Ard Mor (Bettyhill)

[NC 700 619]–[NC 704 628]

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Introduction

Ard Mor is a small promontory at Bettyhill in north Sutherland that provides excellent coastal and inland exposures of strongly deformed, migmatitic, Moine metasedimentary rocks and intrusive igneous rocks of various ages (amphibolites, appinitic diorites and granitic sheets). The Moine rocks are part of the Bettyhill Banded Formation (previously termed the 'Bettyhill migmatites'). This coastal section lies within the Torrisdale Steep Belt in the structurally lower part of the Naver Nappe (Moorhouse, 1979; Holdsworth *et al.,* 2001).

The numerous pegmatitic granite intrusions form part of the Torrisdale Vein-Complex that were originally described by Read (1931, 1934), who termed them the 'zone of veins'. Crosscutting relationships between variably deformed minor intrusions, as well as transposed planar fabrics and interference fold structures provide evidence for a polyphase history of deformation, metamorphism and igneous intrusion (Table 6.1).

The largest of the early mafic sheets, the Ard Mor Amphibolite, is well exposed on the highest point of the promontory [NC 6995 6270]. It is part of the Bettyhill Suite of 'early Moine amphibolites', first recognized by Moorhouse and Moorhouse (1979). Evidence for its tectonometamorphic development is preserved within this site. The emplacement and structural age of the amphibolite are important in determining the age of deposition and deformation sequence of the Sutherland Moine succession. It is laterally equivalent to the intrusions of the Ben Hope Suite (see Allt na Caillich GCR site report, this chapter) and the early mafic intrusions in the Moine rocks farther south (see Comrie GCR site report, this chapter).

B.N. Peach first mapped the Bettyhill area for the Geological Survey in 1891–1892. Cheng (1943) later carried out pioneering work in this area, integrating geochemical, petrological and structural studies to try and unravel the complex metamorphic history. The area was remapped by I.M. Burns (1994) as part of a wider study of the tectonometamorphic history of the Naver and Swordly nappes. Friend *et al.* (2000) reported relict granulite-facies assemblages in some of the early amphibolite sheets, and Kinny *et al.* (1999) obtained zircon and monazite U-Pb age dates from the basal part of the Naver Nappe to the west, and from the Swordly Nappe to the east. The ages showed that the main migmatization event in both nappes occurred during the Grampian Event in the Early Ordovician.

Description

The rocky promontory of Ard Mor provides a near-continuous, mostly accessible, coastal section and good inland exposure, including the highest point of Ard Mor (101 m) itself. This small site provides a cross-strike section through the varied Moine lithologies representative of the Bettyhill Banded Formation. They are dominantly flaggy, thinly interlayered, gneissose pink-grey psammites and subordinate darker-grey semipelites and pelites that strike NNW and dip steeply eastwards (Holdsworth *et al.,* 2001).

(Table 6.1) Sequence of tectonometamorphic events recognized in the Naver Nappe.

1. Deposition of arenaceous and argillaceous Moine sediments unconformably upon Lewisianoid gneiss basement.
2. Emplacement of early tholeiitic igneous intrusives (now represented by the Bettyhill Suite amphibolites). These include the Ard Mor Amphibolite.
3. D1: Upper amphibolite-facies metamorphism producing gneissose layering (S1) and extensive lit-par-lit regional migmatization. Early mafic intrusives deformed and metamorphosed to foliated garnet amphibolites.

4. D2: Development of tight NW- and SE-plunging (F2) folds and associated strong mineral extension lineation L2. Some folds show extreme curvilinearity, associated with distinct zones of high strain. Retrogression of D1 mineral assemblages in some 'early' amphibolites and imposition of D2 fabric. Movement along Naver Thrust Zone. Partial melting of gneisses at the end of this event to produce foliated (G2) granite sheets (early phases of the Torrisdale Vein-Complex). U-Pb zircon dating suggests an Early Ordovician age (Kinny *et al.,* 1999).
5. D3: Upright, tight SE-plunging (F3) folds with steep E-dipping axial surfaces, largely coaxial with F2 folds. Associated extension, intersection and pronounced rodding lineation (L3). Coaxial F2–F3 refolds. Further retrogression and foliation of 'early' amphibolites.
6. Syn-D3 emplacement of the Clerkhill Intrusion followed by generation of foliation and folding of foliated appinitic amphibolite sheets. U-Pb zircon dating suggests Mid-Silurian age.
7. Emplacement of post-F3 microdiorites and unfoliated (G3) pegmatites and granites of the Torrisdale Vein-Complex.
8. D4: Localized brittle folding, faulting and development of en echelon tension gashes.
9. Emplacement of cross-cutting (G4) microgranites as well as porphyritic microgranite and lamprophyric sheets.

The layering is on a scale of 10–30 mm. All rocks are characterized by the presence of numerous concordant quartzofeldspathic segregations, which are particularly abundant in the pelitic units. Feldspar porphyroblasts are also common in the pelitic lithologies. Sedimentary structures are not preserved, in contrast to the psammitic rocks of the A! Mhoine Nappe to the west (see for instance Aird Torrisdale GCR site report, this chapter).

The Moine rocks are cut by abundant concordant to discordant sheets, dykes and lenticular bodies of amphibolite, pegmatitic granite, microgranite, and appinitic diorite (Figure 6.25). These intrusive rocks are very well exposed on the eastern side of Creag Ruadh [NC 6986 6310] and in the sea cliffs to the southeast. The amphibolites occur as sheets, mostly up to 3 m in thickness, but with larger bodies, such as the Ard Mor Amphibolite, reaching up to some 80 m thick. Although lenticular along strike, they are generally concordant with the compositional layering in the host Moine gneisses and contacts are sharply defined (Holdsworth *et al.,* 2001). In fact, the Ard Mor Amphibolite forms a linear array of NNW-trending discontinuous tabular outcrops through the centre of the site and continuing SSE (British Geological Survey, 1996, 1997b). It is a foliated garnetiferous amphibolite, partially retrograded to biotite and chlorite, and shows internal folding of early-formed fabrics. An early D1 metamorphic fabric is preserved in the moderately coarse-grained garnet-amphibolite in relatively low-strain areas, and is also recognizable in some F2 fold hinge zones. The D2 and D3 deformation and accompanying metamorphic events have progressively reduced this assemblage to fine-grained schistose amphibolite, notable on the fold limbs. The early S1 foliation is transposed in the fold limbs and the early garnets are retrograded to plagioclase feldspar and streaked out to become concordant with the regional foliation. Small, later garnets of possible D3 age locally overprint this composite S1–S2 fabric.

The Torrisdale Vein-Complex comprises a suite of pegmatitic granite intrusions that are very abundant in the Ard Mor area, where locally they comprise up to 50% of the outcrop (Holdsworth *et* ed., 2001). Individual intrusions vary from millimetre-thick veins to large, sheet-like bodies up to tens of metres thick, generally with sharp contacts. Most sheets clearly crosscut the migmatitic layering in the host gneisses (Moorhouse *et al.,* 1988). Where intrusions are ever, those at a low angle to the compositional markedly discordant to the gneissose layering in layering are asymmetrically boudinaged, with the host rocks they are generally folded. How- their geometry implying a dextral sense of shear (Holdsworth *et al.,* 2001). There are foliated and unfoliated granitic sheets representing a history of successive intrusive phases. For example, in a sea stack at [NC 6993 6210] a pink, pegmatitic granite with a foliated marginal fine-grained zone cuts the migmatitic fabric in the adjacent amphibolite within the Bettyhill Banded Formation. Foliated granites tend to be concordant with, or slightly discordant to, the regional gneissosity/foliation, interpreted as a composite S1–3fabric. Locally, subconcordant foliated granite sheets, locally termed 'G2', truncate the composite migmatitic fabric. A later phase of intrusive granitic veins, G3, cross-cuts F2 and locally F3 folds, and D2 fabrics. These G3 veins and sheets commonly have an L–S fabric defined by aligned quartz and feldspar aggregates and are folded where their orientation lies at a high angle to the regional fabric. A final phase, G4, comprises E–W-trending sheets of unfoliated microgranites and quartz-feldspar pegmatites that markedly cross-cut all the structures and lithologies, except for later minor faulting (Figure 6.26).

According to Holdsworth *et al.* (2001) the sheets and veins of the Torrisdale Vein-Complex vary from medium-grained to pegmatitic granites with varying proportions of perthitic K-feldspar, quartz and plagioclase with minor garnet, muscovite,

biotite, apatite, zircon and opaque minerals. The central parts of the granite intrusions comprise mainly equant feldspars with extensive patches of marginal myrmekite and interstitial quartz aggregates. Sheet and vein margins are commonly highly strained with a penetrative L–S fabric defined by muscovite-rich laminae and quartz-feldspar aggregates that lie parallel to the composite planar fabric in the host gneisses. Feldspar porphyroclasts within the fabric are deformed in a brittle manner and show internal cracking and undulose extinction in thin section.

A distinctive bluish-tinged, pale-grey, quartz-biotite rock is discontinuously developed along the boundaries of the Ard Mor Amphibolite and was noted by Cheng (1943) and Moorhouse (1979). The rock is an L-S tectonite with a strong, steeply E-dipping S2 planar fabric, concordant with the regional gneissosity, and a rodding lineation, locally coaxial with the later upright D3 folds that fold the S2 fabric.

At least four phases of deformation can be demonstrated within the Ard Mor site (Table 6.1). A pervasive regional migmatitic gneissose fabric, S1, is folded by tight, flat-lying F2 folds, themselves refolded by upright F3 folds. Examples of the upright F3 folds occur on Creag Ruadh [NC 6967 6306] where the excellent exposure allows hinge lines to be traced and composite fabrics to be studied in natural cross-sectional profiles. Penetrative schistose fabrics relate to the various fold phases. F2 folds locally form 'eye' structures; a good example of a hook-shaped fold interference structure (F2 + F3) occurs on the hillside above Creag Ruadh, where it is cross-cut by a late-stage, unfoliated pegmatite vein (Figure 6.26).

Holdsworth *et al.* (1991) recorded that linear structures within the Torrisdale Steep Belt have regionally anomalous orientations (see also Aird Torrisdale GCR site report, this chapter). L2 mineral lineations and F2 fold axes plunge gently SSE or NNW at < 20° to the strike of the regional foliation. In contrast, to the west and south L2 and F2 generally plunge south-east and down-dip in the plane of the foliation. The F3 folds are mostly close to tight in style and their axes plunge similar to those of the F2 structures. They mostly verge to the ENE and are particularly strongly developed in this part of Sutherland. The latest (D4) deformation developed brittle-style folds and faults that affected all other folds and fabrics.

Interpretation

The complex inter-relationships between the various structural and metamorphic fabrics in the migmatitic Moine metasedimentary rocks and the numerous minor amphibolitic, granitic, and appinitic intrusives within the Naver Nappe are readily studied within this site. Evidence of polyphase deformation and metamorphism is widespread, with examples of Type-3 fold interference structures (Ramsay and Huber, 1987) of particular note. As noted above at least four separate phases of deformation can be distinguished (see also (Table 6.1)).

The Ard Mor Amphibolite is part of a swarm of metamorphosed, early (pre-D1) tholeiitic intrusives ('early Moine amphibolites' of Moorhouse and Moorhouse, 1979). Note that the different mappers (B.N. Peach, Y.C. Cheng, V.E. Moorhouse, I.M. Burns and G.I. Alsop) disagree as to the exact position and extent of the various amphibolite outcrops. Amphibolite sheets and lenses of the Bettyhill Suite are abundant in the Moine succession, but it is difficult to define large individual masses or concentrations. Within the Ard Mor Amphibolite an early schistosity and associated garnet-hornblende mineral assemblage are folded, with original fabrics only preserved within some low-strain fold hinge regions. The early schistosity is transposed and garnets progressively retrogressed and streaked out into a composite planar fabric on the fold limbs. In parts this S1-S2 fabric is overgrown by small, euhedral garnets, probably of D3 age. Burns (1994) used equilibrium garnet-biotite assemblages to calculate the metamorphic temperature of about 550° C (assuming a pressure of 5 kbar) at the time of growth of these later garnets. Moorhouse (1979) interpreted the quartz-biotite rock, found locally adjacent to the Ard Mor Amphibolite, as a high-strain restite derived from psammitic gneiss. She inferred that under conditions of high D2 strain the migmatized psammitic gneisses were segregated or possibly partially melted to produce foliated granites and a quartz-biotite restite.

The migmatitic fabrics and abundant granitic minor intrusions exposed in the coastal cliff-sections of Ard Mor are a characteristic feature of the Naver Nappe. Although the migmatitic fabric is folded by F2 folds, and hence attributed to D1 deformation and metamorphism, the main fabric has been dated from zircon overgrowths at 467 Ma (Kinny *et al.,* 1999) implying its formation during the Early Ordovician Grampian Event. Its origin appears to be multi-phase with an earlier Neoproterozoic D1 amphibolite-facies metamorphic event overprinted by the Ordovician event. The G2 and G3 intrusive

phases form the main part of the Torrisdale Vein-Complex and locally show dextral shear indicators. In places the granitic sheets and veins cut across F3 upright folds (including F2 + F3 refolds) and show little evidence of deformation.

Holdsworth *et al.* (2001) suggested that the Torrisdale Steep Belt formed during a localized, post-F3 dextral transpressive event to explain the strike and dip of structures in this belt, as well as the tightness of the minor F3 folds (see Aird Torrisdale GCR site report, this chapter). They also suggested that the Torrisdale Vein-Complex was emplaced over an extended time-period during the late stages of the Caledonian deformation event. Dallmeyer *et al.* (2001) obtained ^{40}Ar-^{39}Ar plateau muscovite ages of 419 Ma and 423 Ma from migmatitic Moine rocks sampled adjacent to the Ard Mor peninsula. They interpreted these ages as dating the late-stage Torrisdale Steep Belt fabric, implying that its formation was Scandian and hence Late Silurian in age.

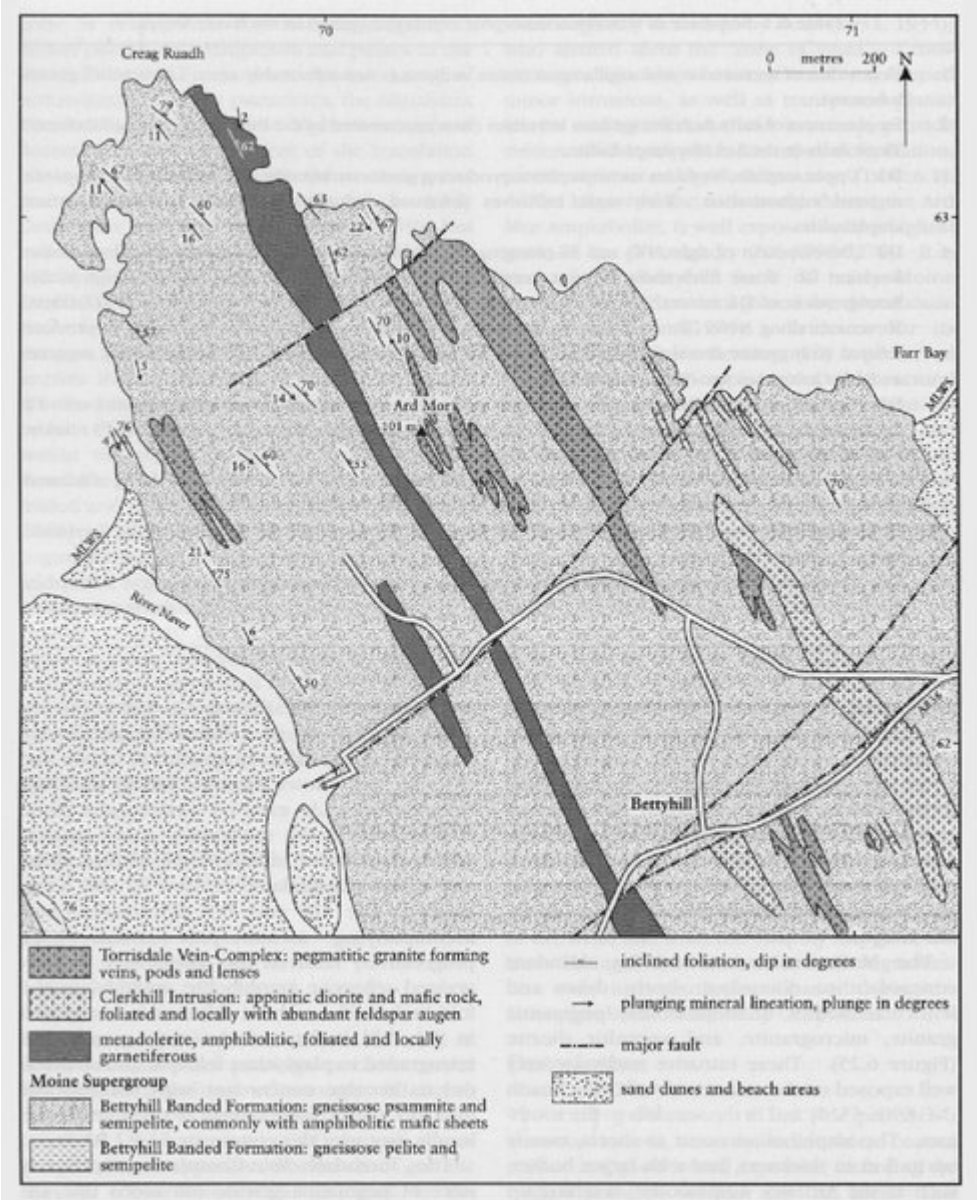
Conclusions

The Ard Mor coastal promontory provides good exposures of diverse, high metamorphic grade, Moine semipelites, pelites and psammites (Bettyhill Banded Formation), 'early' mafic amphibolite sheets, and later granitic veins and sheets within the Naver Nappe. The rocks record a complex history of deformation, metamorphism and emplacement of minor intrusions. Evidence of at least four separate phases of deformation and metamorphism can be distinguished, with excellent examples of refolded folds illustrating the polyphase orogenic history of these Moine rocks. Three phases of minor granitic intrusions, termed 'G2', 'G3' and 'G4', can be distinguished on the basis of their relationships to particular deformation episodes, with the oldest phase post-dating an early D1 migmatization. Granitic veins of the Torrisdale Vein-Complex (G3) were emplaced over a protracted time-period during the later stages of the regional Caledonian deformation, probably during the Scandian Event in the Late Silurian. The Ard Mor Amphibolite is part of the Bettyhill Suite, a swarm of metamorphosed tholeiitic basic intrusive sheets. It preserves evidence of early (D1) tectonometamorphic events and of progressive reworking by later D2 and D3 deformation events. The regional gneissosity/foliation can be shown to be a composite (S1-S3) fabric. The Ard Mor site is of regional importance and is an excellent place to start to unravel the complex geological history of the metamorphic Moine rocks of the Naver Nappe.

References

Name of swarm/ sub-suite/suite	Age	Area of occurrence	Abundance	Rock types	Nature and trend of intrusion	Thickness of intrusion	Deformation	Reference
Quartzose Amphibolite	Upper Ordovician	Near Fort Augustus.	Local	Quartzose amphibolite, tonalite	Elliptical masses, elongated north-east, rarely dykes. Found within Fort Augustus Granite Gneiss.	Bodies up to 1 km long but also as smaller pods. Rare dykes c. 5 m thick.	Low	May and Highton, 1997
Glen Morieston Vein-Complex	Upper Ordovician	In Glen Morieston, extending north to Strathglass.	Abundant	Muscovite-biotite granite, aplitic and pegmatitic granite	Lenticular sheets, veins, mainly concordant. Thicker sheets trend north-east.	From a few cm up to 40 m thick, but typically < 2 m thick.	Foliated, folded, boudinaged.	May and Highton, 1997
Loch Ba Granite Vein-Complex	Late Silurian	West end of Loch Ba, Glen Fiosneighe.	Abundant	Granite, including aplitic and pegmatitic granite	Rambling network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
Loch Arkaig Granite Vein-Complex	Late Silurian	Centred on Meall Blair north of Loch Arkaig.	Abundant	Granite, including aplitic and pegmatitic granite	Rambling network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
Mallie Granite Vein-Complex	Late Silurian	In Glen Mallie, south of Loch Arkaig.	Abundant	Granite, including aplitic and pegmatitic granite. Includes small granodiorite body	Rambling network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
porphyritic microgranodiorite ('Pelitic Porphyrites')	Late Silurian	Channic area, upper Glen Morieston.	Moderately abundant	Porphyritic microgranodiorite	Dykes and sheets, trending approximately east. Some irregular bodies.	Typically c. 2 m thick but up to 5 m recorded.	Weakly schistose and recrystallized.	Peacock *et al.*, 1992; May and Highton, 1997
Microdiorite Sub-suite	Late Silurian	Widespread across Moine outcrop south of Glen Morieston to the Sound of Mull. Also present in Ross-shire.	Very abundant, reaching maximum concentrations in central zone between Channic and Sabrei	Range from microgranodiorite to melanocordierite	Sheets and dykes with chilled margins. Mineral assemblages altered and in part recrystallized under greenschist- or epidote-amphibolite-facies conditions. Some irregular sheets in west-coastal area exhibit largely unmodified igneous textures and microalogues. Most sheets dip moderately south-east, but swarms of NNE- and E-W-trending sheets can be distinguished locally.	Up to 30 m thick but typically c. 1 m thick. Variable thickness along length of intrusion.	In parts show flow foliation in chilled zones. Locally sheared, both in marginal zones and throughout whole intrusion.	Smith, 1979; May and Highton, 1997; Peacock *et al.*, 1995; May *et al.*, 1992
Appinite Suite	Late Silurian	Widespread across the Moine outcrop but concentrated in Sunmhin–Sunart–Moidart area and in Glen Garry. Associated with the Strontian Pluton. Sparse to north of Glen Affric and Glen Shiel	Abundant within clusters	Mainly coarse-grained hornblende-diorite but range from monzonite to pyroxenite and olivine-bearing hornblende-rich ultramafic rocks	Small bosses and pods. Also thick sheets.	Bosses typically 30 m to 50 m across. Sheets mainly in range 2 m to 10 m across.	Foliated in part, particularly at margins.	Smith, 1979; May and Highton, 1997
porphyritic microgranodiorite ('Main Pelitic Porphyrites')	Late Silurian	From Glen Affric south-west via Channic, Loch Arkaig and Loch Shiel down to Loch Aline on the Sound of Mull.	Abundant	Porphyritic microgranodiorite ranging to quartz microdiorite	Dykes and sheets, mainly dipping moderately to the south-east and steeply to north-west.	Dykes typically < 1 m thick, sheets commonly around 5 m thick , but up to 15 m.	Oblique internal schistosity common. Recrystallized to greenschist.	Smith, 1979; Peacock *et al.*, 1992; May and Highton, 1997
Banavie Vein-Complex	Late Silurian	Adjacent to the Great Glen south of Loch Lochy. Extends up to 5 km north-west of Great Glen Fault.	Abundant	Granitic and subsidiary aplitic granite and quartz feldspar pegmatite veins	Veins and vein networks. No obvious preferred orientation.	Typically up to 1 m in width but locally thicker.	Not foliated.	Johnstone and Stykura, 1989
Glen Garry Vein-Complex	Late Silurian	From Channic south-east to Loch Lochy, centred on Glen Garry.	Abundant	Mostly medium- to coarse-grained granodiorite, but ranging from quartz diorite to microgranite	Discrete veins, sheets and larger bodies, which show a general north-east alignment.	Veins from a few centimetres up to tens of metres thick. Larger masses up to several hundred metres across.	Not foliated.	Fettes and Macdonald, 1978
microgranite swarm ('Schists')	Early Devonian	Widespread but only abundant in swarm east of Ratagain Pluton.	Not abundant except in Ratagain swarm	Microgranitic and microgranodiorite, locally porphyritic	Dykes commonly aligned east–west.	1 m to 10 m wide (average 5 m) in Kintail swarm.	Not foliated.	May *et al.*, 1992
Lamprophyre Sub-suite	Early Devonian	Widespread but concentrated in Ratagain swarm stretching from Loch Hourn north-east through Kintail to Glen Affric and Glen Cannich. Dykes extend west of Moine Thrust on Skye and in Applecross area.	Not abundant except in Ratagain swarm	Pyroxene minette, but some vogesite and rare acmeite	Dykes with chilled margins. Commonly altered mineralogy.	Range from 0.2 m to 6 m. Average thickness *c.* 3 m.	Not foliated.	Smith, 1979
camptonite-monchiquite suite	Permo-Carboniferous	Widespread but concentrated in swarms – Morar, Killilan, Moray, Ed-Arkaig, Ardgour and Iona-Ross of Mull.	Locally abundant	Camptonite and camptonitic basalt mainly, rare monchiquite	Dykes with chilled margins. Dykes subvertical. Trend east–west in north and ENE in Ardgour swarm and south-east in Ross of Mull.	Average thickness *c.* 1 m.	Not foliated.	Rock, 1983
Palaeogene dykes, mainly of the Skye, Mull, and Ardnamurchan swarms	Palaeocene to Early Eocene	Widespread on Skye and west coast south of Loch Sunart.	Locally abundant	Dolerite, basalt	Dykes with chilled margins, commonly vesicular.	Commonly 0.5 m to 2 m thick but averages 4.5 m in Mearr and can be 10 m or more.	Not foliated.	Speight *et al.*, 1982

(Table 7.1) Caledonian and later minor intrusions — Moine (Central) and Moine (South) areas.



(Figure 6.25) Map of the Ard Mor GCR site. Compiled from data from British Geological Survey 1:50 000 Sheet 115W, Strathy Point (1996), Cheng (1943) and from mapping by G.I. Alsop.

(Figure 6.26) Hook-shaped fold formed by superimposition of an upright F3 fold on an earlier tight recumbent F2 minor fold. A later non-foliated pegmatitic granite vein cross-cuts the refolded structure. On hillside above Creag Ruadh at [NC 6982 6300]. (Photo: V.E. Moorhouse, BGS No. P580517, reproduced with the permission of the Director, British Geological Survey, © NERC.)