxene then replaced by green hornblende, and finally the whole symplectite retrogrades to either a single hornblende or a hornblende aggregate. Hornblende also develops in reaction rims around the garnets, which are altered internally to epidote and biotite. Ruffle is retrogressed to sphene, and other retrogression products include scapolite and calcite. In many amphibolites, their high-pressure history can only be recognized by the presence of relict eclogitic textures.

In the field, dark-green hornblendite and pale quartz-feldspar veins cross-cut massive outcrops of eclogite. Eclogitic rocks show successive stages of deformation and retrogression into gneissose or schistose amphibolite, reflecting the intensity of deformation and veining. Pods of massive, relatively unaltered eclogite are typically enclosed in a carapace of amphibolite. It is evident that many former eclogite bodies are now represented only by foliated amphibolite.

The other major rock-type in the Totaig area is metacarbonate rock commonly termed forsterite 'marble'. Apart from the two main outcrops south-westwards from Totaig pier and Druidaig Lodge (Figure 7.19), many smaller layers occur within the felsic gneisses, and are particularly well exposed along the shore of Loch Duich. Similar lithologies are described in the Dornie–Inverinate Road Section and Druim Iosal GCR site reports (this chapter). The 'marble' outcrops have rough weathered surfaces with a dark-grey to black crust studded with green to grey calc-silicate minerals, contrasting with freshly broken surfaces that are white and spotted with brighter green flecks. Outcrops show a rough layering, with layers rich in calc-silicates alternating with calc-silicate-poor layers. Pale-green nodules, up to 2 m across, form augen structures wrapped by the layering (Figure 7.20). They consist of coarsely crystalline, randomly orientated diopside surrounded by rims of rusty-weathering amphibole (Peach *et al.,* 1910, plates II and III). More-angular inclusions of other rock-types, mainly amphibolite and mafic gneiss, also occur within the metacarbonate units.

In thin section, the metacarbonate units have a coarse granoblastic texture consisting mainly of calcite and dolomite, but contain a variety of other minerals, including forsterite, diopside, phlogopite, chlorite, sphene, apatite and iron pyrites. Forsterite, enclosing trails of graphite, is partially or completely altered to serpentine. Small granular yellow pleochroic crystals, identified initially by Read and Double (1935) as chrondrodite, but more recently determined as clinohumite (Sanders, 1972), commonly mantle the forsterite crystals. Garnet and spinel have also been reported at a few localities (Peach *et al.,* 1910, p. 23). Chemical analyses of samples of forsterite 'marble' from Totaig pier and elsewhere in the Eastern Unit show that their magnesium content lies close to that of pure dolostones (Moorhouse and Moorhouse, 1983; May *et al.,* 1993). The diopside nodules may have formed by the reaction of dolomite with chert nodules. Angular inclusions of other rock-types perhaps represent remnants of originally continuous layers or dykes within the meta-carbonate rocks, disrupted by deformation.

An unusual type of peridotite consisting of olivine, clinopyroxene, garnet and magnetite, forms a rocky knoll 200 m south-west of Druidaig Lodge [NG 878 245], where it occurs in association with other iron-rich rocks within gneissose pelite. Tilley (1936) originally described the rock and termed it a 'eulysite', but in modern terminology it is classified as a wehrlite. The olivine is a manganiferous iron-rich fayalite and the clinopyroxene lies in the range diopside-hedenbergite. Outcrops in the Totaig area are conspicuous because of their blue-black, iron-manganese weathered crust. Associated lithologies are layered hedenbergite-garnet-magnetite rocks and schistose rocks containing the iron amphiboles grunerite and cummingtonite. Tilley (1937b) also reported the occurrence of the pink manganese minerals pyroxmangite and rhodonite, the latter in veins up to 2 cm thick, in grunerite schist. Wehrlite has a very high density, reflecting its iron and manganese content, and in addition to olivine (fayalite), also contains iron-hypersthene, hedenbergite (or pyroxmangite), spessartine-almandine garnet, calcite, magnetite and apatite (e.g. Tilley, 1936). In thin section, olivine and pyroxene are seen partially altered to grunerite, which also occurs as fibrous vein fillings. Field relationships suggest that the wehrlite has been altered by later hydration and deformation to form the adjacent schistose garnet, magnetite and cummingtonite-grunerite rocks.

Gneissose biotite-rich pelite containing abundant garnet and kyanite is also abundant in the Eastern Unit (see also Druim Iosal GCR site report, this chapter). In the Totaig area, it outcrops as a broad zone between Totaig and Druidaig Lodge extending south-westwards to Beinn Fhada (Figure 7.18). SSW of Totaig pier at [NG 870 243] the rock consists largely of garnet and quartz, with some kyanite and shimmer aggregate, whereas just south-west of Druidaig Lodge at [NG 878 245] kyanite or shimmer aggregate are dominant (Clough in Peach *et al.,* 1910, p. 27). In the latter exposures kyanite crystals up to 10 cm long enclose garnet; staurolite has also been reported here. Clough also noted that the pelitic gneiss contains graphitic layers up to 20 cm thick, for example 120 m SSE of Lochan Beinne Faide at [NG 862 235].

Hornblende- and biotite-bearing felsic gneisses constitute a large part of the Lewisianoid outcrop in the Totaig area (Figure 7.19). The gneisses are characterized by an alternation of felsic and mafic layers ranging from 1 cm up to several metres in thickness. Locally, it can be seen that the gneisses have formed from agmatites. Amphibolite has been intruded by quartz-feldspar veins and subsequently deformed, so that mixed felsic and mafic materials are sheared or flattened to form thin layers. At some localities the felsic component contains garnet, omphacite, oligoclase, and locally kyanite, K-feldspar, rutile and biotite, representing an eclogite-facies assemblage (Sanders, 1979, 1989). The mafic component is represented by eclogite, and the two components are inter-layered on millimetre- to metre-scale (e.g. (Figure 7.21)). Clearly the two components are closely related, having been tightly folded and metamorphosed together under eclogite facies.

Fine-grained, blastomylonitic felsic gneisses were mapped by Sutton and Watson (1958) as a thin unit along the shores of Loch Alsh near Creag Ruairidh and Eilein Aoinidh. Here, the gneisses appear to immediately overlie the highly deformed Moine rocks within the shear zone that separates the Eastern and Western units. Blastomylonitic gneisses also occur on either side of the wide outcrop of the garnetiferous gneissose pelite and are well exposed near Totaig pier (Figure 7.19). They are finely layered on a centimetre- to millimetre-scale with intra-folial tight to isoclinal folds common. Such rocks are extremely fine grained with a compact texture, and are studded with ovoid less-deformed augen up to several centimetres across that contain porphyroclasts of garnet, hornblende, plagioclase and rarely omphacite. The blastomylonites were derived from coarser-grained rocks, including eclogites, by intense deformation and recrystallization. The fine-grained matrix has a granoblastic texture indicating that recrystallization continued after deformation.

Interpretation

The Eastern Unit of the Glenelg–Attadale Inlier in the Totaig area represents a high-grade complex of Archaean and/or Palaeoproterozoic metasedimentary and meta-igneous rocks, metamorphosed under eclogite-facies conditions, but now largely retrograded to amphibolite facies. The interest of the area lies in the preservation of numerous high-pressure metamorphic relics including eclogite, forsterite 'marble', pelitic gneiss, garnet quartzofeldspathic gneiss with omphacite and other unusual rock-types such as wehrlite, cummingtonite-grunerite schist, garnet-magnetite schist, schistose graphitic pelite, clinopyroxenite and websterite.

The oldest part of the complex is probably the felsic gneisses, which are dominantly granodioritic or tonalitic, and are intimately mixed with mafic rocks. This part of the complex may represent the basal part of a volcanic arc complex, composed of acid and basic intrusions. The mafic rocks may have originally included large layered laccolithic bodies in which cumulates developed, represented by websterite (Mercy and O'Hara, 1965; Rawson *et al.,* 2001) and the Al-Ti-augite cumulate described by Sanders (1978), as well as small cross-cutting basalt dykes. Most of the mafic rocks in the complex were subsequently converted to eclogite during the Grenville Orogeny (see below).

The Sm-Nd ratio of an eclogite analysed by Sanders *et al.* (1984) gave a model Nd age of approximately 1700 Ma, suggesting that the basic magma from which it formed separated from the mantle at that time. Geochemical analyses show that the eclogites have tholeiitic and nepheline-normative basaltic compositions (Sanders, 1989; Mercy and O'Hara, 1968). The latter are unlike the mafic intrusions of the Lewisian Gneiss Complex in the foreland to the Moine Thrust Belt and thus attest to a different pre-Grenvillian evolution of the Eastern Unit.

The forsterite 'marbles' and the garnet kyanite pelites were both clearly derived from sedimentary rocks. They are closely associated with the wehrlites and the other iron-rich rock-types, suggesting that some of these rocks are also of

sedimentary origin. Their enrichment in Fe and Mn, and silica and calcium contents, have prompted a comparison with the banded ironstones of the Lake Superior region in the United States and Canada (Tilley, 1936). Where the latter lie within the aureole of the Duluth Gabbro, they have developed similar mineral assemblages to those seen in the Totaig wehrlite and associated iron-rich rocks (Tilley, 1936). The gneissose pelites, forsterite 'marbles' and the iron-rich rocks possibly represent shales and limestones with chert nodules that were deposited as an evaporitic sequence in a sabkha-like environment (see also Druim Iosal GCR site report, this chapter). The occurrence of graphitic layers within the pelites indicates that locally these sediments included high proportions of organic matter. It is likely that the sediments were deposited unconformably on a basement now represented by the meta-igneous rocks, although there is no direct evidence for an unconformity.

The Sm-Nd ages on eclogite of 1082 Ma and 1010 Ma (Sanders *et al.,* 1984) and the U-Pb zircon age of *c.* 995 Ma in retrogressive amphibolite (Brewer *et al.*, 2003) show that the Eastern Unit underwent eclogite-facies metamorphism followed by rapid exhumation during the Grenville Orogeny. Eclogite with similar ages have been dated in the Grenville Province in Canada (Indares and Dunning, 1997) and in the Sveconorwegian Orogen in south-west Sweden (Moller, 1998).

A range of thermobarometric measurements on mineral assemblages from the eclogite, gneissose pelite and websterite of the Totaig area and elsewhere in the Eastern Unit give peak metamorphic temperatures around 730° C at pressures of 16–20 kbar, indicating that the Eastern Unit was buried to a depth of 50–60 km during the Grenville Orogeny (Sanders, 1988, 1989; Rawson *et al.*, 2001; Storey *et al.,* 2005). Rapid exhumation is indicated by the common occurrence of exsolution phenomena in pyroxenes from the eclogitic rocks, implying isothermal decompression. In the inlier large basic bodies have been completely disrupted with the resultant fragments occurring as isolated boudins, whereas mafic dykes have been rotated into concordance with the layering in the surrounding gneisses; all testify to the intensity of the deformation, a significant component of which may be of Grenvillian age. Temperley and Windley (1997) suggested that exhumation of the high-pressure Glenelg–Attadale , Inlier was caused by top-to-the-E shearing along a low-angle detachment that also involved the Moine metasediments. However, the presence of an apparently unconformable basal meta-conglomerate in the overlying Moine succession (for instance at the Attadale and Allt Cracaig Coast GCR sites) suggests that the uplifted eclogitic-facies complex was exposed at the surface before the deposition of Moine sediments that occurred between *c.* 950 Ma and 870 Ma (e.g. Friend *et al.,* 2003; see also 'Introduction', this chapter). The amphibolite-facies retrogression, dated by U-Pb in zircon at *c.* 995 Ma (Brewer *et al.,* 2003), pre-dates the youngest population of detrital zircons (*c.* 950 Ma) recovered from the Moine. It may be that the blastomylonites developed in the Lewisianoid gneisses of the Eastern Unit represent shear zones related to the exhumation of the complex. An unconformable relationship between the blastomylonites and the overlying Moine succession is indicated by the distribution of these units on the north-eastern side of Loch Duich (see (Figure 7.14)); the shearing responsible for the formation of the blastomylonites appears to have occurred mainly before deposition of the Moine sequence.

Subsequent to deposition of the Neoproterozoic Moine succession, the metasedimentary cover and the Glenelg–Attadale basement were deformed in the Caledonian Orogeny and possibly during the earlier Knoydartian Orogeny. The first phase of deformation appears to have resulted in tight to isoclinal folding of the cover and basement into anticlines and synclines, producing the alternating Moine and Lewisianoid strips that now characterize the Glenelg–Attadale Inlier. In the Totaig area these strips were refolded by the Letterfearn Fold, as seen clearly in outcrops of Moine rocks above Fern Villa [NG 875 234] (Sutton and Watson, 1958). The Letterfearn Fold is a reclined F2 fold with an E-plunging axis and E-dipping axial plane. It is one of a series of kilometre-scale F2 structures that fold the eastern boundary of the Glenelg–Attadale Inlier (see Beinn a' Chapuill GCR site report, this chapter).

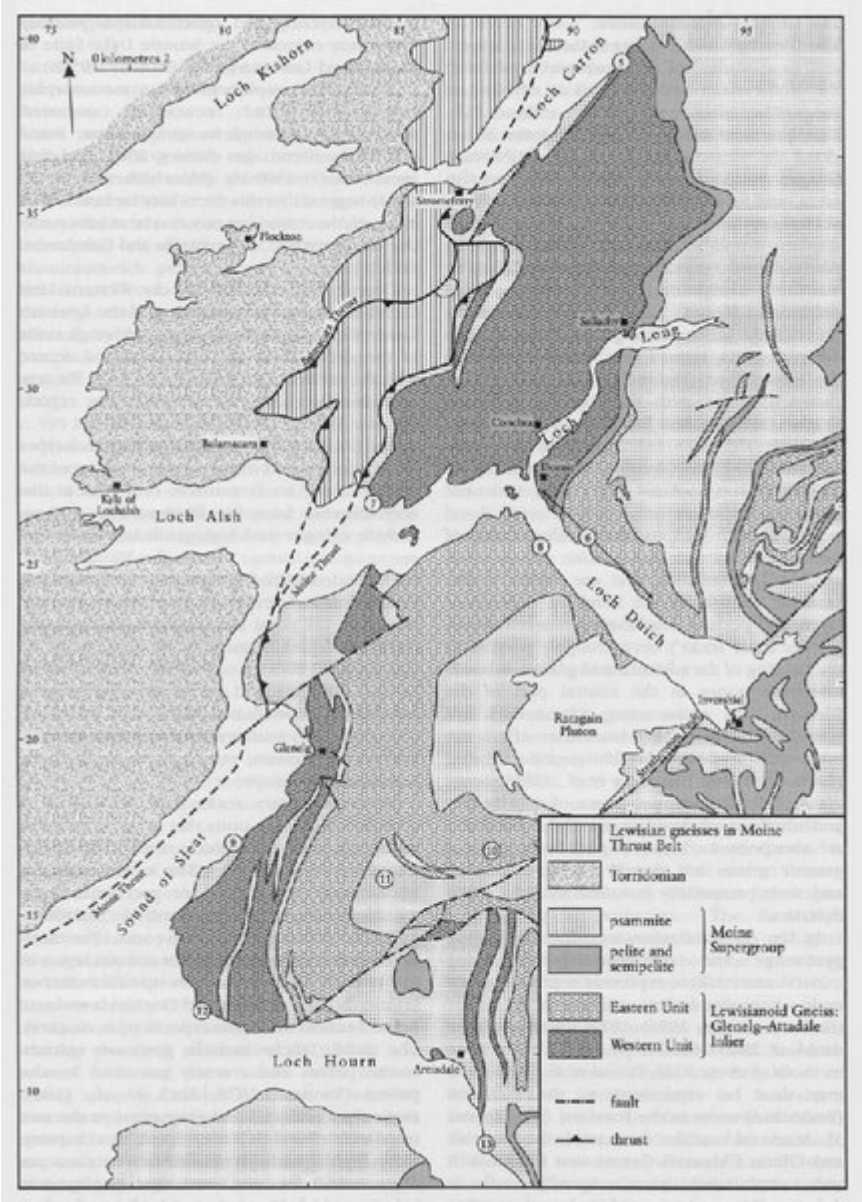
Conclusions

The Totaig GCR site lies within the Eastern Unit of the Glenelg–Attadale Inlier and contains the first recorded, best-exposed and most studied eclogites in Britain. Petrological and geochemical studies, isotopic dating, thermobarometric measurements and experimental studies have all been carried out on the eclogites and associated rock-types over the past 100 years. The GCR site is also unique in Britain for its variety of other unusual rock-types. These include garnetiferous quartzofeldspathic gneiss containing omphacite, clearly related to the eclogite *sensu stricto,*

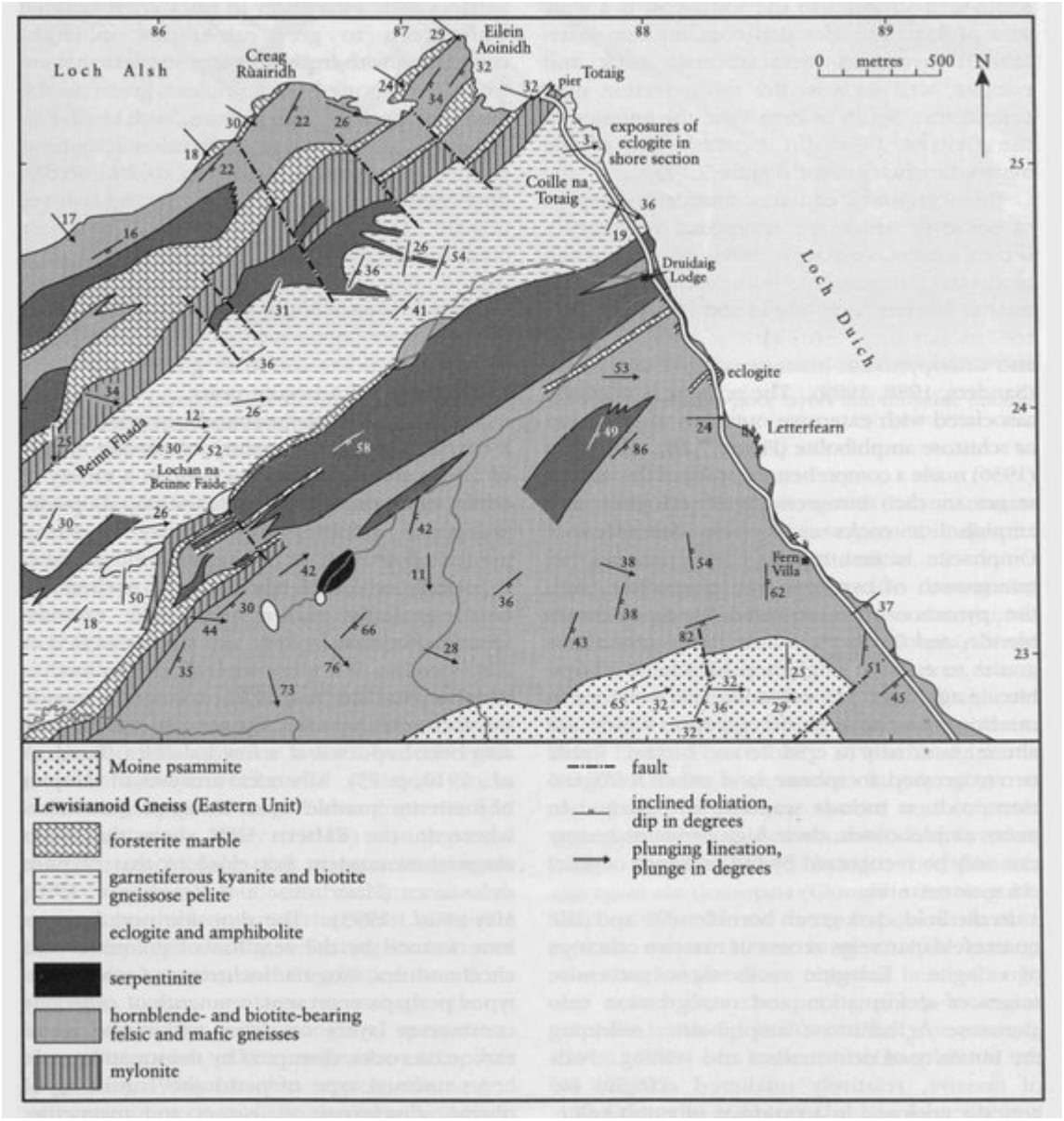
garnetiferous kyanite-biotite gneissose pelite, forsterite 'marble' containing a great variety of talc-silicate minerals, and iron-rich rock-types, such as garnet-magnetite rock and grunerite-cummingtonite schist, and rare ultramafic rocks, including wehrlite, websterite and clinopyroxenite. These rock types have been intensively studied and the work constitutes a major contribution to the mineralogical and geochemical literature.

The Grenvillian Sm-Nd age of *c.* 1080 Ma obtained from the eclogites at Totaig (Sanders *et* at, 1984) was unexpected, but has been confirmed by more-recent U-Pb zircon geochronological studies (Brewer *et* ed., 2003). The ages have led to a major re-assessment of the correlation of the Glenelg–Attadale Inlier with both the Lewisian gneisses of the foreland, west of the Moine Thrust Belt, and with the other Lewisianoid inliers in the Moine succession. They also provoked a radical revision of the Proterozoic tectonic history of the Scottish Caledonides. The significance of these results is still the subject of active controversy among Highland geologists. The area remains suitable for further studies that hopefully may resolve some of the outstanding problems. The area is of national and international importance, as it provides a potential link between eclogite-facies terranes of similar age in Canada and Scandinavia.

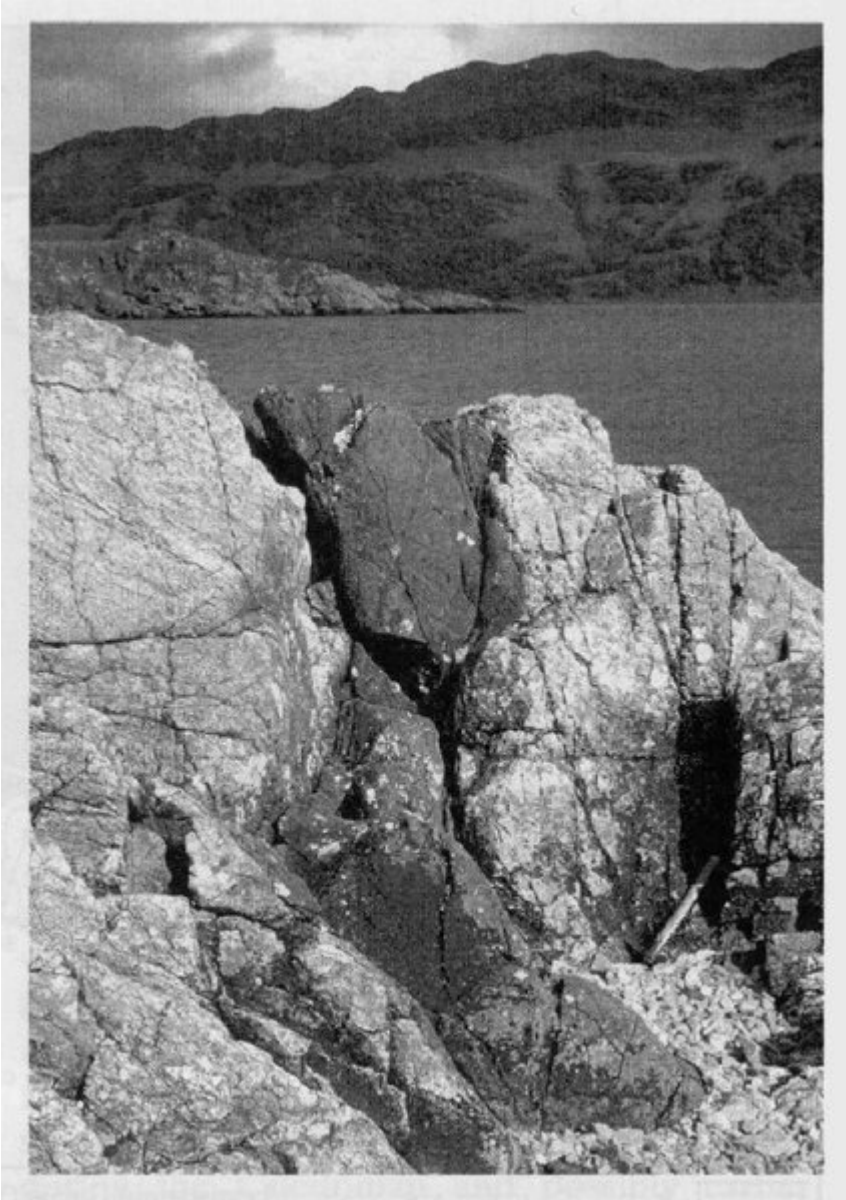
References



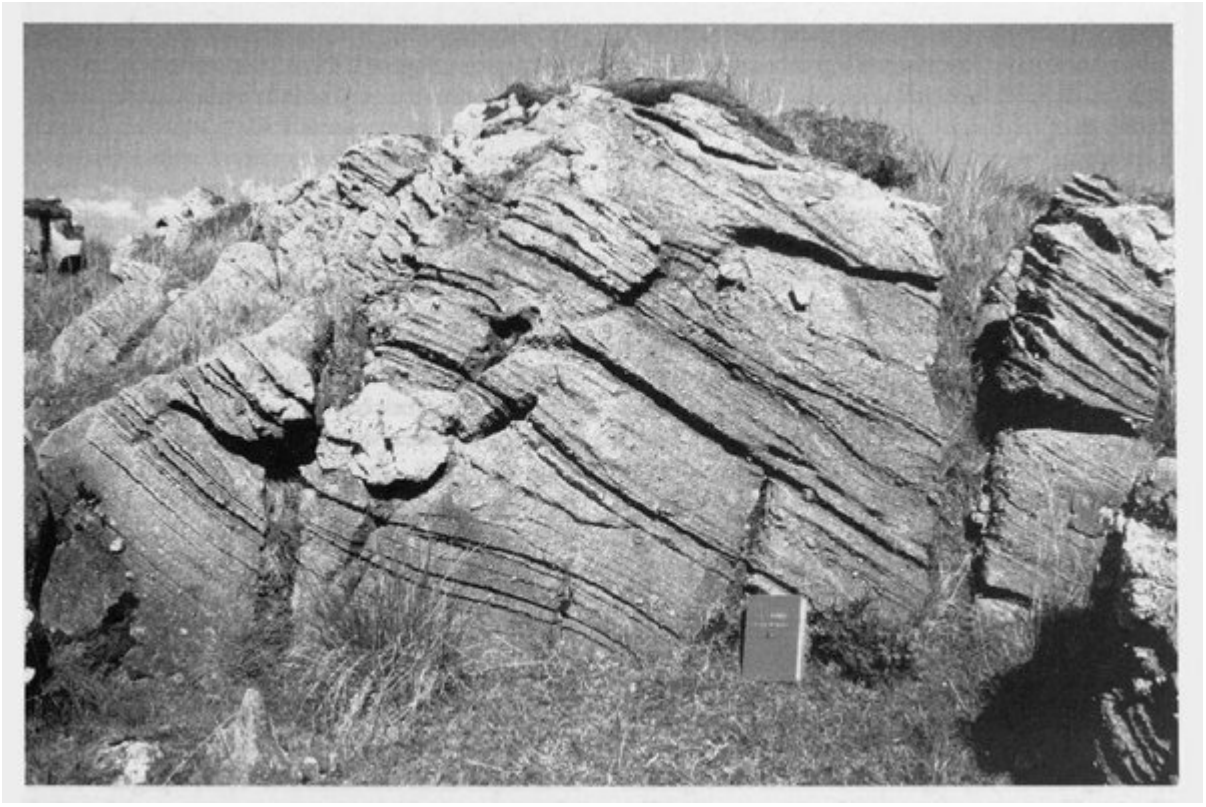
(Figure 7.2) Geological sketch map of the Glenelg–Attadale Inlier and surrounding area (after Barber and May, 1976), showing the location of the GCR sites within or marginal to the Glenelg–Attadale Inlier. 5 — Attadale; 6 — Dornie—Inverinate Road Section; 7 — Avernish; 8 — Totaig; 9 — Allt Cracaig Coast; 10 — Druim Iosal; 11 — Beinn a' Chapuill; 12 — Eilean Chlamail—Camas nan Ceann; 13 — Rubha Camas na Cailinn.



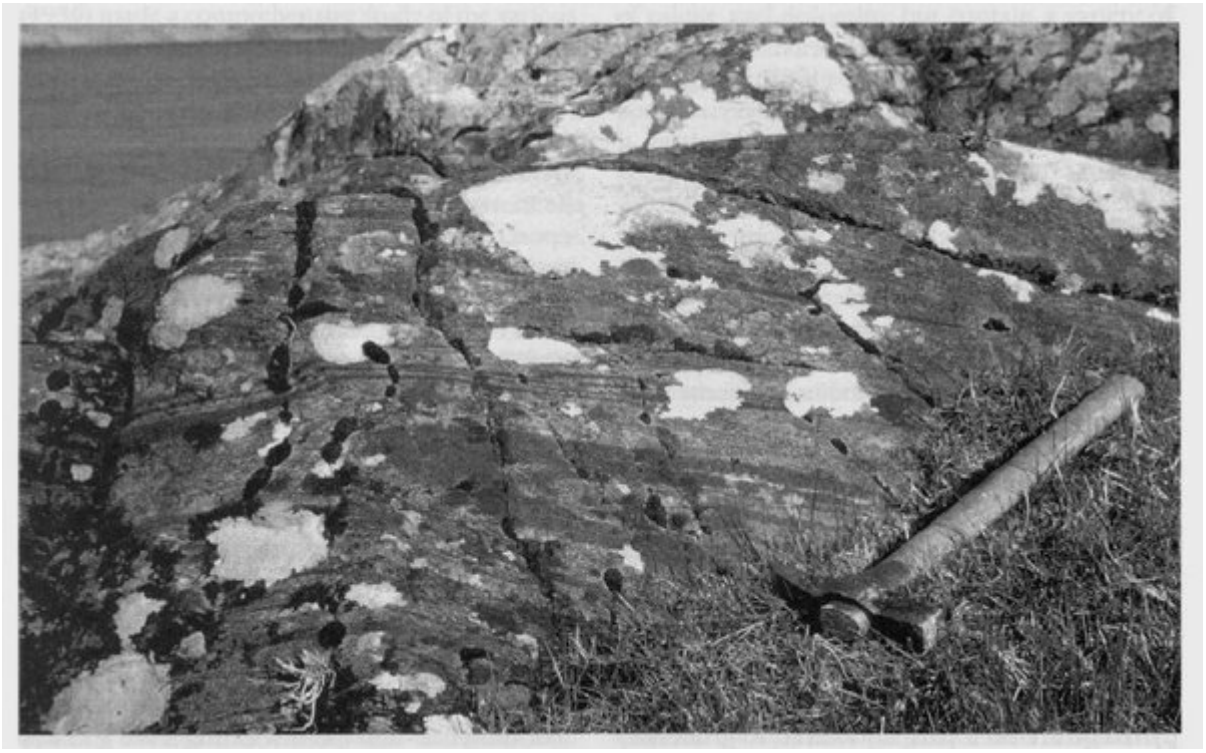
(Figure 7.19) Map of Totaig GCR site. Based on Sutton and Watson (1958) and Geological Survey of Scotland (1909).



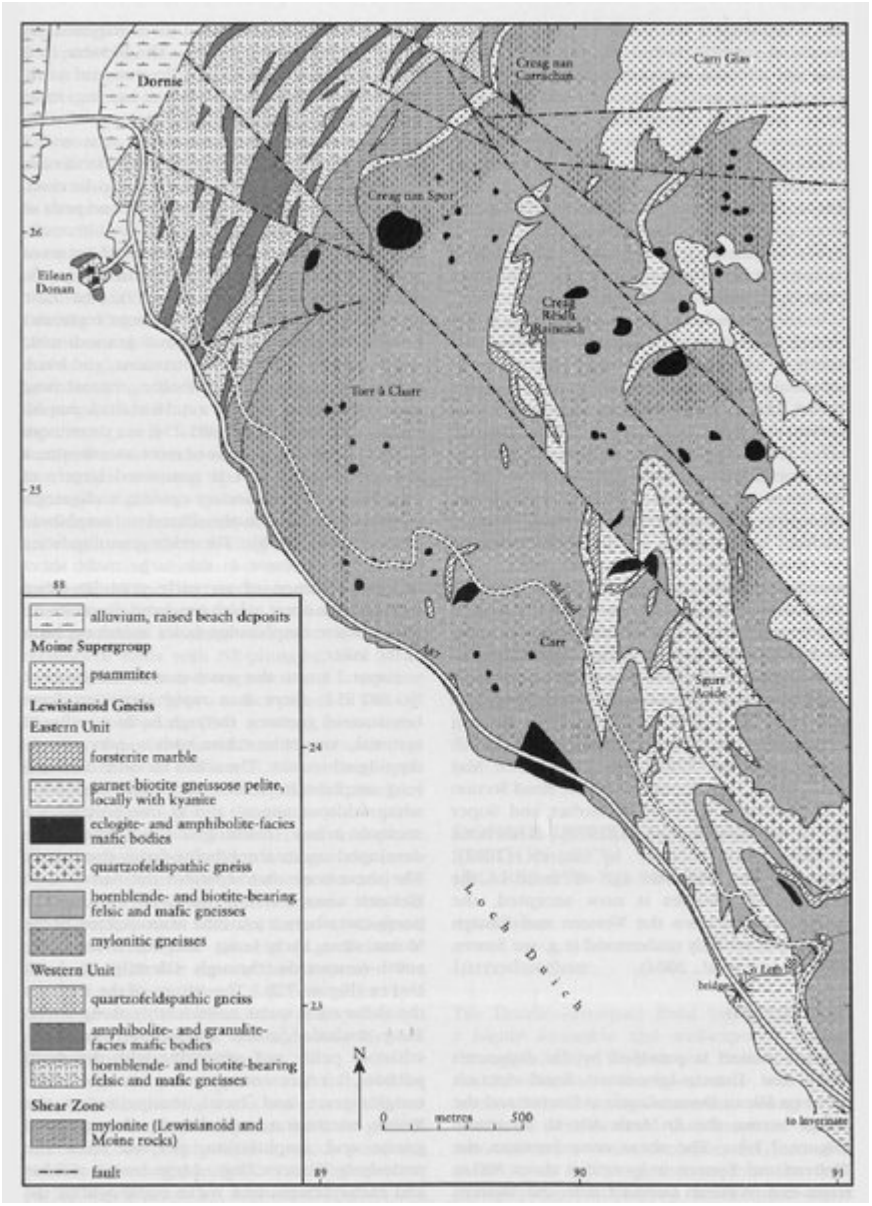
(Figure 7.18) Amphibolite dyke cutting quartzofeldspathic gneiss at high angles to gneissic layering, attesting to the relative low-strain state of the eastern part of the Avernish GCR site, Nostie Bay. The hammer is 37.5 cm long. (Photo: A.J. Barber.)



(Figure 7.20) Layered forsterite marble with calc-silicate-rich and calc-silicate-poor layers and diopside nodule, Beinn Fhada. The field notebook is 16 cm high. (Photo: A.J. Barber.)



(Figure 7.21) Tight fold in layered eclogite, shore of Loch Dutch, Letterfearn. The hammer is 37.5 cm long. (Photo: A.J. Barber.)



(Figure 7.14) Map of the Dornie–Inverinate Road Section GCR site. Based on field mapping by A.J. Barber.