Loch Borralan Intrusion

[NC 235 110]–[NC 277 081]–[NC 297 085]–[NC 306 107]–[NC 298 140]–[NC 260 150]–[NC 235 150]

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Introduction

The Loch Borralan intrusion, in the SW corner of the Assynt region (Figure 7.2) is of international importance for petrological reasons, and of great regional significance for structural reasons. It is the only plutonic complex composed largely of silica-undersaturated (i.e. feldspathoid-bearing) igneous rocks in the British Isles, and many of its members are exceptionally alkaline. It provides Britain's only example of truly ultra-potassic magmatism. The most potassic members, with as much as 15 wt% K_2O, are among the most K_2O-rich rocks encountered on Earth. The site includes the only British example of carbonatite.

The unusual character of the rocks was recognized in the 19th century and the intrusion has held an important place in the international development of igneous petrology. The first specific account of the intrusion was by Horne and Teall (1892) who described the pyroxene-melanite nepheline-pseudoleucite-syenite, which they called 'borolanite'. (There have been several spellings; the current spelling for the Loch is 'Borralan' but 'Borolan' has precedence for the rock name). Additional rocks were described by Teall (1900). The intrusion was mapped, and an account given, by Peach *et al.* (1907), and S. J. Shand carried out pioneering detailed petrographical and analytical work in the following years (1906, 1909, 1910 and 1939). Rock names introduced by these early workers, 'borolanite', 'ledmorite', 'cromaltite' and 'assyntite' (Table 7.2) found some worldwide application as similar rock types were found at other localities, but are now used only very occasionally.

Shand suggested that the Borralan rocks owed their silica-deficient character to disilication reactions between a magma of broadly granitic composition and the Cambro-Ordovician dolomitic limestones that form much of the envelope (Figure 7.4), providing support for the 'Daly–Shand hypothesis', which was developed because of a common association observed between nepheline-bearing rocks and 'limestone'. It is, however, now known that the carbonate rocks that often occur in association with nepheline-syenites are carbonatites, and this association has recently been confirmed just outside the Loch Borralan intrusion in excavations made by Scottish Natural Heritage, near Loch Urigill (Young *et al.,* 1994). Modern petrologists see the source of both magmas as lying in the Earth's upper mantle; modern thinking on the ultimate origins of the Caledonian alkaline rocks is given in the chapter introduction.

Shand (1910) also postulated that the intrusion has the form of a gradationally stratified lac-colith, a model accepted by Bowen (1928) who reproduced Shand's section through the supposed laccolith, and argued that the pseudoleucite-bearing rocks at the base of the laccolith formed as a result of crystal settling under the influence of gravity leaving a silica-oversaturated liquid which crystallized to produce quartz-syenites. He justified this interpretation on the basis of new insights gained from his experimental petrological studies. Tilley (1957) rejected Bowen's hypothesis on the grounds that leucite would not crystallize at likely high water-vapour pressures. He provided some new analyses of 'ledmorites' from Loch Borralan, and compared them with dykes in the Foreland, from Camas Eilean Ghlais, Coigach and from Achmelvich, far from dolomitic limestones of the Durness Group, complementing analyses provided by Sabine (1952, 1953). This connection, between distinctive alkaline dyke rocks in the Foreland, and the Loch Borralan pluton in the thrust zone, is of considerable regional structural and temporal significance.

Subsequent interpretations of the internal structure of the intrusion have questioned the gradational character of the boundaries. The complex has a broadly concentric form (Figure 7.4) but exposure is extremely poor in many critical areas. The diversity of rock types (Table 7.2), many of them very rare on a world scale, is exceptional, but the boundaries of most units are not exposed. The most recent detailed treatment of the internal relationships is that of Woolley (1970, 1973) and his terminology is used here (Table 7.2). The map (Figure 7.4) is based on that of Woolley, modified slightly by Johnson and Parsons (1979) and by later work (Parsons and McKirdy, 1983; Notholt *et al.,* 1985; Young *et al.,* 1994).

Woolley divided the complex into an earlier suite of silica-undersaturated (nepheline- and/or pseudoleucite-bearing) rocks, most members of which are relatively mafic or ultramafic, and a relatively leucocratic later suite of silica-saturated or oversaturated rocks. Woolley accepted the views of Harker (in Tilley, 1957) and Macgregor and Phemister (1937) that the boundary between the two suites is an intrusive one. He considered that the early suite has a laccolithic form, but that the later suite has the form of a thick plug-like body, punching through the earlier units. Since Woolley's work, some re-interpretation has become necessary because of an extensive drilling programme in the vicinity of the SW margin (Matthews and Woolley, 1977; Notholt *et al.,* 1985; Shaw *et al.,* 1992). An excavation made by the Nature Conservancy Council (Parsons and McKirdy, 1983) in Bad na h-Achlaise demonstrated the intrusive character of the ultramafic members of the complex, ruling out an in-situ skarn origin postulated by Johnson and Parsons (1979). A new marble quarty, near Ledbeg, provides exposures of 'borolanite' cutting both highly altered Durness Group dolomitic limestone, with spectacular contact metamorphic and metasomatic effects, and quartzite. This still-to-be-described new locality offers outstanding opportunities for research in metamorphic reactions, and provides superb teaching opportunities.

The structural relationships of the Loch Borralan intrusion are of considerable geochronological importance (Halliday *et al,* 1987), as summarized in (Table 7.1). Van Breemen *et al.* (1979a) obtained U-Pb ages from zircons separated from four units of the intrusion and concluded that it was emplaced over a relatively short period of time at 430 ± 4 Ma, making it a little younger than the 439 ± 4 Ma obtained by Halliday *et al.* (1987) for the nearby Loch Ailsh intrusion, which is petrographically similar to the late syenite suite at Loch Borralan. This rules out a suggestion made by Bailey (1935) that the Loch Ailsh intrusion is an easterly extension of the Loch Borralan intrusion viewed through a 'window' in the Ben More thrust sheet.

There is considerable discussion in the literature concerning the structural relationships between the Loch Borralan intrusion and the Ben More Thrust (sometimes called the Assynt Thrust in this part of Assynt, see Johnson and Parsons, 1979) and the Sole Thrust which crops out slightly to the west of the intrusion and must dip beneath it. Several structurally critical areas of the intrusion are described below in a separate section. The relationship of the igneous rocks to the thrust movements is an important issue, because several workers (Bailey and McCallien, 1934 and Woolley 1970) have suggested that early members of the intrusive complex were emplaced before or during movements on the Ben More Thrust, and hence the complex can provide a very exact date for this episode of movement in the Moine thrust zone. However, more recent work (Parsons and McKirdy, 1983) has shown that the ultramafic and nepheline-syenite members were emplaced after the movements on the Ben More thrust plane, and new exposures in the marble quarry at Ledbeg show 'borolanite' cutting quartzites which have moved on the Ben More thrust plane. The evidence now seems to suggest that emplacement of all the units of the Loch Borralan complex occurred after the movements on the Ben More Thrust had ceased. The Loch Ailsh mass was undoubtedly emplaced in the rocks of the Ben More Nappe before the movements on the thrust plane, so that the 439 ± 4 and 430 ± 4 Ma ages on the two intrusions provide an important bracket on the time of the main movements on the Ben More Thrust. A K: Ar age of 394 ± 8 Ma obtained on a mica from Loch Borralan by Brown *et al.* (1968; recalculated with more recent decay constants by van Breemen *et al.,* 1979a) has been interpreted to mean that some 30 Ma elapsed before the temperature in the pile of nappes fell below an Ar blocking temperature of *c.* 300°C (van Breemen *et* al., 1979a).

The relationship of the Loch Borralan complex to the Sole Thrust cannot be established directly as the two are not seen in contact. The intrusion does not become more deformed as it approaches the Sole Thrust, which crops out about 1 km to the west, in contrast with its behaviour as the Moine Thrust is approached. The alignment of nepheline-syenite ('ledmorite') dykes in the Foreland (Sabine, 1952, 1953) with the Loch Borralan nepheline-syenites suggests that little or no horizontal displacement of the mass has occurred since emplacement. Halliday *et al.* (1987) accepted the implication that the Loch Borralan mass was emplaced after the main movements on the Sole Thrust. However, from structural mapping, Coward (1985) concluded that the Loch Borralan intrusion has been moved at least 30 km on the Sole Thrust since emplacement. These apparent contradictions between structural interpretations in Assynt and the chronology of igneous events remain unresolved.

The Borralan site also provides examples of contact metamorphism and metasomatism of which the most spectacular examples are those seen in the marble quarry NE of Ledbeg [NC 248 136]. Other examples of marble occur in the Ledbeg river around Ledbeg. Examples of alkali metasomatism (fenitization) of quartzite have been described from various localities by Woolley *et al.* (1972), Rock (1977), Martin *et al.* (1978) and Parsons and McKirdy (1983).

Description

The intrusion covers an area of around 26 km^2, and comprises several low hills culminating in Cnoc-na-Sroine at 398 m, surrounded by an area of low, largely peat-covered ground in which most of the more unusual rock types crop out (Figure 7.3). The higher ground is mainly of leucocratic feldspar-rich syenites, quartz-bearing at the top, while the lower ground comprises undersaturated, usually rather mafic syenites (Figure 7.4). At the southern margin pyroxenites occur in isolated exposures; geophysical work (Parsons, 1965a) and drilling (Matthews and Woolley, 1977; Notholt *et al.,* 1985; Shaw *et al.,* 1992) have shown that these are part of an extensive sub-vertical sheet between syenite and altered dolomitic limestones. The igneous rocks are in contact along three sides with Cambro-Ordovician Durness Group limestones, while the northern margin is against Cambrian quartzite.

The description below follows Woolley's (1970) division of the complex into two suites, with an intrusive junction between them. The early suite comprises pyroxenites, nepheline-syenites and pseudoleucite-syenites, while the later suite is feldspathic syenites ('perthosites') and quartz-syenites. The two suites are not now believed to be related by in-situ fractionation processes. The early suite appears to have a sheet-like (laccolithic) form, while the, later suite appears to have the form of a plug punching through the earlier rocks. The variety of rocks in the early suite is extremely large, exposure is very poor, and few exposures reveal contact relationships. The most useful descriptions of field relationships are those of Woolley (1970, 1973), extended by the drilling work mentioned above and by the excavations reported by Parsons and McKirdy (1983) and Young *et al.* (1994).

Early suite

Ultramafic rocks

Biotite-magnetite pyroxenites, with and without melanite (called 'cromalite' by Shand, 1910), and hornblendites crop out only in the low ground in the SW of the intrusion. Despite their extent demonstrated by geophysical means there are only poor exposures. A map of the western corner of the Loch Borralan complex, showing all the exposures and the extent of the pyroxenites deduced from magnetic and gravity anomalies and proved by drilling (Matthews and Woolley, 1977; Notholt *et al.,* 1985; Shaw *et al.,* 1992), shown in (Figure 7.5). The only natural exposures of pyroxenite are in the Ledmore River 200 m downstream from the footbridge [NC 246 119] where coarse-grained biotite pyroxenite, with a few outstanding ribs of syenite, can be seen, and in Bad na h-Achlaise [NC 245 115]. The main evidence for the 'stratified laccolith' structure for the intrusion favoured by Shand (1910, 1939) was the relatively low topographical position of these rocks and the higher position of the leucocratic syenites. However, the considerable magnetic anomaly associated with the hidden ultramafic rocks (Parsons, 1965a; Matthews and Woolley, 1977) clearly indicates that the pyroxenites form a sub-vertical screen between syenite and Durness Group dolomitic limestone. The main pyroxenite body forms a dyke-like mass dipping at approximately 70° to the NE, and plunging beneath less basic rocks towards the SE. The exposures at Bad na h-Achlaise have little magnetic expression and are of limited vertical extent and floored by skarn rocks. Drilling in the main pyroxenite body showed that the pyroxenites are interleaved with screens of heterogeneous melanite-rich syenite, pyroxene syenite, and more leucocratic nepheline-syenite. Only three small natural exposures of these types occur, to the NW of Bad na h-Achlaise, but recently excavations nearby have provided more substantial exposures showing this inter-relationship (Parsons and McKirdy, 1983).

The origin of the pyroxenites is controversial. Matthews and Woolley (1977) favoured the Bowen (1928) hypothesis that the pyroxenites are cumulate rocks from the base of the sheet forming the 'early suite', and postulated that they have been brought to their present attitude by faulting or by squeezing of a partly consolidated layered sequence, but the writer (in Johnson and Parsons, 1979) suggested that they are a metasomatic assemblage at the junction between the syenites and dolomitic limestones. The incorrectness of the latter view was demonstrated by the Nature Conservancy Council excavations near Bad na h-Achlaise reported by Parsons and McKirdy (1983) which clearly show the intrusive character of the pyroxenites into quartzites of the Cam Loch Klippe carried over the Durness Group rocks by the Ben More Thrust (Figure 7.5). These excavations are important, complementing the very limited but historically important exposures in Bad na h-Achlaise itself, and providing the only accessible evidence of the character of the rock types found by the very extensive drilling programme (Figure 7.5). The exposures in and near this small hollow (Bad na h-Achlaise means 'place of the armpit') were recorded in detail by Shand (1910). Melanite pyroxenite ('cromaltite) occurs in the stream where it is cut by a 'two foot dyke' of 'aegirite pegmatoid' (aegirine-nepheline-alkali feldspar pegmatite). A 'dyke' of pyroxene-melanite syenite with 'flesh coloured feldspar' occurs below locality 2 on (Figure 7.5), and a body of carbonate-bearing pyroxenite forms a knob on the east side of Bad na h-Achlaise. Shand considered this rock to be 'half-fused sediment which has absorbed a certain proportion of silicates from the intruded 'cromaltite', and later (1930) considered the exposure to provide 'clear evidence ... supporting the Daly–Shand hypothesis'. However, Phemister (1931) studied this exposure and concluded that it was carbonated melanite pyroxenite, and that the progressive replacement of the silicate minerals by carbonate could be demonstrated.

The excavations (1–3 on (Figure 7.5)) resolve several features of the geology around Bad na h-Achlaise. Locality 1 provides a small exposure of deeply weathered, coarse-grained, melanite-biotite pyroxenite ('cromaltite') with a few thin feldspathic veinlets overlain by a thicker southward-inclined sheet of syenite. Locality 2 was originally a small exposure of leucocratic syenite pegmatite, but the excavation provides a 19 m section through heterogeneous, variably feldspathic, pyroxene-hornblende-melanite syenites, showing a faint, nearly vertical layering, surrounded by pyroxenite. The syenites are cut by a zoned syenite pegmatite with striking 25 cm euhedral, black feldspars. Excavation 3 shows important relationships and is an enlargement of a small exposure of Cambrian quartzite cut by a red syenite pegmatite. Woolley (1970) correlated this syenite with similar sheets cutting the pyroxenites in Bad na h-Achlaise. He suggested that the quartzite (which is part of the Cam Loch Klippe) was brought into place on the Ben More Thrust after emplacement of the pyroxenites and the main body of undersaturated syenite, but before injection of the pegmatite, and that the igneous activity therefore bracketed the movements on the Ben More Thrust. However exposure 3 (a field sketch is given in Parsons and McKirdy, 1983) shows no evidence of a thrust relationship between igneous rocks and quartzite, and at the western end pyroxenite is clearly intrusive into the quartzite, which is fenitized, with rosettes and veins of asbestiform, pale-blue amphibole. The movements on the Ben More Thrust were therefore complete before all the igneous rocks of this part of the complex were emplaced, and the hypothesis of Parsons (in Johnson and Parsons, 1979) that the pyroxenites are an in-situ skarn is disproved.

The commercial interest in the pyroxenites was initially because of their high magnetite content but the more recent drilling work was to evaluate the phosphate potential of the apatite-bearing pyroxenite. While not currently economic, the body constitutes the most significant phosphate resource yet found in the United Kingdom (Notholt *et al.,* 1985).

Nepheline-syenites

In addition to the exposures of syenite at Bad na h-Achlaise (previous section) members of the less mafic part of the early suite crop out extensively in the Ledmore River at Ledmore ((Figure 7.3), [NC 247 121]) and on the A837 [NC 244 132]. These are Shand's (1910) 'ledmorites', mesocratic melanite-pyroxene nepheline-syenites. There are few other exposures (Figure 7.5) and little hint of the petrologically very exotic rocks which extend over at least 3 km from near Ledmore to the SE (Figure 7.4).

In their drillcore material, Notholt and Highley (1981) recognized two generations of syenites intrusive into the pyroxenites: (1) leucocratic, pink syenite veins usually a few centimetres in thickness; (2) two types of more mafic syenite: (a) melanite garnet-bearing, sometimes with as much as 50% garnet; (b) pyroxene syenites, sometimes garnetiferous, showing both intrusive and gradational relationships to the pyroxenites. All of these types can be seen in the very poor exposures near Bad na h-Achlaise although their spatial relationships cannot be established. A pile of large boulders extracted during the building of a forestry road can be inspected in a shallow quarry at the track side just to the north of Bad na h-Achlaise. These include several varieties of nepheline-syenite showing cross-cutting relationships, with some intimate vein networks. There are some pyroxenite xenoliths in syenite, a relationship found in boreholes by Notholt and Highley (1981). They provide good evidence of the fractionation of several magma-types before emplacement. These exposures (and excavations) of plutonic nepheline-syenites are unique in the British Isles.

Pseudoleucite-syenite and associated rocks This suite, which includes the intrusion's best known rock type borolanite', (Horne and Teall, 1892), mainly crops out in the eastern part of the complex, and is particularly well exposed around the Allt a' Mhuillin (Figure 7.6). The most important exposures are in the quarry east of the Allt a' Mhuillin [NC 287 097], and in the Allt a' Mhuillin gorge. These are the best exposed localities for borolanite', which is a pyroxene-melanite nepheline-syenite with conspicuous white spots, which are generally believed to be nepheline-alkali feldspar pseudomorphs after leucite. These 'pseudoleucites' have varying degrees of ellipticity within the quarry, and in the lower part of the Allt a' Mhuillin gorge are flattened into white streaks giving the rock a schistose appearance. This flattening has controversial implications concerning the timing of the thrust movements, noted in the introduction to the Loch Borralan complex and in a later section. The borolanites' are cut by a set of undeformed pegmatite veins containing an assemblage unique in Britain: feldspar, nepheline, biotite, melanite, magnetite, titanite, allanite, zeolites and a blue, sulphatic cancrinite (vishnevite) described by Stewart (1941). 'Borolanites' with white spots more convincingly of the icositetrahedral pseudoleucite shape are best found on the 358 m hill east of Loch a' Mheallain [NC 291 108].

Other silica-undersaturated rocks in the eastern part of the Borralan complex form an extremely diverse suite. They are exposed sporadically in the ground east of Allt a' Mhuillin, for which Woolley (1973) gives an accurate map defining three main types arranged in eastward-dipping sheets (Figure 7.6). At the top, beneath a roof of Durness Group dolomitic limestone forming the eastern margin is a strongly potassic 'muscovite group'. Some of these rocks reach 15 wt% K_2O (Woolley, 1973) and are among the most extreme potassic igneous rocks known on Earth. Below this group are a suite of biotite–magnetite rocks, and then the 'borolanites'. Nepheline and K-feldspar are the felsic minerals in each case. Thinner layers of pyroxene- and hornblende-rich rocks (including 'shonkinites', (Table 7.2)) were encountered below the Allt a' Mhuillin quarry, in boreholes that went to nearly 50 m. Woolley called these unexposed rocks the 'lower suite'. There are numerous xenoliths of a more mafic melanite-pyroxene-biotite syenite in the 'borolanites', well seen on the north wall of the quarry, and ascribed to an earlier, disrupted phase of the intrusion by Macgregor and Phemister (1937). The rocks at the bottom of the deeper boreholes are reddened, and red syenite veins appear, suggesting proximity to the later syenite intrusion.

The lowest exposures in the Allt a' Mhuillin gorge are of highly deformed borolanite', but upstream there are layers of pyroxene-rich 'shonkinite', chemically similar to 'ledmorite' (Woolley, 1973). A fine-grained alkali feldspar-biotite-albite rock called 'vullinite' by Shand (1910) occurs above the gorge. Shand considered it to be a metamorphosed sediment but Macgregor and Phemister (1937) thought it was a metamorphosed earlier igneous rock. Woolley (1973) considered that the lower and pseudoleucite suites had a generally sheet-like form, and that the pseudoleucite-bearing rocks were emplaced after the lower suite. Within the 'borolanites' a roughly contact-parallel boundary (Figure 7.6) separates lower melanite-bearing and upper melanite-free zones, which Woolley suggested could result from in-situ settling of melanite (and also pyroxene). He also suggested that the extraordinary upward increase in potassium to sodium ratio in the pseudoleucite suite could be explained by the settling of sodium-bearing leucite. The origin of the variants found in the eastern part of the Borralan complex is a far from resolved problem and their unique chemistry makes the conservation of this part of the complex a matter of considerable importance.

Rocks of 'borolanite' type occur in the thrust-defined body known as the Loyne mass, at the NW extremity of the intrusion (Figure 7.4), where they have a roof and floor in dolomitic limestone. The Loyne mass is a lenticular 'horse', defined above by the Ben More Thrust and below by the Ledbeg Thrust (Johnson and Parsons, 1979; Elliott and Johnson, 1980). Spectacular examples of 'borolanite' sheets cutting marbles can be seen in the recently opened quarry at Ledbeg. A diversity of igneous rocks are visible in this quarry, some of which are extremely rich in melanite garnet. Melanite syenites with white spots resembling pseudoleucite were recorded by Notholt and Highley (1981) in a borehole near dolomitic limestone exposures at [NC 256 098], but these, and the phlogopite- and serpentine-carbonate rocks that they cut, are never exposed.

Carbonatite

The igneous carbonate rock, carbonatite, was discovered as blocks of orange-brown carbonate rock on the beach at Loch Urigill (at [NC 247 105]) (Figure 7.5), where they are still visible (Young *et al.,* 1994). This is the only British example of this important rock type except possibly some thin carbonate dykes found in association with albitites cutting Moine and Dalradian rocks in the Great Glen near Inverness (Garson *et al.,* 1984). The carbonate-rock blocks contain xenoliths of syenite and biotite pyroxenite with pronounced reaction rims. Subsequently a white sövite (coarse-grained calcite-carbonatite) was found cutting the Durness Group dolomitic limestone a few metres to the north. This exposure was subsequently enlarged by Scottish Natural Heritage using an excavator (Threadgould *et al.,* 1994); a drawing of the new exposure is given in Young *et al.* (1994). The carbonatite contains numerous xenoliths of both nepheline-syenites and pyroxenites which can be matched in the intrusion and xenoliths of Durness Group dolomitic limestone that have been rotated during the emplacement of the carbonatite magma. The carbonatite body is 400 m outside the contacts of the Loch Borralan intrusion but it is very likely to be part of the magmatism that gave rise to the Loch Borralan mass. The association of carbonatite with nepheline-syenites and diopsidic pyroxenites is recognized worldwide. Chemical evidence that the rocks are carbonatites of deep origin, rather than locally mobilized Durness Group carbonates, comes from their distinctive trace element, carbon and oxygen isotope signatures (Young *et al.,* 1994). The overall extent of the carbonatite in this area cannot be established from the topography owing to the poor exposure.

Four varieties of carbonatite have been found, three *in situ.* These are porphyritic sövite, phlogopite sövite, and sövite breccia. The fourth variety, a foliated silicocarbonatite, has been found only as a 30 cm block in the drift. Considerable internal heterogeneity is a common feature of carbonatites, which often involve several generations of brecciation and incorporation into later phases of injection. The most striking rock is the phlogopite sövite, which owes its orange colour to myriads of small phlogopite plates included in a matrix of large calcite crystals. The rock also contains rosettes of apatite. The porphyritic sövite is white in colour, and is made of coarse calcite crystals. On one face of the exposure it is layered, with 2 cm-thick bands of the relatively rare mineral chondrodite (a hydrated magnesium silicate) separated by 25 cm-thick layers of normal sövite. The sövite breccia is a matrix-supported breccia of brown carbonatite fragments in a coarsely crystalline, brown sövite matrix resembling the phlogopite sövite.

Late suite

The silica-saturated and oversaturated alkali feldspar-syenites of the late suite are relatively well exposed on the southern slopes of Cnoc-na-Sroine. The rocks are less exotic and controversial than those of the earlier suite, and are similar to the 'perthosites' and melanite syenites in the Loch Ailsh intrusion. The top of Cnoc-na-Sroine is formed of quartz-syenites ('nordmarkites') which, with around 12 vol.% quartz, are more quartzose than the quartz-syenites at Loch Ailsh and a little richer in potassium relative to sodium (Parsons, 1972). Shand (1910) considered that the quartz-syenites grade downwards continuously into quartz-free syenites, with or without melanite, and eventually into the melanite syenites ('ledmorites') in the Ledmore River.

Woolley (1970) divided the syenites into a downward succession of quartz-syenites, 'perthosites' (with or without melanite) and 'grey perthosites'. The former two variants form the bulk of Cnoc-na-Sroine, and their relationships are best seen in the Allt a' Bhrisdidh (Figure 7.5), [NC 252 119] where the quartz-syenites can be shown to be interleaved with the 'perthosites', with intrusive junctions (Woolley, 1970). The 'grey perthosite' variant is seen only in the low ground west of the Allt a' Mhuillin gorge (Figure 7.4), around [NC 283 099].

Junctions between early and late suites

Exposures illustrating the relationships of early and late suites are of importance because of the bearing they have on the genesis of the rocks of the complex as a whole, and because of the possibility that the two suites were emplaced respectively before and after the main movements on the Ben More thrust plane (as suggested by Woolley, 1970, but disputed by Elliott and Johnson, 1980).

Shand (1910) believed that all boundaries in the complex are gradational, but Woolley (1970) agreed with Macgregor and Phemister (1937) that the later suite is intrusive into the earlier one, with sharp boundaries. Critical relationships are seen only at two localities. The most important junction (Woolley, 1970) is in the lower part of the Allt a' Bhrisdidh [NC 253 119]; see (Figure 7.5). At its confluence with the Ledmore River this stream flows in medium-grained, brownish ledmorite', but upstream this rock becomes darker in colour, and veined and speckled by pink feldspar. About 50 m north of the A837 a fairly sharp but irregular contact can be seen between a pink leucocratic syenite and somewhat foliated mesocratic rock. This contact is overall nearly vertical, and only pink syenite occurs above. Cross-cutting relationships between pink syenite veins and 'ledmorite' can be seen in streams nearer to Ledmore, and in road cuttings SE of Ledbeg, but the correlation of these syenite veins with the main mass of Cnoc-na-Sroine is not certain.

A second critical junction (Woolley, 1970) is in poorly exposed ground about 0.5 km NE of the deep section of the Allt a' Mhuilinn gorge [NC 290 130]; see (Figure 7.6)). Here a tongue of quartz-syenite can be mapped extending into the 'borolanites'. Sharp intrusive contacts can be demonstrated and the later syenite becomes finer grained towards the contact. If penetrative deformation exhibited by the 'borolanites' in the nearby Allt a' Mhuillin quarry is tectonic, this junction is strong evidence that the emplacement of the complex overlapped the thrust movements.

Localities important for structural reasons

Three localities have had particular importance for structural and geochronological reasons. They provide the best evidence for the temporal relationship between the igneous activity and the thrusting, and the measured ages of rocks in the Loch Borralan and Loch Ailsh intrusions provide the best estimate of the timing of movements in the Moine thrust belt in general (Table 7.1). Evidence for minor sub-horizontal movements is provided by the presence of locally developed cleavage in almost all units of the Loch Borralan intrusion, but this is not thought to be associated with large-scale movements on the major thrusts. Overlap of igneous and tectonic activity was postulated first by Bailey and McCallien (1934) on the basis of relationships seen in the quarry in 'borolanite' east of the Allt a' Mhuillin [NC 287 097] where undeformed pegmatites cut 'borolanite', which appears to be deformed. Here, and in the Allt a' Mhuillin itself, the normally equidimensional pseudoleucites are flattened, first into ellipses and ultimately into white streaks (best seen in the Allt a' Mhuillin gorge, [NC 286 098]). Woolley (1973) has suggested that the flattening is due to penetrative deformation associated with the Ben More thrust plane, which presumably lay not far above the present exposures, while Elliott and Johnson (1980) have argued that the flattening is due to 'igneous' displacements during emplacement. Whatever the character of the deformation in the 'borolanites', however, it is certain that the later igneous rocks at this locality escaped deformation, because clearly undeformed pegmatites cut rocks with flattened pseudoleucites. The pegmatites form a network on the wall of the 'borolanite' quarry, and a large zircon from this pegmatite formed part of the dating study of van Breemen *et al.* (1979a).

In Bad na h-Achlaise (Figure 7.5) and in the series of exposures extending 200 m to the west, there was for a time thought to be further evidence that the early igneous activity pre-dated the main movements on the Ben More Thrust. This series of exposures was originally interpreted as showing quartzite overthrust on to syenites and pyroxenites, with residual late pegmatites cutting into the quartzite as well as passing through the pyroxenites (Woolley, 1970; Johnson and Parsons, 1979). However, the excavations reported by Parsons and McKirdy (1983) clearly show that this quartzite mass is actually intruded by massive syenite, syenite pegmatite and pyroxenite. If the interpretation of this quartzite as part of the Cam Loch Klippe (as shown on the original Geological Survey maps of 1892) is correct then movements on the Ben More Thrust pre-date the emplacement of the entire suite of nepheline-syenites and pyroxenites at Borralan. A less attractive hypothesis is that the quartzite is a xenolith that has been carried up from a normal stratigraphical position beneath the Durness limestone, which crops out at Loch Urigill to the south, and which has come to rest, fortuitously, adjacent to the thrust rocks of the Cam Loch Klippe. Because the timing of emplacement of the pseudoleucite suite relative to the nepheline-syenites and pyroxenites is at present unknown, it is still possible that the emplacement of the Loch Borralan mass overlapped the movements on the Ben More thrust plane, but this requires that the emplacement of the pseudoleucite suite pre-dates all other units of the complex, a view accepted by Woolley (1970). However, in the marble quarry at Ledbeg, 'borolanites' cut quartzites in the Cam Loch klippen, so here both pseudoleucite-bear-ing rocks and silica-oversaturated members of the intrusion were emplaced after the thrust movements.

Large-scale evidence that the intrusion punches through the Ben More thrust plane can be obtained by consideration of the relationships between geology and topography at the west end of Cnoc-na-Sroine. To the east of Ledbeg ((Figure 7.4), around [NC 252 140]), in the low ground between the steep slopes formed of late-suite leucosyenites and the A837, are a number of exposures that show Cambrian quartzites carried by the Ben More Thrust on to Durness Group dolomitic limestones, and forming one of the Cam Loch klippen (Peach *et al.,* 1907). Peach and his co-workers considered that the Ben More Thrust passes above the summit of Cnoc-na-Sroine and then dives steeply down to the west. Woolley (1970) rejected this interpretation and instead postulated that the late syenite suite punches through the thrust, and this interpretation is consistent with the relationships at Bad na h-Achlaise.

External contacts

Contacts of the intrusion against country rocks are very badly exposed. On the A837 near Ledbeg [NC 244 133], red early-suite melanite nepheline-syenites are seen enclosing xenoliths of recrystallized dolomitic limestone, with pyroxene selvages, the syenite being strongly deformed at the margins of the xenoliths. Farther north similar limestone–syenite relationships are seen, and the syenites are cut by a leucocratic melanite syenite dyke which Woolley (1970) equates with the later suite of syenites.

An important group of exposures occur to the north of Loyne (around [NC 253 145]). The Loyne mass is a separate thrust wedge (or 'horse' in the terminology of Elliott and Johnson, 1980) beneath the Ben More Thrust. The mass shows a complete section through igneous rocks with both roof and floor exposed. Dolomitic limestones on top of the igneous rocks are tens of metres thick, but only small patches of limestone are exposed beneath. To the south, exceptional ly well-exposed, but very complex, contacts are seen in the new marble quarry near Ledbeg. The marbles are cut by massive sheets of 'borolanite', with the production of beautiful serpentine marbles, with strikingly banded reaction zones, and clear evidence for the contemporaneous presence of both 'borolanite' and mobilized carbonate liquids. Igneous sheets cutting limestones are also exposed in the 'Four Burns' area in the NE of the complex, (around [NC 293 132]; see also (Figure 7.16)). The main body of the intrusion is probably at a shallow depth below this locality, since Woolley (1970) believed that the upper contact of the intrusion dips east beneath the limestones at about 5°.

Contacts between igneous rocks and the envelope are nowhere exposed along the SW and E edges of the intrusion. Only the drilling work (Matthews and Woolley, 1977; Notholt *et al.,* 1985; Shaw *et al.,* 1992) has revealed the extensive zone of metamorphic calc-silicate rocks that forms the contact of the igneous pyroxenite bodies beneath the peat on Mointeach na Totaig. At the NW end of the mixed pyroxenite–nepheline-syenite zone there are a few contacts of syenite with quartzite, of which the excavated example from Bad na h-Achlaise is the most instructive. Fenitization of quartzite exposures from near here has been described by Woolley *et al.* (1972), Rock (1977) who described fenitization of a block in drift, and Martin *et al.* (1978).

Interpretation

The poor exposure of the Loch Borralan intrusion, its exceptional petrological diversity, and its complex tectonic setting, make interpretation of field and petrogenetic relationships extremely difficult. The excavations and drilling that have taken place since the exposure mapping of Shand (1910) and Woolley (1970) have invariably led to major re-assessments, and the recent report of carbonatite (Young *et al.,* 1994) shows that even exposural evidence has not yet been fully exploited. The reader should have an open mind when assessing the following brief interpretation.

The original interpretation of the whole intrusion as a continuously stratified laccolith, with the various rock types related by crystal settling, has not stood the test of time. The leucocratic, silica-saturated and oversaturated members have an intrusive relationship to the earlier, generally more mafic, undersaturated suite, which may be demonstrated in Allt a' Bhrisdidh and near Allt a' Mhuillin. Both suites show clear internal evidence of the emplacement of pulses of magma of different composition, presumably fractionated before emplacement. Nepheline-syenites, melanite syenites and pyroxene syenites around the critical exposures at Bad na h-Achlaise were certainly emplaced in several phases. The mafic melanite syenites and ledmorites' are part of this suite, and all types show complex cross-cutting relationships. The more leucocratic syenites cut the pyroxene syenites and both types cut the pyroxenites and the skarn rocks. The western edge of the intrusion appears to be a complex interleaving of all these rock types but even the considerable drilling programme does not reveal the overall structure.

Woolley's (1973) mapping of the main area of pseudoleucite-bearing rocks in the SE part of the intrusion suggests that the rocks there are stratified and possibly fractionated *in situ.* The structural relationship between the main pseudo-leucite suite and the nepheline-syenites that are now known (through drilling only) to occupy a large part of the SW margin of the intrusion is not clear, although there are several localities in the western part of the intrusion (Loyne, Ledbeg quarry and the hidden contacts on Mointeach na Totaig) where 'borolanites' occur, interestingly always in close association with limestones. Evidence that the early pseudoleucite-bearing suite around Allt a' Mhuillin was emplaced early, before the ledmorites' and nepheline-syenites, as suggested by Woolley (1970), hinges on the interpretation placed on the flattening of the pseudoleucites. As the pyroxenite and nepheline-syenite members of the early suite are clearly intrusive into rocks of the Ben More Nappe at Bad na h-Achlaise, but are undeformed (Parsons and McKirdy, 1983), the pseudoleucite-bearing assemblage must be earlier. But if the fabric in the pseudoleucite-bearing rocks at Aultivullin is related to their mode of emplacement, their relative emplacement age is equivocal. There is an urgent need to investigate the structural relationship between these exotic rocks and the remainder of the intrusion, particularly the newly exposed 'borolanites' at Ledbeg.

The large, steeply dipping mass of biotite-magnetite pyroxenite under the peat of Mòinteach na Totaig is earlier than at least three generations of the nepheline-syenites, which occur, largely unseen, to the NE. The pyroxenites are known by drilling to be interleaved with skarn rocks, but were undoubtedly magmatic as is demonstrated by their intrusive relationships at Bad na h-Achlaise, where the pyroxenites are intrusive into quartzites that were moved previously into position on the Ben More Thrust. The high temperatures implied by their bulk mineralogy remain problematical. The cumulate origin favoured by Matthews and Woolley (1977) requires faulting or emplacement as a crystal mush to explain both their near-vertical form and structural level. Their evidence for a cumulate origin is the presence, in borehole material, of alternating, sharply defined pyroxene- and hornblende-rich layers, a few centimetres thick, in which the hornblende shows a preferred orientation. The 'cumulate' textures are not unequivocally due to crystal settling, although it is a possible interpretation, and it is not clear how the layering would survive the proposed squeezing of a crystal mush. Furthermore, the rocks are similar (apart from the presence of garnet) to the pyroxenites in the nearby Loch Ailsh complex which have a dyke-like form between syenite and dolomitic limestone. Although the pyroxenites are intrusive rocks, their intimate association with a major calc-silicate and magnesium-silicate skarn body at the margin of the silicate rocks is at least suggestive of an origin involving reactions between silicate magma and the dolomitic limestones. Young *et al.* (1994) provided Rare Earth Element (REE) plots of a range of rocks from Loch Borralan. The Bad na h-Achlaise pyroxenites and a diopside-rich skarn rock from a borehole nearby have very similar patterns, as do borolanites' and 'ledmorites'. In contrast, the leucocratic nepheline-syenites and the carbonatite show much greater enrichment in the light REE. Although the alkaline magmas undoubtedly originated in the Earth's mantle, the visitor to the Loch Borralan and Loch Ailsh intrusions should be open-minded about the origin of the pyroxenites. Perhaps, to this extent, Shand's ideas live on.

The affiliation of the recently discovered carbonatite to the Loch Borralan intrusion is demonstrated by the syenite and pyroxenite xenoliths it contains, and its true character as a carbonatite by its trace and rare-earth element contents and patterns, and its carbon and oxygen isotopes (Young *et al.,* 1994). The mineralogy and internal heterogeneity are characteristic of carbonatites. While it is perhaps surprising that these rocks went unnoticed until 1988, the association of carbonatite with nepheline-syenite magmatism is seen worldwide and the occurrence itself is unsurprising. Diopsidic pyroxenites are also commonly associated with carbonatites. The shape of the Loch Urigill carbonatite is unknown but it cannot be more than approximately 100 m in diameter.

The late suite of melanite alkali feldspar-syenites and quartz-syenites is internally much simpler than the early suite. Cnoc-na-Sroine shows an upward progression from 'perthosites', often with melanite, to quartz-syenites at the top, complicated only by the presence of some quartz-syenite sheets at lower levels. The contact relationships with the early suite give little information on the overall shape but it is perhaps a stock-like body at least 275 m thick (Woolley, 1970). These rocks are generally similar to the alkali feldspar-syenites at Loch Ailsh, but are chemically subtly different (Parsons, 1972) and were emplaced significantly later, after the movements on the Ben More Thrust (Halliday *et al.,* 1987), so that their current proximity may hide an initial separation of perhaps several tens of km. The overall shape of the early suite seems to be sheet-like (see Woolley, 1980) as is its internal structure in the eastern part of the complex. Exposed contacts with country rocks are extremely rare, but the quartzite–pyroxenite contact at Bad na h-Achlaise and the dolomitic limestone–'borolanite' contacts in the Ledmore marble quarry are particularly important. Huge volumes of skarn rocks occur beneath Mòinteach na Totaig but are unexposed.

Conclusions

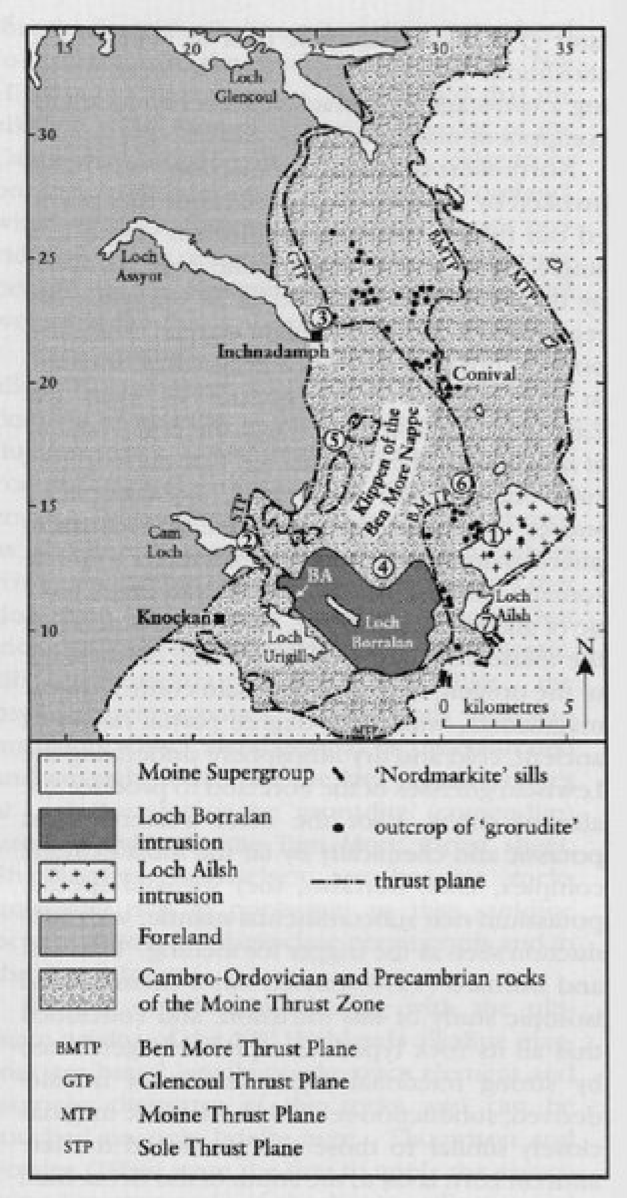
The Loch Borralan intrusion is the only plutonic igneous complex composed of silica-undersaturated rocks in the British Isles, and it contains several rock types that are extremely rare on a worldwide scale. Some of its members are among the most potassium-rich rocks on Earth. Very recently, a small body of igneous carbonate rock (carbonatite), with syenite xenoliths, has been discovered just outside the main intrusion. This too is a unique occurrence of this rock type in the British Isles. Exposure around Loch Borralan is notoriously bad but the intrusion has an important historical position in the development of igneous petrology through its contribution to the concept of silica saturation. It also has historical prominence because of the idea that reactions between limestone and silicate magma (desilication) were essential to the formation of feldspathoid-bearing rocks (the 'Daly–Shand hypothesis'), and the suggestion that the intrusion was a single, internally stratified, gravitationally differentiated laccolith. Neither hypothesis has stood the test of time; the modern view of such magmatism is that it has its origins in the Earth's mantle, but the detailed geotectonic setting of the Borralan mass and its associated rocks is still a matter of debate.

The current structural view is that the intrusion was emplaced in two major episodes. An early suite, consisting of ultramafic and feldspathoid-bearing rocks involving several (at least five, and perhaps several more) pulses of already differentiated magmas, is extremely complex. It includes the celebrated pseudoleucite-bearing 'borolanites', has a sheet-like, laccolithic form and may have partly differentiated *in situ.* The ultramafic rocks (biotite-magnetite pyroxenites) contain Britain's largest reserves of phosphate (as apatite) and form a steep-sided, extended lenticular dyke-like body, cut by several generations of feldspathoidal syenite, and interleaved with diopside-, phlogopite- and forsterite-rich rocks produced by reactions with Durness Group dolomitic limestones. A new quarry, at Ledmore, provides outstanding exposures illustrating reactions between 'borolanites' and carbonate rocks.

The later suite is composed of alkali feldspar-syenites ('perthosites') and quartz-syenites. It appears to punch through the early suite and may have a stock-like form. It becomes more quartz-rich upwards but sheets of quartz-syenite cut 'perthosite' lower in the mass. These rocks are mineralogically quite similar to, although chemically distinct from, the syenites in the neighbouring Loch Ailsh intrusion.

The intrusion provides an important time-marker for movements in the Moine thrust zone. Most (and perhaps all) of the early suite were emplaced after the main movements on the Ben More thrust plane. Thus its U-Pb age of 430 ± 4 Ma provides a minimum age for these movements, while the just-significantly-different age of 439 ± 4 Ma for the neighbouring Loch Ailsh complex provides a maximum. It is possible that a flattening fabric affecting the 'borolanites' was produced during movements on the Ben More Thrust. This interpretation is controversial, but if correct it implies that the 'borolanites' result from the earliest phase of emplacement, and that the movements on the Ben More Thrust were very close to 430 Ma. Evidence that the Loch Borralan complex post-dates large-scale movements on the Sole Thrust comes from its alignment with nepheline-syenite dykes in the Foreland, which also place the source of this extreme magmatism firmly in the mantle underlying the Lewisian gneisses.

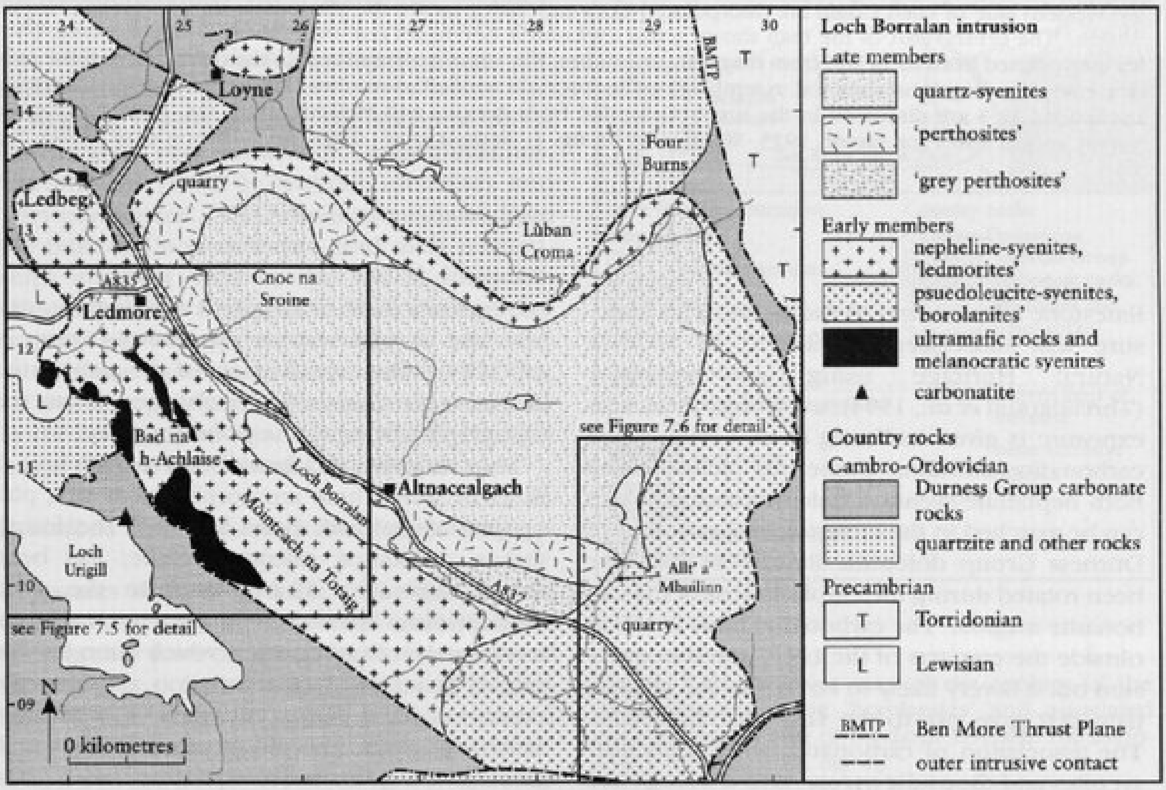
References



(Figure 7.2) Map of the Assynt district showing the major thrusts, the two major alkaline intrusions, and the distribution of two of the six types of minor intrusive rocks. BA is the critical locality, at Bad na h-Achlaise, where nepheline-syenites and pyroxenites of the Loch Borralan intrusion are intruded into one of the klippen (the Cam Loch Klippe) of the Ben More Nappe. GCR sites in the thrust zone related to minor intrusive rocks are shown by circled numbers. 'Grorudite': 1, Glen Oykel South; 2, Creag na h-Innse Ruaidhe. 'Hornblende porphyrite': 3, Cnoc an Droighinn; 4, Luban Croma. 'Vogesite': 5, Allt nan Uamh; 6, Glen Oykel North (diatreme). 'Nordmarkite': 7, Allt na Cailliche. (After Sabine, 1953 and Johnson and Parsons, 1979, fig. 3.)

Rock name	First use in NW Highland's literature	Modern equivalent(s)	Petrography and mineralogy	Comments
Assyntite	LB. Shand (1910) NW of Cnoc na Sroine	Sodalite nepheline-syenite	Trachytic texture; alkali feldspar, interstitial nepheline, both enclosing sodalite, with biotite, magnetite and titanite	Obsolete name. An exotic rock but poorly exposed
Borolanite	LB. Horne and Teall (1892) from SE end of intrusion	Melanite-biotite (pseudoleucite-) nepheline-syenite	Alkali feldspar-nepheline intergrowths (both in pseudoleucite and matrix), well-formed melanite and biotite. Pseudoleucite not always present	The original name is still occasionally used informally
'Canisp Porphyry'	MI. Adopted by Sabine (1953) from early usage	Porphyritic quartz-microsyenite	Alkali and plagioclase feldspar phenocrysts in a groundmass of turbid feldspar and quartz	Forms major sill complex
Cromaltite	LB. Shand (1910) from Bad na h-Achlaise. After Cromalt Hills	Melanite-biotite pyroxenite	Diopsidic pyroxene and ilmenomagnetite enclosed by biotite and replacive melanite	Obsolete name. Similar pyroxenites without melanite at LA
Grorudite	MI. Sabine (1953)	Peralkaline rhyolite Comendite	Alkali feldspar and aegirine phenocrysts in fine quartz-feldspar matrix full of aegirine needles	Dykes. Equivalents are strictly volcanic
Hornblende porphyrite	MI. Sabine (1953) following Bonney (1883)	Hornblende microdiorite Spessartite	Phenocrysts of hornblende and plagioclase, sometimes biotite, in fine feldspathic groundmass	Many sills. Calc-alkaline
Ledmorite	LB. Shand (1910), from Ledmore River	Melanite-augite nepheline-syenite Melanocratic nepheline-syenite	Equigranular, medium grained with closely intergrown melanite, diopsidic augite, biotite. Alkali feldspar intergrowths with nepheline	Name occasionally used informally
Nordmarkite	LA. Phemister (1926), after Nordmarken, Norway	Quartz-syenite	Leucocratic syenites made of alkali feldspar and interstitial quartz with variable aegirine-augite and/or alkali amphibole	Main rock of BL. Also occurs as deformed sills
Perthosite	LA. Phemister (1926), main syenite unit	Alkali feldspar-syenite	Nearly monomineralic alkali feldspar rock. Name refers to microperthitic texture	Name still widely used
Pulaskite	LA. Phemister (1926) after Pulaski Co., Arkansas	Pyroxene syenite Melasyenite	Similar to 'nordmarkites' and 'perthosites' but with more aegirine-augite. Some variants have melanite at LA, with minor nepheline and melanite at LB	Type example is nepheline-bearing so use at LA is incorrect
Shonkinite	LA. Phemister (1926) after Shonkin Sag, Montana	Pyroxene (nepheline-) melasyenite	At LA diopside and biotite, sometimes hornblende occur in glomeroporphyritic clusters set in alkali feldspar. Nepheline-bearing at LB	Nepheline usual but not essential. Associated with ledmorites at LB
Sövite	LB. Young *et al.* (1994)	Calcite carbonatite	Porphyritic sövite has large calcite rhombs set in finer calcite matrix. Phlogopite sövite has small phlogopite crystals together with apatite set in calcite matrix	Small body with xenoliths from LB outside southern contact
Vogesite	MI. Sabine (1953) after Vosges mountains	Vogesite Hornblende-rich lamprophyre	Hornblende phenocrysts set in fine-grained matrix of euhedral plagioclase, alkali feldspar, hornblende and minor quartz. Diopside occurs as glomeroporphyritic clots and rare phenocrysts	Many sills. Calc-alkaline
Vullinite	LB. Shand (1910), from Allt a' Mhuilinn	None	Fine-grained, sometimes schistose rock, with altered plagioclase set in matrix of alkali feldspar, plagioclase, diopside, hornblende and biotite	Obsolete name. Shand considered it probably metamorphic

LB: Loch Borralan intrusion; LA: Loch Ailsh intrusion; BL: Ben Loyal intrusion; MI: Minor Intrusion.
Rock names in **bold** were named from type examples in Assynt. Historical details are from Holmes (1920) and Brögger (1921). Note that many of the old varietal rock names are used in the text, between quotation marks, for clarity when referring to earlier publications.

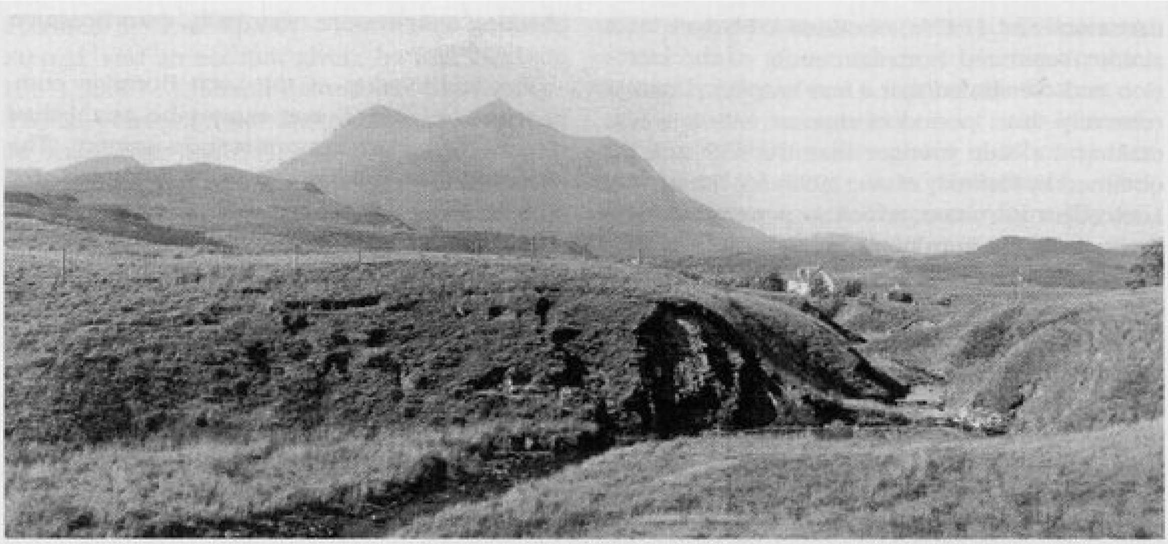


(Figure 7.4) Map of the Loch Borralan intrusion and its envelope rocks (modified after Johnson and Parsons, 1979).

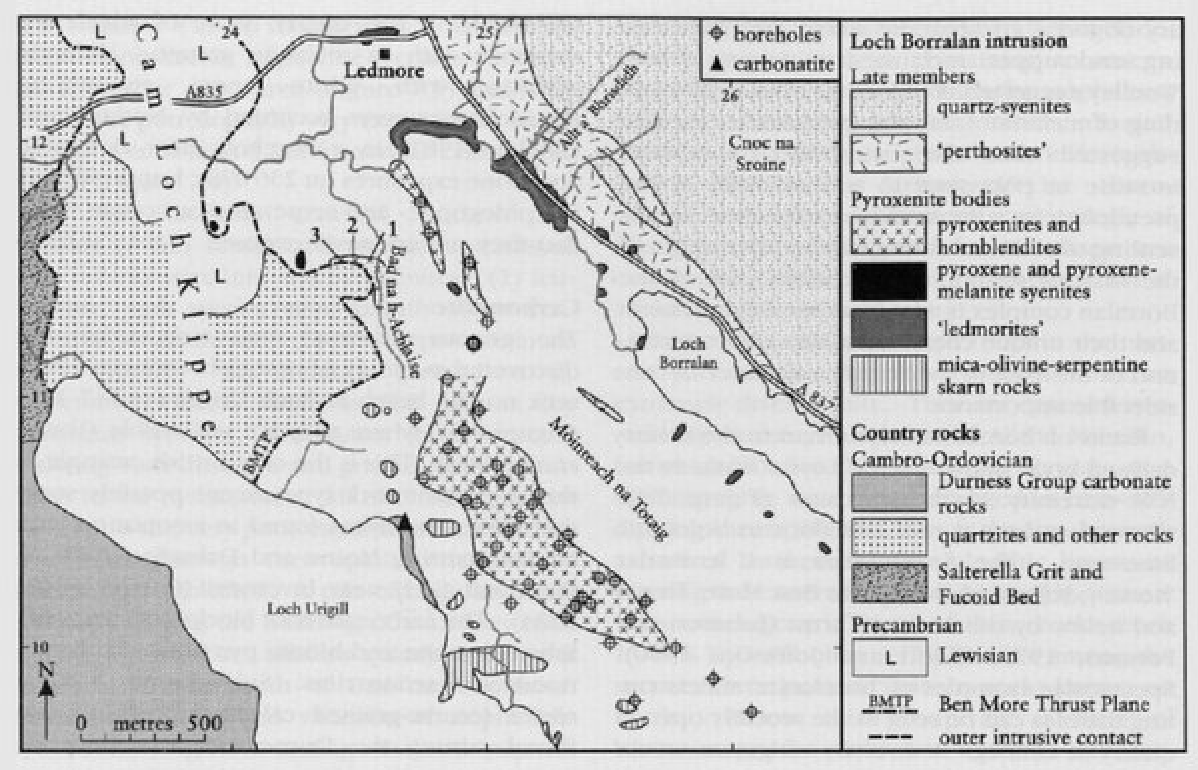
Table 7.1 Inter-relationship of alkaline igneous activity and major tectonic events in the Moine thrust zone (after Halliday *et al.*, 1987).

FORELAND	SOLE THRUST SHEET	BEN MORE NAPPE	MOINE NAPPE	AGE (Ma)
Peak of illite metamorphism in Foreland sediments				*c.* 408[1]
		Ross of Mull Granite cuts Moine thrust plane		414±4[2]
Nepheline-syenite dykes	*Late undeformed pegmatites in Loch Borralan*		*Cnoc-nan-Cùilean intrusion*	426±9[3]
	Penetrative deformation of pseudoleucite rocks at Loch Borralan. Crush Zones in quartz-syenites		*Final movements on the MTP*	
		Late crushing in Loch Ailsh		
		'Nordmarkite' sills near the MTP		
	Loch Borralan intrusion			430±4[3]
	Main movements on the STP, folding BMTP?			
		Main movements on the BMTP		
		'Grorudite' dykes		
		Mylonites and greenschist-facies metamorphism in Loch Ailsh	Moine mylonites and 'D1' Main movements on MTP	
		Sgonnan Mór folds and fabric		
		Loch Ailsh intrusion		439±4[5]
Canisp Porphyry	'Hornblende-porphyrite' and vogesite sills and dykes			
			'D3' of Glen Dessarry Moine. Deformation of syenite	
			Glen Dessarry intrusion	456±5[4]

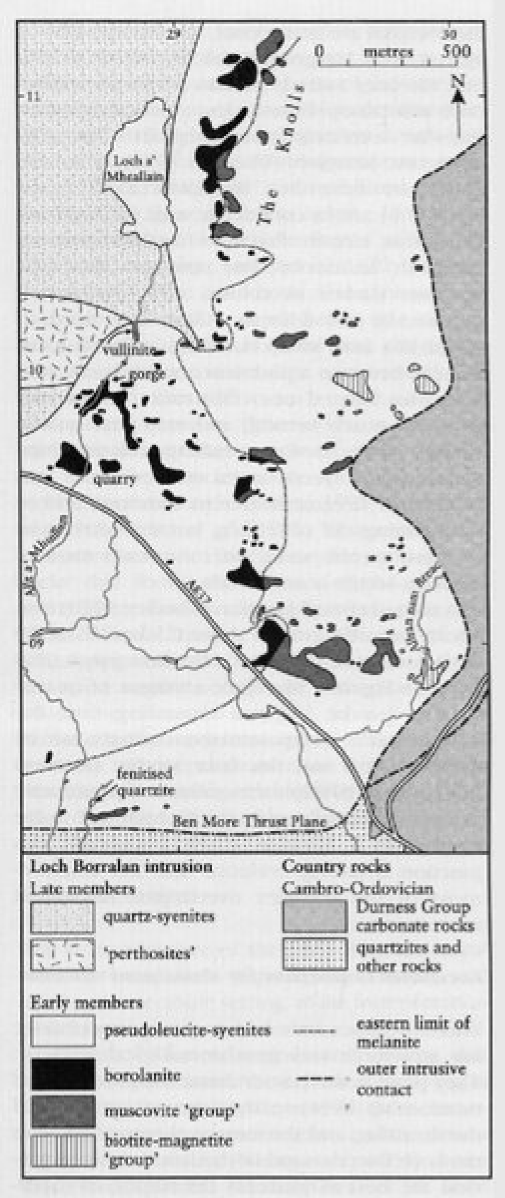
Events in italic were essentially synchronous. MTP: Moine thrust plane. BMTP: Ben More thrust plane. STP: Sole thrust plane. The radiometric ages are from the following sources: 1. Johnson *et al.*, 1985. 2. Halliday *et al.*, 1979a. 3. Van Breemen *et al.*, 1979a. 4. Van Breeman *et al.*, 1979b. 5. Halliday *et al.*, 1987.



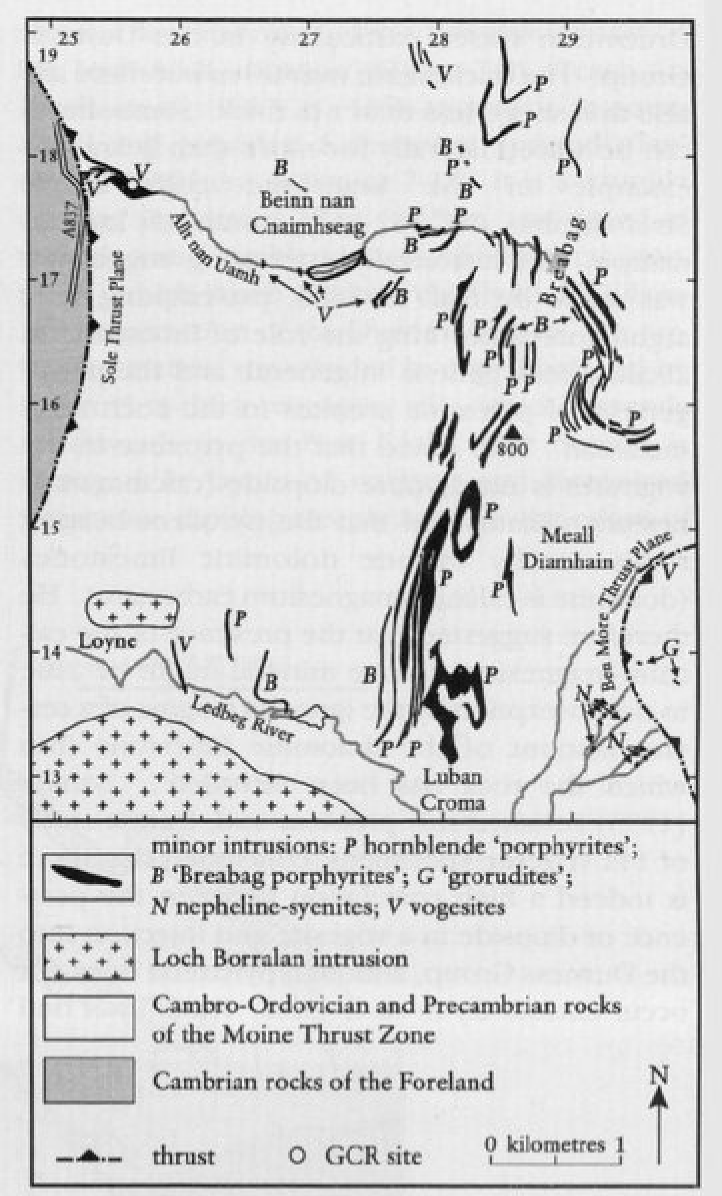
(Figure 7.3) 'Ledmorite' (melanite-augite nepheline-syenite) exposures at Ledmore in the Loch Borralan intrusion, looking west, with Cùl. Mòr (849 m) behind. Cùl. Mòr is in the Foreland and is composed of Torridonian and Cambrian sandstones. The Sole Thrust runs beyond the low hills in the middle distance. (Photo: I. Parsons.)



(Figure 7.5) Map of the western part of the Loch Borralan intrusion. Units within the Cam Loch Klippe and on the western side of Loch Urigill are interpolated from exposures, as are the alkali feldspar-syenites of Cnoc na Sroine. The central part of the map shows actual exposures, boreholes and the extent of the pyroxenite bodies interpolated from them and from magnetic anomalies. The unornamented area in the central part of the map is a complex, largely unexposed assemblage of leucocratic nepheline-syenites, ledmorites and pyroxenites. Localities 1 to 3 are discussed in the text. (Compiled from Parsons and McKirdy, 1983, fig. 1; the Geological Survey special sheet for Assynt, 1923; Woolley, 1970, fig. 1; Notholt et al., 1985, fig. 3; Young et al., 1994, fig. 1.)



(Figure 7.6) Exposure map of the geology of the pseudoleucite-bearing 'borolanites' and associated rocks of the SE part of the Loch Borralan intrusion. (After Woolley, 1973, fig. 2.)



(Figure 7.16) Distribution of sills and dykes between the Luban Croma and Allt nan Uamh sites, north of the Loch Borralan intrusion. (After Sabine, 1953, fig. 8.)