Ben Klibreck

[NC 574 343]–[NC 585 299]

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Introduction

The Ben Klibreck site is an important area for the study of basement–cover relationships and ductile thrust tectonics within the Caledonian orogenic belt of northern Scotland (Moorhouse, 1977; Barr *et al.,* 1986; Strachan and Holdsworth, 1988). The site is also of historical importance because of its contribution to early studies of migmatites (Read, 1931). West of Ben Klibreck, psammites and semipelites of the Morar Group (Moine) are interfolded with highly reworked orthogneisses broadly correlated on lithological and geochemical grounds with the Lewisian Gneiss Complex of the Caledonian Foreland (Read, 1931; Soper and Brown, 1971; Moorhouse, 1977; Barr, 1983; Strachan and Holdsworth, 1988; Friend *et al.,* 2008). Eastwards and structurally upwards, these Lewisianoid gneisses are overlain by Moine psammitic and semipelitic gneisses that contain thin, highly tectonized slices of similar Lewisianoid basement orthogneisses. Three main ductile thrusts can be identified, the Naver, Torrisdale and Swordly thrusts. The upper slopes of Ben Klibreck are composed mainly of migmatitic Moine semipelitic and pelitic gneisses of the Bettyhill Banded and Loch Coire formations. Granites and pegmatites intrude this structural succession and become progressively more-abundant eastwards in the site area, particularly within the overlying migmatitic Moine rocks (Figure 6.34).

Differing opinions have been expressed on the nature of the boundaries between the various Moine rocks and on the origin of, and relationships between, the migmatites, granites and pegmatites. Read (1931) considered that there was a transition from unmigmatized to migmatitic rocks, and Soper and Brown (1971) concluded that this represents a prograde but inverted metamorphic gradient. Brown (1967, 1971) interpreted the geochemistry of the migmatites to indicate that they formed *in situ* as a result of sodium metasomatism, with the granites and pegmatites providing channel ways for the infiltration of sodic fluids. Contrasting mechanisms proposed for the formation of these and related migmatites in Sutherland include subsolidus segregation (Barr, 1985) and partial anatexis (Burns, 1994; Watt *et al.,* 1996). The present consensus view is that Caledonian displacement along the ductile Naver Thrust emplaced migmatitic gneisses onto unmigmatized rocks giving the apparent metamorphic inversion, and that the granites and pegmatites were intruded at various stages during and following thrusting (Moorhouse, 1977; Barr, 1983, 1985; Strachan and Holdsworth, 1988). If the Moine migmatites are mainly Neoproterozoic in age (cf. Barr *et al.,* 1986), then a genetic relationship between these and the Caledonian granites and pegmatites is clearly unlikely. U-Pb zircon isotopic data indicates that the Moine migmatites in Sutherland may well be Caledonian in age (Kinny *et* at, 1999), and hence a re-appraisal of the petrogenetic relationship between the migmatites, granites and pegmatites is appropriate.

Description

The site area stretches from the low undulating peaty ground on the eastern side of Strath Vagastie to the steep W-facing rocky slopes of Ben Klibreck up to its summit at Meall nan Con (961 m). The low undulating ground that lies west of Ben Klibreck is underlain mainly by Moine psammites but includes several Lewisianoid gneiss inliers ((Figure 6.34); Moorhouse, 1977; Strachan and Holdsworth, 1988). The bedding and regional foliation within these rocks both dip gently to moderately to the ESE. The most extensive outcrops of Lewisianoid rocks form part of the Naver Inlier that thickens markedly to the north. The main lithology is a layered felsic and mafic orthogneiss characterized by the alternation of quartz-plagioclase feldspar and hornblende-rich (locally with garnet and biotite) layers normally on a scale of 0.5–2cm (Figure 6.35). With increasing tectonic strain, the mafic gneiss takes the form of pods and layers of hornblende-biotite schist. Small pods of ultramafic lithologies are present locally, and include hornblendite (e.g. at [NC 563 304]), and talc-tremolite rocks with serpentine (e.g. at [NC 591 336]).

The Moine rocks in the western part of the site area belong to the Altnaharra Psammite Formation (Moorhouse, 1977), part of the Morar Group (see (Figure 6.2)). They are mostly pale-grey to pink, medium-grained, flaggy to blocky, thinly

bedded, feldspathic and micaceous psammites with subsidiary schistose garnet-biotite setnipelite and pelite interbeds and some striped siliceous psammite units. The layering in the psammites is generally modified bedding, but sedimentary structures are rare. In places, the psammites contain 1–5mm-thick layers of quartz, plagioclase and microcline clasts. Pods and ribs of pale-grey, hornblende-garnet-bearing calc-silicate are also present (e.g. at [NC 560 307]), indicating that the rocks have been subject to at least lower amphibolite-facies metamorphism. Lensoid masses of variably foliated amphibolite, up to 5 m thick, occur locally (e.g. [NC 567 308]) and probably represent deformed and metamorphosed basic intrusions. These mafic sheets are a southerly extension of the Ben Hope Suite. Contacts between the Moine and Lewisianoid units are sharp and normally concordant, but are not apparently marked by abnormally high tectonic strains.

Two phases of deformation, D1 and D2, have been identified in the Moine. The dominant structures are of D2 age and are represented by tight to open folds. Many of these have a reclined attitude and F2 fold axes lie parallel to a SE- to SSE-plunging L2 mineral and extension lineation. Shear bands and asymmetrical quartz-feldspar augen indicate a general top-to-the-NW direction of tectonic transport parallel to L2. F2 folds display large- and small-scale curvilinear hinge geometries characteristic of 'sheath folds' (Strachan and Holdsworth, 1988). A bedding-parallel S1 mica fabric passes around the hinge zones of the F2 folds, within which the axial-planar S2 fabric is seen as a tight crenulation cleavage in semipelitic and pelitic units. Minor F1 folds are rare. Prominent folds deform the western boundary of the Naver hiller and these are designated F2 (Figure 6.34). The three smaller Lewisianoid inliers that lie west of Ben Klibreck occupy the cores of major F2 antiforms that have been modified locally by ductile thrusts developed during folding (Strachan and Holdsworth, 1988). In the Lewisianoid gneisses a pervasive hornblende lineation orientated sub-parallel to L2 in the Moine rocks is commonly seen.

A major D2 ductile thrust, the Naver Thrust, is located along the base of the steep western slope of Ben Klibreck (Figure 6.34). This was first identified here by Moorhouse (1977) and forms the type locality. In the north of the Ben Klibreck site, this thrust is marked by a sharp contact between Lewisianoid rocks (Naver Inlier) and the overlying, coarse-grained gneissose psammitic to semipelitic Klibreck Psammite Formation ((Figure 6.2); Strachan and Holdsworth, 1988). Traced southwards, the easternmost 'arm' of the Lewisianoid outcrop diverges from the Naver Thrust so that a very narrow strip of Altnaharra Psammite intervenes (Figure 6.34). Here, a thin allochthonous slice of Lewisianoid gneisses lies along the thrust plane. F2 folds within the Altnaharra Psammite and the Naver Lewisianoid rocks progressively tighten towards the thrust, and for 20–30 m below the thrust the Moine and Lewisianoid rocks exhibit an intense blastomylonitic S2 schistosity sub-parallel to the thrust plane.

The Moine rocks of the Klibreck Psammite Formation are compositionally similar to the Altnaharra Psammite Formation. However, they are noticeably coarser-grained (*c.* 2 mm vs *c.* 1 mm grain diameter) and contain numerous concordant quartz-feldspar segregations, features absent in the Moine rocks west of the Naver Thrust. The precise metamorphic grade is uncertain but comparison with other Moine gneisses suggests they were deformed and metamorphosed under middle amphibolite-facies conditions (Barr, 1983). The gneissose fabric, termed 'S1', is deformed by attenuated, tight to isoclinal F2 folds whose axial plunge varies from gently to the ESE to gently to the SSW D2 linear fabrics are rather weakly developed by comparison with those present west of the Naver Thrust; this probably results from continued grain-size coarsening and annealing within these higher-grade rocks during and following D2 deformation. Two sheets of Lewisianoid gneisses outcrop along strike from each other approximately halfway up the north-western slope of Ben Klibreck (Figure 6.34). Similar Moine lithologies occur on either side of these inliers, suggesting that they could be occupying fold cores. However, they occur at the same structural level as the ductile Klibreck Thrust (D2) identified some 3 km farther south (Strachan and Holdsworth, 1988). Hence, it seems more likely that they are allochthonous sheets marking the northward extension of this structure. The Klibreck Psammite Formation is confined to the Naver Thrust Zone and hence is equivalent to the Druim Chuibhe Psammite Formation farther north (see Aird Torrisdale GCR site report, this chapter).

The Klibreck Psammite Formation is overlain tectonically on the western slopes of Ben Klibreck by the Bettyhill Banded Formation, which comprises migmatitic semipelitic, pelitic and striped psammitic gneisses with small calc-silicate pods, with lenticular garnetiferous amphibolite bodies (Figure 6.34). The lower contact of the Loch Coire Formation is a major D2 ductile thrust, the Torrisdale Thrust, which has been mapped southwards from the north coast (British Geological Survey, 2004c; see Aird Torrisdale GCR site report, this chapter). Barr *et al.* (1986) mistakenly correlated this structure with the Swordly Thrust. The Torrisdale Thrust is marked by a sharp contact between striped psammite and semipelite

(Klibreck Psammite Formation) and gneissose psammite (Bettyhill Banded Formation) along which discontinuous slices of mafic and felsic Lewisianoid gneisses occur. The lower parts of the Bettyhill Banded Formation carry a strongly blastomylonitic layering and sparse SSE-plunging F2 tight to isoclinal folds. Sub-parallel L2 lineations are once again weak, owing to the strong syn-to post-D2 recrystallization and grain-size coarsening. The migmatitic layering and early isoclinal folds (F1?) are both deformed by the F2 folds. The local preservation of pyroxene and brown hornblende within amphibolite lenses and pyroxene–bytownite assemblages in calc-silicate lenses indicates that the rocks have undergone middle amphibolite-facies metamorphism (Barr *et al.,* 1986; Strachan and Holdsworth, 1988).

Above the Bettyhill Banded Formation lies the Swordly Thrust, whose trace just clips the summit of Ben Klibreck, Meall nan Con (961 m). Overlying the thrust are migmatitic pelites and semipelites of the Loch Coire Formation, containing biotite, muscovite and garnet. Only minor interbanded psammite units are seen in this lower part of the unit. Quartz and quartz-feldspar segregation veins and pods are abundant in these coarsely foliated gneissose rocks, and leucotonalitic and granitic veining and patches are also present.

The Moine rocks of the Ben Klibreck site area are intruded by discrete sheets of granite (*sensu lato)* and pegmatite. These intrusions are generally absent 1–2km west of the Naver Thrust, but become progressively more-common eastwards until they are locally abundant within the Klibreck Psammite, Bettyhill Banded and Loch Coire formations. Barr (1985) divided these intrusions into three 'suites' on the basis of their structural relationships. The earliest is represented by a series of subconcordant, pink granitic 'sills'. These range from 10 cm to 30 m in thickness and are clearly intrusive, with disorientated xenoliths and pegmatitic apophyses that cross-cut the bedding in the adjacent country rocks. The most prominent is the Ben Klibreck Sill, a pink biotite granite and granodiorite with hornblendic dioritic patches, which crops out within the Klibreck Psammite Formation (Figure 6.34). Kinny *et al.* (2003b) obtained U-Pb SHRIMP ages from zircons and U-Pb TIMS ages from titanites from the Klibreck Sill. Inherited zircon cores gave ages ranging from *c.* 1200 Ma to 1800 Ma, but the rims gave a $^{206}Pb–^{238}U$ age of 420 ± 6 Ma, taken as the age of intrusion. Titanite ages of 416 ± 3 Ma overlap the zircon rim ages. These intrusions cut F2 folds of bedding but carry a penetrative L–S fabric defined by quartz ribbons and feldspar augen and which is parallel to S2. Emplacement is interpreted as syn- to late-D2. They are normally granites or granodiorites and comprise plagioclase ($An_{20}–An_{32}$), microcline, quartz and biotite with accessory hornblende, titanite, magnetite and zircon. The second 'suite' is represented by a series of slightly discordant granitic and pegmatitic granite veins, which range from a few centimetres to a few metres in thickness and have generally N-dipping contacts. They consist of approximately equal proportions of quartz, microcline and plagioclase. They contain a weak S2 fabric, defined by quartz ribbons that wrap perthite and antiperthite porphyroclasts; intrusion probably occurred during the late stages of D2. Finally, very coarsely pegmatitic (several centimetres grain size), graphic-textured, quartz-albite-microcline leucogranites showing little or no internal deformation, crosscut all folds and foliations. They were evidently emplaced after D2 deformation had ceased. The first and second of these intrusive suites probably represent parts of one essentially continuous phase of syn-D2 magmatism. Some intrusions are peraluminous and may have formed from melting of Moine metasedimentary rocks or parts of the Lewisianoid basement, whereas the more-granodioritic members have normal I-type mineralogies.

Interpretation

The site contains three features that make it particularly significant:

1. variable basement–cover relationships;

2. a major ductile thrust zone associated with the emplacement of high-grade, migmatitic Moine gneisses onto lower-grade, non-migmatitic Moine rocks;

3. syn- to post-tectonic Caledonian granitic rocks emplaced during and after ductile thrusting.

The Lewisianoid basement rocks occur in two distinct structural settings. The basement west of the Naver Thrust occurs in the cores of F2 antiforms as a series of paraautochthonous inliers. The absence of high-strain tectonic fabrics along the contacts with the Moine psammites suggests that these contacts are modified unconformities (Strachan and Holdsworth, 1988). The gneissic layering characteristic of the Lewisianoid inliers is a relic of the Archaean and/or

Proterozoic high-grade metamorphic events that affected these basement rocks prior to deposition of the Moine sediments. The Lewisianoid inliers east of the Naver Thrust are allochthonous sheets that apparently rest on ductile thrusts, but their upper contacts may also represent modified Moine–Lewisianoid unconformities.

Read's (1931) conclusion that the Ben Klibreck section represents an eastward transition into migmatized rocks requires revision in the light of the recent research. There is a consensus that the junction between gneissose and non-gneissose Moine rocks is a sharp lithological boundary, the Naver Thrust, which is associated with a zone of blastomylonites typical of high tectonic strains. Structural analysis indicates that NW-directed D2 ductile thrusting of high-grade migmatitic Moine rocks onto lower-grade, unmigmatized Moine rocks was broadly synchronous with widespread F2 interfolding of Lewisianoid and Moine rocks in the footwall of the thrust (Strachan and Holdsworth, 1988). The Naver Thrust has been traced to the north coast of Sutherland (Moorhouse and Moorhouse, 1983) and extends south to near Golspie, where it is concealed beneath the Old Red Sandstone cover (Figure 6.2). It may represent the northern continuation of the Sgurr Beag Thrust, which can be traced north from Inverness-shire and Ross-shire to the Dornoch Firth (Barr *et al.,* 1986; Strachan and Holdsworth, 1988). However, correlations between the Moine rocks of the Naver Nappe and overlying Sutherland nappes with Morar Group and Glenfinnan Group sequences farther south remain problematical. Thus, the east Sutherland Moine rocks, structurally derived from some considerable distance to the east (at least tens of kilometres), are viewed here as discrete but separate parts of the Moine succession (see also Strachan *et* al., 2002a).

The SE- to SSE-trending L2 mineral and extension lineation developed within the Moine and Lewisianoid rocks of the Ben Klibreck area is traceable westwards across central Sutherland to the Moine Thrust Belt ((Figure 6.4); Soper and Brown, 1971). D2 ductile thrusting and folding at Ben Klibreck is hence mainly Caledonian (Ordovician–Silurian) in age. The age of earlier events within the Moine rocks is uncertain. Barr *et al.* (1986) suggested that migmatization of the Moine rocks above the Naver Thrust occurred during the Neoproterozoic partly on the basis of correlation with migmatitic Moine rocks of the Glenfinnan area (see Fassfern to Lochailort Road Cuttings GCR site report, Chapter 8). These authors were also influenced by an Rb-Sr isochron age of 649 ± 30 Ma for the post-tectonic Strath Halladale granite (M. Brook in Pankhurst, 1982), which intrudes migmatitic Moine rocks in east Sutherland and Caithness (McCourt, 1980). However, recent TIMS U-Pb zircon age dating has revised the age of intrusion to 426 ± 2 Ma (Kocks *et al.,* 2006). This is in accord with similar Late Silurian ages for the emplacement of the Strath Naver and Vagastie Bridge granites (Kinny *et al.,* 2003a), suggesting that sheeted granite bodies were intruded coeval with the later phases of the Scandian Event. It also fits with the Early Ordovician (Grampian) age inferred for Moine migmatites along strike from Ben Klibreck on the north Sutherland coast (Kinny *et al.*, 1999).

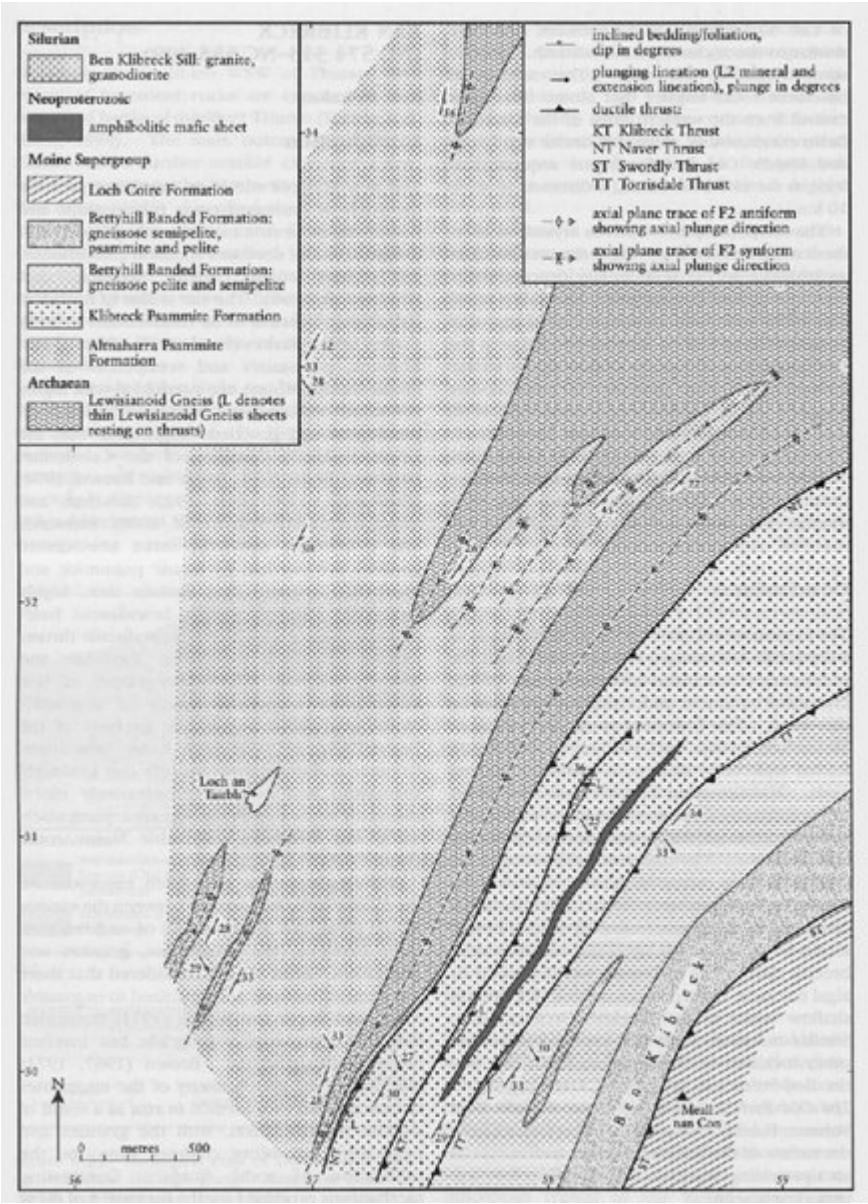
The spatial concentration of granites and pegmatites within the Naver Thrust Zone combined with the field evidence, which indicates a syn- to post-D2 (i.e. late Scandian) age of emplacement, imply that this structure exerted a strong control on granitic intrusion (Strachan and Holdsworth, 1988). Read (1931), Brown (1967, 1971) and Soper and Brown (1971) considered that there was a close genetic relationship between migmatization of the Moine rocks and formation of the various granites and pegmatites. Brown (1967, 1971) interpreted the geochemistry of the migmatites to show that they formed in *situ* as a result of sodium metasomatism, with the granites and pegmatites providing channelways for infiltration of sodic fluids. Irrespective of the precise origin of the migmatites, a genetic relationship with the Late Silurian-age granites and pegmatites is clearly unlikely if the Sutherland migmatites are of Neoproterozoic or Early Ordovician (Grampian) age as suggested by Kinny *et al.* (1999). Only some of the earlier patchy granitic and leucotonalitic bodies that are prominent in the Badanloch and Strath Halladale areas appear to relate to the Early Ordovician event.

Conclusions

The site is of national importance because it includes the type locality for the Naver Thrust, a regional-scale ductile thrust within the Caledonian belt of northern Scotland. NW-directed displacements along the Naver Thrust emplaced high-grade, migmatitic Moine semipelitic gneisses onto lower-grade, non-migmatitic, generally psammitic Moine rocks. Ductile thrusting was accompanied by widespread tight to isoclinal folding and formation of large-scale sheath-folds in the footwall. Inliers of Lewisianoid gneiss basement occur in two contrasting settings: as thin, discontinuous allochthonous sheets, which rest on ductile thrusts in the hangingwall of the Naver Thrust, and as para-autochthonous antiformal fold

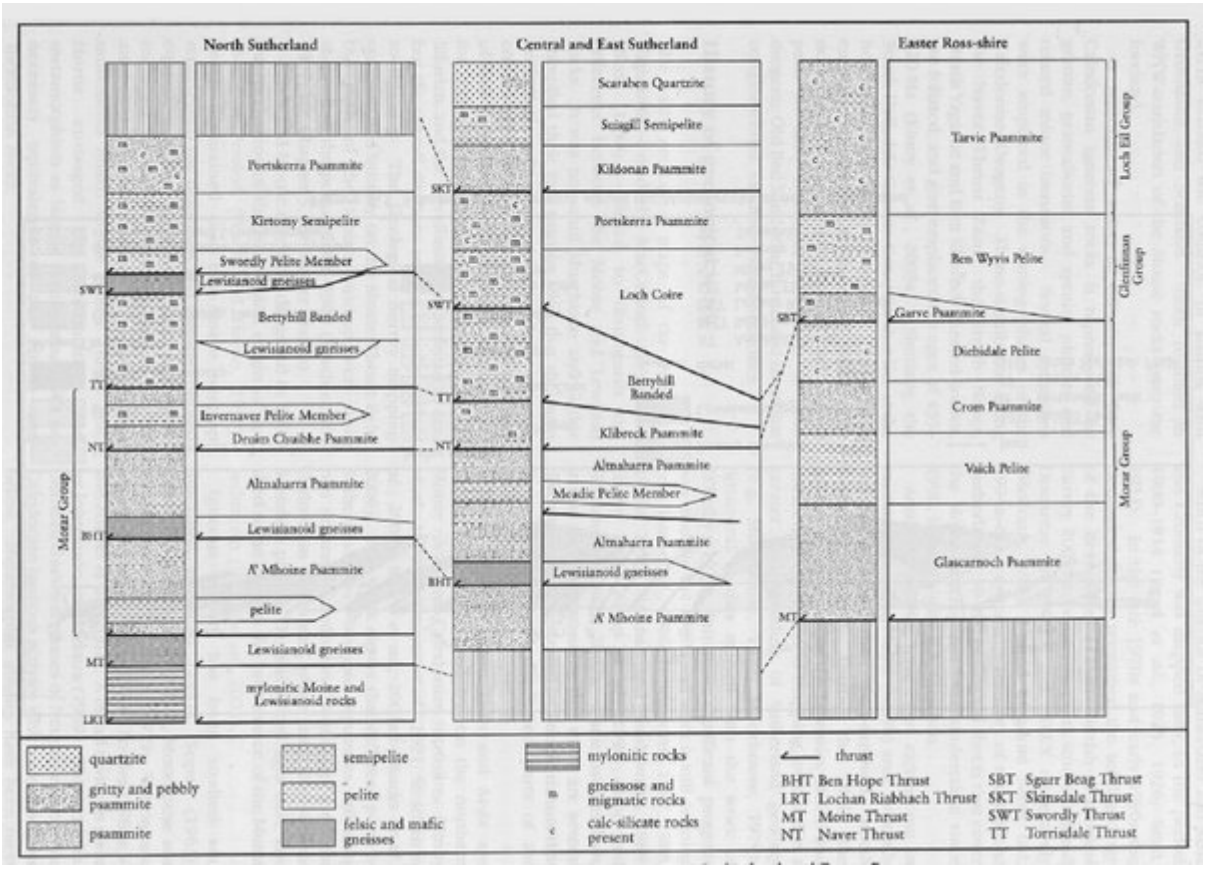
cores in the footwall. The Naver Thrust also exerted a strong structural control on the emplacement of a variety of Late Silurian-age granites and pegmatites, intruded during and immediately following thrusting. The limited geochemical data available is consistent with formation of the granites and pegmatites by melting or partial assimilation of Moine rocks and possibly also of some Lewisianoid basement. Zircon dating has shown that movement on the Naver Thrust occurred in the Late Silurian (Scandian) event of the Caledonian Orogeny. The migmatites seem to relate only to the Grampian (?D2) or possibly earlier Neoproterozoic events, whereas the main granite bodies were intruded towards the end of the subsequent Scandian Event at *c.* 425 Ma.

References

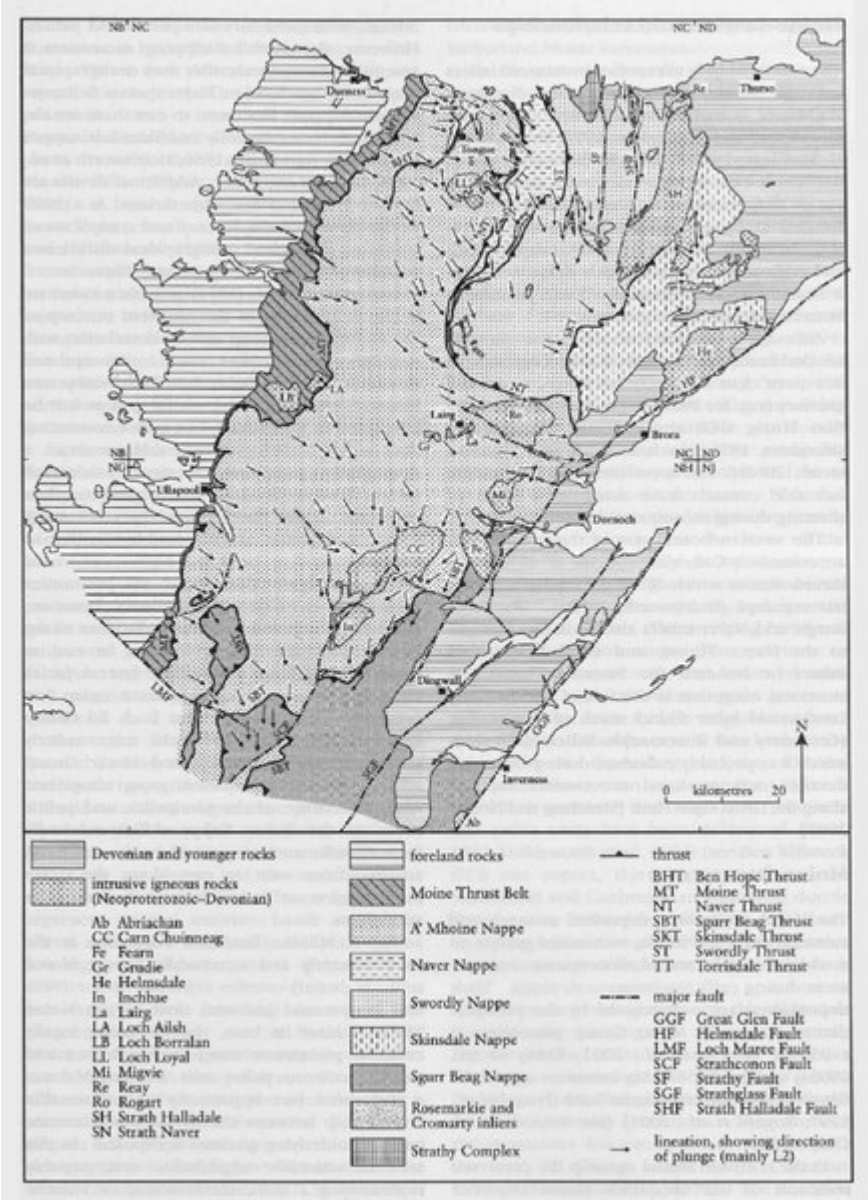


(Figure 6.34) Geological map of the Ben Klibreck area.

(Figure 6.35) Banded felsic and mafic Lewisianoid orthogneiss of the Naver Inlier at [NC 584 325]. The map case is 32 cm high. (Photo: R.A. Strachan, BGS No. P580516, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 6.2) Stratigraphy of the Moine Supergroup in Sutherland and Easter Ross.



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