Ardalanish Bay (Mull)

[NM 376 188]–[NM 363 168]

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Introduction

The Ardalanish Bay GCR site provides a traverse through the thermal aureole of the Ross of Mull Granite Pluton. In the aureole, medium-pressure, kyanite-bearing, regional metamorphic assemblages in the surrounding Moine metasedimentary rocks have been replaced by high-temperature contact metamorphic minerals. The Ross of Mull Pluton is notable for showing one of the finest examples of a 'ghost' country rock stratigraphy within an intrusion. This demonstrates that the pluton was intruded through a process of sheeting, wedging and stoping, but with little disruption of the country rocks. Details of the pluton and its emplacement mechanism are described in the Cnoc Mor to Rubh' Ardalanish GCR site (Highton, 1999) and by Zaniewski *et al.* (2006); this description focuses on the thermal aureole. Halliday *et al.* (1979) obtained a mineral-whole-rock Rb-Sr age of 414 ± 3 Ma from the outer granite, but this probably dates the cooling of the pluton rather than its emplacement.

The raised shoreline of Ardalanish Bay on the Ross of Mull exposes the most westerly known outcrops of the Neoproterozoic Moine succession (Cunningham Craig *et al.,* 1911; Bailey and Anderson, 1925; Riley, 1966). The Moine rocks are bounded to the west by the Ross of Mull Pluton. The Moine succession on Mull comprises an older Shiaba Group and a younger Assapol Group, which have been correlated with the Morar and Glenfinnan groups respectively of the mainland Moine succession (Holdsworth *et al.,* 1987; (Figure 8.3)). The nature of the contact between the two groups has been subject to various interpretations. Rathbone (1980) and Barr (1983) described it as high-strain contact, equivalent to the Sgurr Beag Thrust, which on the mainland separates the Morar and Glenfinnan groups. However, more-recent work favours a transitional stratigraphical boundary along which there is some localized ductile high strain (Holdsworth *et al.*, 1987). If the later interpretation is correct, and correlation with the mainland succession valid, then the Ross of Mull uniquely preserves the original stratigraphical relationships between the Morar and Glenfinnan groups or their equivalents. Unusually, the Moine succession contains metamorphic index minerals with kyanite and staurolite present in some pelitic and semipelitic lithologies as a result of the regional amphibolite-facies metamorphism. The regional metamorphic assemblages are overprinted by contact metamorphic effects close to the Ross of Mull Pluton, with development of andalusite, sillimanite and cordierite (Bosworth, 1910; Bailey and Anderson, 1925; MacKenzie, 1949; Brearley, 1984; Mangan, 1996, Wheeler *et al.,* 2004). Hence, all three aluminosilicate polymorphs occur at the site, although not within a single sample as previously reported by Bosworth (1910). Clough (in Bailey and Anderson, 1925) noted the occurrence of a small suite of hornfelsed microdioritic intrusions ('lamprophyres') close to the eastern margin of the pluton, which pre-date granite emplacement.

Description

The Ardalanish Bay GCR site encompasses the raised rocky coastal outcrops along the western side of Ardalanish Bay and on the Rubh' Ardalanish peninsula on the southern coast of the Ross of Mull (Figure 8.29). Of special interest are the contact metamorphic effects on the originally kyanite-grade Moine country rocks that resulted from the emplacement of the Ross of Mull Pluton. East of Port Mòr˙, the eastern margin of the granitic pluton is in contact with the Assapol Striped and Banded Formation (Assapol Group). The formation comprises thinly to thickly interbedded feldspathic and micaceous psammite, semipelite and minor pelite (Figure 8.30). Small pods and lenticles of grey-cream to green calc-silicate rock within the micaceous psammites locally exhibit compositional zoning, shown by the distribution of garnet, hornblende and/or biotite. Numerous mafic lenses of garnetiferous amphibolite up to several metres thick are also present. These amphibolitic bodies are typically concordant with bedding in the surrounding Moine rocks, but examples of cross-cutting bodies do occur farther east (see Holdsworth *et al.,* 1987). They are generally interpreted to represent pre-tectonic mafic intrusions, but Rock and Macdonald (1986) describe amphibolite layers within the Assapol Striped and

Banded Formation which they interpreted to be of sedimentary origin (see also Highton, in prep).

The semipelitic and pelitic layers are variably gneissose, with abundant thin quartzofeldspathic segregations that lie generally parallel to the predominant schistosity. The overall resultant foliation is generally a transposed penetrative fabric (S2) within which relict early tight to isoclinal folds of the primary gneissose foliation (Si) are locally preserved [NM 3767 1870]. A finer bedding-parallel mica fabric in the psammitic lithologies is inferred to be S1. F2 folds are typically small-scale, reclined, tight to near-isoclinal structures, accompanied by intense L2 rodding [NM 3817 1868]. The GCR site lies on the western limb of the tight, near-upright SSW-trending F3 Assapol Synform. Locally, minor F3 folds are abundant, and an accompanying upright crenulation cleavage is typically developed where the rocks are pelitic or semipelitic.

Scattered beach outcrops south of Ardalanish Bay (Figure 8.29) expose pelitic units that contain kyanite, garnet, tourmaline and subsidiary staurolite. Blades or granular aggregates of blue-grey to blue-green kyanite up to 5 cm long stand out in relief on the weathered surfaces. The larger blades are skeletal and contain inclusions of quartz, biotite, monazite, sphene and zircon. Most kyanite and staurolite porphyroblasts lie within the plane of the regional schistosity, and clearly pre-date the S3 crenulation cleavage. Replacement by fine-grained white mica (shimmer aggregate) is common, with kyanite (and less commonly staurolite) preserved only as corroded relict grains. Locally these white mica aggregates have recrystallized to larger muscovite porphyroblasts. The larger garnet porphyroblasts show composite zoning and prominent curved inclusion trails at a high angle to the regional fabric. The outer margins of these porphyroblasts and the smaller inclusion-free porphyroblasts both commonly overgrow the penetrative S2 cleavage foliation. A short distance east of Ardalanish Bay at Port Bheathain [NM 4036 1891], examples of ragged relict inter-grown kyanite and staurolite porphyroblasts, armoured by muscovite, are found. These aggregates and porphyroblasts of muscovite are wrapped by the penetrative S2 fabric and folded by the D3 crenulation.

Evidence for contact metamorphism is found throughout the exposed Moine metasedimentary rocks. The outer limit of the aureole, some 2 km from the pluton boundary, is marked by the incoming of a 'foxy' red-brown biotite. However, thermal metamorphic minerals only become abundant within the inner aureole, marked by the incoming of andalusite some 500 m from the granite contact. Indeed, Bailey and Anderson (1925) placed the outer margin of the aureole at this point. Within the gneissose pelite outcrop of Dùn Fuinn [NM 3754 1888], the blue colour of the kyanite porphyroblasts becomes less intense as the rocks take on the pink colouration of andalusite. Knots of sillima-nite (up to several centimetres across) and small porphyroblasts of andalusite are prominent in the semipelitic and pelitic lithologies, and small dark-grey well-formed circular to ovoid crystals of cordierite are ubiquitous. Cordierite grows at the expense of biotite in the more-micaceous psammitic lithologies. Regional metamorphic muscovite disappears from the Moine metasedimentary rocks in reactions associated with the growth of andalusite (Figure 8.29). Large ragged porphyroblasts of white mica commonly replace andalusite with the incoming of silli-manite and further breakdown of biotite. Within 300 m of the pluton the rocks are strongly hornfelsed. In outcrops close to Port Mòr-[NM 368 182] and west of Ardachy [NM 371 193] the regional tectonic fabrics and mineral assem blages are locally barely recognizable owing to recrystallization. The higher-grade assemblages containing fibrolite and sillimanite only appear within the inner aureole close to the granite contact (Brearley, 1984; Mangan, 1996). Here, there is evidence of small-scale partial-melting and migmatization. The weakly foliated microdiorite sheets outcropping at [NM 3682 1822] and [NM 3615 1907] are extensively recrystallized, with hornblende overgrown and replaced by red-brown biotite.

Interpretation

The presence of kyanite and staurolite in the pelitic and semipelitic rocks of the Moine succession points to a regional lower amphibolite-facies metamorphism (Rock and Macdonald, 1986; Holdsworth *et al.,* 1987), with the mineralogies implying pressures of *c.* 7 kbar and temperatures in the range 650 ± 50° C (Mangan, 1996). This metamorphism was probably contemporaneous with generation of the gneissose fabric and quartz-feldspar segregations and coeval with the D2 deformation; hence probably of Neoproterozoic age (Fettes *et al.,* 1985; Tanner and Evans, 2003; see also 'Introduction', this chapter). The replacement of the kyanite and staurolite by shimmer aggregate and subsequent recrystallization to muscovite porphyroblasts is a regional metamorphic transformation that pre-dates the F3 folding and is attributed to Caledonian events. This 'retrograde' hydration reaction, which also consumed enclosing biotite and

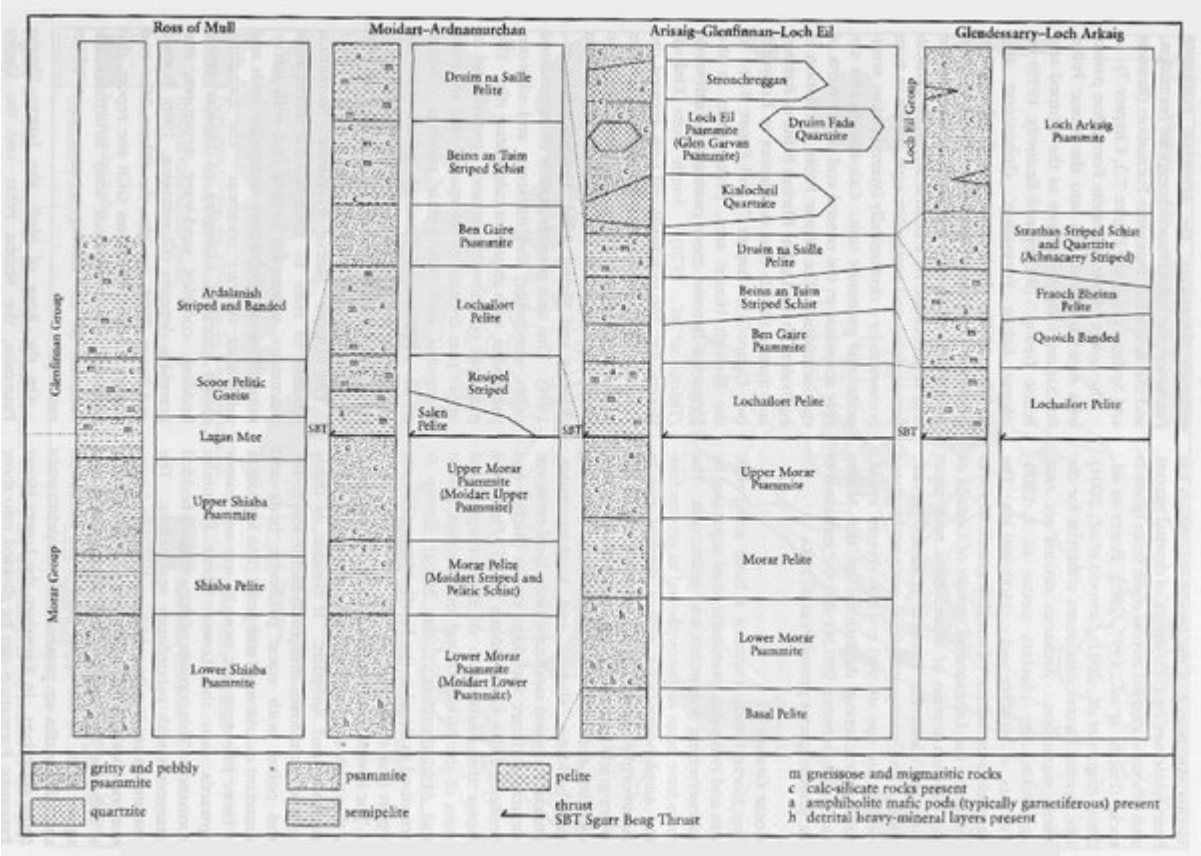
plagioclase, is found in assemblages outside the aureole and thus not directly related to the contact metamorphism associated with the emplacement of the Ross of Mull Pluton.

Within the metamorphic aureole of the Ross of Mull Pluton, the regional metamorphic assemblages are preserved locally as metastable relics. The thermal effects of the Pluton are defined by a series of discontinuous reactions that took place under isobaric conditions, with the partial pressure of water (aH_2O) varying from 0.4 to 0.55 at the upper stability of muscovite (Brearley, 1984). Mineral assemblages show apparent disequilibrium textures, suggesting that reactions were incomplete on the attainment of kinetic equilibrium (Mangan, 1996; Wheeler *et al.,* 2004). The inner aureole is defined by the development of a discrete andalusite-bearing zone with both fibrolite and/or sillimanite absent. Andalusite appears to be stable at the first development of fibrolite, but becomes metastable and replaced by white mica at the incoming of coarse sillimanite, approximately 200 m from the contact. Closer to the contact, sillimanite is the only Al_2SiO_5 poly-morph present. Here, localized partial-melting is seen in the pelitic rocks, and is reflected in the lowering of aH_2O from 0.55 to 0.4 (Brearley, 1984). Metastable kyanite is locally present within the andalusite-bearing zone, but it is mostly pseudomorphed by andalusite. The reported co-existence of all three aluminosilicate phases within a single specimen as reported by Bosworth (1910) is erroneous (Rock and Macdonald, 1986). However, the conditions at the time of granite emplacement (Brearley, 1984) should have allowed the regional metamorphic kyanite to remain stable within the outer aureole. Within the aureole, temperatures range from 700° C at the contact to 525° C in the outer aureole, with the rocks lying at a crustal depth of approximately 12 km (pressures of *c.* 4 kbar) (Brearley, 1984).

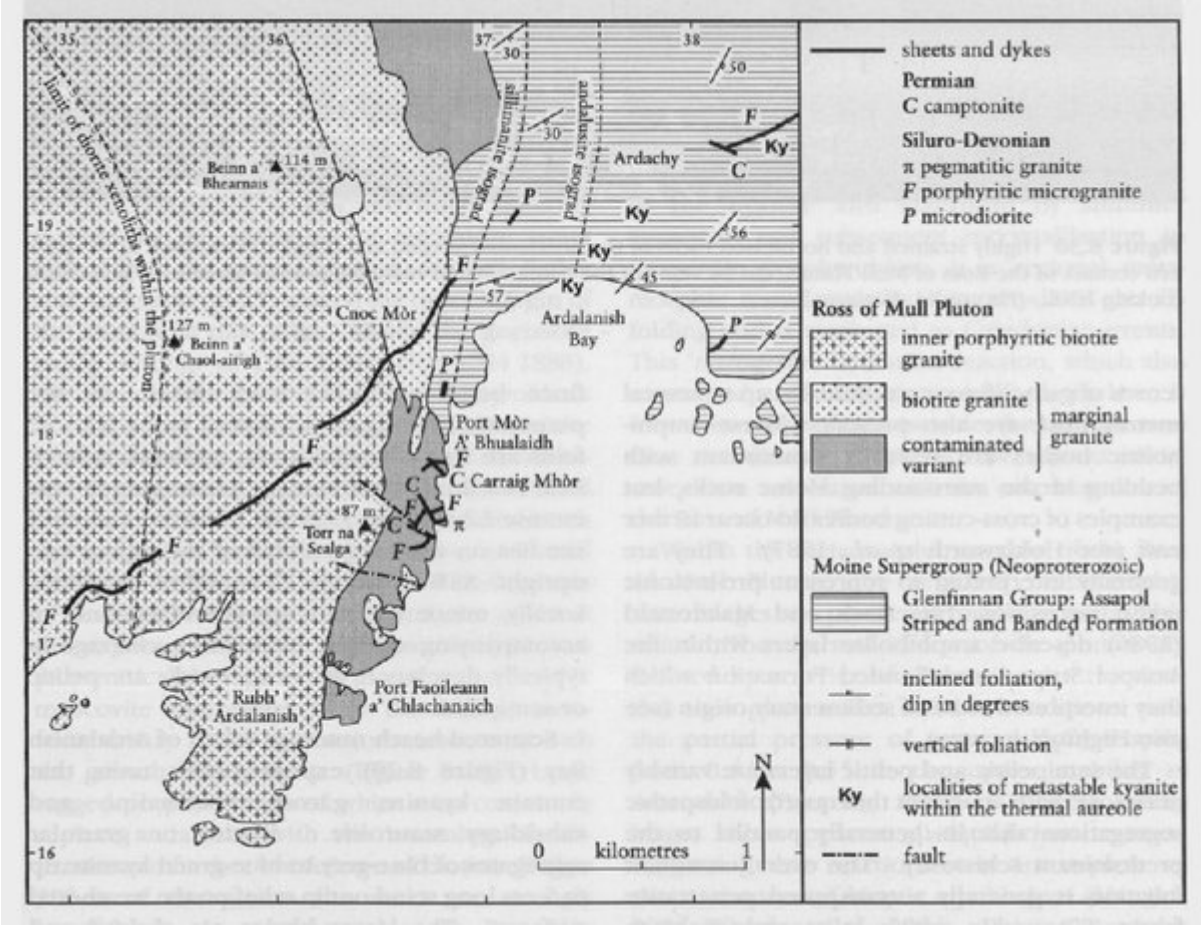
Conclusions

The Ardalanish Bay GCR site preserves the most westerly known outcrop of the Neoproterozoic Moine succession in Scotland. The succession on Mull comprises an older Shiaba Group and a younger Assapol Group, correlated with the Morar and Glenfinnan groups respectively. At Ardalanish Bay regional lower amphibolite-facies metamorphic assemblages that include kyanite and staurolite are locally well developed, notably in the semipelite and petite lithologies. The regional structures, fabrics and metamorphism relate to the D2 deformation, but are overprinted by a thermal aureole associated with the emplacement of the Silurian-age Ross of Mull Pluton. Within the aureole, contact metamorphic minerals developed, including andalusite, sillimanite and cordierite. Throughout much of the broad metamorphic aureole, kyanite is metastable. However, kyanite disappears within the high-temperature inner aureole, where andalusite and sillimanite are the successively stable polymorphs. Although all three alumi-nosilicate polymorphs occur within the thermal aureole, they do not co-exist at a single locality. The site is nationally important as it provides a well-documented example of the effect of the late orogenic granitic plutons on the earlier regional metamorphic assemblages in the Moine succession. It shows that the three distinct aluminosilicate (Al_2SiO_5) polymorphs can occur within a restricted area where thermal metamorphic effects overprint regional assemblages. It also provides an apparent stratigraphical transition from Morar Group to Glenfinnan Group rocks, a boundary obscured by the Sgurr Beag Thrust elsewhere in the North-west Highlands.

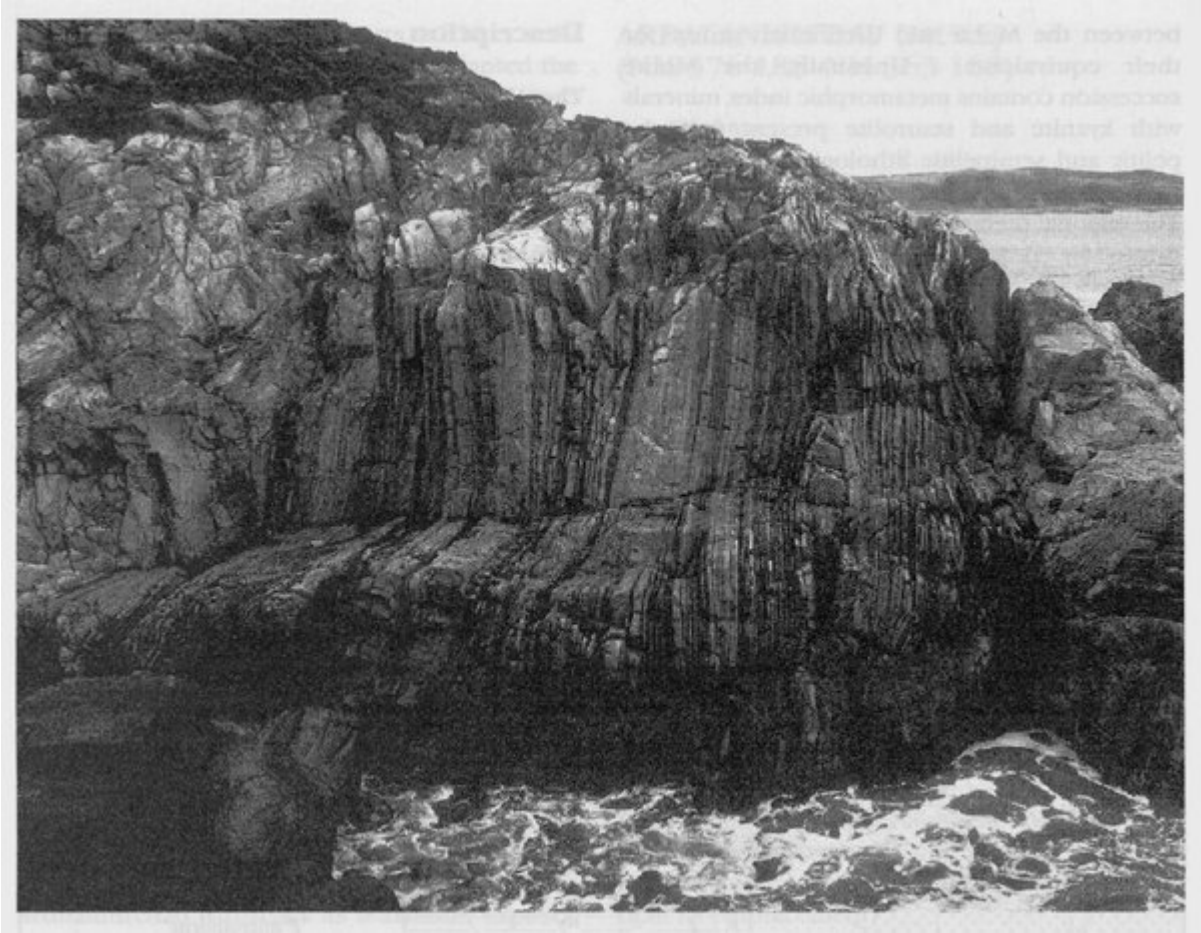
References



(Figure 8.3) Tectonostratigraphy of the Moine succession within the Moine (South) area, showing the main formations.



(Figure 8.29) Map of the Ardalanish Bay GCR site on the eastern margin of the Ross of Mull Pluton. Adapted from 1:50 000 Sheet 43S, Ross of Mull (British Geological Survey, 1997a) and unpublished work, University of Liverpool.



(Figure 8.30) Highly strained and hornfelsed rocks of the Ardalanish Striped and Banded Formation at the eastern contact of the Ross of Mull Pluton, cut by veins of the contaminated marginal granite variant. A' Bhualaidh looking NNE. (Photo: A.J. Highton.)