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## Allt na Caillich (Ben Hope)

[NC 464 455]

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### Introduction

At the Allt na Caillich GCR site on the eastern flank of Strath More, a spectacular waterfall and cliff section through the Ben Hope Thrust is exposed. This structure is one of the main Caledonian ductile thrusts within the A' Mhoine Nappe in Sutherland (Figure 6.3), (Figure 6.4). It formed under lower amphibolite-facies conditions. It carries an intensely deformed sheet of Lewisianoid gneisses in its immediate hangingwall and, above this, the southernmost exposures of the 'Ben Hope Sill'. This Early Neoproterozoic, pre-metamorphic mafic sheet is one of the largest examples of the regional Ben Hope Suite. The asymmetric distribution of lithologies is typical of ductile thrusts in the Moine succession (Holdsworth, 1989a). During the primary mapping carried out in the region by the Geological Survey (Geikie, 1888; Peach *et al.*, 1907), a prominent belt of garnetiferous hornblende and micaceous schists was recognized running southwards from the Kinloch River, around the northern and western flanks of Ben Hope, and down into Strath More. At least some of these rocks were considered to be of metamorphosed igneous origin (Geikie, 1888; Read, 1931); they became generally known as the 'Ben Hope Sill' (e.g. Moorhouse and Moorhouse, 1979). Read (1931, pp. 29 and 84) also suggested that a thrust ran around the western face of Ben Hope based on the reported occurrence of 'Eireboll Schists' (= mylonites?) by H.M. Cadell in 1886 in the north-west face of the mountain. Several authors refer briefly to the presence of a sheet of highly deformed Lewisianoid rocks on Ben Hope (e.g. Peacock, 1975; Floyd and Winchester, 1983; Evans and White, 1984; Winchester and Floyd, 1984), but more recently Holdsworth (1987, 1989a) and Grant (1989) have carried out detailed mapping of this Lewisianoid inlier and the Ben Hope Sill amphibolites. These authors have shown that the lower contact of the inlier is the Ben Hope Thrust, a structure that can be traced for over 25 km from the north coast (see Melness GCR site report, this chapter) to Allt na Caillich. Prior to orogenesis, the intrusion of the main sill occurred along the Moine–Lewisianoid unconformity, but Holdsworth (1987) showed that the Ben Hope Sill was both regionally and locally discordant. Geochemical studies of the Ben Hope Suite (Moorhouse and Moorhouse, 1979; Floyd and Winchester, 1983; Winchester and Floyd, 1984) showed that, despite pervasive amphibolite-facies metamorphism, the sills still have fractionated tholeiitic basaltic compositions with affinities to within-plate basalts, transitional towards plate-margin types. Evans and White (1984), Grant (1989) and Holdsworth and Grant (1990) describe textural and quartz c-axis orientation data from the psammites associated with the Ben Hope Thrust from the Kyle of Tongue southwards to Allt na Caillich.

### Description

The Allt na Caillich flows over a waterfall at the southern end of the NNE-trending cliffs of Leitir Mhùiseil (Figure 6.12), (Figure 6.13) at [NC 464 455], some 5 km SSW of Ben Hope summit; most of the key exposures for this site lie within or adjacent to these cliffs. The Ben Hope Thrust overlies a thick succession of Moine psammite. In its hangingwall are the following units (from base to top): Lewisianoid-derived mylonites, a thin sliver of Moine psammite, the Ben Hope Sill amphibolite, overlain by garnetiferous mica schist. Above this lies another thick succession of Moine psammites. All the units have a shallow dip to the ESE and were deformed under lower-amphibolite- to upper-greenschist-facies metamorphic conditions. Exposed contacts are sharp apart from the boundary between the mica schist and the overlying psammites, which is gradational. The Lewisianoid gneisses, Ben Hope Sill and mica schist units all progressively thin towards the south and appear to peter out where the Ben Hope Thrust intersects the Allt Dornaigil stream section 0.5 km to the south of Allt na Caillich.

The Moine psammites below the Ben Hope Thrust comprise several hundred metres of cleaved, lithologically monotonous feldspathic psammites, which are well exposed in the Allt na Caillich stream section up to the waterfall. They are part of the A' Mhoine Psammite Formation (Holdsworth *et al.*, 2001). Traces of primary bedding are poorly preserved,

although rare pebbly lenses and heavy-mineral layers are present locally. On approaching the thrust plane, the psammites become increasingly flaggy, finer-grained and more muscovite-rich, reflecting the increasing strain, until all traces of original planar discordances disappear. The razor-sharp lower contact between the psammites and Lewisianoid rocks is well exposed in the waterfall section, in the cliffs of Leitir Mhuisseil for 250 m to the north and in the small, tributary stream section to the south (location 'a' in (Figure 6.12)). The Lewisianoid rocks comprise a heterogeneous sequence of mainly dark-coloured, fine-to medium-grained, laminated, sometimes platy schists derived from intense deformation and shearing of interlayered felsic and mafic gneisses. Dark green-black, schistose amphibolites form the dominant lithology in the lower two-thirds of the Lewisianoid unit. They differ petrologically from the Ben Hope Suite as they generally lack garnet and contain abundant pyrite and chalcopyrite crystals up to 2 mm across; large veins of coarse-grained calcite are also locally present. Lenses of speckled hornblende-biotite schist up to 10 cm thick occur throughout the Lewisianoid rocks and are thought to represent dioritic or possibly thin altered mafic gneisses. Striped felsic units dominate the upper third of the Lewisianoid outcrop, although thin horizons are found throughout the sequence. They typically contain numerous concordant lenticles of pink, potash-feldspar-rich material thought to be deformed migmatitic segregations or granitic/pegmatitic veins (Holdsworth, 1987). Small, centimetre-scale hornblendite pods are a subordinate but characteristic additional lithology. In the waterfall and location 'a' sections, the 12–15 m-thick Lewisian sequence is overlain by 0.5 m of platy Moine psammite which is in turn overlain by a concordant, 2.0 m-thick unit of schistose garnetiferous amphibolite, the Ben Hope Sill (Figure 6.12). This comprises interlayered units of highly foliated fine- to medium-grained garnet-rich amphibolite and more-massive horizons of coarse-grained, garnet-poor amphibolite in which individual hornblende laths reach 2 cm in length. At the top of the cliff, the amphibolites are overlain by a 1–2m-thick unit of grey, medium-to coarse-grained garnetiferous mica schist with occasional hornblende prisms up to 1.5 cm long. In the Allt na Caillich stream section, this unit is biotite-rich at the base, becoming richer in white mica upwards; it then passes gradationally into schistose Moine psammites above. A further thin (0.5 m), concordant unit of fine- to medium-grained garnetiferous amphibolite occurs within the psammites 140 m upstream. Otherwise, the upper sequence of Moine psammites is similar to the lower succession, although primary bedding structures and occasional cross-laminations are preserved showing that the sequence here is right-way-up (Figure 6.12), (Figure 6.14). These upper psammites are part of the Altnaharra Psammite Formation (Holdsworth *et al.*, 2001).

The main penetrative tectonic fabric (S2) defined by the alignment of mineral grains and elongate mineral aggregates lies mainly parallel to the bedding/layering, and dips are uniformly shallow towards the ESE, although there are some minor local variations due to the effects of later open folding. The dominant mineral-stretching lineation (L2) that plunges uniformly to the ESE (Figure 6.12) is defined by aligned and elongate mineral aggregates. In most of the rocks for 50–100 m above and below the Ben Hope Thrust, the D2 L–S fabric is mylonitic, although widespread secondary recrystallization gives the textures an annealed appearance in thin section (Grant, 1989; Holdsworth and Grant, 1990). Folds are largely absent from the psammites in the site area, but locally sets of ESE-verging brittle kink- and box-folds are seen, for example in the Allt Dornaigil stream section [NC 459 450]. Isolated examples of centimetre-scale, close to tight minor F3 folds occur in the intensely deformed Lewisianoid gneisses and Ben Hope Sill amphibolite units, where they are seen to fold both S2 and L2. More-open F3 folds of this scale are also widespread in the garnetiferous mica schist unit. F3 plunge and vergence patterns are variable and the folds are typical products of progressive deformation in high-strain zones (Holdsworth, 1990). Some F3 folds are seen to be associated with discrete shear-zones orientated oblique to the main foliation which lead to the localized development of an anastomosing foliation in lower parts of the Lewisianoid unit (Grant, 1989). Shear-sense criteria visible in the field include shear-band fabrics, asymmetrical wrapping of porphyroblasts and F3 fold asymmetry; all consistent with overall top-to-the-WNW displacement.

## Interpretation

The Ben Hope Thrust lies at the lower contact of the Lewisianoid unit and can be traced northwards along the Leitir Mhuisseil cliffs where the presence of further Lewisianoid inliers shows that this thrust plane is the uppermost of three dislocation surfaces (Figure 6.14); the overlying Ben Hope Sill also thickens to over 100 m. These thrusts can be traced northwards into the steep western scarp of Ben Hope where they merge together to form a single Ben Hope Thrust plane. Thus the lower section of psammites at Allt na Caillich probably contains several ductile thrusts, but only the uppermost, and largest displacement surface is obvious due to the presence of the basement thrust slice and overlying Ben Hope Sill amphibolite. Ductile thrust ramp angles are uniformly low (< 5°) in the Leitir Mhuisseil–Ben Hope area, and

at several locations the Ben Hope Sill amphibolite sits directly on the thrust plane (Figure 6.14). This may occur either because the thrust has cut up-section laterally in the hangingwall or because the original basic sill intrusively cut down into the Lewisianoid below. The low ramp angles are typical for the region and reflect the intense, pervasive nature of the strains associated with ductile thrusting. Due to the lack of an extensive regional topography, it is difficult to determine accurately the position of any frontal hanging-wall or footwall cut-offs. It is difficult, therefore, to estimate displacements across ductile thrusts or to quantitatively restore a deformed cross-section. However, the topography of Ben Hope does permit a minimum displacement estimate of 7.55 km to be made for the Ben Hope Thrust (Holdsworth, 1989a, fig. 2).

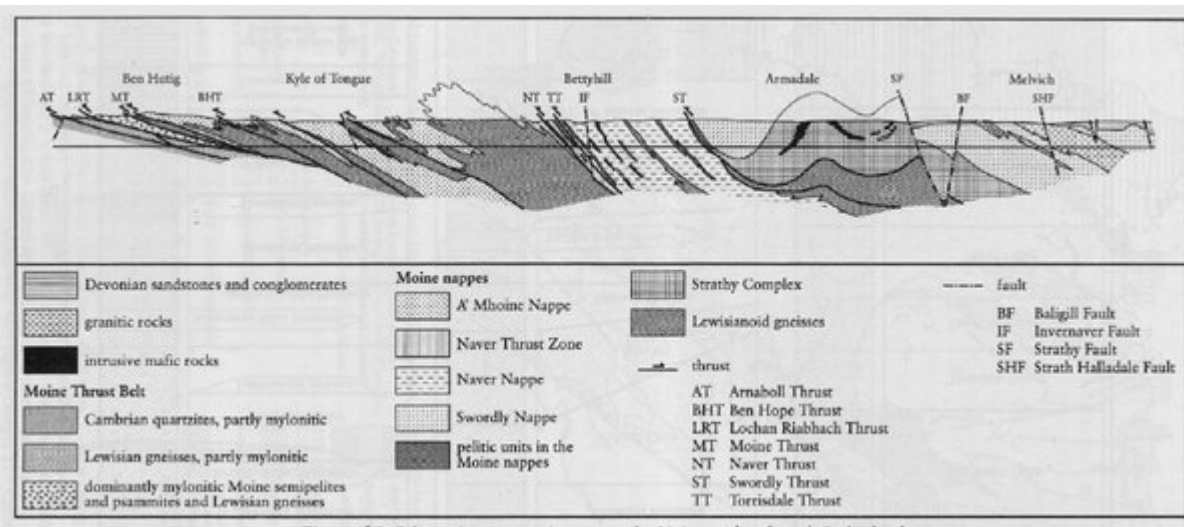
The garnetiferous mica schist is typical of a lithology closely associated with the margins of some Moine amphibolites and Lewisianoid inliers interlayered with Moine psammites in Sutherland (the 'tectonic schists' of Peacock, 1975). Floyd and Winchester (1983) and Holdsworth (1987) have suggested that such schistose units form due to retrogression and metasomatism of amphibolites and adjacent psammites associated with the focused flow of hydrous fluids within shear zones.

The structurally simple nature of the platy rocks in the footwall and hangingwall of the Ben Hope Thrust is attributed to intense ductile deformation. The observed metamorphic assemblages (e.g. hornblende-biotite-garnet-albite-epidote in amphibolites) and annealed mylonitic textures are consistent with deformation under lower-amphibolite- to uppermost greenschist-facies metamorphic conditions (Holdsworth, 1987; Grant, 1989, Holdsworth and Grant, 1990). Evans and White (1984) measured the quartz c-axis orientations from a specimen of psammite adjacent to the Ben Hope Thrust and showed that they displayed asymmetric girdle patterns similar to those obtained from the mylonites of the Moine Thrust Belt. Grant (1989) carried out a detailed microstructural and quartz c-axis orientation study in the section between Ben Hope and Allt na Caillich. His results suggested that deformation associated with the Ben Hope Thrust was heterogeneously distributed, with distinct domains of coaxial and non-coaxial (mainly top-to-the-WNW) shear that changed location with time. He also found microstructural evidence for localized domains of top-to-the-ESE shearing, at least some of which formed late in the deformation history due to extensional reactivation along the foliation. This event probably relates to the late Caledonian phase of top-to-the-ESE shear recognized by Holdsworth (1989a) in the Kyle of Tongue region to the north.

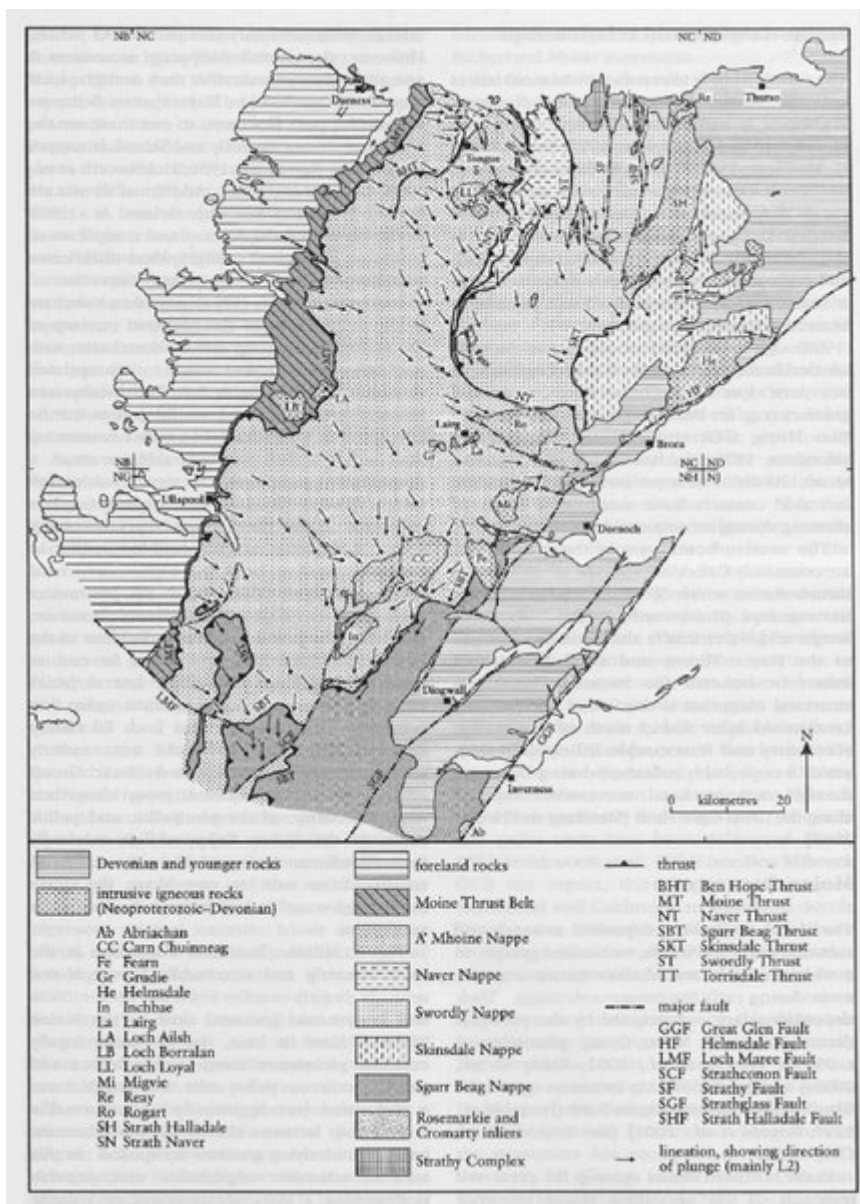
## **Conclusions**

The Allt na Caillich site is of national importance as it preserves a spectacular vertical section through the Ben Hope Thrust, a major, low-angle Caledonian ductile fault formed at mid-crustal depths in the Moine succession of Sutherland. The site displays a sequence of intensely deformed Lewisianoid basement gneisses typical of those found in the hanging-walls of ductile thrusts in western Sutherland. The southernmost part of the Ben Hope Sill is also exposed lying close to the upper contact of the Lewisianoid inlier and is overlain by a typical example of a metasomatic 'tectonic schist' (Peacock, 1975). The site is good for teaching as it displays a typical and lithologically diverse sequence of annealed mid-crustal mylonites deformed under lower-amphibolite- to uppermost greenschist-facies conditions.

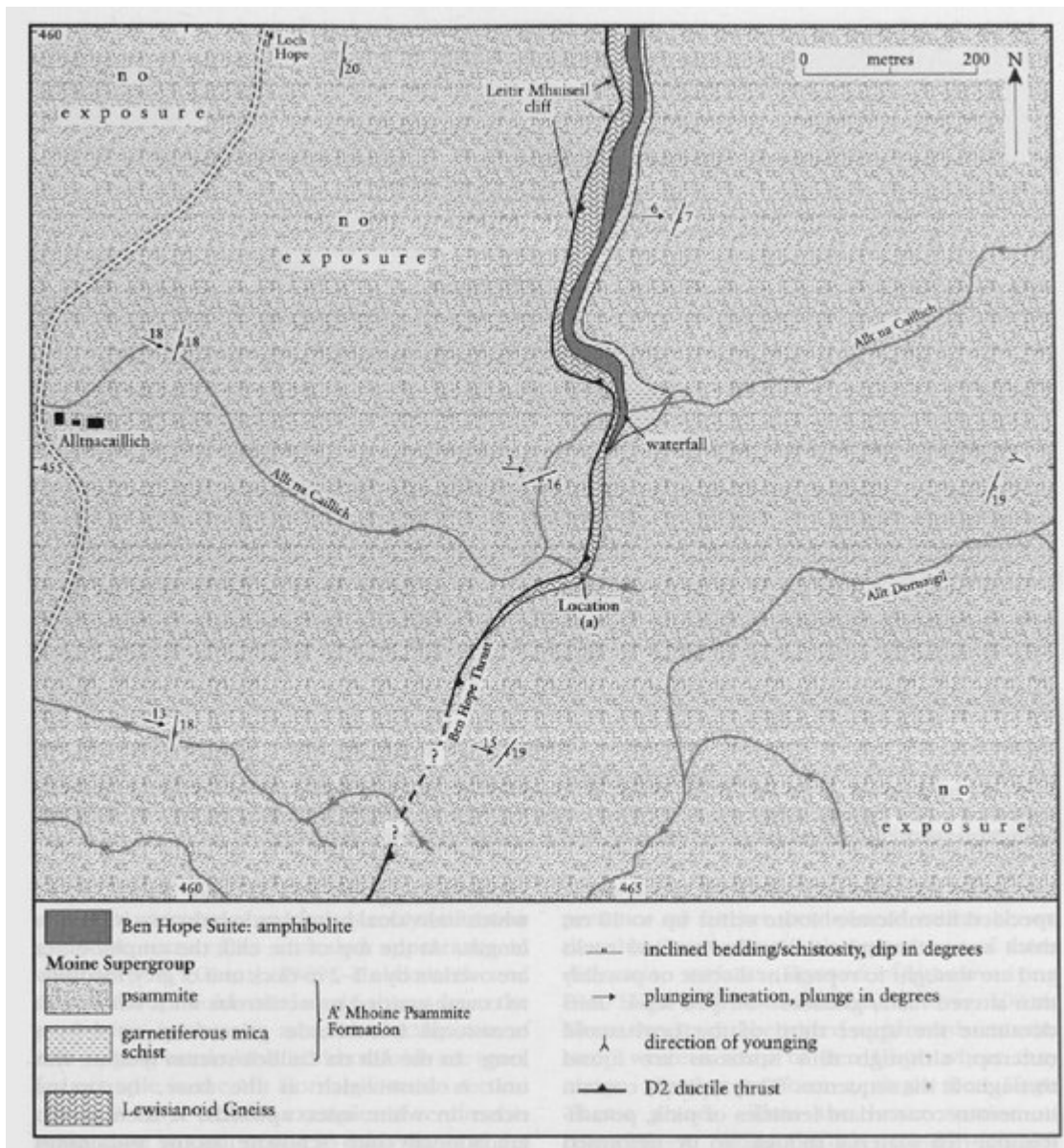
## **References**



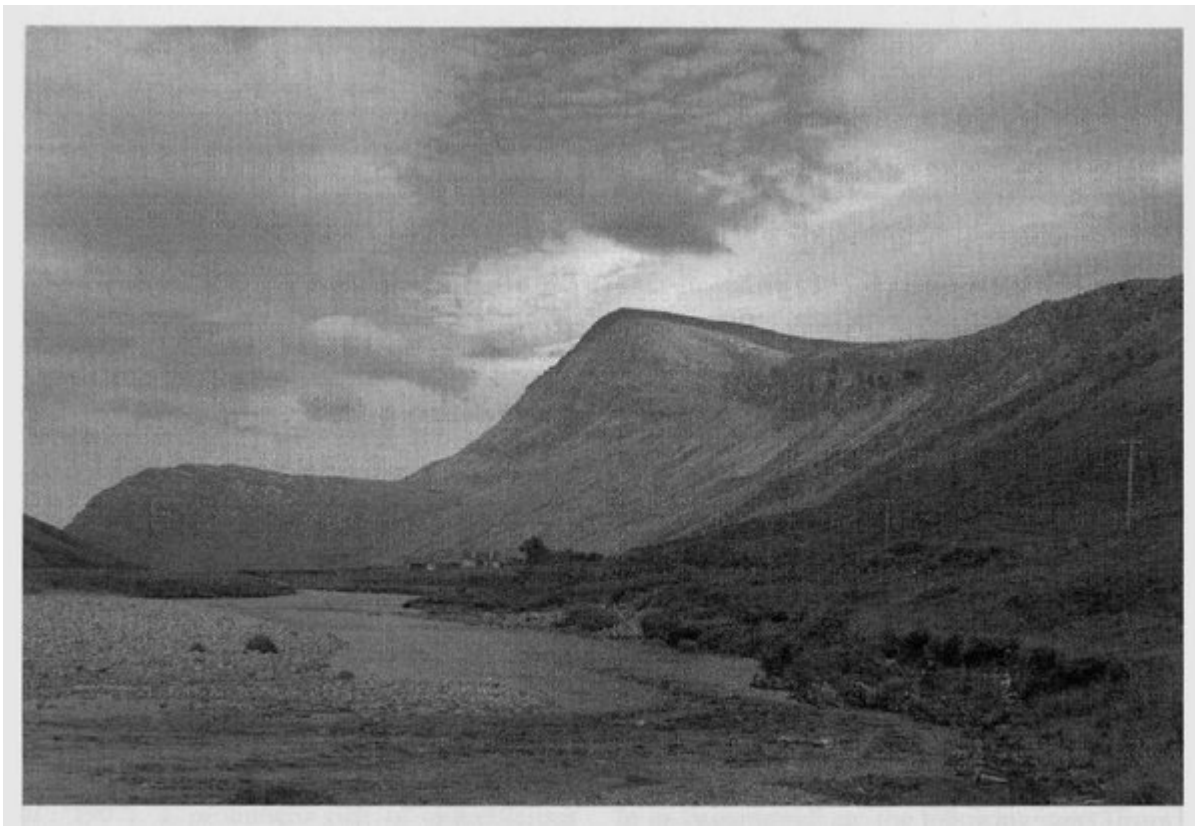
(Figure 6.3) Schematic cross-section across the Moine rocks of north Sutherland.



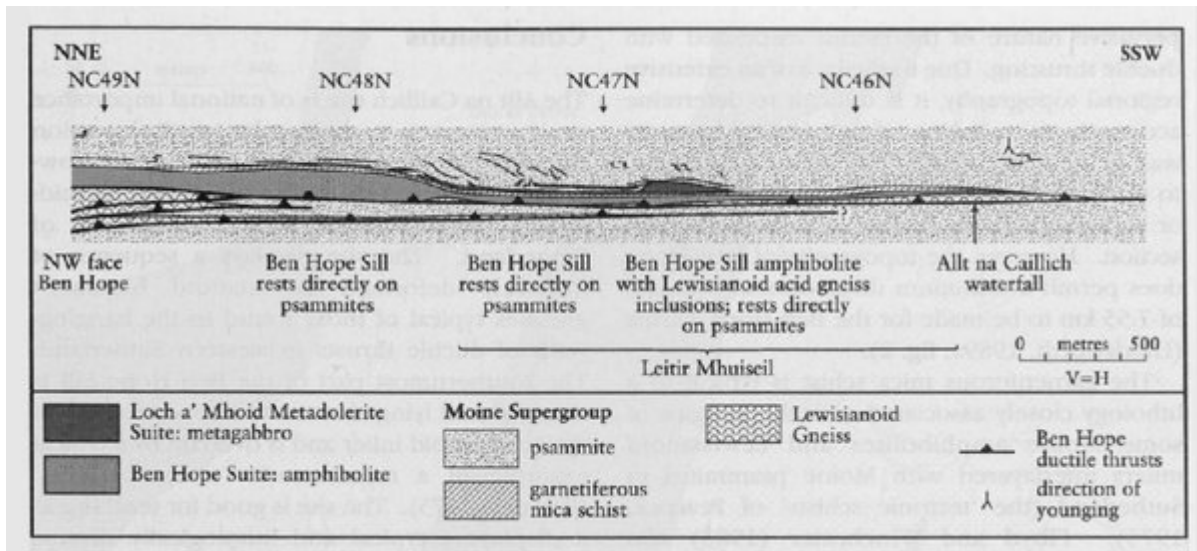
(Figure 6.4) Tectonostratigraphy of the Moine (North) area.



(Figure 6.12) Map of the Allt na Caillich GCR site.



(Figure 6.13) View north from Dun Dornaigil to Allnacaillich farm and Ben Hope. The Ben Hope Sill and Lewisianoid gneisses form the mid- and upper parts of the prominent cliffs of Leitir Mhuiseil to the right. They lie in the hangingwall of the Ben Hope Thrust with gently E-dipping psammites of the Moine Psammite Formation in the footwall below and in the bluff to the left. (Photo: British Geological Survey, No. P002763, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 6.14) NNE-SSW longitudinal cross-section showing thickness changes and lateral branching of the Ben Hope Thrust that occurs between the north-west face of Ben Hope and Allt na Caillich, including the cliffs of Leitir Mhuiseil. After Holdsworth (1989a, fig. 4).