Dykes of metamafic rock up to 30 m wide have been described from Jura (Graham and Borradaile, 1984) but they are rare on Islay and on the mainland, where sills predominate. Graham and Borradaile made the significant point that on Jura the host rocks are stratigraphically older than those on Islay and the mainland. This suggests that the igneous 'plumbing system' here may have followed the model of Francis (1982), where the level of intrusion of sills is constrained by the lithostatic pressure in the country rock and the hydrostatic pressure in the feeder dyke. Intrusion of sills will only occur where the hydrostatic pressure of the magma in the feeder dyke is greater than the lithostatic pressure of the country rocks; the lithostatic pressure directly relates to depth of burial. At the time of intrusion of the sills and dykes, the stratigraphically older rocks on Jura will have been at a greater depth than the Port Ellen Phyllite and Laphroaig Quartzite formations on Islay and, critically, too deep for the intrusion of sills. It is probable that the dyke described above was a feeder dyke for the nearby or higher sills.

The igneous dykes are important indicators of the extensional stress regime associated with the Dalradian sedimentary basin. The orientation of this dyke is similar to the majority found on Jura and indicates an extension direction approximately east–west.

8.4. Conclusions

Although sedimentary dykes are not uncommon in the Scottish Dalradian, none of the other reported examples are as spectacular as those found at the Surnaig Farm GCR site. In fact these are some of the best examples of sedimentary dykes in Britain and are certainly the best found in deformed rocks. They are most likely to have resulted from interstratal dewatering, as has been proposed here for sandstone dykes at the *Caol Isla* GCR site, but some of the diagnostic features have been obscured or destroyed at Surnaig Farm by subsequent deformation.

The shoreline here also reveals several other intriguing aspects of Dalradian geology, including a fine example of a sill of metamafic rock and, rare for Islay, an unequivocal example of a metamafic-rock dyke. The GCR site, therefore, provides evocative snapshots of the evolution of the Argyll Group, from the sedimentation and igneous activity associated with its early depositional history, to the deformation and metamorphism of these rocks in the subsequent mountain building episode now referred to as the Grampian Event.

9. Ardbeg, Islay (NR 413 459–NR 422 464) (C.A. Bendall)

9.1. Introduction

The rocks on the foreshore near the Ardbeg Distillery on the south-east coast of Islay (Fig. 20) include a tightly folded and metamorphosed doleritic sill, first described by Wilkinson (1907). Towards the top of this sill, there are lenses containing the mineral stilpnomelane. This rather unusual mineral (a sheet silicate) is found scattered sporadically through low-grade metamorphic rocks in the British Isles, but it is comparatively rare. It is unusual to find it in such high concentrations and as coarsely grained as it is at this locality.

The sill is one of a suite of pre-tectonic basic intrusions that are ubiquitous throughout the Dalradian of the south-west Grampian Highlands. However, this sheet has clearly been folded which is rarely seen on Islay, although folded sills are commonly observed on the mainland, for example at Tayvallich (Wilson and Leake, 1972) and at the Point of Knap (Roberts, 1966a). The mineral paragenesis of the sill gives an indication of the grade of regional metamorphism that the rocks have experienced.

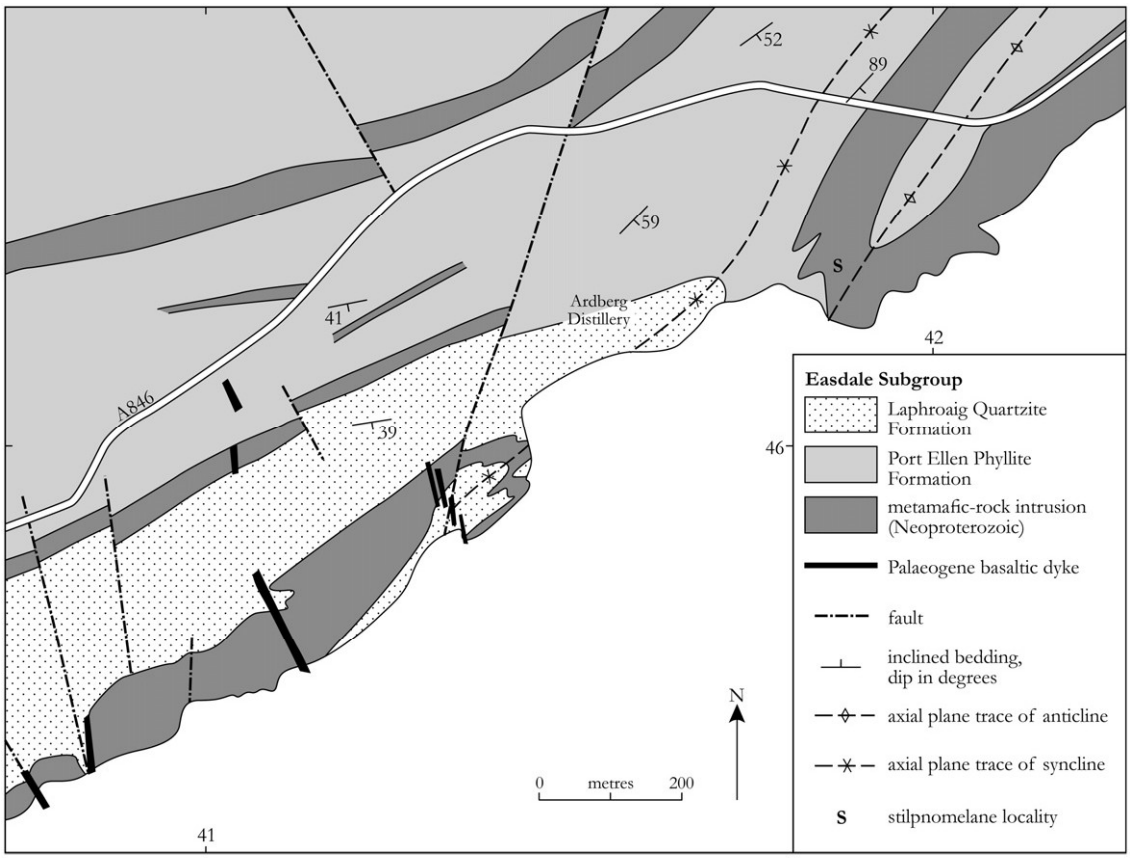

Fig. 20. Map of the area around the Ardbeg GCR site, south-east Islay, showing the stilpnomelane locality.

The host rocks are metasandstones, metasiltstones and metamudstones belonging to the Port Ellen Phyllite and Laphroaig Quartzite formations of the Easdale Subgroup, and are at approximately the same stratigraphical level as the rocks at the *Surnaig Farm* and *Ardilistry Bay* GCR sites. These rocks demonstrate a variety of sedimentary features, but are also quite important in unravelling the geological history of the area, as they preserve evidence, in the form of tectonic cleavages, for at least three deformational events. Hence at this locality the growth of the stilpnomelane may be considered in both a structural and metamorphic context.

9.2. Description

The metasedimentary rocks at this GCR site comprise the upper part of the Port Ellen Phyllite Formation and the lower part of the Laphroaig Quartzite Formation. North of the site, the Port Ellen Phyllite consists mostly of metamudstone but towards the top of the formation (within the GCR site), metasandstone beds become more prevalent. The boundary with the overlying Laphroaig Quartzite is gradational, passing up into interbedded metasandstones and metamudstones with rare metacarbonate rocks. The metasandstone beds are dominant and vary in thickness between *c.* 0.5 and 2 m. A wide range of sedimentary structures may be observed in this formation, such as cross-bedding, dewatering structures and scours, and sandstone dykes may be seen cross-cutting the bedding in the metamudstones (Borradaile, 1974).

Subsequent basic magmatism resulted in the intrusion of a series of doleritic sills. The sills are conspicuous in this part of the island, as the intervening metasedimentary rocks have been preferentially eroded leaving prominent ridges of metadolerite. It is highly likely that they are genetically and spatially related to the Tayvallich lavas found on the mainland, which have been dated at *c.* 600 Ma using U-Pb dating techniques on zircons (Halliday et al., 1989; Dempster et al., 2002).

The major structure in the Dalradian of Islay is the upward- and north-west-facing Islay Anticline that formed during the first phase of deformation of the Grampian Event (Bailey, 1917; Roberts and Treagus, 1977). This GCR site lies on the south-east limb of the anticline, so the beds generally have moderate (40–60°) dips and young to the south-east. The syncline–anticline fold pair that folds the stilpnomelane-bearing metadolerite sill is parasitic to the major Islay Anticline (as indicated by their north-west sense of vergence). Associated with this folding is a penetrative cleavage, which is best developed in the finer grained rocks such as those found in the Port Ellen Phyllite Formation, where it is continuous and slaty in some beds. This cleavage dips steeply to the south-east and is axial planar to minor F1 folds (e.g. at NR 4170 4619).

At least two later stages of deformation can be recognized on the foreshore beneath the distillery; these take the form of crenulation cleavages and some minor open folding. One of the crenulation cleavages dips steeply (*c.* 80°) to the north and in places is the dominant fabric in the rock. The other crenulation cleavage is only developed sporadically, and dips at a shallow angle to the east. It is not clear which of these later cleavages pre-dates the other, and there is no record of any major folds on Islay associated with either cleavage.

Stilpnomelane is found in irregular lenses towards the top of the 70 m-thick folded metadolerite sill that crops out on the foreshore just to the west of the distillery at NR 4185 4625 (Fig. 20). It is a bronze-coloured mineral with a metallic lustre and forms radiating clusters, with individual grains up to 1 mm in length. In thin section it resembles biotite but has a more reddish brown colour and lacks the perfect mica cleavage (Fig. 21). The colour indicates that it is probably ferri-stilpnomelane. The metadolerite host rock has a relict ophitic texture that is obvious in hand specimen but less well defined in thin section. The stilpnomelane-bearing lenses also contain actinolite, epidote, albite, quartz, chlorite, calcite (rare) and leucoxene. The actinolite is distinctly green and pleochroic; microprobe analysis shows it to be iron-rich (Bendall, 1995) and recalculation of microprobe data, based on the procedure outlined in Droop (1987), implies a high ferric iron component. There does not appear to be a tectonic fabric in the rock and the stilpnomelane clearly cross-cuts all the other mineral phases; it is randomly orientated, commonly forming radiating clusters (Fig. 21).

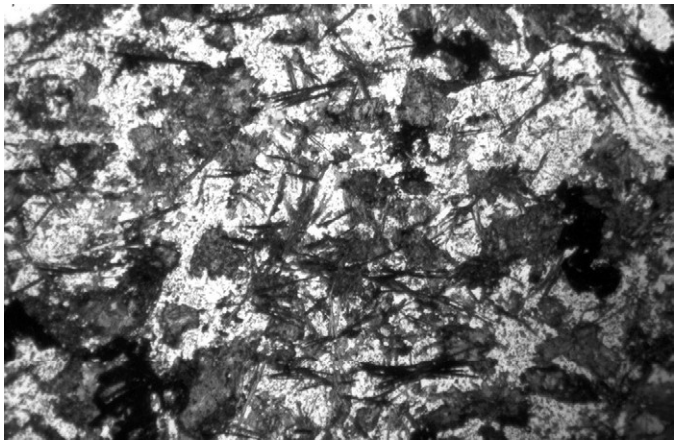

Fig. 21. Photomicrograph (in plane-polarized light) of the stilpnomelane-bearing metamafic sill on the foreshore 400 m east of Ardbeg Distillery at NR 4185 4625. Radiating clusters of stilpnomelane can be seen overgrowing actinolite, albite, quartz, and epidote. The field of view is 6 mm (photo: A. Condron).

9.3. Interpretation

Stilpnomelanes have the general formula: $(K,Na,Ca)_{0.6}(Mg,Fe^{2+},Fe^{3+})_6Si_8Al(O,OH)_{27}{\cdot}2–4H_2O$ (Deer et al., 1992). They tend to be iron-rich but the composition can vary between the ferric end-member ferri-stilpnomelane and the ferrous end-member, ferro-stilpnomelane. Consequently stilpnomelanes are most likely to occur in iron-rich rocks, such as metamorphosed ironstones and iron-rich meta-igneous rocks, but they are generally restricted to lower- to middle-greenschist-facies metamorphic rocks. At Ardbeg, the ferri-stilpnomelane is associated with actinolite that has high ferrous and ferric iron concentrations with respect to its Mg concentrations, supporting the association of stilpnomelane with Fe-rich rocks.

Metamorphic mineral assemblages in the finer grained metasedimentary rocks at this GCR site are indicative of the biotite zone, and metadolerite assemblages are typical of greenschist-facies metamorphism. The peak of metamorphism here was probably associated with the D1 phase of deformation that was responsible for the development of the Islay Anticline (Skelton et al., 1995). The stilpnomelane appears to have grown later than the other minerals that occur with it. However, it does not appear to be retrogressive and therefore probably formed around the peak of metamorphism, which was somewhere around 470 °C, according to Skelton et al. (1995). The pressure estimates of 10 kbar assumed in that study were all derived from sources that utilize phengite equilibria (Powell and Evans, 1983). The authors conceded that they are rather on the high side and expressed reservations as to the reliability of such geothermometers. Pressures of around 5 kbar, which imply burial depths of between 15 and 20 km, are more typical of greenschist-facies metamorphism.

9.4. Conclusions

The Ardbeg GCR site is notable and of some international importance for the occurrence of the metamorphic mineral

stilpnomelane within a metadolerite sill. Although stilpnomelane occurs sporadically elsewhere in the Scottish Dalradian, here it is relatively abundant and the fresh crystals are up to 1 mm in size, which is quite large for stilpnomelane. This poorly understood mineral is preserved here in a host rock that has not been significantly retrogressed. Its growth is reasonably well constrained with respect to the regional deformation and metamorphism, and the overall mineral assemblage can be used to quantify the temperature and pressure of metamorphism under which this particular stilpnomelane formed. An important constraint on the formation of stilpnomelane is the iron-rich chemical composition of the host rock, which can be reliably established at this site as the rock is relatively fresh.

This small site also exhibits good examples of sedimentary structures such as cross-bedding, dewatering structures and scours, which are found within the Laphroaig Quartzite. Three different small-scale tectonic fabrics are easily distinguished here and these could prove important in establishing tectonic relationships in south-east Islay.

10. Ardilistry Bay, Islay (NR 443 485–NR 447 483) (C.A. Bendall)

10.1. Introduction

Along the coastal sections at Ardilistry Bay, 8 km east of Port Ellen in south-east Islay, metamorphosed basic sills account for over half the succession. One of the sills, exposed along the south-east shoreline of the bay (NR 4415 4816–NR 4441 4837), is almost certainly unique in the British Isles. This sill is around 12–14 m thick and, towards the base, there is a 3 m-thick layer that consists almost entirely of the amphibole, actinolite. The protolith of this rock was almost certainly a pyroxene-cumulate and the pyroxene has been replaced by actinolite during greenschist-facies metamorphism. Although the mineralogy has changed, the original cumulate texture is retained. The metapyroxenite is overlain by a metamorphosed plagioclase layer approximately 1 m thick, in which albite and epidote have replaced the original plagioclase.

The country rocks around the bay are Dalradian metasedimentary rocks belonging to the Easdale Subgroup of the Argyll Group. These rocks were first described by Wilkinson (1907), and have received relatively little attention since. Wilkinson also provided the most comprehensive description of the Islay sills, although this was rather general and he made no mention of this particular sill. The area was resurveyed by Basahel (1971) and much of the revised 1998 edition of the BGS 1: 50 000 Sheet 19 (South Islay) is based upon his work.

10.2. Description

Two formations crop out at Ardilistry Bay; the Port Ellen Phyllite is poorly exposed, especially inland, but the younger Laphroaig Quartzite is exposed intermittently around the coastline (Fig. 22). The Port Ellen Phyllite Formation consists mainly of metamudstones with subordinate metasandstones and impure metasandstones. The metasandstones become more common towards the top of the formation, where there is a gradation into the thickly bedded metasandstones with subordinate metamudstones of the Laphroaig Quartzite Formation. This low-lying coastal region is dominated by a series of ridges, parallel to strike, that are formed by sills of resistant metamafic rock (Fig. 23). Thinner sills are generally schistose but, while their margins may be schistose, many of the thicker sills retain relict igneous textures that are commonly ophitic. The mineral assemblage of the sills is typical of the greenschist facies and consists of chlorite, actinolite, albite, epidote, calcite, quartz and leucoxene.

Among several curious features to be found in these sills, are pods rich in the yellow-green mineral epidote. They are quite conspicuous in some of the thicker sills along the north-east shore of the bay.

The metapyroxenite-bearing sill is found at NR 4431 4831. There is good exposure in low cliffs along the shoreline, but it is poorly exposed when traced inland. A schematic section of this sill is presented in Fig. 24. The basal part is schistose; little remains of the original igneous texture except for relict phenocrysts, which were probably once calcium-rich plagioclase. These have been pseudomorphed by albite, epidote and calcite during greenschist-facies metamorphism and have been flattened during the deformation that produced the schistosity. Although the base of this schistose unit cannot be observed directly, the unit appears to be no more than about a metre thick, and could represent the original fine-grained basal margin to the sill. Immediately above this is the actinolite-rich layer, which is approximately 3 m thick and consists almost entirely of actinolite pseudomorphs after clinopyroxene. These are mostly euhedral to subhedral, dark olive

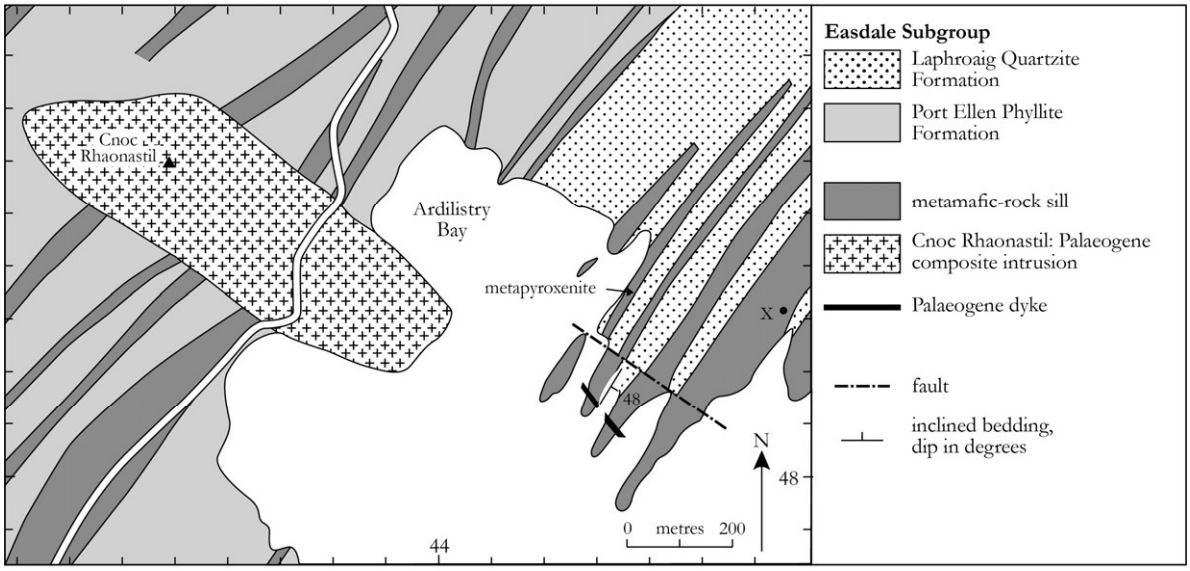

Fig. 22. Map of the area around the Ardilistry Bay GCR site, south-east Islay.