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## Excursion 3 Glenfinnan to Morar

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*Purpose:*

A general traverse across the structurally complex, high grade rocks of the eastern 'vertical' belt in the southwest Moine (= Northern Highland Steep Belt) and some of the lower grade rocks of the type area of the Morar Group to the west.

*Aspects covered:*

Various metasedimentary lithologies and aspects of their sedimentology; tectonic structures and fabrics; metamorphic minerals and migmatites; igneous rocks such as microdiorites and pegmatites; features relating to the development of ductile thrusts.

*Useful information:*

Hotel, B&B accommodation and camping are available in Fort William, or alternatively, sporadically along the road between Lochailort and Mallaig.

*Maps: OS:*

1:25,000 Explorer sheet 397 Loch Morar & Mallaig; BGS: 1:50,000 sheets 52 Tobermory, 61 Arisaig and 62W Loch Quoich.

*Type of terrain:*

Many roadside exposures that require extreme caution because of the speed of the traffic. Moderately rough hillsides and moorland.

*Distance and time:*

The road route is ~50km long and on foot an additional 10km. 3-4 days are recommended for the whole of this excursion. It is best followed from the east. See each locality for suggested times.

*Short itinerary:*

Visits to Localities 3.1 (A & B), 3.3, 3.4b and 3.6 (B & C) will provide an appreciation of the geology of the area during a full, one-day excursion.

### High-grade rocks of the 'vertical' belt

Despite many years of research, the structural and metamorphic development of the 'vertical' belt of the southwest Moine (= Northern Highland Steep Belt) has proved difficult to unravel because of the high levels of strain and a complex deformation history (Dalziel, 1966; Brown *et al.*, 1970; Powell, 1974; Baird, 1982, 1985). Equally, attempts to date events affecting the belt have proved confusing and controversial (see Summary of Geology). However, recent geochronological work vindicates the earlier view of a complex Neoproterozoic history for the Moine rocks (e.g. Friend *et al.*, 1997; Rogers *et al.*, 1998; Vance *et al.*, 1998; Millar, 1999; Tanner & Evans, 2003). In the 'vertical' belt, at least three sets of tight to isoclinal folds can be detected (Baird, 1982) which pre-date intrusion of a suite of transgressive but folded, Caledonian pegmatites. A later suite of microdiorite intrusive sheets is deformed by open to moderately tight folds (Smith, 1979; Talbot, 1983). Whilst it would appear that many of the fabrics might have originally been Neoproterozoic, the development of the steep belt has been ascribed to crustal reworking during the Caledonian orogeny (Roberts & Harris, 1983).

#### Locality 3.1 The Muidhe. Glenfinnan Group. [NM 857 815]

The Muidhe (Figure 3.1). Glenfinnan Group psammities, pelites and migmatites; pegmatites; microdiorite sheets. [NM 857 815]

Parking is available in a lay-by on the south side of the A830 at [NM 8605 8142], 4.25km west of Glenfinnan. The traverse involves a moderate climb to c.50m above road level – 1-2 hours should be allowed. Climb uphill northwestwards for about 250m to reach a gently inclined glacial pavement at [NM 8575 8150]. Here, at Locality 3.1A, large flat exposures comprise banded metasediments of the Glenfinnan Group. These are interbanded white psammites (originally impure quartzites); light grey psammites (arkoses); dark grey, generally homogeneous semi-pelites (silty mud rocks); and schistose, migmatitic pelites (mud rocks). Though as elsewhere in the Moine, metamorphic index minerals are only rarely preserved (Winchester, 1974), these rocks are at sillimanite grade (amphibolite facies). The pelitic rocks contain garnet (almandine) + biotite + muscovite + oligoclase + quartz, rarely sillimanite (e.g. MacQueen & Powell, 1977). In many places copious, often randomly oriented, late retrogressive muscovite flakes probably represent breakdown products of an aluminium silicate, presumably kyanite or sillimanite, which are both known to be present in the area. The pelites often develop segregations of plagioclase and quartz (migmatitic *lits*), indicating that, in places, partial melting may have taken place, a phenomenon consistent with amphibolite facies conditions.

All exposures lie on the SE limb of the D<sub>3</sub>Sgurr a' Muidhe Synform (Baird, 1982) and many of the open to moderately tight, asymmetric minor folds that verge towards the SW are parasitic to the major synform (Figure 3.1). The minor folds plunge at moderate to steep angles to the NE and are accompanied by crenulations that fold the migmatitic planar fabric in the pelitic rocks. The folds display considerable variation in style, which is largely attributable to variations in rock type and scale of interbanding, and thus ductility and ductility contrasts. They fold previously boudinaged layers and tight to isoclinal folds. Occasionally 'eye' folds occur wherein folded layers close both to the NE and SW; the fold hinges plunge to the northeast and southwest and are thus curved, and probably have a sheath-like morphology (Figure 3.2).

At least three generations of intrusive veins are distinguishable: early quartz veins which cut the early isoclinal folds and may relate to the phase of layer extension that produced the boudinage; thin foliated pegmatites with diffuse margins which in places are sub-parallel to the axial planes of the D<sub>3</sub> minor folds; and usually thick, discrete, coarse-grained pegmatites trending northwest-southeast, which cut all minor folds, but are themselves folded. The latter, transgressive Caledonian pegmatites, are discussed further below at Locality 3.1B.

Return to the road by following the cliff edge near the road to the SE until a small valley is reached giving easy downhill passage. Along the top of this cliff, many exposures display fine examples of sheath folds. Some 350m to the W, roadside exposures, Locality 3.1B, occur on the NE side of the road opposite the lay-by at [NM 8570 8127] (Figure 3.1), and provide sections that lie normal to those of the previous locality. At the SE end of the exposure, an E–W-trending vertical dyke belonging to the Permo-Carboniferous camptonite-olivine basalt suite cuts a 2m-wide, steeply dipping pegmatite, which exhibits a strong crystal growth fabric lying at a high angle to its contacts. The pegmatite is one of the transgressive early Caledonian suite characterised by their coarse grain-size and the presence of both muscovite and biotite with plagioclase + K-feldspar + quartz ± garnet. Similar bodies have given isotopic ages of about 450 ± 10 Ma (van Breemen *et al.*, 1974), *i.e.* late Ordovician.

A few metres to the NW, a partly foliated, intrusive microdiorite sheet crops out. At its NW end, the sheet dips moderately to the east, thins rapidly upwards and contains in places an oblique, internal, metamorphic fabric that lies clockwise of the sheet margins. The schistosity is most strongly developed adjacent to the margins but progressively decreases in intensity, and increases in dip, towards the centre. In the lower part of the exposure, the microdiorite cuts a coarse-grained pegmatite and appears to contain a xenolith of the same pegmatite plus country rock. At the bottom of the exposure, what may be the same pegmatite appears to have been displaced across the microdiorite with an apparent 0.5m shift. Above and to the left of the xenolith, the internal schistosity is seen to be axial planar to the folds of internal veins, whilst above and to the right the microdiorite margin displays cusp and lobe form indicating that during deformation the microdiorite was less ductile than the country rocks. Traced to the SE, part of the sheet changes attitude to dip westwards and thence it becomes horizontal before thinning and terminating. With these changes of dip the geometry of the internal schistosity becomes more complex but appears to relate to the overall folded form of the sheet; possibly relating to flexural flow on the fold limbs. Within the schistose margins of the sheet an extension mineral lineation in the schistosity relates to the movement across the sheet during its deformation; here NW–SE.

Microdiorite sheets occur throughout the south-western Moine areas and are thought to belong to a late Caledonian suite (Smith, 1979). Their structural development has been discussed by Talbot (1983). Generally sheets dipping to the west

contain a schistosity, often sinusoidal, which dips westwards at steeper angles than the sheet margins, those dipping eastwards show the opposite relationships, whilst folded sheets have sub-horizontal enveloping surfaces and show changes in the attitude of the internal schistosity that relate to fold limbs. The sheets cross-cut structures generated during the first three deformation phases affecting the Moine, and the early Caledonian pegmatites. According to Smith (1979) they are earlier than the Strontian and Ross of Mull granites, which have, respectively, given isotopic ages of  $425 \pm 3$  Ma (Rogers & Dunning, 1991) and  $421 \pm 5$  Ma (Oliver *et al.*, 2008). Thus intrusion of the microdiorites together with syn-metamorphic regional deformation of both the sheets and their host rocks, would appear to have taken place between c.450 and 425 Ma, *i.e.* during the late Ordovician or early Silurian. Post-orogenic cooling of the southwestern Moine is dated by common K-Ar muscovite and biotite cooling ages between 420 and 410 Ma (Brook & Powell, unpublished data).

### **Locality 3.2 The Loch Eilt Antiform eastern limb [NM 828 821] to [NM [NM 817 824]**

The Loch Eilt Antiform eastern limb (Figure 3.1). Glenfinnan Group pelites; Morar Group psammities and pelites; Sgurr Beag Thrust Zone. [NM 828 821] to [NM [NM 817 824]

Proceed west from Locality 3.1B for 3.5km and park in a lay-by on the south side of the road at an emergency telephone [NM 8290 8210]. Exposures along the north side of the road to the east of the lay-by are Locality 3.2A, and display at their western end strongly schistose pelites of the Glenfinnan Group which contain lenses, knots and stringers of migmatitic, plagioclase-quartz *lits*. Characteristic small, claret-coloured garnets are common and chemically homogeneous in contrast to the larger red-brown garnets of low-grade Morar Group rocks to the west (Anderson & Olympio, 1977; MacQueen & Powell, 1977; see below). The exposure lies within the Sgurr Beag Thrust Zone (Ranochan Slide of Baird, 1982) where this is brought to ground surface on the eastern limb of the Loch Eilt Antiform (Figure 3.1), (Figure 3.3). The junction, not here exposed, between the Morar and Glenfinnan groups lies some 50m to the west. Note the occasional ribs of blue-grey psammite that lie parallel to the predominant, near vertical schistosity, and the development of small sinistral (extensional?) shear bands dipping eastwards.

To the east, along the exposure, more varied rock types come in, with the proportion of psammitic layers increasing. Note the thin (Caledonian?), cross-cutting pegmatitic veins containing garnet + muscovite + feldspar + quartz, and the tight to isoclinal folds of early migmatitic veins and lithological layering. One hundred metres to the west of the emergency telephone, exposures on the north side of the road comprise disturbed and considerably altered rocks of the Morar Group. At the extreme western end of the road cut, interbanded psammitic and pelitic rocks are folded by open to tight minor folds plunging to the SE that are crossed by open folds and coaxial crenulations plunging SW. The pelitic layers do not contain migmatitic segregations; rather they are highly schistose and muscovite-rich. A concordant biotite + feldspar + quartz pegmatite is boudinaged and a folded cross-cutting microdiorite sheet, in places, contains a strong, internal schistosity that is oblique to the sheet margins on fold limbs, but axial planar in the axial zones of the folds. These exposures lie on the western limb of the D<sub>3</sub>Ranochan Synform (Baird, 1982) whose western limb is, according to Baird (1982), replaced by the Sgurr Beag Thrust Zone (Figure 3.3). Because the Sgurr Beag Thrust is folded over the Loch Eilt Antiform to reappear further west (Figure 3.1), (Figure 3.3), it follows that formation of the thrust zone and generation of Baird's D<sub>3</sub> folds are earlier.

Displacements on the Sgurr Beag Thrust are a minimum of 15km in this area (Powell *et al.*, 1981), but 50km elsewhere (Kelley & Powell, 1985), and it is therefore significant that this microdiorite sheet shows no greater degree of deformation than outside the thrust zone. Clearly, thrusting predated emplacement of the microdiorite sheet. Petrographic and geochemical analysis of the microdiorites suggests that they are members of a consanguineous, igneous suite (Smith, 1979), thus they provide relative time markers which were here emplaced after Baird's third phase of deformation and formation of the thrust, but before at least one late phase of ductile deformation (see also Baird, 1985; cf. Talbot, 1983).

About 1km along the road to the west, park in a lay-by on the south side at [NM 8175 8238]. Exposures on the north side of the road, some 80m to the west, are Locality 3.2B and show small claret-coloured garnets, and migmatitic segregations parallel to a dominant schistosity. Staurolite and sillimanite (fibrolite) occur sporadically in this unit which forms, together with adjacent rocks, part of the Morar Group succession lying within the Loch Eilt Antiform (Figure 3.3).

Walking westwards some 130m, the contact of the pelitic unit with a predominantly psammitic group is encountered. The psammite is exposed for a further 200m. Inter-layered striped and banded psammites, blue-grey semi-pelites and occasional pelitic layers show no unequivocal evidence of sedimentary structures. Indeed the presence of tight to isoclinal minor folds of the lithological layering, concordant pegmatites and boudinaged pegmatites, and the platy nature of many of the psammites indicate the high levels of strain that these rocks have undergone. The exposures lie within 1km of the Sgurr Beag Thrust Zone (Figure 3.1). Microdiorite sheets dipping to the east show a remarkable variation in the intensity of the internal schistosity, but are not folded.

### **Locality 3.3 Morarian (= Knoydartian) pegmatites at Loch Eilt [NM 806 827]**

Morarian (= Knoydartian) pegmatites at Loch Eilt (Figure 3.1). Pegmatites, Morar Group psammites and pelites; isoclinal folds; microdiorite sheet.

#### **PLEASE DO NOT HAMMER THESE EXPOSURES.**

Some 1.2km along the road to the west, limited parking is available on the south side of the road at [NM 8060 8270]. Allow about an hour here. A further 250m west is a rocky knoll on the south side of the road, partly hidden by a road-sign, that displays near vertical, interbanded psammitic and semi-pelitic rocks with occasional layers of migmatitic pelite. These Morar Group rocks lie near the core of the Loch Eilt Antiform (Figure 3.1), (Figure 3.3). In the large vertical rock face, isoclinally folded, boudinaged and apparently concordant pegmatites are composed of garnet + muscovite + microcline + plagioclase + quartz + accessory green apatite. In the boudin cores, the pegmatites are coarse-grained and non-schistose, but at the boudin margins, and where they are thin, the pegmatites are finer grained and schistose. The pegmatites belong to the Knoydartian suite and at this locality have been dated at  $730 \pm 20$  Ma (van Breemen *et al.*, 1974) and  $740 \pm 30$  Ma (van Breemen *et al.*, 1978).

From exposures such as these, several authors have argued that the pegmatites, because they are concordant to the migmatitic foliation, are deformed, and have a metamorphic mineralogy, constitute *in situ* metamorphic segregations. Thus the isotopic ages record regional metamorphism at, or shortly before, 740 Ma (Giletti *et al.*, 1961; Lambert, 1969; van Breemen *et al.*, 1974, 1978). Further, on this basis, these authors postulate a Morarian (= Knoydartian in present usage) orogeny. With this in mind it is pertinent to note that the rocks exposed here have suffered high levels of strain subsequent to formation of the pegmatites, and that the pegmatite bodies lack the continuous biotite selvages characteristic of segregations and contain microcline. It is difficult at this, and similar high grade/high strain localities, to assess the original relationships of these pegmatites. The only pegmatite of this suite so far discovered in a relatively low grade, low strain environment, is on the Ardnish peninsula [NM 6937 8127], 11 km to the WSW (Powell *et al.*, 1983). Here the relationships of the pegmatite were originally interpreted as indicating pre-pegmatite Precambrian deformation and metamorphism to garnet grade with pegmatite intrusion at or before  $776 \pm 15$  Ma (Powell *et al.*, 1983). It was suggested that this and other similar-aged pegmatites might represent a suite of intrusive bodies generated during crustal extension. However subsequent work suggests intrusion of the Ardnish pegmatite during deformation and metamorphism at  $827 \pm 2$  Ma with the pegmatite suite as a whole being diachronous (Rogers *et al.*, 1998).

In the exposures directly opposite, on the north side of the road, open sinusoidal folds of a microdiorite sheet have vertical axial surfaces and a southerly plunge. Note the obliquity of strike of the country rocks to the fold hinges; crustal shortening which generated the folds of the intrusive sheet has been accommodated by ductile, homogeneous strain in the host rocks. Forty metres to the east, a 35cm-thick, transgressive, garnet + muscovite + K-feldspar + plagioclase + quartz pegmatite, probably of early Caledonian age (450 Ma), cuts isoclinal folds of the lithological layering. The isoclines also fold a lens of Morarian (Knoydartian) pegmatite and both are cut by a thin pegmatite, which is folded by apparent dextral shearing along the lithological layering.

### **Locality 3.4 The Glenshian Synform and the Sgurr Beag Thrust [NM 789 828] to [NM 777 830]**

The Glenshian Synform and the Sgurr Beag Thrust (Figure 3.1). Glenfinnan Group pelites in the core of the Glenshian Synform and Morar Group psammites and migmatitic pelites on the limbs; foliated microdiorites; strong planar and linear fabrics of the Sgurr Beag Thrust Zone.

This traverse, which will take 3-4 hours, crosses a major, tight to isoclinal fold, the Glenshian Synform (Figure 3.1), (Figure 3.3), which regionally can be traced for at least 22km along strike. It has the form of an elongate boat (BGS sheets 52 and 61) and folds the Sgurr Beag Thrust (Powell *et al.*, 1981). The fold core is occupied by rocks of the Glenfinnan Group, the Lochailort Pelitic Group of Powell (1964), whilst Morar Group rocks form the limbs to east and west – the Arieniskill and Ardnish psammitic groups of Powell (1964). Although difficult to assess accurately, the amplitude of the Glenshian Synform is likely to measure several kilometres and thus the repeated outcrops of the Sgurr Beag Thrust Zone would have originally been at different crustal depths (Powell *et al.*, 1981).

From Locality 3.3 drive 1.6km westwards to park in a lay-by adjacent to the railway line at Locality 3.4A [NM 7885 8285]. NB: the road here is extremely dangerous for unwary pedestrians. The road cut opposite the layby continues to the east around a sharp bend for some 200m. The exposure comprises near vertical interbanded grey psammities, blue-grey semi-pelites and migmatitic pelites of the Morar Group. *Please do not hammer these exposures.*

Just to the north of the lay-by, predominantly psammitic rocks give way, moving to the south and east, to more varied rock types. Eastward-dipping microdiorite sheets which cross-cut quartz veins and several generations of pegmatite, have internal schistosity indicating a sinistral shear sense across them. The attitude of the schistosity and associated extension lineations suggest NW–SE movement and in one case a displacement of at least 2.5m can be deduced from the offset of markers in the country rocks. In many cases the dramatic increase in the intensity of the internal schistosity toward the margins of the sheets testifies to the rapid increases in shear strain and it is likely that detachment along the contacts has taken place (Smith, 1979). For accounts of the petrography, and further significance of the microdiorite suite, the reader is referred to Johnson & Dalziel (1963), Smith (1979) and Talbot (1983) wherein very different opinions are expressed.

Tight to isoclinal minor folds of the lithological layering have very variable plunges and where these fold pale, thin calc-silicate layers and lenses a strong, axial planar, penetrative schistosity is apparent. In many places the obliquity of the dominant schistosity to layering is noticeable and it is deformed by crenulations that plunge moderately to the SW. At the eastern end of the exposure stacks of minor folds, verging towards the east, form cores to large boudin pods some 3m long. Judging by the intensity of folding of the layering, boudinage of pegmatites and fold stacks, folding of cross-cutting pegmatites, and the deformation of the microdiorites, the country rocks at this locality have suffered several phases of shortening normal to the layering. Thus the 'flattening' strains must be intense, and planar fabrics likely to be composite. Minor and major folds probably have sheath geometry. Along strike in this zone, pelitic rocks contain sillimanite and staurolite, while the calc-silicate ribs and lenses comprise garnet + hornblende + biotite + plagioclase (An<sub>80-90</sub>) + quartz; the grade of regional metamorphism is therefore high (Powell *et al.*, 1981).

The next locality can be reached by either traversing up and across the hillside to the north then the NW for some 700m to reach the line of crags that form Locality 3.4B at [NM 7877 8335], or by driving west to park in a lay-by at [NM 7832 8318] from which the crags are accessible via the footpath signposted to Meoble, which leaves the north side of the main road, under the railway, some 200m to the east. Climb 250m towards 050° to reach the crags. Here vertical, banded psammities of the Arieniskill Psammitic Group (Morar Group) that lie 350m east of the Glenfinnan Group-Morar Group contact (the Sgurr Beag Thrust) can be examined. Following the 100m contour, traverse west across Arieniskill Burn for 350m towards the WSW. The banded, generally platy, psammitic rocks in the exposures near Allt Dileige, lie adjacent to the major lithological contact (Figure 3.1) and display characteristic features of high strain psammities within the Sgurr Beag Thrust Zone. Note the regular, small scale, interbanding of quartz-rich psammite and thin mica-rich lamellae, and the apparent structural simplicity. In many exposures concordant and isoclinally folded quartz veins can be found and occasionally isoclinal folds of the lithological layering. A steeply-plunging grain-alignment lineation is in places apparent. The extremely strong planar fabric of these rocks and the lineation are attributed to movement on the Sgurr Beag Thrust. The characteristics of similar thrust zones are discussed by Tanner (1971), Rathbone & Harris (1979), Powell *et al.* (1981), Baird (1982), Rathbone *et al.* (1983) and Kelley & Powell (1985).

Examination of the exposures on either side of Allt Dileige allows the contact of the predominantly migmatitic pelitic rocks of the Glenfinnan Group rocks to the west (Lochailort Pelitic Group) and Morar Group psammities (the Arieniskill Psammitic Group), to be traced up and down the hillside. Within the pelitic rocks, migmatitic *lits* have suffered disruption and a reduction in size, when compared with similar rocks further west. Because of the mineral assemblages developed

in pelitic and calc-silicate rocks across the Sgurr Beag Thrust Zone here, it would appear that movement took place under medium to high grade metamorphic conditions and the Glenfinnan Group rocks have been brought from crustal depths of 15-20km, assuming a 30°C/km geothermal gradient (Powell *et al.*, 1981; Powell, unpublished data). Whilst tectonic slivers of gneissic basement rocks, which provide the most obvious evidence for the magnitude of displacement on the thrust further north (Tanner *et al.*, 1970; Tanner, 1971), are absent in the SW Moine, contrasts in metamorphic grade across it at its most westerly outcrop, indicate considerable displacement (Powell *et al.*, 1981). Unfolding the Glenshian Synform and the Loch Eilt Antiform (Figure 3.3), suggest that the thrust zone, though now vertical, originally had a gentle to moderate easterly dip and assuming a NW–SE displacement, minimum movements of 15-20km can be suggested but they are likely to be much greater.

Throughout the Moine Supergroup generally, but particularly in this area, discontinuous bands and pods of calc-silicate rocks commonly occur. These are interpreted to represent calcareous concretions that probably formed during diagenesis. In the Lochailort area, the calc-silicate layers show a wide range of mineral assemblages and accordingly have been used to define several distinct metamorphic zones (Tanner, 1976; Fettes, 1979; Powell *et al.*, 1981). In the Morar Group below the Sgurr Beag Thrust, on the western side of the Loch Eilt Antiform (Figure 3.1), assemblages contain quartz + bytownite + garnet + hornblende + titanite + zircon + biotite ± chlorite, assigned to zone 3, equating to kyanite/sillimanite grade metamorphism. Titanite from a calc-silicate assemblage within the Morar Pelite, sampled between Localities 3.4A and 3.4B at [NM 7914 8318], has been dated using conventional U-Pb techniques (Tanner & Evans, 2003). The results indicate that the reactions forming titanite in these layers occurred at  $737 \pm 5$  Ma. This age equates well with the c.750 Ma ages on muscovite from nearby minor shear zones in the same group of rocks (Piasecki & van Breemen, 1983; Piasecki, 1984). This metamorphic event is thus quite separate from the anatexis event that formed the West Highland Granite Gneiss, which is dated at c.870 Ma, for example, at Ardgour and Fort Augustus (Friend *et al.*, 1997; Rogers *et al.*, 2001).

These titanite ages force us to examine the time at which the Sgurr Beag Thrust was formed. Currently there are two hypotheses: (1) it is an early Caledonian ductile structure, which carries the already gneissose Glenfinnan Group rocks over lower-grade Morar Group rocks to the west (e.g. Rathbone *et al.*, 1983; Barr *et al.*, 1986); (2) the main movements on the Sgurr Beag Thrust occurred during the regional metamorphism that affected both the Glenfinnan and Morar group rocks for the first time (Powell *et al.*, 1981). In this hypothesis, both the Moine and Sgurr Beag nappes share the same metamorphic history. In a study of micro-fabrics (Grant & Harris, 2000) it was discovered that the Sgurr Beag Thrust has two phases of movement; an earlier phase of compressive movement and a later extensional phase. It is plausible therefore, that the early phase is Neoproterozoic and that the later phase might be Caledonian (Grampian). Some 850m west along the road, parking is available in the lay-by (north side) at Locality 3.4C [NM 7773 8308], just west of Susan Macallum's memorial cairn. *Please do not hammer these exposures.* The roadside exposures at the cairn lie near the core of the Glenshian Synform (Figure 3.3) and display typical interbanded migmatitic pelites, impure quartzites and micaceous psammites of the Lochailort Pelitic Group, here vertical in attitude. Examination of both the vertical faces and sub-horizontal surfaces above, reveals the presence of early pegmatites and the development of steeply-plunging, asymmetric, sub-angular folds accompanied by crenulations of the migmatitic fabric, which refold earlier isoclinal folds. Opposite the western end of the exposure, proceed SE from the road to a low ridge running south toward the River Ailort. Here the complexities of the folding are picked out by upstanding ribs of white psammite. Isoclinally refolded isoclinal folds (Figure 3.4) demonstrate the composite nature of the dominant schistosity and many of the folds of both generations have curvilinear hinges and resemble sheath folds. To the east, small boudins of amphibolite have biotite-rich, often highly garnetiferous rims. These amphibolites belong to a regionally developed suite of early basic intrusives which, in this area, only occur in the Glenfinnan Group.

The Lochailort pegmatite, emplaced in migmatitic Glenfinnan Group pelites, can be seen at Locality 3.4D. Parking for cars can be found near the entrance to the electricity substation [NM 7715 8275]. Cross the road, and then walk 170m southwards to reach hummocky exposures of a coarse-grained feldspar + quartz pegmatite containing large muscovite plates, Locality 3.4D [NM 7722 8261]. The pegmatite exhibits little deformation, largely because of its competence and coarse grain size. In contrast, the host rocks comprise isoclinally folded migmatitic pelites of the Glenfinnan Group. Muscovite samples from the pegmatite have been isotopically investigated and the c.750 Ma ages for the cores represent either ages of crystallization or the effects of resetting. Pelitic schists at this locality and elsewhere in the Glenfinnan

Group, contain abundant, randomly-oriented flakes of late, retrogressive(?) muscovite that cross-cut earlier fabrics. The thermal event causing this late development of muscovite could be responsible for extensive resetting of isotope systems. The muscovites are sometimes intergrown with fibrolite and this may be significant as staurolite, kyanite and sillimanite have been found in high-grade migmatites of the Lochailort Pelite but are very rare. Winchester (1974) suggests that this is because of the overall, inappropriate bulk chemistry of the rocks. However, some of the abundant, retrogressive muscovite flakes may be derived from aluminosilicates.

## **Western margin of the 'vertical' belt and low grade rocks of the western 'flat' belt**

From the western limb of the Glenshian Synform as far as the coast, in the Morar-Arisaig districts some 17km to the west, the Moine rocks whilst folded on a major and minor scale, locally vertical and overturned, form a regional 'flat' belt (Figure 3.3). Throughout, the metamorphic grade is low, rising from greenschist to lowest amphibolite facies from west to east (Kennedy, 1949; Lambert, 1959; Tanner & Miller, 1980; Powell *et al.*, 1981). It was within this belt, and its extension northwards into Knoydart, that the lithostratigraphic succession of the Morar Group was originally established (Richey & Kennedy, 1939; Kennedy, 1955; Ramsay & Spring, 1962; Powell, 1964, 1974) and a four-phase deformation sequence recognized (Powell, 1964, 1974; Powell & MacQueen, 1976).

A rapid drop in metamorphic grade coincides with the western outcrop of the Sgurr Beag Thrust Zone near Lochailort (Figure 3.1). However, the change from the vertically disposed rocks of the 'vertical' belt to the more variable attitudes of the 'flat' belt does not occur until 2.5km to the west. Rocks, within which unequivocal and common sedimentary structures are recognizable, crop out within 500m of the contact between the Morar and Glenfinnann groups (Powell, 1964; Rathbone & Harris, 1979) suggesting that the high levels of strain associated with both the 'vertical' belt and the Sgurr Beag Thrust Zone die away quite rapidly. Sedimentary structures are common in many of the psammitic rocks of this western belt and have allowed detailed control of structural mapping. In particular, changes in younging directions within the Ardnish Psammitic Group (Powell, 1964) delimit several late major fold closures (Figure 3.1) and show that the Ardnish Psammitic Group youngs away from the underlying Loch Mama Pelitic Group, and towards the Lochailort Pelitic Group (Powell, 1964, main map). The major folds are extremely variable in style and geometry (Powell, 1966).

### **Locality 3.5 The western limb of the Glenshian Synform [NM 7675 8236] to [NM 7570 8260]**

The western limb of the Glenshian Synform (Figure 3.1). Morar Group psammites, pelites and calc-silicate lenses; sedimentary structures.

About an hour should be allowed for these localities which lie to the west of the Lochailort Inn. Parking for cars is available on the verge off the south side of the road west of the junction at [NM 7668 8226]. Coaches may be able to park at the Inn on request.

Opposite the road junction west of the Lochailort Inn, near vertical rocks of the Morar Group (Ardnish Psammitic Group of Powell, 1964) crop out in road cuttings which are Locality 3.5 [NM 7675 8236]. This locality lies 500m west of the Sgurr Beag Thrust but is within the thrust zone. It comprises interbanded white-grey psammites, blue-grey micaceous psammites, and dark semi-pelites, together with thin calc-silicate ribs and lenses. In places, levels of strain are sufficiently low to enable deformed sedimentary structures to be seen (main map in Powell, 1964). However, the apparent structural simplicity of the rocks, their uniform attitude and flatness, may reflect their situation just within the thrust zone. Calc-silicate rocks here comprise garnet + biotite + zoisite + plagioclase (An 40-60) + quartz, whilst occasional pelitic horizons in the vicinity, are non-migmatitic garnet + muscovite + biotite + plagioclase + quartz schists (Powell *et al.*, 1981).

On the south side of the road, immediately west of the road junction, further exposures of psammitic rocks at Locality 3.5A reveal sedimentary structures, largely ripples and trough cross-laminations that suggest younging to the east. The cross-sets have been modified by strain relative to their positions on minor folds. Calc-silicate lenses and pods are common. Gently-inclined microdiorite sheets are also well exposed in the southern side of the cutting. The sheets all show brittle, igneous, emplacement features and usually have internal shear fabrics (Figure 3.5). The sheets commonly display a number of features including en-echelon segments and, where the intervening bridge has been breached, *en*

*bayonet* relations. Frequently along the length of a sheet there are apophyses on either side that have opposing directions of termination. These features are interpreted to be related to either the linking of two segments through the brittle extensional fractures into which the magma was emplaced, or represent sidesteps. In most examples the magma has breached the separating bridge to form a semi-continuous sheet. In some dykes elsewhere, isolated xenoliths of the host rock may be found, interpreted to be fragments of the bridges between segments (e.g. Rickwood, 1990).

Locality 3.5B is some 300m to the west, at [NM 7635 8230], where exposures on the both sides of the road display steeply dipping psammities where levels of strain are low. Planar and trough cross-bedding give convincing evidence for younging to the east. A 5m-wide Tertiary basalt dyke is well displayed in the north side cutting.

Locality 3.5C lies a further 800m to the west at [NM 7570 8260], where roadside exposures can be examined. Parking is available on wide grass verges, and outcrops on the north side contain minor folds, which are associated with the major folds (Figure 3.1). Sedimentary structures give clear evidence of directions of younging – predominantly to the east. A thin microdiorite sheet shows displacements across semi-pelitic layers in the host psammities and, internally, a sinusoidal shear fabric indicating a top to the west sense of movement. Dextral shear along the semi-pelitic layers has caused attenuation and thinning of the microdiorite and successive uplift to the west. Shearing was associated with retrogression allowing the growth of chlorite.

### **Locality 3.6 The Ardnish Synform [NM 7478 8305] to [NM 7401 8330]**

The Ardnish Synform – lithostratigraphy of its north-western limb (Figure 3.1). Well-preserved sedimentary structures and minor folds; lithostratigraphy.

Visiting localities 3.6A, B & C will require half a day, but if 3.6D is included allow a further two hours. Park in the lay-by on the north side of the road 1.3 km west of Locality 3.5C, 2.4km from Lochailort [NM 7478 8305]. Cross the road and go through a small gate giving access to the viewpoint above Loch Dubh. Walk west along the fence line to Locality 3.6A which comprises low exposures above the grass verge of the road. These outcrops lie near the core of the Ardnish Synform (Figure 3.1) where levels of deformation are so low that original sedimentary features are very well preserved. Differential weathering has etched out several types of cross bedding which clearly demonstrate that the rocks young to the SW. Similar sedimentary features are still recognizable in the immediately adjacent outcrops, but blasting during road widening has ruined their surface expression.

A further 600m to the NW, parking is available in a large lay-by on the west side of the road [NM 7420 8356]. Some 50m to the north, the public footpath giving access to the Ardnish peninsula (signposted), leaves the road to the SW. About 50m to the north of this new path, low lying exposures adjacent to the south side of the old Ardnish track, Locality 3.6B lies on the NW limb of the Ardnish Synform (Figure 3.1) and contains very well preserved, though folded, cross-bedding. The psammities dip and young to the SE and are arkosic in composition; truncated cross-sets are common and different orientations of foreset beds suggest trough cross-bedding. Herringbone cross-bedding suggests currents with either a northerly or southerly transport direction. The minor folds plunging steeply to the SW show extreme, though systematic, changes in layer thickness from limb to hinge, and variation in style along their axial surfaces. Evidently, the rocks had a high mean ductility during deformation. The folds are parasitic to the Ardnish Synform and characteristically have quartz veins sub-parallel to their axial surfaces. Elsewhere, folds of this generation refold isoclinal folds and are deformed by SE-plunging open folds and crenulations.

The next part of the excursion can be completed quickly, but less informatively, by returning to the main road and walking northwards along it for 100m to reach Locality 3.6C. Here outcrops on the west side of the road start with NW-dipping garnetiferous pelites of the Loch Mama pelite. Retrogressive metamorphism, of uncertain age, has caused chloritisation of both garnet and biotite. Further along the exposure the lithology gradually changes with an increase of semi-pelitic layers and eventual loss of pelites. Characteristic of this outcrop and that of the Loch Mama pelite elsewhere, is the platiness of the layering and rarity of minor folds. A further 200m along the road, on its south side, uniformly banded psammities of the Loch nan Uamh Psammite crop out. Though not obvious here, sedimentary structures in neighbouring psammities indicate younging to the SE, i.e. into the Loch Mama pelite. In this area there is, therefore, evidence for a tri-partite, lithostratigraphic succession starting with the Loch nan Uamh Psammite Group, passing through the Loch



Mama Pelitic Group and up into the Ardnish Psammitic Group. Such a succession is similar to that on the western limb of the Morar Antiform (Kennedy, 1955; Richey & Kennedy, 1939). There is, however, evidence for a thrust running through the lower part of this succession (see below).

If time is available, a more informative traverse across the NW limb of the Ardnish Synform from the Ardnish Psammitic Group into the Loch Mama Pelitic Group (equivalent to the Striped and Garnetiferous groups of the Morar succession) can be made by following the Ardnish path to the SW. On crossing the railway footbridge [NM 7401 8330], walk by way of scattered exposures, across country for 800m WNW, to reach Locality 3.6D at the coast [NM 7320 8340].

The coastal exposures around the small headland immediately to the north contain highly garnetiferous muscovite + biotite + plagioclase + quartz schists. In thin sections the garnet porphyroblasts are seen to contain planar inclusion fabrics, are in places texturally and chemically zoned, and are interpreted as having grown before development of the dominant schistosity (Powell & MacQueen, 1976; Anderson & Olympio, 1977; MacQueen & Powell, 1977). Detailed studies of Sm-Nd isotopes and the chemical zonation of garnets from here, from near Locality 3.6C, and elsewhere (Vance *et al.*, 1998), suggest early garnet growth at  $823 \pm 5$  to  $788 \pm 5$  Ma. These results, taken with the work on the Knoydartian pegmatites and the calc-silicate rock mentioned above (stop 4D), provide very strong isotopic evidence for Neoproterozoic orogenesis. Acceptance of such a conclusion implies that many of the tectono-metamorphic features and fabrics of the south-western Moine are Precambrian rather than Caledonian in age (Brewer *et al.*, 1979; Powell *et al.*, 1983, Holdsworth *et al.*, 1994, Vance *et al.*, 1998, Rogers *et al.*, 1998, 2001; Tanner & Evans, 2003; Cutts *et al.* 2009).

### **Locality 3.7 The Arnipol Slide Zone [NM7421 8370] to [NM 7438 8430]**

The Arnipol Slide Zone (Figure 3.1). Structures associated with a regional ductile thrust.

A traverse, lasting up to three hours, across the lower part of the Ardnish Psammitic Group, the Loch Mama Pelitic Group, into the Loch nan Uamh Psammitic Group (equivalent to the Lower Psammitic Group of Richey and Kennedy, 1939), and across the Arnipol Slide Zone, can be made by leaving the main road at [NM 7421 8370] and taking the following route: walk for 200 m north-eastwards up to the 90-100m contour; follow the 90-100m contour to the north, meeting Arnabol Burn at [NM 7465 8412] and then walk northwards to the sheepfold at [NM 7468 8430]; cross Allt Mama and walk westwards, downhill for 30m, examining outcrops of psammites belonging to the Loch nan Uamh Psammitic Group.

On this traverse the lithological character and low-grade metamorphic state of these three members of the Morar Group can be appreciated both within and, in the case of the psammites, outside the Arnipol Thrust Zone. Whilst initially the thrust zone here was thought to be of only local significance (Powell, 1964, 1966), the contrasts in the attitudes of early minor fold structures across the zone are dramatic; moving from NW to SE, tight isoclinal folds with east to NE gently-plunging hinges ( $D_2$  of Powell, 1964, 1974) are rotated, within the plane of the lithological layering across the zone, to become steeply SE-plunging reclined structures (Powell, 1966). The development of platy fabrics in many lithologies is also apparent and the thinning of the Loch Mama Pelitic Group from north to south is remarkable (Figure 3.1). The Arnipol Thrust may be a major structure representing the southward extension of the Knoydart Thrust Zone (Poole & Spring, 1974).

### **Locality 3.8 The Upper Morar Psammite: Rhue peninsula [NM 613 842]**

The Upper Morar Psammite: Rhue peninsula, by R. Glendinning. Well-preserved sedimentary structures.

There is no access for coaches to this locality; allow about two and a half hours. Drive westwards from Arnipol towards Arisaig (10km). On the outskirts of Arisaig [NM 665 865], turn left off the new A830 and at [NM 661 864] turn left and follow the minor road along the Rhue peninsula for 5km to the end of the metalled road (Figure 3.6). Limited parking is available adjacent to a small boathouse (Figure 3.7). Follow a track to Rhue House, 1km to the SW, and thence walk due west to the coast at [NM 613 842].

Rocks near the top of the Upper Psammite are well displayed on a raised wave-cut platform where the western limb of a large (locally  $D_3$ ) minor anticline is exposed (Figure 3.7). The sequence (Figure 3.8), consists of lenticular sheets of medium- to coarse-grained, occasionally gravely, arkosic sands (now psammites) interbedded with silts and silty clays (now semi-pelites and pelites). Internally, the sand sheets are dominated by trough cross-bedding with subordinate tabular cross-bedding (Figure 3.9), flat-bedding, ripple cross-lamination and climbing ripple cross-bedding. Palaeocurrents measured from cross-bedding show unidirectional, northerly flows. Locally these sheets have erosive bases and frequently incorporate rip-up clasts of the underlying silts. Further evidence for erosion is provided by occasional winnowed sand and gravel layers. Titanite-rich heavy-mineral bands, which appear as thin yellow lines on weathered surfaces, are common. The intervening finer grained sediments are rarely massive and usually contain thin layers and lenses of sand.

### **Locality 3.9 The Upper Morar Psammite: Morar Bay [NM 668 933]**

The Upper Morar Psammite: Morar Bay, by R. Glendinning. Soft-sediment deformation structures in meta-sandstones.

From Rhue, drive back towards Arisaig and turn right to rejoin the A830. Drive north towards Mallaig. Alternatively, a more scenic coastal route can be taken by turning left and following the B8008 to Morar village. Vehicles can be parked just off the road immediately north of the Morar Motors Garage ((Figure 3.6), inset). Two hours should be allowed for this locality; walking time is about 20 minutes.

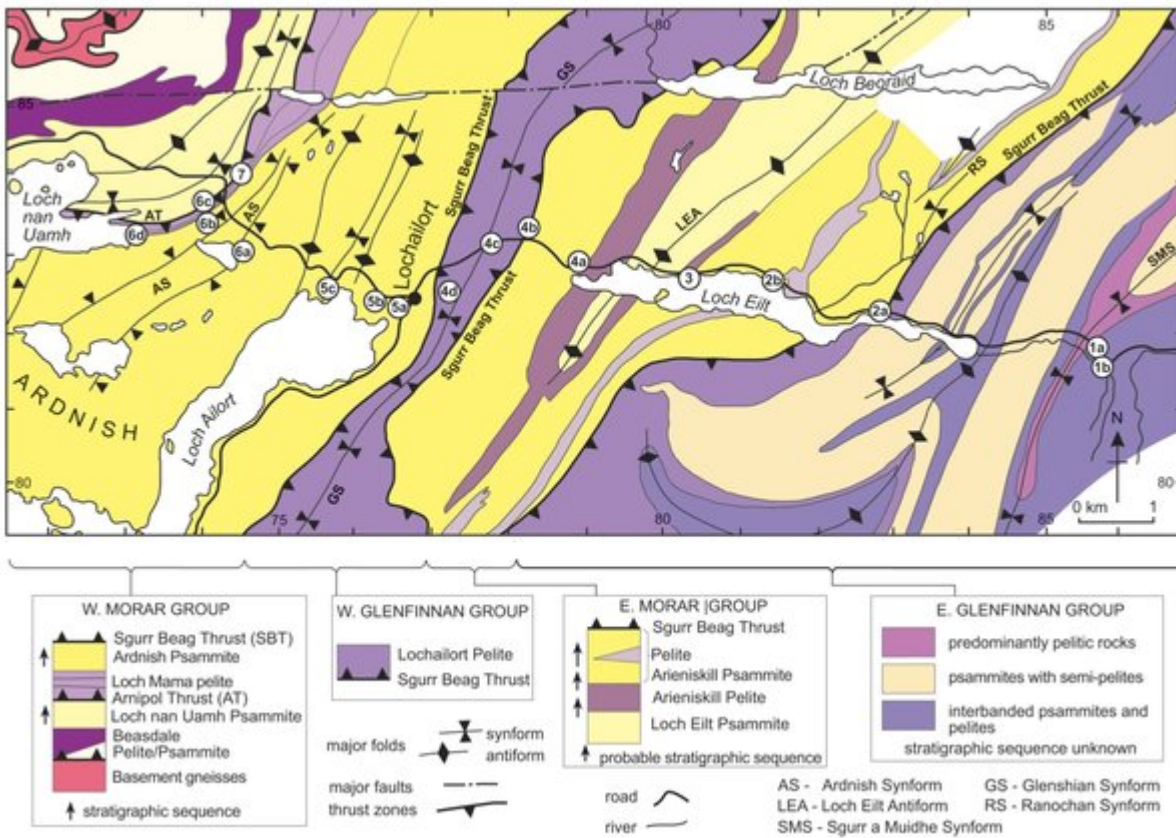
Follow the footpath along the north shore of Morar Bay. This crosses the conformable contact between the Striped and Pelitic schists and the Upper Psammite; both groups are steeply dipping to vertical and young consistently to the west. The former are particularly well exposed around [NM 668 933], immediately to the west of a small rocky headland, and consist of finely interbedded sands and silts with abundant calc-silicate pods and lenses. The Upper Psammite is exposed on an extensive wave-cut platform to the north of Sgeir Mhor (Figure 3.6). The salient features of the sequence are shown in (Figure 3.8). Again, the Upper Psammite consists of laterally extensive sand sheets with intervening silts and silty-clays. The sands contain a variety of sedimentary structures including flat-bedding, trough and tabular cross-bedding and ripple cross-laminations. Of particular interest are thick sand layers, which were subjected to intense soft-sediment deformation. Various mechanisms can be invoked to explain such structures: for example, earthquake-induced shock or slumping; however, in this case the contortions are generally associated with trough cross-bedded sands and intervening sediments are undisturbed. This suggests that under shock of rapid deposition the sediment liquefied generating convoluted bedding and water escape structures. This section, in contrast to that described above (Locality 3.8), lies at the base of the Upper Morar Psammite.

### **Interpretation of the sedimentary environment of the Upper Psammite**

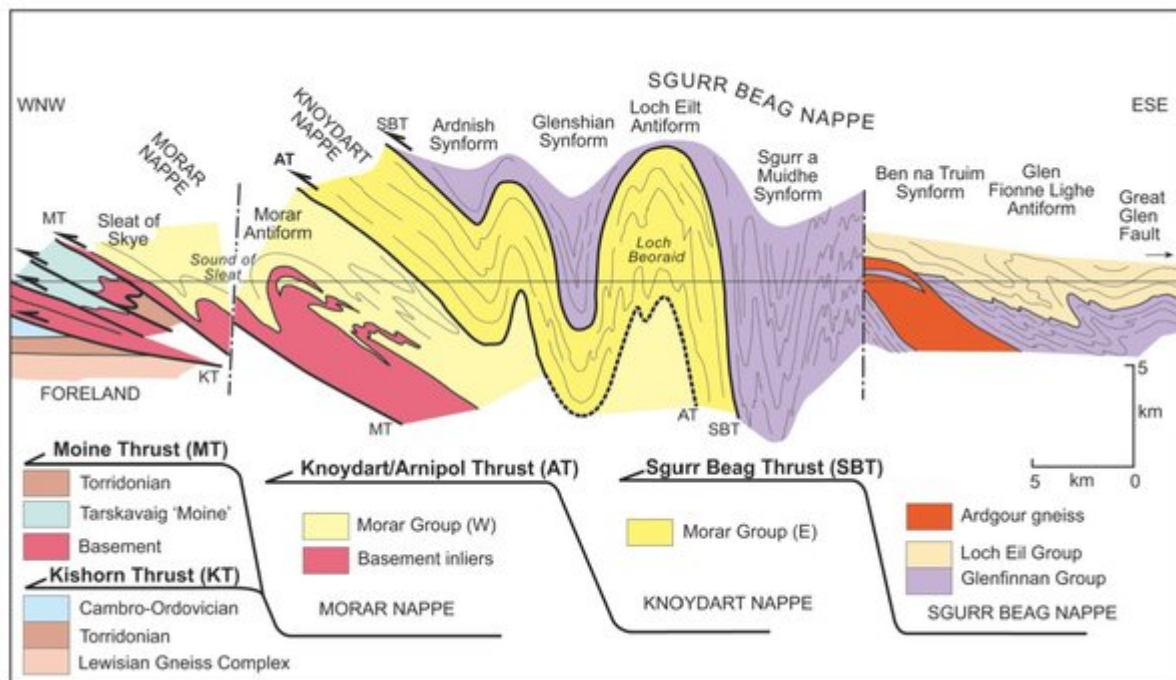
Examination of the Upper Psammite at other localities, around Morar and southwards along strike on Ardnamurchan, confirms the dominance of south to north and SW to NE palaeocurrents. These are accompanied by a northwards decrease in both the grain size and scale of the sedimentary structures within the psammites, and a corresponding increase in the proportion of semi-pelite and pelite. Such a transition suggests two broad depositional truncation of the cross-beds indicates slight inversion and younging to the west. Lighter is 8cm long. models: either (a) a fluvio-deltaic wedge, or (b) a shallow marine shelf with deposition controlled by tidal and/or storm generated currents. Of these, the former is considered unlikely as there are no recognizable fluvial sequences and channelling is rare. Instead, the sands and silts form laterally extensive sheets. Furthermore, abundant sand lenses and layers within the Striped and Pelitic Schists suggest a starved sediment, rather than a low energy pro-delta environment. A shallow marine shelf model is perhaps more feasible (Glendinning 1988) and Johnson (1978) and Walker (1979) describe similar changes in grain size and sedimentary structures along tidal transport-deposition paths. The palaeocurrent reversals identified around Morar (Figure 3.8) may represent a weaker opposed tidal flow. Anderton (1976) emphasizes the importance of winnowed gravel lags and describes a tidal shelf model in which a zone of scour is followed by a sandwave zone and finally by silt and mud deposition. When normal tidal flows are strengthened during storms these zones migrate so that, for instance, sandwaves become eroded. This may explain the distribution of winnowed gravel layers within the Upper Psammite, which are occasionally present around Morar but much more common on Ardnamurchan. For further discussion of the

sedimentation of the Upper Morar Psammite, see Bonsor & Prave (2008) who prefer to interpret it as an alluvial braidplain deposit.

**References**



Geological map of part of the SW Moine between Glenfinnan and Arisaig, showing locations of Localities 3.1-3.7.



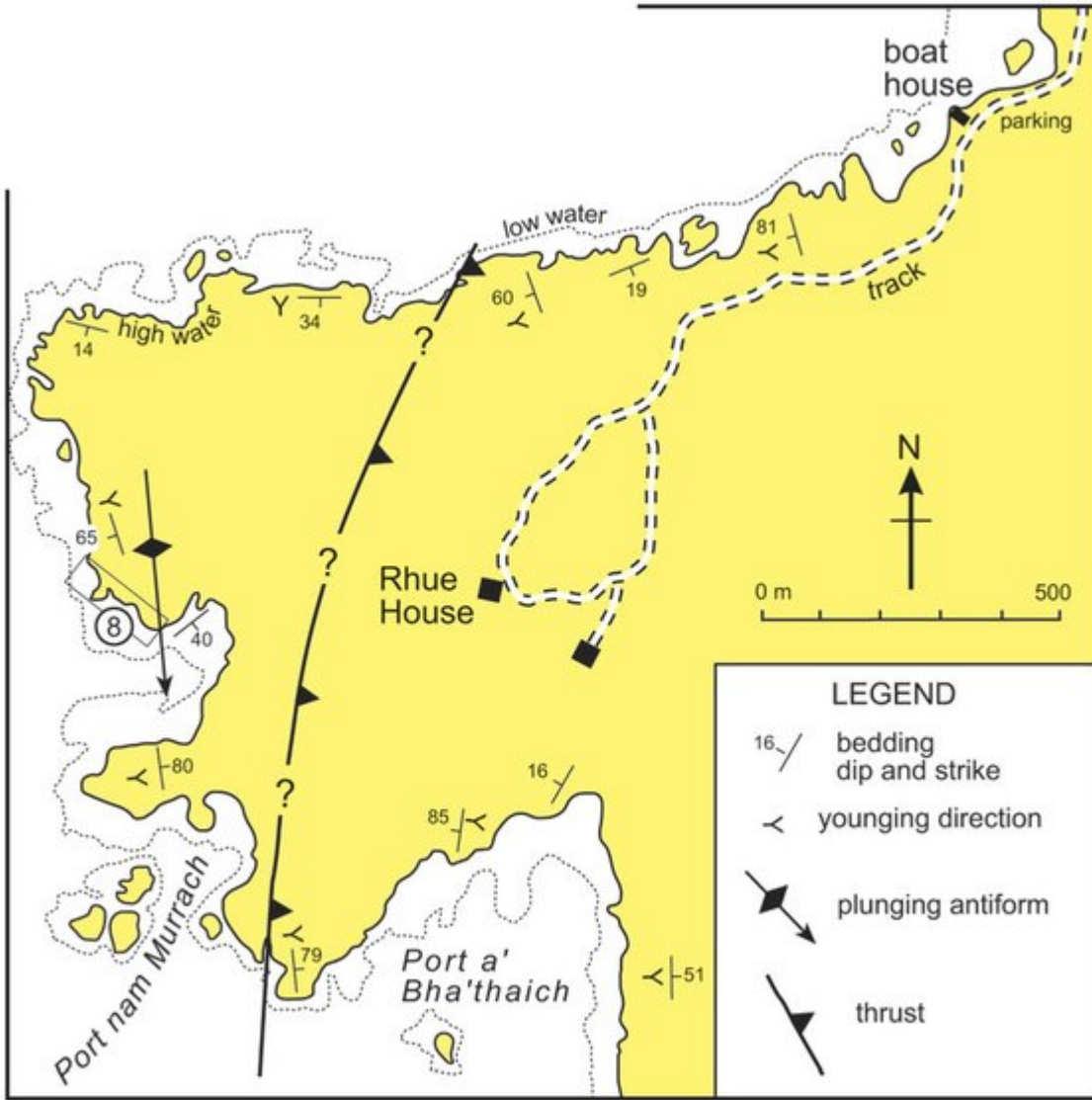
Geological section across the SW Moine.



*Isoclinally refolded isoclines picked out by vertically dipping sedimentary layering in the Lochailort Pelitic Group at Locality 3.4C. Compass-clinometer is 10 cm long.*

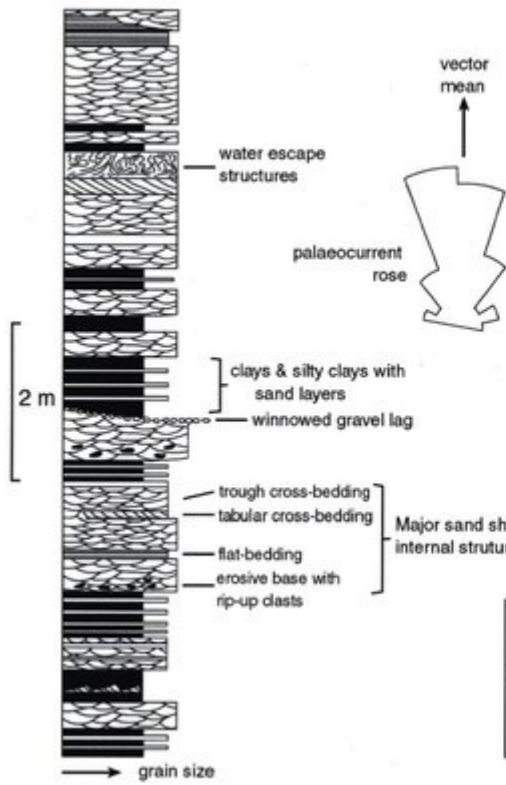


*Foliated microdiorite sheet dipping eastwards and cutting near vertical interbanded psammite and semi-pelites of the Upper Morar Psammite at Locality 3.5A. Note easterly-dipping internal schistosity oblique to sheet margins. Lighter is 8cm long.*

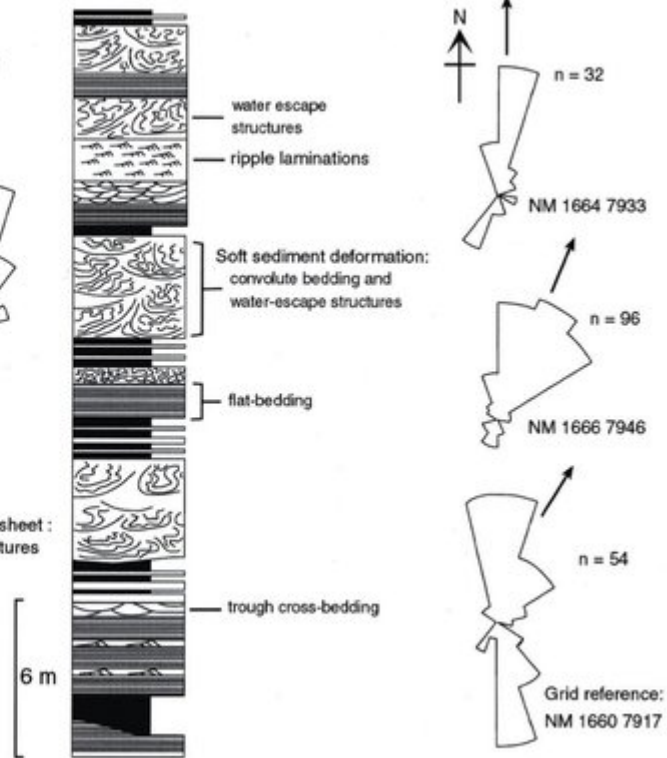


Simplified geology of the Rhue peninsula.

Locality 8: RHUE



Locality 9: MORAR



Examples of graphic sedimentological logs from the Upper Morar Psammite.



*Cross-bedding in psammite layer of an interbedded psammite-pelite sequence of the Upper Morar Psammite at Locality 3.8.*