Excursion 13 North Sutherland

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Purpose:	A general traverse across the Caledonian thrust nappes that outcrop between the Moine Thrust and the sedimentary cover of the Devonian Orcadian Basin.
Aspects covered:	Various metasedimentary lithologies, metamorphic minerals and migmatites, Lewisianoid basement gneisses, Precambrian and Lower Palaeozoic (meta)igneous intrusions, Caledonian ductile structures, late to post-Caledonian brittle faults, Devonian and probable Permo-Triassic sedimentary rocks.
Useful information:	Hotel and B&B accommodation and camping are available at Talmine, Tongue and Bettyhill.
Maps:	OS: 1:25,000 sheets 446 Durness & Cape Wrath, 447 Ben Hope, Loch Loyal & Kyle of Tongue, 448 Strath Naver & Loch Loyal, 449 Strath Halladale & Strathy Point; BGS: 1:50,000 sheets 114W Loch Eriboll, 114E Tongue and 115W Strathy Point.
Type of terrain:	Rocky coastline, moorland, quarry and roadside exposures.
Distance and time:	The excursion is best followed from a base in either Tongue or Bettyhill, taking 4 days. See each locality for suggested times.
Short itinerary:	Localities 13.1, 13.4 and 13.8 could be accomplished in one day.

The traverse along the well-exposed north coast of Sutherland (Figure 13.1) provides the best opportunity to examine the complex regional structure of the Moine and Naver nappes, as well as a number of the Archaean basement inliers that crop out in the area. Particular points of interest include the nature of the relationships of these inliers with the Moine, and the evidence for their pervasive reworking during the Caledonian orogeny. These basement inliers have often been correlated with the Lewisian gneisses of the foreland, although unambiguous correlation remains to be demonstrated. Accordingly, use of the less specific term 'Lewisianoid' is employed here to denote basement that is of similar age and lithology to that of the foreland. Both the basement inliers and the Moine have undergone a complex polyphase deformation history. Complications in attempting to erect a consistent chronology across the traverse arise from the recognition that in the Moine Nappe the earliest structures and metamorphic fabrics recognizable in the field are Neoproterozoic in age, whereas in the Naver Nappe they are Ordovician (Grampian). It is assumed that Neoproterozoic fabrics were originally present within the Naver Nappe, but were extensively reworked during Ordovician high-grade metamorphism and migmatization (Table 1). The Grampian event has so far not been recognized within the Moine Nappe. In the deformation chronology presented in Table 1, we therefore recognize D_1 (Moine Nappe) and D_1N (Naver Nappe) events that are of different ages. Both thrust nappes record a similar polyphase Silurian (Scandian) history: sets of structures assigned to D_2, D_3 and D_4 episodes are thought to have resulted from a continuous, progressive deformation.

Locality 13.1 The Melness area [NC 580 643] to [NC 5850 6501]

The Melness area (Figure 13.2). A comparison of low and high strain Moine metasedimentary rocks of the Moine Nappe; Lewisianoid basement rocks; amphibolite of the Ben Hope Sill Suite; the Strathan basal conglomerate.

From Tongue, turn north off the A838 on the west side of the Kyle of Tongue, continue through Talmine for 1.3km and park where the road forks [NC 580 643] just south of Loch Vasgo. Parking is available for a coach or four to five cars.

Allow 4 hours for this locality.

Examine the low cliffs (1A, (Figure 13.2)) to the east of the fork. Here, relatively low-strain, cross-bedded gritty psammites are folded into a mesoscopic recumbent, north-facing D_2 fold pair that plunges sub-parallel to the ESE-trending L_2 lineation. The foresets dip north, sedimentary transport is from the south, and the lower limb is right-way up. Variations in the state of strain can be estimated by measuring the angles of cross-beds around the fold. The apparent strain increases dramatically on sections parallel to L_2. These psammites are interpreted to rest with modified unconformity upon the basement rocks of the Achinahaugh inlier that are exposed on low-lying outcrops immediately west of Loch Vasgo (Alsop & Holdsworth, 2004a, figure 6). On top of the cliffs, strain and white mica content increase towards a minor ductile thrust that cross-cuts the fold pair. A prominent pelite horizon above the thrust contains garnets up to 5mm in diameter. Small inclusion trails within these porphyroblasts define S_1M; the garnets are wrapped by the dominant S_2 mica fabric and are associated with pressure shadows that are elongate parallel to L_2. The evidence thus suggests that garnet growth occurred post-D_1M and pre-D_2. Formation of the S_1M fabric and garnet growth are tentatively assigned to the Knoydartian orogenic event. Quartz veins are lineated and elongate parallel to L_2. Shear bands within the pelites indicate a top-to-the-west sense of displacement parallel to the lineation. S_2 and the quartz veins are folded by cm-scale, open to close, asymmetric D_3 folds (e.g. [NC 5811 6431]).

Table 1: Table of structural events

	MOINE NAPPE	**NAVER NAPPE**
SCANDIAN (c.435-425 Ma)	Emplacement of the **Loch Loyal Syenite Complex**. D_4formation of the transpressive Torrisdale Steep Belt, as well as the major synform-antiform pair within the Kirtomy gneisses and the Strathy Complex. D_3tight-to-open, asymmetric recumbent folding. D_2NW-directed ductile thrusting (e.g. Swordly, Naver and Ben Hope thrusts) accompanied by widespread tight to isoclinal interfolding of Moine and Lewisianoid basement; recumbent folds commonly curvilinear about NNWto NW-trending mineral and extension lineation.	
GRAMPIAN (c.470-460 Ma)	Not recorded.	D_1N upper amphibolite facies metamorphism and migmatization; minor tight development of S_1N foliation and N-S-trending L_1N mineral and extension lineation.
LATE NEOPROTEROZOIC	Intrusion of alkaline **Loch a' Mhoid Metagabbro Suite.**	Not recorded.
KNOYDARTIAN? c.820-800 Ma)	D_1 **M** garnet-staurolite grade metamorphism, S_1M foliation,minor isoclinal folding.	Amphibolite facies metamorphism and fabric development inferred but not observed due to intensity of Grampian overprint.
EARLY NEOPROTEROZOIC (c.1000-870 Ma)	Deposition of Moine sediments in an extensional basin within the Rodinia supercontinent, accompanied by emplacement of mafic igneous intrusions such as the **Ben Hope Sill.**	

NB: (1) It is envisaged that D_2-D_4 structures formed essentially as a continuum, accompanied by amphibolite facies metamorphism – garnet and hornblende stable; (2) D_2 and D_3 structures are generally only found in structurally lower parts of the Naver Nappe; (3) deformation was accompanied by intrusion of a range of granite and pegmatite sheets, particularly within the Naver Nappe and in the vicinity of the Naver Thrust.

From here, head northeastwards across the intermittently well exposed, undulating ground. Spectacular rodded quartz veins are present at [NC 5820 6440] on the west side of a large hummocky outcrop. Traverse across psammites and occasional pelite bands, displaying good examples of D_2 and D_3 folds. 1B ((Figure 13.2), [NC 5847 6455], 25m on a bearing 195° from the main summit cairn) is marked by a small cairn above a west-facing, 3m high surface displaying D_2 and D_3 folds, including numerous spectacular 'eye' structures (Figure 13.3) that represent cross-sections through the noses of D_2 sheath folds (i.e. not interference patterns). *Please do not hammer these localities*. Detailed analyses of both D_2 and D_3 folds in this area are presented by Alsop & Holdsworth (1999, 2002, 2004a & b). A little further to the east (25m on a bearing of 140° from the main summit cairn) another west-facing surface marked by a small cairn [NC 5851 6454] displays various D_2 eye structures that are refolded by tight, asymmetric D_3 folds. Then walk northeastwards downslope towards the coast.

1C [NC 5892 6487] is by the beach on the west side of the gully (Figure 13.2), where pelites contain prominent 1-2cm diameter garnets. These show obvious zonation with orange cores (some with aligned inclusion trails) and darker rims wrapped by S_2. Prominent shear bands indicate a top-to-the-west sense of displacement parallel to the locally developed L_2 lineation. To the east of the gully, above a thin garnet amphibolite of the Ben Hope Sill Suite, east-dipping surfaces of highly deformed psammites display intersections of S_2 with S_0 /S_1M curving about the E–W-trending L_2 mineral and extension lineation. This reflects the progressive rotation of fold hinges during west-directed D_2 thrusting. Quartzofeldspathic clasts within pebbly horizons show a marked elongation parallel to the intersection lineation. Still further to the east, the L_2 mineral lineation disappears, leaving a uniformly N-S-trending stretching direction thought to represent a relict L_1M lineation (Holdsworth, 1989a).

Head northwestwards, over inclined surfaces of garnet pelite, with isoclinally folded and rodded quartz veins elongate parallel to L_2 . Further excellent examples of garnets wrapped by S_2, showing cores and rims and inclusion trails, are present at [NC 5885 6507]. At 1D [NC 5884 6504], at the south end of the gully (Figure 13.2), an outcrop-scale brittle detachment fault cuts across upright, brittle kink folds of fabric in its footwall. On the west side of the gully are steeply-inclined slabs of garnet amphibolite of the Ben Hope Sill Suite. Garnets are wrapped by the S_2 fabric and some have pressure shadows that are elongate E–W parallel to L_2. Walk westwards across undulating ground towards Port Vasgo. At [NC 5867 6499], pause to look ENE to view steep rock slabs that show mesoscopic tight to isoclinal D_2 folds.

Follow the path down into Port Vasgo (Figure 13.2) to a stony beach at 1E [NC 5850 6501], where NE-dipping, mylonitic psammites define a zone of high D_2 strain. If tides are low, cross the rocks on the east side of the bay to access a pale-weathering lenticular pod of psammite associated with a microdiorite sheet exposed on a SW-dipping cliff at [NC 5862 6508; see Holdsworth *et al*. 2001a, plate 8). The pale eye-shaped area of psammite is a low-strain augen preserving cross-laminations folded by D_2 folds that appear to be cross-cut by a little-deformed, fine-grained sheet of microdiorite, with well-defined chilled margins. On careful inspection, however, it is apparent that the sheet pinches out and passes laterally into bedding-parallel shears that locally preserve irregular isolated pods of microdiorite, often in equivalent small-scale low-strain augen. Other sheets of microdiorite can be traced laterally into the high-strain, platy psammites where they become schistose and carry fabrics parallel to S_2 and L_2 in the adjacent psammites. Although clearly still discordant in both anticlockwise and clockwise senses, they appear to represent intrusions that were emplaced as curviplanar units that have subsequently been deformed during D_2. Similar microdiorite intrusions are common around the Kyle of Tongue and have been grouped as the Port Vasgo Microdiorite Suite by Holdsworth *et al*. (2001a) who interpreted them as being syn-tectonic with respect to the D_2 deformation. It is equally possible, however, that the intrusions pre-date D_2, with some or all of the folds occurring close to the discordant sheets representing flanking folds (Passchier, 2001). If the intrusions are pre-D_2, they may be the same age as the Loch a' Mhoid Metagabbro Suite (see Locality 13.6).

Retrace your steps back to the beach, and follow the road up out of Port Vasgo back to the vehicles. Take the left fork and drive to Strathan Bay (Figure 13.2), parking at the east end of the crash barrier at [NC 5743 6480]. Walk down the slope to the shore on the south side of the bay to 1F [NC 5734 6489] to view exposures of the Strathan Conglomerate (Mendum, 1976), interpreted as a basal Moine conglomerate overlying Lewisianoid basement (Holdsworth, 1987, 1989a; Holdsworth *et al*., 2001a). The conglomerate lies within a high strain zone and contains numerous highly flattened 'clasts' that are up to 30cm in length and elongate parallel with L_2 . 'Clast' types are, in order of decreasing frequency and degree of strain: pale grey quartzite, fine to medium-grained quartzo-feldspathic gneiss, white quartz, dark grey quartz-magnetite rock, and granite/pegmatite. It is doubtful, however, that all these types were genuinely incorporated as clasts within the Moine sediments prior to D_1M. In low strain zones, the grey 'quartzite' and white quartz 'clasts' appear to represent tectonically disrupted, isoclinally folded metamorphic segregations (compare with the segregated pelites and possible conglomerate layers seen at Kinloch Broch, Locality 13.2 below). According to Holdsworth (1987), the only lithologies that can be identified confidently as pebbles in areas of low strain are those of quartz-magnetite rock and pink granite/pegmatite which typically display lower amounts of strain. At low tide and low sand levels, highly strained hornblendic material within the conglomerate could represent early infolds of the Lewisianoid basement. Upstream, the conglomerate is underlain by flaggy, pink acidic basement gneisses that are interleaved with mafic sheets at [NC 5725 6483].

Locality 13.2 Kinloch Broch [NC 5500 5282] to [NC 553 531]

Kinloch Broch (Figure 13.4). The D_2 Ben Hope Thrust, highly strained Lewisianoid basement and Moine psammite, complex D_2 and D_3 folds.

Two to three hours should be allocated to this locality, at the south end of the Kyle of Tongue. Parking is available for a coach or several minibuses in the small gravel pit [NC 5516 5337], 150 m east of the Allt Ach' an t-Strathain.

Follow the burn for 550m SSW, until it turns sharply west [NC 549 629]. Traverse ESE uphill for 100m, noting the flaggy to platy, highly strained, sparsely gritty psammites. At 2A (Fig 13.4b, [NC 5500 5282]), thin (1m) units of what has been interpreted as an intensely deformed, intraformational conglomerate are interbanded with psammites a few metres below a laterally extensive pelite (cf. stop 1A). The pebble 'clasts' are mainly quartzose, resembling closely those in the Strathan Conglomerate (stop 1F), and hence similar questions arise as to their true origin. Psammite adjacent to the overlying pelite displays a marked increase in white mica content. Traverse ESE for 30m over extremely platy psammite, containing the ESE-trending L_2 mineral lineation and isolated small, strongly flattened feldspar clasts, elongated parallel to this fabric. At the top of the slope at 2B [NC 5503 5282], these psammites are overlain by hornblende-biotite schists of the Kinloch basement sheet; this boundary is the D_2 Ben Hope Thrust (Figure 13.4)a, (Figure 13.4)b). This thrust, and the overlying basement sheet, has been traced for at least 25km (Figure 13.1) from south of Ben Hope to Strathan Bay where it is associated with the zone of intense D_2 strain affecting the Strathan Conglomerate (Locality 13.1F). The marked asymmetry across this D_2 thrust contact is demonstrated by the main (pre-D_1M) Ben Hope Sill intrusion occurring above the accompanying basement body, but never below the lower contact with the platy psammites ((Figure 13.3)a). The outcrop pattern of the Ben Hope Thrust suggests a minimum WNW displacement of 7.55 km ((Figure 13.4)a).

Walk NNE for some 150m towards the summit of the hill to 2C. Here a number of open to isoclinal, south- to ESE-plunging folds form a 'Z' geometry pair, distorting the lower Moine-basement contact (i.e. the Ben Hope Thrust) and clearly refolding the D_2 platy fabric and associated lineation. Thus these folds belong to the local third phase, D_3. Note the apparent repetition of the upper pelite and lower basement contacts ((Figure 13.4)b) by a thrust which must lie within the pelite to the north (Figure 13.4)b, (Figure 13.4)c) as the lower boundary of the pelite is unaffected by thrusting or the D_3folding. The common limb of the fold pair is a zone of relatively low strain where D_1M-D_2 refolded folds occur in basement rocks [NC 5507 5288] along with migmatitic fabrics and ultramafics pods; 50m further south at 2D [NC 5507 5282], D_3folds display up to 100° of curvature of their hinges and clearly deform the L_2 lineation.

Traverse SSW for 200m within the basement gneisses. The D_3 folds tighten, becoming progressively smeared out into the foliation and indistinguishable from D_2 structures. The exposed D_3 fold pair appears to form the southern part of a large fold pair of the same age that initially overturned WNW before being modified into highly curved sheath fold geometry by continued shearing (Holdsworth, 1990). The northern part of this structure has been largely removed by erosion, but a remnant of an intensely curved synformal infold of psammite within pelite is still preserved to the northeast at 2E (Figure 13.4), (Figure 13.4)c) [NC 553 531]. Within the Moine Nappe, many D_3 folds are similarly associated with zones of high D_2 strain and so may be genetically related to ductile thrusting processes (Holdsworth, 1990; Alsop & Holdsworth, 2007). This implies that a direct correlation of all D_3 structures may not be valid, with the structures forming at various times during a protracted ductile displacement event.

Locality 13.3 Ribigill [NC 5618 5258] to [NC 5860 5455]

Ribigill (Figure 13.1). Lewisianoid basement gneisses of the Ribigill inlier, the metabasic Ben Hope Sill.

This locality comprises three short stops (each 15-30 minutes), all close to the road between Kinloch Broch and Tongue. Driving from south to north, first of all stop at 3A [NC 5618 5258] where parking is available for three to four cars at intervals along the road. Examine the crag exposures immediately east of the road. The lowest outcrops are of banded Moine psammite with locally well-preserved, inverted cross-bedding. The beds are deformed by mesoscopic, tight to isoclinal D_2 folds with a strong axialplanar S_2 fabric, as well as asymmetric, open D_3 folds. Both sets of folds plunge broadly parallel to L_2. The crags upslope expose planar banded gritty psammites; ductile strain is apparently higher as no sedimentary structures are preserved. Their contact with overlying platy, banded hornblendic gneisses of the Ribigill East basement inlier is concordant and interpreted as a tectonically modified unconformity on the inverted limb of a major D_2 fold (Holdsworth, 1989a). A ^{40}Ar/^{39}Ar age of *c.*416 Ma obtained from muscovite within the psammites is interpreted to date cooling through a closure temperature of *c.*350°C either during or after D_2 (Dallmeyer *et al*., 2001).

Return to the vehicles and drive northwards to [NC 5667 5334] where roadside parking is available for a minibus or four to five cars. Head westwards over the hillside for 150m or so to find west-facing slabs of foliated garnet amphibolite of the Ben Hope Sill at 3B [NC 5660 5338]. The amphibolites carry an intense S_2/L_2 fabric; thin, concordant quartzo-feldspathic layers and quartz veins are often boudinaged. The garnets are wrapped by the dominant schistosity and show well-developed pressure shadows that are elongate parallel to the lineation, indicating that they formed pre-D_2. Inclusion trails of S_1M that are highly oblique to S_2 are present occasionally. The evidence therefore indicates that garnet growth occurred post-D_1M and pre-D_2.

Return to the vehicles and drive northwards to park in the entrance to Ribigill Quarry [NC 5860 5455]. This quarry is in intermediate, banded hornblende-biotite gneisses of the Ribigill East basement inlier. At the back of the quarry at 3C, a unit of homogeneous, finely-banded gneiss is exposed. U-Pb SHRIMP dating of zircons from this unit sampled in the main face of the quarry indicates a late Archaean age of *c.*2850 Ma for the igneous protolith (Friend *et al*., 2008). Mm-cm scale concordant granitic veins may have formed during migmatization of the basement prior to intense reworking during the Knoydartian and Caledonian events. The dominant planar and linear fabrics within the gneisses are essentially parallel to the S_2/L_2 fabric in nearby Moine rocks. A 40Ar/39Ar age of *c.*433 Ma obtained from hornblende within the gneisses is interpreted to date cooling through a closure temperature of *c.*500°C either after or during D_2 (Dallmeyer *et al*., 2001). High in the quarry face, the gneisses are cut discordantly by pink granitic to syenitic veins that may have been intruded at the same time as the late-Caledonian Loch Loyal Syenite Complex some 5km to the south (Holdsworth *et al*., 1999).

Locality 13.4 Coldbackie Bay [NC 6124 6053]

Coldbackie Bay (Figure 13.5). D_2 deformation in the Moine Nappe; brittle deformation, faulting, possible New Red Sandstone (Permian) conglomerates and unconformity.

Extensive roadside parking space is available by the A836 at Coldbackie [NC 612 601]. Allow 1 hour for this locality. In the roadside cutting on the south side of the road, 4A (Figure 13.5), are well-developed mullion structures that are parallel to the hinges of prominent 'Z' geometry D_2 folds. These deform a well-defined, bedding-parallel D_1M planar fabric. Cross-bedding is well preserved in a fold hinge close to the road surface [NC 6102 6003] and indicates that these folds face southwest and lie in the normal limb of a major D_2 synform lying just to the southeast. Some 30m to the south and east of these exposures, psammites with gritty bands lie in the inverted limb of this fold as shown by cross-bedding [NC 6105 5997] and 'S' geometry minor D_2 folds.

Descend through the gate to the beach, 4B, to examine Moine psammites with tight-to-isoclinal D_2 folds and a strongly developed S_2/L_2 fabric. On the east side of the beach, numerous folded, lineated and boudinaged pegmatites and quartz veins were clearly deformed during D_2 (e.g. [NC 6124 6053]). A 40Ar/39Ar age of *c.*419 Ma obtained from muscovite within the psammites is interpreted to date cooling through a closure temperature of *c.*350°C either during or after D_2

(Dallmeyer *et al*., 2001). Undeformed red conglomerates and occasional sandstone layers unconformably overlie the Moine rocks on the beach. The sediments are thought to have been deposited in a series of alluvial fans and braided channels. Rounded to subrounded clasts within the conglomerates are mostly of Moine psammites, basement gneisses and late Caledonian syenite plutons and are therefore essentially locally derived (Blackbourn, 1981). The age of the conglomerates and sandstones is uncertain, with both Devonian (Old Red Sandstone) and Permian ages proposed (see Holdsworth *et al*., 2001a and references therein). However, recent studies suggest that strata of both ages may be present, with the NNW-SSE bounding fault, lower conglomerate and sandstone units (only exposed inland) being of Devonian age, and the upper, syenite-bearing conglomerates (seen at this locality) being of Permian age (Wilson *et al.,* 2010).

Locality 13.5 Sleteil & Skullomie Harbour [NC 6281 6283] to [NC 6180 6150]

Sleteil & Skullomie Harbour (Figure 13.5). D_2 infolds of Lewisianoid basement gneisses in unconformable contact with Moine psammites preserving sedimentary structures; late folds and associated brittle detachments.

At Strathtongue on the A836, turn north on the minor road to Skullomie; parking is available for three to four cars in the lay-by at the end of the road [NC 6191 6132]. Allow 2-3 hours for this locality. Walk north through a gate, pass a house on the right and over a footbridge. Follow the footpath through a gate, turn sharp right parallel to a fence and head NE past a ruined croft and up a steep hillside to Carn an Fheidh (Figure 13.5) [NC 6275 6285] where excellent examples of D_2 folds and sedimentary structures occur in the psammites. A further 700m north at 5A [NC 6281 6283] is a well exposed boundary with locally gritty, feldspathic Moine psammites underlying sheared hornblende, biotite and migmatitic feldspathic basement gneisses. This locality is 250m NE of a prominent coastal inlet and north of three large syenite erratics.

This boundary can be followed around the hinge of an east-plunging D_2 fold; less than 100m to the north [NC 6282 6291], Moine psammites contain poorly preserved cross-bedding younging away from hornblendic basement schists, thus the D_2 fold faces north. Follow the upper boundary of the basement towards 5B [NC 6282 6268] where the Moine psammites young away from the underlying basement schists. In this area, the psammites contain soft-sediment structures and pebbly horizons; crude finingupwards cycles and cross-bedding indicate the direction of younging and enables the disposition and facing of the D_2 folds to be determined even though up to 180 degrees of fold hinge curvature is developed about the ESE-plunging L_2 mineral lineation. Traverse some 200m SE to 5C that lies just within the inverted limb of a syncline (Figure 13.5). Around here, examples of D_2 'eye' structures and along-strike changes in fold plunge, sense of vergence and facing are well displayed, with hinge curvature occurring about a weakly developed, ESE-plunging L_2 mineral lineation. This inverted fold limb underlies basement schists exposed further to the east, with the fold closing to the north and facing SW (Figure 13.5).

The Sleteil basement body lies in the core of complex, en-echelon, anticlinal D_2 folds with curved hinges that appear to close and face both to the north and to the south, and to thus form 'tongue-shaped' sheath structures that originally faced and closed upwards to the WNW; D_2 folds with sheath-like geometry are present on all scales within this area (Figure 13.5) (Holdsworth, 1988; Alsop & Holdsworth, 1999). The boundary of the Sleteil inlier is believed to be a slightly modified Moine-basement unconformity (Holdsworth, 1989a).

Return to the vehicles, drive south for 500m and take a sharp turn right at [NC 6155 6086] to follow the track down to Skullomie Harbour. 5D [NC 6180 6150] is located along the low cliffs east of the harbour and best approached at low tide. Here the Moine psammites are deformed by a series of minor brittle-ductile folds that are related kinematically to a series of detachment faults that have both top-to-the-SSE and ESE senses of displacement. These structures are developed preferentially in belts of pre-existing D_2 strain in which the foliation is markedly flaggy with few folds developed. The generally eastward-dipping detachment faults lie either parallel to the foliation ('flats') or cross-cut at angles of up to 40° ('ramps'). Examples of ramp-flat geometries are well exposed in the cliffs behind the harbour. These structures are thought to have formed during extensional collapse of the thickened nappe pile at a late stage in the Caledonian orogeny (Holdsworth, 1989b; Holdsworth *et al*., 1999, 2007).

Locality 13.6 Loch Cormaic [NC 6234 5858] to [NC 6291 5766]

Loch Cormaic (Figure 13.6). Complex D_2 and D_3folds, Loch Cormaic Metagabbro.

At Strathtongue on the A836, take the minor road to Dalcharn and park at the end of the track by a gate [NC 6222 5864]. There is space for two minibuses or four to five cars. Allocate 2-3 hours for this locality. Go through the gate and ascend the small knoll on the hillside to the SE. At 6A [NC 6234 5858], banded psammites with concordant quartzo-feldspathic segregations (the onset of melting?) are deformed by numerous complex D_2 folds. These display highly curvilinear axes, resulting in closed 'eye' structures and opposing vergence patterns. Most of the fold hinges plunge to the SE, parallel to a strong mineral and extension lineation (L_2). Coaxial, asymmetric D_3 folds (Figure 13.7) locally refold D_2 structures.

Descend and follow the track southeastwards to Loch Cormaic. Note the presence by the track just to the north of the loch [NC 6259 5841] of a tiny outlier of red conglomerate of uncertain age. If water levels allow, continue on the track on the east shore of the loch. At 6B [NC 6283 5803] by the lochside, banded psammites with some semi-pelite bands are deformed by a mesoscopic D_2 isoclinal fold pair with 'Z' geometry and a penetrative, axial-planar S_2 schistosity. Although a strong pre-D_2 fabric is commonly present, in places the strain is lower to reveal probable cross-bedding. Hillside exposures above the SE end of the loch (e.g. [NC 6288 5771]) contain examples of cross-bedding within psammites, here deformed by SE-plunging D_3folds.

Craggy exposures to the southeast are of the Loch Cormaic Metagabbro (a member of the Loch a' Mhoid Metagabbro Suite of Moorhouse & Moorhouse, 1979). It is worthwhile first of all examining the coarse, little-deformed metagabbro that is characteristic of the internal part of the body. At 6C [NC 6291 5766] coarse, randomly oriented hornblende and plagioclase grains define a relict ophitic texture. The boundaries between plagioclase and hornblende clusters are mantled by metamorphic garnet. This may indicate that the mafic domains, now amphibole aggregates, once represented igneous clinopyroxene. Relict layering on the dcm scale is indicated by the alternation of mafic-rich and mafic-poor bands. Near the eastern margin of the body [NC 6292 5758] the metagabbro is noticeably leucocratic and garnetiferous. The igneous and meta-igneous fabrics are commonly reworked within shear zones defined by anastomosing, often curviplanar bands of hornblende and/or actinolite schist. These shear zones typically carry a strong mineral and extension lineation that plunges to the SE, parallel to L_2 in the host Moine rocks. A top-to-the-northwest sense of shear parallel to this lineation can be deduced from the sense of fabric curvature on the margins of some of the southeasterly-dipping shear zones. The margins of the metagabbro body are invariably highly strained, and the intrusion seems likely to have acted in a highly competent manner with respect to its metasedimentary host during deformation. The contact with the adjacent Moine psammites is nowhere exposed, but its location can be narrowed down to within 5-6m.

The field relations are consistent with a pre-D_2 age of intrusion for the metagabbro and it therefore forms an important marker in the regional deformation chronology. U-Pb SHRIMP dating of zircons from a leucocratic part of the Loch Cormaic metagabbro has yielded a late Neoproterozoic age that is interpreted to date intrusion and crystallization of the igneous protolith (Strachan & Kinny, unpublished data). In a regional context, the Loch Cormaic body, and by implication other members of the Loch a' Mhoid Suite, were probably intruded during the period of late Neoproterozoic rifting that resulted in the break-up of Rodinia and formation of the Iapetus Ocean (Kinny *et al*., 2003a).

Locality 13.7 Borgie peat cuts [NC 6380 5770]

Borgie peat cuts (Figure 13.6). Relict garnet-pyroxene gneisses within the Borgie basement inlier.

One kilometre east of Strathtongue on the A836, turn south onto an untarred track at [NC 6320 5912]. There is parking for three to four cars at the end of the track. Allocate 1½ hours for this locality. Walk south-eastwards across the moor to reach the low-lying outcrops around 7A [NC 6380 5770]. These expose gneisses of the Borgie basement inlier. Lenses of mafic gneiss, up to several hundred metres long, contain largely unretrogressed metamorphic assemblages dominated by garnet and clinopyroxene, indicative of at least upper amphibolite facies conditions. These are cut by narrow shear zones defined by hornblende schist, and at their margins pass imperceptibly into host hornblende gneisses typical of large tracts of the Borgie inlier. These carry an east- to SE-dipping foliation and a SE-plunging mineral and extension lineation that is parallel to, and correlated with, L_2 in the Moine. Similar relict garnet-pyroxene mineral assemblages are preserved within the Naver basement inlier in Central Sutherland (Locality 10.6, Excursion 10), and they have been compared with the Scourian granulites of the Caledonian foreland (Moorhouse, 1976). However, in the absence of isotopic data, at the time of writing nothing precludes a significantly younger age.

Return to the cars and pay a brief visit (10-15 minutes) to the small quarry adjacent to the A836 at 7B [NC 6413 5958]. This exposes typical banded hornblendic gneisses of the Borgie inlier, intruded by a mafic sheet, now converted to hornblende schist. This has been correlated with the Scourie Dyke Suite of the Caledonian foreland (Moorhouse *et al*., 1988), but given its state of deformation it could equally be a member of the Ben Hope amphibolite suite or a highly sheared member of the Loch a' Mhoid Metagabbro Suite. U-Pb SHRIMP dating of zircons from a gneiss sampled in the southeast corner of the quarry indicates a late Archaean age of *c.*2850 Ma for the igneous protolith (Friend *et al*., 2008). The strong fabric within the orthogneisses is at least partly Caledonian in age, as it carries a mineral and extension lineation that is parallel to the regional L_2 lineation within the Moine rocks. A 40Ar/39Ar age of *c.*421 Ma obtained from hornblende within the gneisses here is interpreted to date cooling through a closure temperature of *c.*500°C either during or following D_2 (Dallmeyer *et al*., 2001).

Locality 13.8 Torrisdale Bay [NC 6875 6089] to [NC 6896 6169]

Torrisdale Bay (Figure 13.8). The ductile Naver Thrust separating Moine Nappe psammites from high-grade meta-basic rocks and migmatitic gneisses of the Naver Nappe with Lewisianoid basement gneisses along the thrust; Caledonian granitic bodies emplaced during thrusting; development of the Torrisdale Steep Belt.

Turn off the A836 just west of Borgie Bridge [NC 6675 5872], drive northwards for nearly 3km and park by the roadside at [NC 6807 6111]. There is sufficient space for a coach; allow 3 hours for this locality. Walk down to the river, across the bridge, follow the path towards the raised beach over a second bridge, and then climb up the gorse-covered bluff in a gully with a small stream to emerge on a large flat grassy area by a wall. Head ESE to the lowest outcrops on the west-facing slope.

At 8A [NC 6875 6089] platy, high strain psammites of the Moine Nappe contain concordant, thin quartz veins and are deformed by asymmetric, minor D_2 isoclinal folds. These psammites lie in the immediate footwall to the Naver Thrust that occurs in unexposed ground along the line of the next gully uphill. The foliation dips rather more steeply eastwards than is the case at most of the localities thus far, and it carries a mineral and extension lineation that plunges gently to moderately to the SSE. The trend of the lineation does not correspond to the direction of tectonic transport during ductile thrusting. Instead, the steepening, composite fabric and associated low-angle lineation are associated with development of the Torrisdale Steep Belt (D_4) that reworks all pre-existing structures, including major ductile thrusts (Burns, 1994; Holdsworth *et al*., 2001a). Cross the gully containing the Naver Thrust and traverse southeastwards uphill into the next gully and then southeastwards across the next ridge to [NC 6884 6081] to view west-facing exposures of hornblendic basement gneisses that are interpreted to rest as an allochthonous sheet on the Naver Thrust. These gneisses display well-developed tight-to-isoclinal folds and 'eye' structures of probable D_2 age that are interpreted as cross-sections through the noses of sheath folds. The crags above these expose high strain, banded psammitic gneisses of the Naver Nappe, containing migmatitic layering and numerous deformed granitic and quartz veins. Gneissic layering is deformed by isoclinal D_2 and asymmetric D_3 folds. Walk downslope northwards, along the base of the slope, to the first outcrops by the sand dunes.

At 8B [NC 6874 6128] are banded, migmatitic psammitic gneisses of the Naver Nappe. Two generations of granitic rocks are apparent. A series of early, concordant, pink migmatitic leucosomes are attenuated and flattened parallel to the composite gneissic banding; the grey melanosomes that fringe melt layers are dominated by residual quartz. The migmatitic layering is cut by discordant pegmatitic veins of the Torrisdale Vein Complex (Holdsworth *et al*., 2001a). U-Pb SHRIMP dating of zircons from the early migmatitic phase sampled here yielded an age of 467 ± 10 Ma (Kinny *et al*., 1999). This is thought to date to mid-Ordovician (Grampian) high-grade metamorphism and migmatization of the Naver Nappe. An L_4 mineral and extension lineation plunges gently to moderately to the SSE.

Traverse northeastwards upslope across psammitic gneisses, including a prominent garnetiferous semi-pelite, across the (unexposed) Torrisdale Thrust and into an interbanded assemblage of strongly foliated amphibolites, hornblendic gneisses (locally with garnet) and augen granites – the Druim Chuibhe Orthogneiss Complex (Burns, 1994; (Figure 13.8)). Geochemical data indicates that these lithologies are not part of the pre-Moine basement, and they are thus viewed as most likely constituting a series of possibly contemporaneous intrusions that were emplaced into the Moine rocks of the Naver Nappe. At 8C [NC 6886 6159], the amphibolites contain brown-weathering ovoid cores, 1-2m across, that correspond to a relict, anhydrous garnet-pyroxene metamorphic assemblage from which a P-T estimate of 650-700°C and 11-12kb has been estimated (Friend *et al*., 2000). These cores are cut by dark, hornblendic rehydration veinlets, and the margins of the cores pass imperceptibly into the host foliated amphibolites. A few similar smaller cores that are more highly retrogressed can be found along strike to the south. These high-pressure granulite-facies rocks were formed on a very different P-T trajectory to that associated with thrust-related (Scandian) deformation and metamorphism. These unusual assemblages are interpreted to be a relic of burial during early crustal thickening, perhaps during the Grampian orogenic event (Friend *et al*., 2000). The composite gneissic fabrics are deformed by at least two sets of folds: an early set of attenuated isoclines, probably of D_2 age and later asymmetric D_3 structures. Granitic pegmatite sheets of the Torrisdale Vein Complex, ranging in thickness from a few cm to 3-4m, cross-cut the ductile planar fabrics; these sheets are commonly either folded or boudinaged during dextral shear associated with the development of the SSE-plunging L_4 lineation. Those that were apparently intruded clockwise of banding were folded, whilst those that were intruded anticlockwise of banding were boudinaged. A dextral sense of shear parallel to L_4 is apparent from asymmetrically sheared porphyroclasts and granite veins.

Traverse further upslope across extensive exposures that display a variety of intrusive relationships between the granites and host orthogneisses. The percentage of mafic material within the orthogneisses decreases; a common lithology present is a grey, rather homogenous gneiss with feldspar porphyroclasts, and interpreted as a strongly mylonitized granitoid. Refolding of D_2 isoclines and 'eye' structures by asymmetric D_3 folds is apparent at [NC 6896 6169]. The eastern boundary of the orthogneisses with interbanded Moine semi-pelitic and psammitic gneisses is diffuse and apparently intersheeted. Once the presence of Moine rocks is established, it is worthwhile pausing to view the prominent granite sheets of the Torrisdale Vein Complex seen in the cliffs on the northwest and east sides of Torrisdale Bay. These granites, as well as those encountered at outcrop at this locality, are all thought to correlate broadly with the Strath Vagastie Granite (see Locality 10.5, Excursion 10) and similarly to have been emplaced during Silurian (Scandian) displacement along the Naver Thrust. Hornblende and muscovite 40Ar/39Ar ages obtained from basement and Moine lithologies across the Torrisdale Bay section described here all fall within the range *c.*420-415 Ma, corresponding to the time of cooling through closure temperatures, most probably shortly after the formation of the Torrisdale Steep Belt and intrusion of the Torrisdale Vein Complex.

Locality 13.9 Creag Ruadh [NC 6970 6316]

Creag Ruadh (Figure 13.9). Strongly deformed Moine gneisses and amphibolites of the Naver Nappe within the Torrisdale Steep Belt.

If driving into Bettyhill from the west, turn left at the Post Office, and take the next turn left at a T-junction. At [NC 7025 6213] turn right and drive to the end of the track. Parking for a minibus or three to four cars is available at [NC 7005 6231]. Allow 1-1½ hours for this locality. Walk through a gate, follow the path and then walk northwestwards along the western side of the headland to reach the outcrops at [NC 6970 6316]. These are of psammitic gneisses with concordant bands of amphibolite and augen granite, intruded by numerous sheets and pods of pegmatitic granite. The composite foliation is steep and associated with a prominent L_4 lineation that plunges gently to the SSE – structures typical of the Torrisdale Steep Belt. The dextral kinematic indicators that are associated with L_4 elsewhere (e.g. Localities 13.8, 13.12) are not evident here, and the linear fabric is instead defined by rodding and mullion structures. On a steep, west-facing outcrop [NC 6971 6314], the gently curvilinear nose of a relict D_3isocline folds a NW-trending mineral and extension lineation, probably of L_2 age. *Please do not hammer these outcrops*. Cross a small gully to the northwest to see other another example of a NW-trending lineation (L_2 ?) folded by a tight, D_3fold that is itself wrapped by L_4 mullions [NC 6970 6317]. Walk out to the end of the headland and look back to the cliffs to the southeast to see prominent pink granite sheets, some folded, intruding complexly deformed gneisses. Similarly, the views to the northwest to Aird Torrisdale show large-scale intersheeting of Moine lithologies by steeply-dipping granite sheets.

Locality 13.10 Farr Bay [NC 7147 6265]

Farr Bay (Figure 13.9). Farr basement inlier; Moine gneisses and intrusive granites.

Abundant parking space is available on the grassy area adjacent to the Farr Bay Inn at Bettyhill [NC 7163 6223]. Allow 0.5-1 hour for this locality. Walk up the narrow track alongside the parking area, go through the first gate on the right and head through the sand dunes to Farr Bay. In the east corner of the beach [NC 7147 6265], close to the sand dunes, are banded hornblendic mafic gneisses of the Farr basement inlier that is thought to occupy the core of an early isoclinal fold within the Naver Nappe (Moorhouse, 1979; Moorhouse *et al*., 1988). U-Pb SHRIMP dating of zircons from the Farr inlier has yielded an Archaean age of *c.*2900 Ma that is interpreted to date crystallization of the igneous protolith (Friend *et al*., 2008). Gneissic layering is deformed by early 'eye' structures (D_2?) and later asymmetric folds (D_3?); the hinges of both sets of folds are broadly parallel to a gently-plunging L_4 lineation. Low-lying (and somewhat sand-dependent) outcrops a few metres to the NNW show hornblendic gneisses and slightly discordant intrusive amphibolites tightly interfolded by asymmetric folds (D_3?). Outcrops on the east side of the bay are of steeply-dipping, banded psammitic and semi-pelitic gneisses with numerous granite sheets in varying states of deformation from concordant and mylonitic to crosscutting and essentially undeformed. At least two sets of folds can be identified: early isoclinal folds (D_2?) and later asymmetric (D_3?) types.

Locality 13.11 Glaisgeo [NC 7146 6360]

Glaisgeo (Figure 13.9). Contemporaneous mafic and acid magmas deformed and metamorphosed within the Torrisdale Steep Belt.

Turn off the A836 onto a minor road 2.5km east of Bettyhill; after 250m take the left-hand fork and follow the road for 1.5km. Parking for three to four cars is available at the end of the road by the houses at [NC 7147 6265] (please ask permission). Allocate 1 hour for this locality which is best viewed at low tide. Descend the steep, grassy slope and when on the beach walk east over the first rocky ridge to access a small stony beach. Aim for the notch in a second ridge of rock to the east; scramble over this notch into another stony beach. On the east side of this beach [NC 7146 6360] steeply-dipping psammitic gneisses are interbanded with slightly discordant sheets (10-30cm wide) of a foliated horn-blende-bearing granitoid characterized by distinctive K-feldspar augen. This zone represents the eastern margin of a complex intrusive suite. The augen are interpreted as relict igneous megacrysts that have been modified by metamorphic recrystallization and associated deformation. Numerous boulders on the beach provide excellent examples of this intrusive facies. At the back of the beach are hornblendic mafic gneisses, and flat surfaces on the west side of the beach expose mafic and ultramafic streaks and schlieren within felsic hornblende gneiss. These outcrops are interpreted as deformed mixed and/or mingled magmas. Traverse westwards towards the western margin of the intrusive complex, noting the large-scale alternation of augen granite and mafic sheets, some containing screens of metasediment. Late, discordant pink granite veins and sheets intrude the meta-igneous rocks throughout the section. The steep fabric within these meta-igneous rocks is parallel to the composite fabric within the D_4 Torrisdale Steep Belt, although the associated lineation is absent, perhaps as a result of the partitioning of strain into the host metasedimentary rocks (Burns, 1994). The field relations indicate that the igneous protoliths were intruded after regional migmatization of the host Moine gneisses but prior to formation of the Torrisdale Steep Belt.

These meta-igneous rocks were first described by Cheng (1942, 1943) who thought that they belonged to the pre-Moine basement. U-Pb SHRIMP dating of zircons from a sample of augen granite from this locality has yielded a Silurian crystallization age (Strachan & Kinny, unpublished data). The intrusive suite is thus probably a pre-to syn-tectonic member of the Caledonian 'Newer Granites'. Muscovite sampled from within Moine psammitic gneiss at Glaisgeo has yielded a 40Ar/39Ar age of *c.*419 Ma (Dallmeyer *et al*., 2001) and again most probably dates cooling after formation of the Torrisdale Steep Belt.

Also worthy of note at these outcrops are the NE–SW trending normal faults and calcite-filled fractures cutting these rocks. Minor structures associated with these faults are consistent with their development as a result of NW–SE extension during the Permian (Wilson *et al.*, 2010).

Locality 13.12 Swordly Bay [NC 7354 6355]

Swordly Bay (Figure 13.10). Swordly Lewisianoid basement inlier; Swordly Thrust and overlying migmatitic pelites reworked within the Torrisdale Steep Belt.

Turn off the A836 onto a minor road *c.*5km east of Bettyhill; after 300m take the left-hand fork and follow the road for 1.25km. Park with permission by the farm buildings at [NC 7356 6307] where there is sufficient space for a minibus or three to four cars. Allocate 1 hour for this locality. Walk northwards and turn to the right of a ruined building, passing through a gap in the stone wall and then head across the grass towards Swordly Bay. Cross the fence at a small stone stile and walk down to the beach [NC 7354 6355]. Exposures on the west side are of banded, mafic hornblende gneisses of the Swordly basement inlier that is thought to occupy the core of an early isoclinal fold within the Naver Nappe (Moorhouse, 1979; Moorhouse *et al*., 1988). It has not at the time of writing been dated isotopically, but its basement affinities have been confirmed by detailed chemical studies (Burns, 1994). The gneissic fabric is deformed by upright, open (D_4?) folds. If the tide and sand levels are low, the eastern contact of the basement with psammitic gneisses is exposed in the centre of the bay. Walk to the east side of the bay, across the unexposed Swordly Thrust, to see the Swordly Pelite, comprising northeast-dipping, pelitic gneisses and schists with numerous sheets and pods of granitic material. This lithology is interpreted as a strongly deformed and mylonitized migmatitic gneiss; the granitic rocks are thought to represent melt layers, consistent with the local presence of garnet and sillimanite, and the abundant muscovite is most likely of retrogressive origin. A strong L_4 lineation plunges gently to the SSE. Pervasive shear bands and asymmetrically sheared boudins of granitic material indicate a dextral sense of shear parallel to the lineation. On the west side of a rocky knoll at the top of the beach, a low strain zone preserves a NW-trending mineral lineation (L_2 ?) that is variably sheared into parallelism with L_4. This early lineation is interpreted to define the direction of tectonic transport along the D_2 Swordly Thrust prior to steepening within the Torrisdale Steep Belt. A 40Ar/39Ar muscovite age of *c.*423 Ma has been obtained from these mylonitic pelitic gneisses (Dallmeyer *et al*., 2001).

Locality 13.13 Kirtomy Bay [NC 7413 6408]

Kirtomy Bay (Figure 13.10). Moine gneisses within the Torrisdale Steep Belt and unconformably overlying Old Red Sandstone (Devonian) sedimentary rocks.

From the previous locality, drive back 1.25km to the fork in the road, turn sharp left and follow the road towards the small hamlet of Kirtomy. After 1km the road turns abruptly right; instead, carry on straight ahead on the grassy track and parking for a minibus or three to four cars is available at the end of the track [NC 7417 6401]. Allow ½-1 hour for this locality.

Do not take the path to the right down to the small jetty; instead walk to the west side of the headland and descend down the grassy path on a narrow ridge westwards onto a stony beach. On the west side at [NC 7411 6399] are low polished beach outcrops of steeply-dipping banded semi-pelitic gneisses within the Torrisdale Steep Belt showing numerous shear bands and asymmetrically deformed leucosomes and melt pods that demonstrate a dextral sense of shear parallel to a gently-plunging L_4 lineation. Walk back 100m or so to the east and climb over the bottom of the grassy ridge that you descended into the next small bay [NC 7413 6408] to view the cliffs at the back of the beach that comprise Old Red Sandstone boulder conglomerates with thin sandstone layers. Look across the small bay to the north to see the irregular Moine-Old Red Sandstone faulted landscape unconformity completely exposed where sheets of conglomerate drape steeply-dipping gneisses. Boulders within the conglomerate are mostly of Moine migmatitic gneisses of the Kirtomy migmatites (Burns, 1994) and pink granites typical of the late Caledonian 'Newer Granite' Suite. Their rounded appearance most likely indicates fluvial erosion and transportation prior to deposition.

Faults bounding the basin trend NNW–SSE and N-S (the former reactivating basement fabrics) with a system of minor ENE–WSW faults appearing to accommodate along-strike variation in throw. The sedimentary rocks are also cut by various late, brittle faults which are attributed to dextral reactivation of the basin-bounding faults, probably during the Permian (Wilson *et al*., 2010). Before leaving this locality, take a moment to look east across the bay to see the classic half-graben structure, with conglomerate units adjacent to the bounding fault grading into more blocky, moderately-dipping sandstone units outcropping across much of the bay, which then onlap basement exposures on the far hillside.

Locality 13.14 Cnoc Mor [NC 7567 6344]

Cnoc Mor (Figure 13.10). Moine migmatites.

Turn off the A836 *c.*400m east of the minor road to Kirtomy, onto a small tarred track that leads up to the radio and mobile telephone masts on Cnoc Mor. Park in a large space below the mast at [NC 7567 6344]. There is sufficient space for minibuses and cars. Allocate ½ hour for this locality. Walk up the road and examine the first outcrops on the east side. These are of banded migmatitic gneisses with substantial layers of anatectic melt (Figure 13.11). Some melt layers are concordant, whereas others are clearly discordant and have probably migrated locally from their source. Similar migmatitic gneisses along strike to the NNW at Kirtomy Point have yielded a U-Pb zircon (SHRIMP) age of 461 ± 13 Ma that is interpreted to date melting during the Grampian phase of the Caledonian orogeny (Kinny *et al*., 1999). Two sets of folds are present at the present locality: (a) early syn-migmatite folds (D_1N?) that are commonly disharmonic and cut by discordant melt layers; and (b) later asymmetric folds (D_4?) associated with the steep foliation and development of the major upright synform located a few hundred metres to the east. Note that the gently-plunging L_4 lineation and its associated dextral shear indicators are now absent. A U-Pb monazite age of 431 ± 10 Ma has been obtained from the migmatites near here, indicating substantial reheating during the Scandian phase of the Caledonian orogeny (Kinny *et al*., 1999). If weather permits, excellent views can be had from the top of the hill of the entire north coast of Sutherland, the south coast of the Orkney Islands, and various mountains inland.

Locality 13.15 Port Mor [NC 7735 6547]

Port Mor (Figure 13.12). The boundary between Moine migmatites and the rocks of the Strathy Complex.

If driving from the previous locality, continue east on the A836 to the right-hand bend around Crasbackie Hill [NC 7780 6388]. Stop here briefly to look south and view the escarpment of the Moine gneisses above the lower ground of the Strathy Complex to the east. The Strathy Complex is dominated by siliceous gneisses and amphibolites that may be volcanic in origin (Moorhouse & Moorhouse, 1983; Burns *et al*., 2004). The age of the complex is uncertain: limited isotopic evidence suggests a late Mesoproterozoic to early Neoproterozoic age, and thus it may represent local basement to the adjacent Moine migmatites (Burns *et al*., 2004). Turn off the A836 onto the minor road signposted to Armadale. Follow the minor road and continue until the road splits into three at the bus shelter [NC 7861 6466]; coaches should go no further. Smaller vehicles take the left-hand road for 250m and parking is available for a minibus or three to four cars by the house at [NC 7845 6483]. Allow 2 hours for this locality. Take the track signposted to Poulouriscaig westwards across the moor and then follow a narrow valley northwards to reach Port Mor, 15A [NC 7735 6547]. It is best to stay in the valley beside the stream and not to attempt to climb the cliffs on the east side. On the east side of the bay are steeply dipping siliceous gneisses and amphibolites of the Strathy Complex, cut by numerous sheets of discordant granite and pegmatite. At least two sets of folds are present: a tight D_4 fold pair verges east just above high water mark, and later gentle folds with flat-lying to gently inclined axial planes are visible higher in the cliff. The westernmost outcrops before the stream are of a calcite-scapolite-diopside-orange spinel-bearing marble (Harrison & Moorhouse, 1976; Moorhouse & Moorhouse, 1983) that is unlike any Moine lithology in the area. The yellowish-orange marble is interlayered with green calc-silicate bands characterized by abundant diopside with scapolite and plagioclase. A sub-vertical brittle fault located along the western margin of the marble is inferred to separate the Strathy Complex from steeply-dipping and strongly deformed Moine pelitic and psammitic gneisses to the west. These gneisses do not carry any penetrative lineations and the high strains appear to be simply related to flattening: there is no evidence that the two different rock units are separated by, for example, a ductile thrust. A 3-4m-wide vertical sheet of pink, unfoliated granite intrudes the Moine gneisses at the back of the bay. Look up to the steep cliffs on the west side of the bay to see pods of amphibolite within the Moine gneisses, engulfed by ramifying late granite sheets. Walk back up the gorge until it is safe to climb out on the east side. Walk east to Locality 13.15B which corresponds to exposures of bright green ultramafic amphibolite, forming grassy knolls at [NC 7784 6532] and [NC 7777 6545]. The rock comprises anthophyllite with relic clinopyroxene and the Cr-rich chemistry has been interpreted to indicate that they represent retrogressed pyroxenites (Moorhouse & Moorhouse, 1983).

Locality 13.16 Strathy road sections [NC 7992 6395] to [NC 8127 6487]

Strathy road sections (Figure 13.1), (Figure 13.12). Strathy Complex siliceous gneisses and amphibolites, fold structures and cross-cutting granitic intrusions.

This locality comprises three separate roadside exposures; about 20 minutes could be allocated to each. If driving from Armadale, take the A836 east and cross the Armadale Burn and, as the hill starts to rise, turn onto the south side of the road and park by a small turning at [NC 7992 6395]. Cross the road to the cutting at 16A that exposes amphibolites and siliceous gneisses of the Strathy Complex, here dipping moderately to the west and cut by late sheets of granitic material and pegmatite. Upright open D_4 folds verge east towards an antiform. Continue driving eastwards for *c.*800 km and park on the verge on the north side of the road opposite 16B at [NC 8078 6470]. *Care should be taken here – this straight stretch of road is dangerous for unwary pedestrians.* The road cutting shows extensive exposures of layered, siliceous gneisses of the Strathy Complex, mostly dipping east and folded by asymmetric D_4 folds that verge west. The gneisses and the folds are cross-cut by sheets of undeformed white pegmatitic granitoids and later, finer-grained pink granites. Drive a few hundred metres further on to park either on the verge opposite the next large roadside exposure that is 16C at [NC 8127 6487] or a few hundred metres further east in the designated parking area. The road cutting exposes gently undulating interbanded siliceous gneisses and amphibolites. These are intruded by younger metabasic sheets, seen as a series of en-echelon, folded boudins, and ramifying granite sheets that are essentially undeformed. At the east end of the cutting, U-Pb dating of zircons from one of these granite sheets has yielded a Silurian crystallization age (Kinny & Friend, unpublished data).

Locality 13.17 Strathy Point [NC 8282 6964] to [NC 8340 6680]

Strathy Point (Figure 13.12). Rock types and structures in the Strathy Complex.

Continue east along the A836 to the western parts of Strathy and turn north on the road to Strathy Point [NC 8296 6553]. Follow this road to Totegan, where the private road to the lighthouse begins, and park in the extensive car park by the sheep pens [NC 8270 6859]. Allocate two hours for this locality. Walk down the road to the lighthouse, noting various outcrops of siliceous gneiss and fold structures en route. Head for the east side of the lighthouse to 17A at [NC 8282 6964]. In an exposure below the wall, crossed by a drainpipe, a prominent boudin carries an interesting mineral assemblage (garnet-staurolite-sillimanite) and a steep gneissic fabric that is oriented approximately normal to the sub-horizontal enveloping S_1N fabric within the host siliceous gneisses. A second boudin immediately to the north is less accessible. The margins of the boudins are sheared and retrogressed. The mineral assemblage comprises quartz + plagioclase (An47-63) + garnet + staurolite + sillimanite + anthophyllite + brown and green biotite + spinel. The garnet porphyroblasts may show three growth phases, with sillimanite, staurolite and rutile inclusions found in the second phase (Burns, 1994). The idioblastic outlines of phase 2 garnet are marked by fibrolite, and a second phase of sillimanite may be found outside the third zone, intergrown with biotite. Staurolite is replaced by green spinel. It is clear that the boudins, and presumably also their host siliceous gneisses, have undergone a complex metamorphic history. Metamorphic conditions during the formation of the early mineral assemblage have been estimated by Burns (1994) at *c.*700°C and 6kb – substantially lower pressures than those deduced for regional Grampian migmatization in the Moine rocks west and east of the complex. Walk NE from the boudin down the slope onto the rocky headland where there are excellent exposures of interbanded siliceous gneisses and amphibolites cut by discordant granitoids and pegmatites. The dominant S_{1N} fabric dips mostly to the west and is associated with a strong, north-south trending L_{1N} lineation defined by aligned minerals as well as rods and mullions in places. Tight to open D_4 folds plunge gently to the north, more or less parallel to L_{1N}, but can occasionally be seen to fold the lineation.

Return to the vehicles and drive south along the road to the track running east at [NC 8294 6672]. Walk east, through the gate past the bungalow on the south side, then 150m along keep straight on past 'Caberfeidh', through two more gates, and follow the faint track southeast down the cliff to an old fishing slipway and 17B at [NC 8340 6680]. In the exposures behind the winch are flat-lying isoclinal D_1N folds refolded by upright, non-cylindrical, tight to open folds, of probable D_4 age. A L_{1N} lineation trends north-south, approximately parallel to the axes of the D_{1N} folds. Ramifying networks of coarse white pegmatite are cut by sheets of finer-grained, pink granite that occupy distinctive tension gashes in the cliffs to the south of the slipway.

Locality 13.18 Portskerra [NC 8740 6644]

Portskerra (Figure 13.1). Moine migmatitic gneisses; late Caledonian igneous intrusions; Devonian sedimentary rocks.

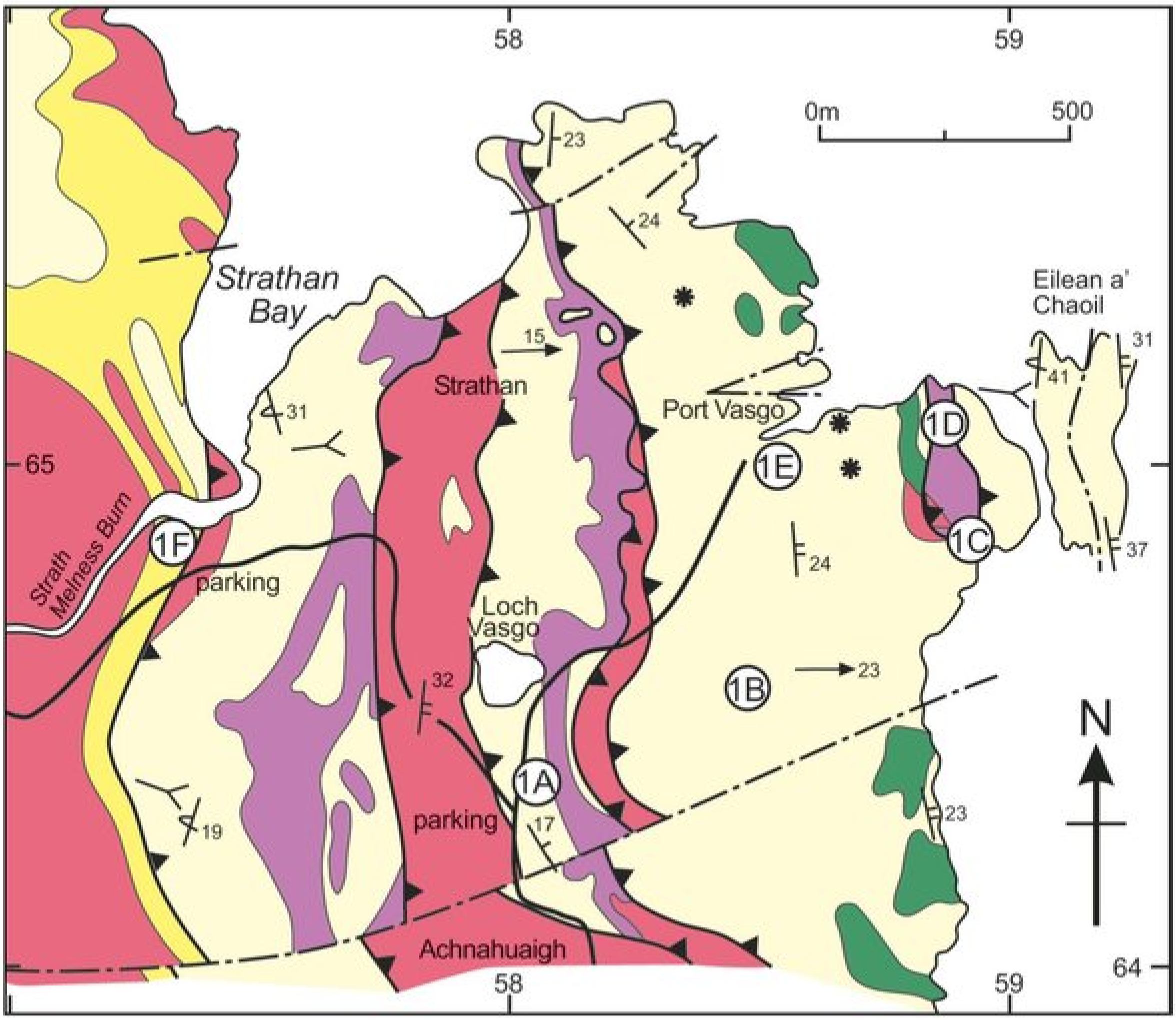
Drive east along the A836, turning left onto the minor road by the Melvich Hotel [NC 8767 6507]. Follow the road for 600m and take the left-hand fork. Continue for 850m around a bend and then park at [NC 8749 6620] or further east at the next bend in the road. Parking here is restricted to two minibuses or cars; coaches would have to park further south in Portskerra. Allocate 1½-2 hours for this locality. Low tide is useful but not essential. From the parking place walk 100m west, turn right at the end of the fence and follow a faint path beside the stream to a grassy flat above the beach. The two stones mark the graves of shipwrecked mariners. Climb down the grassy cliff into a stony cove. Devonian sandstones are exposed on both sides of the cove, resting unconformably on Moine gneisses. The unconformity surface is highly irregular and may be examined at 18A [NC 8755

6633]. The underlying Moine rocks are highly migmatized semi-pelitic gneisses showing several generations of melt layers deformed by complex, often disharmonic folds. These are interpreted to represent the same gneisses seen at Cnoc Mor and Port Mor, on the east side of the broad antiform cored by the Strathy Complex. The gneisses are cut by sheets of undeformed pink granite. Walk along the cliffs on the east side of the cove to emerge on the headland where there are extensive exposures. The semipelitic gneisses appear to pass transitionally eastwards into psammitic gneisses. At 18B [NC 8740 6644], migmatized psammitic gneisses with numerous concordant melt layers are highly veined and sheeted by late, pink granites that are thought to correlate with the *c.*425 Ma Strath Halladale Granite that intrudes Moine rocks 10km to the SE (Kocks *et al*., 2006). Some of the late granite sheets contain magmatic fabrics defined by aligned feldpars and micas. Walk east along the cliff line; keep above the next major cove, but look down into it to observe Devonian sandstones again resting unconformably upon Moine gneisses on the west side. Walk around the inlet and head northwards to the next headland. At 18C [NC 8768 6660], psammitic gneisses are intruded by a large, essentially undeformed diorite body which is itself cut by late granite sheets. The diorite is probably the same age as the Reay Diorite 8km to the east. Walk east a few tens of metres into the next bay to examine in detail exposures of the Moine/Devonian unconformity that preserves some 3-4m of relief. The sedimentary rocks are mostly fine to medium-grained sandstones with siltstones; pebble beds are thin and localized. This facies may be contrasted with those seen at Coldbackie and Kirtomy. If tide allows, continue around to the slipway at 18D [NC 8786 6629] (alternatively, return to the previous locality, scramble up the grassy cliff and walk around to the slipway). At the slipway, look west to view the Moine/Devonian unconformity and observe large-scale gentle variations in dip of the lowermost Devonian strata. Whether these variations represent original depositional angles or the effects of compaction and draping over an irregular Moine land surface is uncertain. The rocks at the end of the slipway are psammitic gneisses and late granites as seen before.

References

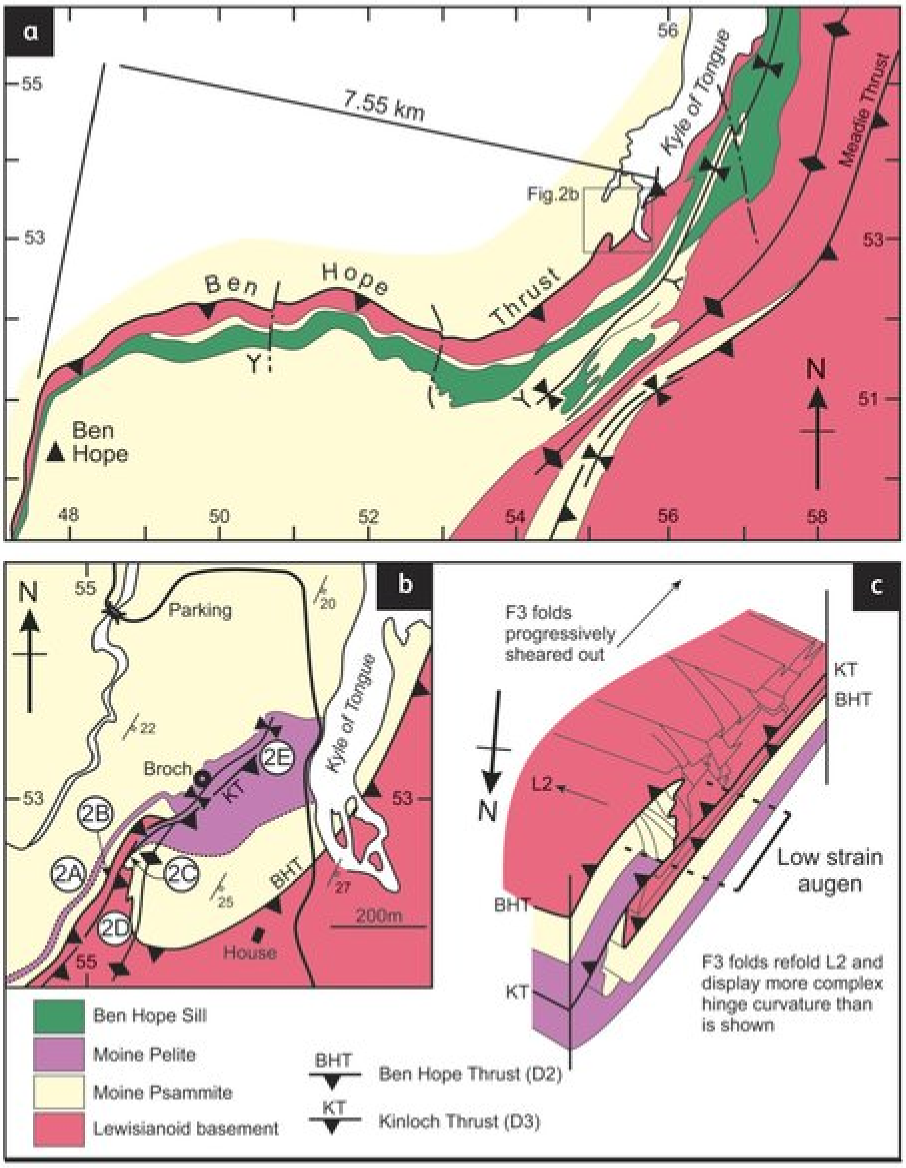
Table 1: Table of structural events		
	MOINE NAPPE	**NAVER NAPPE**
SCANDIAN (c.435-425 Ma)	Emplacement of the **Loch Loyal Syenite Complex**. **D_4** formation of the transpressive Torrisdale Steep Belt, as well as the major synform-antiform pair within the Kirtomy gneisses and the Strathy Complex. **D_3** tight-to-open, asymmetric recumbent folding. **D_2** NW-directed ductile thrusting (e.g. Swordly, Naver and Ben Hope thrusts) accompanied by widespread tight to isoclinal interfolding of Moine and Lewisianoid basement; recumbent folds commonly curvilinear about NNW- to NW-trending mineral and extension lineation.	
GRAMPIAN (c.470-460 Ma)	Not recorded.	D_{1N} upper amphibolite facies metamorphism and migmatization; minor tight development of S_{1N} foliation and N-S-trending L_{1N} mineral and extension lineation.
LATE NEOPROTEROZOIC	Intrusion of alkaline **Loch a' Mhoid Metagabbro Suite.**	Not recorded.
KNOYDARTIAN? c.820-800 Ma)	**D_{1M}** garnet-staurolite grade metamorphism, S_{1M} foliation,minor isoclinal folding.	Amphibolite facies metamorphism and fabric development inferred but not observed due to intensity of Grampian overprint.
EARLY NEOPROTEROZOIC (c.1000-870 Ma)	Deposition of Moine sediments in an extensional basin within the Rodinia supercontinent, accompanied by emplacement of mafic igneous intrusions such as the **Ben Hope Sill.**	

Summary of the Caledonian and pre-Caledonian history of the Moine rocks of the Northern Highlands of Scotland. Timing based on isotopic dates quoted in the text.

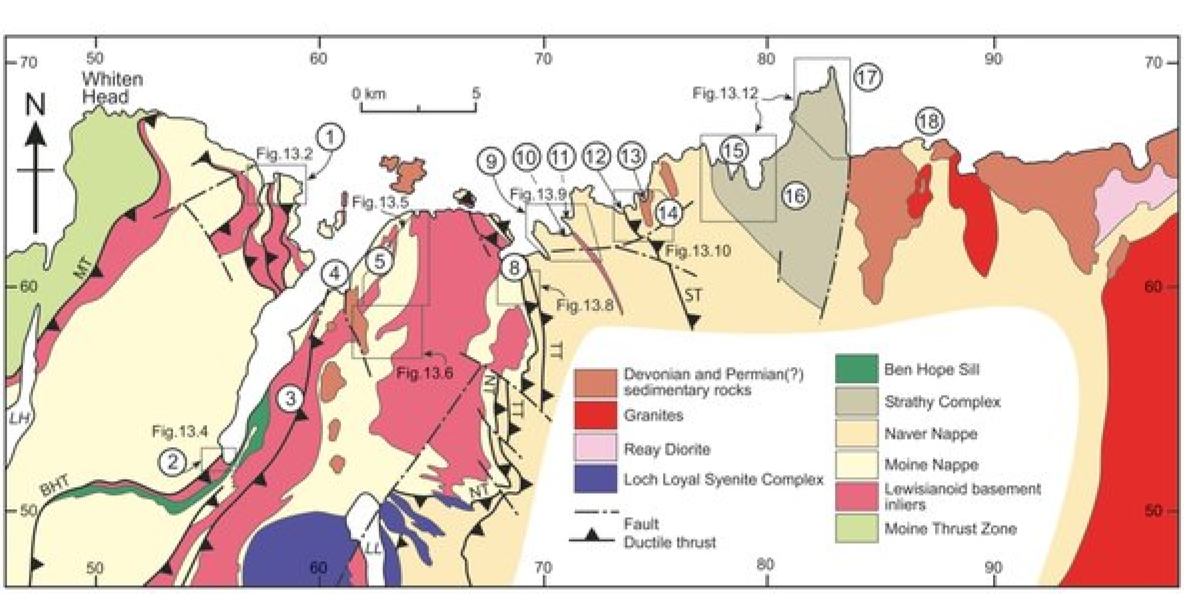


Geological map of Locality 13.1 (modified from British Geological Survey, 1997).

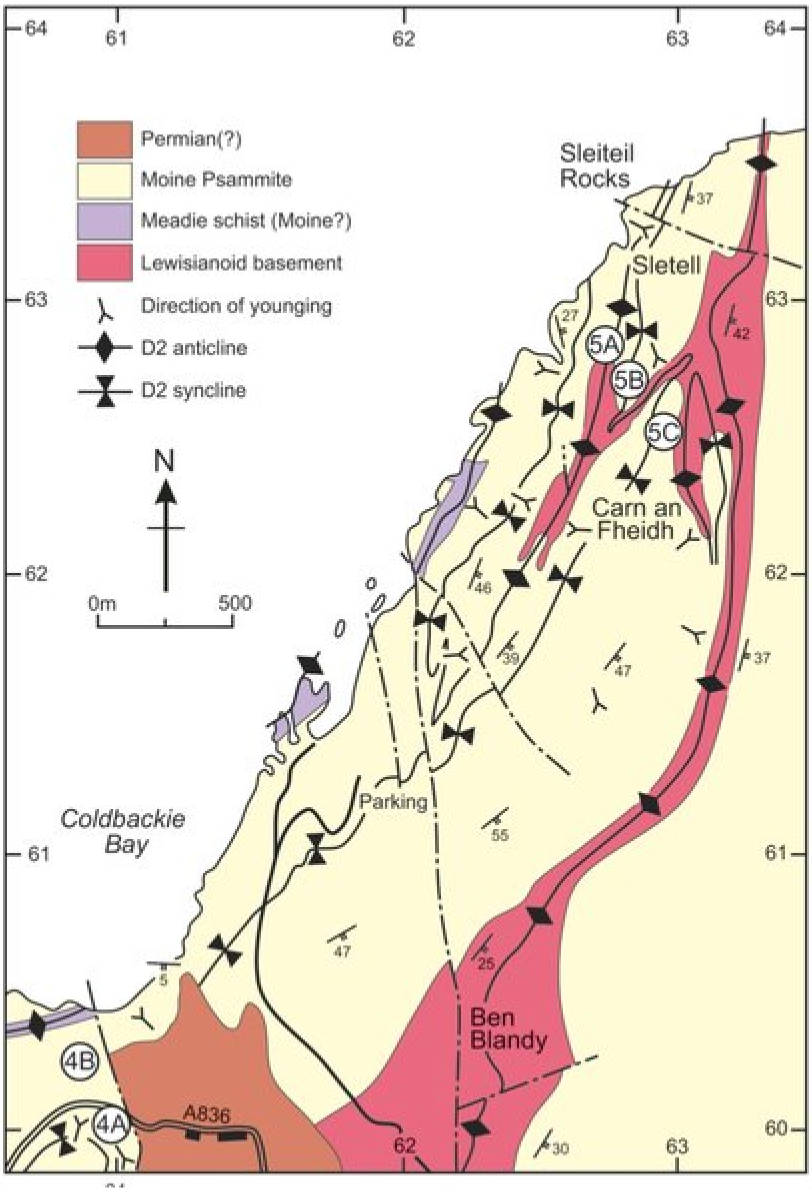
(left) 'Eye' structure developed within Moine psammites at Locality 13.1B. This structure is interpreted as a cross section through the nose of a D_2 sheath fold.



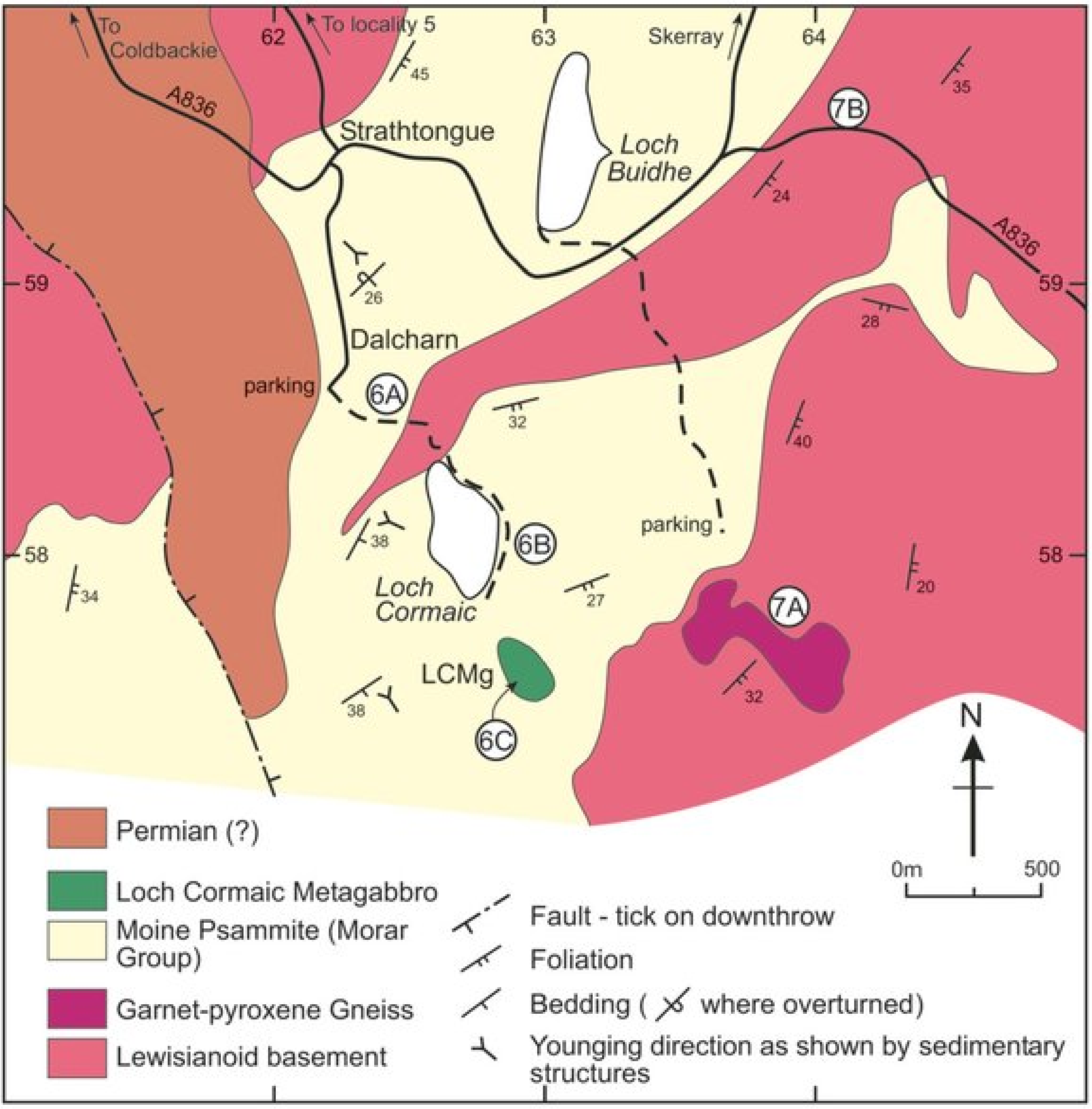
Locality 13.2. (a) the Ben Hope Thrust and basementcover relations in the Ben Hope to Kinloch area of the Moine Nappe; (b) detailed map of the Kinloch area; (c) interpretative sketch of D_3 structures in the Kinloch area (from Moorhouse et al., 1988).



Locality 13.2. A. The Ben Hope Thrust and basement-cover relations in the Ben Hope to Kinloch area of the Moine Nappe; B. detailed map of the Kinloch area; C.Interpretative sketch of D_3 structures in the Kinloch area (from Moorhouse et al., 1988).

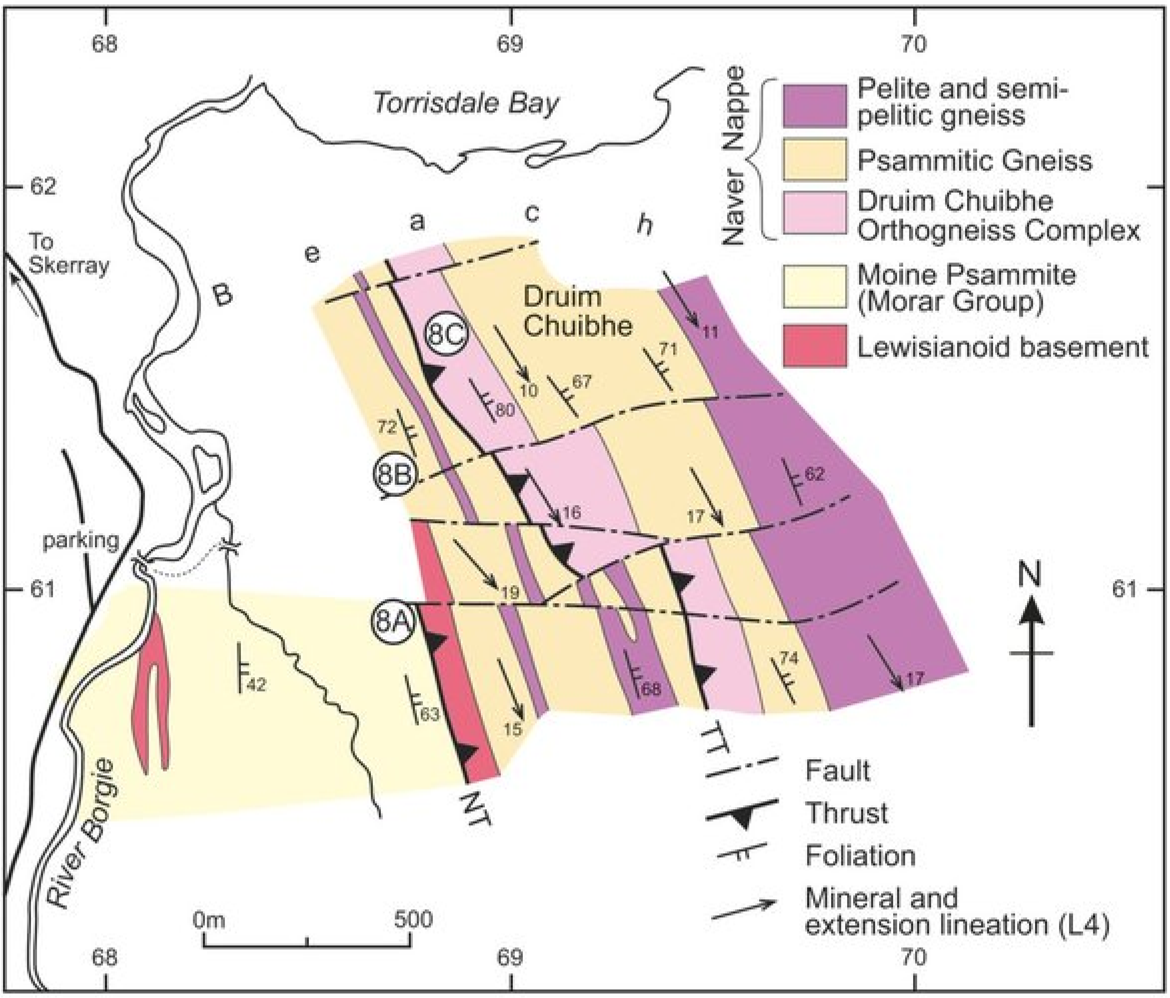


Localities 13.4 and 13.5: basement-cover relationships in the Coldbackie Bay and Sletell area of the Moine Nappe (from Moorhouse et al., 1988).

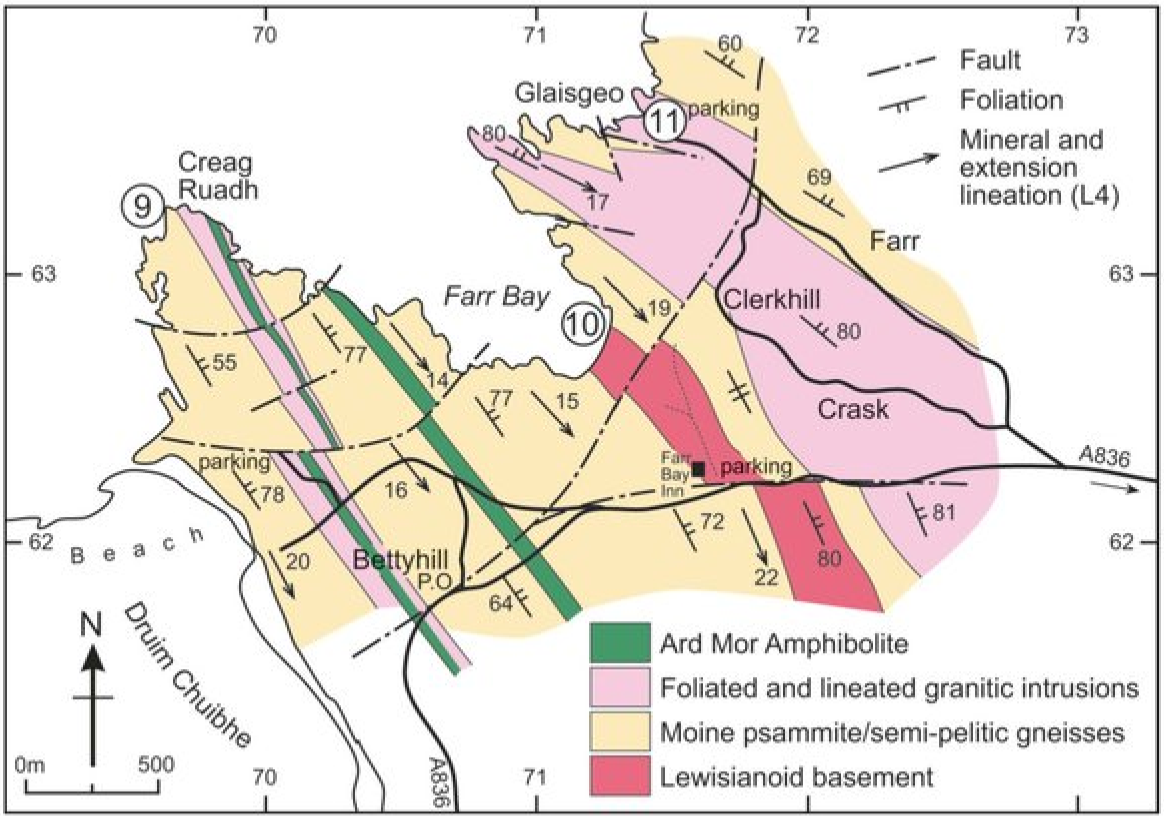


Geological map of Localities 13.6 and 13.7 (modified from British Geological Survey, 1997).

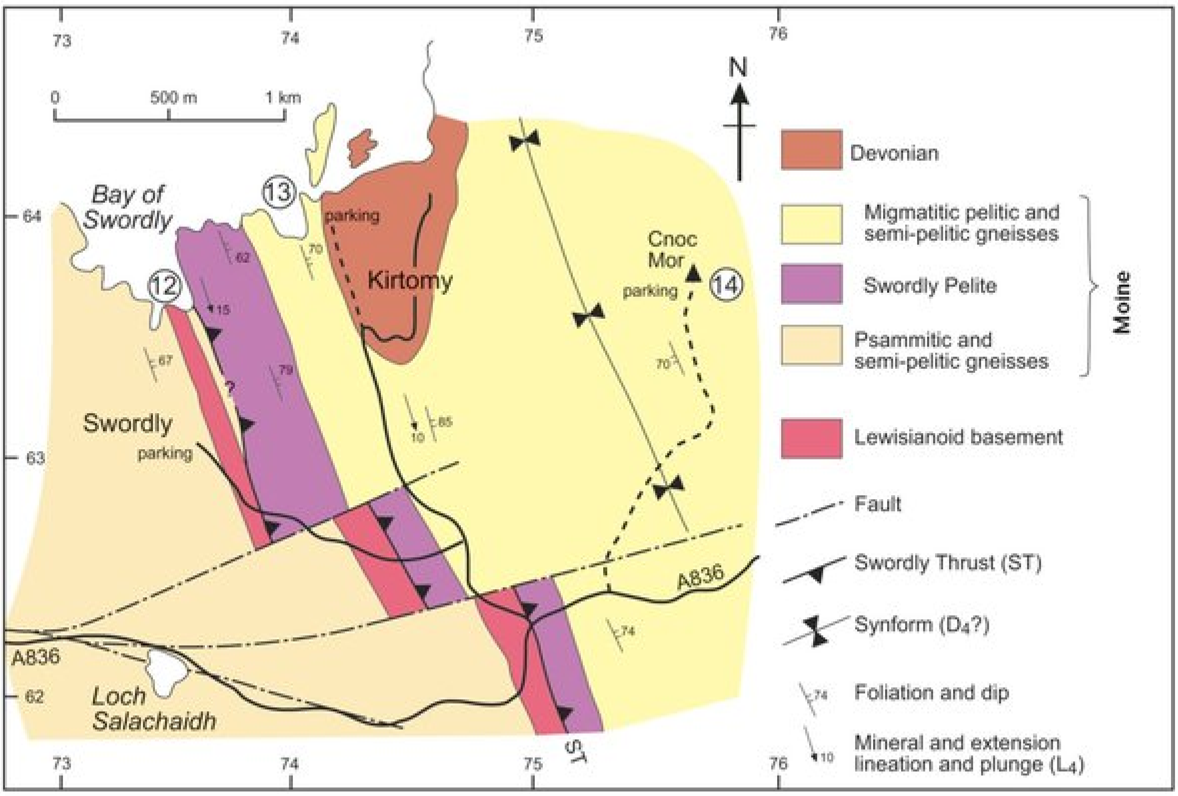
D_3 folds deforming interbanded psammite and garnetiferous semi-pelite at Locality 13.6A.



Geological map of Locality 13.8 (from Burns, 1994). Many granite sheets have been omitted for clarity. NT = Naver Thrust; TT = Torrisdale Thrust.

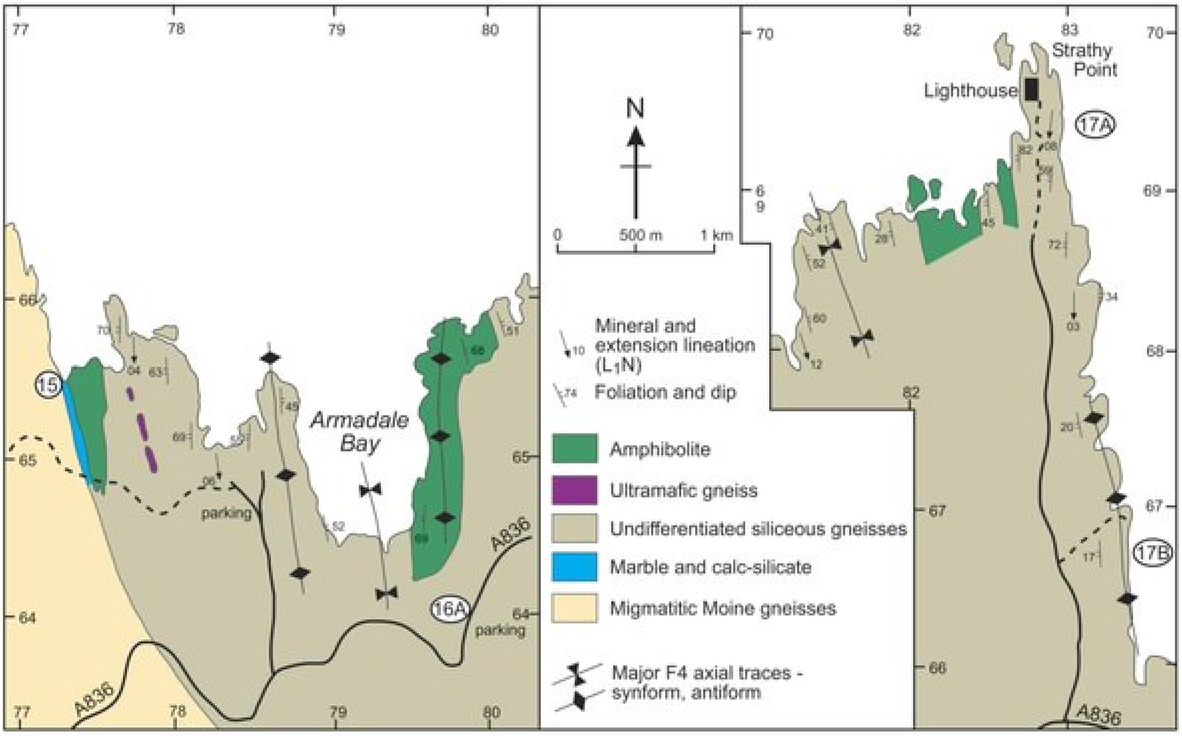


Geological map of Localities 13.9, 13.10 and 13.11 (from Burns, 1994).



Geological map of Localities 13.12, 13.13 and 13.14 (from Moorhouse et al., 1988 and Burns, 1994).

Migmatitic gneisses at Locality 13.14, showing extensive partial melting.



Simplified coastal geology of the Strathy Complex (from Moorhouse et al., 1988 and Burns, 1994) showing Localities 13.15, 13.16A and 13.17.