Loch Loyal Syenite Complex

(NC 610 440–[NC 670 500]–[NC 670 520]–[NC 560 510]–[NC 560 470]–[NC 590 440]

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Introduction

The scenically magnificent Loch Loyal intrusions (Figure 7.11) form the largest area of alkaline rocks in Britain, and contain the only extensive body of the quartz-syenite type, 'nordmarkite'. There are three centres, emplaced in metamorphic Moine and Lewisian country rocks, but unaffected by Caledonian deformation (Table 7.1). The largest intrusion, Ben Loyal itself, is now thought to be separated from two smaller satellites, Ben Stumanadh and Cnoc nan Cùilean, by a major NE–SW dextral oblique fault (Holdsworth and Strachan, in press), called by these authors the Loch Loyal Fault. This may mean that the Ben Loyal body represents a deeper level of erosion through a single intrusion of which the Ben Stumanadh and Cnoc nan Cùilean bodies are upward apophyses.

The Ben Loyal intrusion is the only leucosyenite in the NW Highlands to be truly peralkaline, showing consistent normative *acmite* (Robertson and Parsons, 1974). It has an interesting internal structural subdivision into a two-feldspar (subsolvus) outer syenite and a chemically identical, one-feldspar (hypersolvus) core syenite (Robertson and Parsons, 1974). The Cnoc nan Cùilean intrusion has a distinctly different chemical character, in particular higher K_2O (Robertson and Parsons, 1974) and a high radiometric anomaly (Gallagher *et al.,* 1971). The Ben Stumanadh intrusion is chemically and petrographically similar to the Ben Loyal intrusion. All three intrusions contain numerous xenoliths of Moine and Lewisian country rocks.

The Loch Loyal intrusions are emplaced in Moine psammites or in Lewisian gneisses that are interleaved with them and which were reworked during the metamorphism of the Moine. A suggestion by Robertson and Parsons (1974) that the country rock structures were re-orientated on a large scale by the intrusions has not been supported by recent structural work (Holdsworth and Strachan, in press), and the current view is that a localized change in strike of the country rock is a result of SE-plunging folds pre-dating the emplacement of the intrusions. All the Loch Loyal intrusions were emplaced after the metamorphism of the enclosing Moine. Unlike the Assynt complexes they are not penetratively deformed or mylonitized. A U-Pb age of 426 ± 9 Ma obtained by Halliday *et al.* (1987) on zircon from Cnoc nan Cùilean is, within errors, the same as the age (430 ± 4 Ma) of the Loch Borralan complex in Assynt (Table 7.1).

Heddle (1883b) records descriptions of the Ben Loyal syenite by Murchison and Cunningham and provides entertaining detailed descriptions of the field relationships and mineralogy of the Ben Loyal mass. Read (1931) noted the similarity of the Ben Loyal syenites to the quartz-syenites in the Assynt area, and therefore suggested that they were 'comagmatic'. Since the Loch Loyal syenites are entirely non-metamorphic, while the Assynt rocks are involved in the Moine thrust belt, he came to the important conclusion that metamorphism of the Moine pre-dated the post-Cambrian movements. This was an important deduction in the days before widespread use of radiometric dating.

Description

Ben Loyal intrusion

The outcrop of the intrusion has the form of a half-circle, in area *c.* 16 km^2, with a circular boundary in the NW and straight boundary in the SE (Figure 7.12) which Holdsworth and Strachan (in press) interpret to be the major Loch Loyal Fault. The intrusions form high ground above the surrounding Moine, and the NW flank of Ben Loyal provides some of the most striking mountain scenery in Scotland, with excellent exposure of syenites on its imposing summits (Figure 7.11). King (1942) thought that both the Ben Loyal and Cnoc nan Cùilean intrusions have the form of irregular cones, with apices pointing downwards, but Phemister (1948) thought of the Ben Loyal intrusion as a sheet or laccolith dipping towards the SE. Robertson and Parsons (1974) considered that overall the intrusion has steep outward dips in the NW

and W, citing exposures in Allt a' Chalbach Coire ([NC 568 495] and in the gorge of Allt Fhionnaich ([NC 564 476]. At both these localities the relationships are complicated by syenite sheets, which may be concordant with the Moine or steeply dipping and which contain lenses of Moine rocks in places. Moine rocks can be seen overlying syenite, and there is a gradual decrease downstream in the amount of syenite. The outward dip is steeper in the Allt a' Chalbach Coire than in the Allt Fhionnaich and on the west slope of Sgòr Fhionnaich the contact is nearly vertical. However, Robertson and Parsons' interpretation of the attitude of the contact is disputed by Holdsworth and Strachan (in press) who consider that the contact dips east and SE beneath the pluton, parallel to the compositional layering of the Moine. In the SE, between Ben Loyal and Cnoc nan Cùilean, the syenite contact probably dips gently SE beneath a thickening Moine cover. Inclusions of Moine occur at various points on the southern slopes and the largest, at Bealach Clais nan Ceap [NC 590 490], is exposed over some 800 x 300 m. Other large inclusions crop out on the northern and eastern slopes of Ben Hiel ([NC 595 502], [NC 599 503], [NC 604 497]. Smaller lensoid Moine fragments characteristically between 5 and 15 cm long are common in many of the marginal areas and usually lie in the plane of the lamination in the, syenites. Some of these inclusions are sharply defined, with the same mineralogy as the regional Moine rocks, but others show extensive feldspathization and are represented by diffuse 'ghosts'.

Robertson and Parsons (1974) considered that the intrusion had produced widespread deformation effects. The dip of the regional foliation and the pronounced lineation and quartz-rodding of the Moine rocks change markedly in the vicinity of the intrusion. The regional strike of the Moine is generally NE–SW, with a dip of 20–30° to the SE, but within 2 km of the syenite it begins to swing into parallelism with the margin of the intrusion. Dips are always towards the intrusion and increase towards the contact to 40–60°. Very close to the contact dips decrease again locally and the schists become crumpled. The most recent view of the change of strike in the envelope rocks (Holdsworth and Strachan, in press) is that the intrusion has been emplaced in a zone of large-scale SE-plunging folds of local F3 age, attributable to differential displacements on underlying ductile thrusts before the emplacement of the syenite.

In contrast with the chemically similar pink and grey syenites of Assynt, the Ben Loyal syenites are usually white or cream in colour, although late faulting may lead to development of pink variants. Two distinct variants can be distinguished: an outer, laminated syenite, and a relatively structureless core syenite (Gallagher *et al.,* 1971; Robertson and Parsons, 1974). The boundary between the two variants is gradational over several hundred metres, and faint laminations are sometimes seen even in the core syenites. Chemically, the two variants are indistinguishable (Robertson and Parsons, 1974) and this shows that, despite the quite frequently encountered Moine xenoliths in the laminated syenites, chemical effects of assimilation are unimportant. The lamination dips inward usually at 20–40° and is brought out by parallel prismatic amphibole and pyroxene crystals, and by tabular feldspars. The minerals show minor 'swirl' effects and this, together with the lack of evidence of assimilation, led Robertson and Parsons (1974) to reject the idea that the lamination was a 'ghost' Moine stratigraphy. Instead they suggested that it was caused by movements in a crystal mush during the last stages of consolidation. At the same time as the lamination developed the feldspar assemblage in the syenite changed by strain-facilitated exsolution and marginal recrystallization from a one-feldspar, hypersolvus syenite into a two-feldspar, subsolvus assemblage. The core of the intrusion escaped this flow deformation and preserves the original hypersolvus assemblage. This is an interesting and important textural change in fel-sic rocks, first suggested by Tuttle and Bowen (1958), in their classic memoir on the origin of granite, and it is not seen in the other Scottish syenites. Indeed two-feldspar syenites seem to be rather uncommon rocks, on a worldwide basis.

The Ben Loyal quartz-syenite has a thoroughly peralkaline character and consistently shows normative *acmite* (the pyroxene component $NaFeSi_2O_6$) in analyses (Robertson and Parsons, 1974). This is not true of the majority of the syenites in Assynt. Both core and marginal variants are extremely consistent in quartz content, with 5–10% normative quartz. The most abundant coloured mineral is a bright-green aegirine-augite, but in the laminated marginal syenites a green amphibole of the eckermannite-arfvedsonite series may be present and is dominant in parts. Both syenite units, but particularly the marginal variant, contain vugs lined by a yellow, powdery mineral identified by von Knorring and Dearnley (1959) as a rare-earth-bearing monazite group mineral. These cavities also contain montmorillonite, harmotome and stilbite. Boulders of pegmatite with green amazonite (a variety of K-feldspar), thorite, galena, titanite and topaz were reported by Heddle (1883b, 1901) from the boulder-scree slopes in the NW of the Ben Loyal mass.

A quarry at Lettermore [NC 612 498] provides ready access to good exposures of fresh, very slightly laminated marginal syenite, with rare small schist xenoliths. Druses with the yellow rare-earth-rich mineral coating are common. A much

more remote area, around Allt Fhionnaich ([NC 564 475], Sgòr a' Chleirich ([NC 568 485] and Allt a' Chalbhach Coire ([NC 572 488] can be used to demonstrate all the main features of the complex and its contact relationships. It is an area of quite exceptional scenic grandeur. On the peaks of Sgòr Fhionnaich and Sgòr a' Chleirich the inward-dipping lamination of the marginal variants can be readily mapped (Robertson and Parsons, 1974). The unlaminated core variant appears on the NE slopes of Sgòr a' Chleirich and in the upper Allt a' Chalbach Coire ([NC 573 483].

Cnoc nan Cùilean intrusion

This pluton has an oval exposure over an area of about 3 km^2 to the south of the main Ben Loyal mass and forms an imposing conical hill rising above the Moine rocks. On the early maps of the Geological Survey it is shown connected to the Ben Loyal intrusion in the poorly exposed ground at the head of Allt Tòrr an Tairbh, but mapping and geophysical work reported by Robertson and Parsons (1974) suggested that the two intrusions are separated by an area of Moine and Lewisian rocks. This separation has been confirmed by the recent mapping of Holdsworth and Strachan (in press) who see the Cnoc nan lean body as separated from the main Ben Loyal mass by the major Loch Loyal Fault (Figure 7.12). That the two intrusions are separate is further supported by their chemical differences. Normal Cnoc nan Cùilean syenites, which are usually pink in colour, have little or no normative quartz, have more normative orthoclase than the Ben Loyal syenites, and no normative acmite. They are also richer in mafic minerals and have a larger radiometric anomaly because of high concentrations of thorite (Gallagher *et al.,* 1971). Mapping by McErlean (1993) reported by Holdsworth and Strachan (in press) has revealed that the Cnoc nan Urilean intrusion was emplaced as a series of NW-trending sheets, and that the syenites have internal foliations similar to those in the other Loch Loyal intrusions. They therefore suggest that the 426 ± 9 Ma U-Pb age obtained for the Cnoc nan Cùilean syenite can be used reliably to date the emplacement of all the Loch Loyal syenites as a whole.

King (1942) presented a map of the Cnoc nan Cùilean body that showed a pronounced concentration of basic xenolithic inclusions around the margins. Such inclusions are not uncommon in the interior of the mass as well. King noted that there is a considerable gradation in appearance of these basic inclusions, from those that are obviously schistose and were clearly originally Moine rocks, to much more highly recrystallized, structureless inclusions. He presented a detailed account of the metasomatism of these inclusions, which was a highly topical field at what was the time of the 'granite controversy'. Although the scale of metasomatism envisaged was probably greater than would now be accepted, the study nonetheless is a very valuable account of the progressive metasomatism of these Moine inclusions, and the textural variety can readily be appraised in the field. Excellent examples of the xenolithic rocks can be obtained in the stream section of Allt Tòrr an Tairbh [NC 612 473]–[NC 609 469] where the sheet-like form of the syenite can also be seen. Less clear exposures can also be seen in the cliffs above Loch Loyal Lodge (around [NC 615 465]), and on top of the ridge, areas of 'normal' relatively xenolith-free syenite can be seen.

Ben Stumanadh intrusion

This set of intrusions is of less general petrological interest than the other Loch Loyal intrusions but is structurally important. Robertson and Parsons (1974) showed that the rocks are chemically similar to those of Ben Loyal and suggested that they might be easterly protrusions. More recent mapping (Holdsworth and Strachan, in press) has led to the suggestion that the Ben Stumanadh syenite is separated from that of Ben Loyal by the Loch Loyal Fault. The new mapping shows a set of at least five, major, steeply dipping, NW-trending sheets of syenite (Figure 7.12) which appear to be coalescing to the NW There are also many, thinner, steeply dipping sheets that occur on all scales from centimetres to several hundreds of metres thick. The sheets are emplaced sub-parallel to the strike of the foliation of the country rocks. Contacts are usually sharp although in places feldspathization of the Moine can be demonstrated, and the junctions can be gradational. Hornfelsing of country rocks is visible for tens of metres from contacts, and the development of fibrolitic sillimanite in the Moine semipelites around the summit and to the NE of Ben Stumanadh e.g. [NC 647 508] may be due to a thermal metamorphic overprint. There are deformational structures in the Moine which seem to be associated with the emplacement of the sheets. Folds in the country rocks and offsets of bedding in host psammites at the margins of foliated members of the Ben Stumanadh sheets (e.g. on Ben Stumanadh itself, [NC 649 502]) indicate a steep NW-trending dextral sense of shear parallel to sheet walls during emplacement.

Despite their chemical similarity to the Ben Loyal syenites, the Ben Stumanadh rocks are dark-brown to pink in colour, the colour variation perhaps depending on late faulting (Holdsworth and Strachan, in press). They are usually two-feldspar syenites (like the outer unit in the Ben Loyal mass) with strongly aligned aegirine-augite and arfvedsonitic amphibole. Up to 16% quartz may be present, locally occurring in graphic intergrowth with feldspar. Miarolitic cavities similar to those in the Ben Loyal syenites also occur. large parts of the Ben Stumanadh intrusions display cataclastic textures associated with low temperature brittle faulting. Exposures showing both the overall structure, petrography and contact relationships are conveniently found in the wooded slopes of Sron Ruadh [NC 627 507] east of the northern end of Loch Loyal.

Interpretation

The Loch Loyal syenites are petrographically relatively simple compared with the Assynt plutons, only the Cnoc nan Cùilean intrusion showing obvious petrographical variety in the form of mafic inclusions. These are in all probability variably metasomatized xenoliths of Moine and Lewisian envelope rocks. Chemically, the Ben Loyal and Ben Stumanadh syenites are similar, although there are textural and colour differences that perhaps reflect more intensive, late brittle deformation, and associated alteration, in the Ben Stumanadh rocks. The Cnoc nan Cùilean intrusion is chemically distinctive, which perhaps suggests multiple emplacement of two magmas, fractionated at depth.

Internally, the Ben Loyal syenite can be roughly sub-divided into chemically indistinguishable outer laminated and inner structureless syenites. There is general agreement that the lamination is non-metamorphic and formed during the late stages of consolidation, very probably during a 'ballooning' diapiric form of emplacement in which the core syenites were emplaced last. There is a degree of controversy about the attitude of the contacts on the north and west sides of the intrusion, but the body appears to dip beneath country rocks to the SE, and to be truncated by a large fault. The Cnoc nan atilean and Ben Stumanadh syenites occur to the SE of this fault. A good case can be made that the Ben Stumanadh syenites, which have the form of a series of steeply dipping sheets, represent a high-level section, brought down by the Loch Loyal Fault, equivalent to the eroded upper part of the Ben Loyal intrusion. The Cnoc nan Cùilean body also has a sheeted internal structure, but the distinctive mineralogy (little or no quartz, and significant enrichment in normative orthoclase relative to the other feldspar components when compared with the Ben Loyal syenites) and abundant metasomatized schist and gneiss xenoliths, set it apart from Ben Loyal and suggest that it represents a separate phase of intrusion. The chemistry of the syenites at Cnoc nan Cùilean suggests that they formed from a slightly less evolved magma than those of Ben Loyal, but care must be taken in this interpretation because of the clear evidence for assimilation of country rocks.

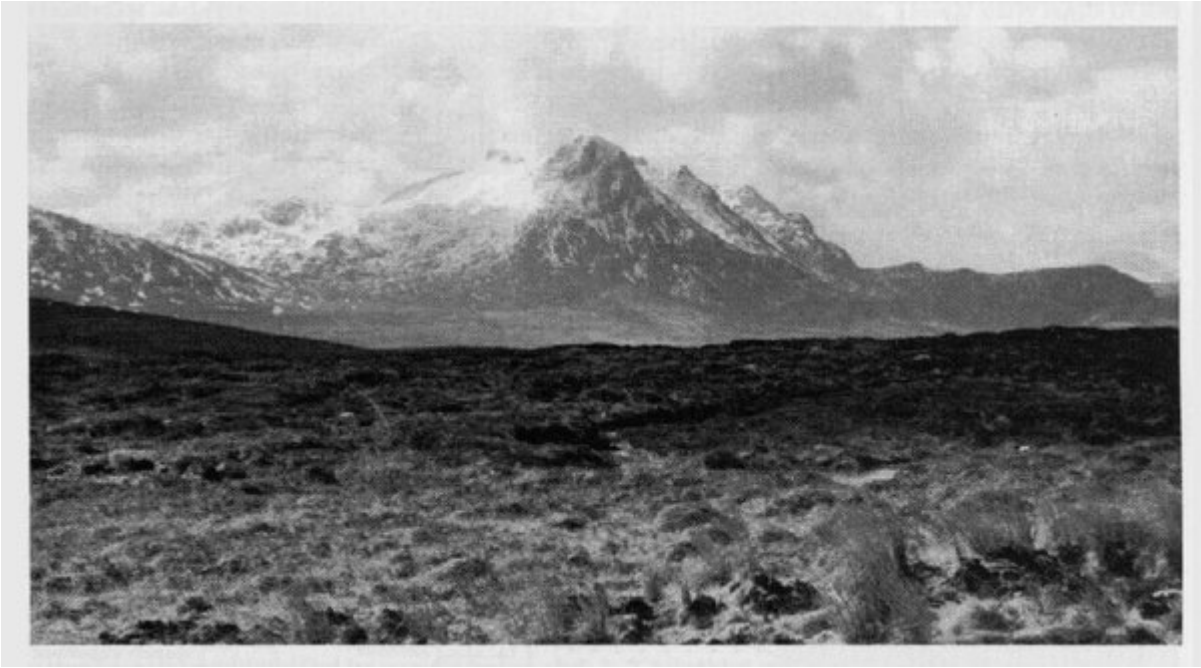
The Ben Loyal syenites are consistently peralkaline and quartz bearing. The marginal, laminated syenites are unusual in being two-feldspar rocks, in contrast with the one-feldspar, hypersolvus core syenites. The development of a two-feldspar assemblage probably occurred by a continuous process of exsolution and recrystallization during the mild deformation accompanying the ballooning period of emplacement. McErlean (1993) has suggested that serrated grain boundaries in syenites from Ben Loyal may be due to a solid-state overprint representing a late deformational phase. However, such textures are seen in undeformed syenites elsewhere and in the writer's view textures like those illustrated by Robertson and Parsons (1974, plate 2) do not necessarily imply externally imposed deformation. The yellow rare-earth monazite-group mineral, often present in miarolitic cavities, is a thoroughly alkaline characteristic, and was no doubt deposited from a late-stage aqueous fluid phase. The Cnoc nan Cùilean and Ben Stumanadh intrusions lack normative acmite in bulk analyses, although at Ben Stumanadh the presence of alkali pyroxenes shows the similarity to the Ben Loyal syenites. A U-Pb age for the Cnoc nan Cùilean intrusion of 426 ± 9 Ma is probably representative of the Loch Loyal intrusions as a whole. Within errors it is the same as the age of the Loch Borralan complex in Assynt. The Loch Loyal intrusions were certainly emplaced after the regional metamorphism of the Moine in Sutherland and Caithness, which also pre-dated the emplacement of the perhaps slightly older (439 ± 4 Ma) Loch Ailsh intrusion, which is cut by the Moine Thrust in Assynt.

Conclusions

The Ben Loyal intrusion is the grandest expression of alkaline magmatism in the British Isles. It is composed of a peralkaline quartz-syenite ('nordmarkite') and its alkaline character is underlined by the common presence of an unusual rare-earth mineral. The laminated, outer unit of the intrusion is a two-feldspar syenite (the only British example) which shows important microtextural changes in its transitional relationship to the chemically identical, unlaminated, one-feldspar core syenite. The fabric of the outer unit was produced during emplacement as a 'ballooning' diapir and is the only proven example of such a style of intrusion in the NW Highlands alkaline suite.

The two satellite intrusions, of Ben Stumanadh and Cnoc nan Cùilean, have different characters. They are separated from the Ben Loyal intrusion by the major Loch Loyal Fault. The Ben Stumanadh syenites are similar to the outer unit of Ben Loyal and were emplaced as a set of steeply dipping, NW-trending sheets in Moine psammites. A good case can be made that they represent a downfaulted portion of an upper section of the Ben Loyal mass, and the two intrusions thus provide important insights into emplacement mechanisms of plutons. The Cnoc nan Cùilean satellite has an internal sheeted structure but is chemically less evolved than the other two intrusions, suggesting that the Loch Loyal magmatism proceeded in at least two pulses, the magmas fractionating at depth prior to rising to their present level. The presence of numerous metasomatized Moine and Lewisian xenoliths in the Cnoc nan Cùilean intrusion, many of which show signs of assimilation, also sets this satellite apart from the Ben Loyal mass, in which xenoliths are relatively rare. Early descriptions of metasomatic reactions seen in the Cnoc nan Cùilean xenoliths have a historical place in discussions on the origin of granite (the 'granite controversy'). The Loch Loyal intrusions were emplaced after the metamorphism of the Moine envelope rocks, the only thoroughly alkaline rocks in this tectonic setting. A U-Pb age of 426 ± 9 Ma for the Cnoc nan Cùilean intrusion probably applies to the entire group of intrusions, providing an important regional time-marker. It is, within errors, the same as the age of the Loch Borralan intrusion in Assynt. In Assynt there are late displacements post-dating the Loch Borralan and Loch Ailsh intrusions, and it seems probable that the Loch Loyal intrusions will have been displaced towards the west by these late movements on the Moine Thrust.

References

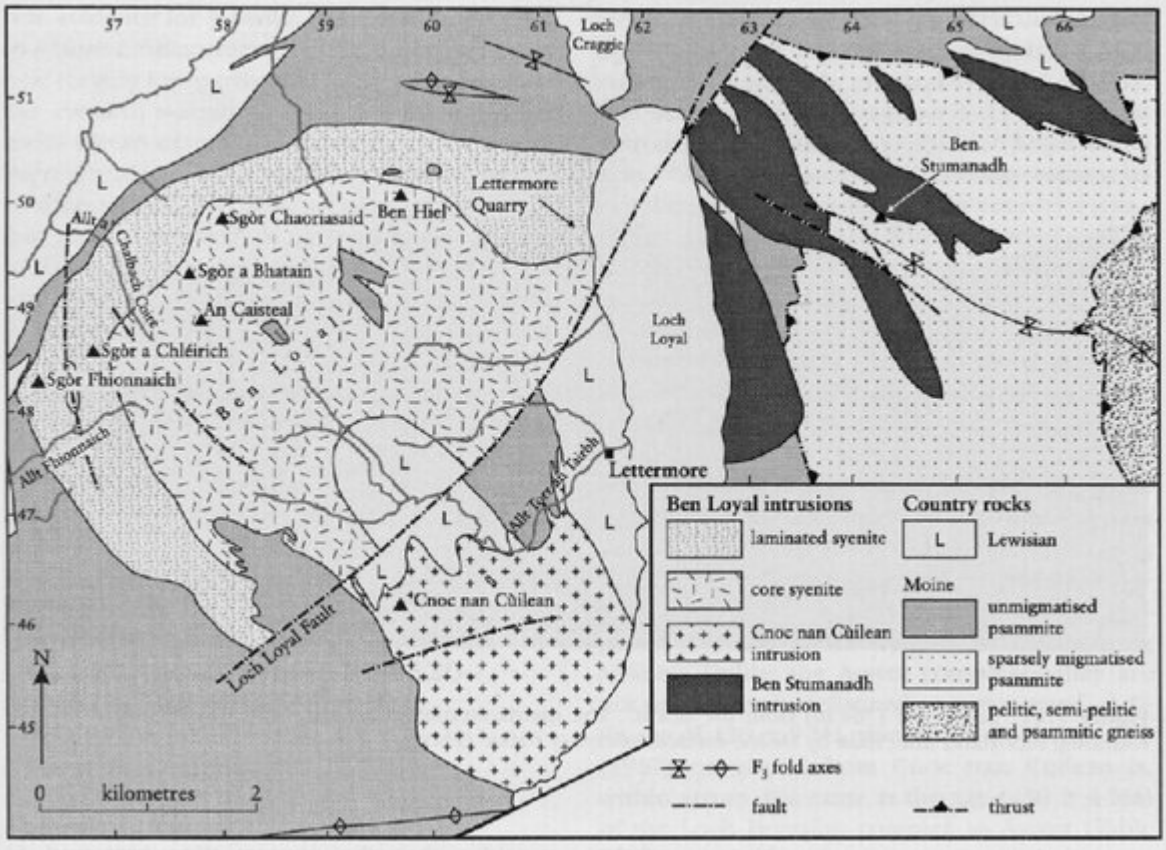


(Figure 7.11) Ben Loyal (764 m) from the north. The quartz-syenite peaks rise dramatically out of the surrounding moorland underlain by Moine metasedimentary rocks. (Photo: I. Parsons.)

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[5]
	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	Moine mylonites and 'D1' Main movements on MTP	
		'Grorudite' dykes		
		Mylonites and greenschist-facies metamorphism in Loch Ailsh		
		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 7.12) Map of the Loch Loyal syenite intrusions and their envelope rocks (compiled from Holdsworth and Strachan, in press; and Robertson and Parsons, 1974, fig. 1).