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# Revision of the solid geology shown on the 'Assynt District' special geological map. A report on the 2002 fieldwork

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# Revision of the solid geology shown on the 'Assynt District' special geological map. A report on the 2002 fieldwork

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*Key words*

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# Foreword

This report succinctly describes the main conclusions regarding the solid geology of the Assynt District based on fieldwork carried out for the Moine Thrust Project in the summer of 2002. The aim of the fieldwork was to revise, rather than resurvey, the solid geology of the Assynt Special Sheet (which includes parts of Sheets 107E, 108W, 101E, 102W). Reports concerning the survey of the drift, and the minor intrusions within the Assynt half-window, will be issued separately.

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# SUMMARY

The report provides an overview of the main findings from the first field season in the Assynt District of the Moine Thrust Project. Detailed mapping in the eastern part of the Assynt half-window has resulted in a new interpretation of the geometry and behaviour of the Ben More Thrust. This reinterpretation of the thrust satisfactorily resolves the conflicts between the various previous models. The remapping confirmed that the Ben More Thrust can be traced, as shown on the published 1923 Assynt District geological map, along the western flank of Na Tuadhan to Bealach a' Mhadhaidh. The Ben More Thrust is then traced to [NC 30026 24416] where it is displaced across a steep reverse fault to [NC 30514 23953]. It then continues NNW as a readily traceable feature placing gneisses of the Lewisian Gneiss Complex over quartzite along Leathaid Riabhach [NC 298 252]. Here the Ben More Thrust progressively steepens into a sub-vertical structure that has gneiss to the NE and quartzite to the SW. The thrust follows a prominent gully along Leathaid Riabhach to A' Chailleach. From here the Ben More Thrust more or less follows the top of a monoclinally folded quartzite that forms the summit of Beinn Uidhe and is exposed in the valley floor NW of A' Chailleach. It retains thrust geometry with hangingwall gneisses and footwall quartzites and becomes a steep feature that approximately follows 'Glen Beag' (the un-named glen south of the Stack of Glencoul). The Ben More Thrust meets, but does not displace the Glencoul Thrust at the head of Loch Glencoul. Therefore it is proposed that there is a branch line here where the two thrusts meet so that all the rocks NE of Loch Glencoul and east of Loch Beag are part of the Ben More Thrust Sheet. Figure 2.7 in the report provides a clear pictorial description of the geometry of the Ben More Thrust in the northern part of the Assynt half-window.

A significant new ductile structure has been identified within the Ben More Thrust Sheet, termed the Coire a' Mhadhaidh Detachment, that mostly follows the Lewisian gneisses/quartzite contact. It has been traced from the northern limits of the Loch Ailsh intrusion across Ben More Assynt, along the eastern slopes of Na Tuadhan, across Cailleach an t-Sniomha to the west of Gorm Loch Mòr and immediately west of the Stack of Glencoul into Glen Coul (Figure 2.1 in the report). The sense of shearing in the detachment is almost always top-to-west. Similar smaller shears have also been recognised within the Lewisian gneisses in the thrust sheet. However, no ductile shearing was noted at the gneiss/quartzite contact below the Ben More Thrust.

Several of the complex imbricate structures mapped by previous workers were revisited. The imbricates in the Loch an Eircill–Loch nan Caorach area appear to be simpler than shown on the published Assynt District map. An alternative solution is provided for the southern termination of the Glencoul Thrust south of Inchnadamph although it is noted that more detailed work needs to be done, notably south of Conival.

Brief descriptions are given of Moine rocks above the Moine Thrust in the north-eastern part of the Assynt District map. There appears to be a lateral facies change with semipelitic schists dominant in upper Glen Cassley and psammites becoming dominant to the north. Fabrics associated with several deformation phases have largely obliterated sedimentary structures although transposed bedding traces can be seen between a spaced foliation that controls the flaggy character of the psammites.

Widely spaced traverses across the major Lewisian outcrop areas, within the Assynt half-window as well as in the western foreland to the thrust belt, largely confirmed the work of the primary surveyors. Thus all of the Lewisian comprises orthogneisses, mostly hornblende-gneisses but with more felsic pyroxene-bearing gneisses in the north, that all contain ultramafic and mafic

pods and layers. The traces of the various Scourie dykes are correctly shown on the published Assynt District map. The Canisp Shear Zone has been traced eastwards, south of Canisp, eventually disappears under Cambrian quartzites. A second parallel shear has also been delineated north of Loch Assynt. The polyphase nature of ductile deformation in the Lewisian gneisses elucidated by previous workers is confirmed. However, the deformation state of the gneisses is extremely variable on all scales, with intense deformation confined to specific (shear) zones that vary in thickness from several centimetres up to hundreds of metres.

Descriptions of the numerous minor intrusions and the Quaternary deposits studied during the fieldwork are given in separate reports.

# 1 Introduction: aims and strategy of fieldwork

The Moine Thrust Project started in 2001. The long-term aim of the project is to publish modern and up-to-date geological maps of all the sheets that contain the Moine Thrust, all the way from Loch Eriboll to Skye. The two most northerly sheets (114 W Loch Eriboll and 114 E Tongue) have recently been revised by RE Holdsworth, RA Strachan and GI Alsop and co-workers, and therefore fall outside the mapping goals. It was decided to start the revision with the Assynt District Special Sheet, as this is the most widely known and popular (in terms of sales) geological map in the project area.

The original geological surveys, carried out in the 1880s, are of extremely high quality. Since that time much work has also been carried out by academic geologists, some of whom produced outstanding maps of specific areas. As a result the project has taken the view that a complete resurvey is not required. Instead, the new maps will be compiled from a variety of sources, with selected remapping in areas where problems are known to exist. For instance, from the discussions in Elliot and Johnson (1980) it is clear that the northern termination of the Ben More Thrust and the southern termination of the Glencoul Thrust are problematic. In other areas, the original survey seems at odds with what we know now in terms of folding and lateral ramps. Much work in the 1980s, carried out by Coward and co-workers (e.g. Coward and Kim, 1981; Coward, 1982; Coward, 1985a, b) focused on the western half of the Assynt half-window. In contrast, the eastern half of the half-window has not received so much attention and much effort has gone into the remapping of this area, which is on high ground and susceptible to times of poor visibility when cloud base is at or below 700 m, as proved to be often the case.

## 1.1 PREVIOUS WORK

The original survey was carried out in the late 19th century, with Sheets 101, 102, 107 and 108 published between 1892 and 1931. The compilation of the Assynt Special Sheet was published in 1923, whereas the results of the survey were published in the notable Memoir, 'The geological structure of the North-West Highlands of Scotland' (Peach et al., 1907). Subsequent academic work specific to the Assynt area includes Christie (1963) who carried out a detailed structural analysis of the Moine Thrust and its related minor folds and quartz fabrics. Elliot and Johnson (1980) published a reinterpretation on the sequence of thrusting, forwarding the idea of foreland-propagating thrusts. Subsequent work by Coward led to very detailed analysis of some of the imbricate-systems (e.g. Coward, 1985a, b). Some thrusts were reinterpreted by Coward (1982) as extensional faults as part of surge zones. The Assynt area, and specifically the Stack of Glencoul, has served as a natural laboratory for the study of the development of petrofabrics and microstructures. This work is not reviewed here, but Wilkinson et al.(1975), White et al. (1980), Law (1987) and Law et al. (1986) are good starting points on this type of work.

## 1.2 LITHOLOGY AND STRATIGRAPHY

No new lithostratigraphical terms have been introduced as a result of the fieldwork. The Lewisian gneisses that form the foreland to the Moine Thrust are now formally referred to as the Lewisian Gneiss Complex by BGS. No detailed work was undertaken on the Torridonian rocks, and insufficient work was done on the Moine strata to justify any changes to the local stratigraphical terminology. The preferred lithostratigraphical nomenclature for the Cambro-Ordovician succession of NW Scotland is given in Table 1. More details can be found in Peach et al. (1907), Swett (1969), McKie (1990) and Prigmore and Rushton (1999).

## 1.3 AREA COVERED DURING SUMMER 2002 SURVEY

A total of 24 days in early May 2002 was spent by Kathryn Goodenough, Elizabeth Pickett, Tom Bradwell and Maarten Krabbendam on work concerning the popular walking guide. In late May and July a total of 80 days was spent in the field by Kathryn Goodenough, Elizabeth Pickett, Tom Bradwell, Maarten Krabbendam, Roger Key, Sue Loughlin, Graham Leslie, working on both solid and drift surveying, of which about 10 days were lost through poor weather or recuperation. Table 2 lists the 1:25k sheets that were revised with regard to the solid geology; their location is shown in Figure 1.1. Figure 1.2 shows the areas that were resurveyed and an overview of the geology is shown in Figure 1.3.

| **Stratigraphy of the Cambro-Ordovician succession:** | | **Approx. thickness** | **Short description** |
|---|---|---|---|
| Durness Group | Durine Formation | Not exposed in Assynt | |
| | Croisaphuill Formation | | |
| | Balnakiel Formation | | |
| | Sailmhor Formation | 150 m | Dolomitic limestone with burrow mottling |
| | Eilean Dubh Formation | 60–200 m | Pale-grey dolomitic limestone |
| | Ghrudaidh Formation | 36–60 m | Dark-grey dolomitic limestone |
| An t-Sron Formation | Salterella Grit Member *(Serpulite Grit)* | 5–25 m | Coarse-grained quartz-arenite and feldspathic arenite, commonly with dissolution pits and Salterella fossils |
| | Fucoid Beds Member | 10–25 m | Brown-orange dolomitic mudstone, potash-rich |
| Eriboll Sandstone Formation | Pipe Rock Member | 80–100 m | White to pink quartz-arenite with abundant *Skolithos* borrows |
| | Basal Quartzite Member *(False Bedded Quartzite Member)* | 70–120 m | Quartz arenite with cross-bedding; pebble-rich base |

Table 1. Stratigraphy of the Cambro-Ordovician succession in the NW Highlands. Thickness estimates are from the General Vertical Section on the Assynt Special Sheet (1923), Swett (1969) Elliot and Johnson (1980) and McKie (1990). Alternative, not preferred names in italics and brackets.

| | **Part of sheet on 1:50k Assynt District Special Sheet** | **Solid** |
|---|---|---|
| NC 10 | ¼ sheet | Needs minor work |
| NC 11 | ½ sheet | Partially revised ready for clean copying |
| NC 12 | ½ sheet | Partially revised ready for clean copying |
| NC 13 | ¼ sheet | Partially revised ready for clean copying |
| NC 20 | ½ sheet | Needs more work |
| NC 21 | Whole | Needs more work |
| NC 22 | Whole | 90% revised; ready for clean copying |
| NC 23 | ½ sheet | Needs minor work |
| NC 30 | ¼ sheet | Needs minor work |
| NC 31 | ½ sheet | Partially revised; ready for clean copying |
| NC 32 | ½ sheet | Revised; ready for clean copying |
| NC 33 | ¼ sheet | Needs minor work |

Table 2. 1:25 000 sheets of Assynt Special Sheet surveyed during 2002 and/or ready to be clean copied (only for those parts appearing on Assynt Special Sheet).

# 2 Mapping in the Assynt half-window

## 2.1 COURSE OF BEN MORE THRUST

In the area between Sgonnan Mor [~NC 31 14] and Na Tuadhan [NC 305 215], the Ben More Thrust is a well defined thrust emplacing a thick thrust sheet containing Lewisian gneisses and lower parts of the Cambro-Ordovician sequence on top of the Glencoul Thrust Sheet and structurally lower rocks (mainly quartzite) south of Conival. The course of the Ben More Thrust here is not in dispute. To the north of Na Tuadhan, however, its course is less clear and several alternatives have been proposed, as summarised by Elliot and Johnson (1980, p.83), and shown in Figure 2.1. Peach and Horne (1914, fig. 3) have the Ben More Thrust turning east towards Gorm Loch Mor and then flattening out to disappear under the Moine Thrust just to the SSE of the Stack of Glencoul. However, near Gorm Loch Mor their fault emplaces Pipe Rock onto Lewisian gneisses and is therefore not a thrust. Clough (in Peach et al., 1907, p.506) and Bailey (1935) preferred to continue the Ben More Thrust in a NNW direction (without the easterly swing), presumably following the gully of Leathaid Riabhaidh (Figure 2.1). This steep fault was interpreted by Coward (1982) as an extensional fault at the back of the Glencoul 'Surge Zone'. Elliot and Johnson (1980) suggested that later extensional faults might have cut out the Ben More Thrust.

Our remapping (Figure 2.2) confirmed that the Ben More Thrust can be traced, as shown on the published Assynt District map, along the western flank of Na Tuadhan to the Bealach a' Mhadhaidh, where it emplaces Basal Quartzite over Pipe Rock. It is well exposed on the southern side of the bealach [NC 30107 23306] with a prominent anticline/syncline pair in the hangingwall with a common limb that is subvertical (i.e. similar to Na Tuadhan fold set further south). A complimentary footwall syncline is present in the coire floor below the bealach with steep westerly dipping quartzites and a slab of gneisses with subhorizontal foliations mapped in the immediate footwall of the Ben More Thrust (Figure 2.2). The Coire a' Mhadhaidh Detachment (see below) is also seen in the immediate hangingwall (see short stream section at [NC 30321 23549]).

The Ben More Thrust is then traced to [NC 30026 24416] where it is displaced across a steep reverse fault to [NC 30514 23953]. This reverse fault is one of a set trending c.125° (dip 70° to NE) that can be traced from A'Chailleach and Loch Bealach a Mhadhaidh to upper Glen Cassley where they clearly cut the Moine Thrust. One example of this set is well exposed in the stream section at [NC 36369 18738] where reverse slickenfibres can be found. The fault set throws down to the SW.

From the above point, the Ben More Thrust continues NNW as a readily traceable feature placing Lewisian over quartzite along Leathaid Riabhach [NC 298 252]. It is interesting that both AGL, coming from the SE, and MK, coming from the NW arrived at the same conclusion here. Along Leathaid Riabhach the Ben More Thrust becomes progressively steeper such that it appears as a subvertical structure that has gneiss on the NE side and quartzite on the SW side. The relationships of the Coire a' Mhadhaidh Detachment and Ben More Thrust in this region are dealt with in more detail below.

The trace of the Ben More Thrust follows a prominent gully feature along Leathaid Riabhaid all the way down to A' Chailleach. The hangingwall gneiss shows locally steeply dipping (subvertical) shear bands with top to SW shear sense. The quartzite in the footwall is not mylonitic but is folded with a fracture cleavage. Locally the folding is intense with several fold closures within some tens of metres. One tight syncline follows the gully for several hundreds metres. In this vertical configuration, the fault is neither a thrust nor an extensional feature: Coward (1982) interpreted this as an extensional fold on the back of the Glencoul 'Surge Zone'.

Where the Leathaid Riabhaidh ridge hits the valley floor [NC296 260], quartzite is exposed. The quartzite has a stratigraphic/unconformable boundary with Lewisian on its western side, dipping some 55° to the ENE. To the east is the subvertical faulted contact with the mass of Lewisian gneiss forming the upper Leathaid Riabhaich ridge. The eastern fault is interpreted as the continuation of the Ben More Thrust.

A quartzite occurrence in the valley floor NW of A' Chailleach [NC 286 267] forms a close syncline (Figure 2.3). To the NE, this syncline is cut by a steep fault that more or less follows 'Glen Beag' – the unnamed glen south of the Stack of Glencoul. The nearest quartzite to the NE is about 300 m higher, so that the fault along Glen Beag must have a significant displacement. To the SW the quartzite of the syncline is probably continuous with the flattish quartzite slab on top of Beinn Uidhe, linked by a large monocline, which includes some parasitic box folds (Figure 2.3).

The resurvey thus suggests the following (Figure 2.7):

- The subhorizontal slab of quartzite that forms the summit plateau of Beinn Uidhe forms the top of the Glencoul Thrust Sheet. This quartzite slab bends over to the NE in a large monocline (with parasitic box folds), with large quartzite exposures west of Leathad Riabhach, and is continuous with the quartzite syncline in the valley floor of Glen Beag.

- The Ben More Thrust more or less follows the top of this quartzite slab. In this way, it is always a thrust as it has Lewisian gneiss in its hangingwall and quartzite in its footwall. The Ben More Thrust also follows the monocline and becomes a steep or subvertical NW trending fault that approximately follows Glen Beag. There is a subvertical foliation in the gneisses exposed on the western side of Glen Beag that cuts gently dipping gneissosity (e.g. at [NC 28469 27615]). It is possible that the Ben More Thrust re-activates an older ductile shear in the gneisses, and that this shear influenced the location of the Ben More Thrust. Later faults (e.g. the A' Chailleach Fault) developed sub-parallel to the steepened Ben More Thrust.

- The subvertical tract of the Ben More Thrust that follows the Glen Beag has a significant displacement (at least 300 m in a vertical sense), as the 'Quartzite Syncline' shows. However, it does NOT displace the 'Glencoul Thrust' and the 'Sole Thrust' at the head of Loch Glencoul. The best explanation for this is that at the head of Loch Glencoul there is a branch line, where the Ben More Thrust and the Glencoul Thrust meet. This means that all the rocks to the NE of Loch Glencoul and east of Loch Beag belong to the Ben More Thrust Sheet. The Ben More Thrust Sheet thus contains a slab of Lewisian gneiss and quartzite with locally thin An t-Sron Formation and Durness Group. The quartzite is therefore continuous all the way from Loch Ailsh, via Fion Loch Beag, Gorm Loch Mor, Stack of Glencoul to Glendhu. Most of this tract is fairly flat lying except along Glen Beag, where it is steepened into a lateral ramp. This lateral ramp is caused by the subsequent uplift of the Glencoul Thrust developing underneath. The Glencoul Thrust *sensu stricto* thus terminates at Glen Beag, but may have reactivated some tract of the Ben More Thrust to the north of the branch line.

## 2.2 INTERNAL STRUCTURE OF THE BEN MORE THRUST SHEET

### 2.2.1 Coire a' Mhadhaidh Detachment

A significant detachment, termed here the Coire a' Mhadhaidh Detachment, has been recognised along the contact of Lewisian gneiss and quartzite *within* the Ben More Thrust Sheet (Figure 2.1, 2.4, 2.5). Previously, most of this contact was mapped as stratigraphic or unconformable. The relationships on the Coire a' Mhadhaidh and Ben More thrusts in this region are illustrated on three sections in Figure 2.5. Note the tendency for intense folding to be developed in both the hangingwall and footwall of both structures which might be interpreted as the thrusts cutting up section in the transport direction through earlier formed folds which are then tightened/disrupted as a consequence.

The contact between the Lewisian gneisses and the overlying quartzite within the Ben More Thrust Sheet is almost always a detachment surface, marked in many stream sections by one or more metres of highly sheared, now schistose Lewisian gneiss (Figure 2.6). The sheared contact is well exposed at [NC 34337 20343], [34050 20070], [NC 33779 20048] and [NC 32425 20601]. At the last locality the sheared Lewisian is about 10 m thick. The sense of shearing is almost always top-to-west on a moderately east-dipping shear plane; linear fabrics are typically slightly south of east, (i.e. top-to-c. 280°). Local variations are seen however, as at [NC 326 225] where top-to-south movement is clear. The overlying Cambrian quartzites are variably deformed at this contact and though occasionally schistose and strongly sheared, commonly appear to lack any penetrative deformation. Basal beds are commonly conglomeratic; pebbles are typically 10 mm across, occasionally up 50 mm, and are angular and subrounded with grain-to-grain contacts preserved. Pebbles generally appear undeformed, and are certainly not strongly stretched in the shear direction.

The rock platform SW of Loch Bealach a' Mhadaidh has quartzite resting on Lewisian. Around [NC 30369 22636] the Lewisian surface retains original (erosional?) irregularities on a scale of a few metres and is also folded along with the quartzites. To the west and SW the "Felsite" marked at [NC 304 224] is probably sheared gneiss; fragments of the original unconformity surface are preserved above the detachment.

This detachment, which is not linked to any thrust described as yet in the literature, can be traced from the northern limits of the Loch Ailsh intrusion, across Ben More Assynt, along the eastern slopes of Na Tuadhan, and across Cailleach an t-Sniomha, west of Gorm Loch Mòr (Figure 2.1). In most of this ground, Basal Quartzites are detached from Lewisian gneisses.

A similar sheared relationship between Torridonian strata and underlying Lewisian is exposed in Coire a' Mhadhaidh. For example, at [NC 30597 20427] there are 2 m of sheared Torridonian conglomerates overlying 1.5 m of schistose Lewisian gneisses. The sense of movement indicated by deformed pebbles in the Torridonian conglomerate suggests top-to-250º related to a horizontal schistosity.

From Gorm Loch Mòr to Loch nan Caorach, Pipe Rock rests directly on the detachment surface and Basal Quartzite is cut out, except to the south of Loch nan Caorach [NC 300 260] where a thin sliver of Basal Quartzite is preserved in the hinges of a west-verging fold pair. Just to the south of this point, Fucoid Beds occur very close to the detachment. North of the Stack of Glencoul the 'detachment' seems to revert to the basal quartzite/Lewisian contact (including sheared Lewisian?, marked as Felsite); but this area has not been revisited. There are also parallel 'detachments' confined in the Lewisian gneisses in the Ben More Thrust Sheet that are defined by thin (c.1 m) schistose bands seen in stream sections.

No ductile movement was seen along the Lewisian/quartzite contact below the Ben More Thrust in contrast to the ductile deformation seen along this contact in the Ben More Thrust Sheet.

Brittle deformation was noted along the contacts of the various Cambro-Ordovician formations under the Ben More Thrust.

### 2.2.2 Imbricates in the Loch an Eircill–Loch nan Caorach area [NC 29 27–NC 30 26]

The imbrication in this area appears to be rather simpler than was previously mapped. The position of the Moine Thrust is as shown on the Assynt District map, although mylonites appear to be rather thicker than they are indicated on this map. The Pipe Rock thrust sheet beneath the Moine Thrust also appears to be correctly shown on the map, and much of the quartzite in this thrust sheet is mylonitised. Beneath this thrust sheet are a series of imbricates in the Salterella Grit/Ghrudaidh limestone sequence that can be mapped out. The stratigraphical contacts within the imbricates appear to be approximately parallel to the thrusts, rather than perpendicular as shown on the published map. Below these imbricates is what appears to be a normal stratigraphic sequence, although the over-thickening of the Fucoid Beds and the Salterella Grit is probably due to folding, and NW–SE fold axes have been recognised in the better exposed ground to the south. The 'thrust' mapped by the original surveyors on the east side of Loch nan Caorach is near vertical and was thought in the field to be a normal fault. However, it is more likely to be the steep continuation of the Coire a' Mhadaidh Detachment.

### 2.2.3 Cnoc Chaornaidh [NC 30 08]

There is a mapped series of imbricates involving the Cambro-Ordovician strata around Cnoc Chaornaidh, just south of Loch Ailsh. The ground west of the summit of Cnoc Chaornaidh is much as mapped by Christie (1963) on the small scale, but not in terms of large-scale structures. The trace of the Moine Thrust shown on the published map appears to be correct with an underlying zone of quartzite mylonite. A sheared igneous intrusion repeated in the Durness limestone/Salterella Grit imbricates west of the Moine Thrust may be a member of the 'nordmarkite' suite. Further west, around [NC 298084] the Fucoid Beds/Salterella Grit/Ghrudaidh limestone succession is intruded by thick red, microgranitic sills (members of the 'grorudite' suite?) and this succession is imbricated, much as shown by Christie (1963) with some minor variations in detail. A similar succession is seen in crags along the track to the northeast around [NC 306092]. Christie drew the Ben More Thrust dividing these two latter areas, which seems highly unlikely in view of their similar rock sequences, especially the unusually thick micrograntic sills. The Ben More Thrust probably follows its trace shown on the published Assynt District map. However, there is clearly a structure running north–south across the Cnoc Chaornaidh imbricates where Christie (1963) drew his Ben More Thrust (an unexposed gully across which contacts are clearly cut off), but this is much more likely to be a steep fault. Whether or not this fault cuts the Moine/Ben More Thrusts is uncertain owing to no exposure.

The similarity between the Loch nan Caorach and the Cnoc Chaornaidh imbricates is worthy of note. In both cases the Moine Thrust is underlain by a thin thrust sheet carrying mylonitised Pipe Rock, which is in turn underlain by imbricates in the Salterella Grit/Durness limestone sequence. If the dynamics of the Ben More Thrust discussed in Section 2.1 are correct, than there appears to be some north–south symmetry in the Ben More Thrust Sheet.

### 2.2.4 Glencoul [NC 29 28]

The Stack of Glencoul has not been mapped in detail as there has been a great deal of published and unpublished academic work specific to this small area (Butler, pers. comm.). In the valley floor of Glencoul there is no evidence of the isolated occurrence of Lewisian gneisses shown on the published Assynt District map. The gneisses exposed in this area can probably be explained by displacement along a steep fault parallel to Glencoul. The Moine Thrust is well exposed in the Glencoul River. Here mylonitic quartzites locally *overlie* Moine-derived mylonite to indicate the presence of large-scale in-folding. This is an excellent locality to examine mylonite–fold relationships and should be included in the Assynt Excursion Guide. Imbricates below the Glencoul Thrust (or the Ben More Thrust – see section 2.1) at the head of Loch Glencoul are locally vertical, as shown on the existing map. Nevertheless, the map face in this area can be greatly simplified.

## 2.3 THE SOUTHERN TERMINATION OF THE GLENCOUL THRUST [NC 26 22-NC 28 21]

The Glencoul Thrust is an unambiguous structure north of Inchnadamph, where it emplaces quartzite over limestone. The southern termination of the Glencoul Thrust, however, remains problematic (see Elliot and Johnson, 1980). The following solutions have been proposed:

1. Peach et al. (1907) traced it via the Allt Poll an Droighinn to the thrust below (west and south of) Beinn an Fhurain. This thrust is now often referred to as the Ben Uidhe Thrust.
2. Bailey (1935) could not find the critical bits of Fucoid Beds in the Allt Poll an Droighinn at [NC 2693 2237] (point A on Figure 2.1). He also pointed out that the Droighinn antiform folds ground on either side of the Allt Poll an Droighinn, and that Peach and Horne's Glencoul Thrust would cut across this fold without displacing it. Bailey (1935) suggested that the Glencoul Thrust dies out near where it crosses the Allt Poll an Droighinn (point A). He envisaged a separate thrust, the Beinn Uidhe Thrust, to run from below Beinn an Fhurain all the way to the col between Glas Bheinn and Beinn Uidhe.
3. Elliot and Johnson (1980) doubted whether the thrust on Beinn Uidhe can be traced all the way to Beinn Fhurain. They also suggested that the Traligill and Beinn Uidhe Thrust are the same structure, being folded over by the Droighinn antiform.
4. Coward (1982) suggested that the Beinn Uidhe Thrust below Beinn an Fhurain is the same structure as the Glencoul Thrust and was faulted downward by the Allt Poll an Droighinn Fault.

Our resurvey did not entirely solve the problem but the following constraints were found:

- There *are* two small occurrences Fucoid Beds in the Allt Poll an Droighinn at Point A, but they are not in situ. Is it possible that this occurrence is related to the Allt Poll an Droighinn Fault?
- The Allt Poll an Droighinn Fault at Point C is a subvertical structure, against which close NNW–SSE trending folds in quartzite to the NW side are truncated.
- At point B, the Glencoul Thrust is truncated by the Allt Poll an Droighinn Fault. Although the map face suggests that the structure could be continuous (with quartzite to the east and limestone to the west) this is impossible, because the Glencoul Thrust to the north is east dipping, so that quartzite is structurally *above* the limestone (and the Glencoul Thrust is a real thrust) thrust, whereas to the SE of Point B the quartzite is *below* the limestone and dipping to the SW along a normal stratigraphical contact. Overall this gives the effect of a pair of scissors.
- The Droighinn antiform to the SE is a fairly tight structure, with a very steep SW limb. On Cnoc an Droighinn to the NW it appears to be a more open structure with several smaller folds of lesser amplitude.

A possible solution maybe that the Glencoul Thrust (truncated at point B), the Beinn Uidhe Thrust (reappearing at Point D) and the Traligill Thrust (with associated imbricates) are one and the same structure. This thrust was folded by later underlying imbricates which would have a lateral ramp parallel to (i.e. underneath) the Allt Poll an Droighinn Fault. This would explain differential uplift of the segments on either side of this fault, with different amplitudes of the

Droighinn antiform. It would imply, however, a WSW-directed movement along these buried imbricates. The thrusts in the area of Bheinn Uidhe and Glas Bheinn would then be subsidiary thrusts within the Glencoul Thrust Sheet (see also below). More work is necessary: targets should be the quartzite–gneiss contact north of Cnoc an Droighinn, and the area where the Traligill, Beinn Uidhe and Ben More thrusts meet (south of Conival). The geology of the latter area is incorrectly shown on the published map, but is correct on the clean copies (see Section 5).

## 2.4 VARIOUS AREAS WITHIN THE GLENCOUL AND SOLE THRUST SHEETS

### 2.4.1 Glas Bheinn area

- Imbricates just east of the A894 [NC 23 27] can be reliably mapped into an area formerly mapped as peat.
- Northern slopes of Glas Bheinn: the Lewisian–quartzite contact is a floor thrust to a series of imbricates of Basal Quartzite and Pipe Rock that can be seen in the corries north of Glas Bheinn and that can be traced through the blockfields on top of the Glas Bheinn plateau. This suggests that there is an in situ blockfields at ~700m above mean sea level). Further to the east (e.g. on the northern slopes of Beinn Uidhe) the Basal Quartzite–Lewisian contact is generally undisturbed, but must be sheared (as indicated on the six-inch maps of the primary survey) to take up the displacement caused by the aforementioned imbricates.
- At Coire Dearg there is a west-dipping fault in the Basal Quartzite (with an anticline–syncline pair in its hangingwall) that is either a backthrust or an extensional fault. A back thrust interpretation is more likely given the strong folding in the hangingwall. (See Figure 2.8).
- Looking south from [NC 28107 26408] it is possible to see a steeply dipping fault in the northern cliff face of Beinn Uidhe with a downthrow to the east of over 10 m that displaces the gneiss–quartzite contact. The quartzites immediately east of the fault define an asymmetrical syncline with a steep western limb against a gneiss buttress on the western side of the fault. Away from the fault the eastern limb of the fold is defined by gently undulating subhorizontal quartzite beds.

### 2.4.2 Cnoc an Droighinn [~NC 265 235]

The intricate interplay between minor intrusions and quartzite on Cnoc an Droighinn is very much as mapped by Coward (unpublished fieldslips). The Glencoul Thrust is clearly defined placing Pipe Rock over limestone. Minor intrusions clearly define folds and minor thrusts above the Glencoul Thrust. Peralkaline rhyolites (‘grorudites’) are only seen above the Glencoul Thrust in this area, as noted by Sabine (1953).

### 2.4.3 Beinn an Fhurain (north) [~NC 28 21]

The authors confirmed Coward’s geological map of this area (unpublished. fieldslips). Deformed minor intrusions again define folds in Basal Quartzite/Pipe Rock strata above the ‘Beinn Uidhe’ Thrust. The folds can be seen on the slopes of Creag Mhor Fuaran nan Each. The style of folding and the relationships of the minor intrusions to the folds are similar to those seen above the Glencoul Thrust at Cnoc an Droighinn.

### 2.4.4 Cnoc nan Uamh Thrust [~NC 27 20]

The geology of this area is very much as mapped by the original survey and the Cnoc nan Uamh Thrust does NOT form a klippe as mapped by Coward. The Traligill Thrust, which puts Ghrudaidh limestones over Eilean Dubh limestones, exposed in the dry riverbed of the Traligill River, can be followed along the north side of Cnoc nan Uamh before disappearing to the SE under peat. The Cnoc nan Uamh Thrust, which emplaces an overturned Pipe Rock–Fucoid Beds–Salterella Grit–limestone succession over limestone on the north side of Cnoc nan Uamh, can be traced southwards on both sides of the hill, much as shown by the original survey. Minor intrusions are common. Of particular interest is a peralkaline rhyolite ('grorudite') around the western and northern slopes of Cnoc nan Uamh below the Cnoc nan Uamh Thrust. This type of intrusion is supposedly only seen in the Glencoul and Ben More thrust sheets, possibly suggesting that the Cnoc nan Uamh Thrust lies above the Glencoul Thrust.

### 2.4.5 Beinn an Fhuarain (south); south of Allt nam Uamh [~NC 26 15]

The geology of this area is more or less as shown on the published map with a klippe of Ben More Thrust Sheet comprising Lewisian and Torridonian rocks and overturned Basal Quartzite at its western end. The Basal Quartzite's boundary can be mapped through regolith and is readily demarcated on aerial photographs.

# 3 Minor Intrusions

A full report on the minor intrusions ('minor intrusions field report') is available in the Moine Thrust Folder on the v drive. A summary of this report is reproduced below.

The fieldwork during 2002 has clearly demonstrated that the hornblende-microdiorite and peralkaline rhyolite ('grorudite') sills predate thrusting and folding within the Glencoul Thrust Sheet. Samples of peralkaline rhyolite (KG24) and hornblende-microdiorite (KG45) were collected for dating. A peralkaline rhyolite sill within limestones at Gleann Dubh, supposedly below the Glencoul Thrust Sheet, has also been identified. This should be compared with the sills seen at Knockan during the 2001 fieldwork, but may necessitate a reconsideration of the structural relationships – either the pattern of the Glencoul Thrust plane is markedly different to that previously mapped, or the peralkaline rhyolites do in fact occur in all the thrust sheets.

The quartz-microsyenites ('nordmarkites') have been found at various localities immediately above the Moine Thrust, where they are intensely sheared and mylonitised. They therefore cannot postdate thrusting, but some lines of evidence suggest that they may have been intruded during thrusting – further work is needed to confirm this. A sample (KG41) has been collected for dating. A possible member of this suite has been found below the Moine Thrust on Cnoc Chaornaidh.

The field relationships of the vogesites and 'Canisp Porphyry' have been studied in less detail, but a previously unmapped dyke of 'Canisp Porphyry' has been identified and a sample of a sill from Beinn Garbh has been collected for dating (KG23). Many of the felsite dykes shown on the published map are not exposed. For example, the numerous felsites shown in the Cambrian quartzites below the Moine Thrust in the Alltan Aonghais (west bank tributary of the River Cassley) are not exposed.

# 4 Moine

## 4.1 COIRE CEANN LOCH–CORRIEKINLOCH–LOCH MERKLAND

Moine metasedimentary rocks have been studied in a traverse from Coire Ceann Loch, [NC 35 26] to Corriekinloch [~NC 37 26] to Loch Merkland [~NC 39 31]. In this area they comprise thinly banded (3–20 cm-scale) psammite, micaceous psammite and semipelite, with semipelites typically making up <10% of the section. No calc-silicate rocks were observed. The psammites vary from grey rocks to paler grey quartz-rich psammites with associated quartzites. The micaceous psammites contain biotite with subsidiary muscovite. Millimetre-scale compositional layering in all psammites defines internal laminations (colour banding). No graded beds were seen but traces of right-way-up cross-bedding were noted. Semipelites form thin seams mostly on a Centimetre-scale in the psammites. A shallow water deposition is inferred for these Moine metasedimentary rocks.

Bedding ($S_0$ compositional layering) is generally very gently north-dipping (between NNW and NNE) in the southern part of the traverse (in Coire Ceann Loch, [NC 35 26]), but gently to moderately west-dipping in the northern part of traverse (on Meall an Fheur Loch [NC 36 31]). This indicates regional open folding. Shallow, north-plunging folds are exposed in cliff sections on Creag an Sgamhlainn [NC 375 325]. The main foliation/schistosity is a strongly developed mica (muscovite + biotite) fabric (regarded here as S2 since it crenulates an earlier tectonic planar fabric (see below). In semipelites the S2 foliation planes are strongly muscovitic. S2 strikes c.140° with steeper north-easterly dips than (north-dipping) $S_0$ to indicate south-westerly vergence. The S2 fabric is anastomising in semipelites, but planar in psammites.

F2 (similar-style) folds observed at one locality [NC 34787 27417] on a steep F3 fold limb would be NE-verging if the effect of the F3 folding were removed. The main mica fabric is axial planar to the F2 folds. In the hinges of these folds it is possible to observe an earlier (S1) foliation that is parallel to $S_0$ being crenulated. No mineral or rodding lineation was seen on $S_0$ or S2. However, quartz veins in semipelites do show a strong rodding lineation and are also locally boudinaged/lenticular and very locally define hook-shaped microfolds. The rodding trends 310/130° on gently north-dipping F3 limbs and plunges steeply south (parallel to F2 fold hinges) on steep F3 limbs.

F3 folds are the dominant macroscopic structures deforming $S_0$ and the main S2 fabric/F2 folds. The F3 are decametre-scale reclined NW-vergent folds with steep (NW or SE dips) short limbs often c.100 m wide. Cross-bedding, locally well displayed on these steep limbs, youngs westwards to indicate that the longer, flat fold limbs are the right way up. There is a strong axial planar crenulation in semipelitic lithologies in F3 hinge areas. F3 fold axes trend 030/210° with gentle NE-plunges. Axial surfaces are upright to moderately SE-dipping.

## 4.2 UPPER GLEN CASSLEY

Moine strata are well exposed on the banks of the River Cassley as well as in the numerous side streams. The dominant lithology is semipelitic schist with a strongly crenulated fabric in contrast to the psammite-dominated succession seen to the north. There are interbeds of thinly flaggy, variably micaceous psammite in the semipelites and less common quartzite and metapelite interbeds. No calc-silicate rocks were observed. The psammites are locally thinly laminated and the metapelites are deformed into lenticular bodies within the dominant (S2) foliation.

The flaggy character of the psammites is not a primary fabric but is controlled by a strong spaced foliation. Bedding is transposed by the foliation. Good examples of transposed bedding can be seen in the clean stream section at [NC 36562 18650]. At [NC 36582 18638] there are intrafolial, tight to isoclinal folds within an east-dipping foliation. A strong mica lineation is developed on the foliation planes with chlorite (+/- biotite) knots within the lineations (after garnet). Top-to-the NW tectonic transport can be seen in foliated psammites at [NC 36201 20672] and [NC 35926 18976].

# 5 Lewisian Gneiss Complex

## 5.1 INTRODUCTION

All of the Lewisian rocks on the published 'Assynt District' geological map are collectively referred to as 'Massive and Foliated Pyroxenic, Hornblendic and Micaceous Rocks' (BGS, 1986). The only subdivision of the foreland Lewisian (i.e. Lewisian west of the Moine Thrust Zone) shown on the map face is a ~NW–SE trending zone (Canisp Shear Zone) where the Lewisian gneisses are 'modified by Pre-Torridonian movements'. The only subdivision of the Lewisian inliers within the Moine Thrust Zone is indicated by a special letter symbol (Λ′) for areas where the gneisses are affected by 'Post-Cambro-Ordovician movements'. The map legend follows Peach et al. (1907) who noted that the Lewisian gneisses above the Glencoul and Ben More thrusts are lithologically similar to the foreland Lewisian but become sheared and schistose close to tectonic contacts with younger strata. Thus, Peach et al. (1907) noted that the three major lithologies (ultrabasic rocks, pyroxene gneisses and hornblende-gneisses) seen to the west of the Moine Thrust Zone are present in the thrust-bound Lewisian inliers. The NW-trending Scourie dykes are also common to foreland and thrust-bound Lewisian areas. Peach et al. (1907) described a NNW-trending gneissosity in the Ben More Thrust Sheet. Subsequent academic work has locally embellished the primary mapping. For example, Coward and Kim (1981) illustrated large-scale folds in the Glencoul Thrust Sheet defined by surface traces of gneissosity.

The 2002 mapping has confirmed the lithological descriptions of the primary surveyors. The dominant lithology over most of the outcrop area is hornblende-gneiss. However, in the north the dominant lithology is a more felsic gneiss. It has not been possible to draw an accurate boundary between these two units owing to the shortness of the field season. The Canisp Shear Zone has now been traced south-eastwards to disappear beneath younger (Torridonian and Cambrian) strata, and a second parallel shear zone has been demarcated north of Loch Assynt. The position of the western part of the Canisp Shear Zone has also been modified slightly. The traces of gneissosity shown by Coward and Kim (1981) have been extended in the Lewisian outcrop in the Glencoul Thrust Sheet. Our mapping has also delineated, for the first time, ductile shear zones that locally control the orientation of the gneissosity traces in the Glencoul Thrust Sheet.

The distribution of Scourie dykes and of ultramafic dykes shown on the published Assynt map has been confirmed by the 2002 mapping. A number of brittle fractures has also been identified based on an examination of air photographs. Beacom et al. (1999) related brittle fractures in the Lewisian to ESE-WNW extension that controlled intracontinental rifting associated with Torridonian sedimentation.

Table 3 summarizes the latest terminology and tectono-thermal history for the Lewisian of the Assynt District (as part of the Central region of the mainland Lewisian outcrop).

## 5.2 LITHOLOGIES NOTED DURING THE 2002 MAPPING

The dominant Lewisian lithology in the foreland terrane of the Assynt area is a medium-grained, equigranular, stromatic hornblende-gneiss, commonly with small (<1 m long) mafic and ultramafic pods and lenses, and with variable amounts of pink-weathering, generally medium-grained granite as veins, sheets and diffuse (partial melt) patches. These granitic components are generally on a centimetre scale to form a much finer fabric than is seen in the northern Moine, for example at Laxford Bridge.

The gneissosity is commonly defined on a centimetre scale by parallel pale grey quartzofeldspathic bands and darker grey hornblende-rich, locally amphibolitic bands. There is also a parallel, millimetre-thick mineral layering with essentially monomineralic, impersistent, black hornblende seams. Locally aligned mineral grains define the gneissosity. Where the rocks are strongly deformed the gneissosity is lenticular and can be defined by lenses of amphibolite, stringers and lenses rich in hornblende, quartz lenses, pink granitic lenses and grey quartzofeldspathic lenses. Individual lenses are up to several centimetres in thickness and up to tens of centimetres in length. Figures 5.1 to 5.12 inclusive illustrate the variety of gneissic fabrics and textures noted during the fieldwork. The gneisses are generally flaggy although massive, coarse-grained, and weakly gneissose rocks are also present.

The original surveyors (Peach et al., 1907) regarded the Lewisian gneisses as orthogneisses, a view shared by the present authors (RMK and SCL). However, the field evidence is ambiguous as to whether the gneissosity mimics a primary igneous layering. No primary igneous layering was noted during the fieldwork in any gneiss although the larger metabasic/ultrabasic pods and sheets do locally possess a mineral layering that is interpreted as a primary fabric (Figure 5.5). However, a petrographic examination of the hornblende-gneisses did find primary igneous textures (Phillips, 2002). No metasedimentary rocks were encountered in the Lewisian outcrop during the fieldwork.

The dominant minerals recognised in the hornblende-gneisses during the fieldwork are quartz, plagioclase, K-feldspar, hornblende and pyrite with minor amounts of red garnet, biotite, clinopyroxene and opaques with secondary epidote (especially where the gneisses are badly fractured e.g. at [NC 22464 33870]). The amount of hornblende in the gneisses is variable. Hornblende-rich gneisses are associated with common sheets and pods of banded ultramafic rocks. There is a higher proportion of small (<50 cm long) ultramafic pods in the hornblende-rich gneisses relative to the more felsic gneisses. Pyrite is ubiquitous in the more mafic gneisses as disseminated grains visible to the naked eye. Post-tectonic garnets up to 2 cm in diameter were noted at [NC 14610 22379].

| EVENT | DETAILS | Central Region (Assynt Terrane) | NOTES |
|---|---|---|---|
| LAXFORDIAN | NW-SE foliation; amphibolite facies metamorphism with a late retrogression to greenschist facies, associated with granite and pegmatite emplacement | 1750-1670 Ma | 2 events dated at c.1750 Ma and c.1670 Ma (Corfu et al., 1994; Kinny and Friend, 1997; Zhu et al., 1997). Late brittle shears are imprecisely dated at ~1150 Ma (K-Ar method) |
| EMPLACEMENT OF SCOURIE DYKES | Possibly an early and later suite of Scourie dykes. NW–SE-trending metamorphosed and sheared basic and ultrabasic dykes; intruded into hot country rocks and in part overlapping with the Inverian metamorphism | Late suite emplaced at c. 2020-1920 Ma (Heaman and Tarney, 1989)<br><br>Early suite emplaced between 2420 Ma and 2400 Ma (Heaman and Tarney, 1989; Corfu et al., 1994) | |
| INVERIAN | Amphibolite facies metamorphism at northern and southern margins of the Central Region, near vertical belts of deformation. Hydrous deformation and emplacement of pegmatites | Scourie area: 2490-2480 Ma (Corfu et al., 1994; Friend and Kinny, 1995; Kinny and Friend, 1997)<br><br>Gruinard Bay area: no evidence for an Inverian event in this area (Corfu et al., 1998; Kinny and Friend, 1997) | Loch Inver Antiform and Canisp Shear Belt |
| BADCALLIAN | Granulite facies metamorphism and deformation | Scourie area: 3030-2960 Ma (Kinny and Friend, 1997; Friend and Kinny, 1995)<br><br>Gruinard Bay: 2736-2726 Ma; 2825-2790 Ma and 2850-2750 Ma (Corfu et al., 1998; Whitehouse et al., 1997) | Disputed Scourie TTG protolith ages (~3 Ga vs. 2.8 Ga). Gruinard Bay: minimum protolith ages of trondhjemites and granulite facies metamorphism at ~2730 Ma. Mafic and felsic gneisses ~2.825-2.79Ga |
| MAFIC-ULTRAMAFIC PROTOLITH | | | Pre-TTG intrusion and metamorphism. No attempt yet made to date the emplacement ages of the mafic-ultramafic protolith material in the terrane |

Table 3. A summary of the pre-Caledonian events in the Central region of the Lewisian Foreland

In the northern part of the Assynt district (north of the B869 Drumbeg road) there are flat lying, pinkish grey weathering, stromatic, felsic gneisses (Figures 5.7 and 5.8). On the coast they are the dominant lithology although traced inland they become interlayered on a metre scale with the hornblende-gneisses. The felsic gneisses are quartz-rich and contain minor amounts of biotite and pyroxene. Teall in Peach et al. (1907) described these rocks as quartzose pyroxene gneisses and states that they are common between Scourie and Loch Inver. He noted that clinopyroxene is the main ferromagnesian constituent although hypersthene, biotite, primary hornblende and garnet are locally present. Examples of two-pyroxene granulites were noted at Unapool on the shores of Loch Glencoul. Given sufficient time it would be possible to separate areas underlain by these gneisses from areas underlain by the hornblende-gneisses. Teall (in Peach et al., 1907) noted that the two rock types grade into each other and the 2002 mapping confirmed that the two lithologies are interbanded on a metre scale in a broad contact zone in the general area west of Quinag next to the B869 road.

Speckled black and white mafic pods and dull green, coarser grained ultramafic pods are common as minor components of most exposures and rarely exceed a few tens of centimetres in diameter. There are large metagabbroic bodies, for example in the Canisp Shear Zone, where the largest example is about 80 m in length and up to about 35 m thick. They are cut by white quartzofeldspathic veins that are undeformed in the centre of the metagabbros, but that are flattened in a marginal foliation. The veins contain small angular clasts of metagabbro. A primary mineral layering is preserved in the centre of the metagabbros and is discordant to the strong foliation in the surrounding gneisses (Figure 5.5). Within the gneisses adjacent to the larger bodies there are rotated smaller metagabbroic blocks. At one locality [NC14645 19320] on the north side of Suilven there is a massive, medium-grained, equigranular meta-olivine-gabbro sheet (~3 m thick by >20 m in length) in hornblende-gneisses with over 20% by volume of ultramafic pods. This metagabbro pod has a distinctive dark reddish-brown colour that may be due to weathering close to the Torridonian–Lewisian unconformity.

Mafic pods are commonly deformed into thin lenses or slivers (Figure 5.6) within the gneissosity or a later foliation, whereas the ultramafic pods tend to retain their rounded, irregular outlines (Figure 5.3) unless the host gneisses are intensely sheared. Pink granitic veins locally cut the pods and they are rotated within shears. Mafic sheets are commonly boudinaged and tightly folded within the gneissosity giving the impression of numerous discrete pods from certain angles. The sheared margins of the mafic and ultramafic pods are micaceous. The ultramafic pods comprise amphibole and clinopyroxene with disseminated pyrite. Teall (in Peach et al., 1907) noted that olivine and garnet are also locally present in the ultramafic pods. Pyroxene-rich ultramafic pods are present at [NC 22643 31749].

Pink-weathering granitic veins and patches, generally with diffuse margins are common in all the gneisses (Figures 5.2 and 5.4) although quartz veins are rare. Locally the granitic veins are folded and disrupted into pods. In the less deformed gneisses the granitic veins form a network of intersecting veins, locally containing angular clasts of the host gneisses. Larger patches of granite, up to several metres in diameter comprise a series of closely spaced veins rather than a coherent sheet. Partial melting of quartz-rich granitic gneisses occurs in hinge zones of folds and neosome granite commonly has an envelope of mafic-rich gneiss.

Metabasic (Scourie) dykes are very common and are accurately shown on the existing clean copies. Peach et al. (1907) noted that these dykes are more conspicuously developed in the Assynt area than in any other part of the Lewisian outcrop. They recognised three types of dykes: ultrabasic (picritic) dykes, abundant basic dykes of variable composition including epidiorites, and rare intermediate biotite-diorite dykes. Tarney and Weaver (1987) defined four types of Scourie dykes with quartz-dolerites (epidiorite suite of Peach et al., 1907) as the dominant type. The abundant basic dykes seen during the 2002 fieldwork generally trend WNW–ESE and are vertical. They are well exposed as distinctive ice-moulded crags so that it is easy to trace out individual dykes over hundreds of metres of strike length. They vary in thickness from about 10 cm up to tens of metres. The dykes coarsen inwards from chilled, commonly sheared margins. There are diffuse feldspathic segregations in the centres of the dykes that Peach et al. (1907)

described as hornblende-granite. The Scourie dykes are variably deformed. In major shear zones they are disrupted into pods and comminuted to form mafic schists with biotite as well as hornblende. Primary textures are variably preserved. The thicker, undeformed dykes have chilled margins with metadoleritic cores and, locally, with an internal mineral layering defined by felsic seams.

In addition to the Scourie dykes there are also breccia 'pipes' in which angular fragments of metagabbroic rock (up to about 1 m in length) are supported in a hornblende-gneiss groundmass. The angular metagabbroic fragments commonly show a primary fabric which in some cases is folded. The host rock is massive (granitic) in the centre of these brecciated zones but the intensity of gneissosity increases towards the margins. Ultramafic lenses and quartz-feldspar pegmatites cut the breccias. A good example of this lithology is present at [NC 15063 20130] immediately south of the Canisp Shear Zone.

## 5.3 DEFORMATION AND METAMORPHISM

### 5.3.1 Introduction

A complex, polyphase history of deformation is recorded in the Lewisian gneisses. This was recognised by the early surveyors. For example, Peach et al. (1907) described lenticular fabrics in the gneisses and attributed them to a late (post-Scourie dyke) deformation in discrete WNW–trending zones. Subsequent academic studies (commencing with Sutton and Watson, 1951) have identified and named the major deformation events that can be recognised on a regional scale. This detail is summarised in Table 3.

### 5.3.2 Our observations

The (Badcallian) gneissosity (as shown in Figures 5.1 to 5.11 inclusively) varies from a strongly defined planar fabric on millimetre to centimetre scale to a weakly defined fabric in massive hornblendic rocks. It is not known to what extent this metamorphic fabric mimics and/or transposes an earlier primary layering (see also Attfield, 1987). Away from major shear zones (Inverian and Laxfordian, see below) the gneissosity is generally shallow-dipping.

The gneissic fabrics are variably deformed (on all scales) and recrystallised during the later (Inverian and Laxfordian) metamorphic episodes. Minor ductile shears are ubiquitous, as are minor folds of gneissosity and veins. It is only where the temporal relationship of a minor structure or fabric to a Scourie dyke can be observed in an exposure that it is possible to distinguish between Inverian (pre-dyke) and Laxfordian (post-dyke) structures. Otherwise, where a structure is confined within the gneisses, its age is generally not known. The Canisp Shear Zone (see below) is clearly a composite structure with pre- (Inverian) and post- (Laxfordian) Scourie dyke deformation.

The gneissic fabrics are disrupted in shear zones into lozenge-shaped or lenticular pods, or define rootless folds in a new foliation. In high-strain rocks there is a mineral shape fabric with strong alignment of quartz, biotite and hornblende. In low-strain rocks quartz grains are not shape aligned although the mafic grains show a degree of preferred orientation.

As a result of the post-Badcallian deformation, mafic-rich gneissic bands are invariably boudinaged and the entire gneissic fabric is locally lenticular. The shapes of the mafic and ultramafic pods give an indication of the amount of flattening of the host gneisses. In undeformed gneisses the mafic pods are angular and may have an internal network of intersecting felsic veins. As deformation increases the mafic pods become more and more lenticular and aligned in a new planar (shear) fabric and locally define a new gneissosity. However, the ultramafic pods are less susceptible to deformation and only lose their irregular rounded shapes in intensely deformed gneisses where they also become lenticular within anastomising shears. Individual pods are locally rotated in the shear zones and provide good indicators of the sense of shearing. Linear fabrics are rare.

Shears commonly define the boundaries between the thicker layers of mafic and felsic gneisses. There are several generations of minor shears with early (Inverian) shears, and late (Laxfordian) shears cutting the dykes and all other phases in the gneisses. Enveloping surfaces of minor folds (of gneissosity and later granitic veins) are planar and commonly gently dipping or subhorizontal. Early folds of gneissosity trend NE–SW with SW plunges. Sheath folds were noted on the excellent coastal section in intensely folded flaggy grey felsic gneisses (Figures 5.8 and 5.11). There are isoclinal folds with an axial planar foliation seen in major (late) shear zones. The isoclines are defined by the gneissosity, by individual quartz grains (rootless microfolds) and by amphibolite sheets that are disrupted into a series of folded pods. Ductile thrusts are exposed below the Glencoul Thrust and appear to be late structures, possibly contemporaneous with the Caledonian thrusting.

There were at least two phases of Scourie dyke emplacement parallel to, and along Inverian shears with ‘early’ dykes deformed into rootless folds and ‘later’ dykes forming more linear features. Later Laxfordian shears affect marginal zones of dykes and Laxfordian folds refold earlier folds. Within the Canisp Shear Zone the dykes deform in a characteristic manner. Strain is accommodated in discrete shears that form an anastomosing array in the dykes and along their margins. The dykes have only sheared along their margins outside the shear zones.

A ‘late’ foliation associated with major WNW–trending shear zones is present in the gneisses, the Scourie dykes and pegmatitic granite veins. Quartzofeldspathic veins along foliation planes within shear zones define a new gneissic fabric. There is a strong quartz leaf fabric in the Canisp Shear Zone with fine-grained amphibolitic lenses defining rootless folds in the fabric. The new foliation is tightly folded and cut by weakly discordant sinuous microshears. Some shears are reactivated as brittle, extensional faults.

### 5.3.3 Canisp Shear Zone and Lochinver Monocline

The gneisses south of the Canisp Shear Zone are folded by the (Inverian) broad Lochinver monocline with its steeply dipping north limb against the southern boundary of the shear zone. The deformation in the Canisp Shear Zone is extremely heterogeneous with lenses of low strain enclosed in anastomosing bands of highly deformed, sheared gneisses. The widths of individual shears in the Canisp Shear Zone vary from several centimetres up to tens of metres. The northern margin of the Canisp Shear Zone is not well defined as there are parallel Inverian shears to the north of the main zone. Folds were noted in the northern gneisses trending ESE–WNW with associated sheared limbs that predate Laxfordian shearing. Weak steeply plunging lineations were measured in Inverian shears. Attfield (1987) provided evidence for two phases of movement in the Canisp Shear Zone:

An early (Inverian) dip-slip movement downthrowing to the north with a small dextral strike-slip component. This produced a steeply inclined foliation and steeply plunging to the SE lineation.

A later (Laxfordian) strike-slip movement concentrated in narrow high strain zones of reactivation with a strong lineation plunging gently to the ESE. The shear sense is predominantly dextral with a small downthrow to the north.

### 5.3.4 Brittle deformation

The presence of brittle faults is indicated by linear gullies between the rock crags and these are clearly defined on air photographs and even on the detailed topographical maps.

## 5.4 OVERVIEW OF THE EVOLUTION OF THE LEWISIAN GNEISS COMPLEX IN ASSYNT

The foreland Lewisian rocks in the Assynt area comprise a sequence of altered intrusive rocks represented as variably hornblendic grey gneisses. There are no indications of any paragneisses or other metasedimentary lithologies. The original surveyors reached the same conclusion referring to these rocks as their ‘fundamental complex’ (Peach et al., 1907). Subsequent petrological and geochemical work has shown these Assynt Lewisian rocks to represent an altered Tonalite-Trondhjemite-Granodiorite (TTG) suite of layered intrusions (Bowes et al., 1964; Sheraton et al., 1973; Weaver and Tarney, 1980; Rollinson and Fowler, 1987; Tarney and Weaver, 1987). Primary igneous textures with randomly orientated plagioclase laths with intergranular, locally ophitic clinopyroxene can be seen in thin sections (Phillips, 2002). However, for the most part the primary fabrics are obliterated by high-grade (amphibolite to granulite facies) metamorphic fabrics in which hornblende appears to be the main mafic mineral phase. The oldest, locally layered mafic to ultramafic rocks are preserved as variably deformed pods in the gneisses. They may represent the early phases of the TTG suite or a completely separate intrusive event. The mafic-ultramafic rocks have been interpreted as disrupted pieces of oceanic crust (Park and Tarney, 1987; Rollinson and Fowler, 1987). An alternative possibility is that they may be a disrupted layered intrusion such as the Bushveld Complex. It has also been suggested that they represent the source material for the hornblendic gneisses (Rollinson and Fowler, 1987) although Whitehouse et al. (1996) suggested a separate basaltic source for these gneisses. Protolith ages of between 3030 and 2960 Ma have been reported for the gneisses (Friend and Kinny, 2001).

A deformation event at granulite facies grade produced the gneissic fabric with a high strain deformation producing regional flat lying structures. This event is referred to as the Badcallian with maximum PT conditions estimated at 1000ºC and 10 Kbars (Barnicoat, 1987). Several authors have suggested that this event was long-lived with a thermal peak prior to about 2760 Ma and ductile deformation at about 2500 Ma (Cohen et al., 1987; Corfu et al., 1994; Friend and Kinny, 1995; Kinny and Friend, 1994).

The REE patterns in the hornblendic gneisses are consistent with partial melting of a mafic source under high-pressure hydrous conditions (Rollinson and Fowler, 1987). The question remains as to whether the protolith TTG suite was emplaced at deep crustal levels and remained at these deep levels during the Badcallian event, or whether the TTG suite was formed at high crustal levels by, for example shallow melting of ocean crust and subsequently buried (Tarney and Weaver, 1987). Crystallization at deeper crustal levels of the relatively dense tonalitic magma generated by the melting of oceanic crust would progressively thicken the crust by underplating.

Injection of granite veins followed the early metamorphism and was succeeded by Inverian vertical shearing and associated amphibolite facies metamorphism in well-defined zones in the Assynt area. Isotopic dating indicates the shearing took place at about 2480 Ma (Table 3). Attfield (1987) suggested that early deformation in the Canisp Shear Zone is part of the Inverian event. There is certainly a complex tectonic history recorded in the Canisp Shear Zone where it is exposed in the Assynt area, with pre- and post-Scourie dyke deformation. The Canisp Shear Zone is now traced right across the Lewisian outcrop area to eventually disappear in the east under Cambrian quartzite cover. It is also possible to show on the revised Assynt District map a similar shear zone on the north side of Loch Assynt that was described in Peach et al. (1907). Sheath folds orientated NW–SE seen in the gneisses exposed in the northern coastal section may be Inverian folds or interference structures due to more than one episode of folding.

Steep, NW–SE to WNW–ESE Scourie dykes were emplaced after the initial phase of deformation in the Canisp Shear Zone, but are clearly deformed by later ductile deformation in this zone. Dykes in the shear zone are foliated and have amphibolite facies mineral assemblages. Previous workers have suggested that there were possibly two phases of dyke emplacement with an early 2420–2400 Ma suite emplaced into hot rocks and a later 2020–1920 Ma suite (Table 3).

## 5.5 LEWISIAN INLIERS IN THE BEN MORE AND GLENCOUL THRUST SHEETS

### 5.5.1 Present work

The Lewisian in the Glencoul Thrust Sheet comprises grey hornblende-gneisses and paler grey quartzose pyroxene gneisses, all cut by NW to WNW trending Scourie dykes. As a result of the latest fieldwork it is possible to show the trend of gneissosity throughout this thrust sheet to extend the work of Coward and Kim (1981). It is also possible to demarcate for the first time ductile shear zones in which tightly folded gneissosity is cut by a new penetrative foliation. The NW-trending valley running into Loch Beag follows one of these ductile shears.

The Lewisian in the Ben More Thrust Sheet is lithologically more varied. Rust-brown weathering quartz-bearing schists and phyllonites up to about 10 m in thickness are found where Lewisian rocks are in contact with quartzites. For example, coarse-grained quartz-green biotite-schists with quartz knots are exposed at [NC 32571 20619] and 10 m of phyllonite underlie a 50 cm thick mylonite next to quartzites at [NC 32425 20601]. Pyrite is disseminated in the schists. Similar schists are also present within the Lewisian gneisses e.g. at [NC 33834 21227] where they are about 2 m thick.

The dominant Lewisian gneiss in the northern part of the Ben More Thrust Sheet is stromatic hornblende-gneiss with disseminated pyrite identical to the foreland hornblende-gneisses. These gneisses are fine- to medium-grained, equigranular rocks, locally with a discordant shear fabric. White quartzofeldspathic seams on a ,millimetre to centimetre scale are cut by a variable amount of pink pegmatitic granite veins and sheets. The veins locally form a network of intersecting pegmatites, for example at [NC 33878 21223] where they are very tightly folded. The gneissosity is locally lenticular and defined by quartzofeldspathic lenses, and is locally defined by aligned hornblende blades, for example at [NC 33863 19837]. Minor folds of gneissosity that vary from open structures to rootless isoclines are common. For example, isoclinal folds are defined by gneissosity and by pink granite veins at [NC 32812 20558]. Dull green ultramafic pods in the gneisses are up to 2 m in length and are locally common e.g. at [NC 33391 17932]. At [NC 34130 19682] there are individual pyroxene grains in the gneisses that are deformed into augen. Linear fabrics are relatively common compared to the foreland gneisses. At NC 32374 20645] a stretching lineation is defined by felsic seams and quartz grains. The gneisses are locally cut by brittle fractures in addition to the various ductile structures.

The gneisses in the southern part of the Ben More Thrust Sheet around [NC 32000 17700] comprise agmatitic migmatites with a white granitic vein network in a grey gneiss palaeosome. Here the gneissosity is variably developed and only locally defines a stromatic fabric. Further to the south the gneisses vary from weakly gneissic hornblende granite [NC 29480 14271] to massive metagabbro with disseminated ragged and euhedral pyrite. Amphibolite lenses as well as mafic-rich and felsic seams define the gneissosity. Dull green ultramafic pods are locally common in the metagabbroic gneisses and metagabbroic pods are locally present in the more felsic gneisses. All of these pods are variably deformed in the gneissosity. Pink granite veins and clots in the southern gneisses have diffuse margins merging into the groundmass of the gneisses, for example at [NC 23481 12709]. Acicular plagioclase grains define a weakly penetrative foliation at [NC 31730 14658]. Tight intrafolial folds and rootless folds are defined by gneissosity in the strongly foliated gneisses that have a quartz leaf foliation on the north side of Sgonnan Mor.

The Scourie dykes in the Ben More Thrust Sheet are mostly amphibolitic with speckled, medium to coarse-grained assemblages of hornblende, plagioclase, quartz and opaques including tiny pyrite grains. Chilled margins are locally preserved, for example at [NC 324324 16217]. A dyke at [NC 31165 21295] is basaltic. The dykes are generally massive with discrete internal ductile shears infilled by quartz and are also locally strongly fractured. Locally there are white granitic veins in the dykes.

# 6 Torridonian

The narrow strips of deformed Torridonian shown along the Moine Thrust on the Assynt District map are felsic schists that look more like sheared Lewisian. It is probably better to rename these rocks as quartz-schists with no definite lithostratigraphical association.

The Torridonian outcrop shown on the published 50k map in the hanging wall of the Ben More Thrust in Glen Oykel is not correct. However, it is correctly shown on the six-inch clean copy of this area. The Torridonian strata define a tight syncline immediately above the thrust as indicated by the original surveyors. Bedding is poorly defined and lenticular rather than planar and cut by a strong foliation. The contact between Torridonian pebbly sandstones and overlying Lewisian is sheared on the overturned upper limb of the synforms.

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# Figures

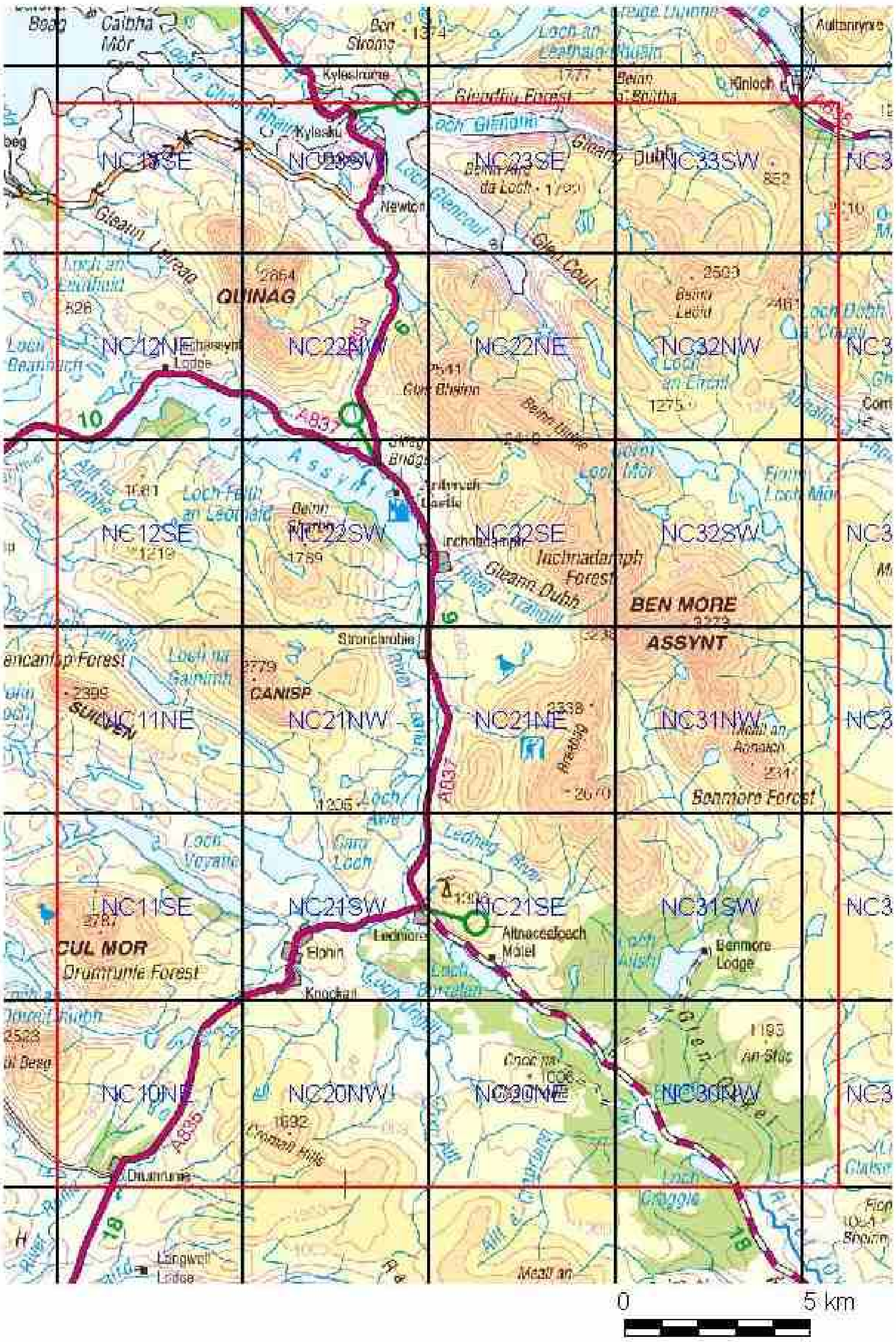


Figure 1.1 Overview topographical map of the Assynt area.

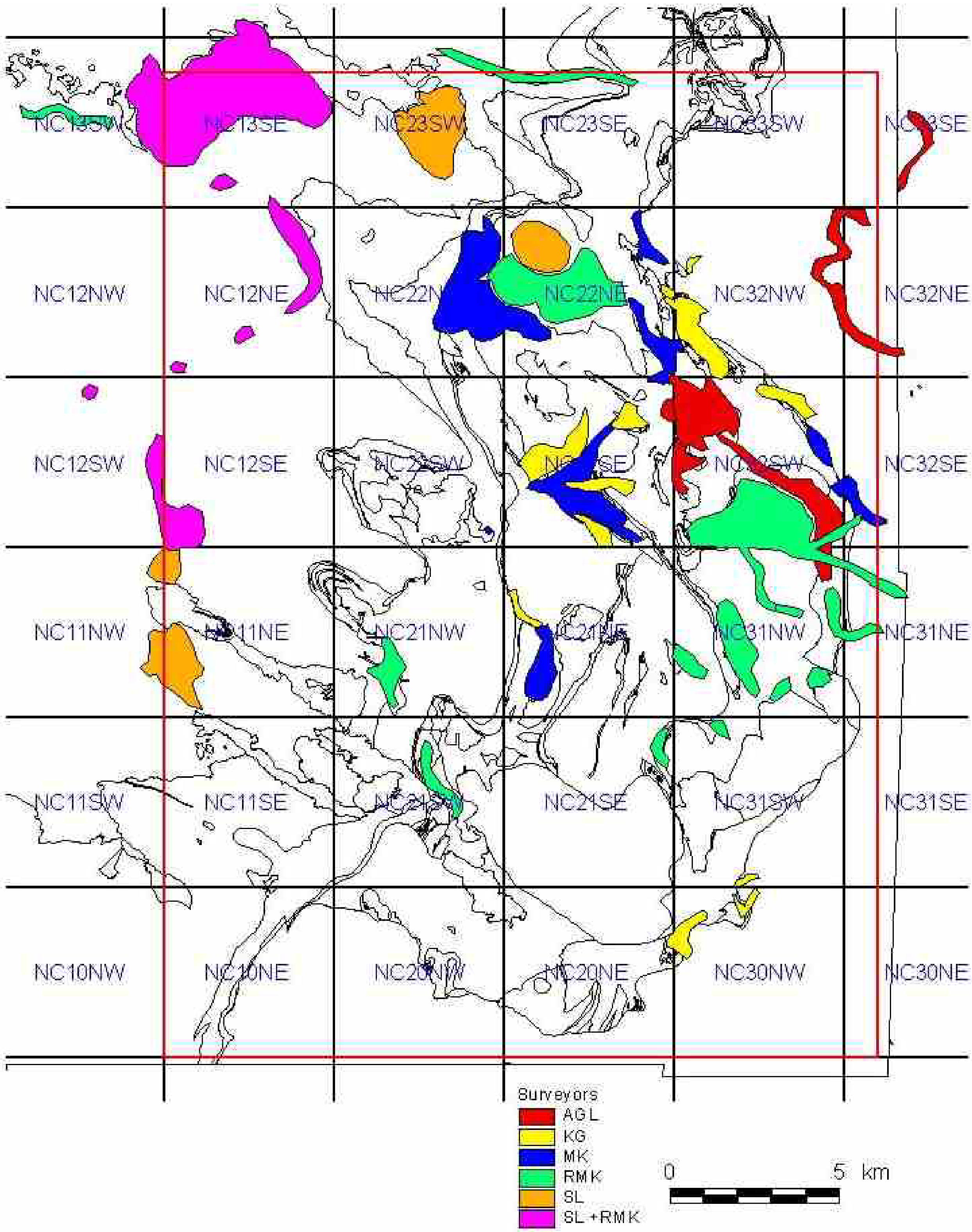


Figure 1.2 Areas resurveyed during the 2002 field season

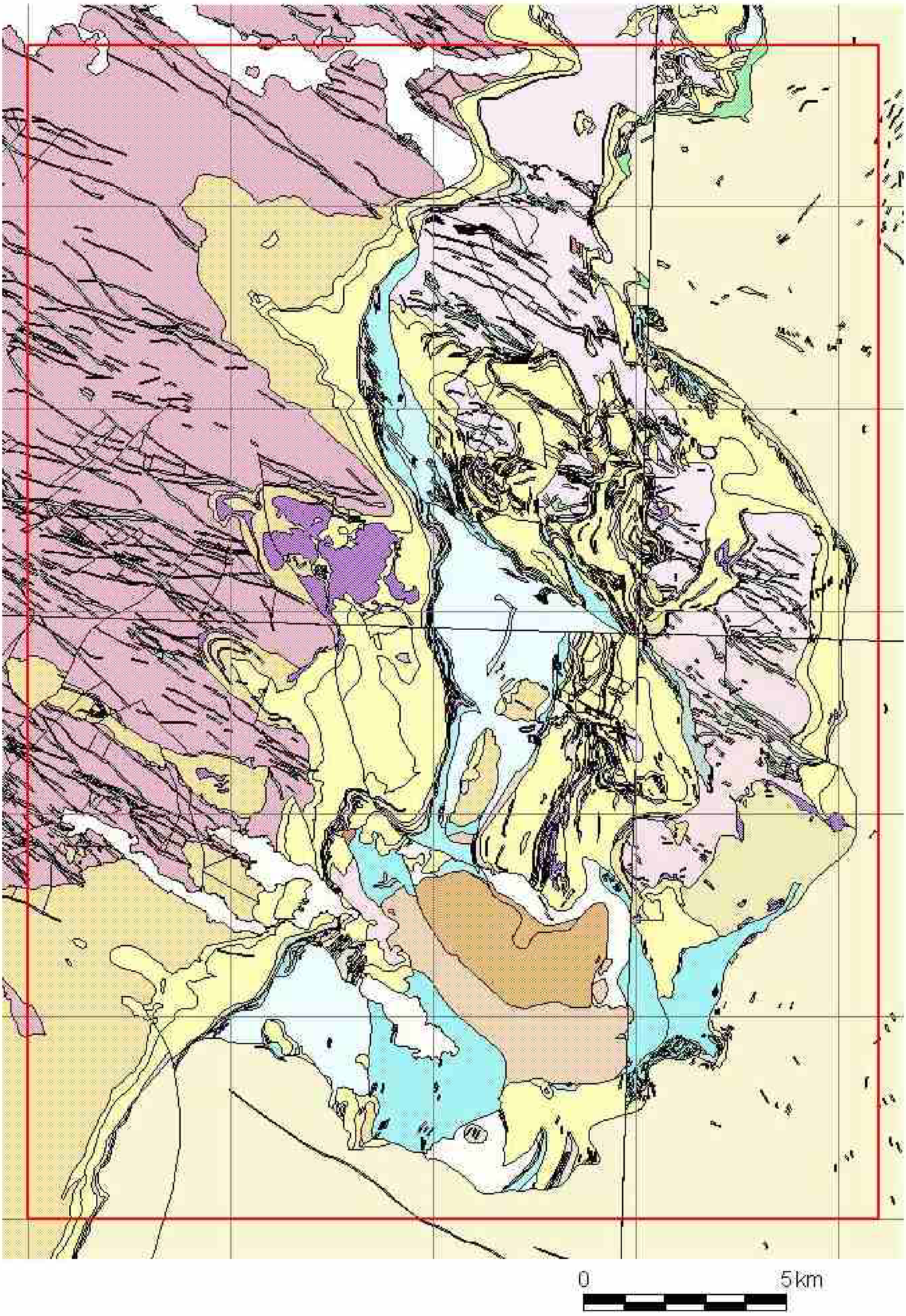


Figure 1.3. Overview of geology of the Assynt District 'Special Sheet', based on current DigMap v1 databases

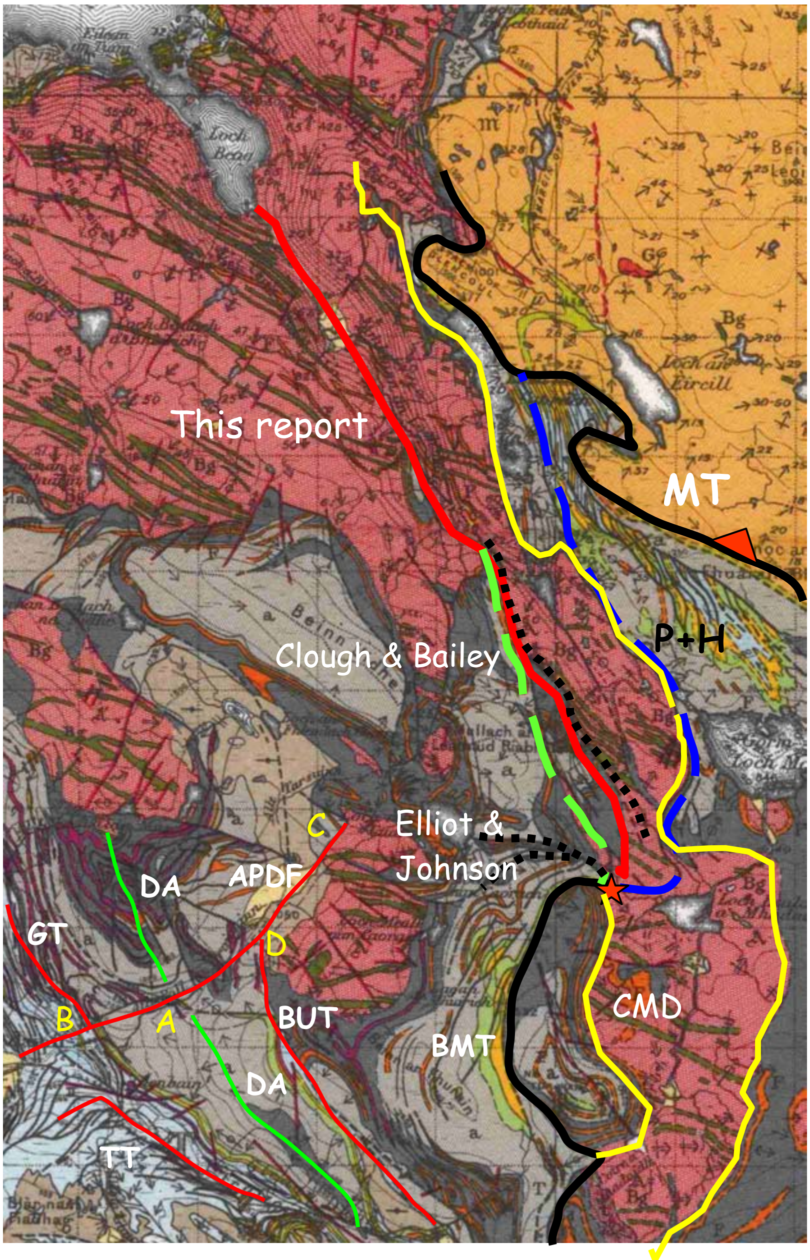


Figure 2.1. Geological map showing the different interpretations of the trace of the Ben More Thrust (in the northern half of the Assynt District geological map, 1923). P + H (in blue) = course of Ben More Thrust as proposed by Peach & Horne (1907, 1914). Green dashed line as proposed by Clough (1907) and Bailey (1935). Elliot & Johnson (1980) suggested the BMT was cut out by several extensional faults (black dashes). The new proposed course of the Ben More Thrust is the thick red line and the Coire a' Mhadaidh Detachment is shown in yellow.
APDF = Allt Poll an Droighinn Fault; BMT = Ben More Thrust; BUT = Beinn Uidhe Thrust; CMD = Coire a' Mhadaidh Detachment: DA = Droighinn Antiform: GT = Glencoul Thrust. For points A, B, C see section 2.3.

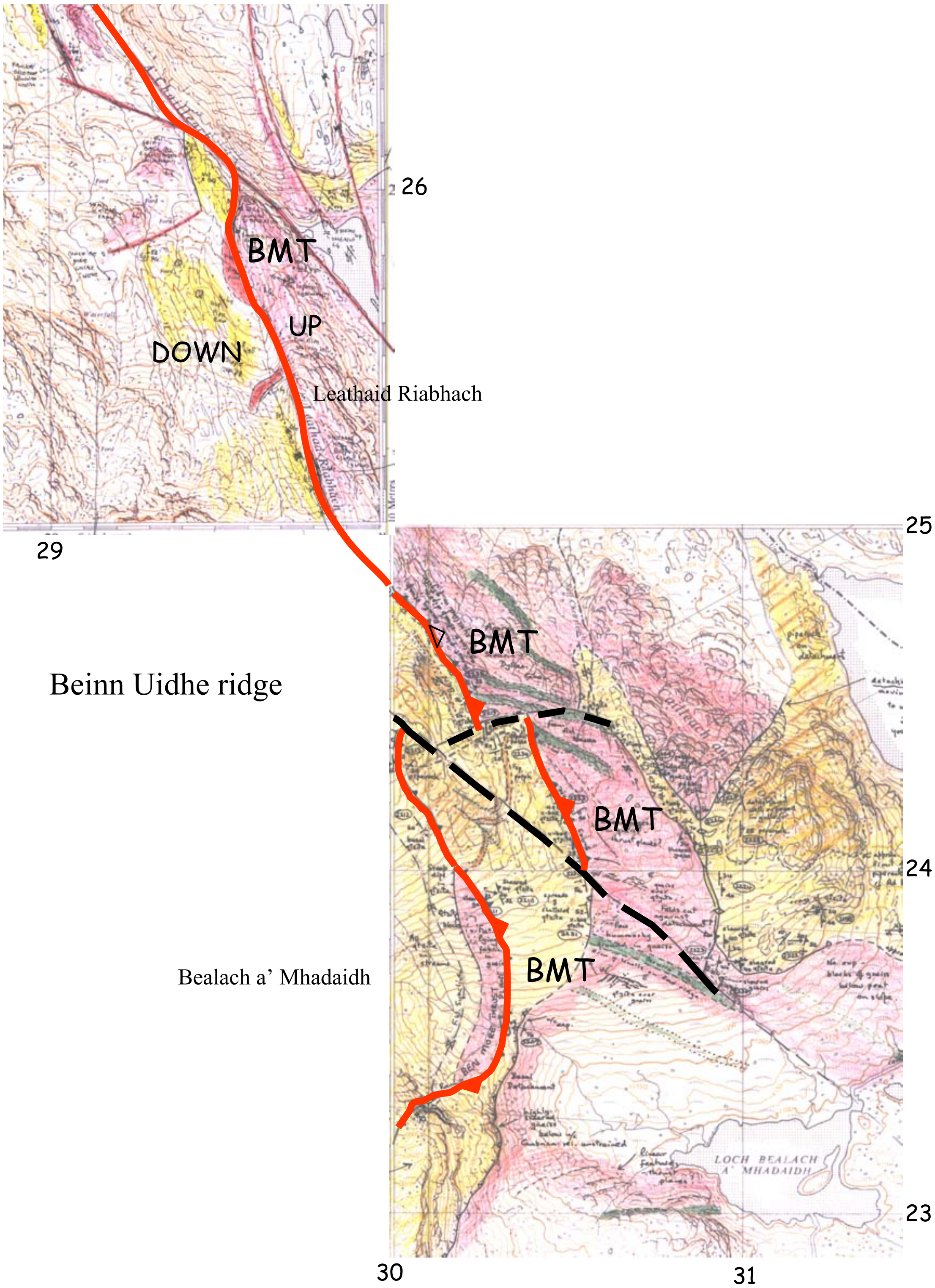


Figure 2.2. Field slips of the area west and north of Beinn Uidhe, showing the newly mapped course of the Ben More Thrust (BMT). Mapping by MK and AGL, 2002. Areas shaded yellow are underlain by quartzites and the Lewisian Gneiss outcrop is shown in pink.

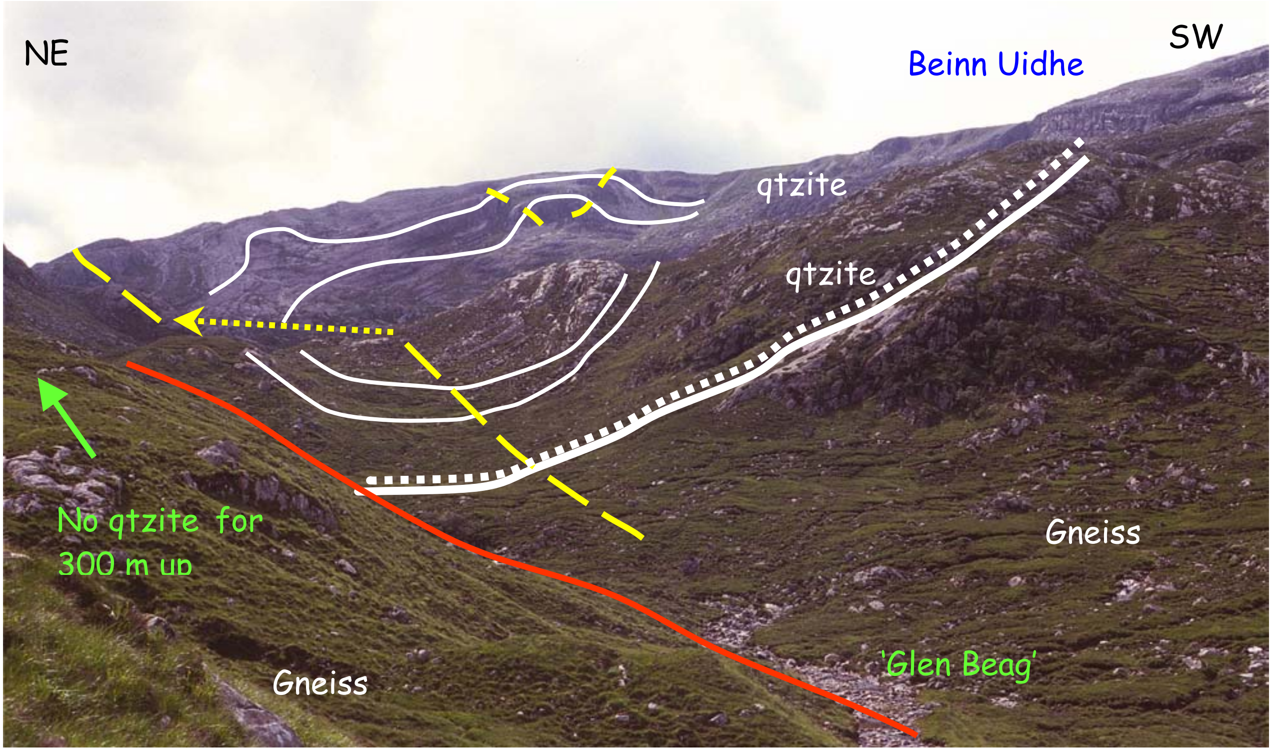


Figure 2.3. View along 'Glen Beag' (unnamed glen to the south of the Stack of Glencoul) to Beinn Uidhe, showing folded quartzite in background and truncation of quartzite syncline against fault (in red) in fore ground. White lines are bedding marks; yellow lines follow anticline. BGS Photo P514909.

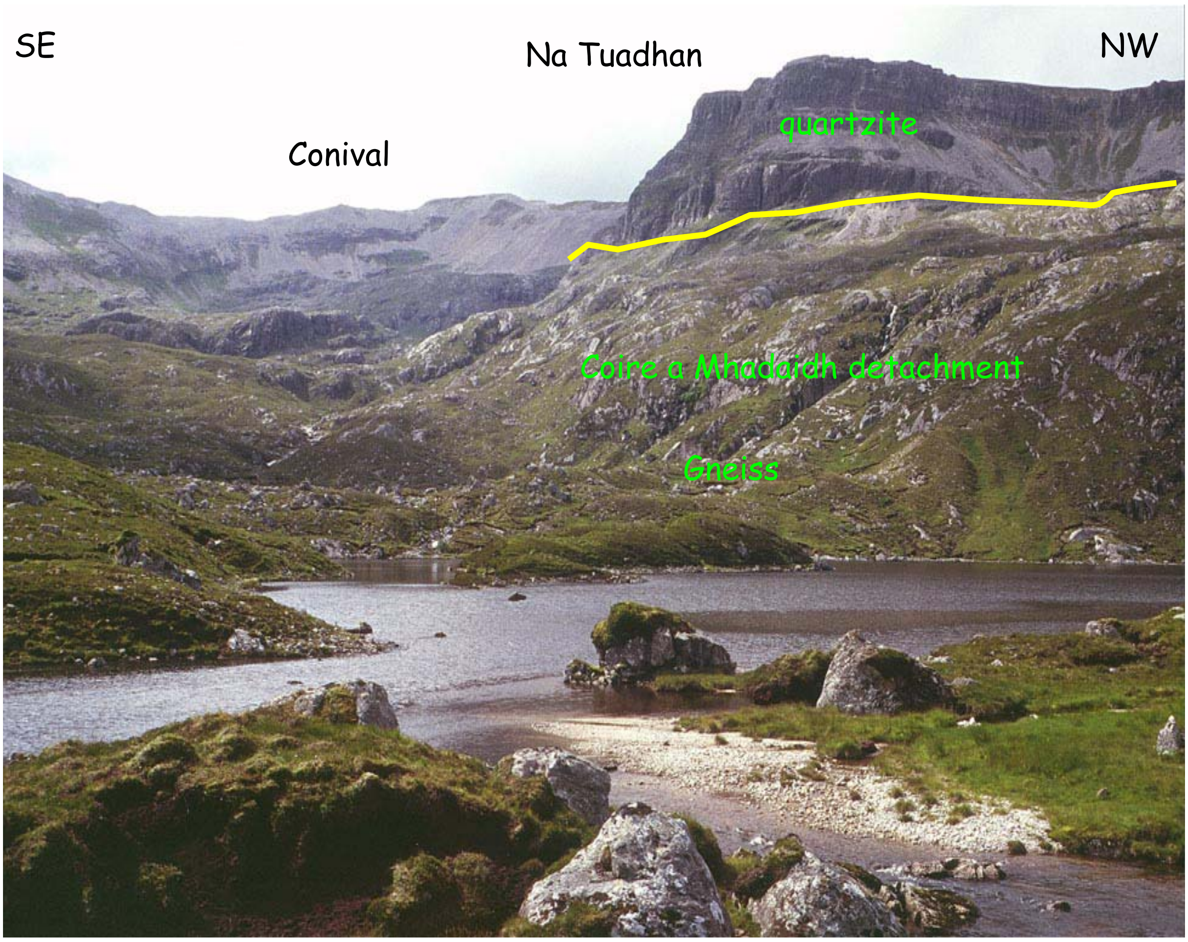


Figure 2.4. View of east Face of Na Tuadhan, with position of Coire a' Mhadaidh Detachment in yellow. BGS Photo P521764

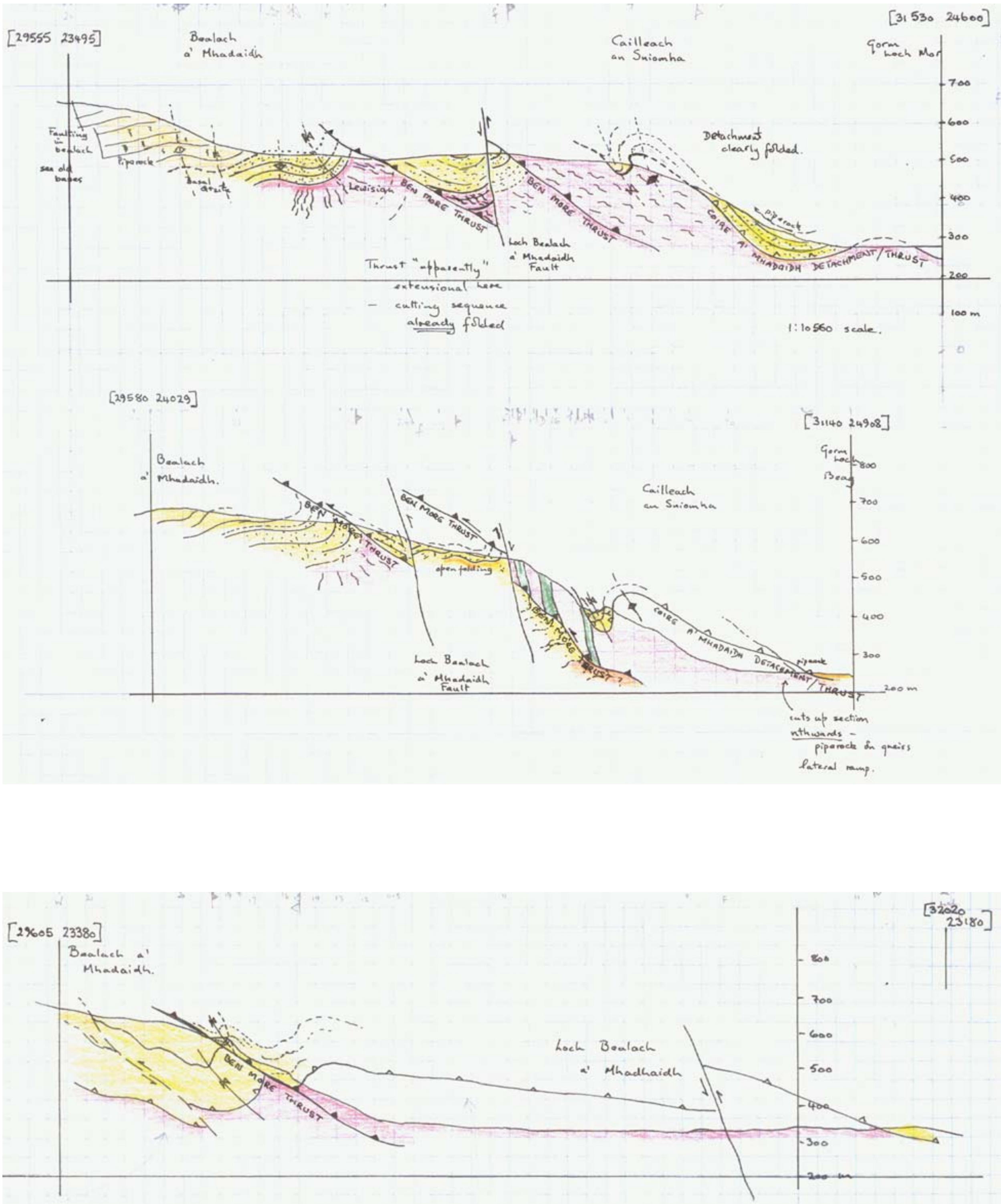


Figure 2.5. Sketch cross-sections (V = H) showing the internal structure of the Ben More Thrust Sheet and the relationship of the Ben More Thrust and the Coire a' Mhadaidh Detachment.


Figure 2.6. Contact between Lewisian Gneiss and Basal Quartzite, within Ben More Thrust Sheet. This contact is a sheared unconformity. BGS Photo P521754

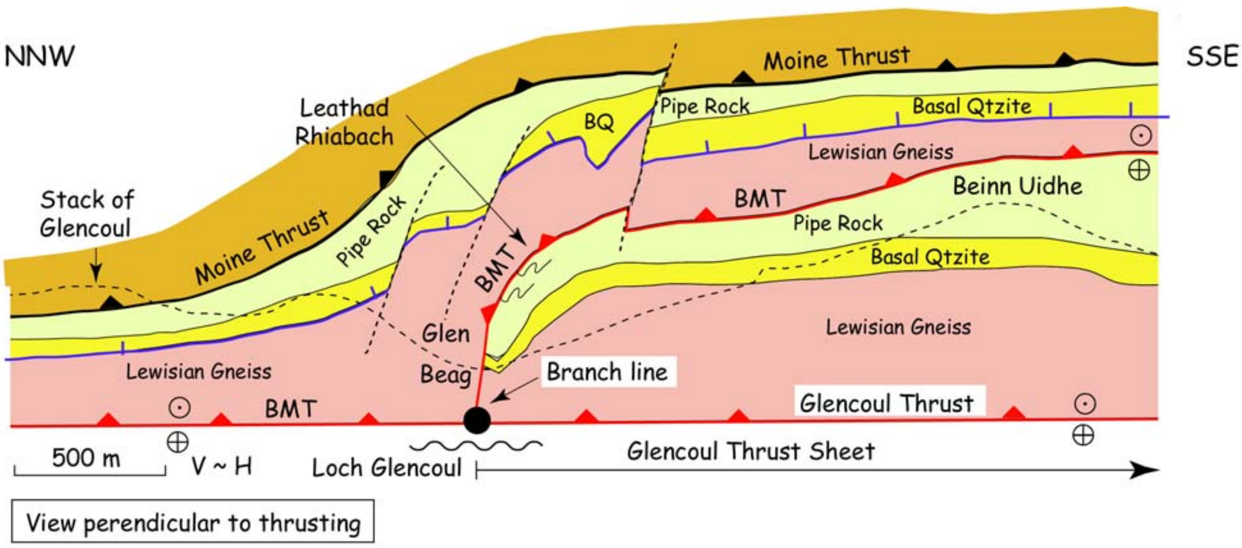


Figure 2.7. Schematic north–south down-plunge section, from the Stack of Glencoul to Beinn Uidhe, taken approximately perpendicular to the transport direction. The Coire a' Mhadaidh Detachment is shown as a blue line with ticks. Present-day land surface is shown as a dashed line.

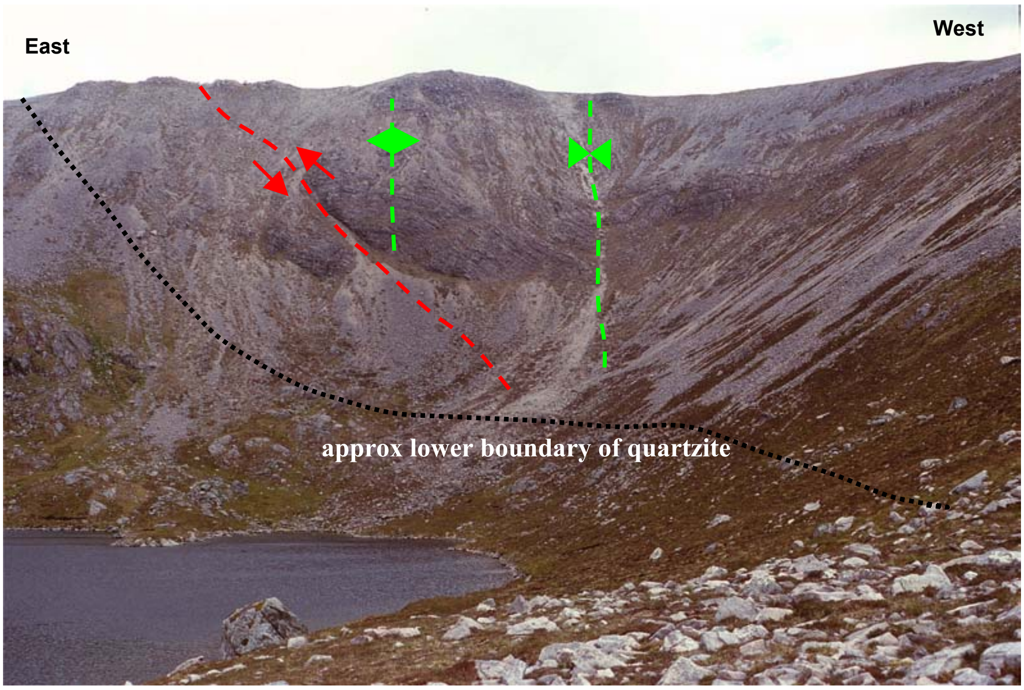


Figure 2.8. View southwards into Coire Dearg on northern side of Glas Bheinn. Most exposed rock is quartzite, which shows a west-dipping fault (red), with an anticline and syncline pair (green) in its hanging wall. This structure is more likely to be a backthrust than an extensional fault. BGS Photo P513609.

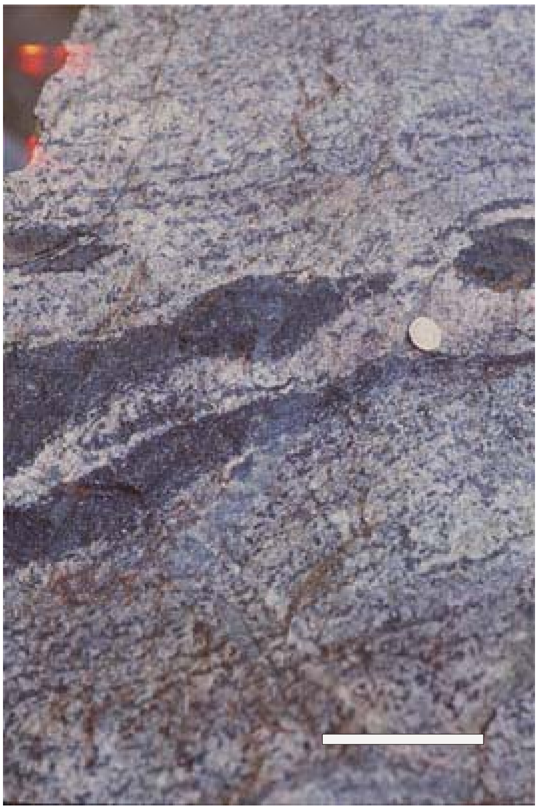

Figure 5.1. Lewisian migmatites exposed in a road cut on the north side of Loch Assynt. Discontinuous and boudinaged amphibolitic layers in hornblende-gneiss. The gneissosity is defined by the amphibolitic layers and by trails of individual hornblende grains. Quartzofeldspathic material infilling the boudin necks has recrystallised and lost its gneissic fabric. [NC17334 26187]. White scale bar is about 15 cm long. BGS Photo P517131.

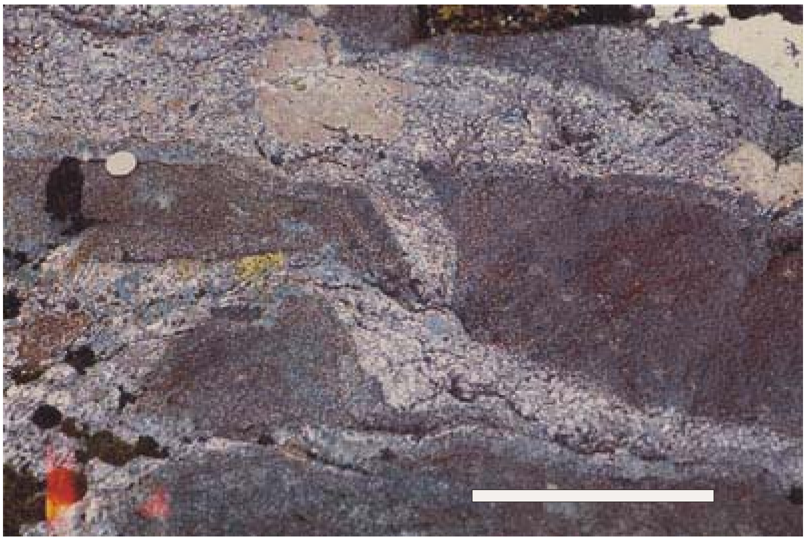

Figure 5.2. Lewisian migmatites (agmatites) exposed on rock pavements on the north side of Loch Assynt. Coarse-grained white granitic neosome supporting disrupted and rotated, angular hornblendic gneiss fragments. Partial assimilation of the older rock can be seen on the margins of each fragment. Note the absence of a gneissic fabric in the granitic rock and the lack of ductile fabrics in the palaeosome. [NC19369 27828]. White scale bar is about 25cm long. BGS Photo P517134.

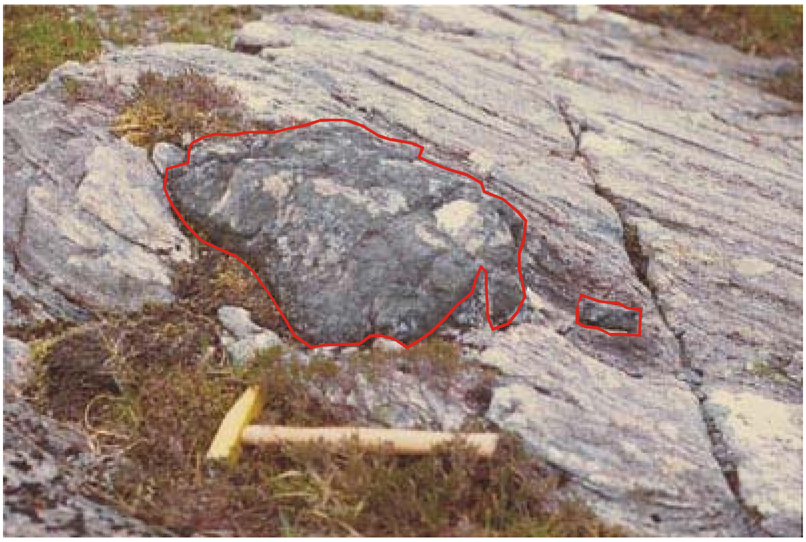

Figure 5.3. Lewisian migmatites exposed on rock pavements on the north side of Loch Assynt. A typical rounded ultramafic pod and detached angular clast (outlined in red) in hornblende-gneiss that has a mm-thick gneissic fabric. [NC19369 27828]. BGS Photo P517135

Figure 5.4 Granitic vein network in Lewisian hornblende-gneiss west of Quinag. The gneiss is relatively undeformed compared to the gneiss seen immediately to the south (towards Loch Assynt). Partial assimilation of the host hornblende-gneiss can be seen. [NC17556 30393]. White scale bar is about 15cm long. BGS Photo P517139

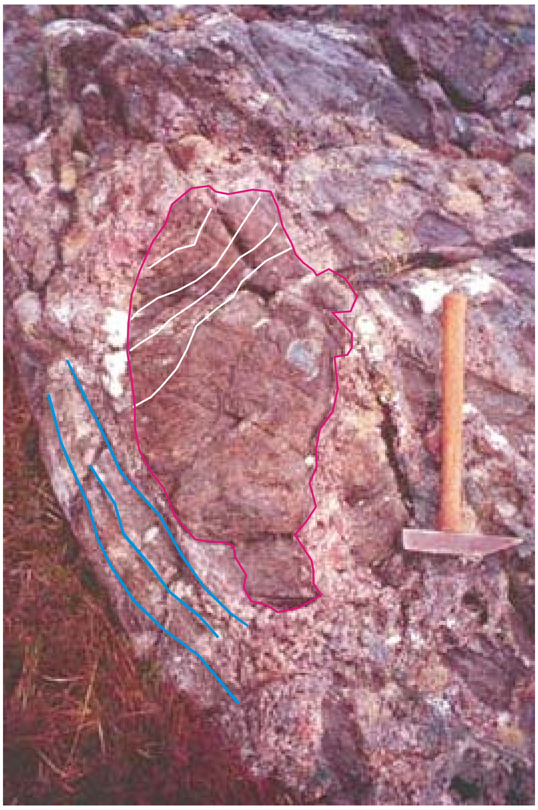

Figure 5.5 Metagabbroic pod (outlined in red) in variably hornblendic granite gneiss to the south of Suilven. There is a layering (white lines) in the pod that is at a high angle to the gneissosity (blue lines) in the surrounding rock. [NC 15864 17332]. BGS Photo P524523.

Figure 5.6. Mafic (amphibolitic) pod flattened in the gneissic fabric in gneiss exposed to the south of Suilven. [NC15864 17332]. BGS Photo P524520.

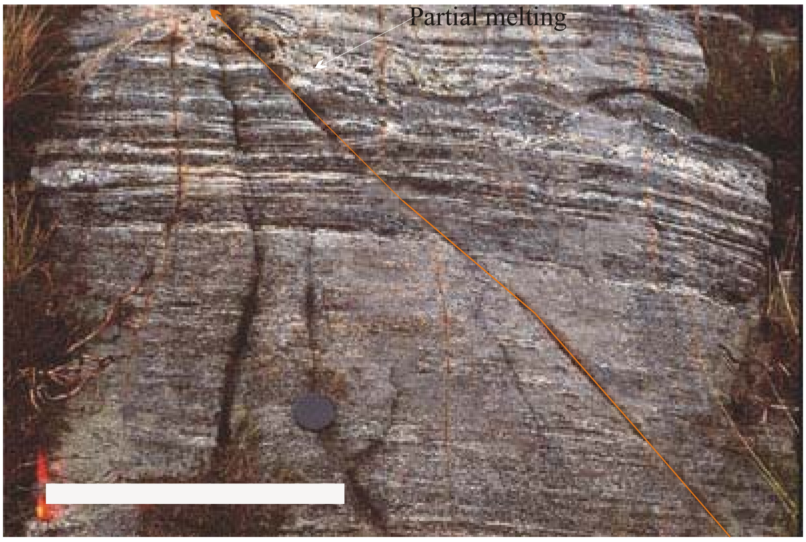


Figure 5.7. 1 mile east of Nedd. Lewisian gneisses with white felsic veins accentuating the fabric and with boudinaged mafic seams. The gneiss in the lower half of the picture has a mm-thick gneissosity with minor amounts of parallel felsic veins. By contrast the gneiss in the upper half of the exposure is full of felsic veins. The regular gneissosity is locally disrupted where the grain size increases, possibly related to partial melting during metamorphism. A brittle normal micro-fault (outlined in red) cuts through the centre of the picture. [NC 15553 31430]. White scale bar is about 30cm long. BGS Photo P517166.

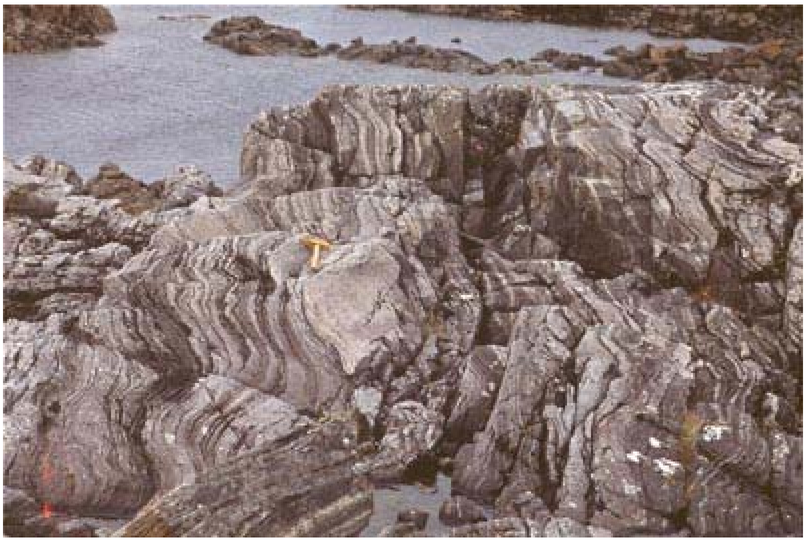

Figure 5.8. 1.5 miles NE of Nedd. Asymmetrically folded Lewisian stromatic gneiss with variably oriented folds. Here the gneissosity is on a centimetre or greater scale in contrast to the finer fabric seen in the hornblende-gneiss to the south close to Loch Assynt. [NC 15117 33686]. BGS Photo P517175.

Figure 5.9. NW of Suilven in the Canisp Shear Zone. Strongly deformed (and bleached) Lewisian gneiss. Hornblende gneiss with a strong, mm-thick, planar fabric accentuated by lenticular pods (prolate ellipsoids) of amphibolite. The primary relationship between the gneiss and amphibolite has been obliterated by the intense flattening deformation. [NC15015 20466]. Hammer handle (for scale) is just visible in grass at base of exposure. BGS Photo P517148.

Figure 5.10. 1 mile east of Nedd. Lewisian gneiss with two gneissic fabrics. An early gneissosity is asymmetrically folded with shearing along flat-lying limbs. A new gneissosity, defined by segregation of felsic lenses, locally develops in the shears. The new gneissosity can be seen immediately above the hammer handle in the photograph. [NC 15312 31575]. BGS Photo P517168

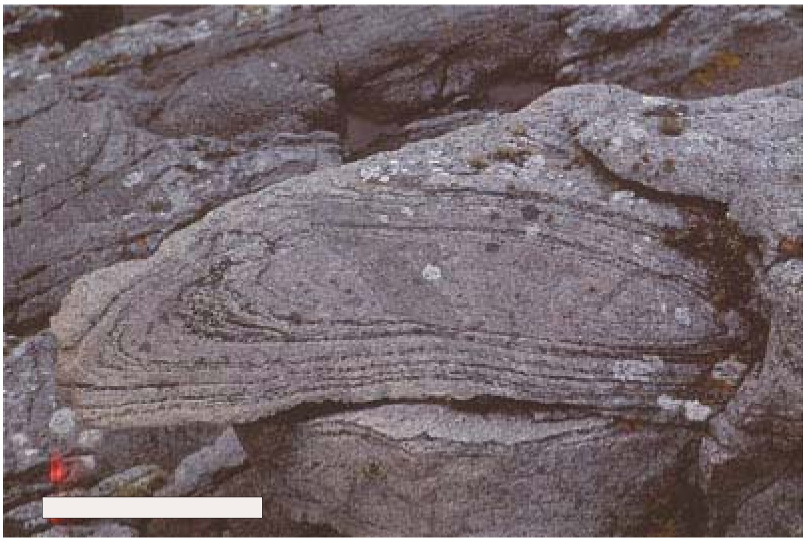

Figure 5.11. 1.5 miles NE of Nedd. Sheath fold in Lewisian gneiss. The axis of the fold trends towards 317º (into the picture). The white scale bar is about 30 cm in length. [NC15117 33686]. BGS Photo P517172.

Plate 5.12 Asymmetrical folds defined by quartz-rich seams in granitic gneiss south of Suilven. Lenticular amphibolite pods are visible on the extreme right side of the picture. [NC 15864 17332]. BGS Photo P524524.