Caledonian Igneous Rocks of Great Britain

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Chapter 7

Late Ordovician to mid-Silurian alkaline intrusions of the North-west Highlands of Scotland

INTRODUCTION

I. Parsons

A group of small alkaline igneous plutonic complexes and a suite of associated dykes and sills of late Caledonian age occur in a belt roughly parallel to the Moine Thrust in the NW Highlands of Scotland (Figure 7.1). This alkaline magmatism represents the NW edge of the otherwise overwhelmingly calc-alkaline Caledonian Igneous Province north of the Highland Boundary Fault. Radiometric ages show that the alkaline activity was protracted, spanning the period 456–426 Ma (Table 7.1). The rocks were thus emplaced concurrently with the earlier members of the 'newer granite' suites, although most of these intrusions are a little younger, with a peak of activity around 410–400 Ma (Brown, 1991). The earliest alkaline pluton, the Glen Dessarry syenite (Richardson, 1968), was penetratively deformed by late orogenic events, while the younger intrusions are deformed only locally. The Loch Loyal intrusions were emplaced after the regional metamorphism of the enclosing Moine and interleaved Lewisian rocks. The intrusions in Assynt occur in all the thrust sheets, including a minor development in the Moine, and also in the unmoved Foreland, the only incursion of Caledonian magmatism into that structural unit. The reader must bear in mind that what is now a relatively compact area of alkaline rocks in Assynt includes rocks which must have been emplaced in a belt extending perhaps of the order of 50 km towards what is now the ESE, that has been shortened by movements on the lower thrusts.

Alkaline magmas were available during several other phases of igneous activity in the British Isles (for example in the Carboniferous magmatism in the Midland Valley, and in the British Tertiary Igneous Province) but no highly evolved plutons occur. Many of the rock types in the NW Highlands are therefore unique in a British context, and all are rare in a world context. The ultrapotassic rocks of the Loch Borralan intrusion (Figure 7.1), in particular, have extreme compositions matched at only a handful of localities worldwide. Like most alkaline suites, that of the Scottish Caledonian Province has its own distinctive character. Reviews of the alkaline suite have been provided by Sutherland (1982) and Brown (1991).

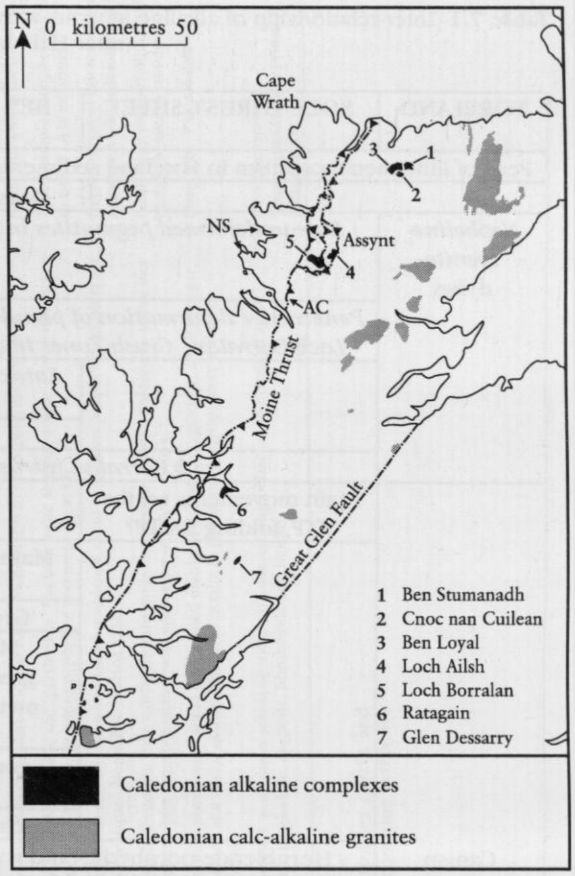

Figure 7.1 Map of NW Scotland showing localities of alkaline intrusions, aligned roughly parallel to the Moine Thrust. Many alkaline dykes and sills occur in the Assynt district and also near Ullapool in the Achall Culmination (AC). GCR sites exemplifying nepheline-syenite dykes in the Foreland are indicated by NS. Caledonian calc-alkaline granites NW of the Great Glen are also shown. The Ratagain intrusion is largely calc-alkaline in character but has minor syenitic members (after Halliday *et al.*, 1987, fig. 1).

Because of the early recognition of their unusual mineralogy, the Caledonian alkaline rocks were prominent in the evolution of ideas in igneous petrology in the early part of the 20th century. The province provided type localities of many rock types named by these early workers (Table 7.2), some of which have remained in widespread use. Adoption of a modern terminology for the suite makes much of this classic early work very hard to follow and in the text the old names have been used, but with their newer equivalents, and rather clumsy mineral-based names, added where appropriate. Credit for the first chemical recognition of the alkaline character of the rocks appears to be due to Heddle

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		
		'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.

(1883a; see Teall, 1900, p. 26) who analysed an albitite from Assynt. Murchison and Cunningham made earlier references to 'syenite' and described Ben Loyal (Ben Laoghal) in some detail (see Heddle, 1883b). These early workers regarded syenite as differing from granite only by 'a mineralogical accident'. The first descriptions of the alkaline rocks with a modern ring are those of Horne and Teall (1892) and Teall (1900), who introduced the name 'borolanite' for the exotic melanite-garnet nepheline-pseudoleucite-syenites for which the Loch Borralan intrusion is most famous.

For more than thirty years, Shand (1906–1939) maintained the province at the forefront of the developing science of igneous petrology by his introduction of the important concept of 'silica saturation' and his assertion that the silica-undersaturated character of some alkaline rocks (in his view a good example being the Loch Borralan intrusion) was a result of the extraction of silica from granitic magmas by reactions with limestones, precipitating calcium silicate minerals and releasing carbon dioxide. The idea was taken up by Daly (1914) and became known as the 'Daly–Shand hypothesis'. The hypothesis has fallen out of favour, not least because it is now recognized that the carbonate rocks often associated with nepheline-syenites are themselves intrusive igneous carbonatites. The discovery, as recently as 1988 (Young *et al.*, 1994), of a carbonatite body slightly outside the

Table 7.2 Glossary of uncommon or varietal rock names employed for members of the alkaline suite in the NW Highlands.

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 interstial 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'Mhuillin	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.

Loch Borralan intrusion, rounds-off a long diversion in petrological thinking, and shows the potential for continuing field research in the province.

The ultimate source of the alkaline magmas, and the processes that have affected them on their rise through the crust and during their final crystallization, remain topics of intense research. The modern view of alkaline magmatism is that it is initiated by small degrees of partial melting in the Earth's mantle, which has sometimes been subject, before it melts, to a metasomatic process that enriches it in alkalis and certain other elements characteristic of alkaline magmas. These elements, particularly potassium, titanium, phosphorus, barium, strontium, uranium, thorium and the rare-earth elements, are normally present in very low concentrations in mantle rocks but reach high concentrations in alkaline magmas. The carrier that introduces these elements may be melts related to the carbonatites that are commonly associated with alkaline silicate magmas. Whatever the ultimate sources, basic alkaline parental magmas fractionate strongly as they ascend to give rise to a vast range of alkaline igneous rocks. The relative importance of variation arising during mantle metasomatism, partial melting of the mantle, crystal–liquid fractionation during uprise through mantle and crust, and reactions with wall-rocks, remain contentious, and no doubt vary from one instance of alkaline magmatism to another, accounting for the extraordinary diversity in the final consolidated products. The field relationships described in this chapter provide evidence of differentiation prior to emplacement, fractionation during final solidification, reactions with country rocks, and subsequent metasomatic reactions during cooling. It is necessary to take account of all these processes when attempting to deduce the ultimate sources of the magmas using sophisticated geochemical and isotopic techniques.

The structural setting of the Scottish alkaline suite is somewhat unusual in that its emplacement overlaps, both in time and space, a period of intense crustal shortening. Worldwide, the greatest upwellings of alkaline magma are in environments of major crustal extension, often preceded by large-scale doming, such as in the present-day East African rift system. Much early discussion on the rocks of the NW Highlands centred on this established correlation. For example, van Breemen *et al.* (1979a) suggested that the Scottish alkaline magmatism was related to arching on the scale of the entire NW Highlands Moine outcrop. They noted that the alkaline rocks formed a zone at the edge of the Caledonian mobile belt (Figure 7.1), close to or on, the rigid older crust of the stable Foreland, which could withstand differential stresses provided either by orogenic compression or in compensation for isostatic sag produced by the weight of the thrust sheets.

More recently it has become accepted that alkaline magmatism can be associated with small degrees of melting in the deeper parts of subduction zones, or with regions of the mantle that contain relics of earlier, now inactive subduction zones. This type of igneous association, known as shoshonitic magmatism, includes members with calc-alkaline affinities (like the granites that dominate Caledonian igneous activity) but includes some members with a strongly potassic, silica-undersaturated character, like the pseudoleucite-syenites in the Loch Borralan intrusion. Other members may be oversaturated and strongly sodic, like the late quartz-syenites at Loch Borralan or the 'grorudite' (comendite) suite of dykes in the Ben More thrust sheet. Shoshonites themselves are basaltic rocks unusually rich in potassium so that sanidine occurs as rims on plagioclase phenocrysts and in the groundmass.

Recent contributions dealing with the ultimate origins of the NW Highlands alkaline magmas are based largely on the trace element and isotopic chemistry of the rocks and can be touched on only briefly here. Thompson and Fowler (1986) were the first to apply the association between rocks of shoshonitic affinities and subduction to the Caledonian alkaline suite. Thirlwall (1981a) had postulated the existence of a NW-dipping subduction zone beneath the Scottish Caledonides from the chemistry of Old Red Sandstone lavas. Basing their work primarily on the trace element chemistry of the leucocratic syenite members of the major intrusions, Thompson and Fowler suggested that the parental magmas of the Caledonian alkaline rocks were ultrabasic shoshonitic magmas developed by deep melting of the asthenosphere with included slabs of crustal rocks, perhaps carried down as far as the seismic discontinuity at 670 km by this subduction zone. Fowler (1988b) later showed that basic members of the Glen Dessarry pluton had been contaminated by reactions with the Moine envelope rocks and later (1992) used isotopic data to support the shoshonite hypothesis for Glen Dessarry, invoking a two-stage fractionation model and a multi-component mantle source.

North-west-dipping subduction was also invoked by Halliday *et al.* (1987) but they pointed out that the alkaline magmatism stayed in a single narrow zone, albeit made even narrower by thrusting, over a period of 30 Ma while the region was a convergent plate margin. They also pointed out that there is a progressive increase in the alkaline characteristics of even the Caledonian granitoids towards the NW (Halliday *et al.*, 1985). They considered that these factors rule out a deep, well-mixed, asthenospheric source and pointed to a source in the lithospheric mantle, which had been subject to metasomatic enrichment in the elements characteristic of alkaline magmatism. They considered that the thermal state of the lithosphere, on the edge of the orogen, exercised the main control on the magmatism, with small-degree partial fusion of ancient, cold and dry lithosphere underlying the Lewisian gneisses of the Foreland to produce the alkaline melts. For the most western, most potassic and chemically by far the most extreme complex, Loch Borralan, they invoked special, potassium-rich subcontinental mantle, with subduction seen as the trigger for melting. Thirlwall and Burnard (1990) carried out a chemical and isotopic study of this intrusion, and concluded that all its rock types were primarily generated by strong fractional crystallization of mantle-derived, subduction-related shoshonitic magmas closely similar to those that produced the late Silurian Lorn lavas to the south of the Great Glen Fault. The magmas producing the oversaturated syenites were modified, prior to emplacement, by reactions with Lewisian crust. On geochemical grounds Thirlwall and Burnard ruled out the derivation from old, stable lithosphere favoured by Halliday *et al.* (1987), but they were not able to reach a conclusion as to whether the source was in the deep lithospheric mantle or the asthenosphere. In conclusion, it is fair to say that there is much to be done to explain the origins of Britain's most exotic suite of rocks, and in the writer's view solutions will only come when field relationships, petrography, mineralogy and the modern geochemical approach are made to work more closely together.

The alkaline rocks of the NW Highlands also have great importance because of their structural and geochronological implications. They provide evidence of the order and scale of movements in the Moine thrust zone, and provide the only exact time markers for events in this internationally famous major structure. A number of workers have discussed the possibility that the igneous rocks in Assynt were responsible for the embayment in the Moine Thrust known as the Assynt Culmination. This interweaving of igneous activity and structural events is an unusual and outstanding characteristic of the province and a number of the sites described in this chapter have been chosen to illustrate not only petrographical types but also critical structural relationships.

Although the early map-makers (Peach *et al.*, 1907) thought that all the igneous activity in Assynt occurred prior to the movements on the great thrust planes, it was Bailey and McCallien (1934) who first pointed out evidence that thrust movements actually overlapped the emplacement of the igneous rocks. They noted undeformed pegmatites cutting pseudoleucite-syenites in the Loch Borralan complex in which the normally rounded pseudoleucites had been flattened. They suggested that the flattening occurred as a result of thrust movements. The origin of this flattening is still controversial, but contemporaneity of igneous activity and thrusting was firmly established in an important paper by Sabine (1953), in which he recognized that particular types of minor alkaline intrusion occurring as dykes and sills were restricted to particular structural units in the thrust region.

Figure 7.2 is a simplified map of the structure of Assynt, showing the main thrust planes. The development of nomenclature of the thrusts is reviewed in Johnson and Parsons (1979). There are many minor planes of movement, in particular the arrays of high-angle reverse faults joining low-angle thrusts originally known as imbricate structure but called duplex structure by modern workers. In places the sills of Assynt are repeated by such structures. For modern treatments of the structural setting of the igneous rocks in Assynt the reader is recommended to read Johnson and Parsons (1979), Elliott and Johnson (1980) and Coward (1985). The uppermost thrust is the Moine Thrust itself, bringing the metamorphic Moine Supergroup of the Moine Nappe, mylonitized at the base, over the Lewisian, Torridonian and Cambro-Ordovician rocks of the Ben More Nappe, itself carried westward on the Ben More Thrust. North of Inchnadamph the rocks below the Ben More

Thrust were moved on a lower thrust, the Glencoul Thrust, carrying the Glencoul thrust sheet, but west of Inchnadamph the Ben More and Glencoul thrusts join. Sabine (1953) noted that a type of peralkaline felsite dyke, for which he used the name 'grorudite', occurred only in the Glencoul and Ben More thrust sheets and suggested that this meant that both sheets had behaved as a single tectonic unit, for which he proposed the name Assynt Nappe. He suggested that, south of Inchnadamph, the combined Ben More and Glen Coul thrusts be called the Assynt thrust plane. However Sabine's terminology has not been adopted by recent workers and the early terminology of Peach and Horne (in Peach *et al.*, 1907) is retained in this chapter. Sabine located a solitary 'grorudite' in rocks of the Cam Loch Klippe (Figure 7.2, locality 2), confirming the classic interpretation of Peach and Horne that these rocks were outliers of the Ben More thrust sheet. The lowest thrust sheet, the Sole Nappe, brings thrust rocks over the undisturbed Foreland region.

Sabine noted many other striking restrictions on the distribution of the alkaline dykes and sills in Assynt. These can be used to make important deductions concerning the order of events in the thrust belt, and together with radiometric ages obtained on the plutons, to provide brackets for the ages of the main thrust movements. Table 7.1 is the most recent interpretation. Although some workers (e.g. Macgregor and Phemister, 1937) regarded the thrust sequence as propagating upwards, lower thrusts being truncated by higher ones, the modern view is that thrusts normally evolve downwards, with older thrusts riding piggy-back on younger lower ones. This picture is compatible with the distribution of igneous rocks in Assynt, although all workers agree that late movements on the Moine thrust plane must have occurred.

A final important point is the possible role of the alkaline rocks in Assynt in giving rise to the Assynt Culmination. This embayment in the Moine Thrust (Figure 7.2) is actually a broad upwarp or bulge in the Moine thrust plane, and between it and the almost perfectly planar Sole Thrust is a thick lenticular complex of thrust rocks. Several early workers (Phemister, 1926; Bailey, 1935; Sabine, 1953) suggested that there was a causal connection between this thickening and the presence of the minor and major bodies of igneous rocks, and their view was supported by Elliott and Johnson (1980). The connection

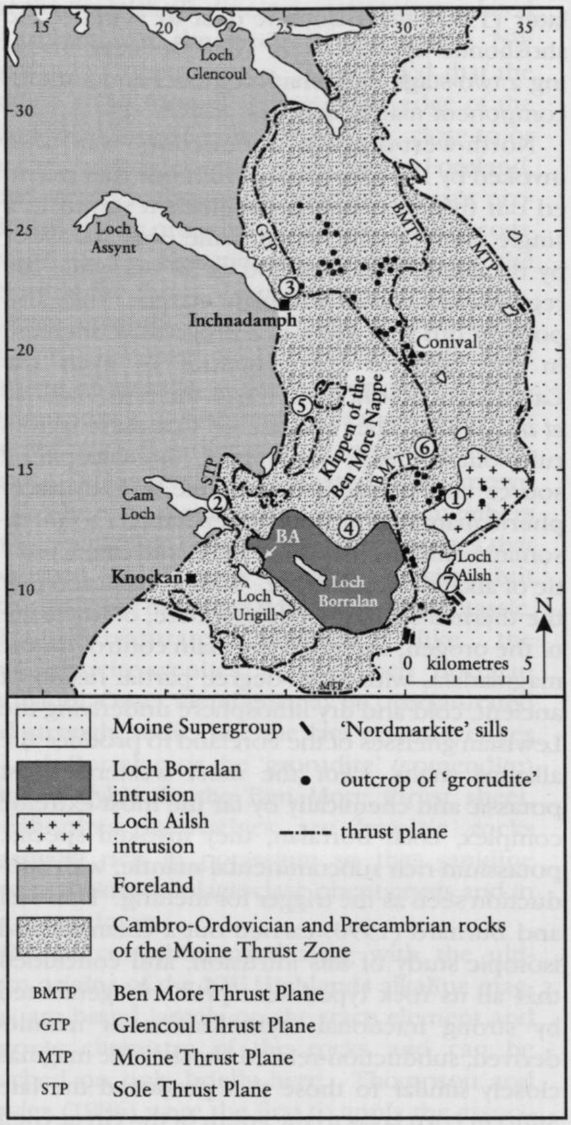

Figure 7.2 Map of the Assynt district showing the major thrusts, the two major alkaline intrusions, and the distribution of two of the six types of minor intrusive rocks. BA is the critical locality, at Bad na h-Achlaise, where nepheline-syenites and pyroxenites of the Loch Borralan intrusion are intruded 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.)

would not be a direct one, because the thickness and volume of the igneous rocks is far less than the thickness and volume of the culmination. But it is plausible that the igneous rocks and their thermal metamorphic aureoles increased the resistance to slip of the Cambro-Ordovician horizons on which most of the thrusts moved, roughening the slip surfaces, and causing duplication and doming.

Three of the sites selected for this Geological Conservation Review are relatively large and complex, and an extended description of each is given. These are the major intrusions at *Loch Borralan* and *Loch Ailsh* in Assynt, and the group of intrusions around *Loch Loyal*, 40 km to the NE (Figure 7.1). Localities have been chosen within these sites that illustrate the great range of unusual rock types, internal and external contact relationships, and structural implications.

The remaining 12 sites are much smaller and of a different character. Examples have been selected of each rock type represented in the extensive suite of dykes and sills that occur in Assynt, on the grounds of typical character, accessibility, and where appropriate, their relationship with the major structures in the thrust belt. The exposures are individually important because of the relatively rare rock types represented, and also important as a suite, because of their petrogenetic, structural and chronological implications. A common introduction to each of the rock types is provided, setting out their petrography and structural implications. Peralkaline rhyolites ('comendites', the 'grorudites' of Sabine, 1953) are described cutting the Loch Ailsh syenite in *Glen Oykel, south*, illustrating an important relative intrusive age relationship, and from the Cam Loch Klippe at *Craig na h-Innse Ruaidhe*, east of the Cam Loch, exemplifying the restriction of this rock type to the Ben More thrust sheet. Porphyritic quartz-microsyenite (the Canisp Porphyry), is described from a large and physiographically important site on *Beinn Garbh*, from the *Laird's Pool* GCR site near Lochinver (which demonstrates its extension into the Foreland), and from a structurally important site west of Loch Awe (*Cnoc an Leathaid Bhuidhe*). Calc-alkaline hornblende microdiorite sills (so-called 'hornblende porphyrites') are extremely common in Assynt and examples of these are described from intense swarms on *Cnoc an Droighinn*, east of Inchnadamph and *Luban Croma*, north of the Loch Borralan intrusion. More mafic but otherwise similar hornblende lamprophyres (vogesites) are also common and are described from *Allt nan Uamh* and from *Glen Oykel, north* where the vogesite is associated with a remarkable diatreme with a carbonate matrix. A set of sills of quartz-microsyenite ('nordmarkite') occurs near the Moine thrust plane (usually just above) and an example from *Allt na Cailliche*, SE of Loch Ailsh, is described. Finally, two examples of melanite nepheline-microsyenite ('ledmorite') cutting Torridonian and Lewisian rocks on the west coast, at *Camas Eilean Ghlais* and *An Fharaid Mhór* show that the source of the most strongly alkaline magmatism was beneath the Lewisian Foreland, and also have important implications for late movements on the Sole Thrust.

ALKALINE PLUTONIC COMPLEXES

LOCH BORRALAN INTRUSION (NC 235 110–277 081–297 085–306 107–298 140–260 150–235 150)

I. Parsons

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 ultrapotassic 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 laccolith, 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 quarry, 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 (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

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.)

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 (246 119) where coarse-grained biotite pyroxenite, with a few outstanding ribs of syenite, can be seen, and in Bad na h-Achlaise (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, 247 121) and on the A837 (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 (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 (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 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 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

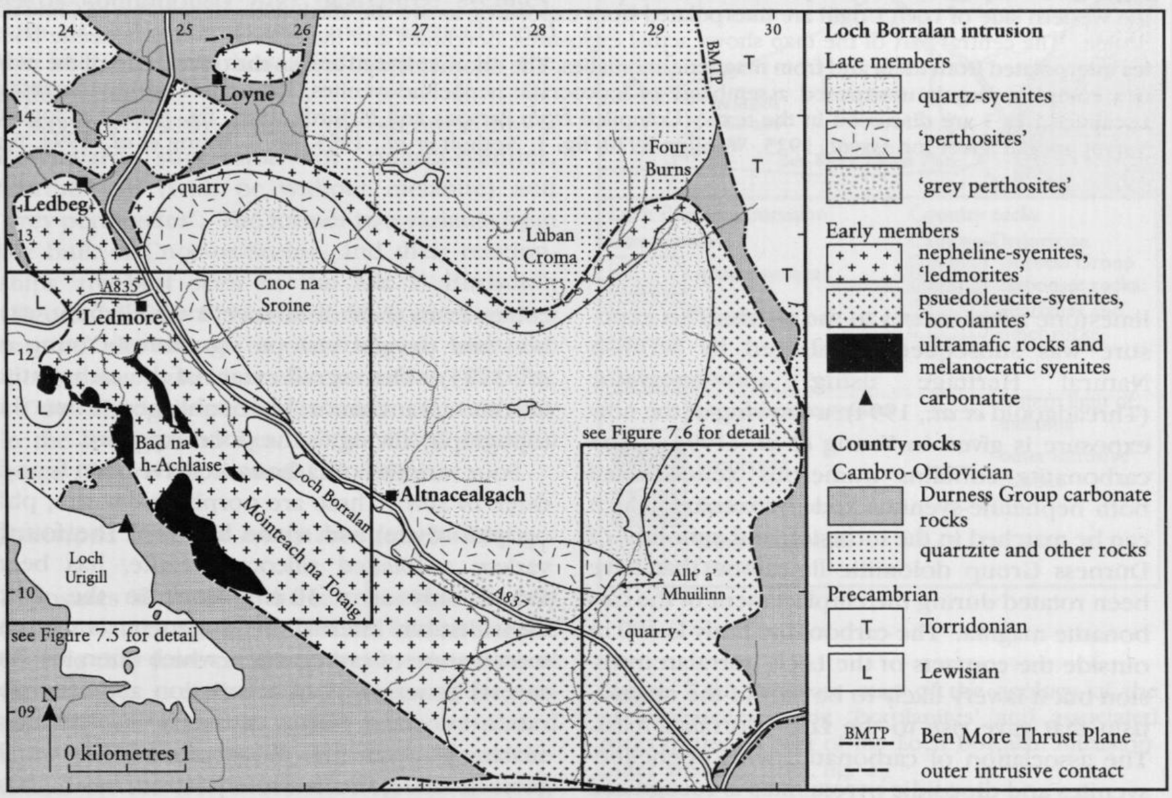

Figure 7.4 Map of the Loch Borralan intrusion and its envelope rocks (modified after Johnson and Parsons, 1979).

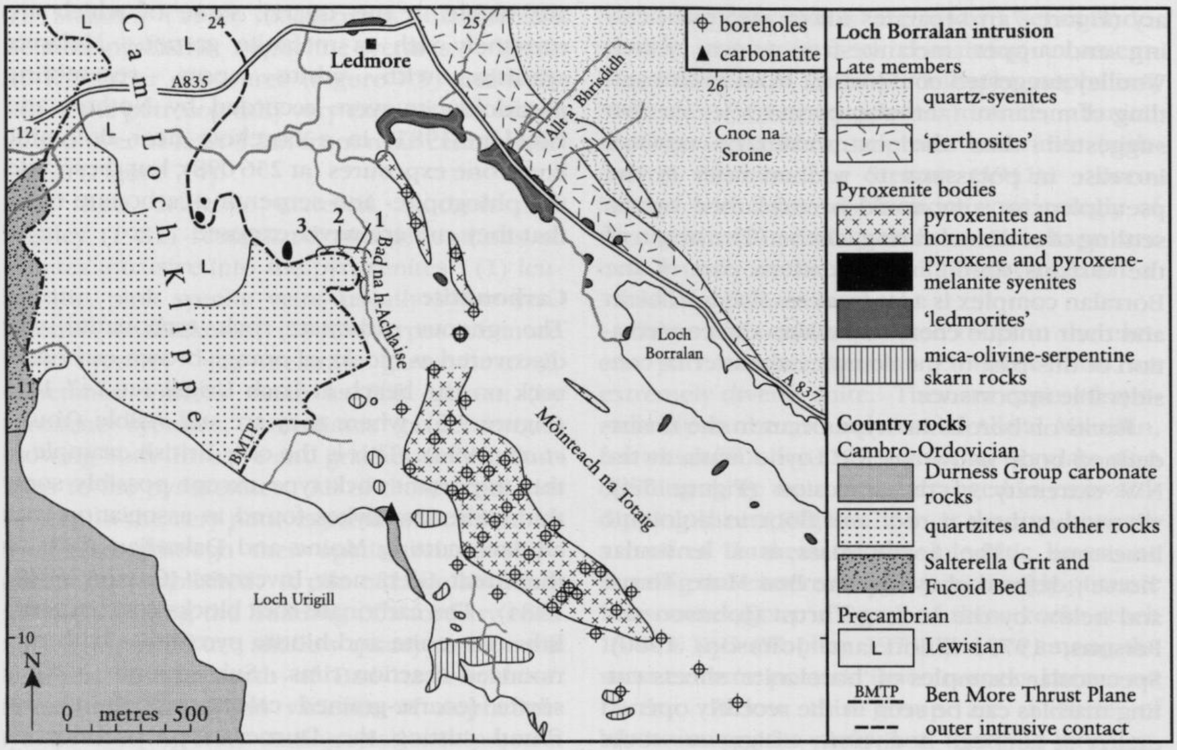

Figure 7.5 Map of the western part of the Loch Borralan intrusion. Units within the Cam Loch Klippe and on the western side of Loch Urigill are interpolated from exposures, as are the alkali feldspar-syenites of Cnoc na Sroine. The central part of the map shows actual exposures, boreholes and the extent 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.)

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, 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 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

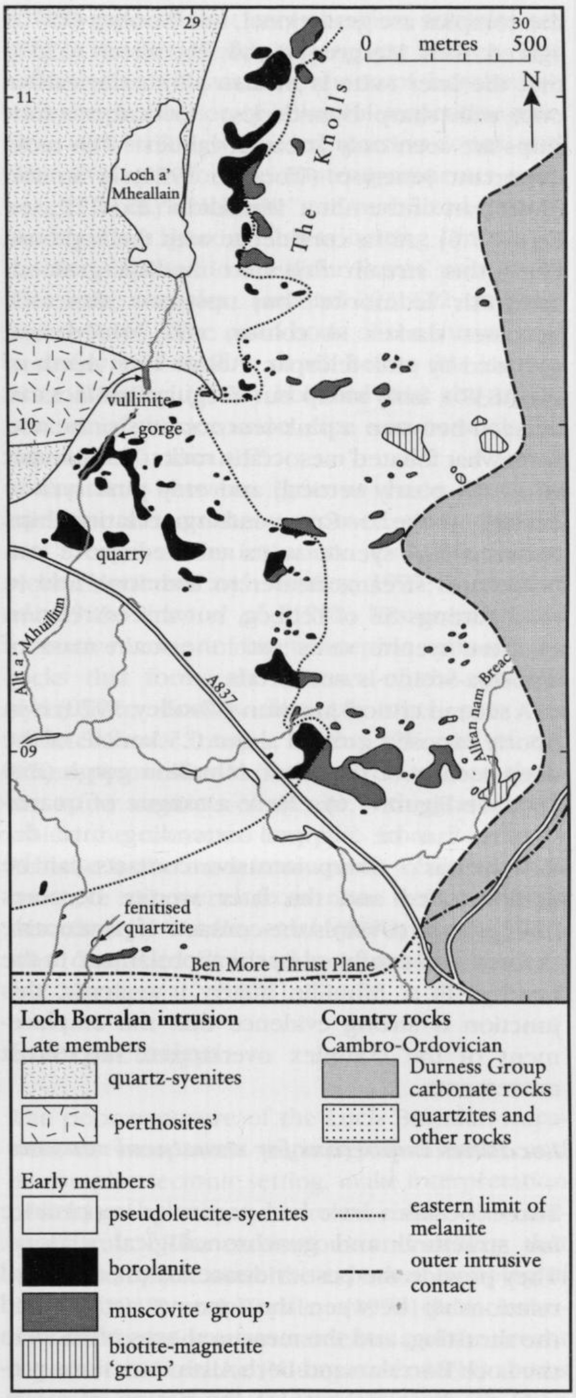

Figure 7.6 Exposure map of the geology of the pseudoleucite-bearing 'borolanites' and associated rocks of the SE part of the Loch Borralan intrusion. (After Woolley, 1973, fig. 2.)

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 (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 (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 (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, 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-bearing 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 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 (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 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, exceptionally 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 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 Mòinteach 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 pseudoleucite 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 Mòinteach 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.

LOCH AILSH INTRUSION (NC 330 115–360 150–330 160–310 140–310 125)

I. Parsons

Introduction

The Loch Ailsh intrusion (Figures 7.7, 7.8), lies at the eastern margin of the Assynt culmination, immediately below the Moine Thrust, which brings metasedimentary rocks of the Moine Supergroup over its eastern edge (Figure 7.2). It is largely composed of syenite, an unusual rock type, both in a worldwide and a British context, and the Loch Ailsh syenites have an unusually high ratio of sodium to potassium. Its main rock types are similar to the late syenite suite in the nearby Loch Borralan intrusion but it does not include the very strongly alkaline silica-undersaturated rocks of the latter intrusion, is mineralogically much less diverse and has figured less in the geological literature. Although it is rather better exposed than the Loch Borralan complex, many critical relationships are nevertheless obscured by peat. The Loch Ailsh intrusion is the world type-locality for the nearly mono-mineralic alkali feldspar rock 'perthosite', and provides evidence for the fractionation, prior to emplacement, of a series of syenitic magmas that become more leucocratic and more peralkaline with time. It is also particularly interesting because of the direct evidence it affords concerning the incorporation of material from Cambro-Ordovician dolomitic limestones, and it provides an instructive range of contact metamorphic rocks from various sedimentary lithologies.

The intrusion was first described by Peach *et al*. (1907), who considered that it rests on a thrust (which they called the Sgonnan Beag Thrust). The petrology and internal structure were first described, in considerable detail, by Phemister (1926). Following a fashion of the time, he considered the intrusion to be a stratified laccolith, with a floor of dense pyroxenites. This interpretation did not survive later geophysical work (Parsons, 1965a), but the overall shape of the intrusion is still enigmatic. The age relationships of the Loch Ailsh and Loch Borralan intrusions are critical in understanding the relative and absolute timing of thrust movements in Assynt.

The igneous rocks are mainly sodium-rich alkali feldspar-syenites, for the most leucocratic of which Phemister (1926) coined the name 'perthosite'. Phemister subdivided the syenites into numerous named varieties (modern equivalents are given in parentheses): 'perthosite' (leucocratic alkali feldspar-syenite); aegirine-melanite syenite; 'nordmarkite' (quartz-syenite); 'pulaskite' (pyroxene syenite); riebeckite syenite; 'shonkinite' (pyroxene-rich syenite). Phemister's use of 'shonkinite' is not followed by more recent terminology, which requires the presence of nepheline. In contrast with Loch Borralan, feldspathoids are not found in the Loch Ailsh pluton. In addition, he recognized ultramafic biotite pyroxenites and hornblendites, similar (apart from the absence of garnet from the Loch Ailsh examples) to the 'cromaltites' described by Shand (1910) in the Loch Borralan complex, and drew attention to the similarity between them and the rock type 'jacupirangite' discovered in other alkaline complexes.

The pyroxene syenites occur chiefly as xenoliths enclosed in the leucosyenites, and form a discontinuous roof to the earlier syenite units, while the pyroxenites and hornblendites form a substantial, although poorly exposed vertical marginal body. These rocks occur between the more felsic intrusive rocks and Durness Group dolomitic limestones along the eastern margin, in a similar structural setting to the equivalent 'cromaltites' at Loch Borralan.

Halliday *et al*. (1987) obtained a U-Pb age of 439 ± 4 Ma on zircons from two samples of Loch Ailsh syenite, a little older than the age of 430 ± 4 Ma obtained for the Loch Borralan intrusion using the same method. Although the western contact of the Loch Ailsh mass is now only about 1 km east of the contact of the Loch Borralan intrusion (Figure 7.2), at the time of its emplacement the Loch Ailsh intrusion may have been several tens of kilometres farther to what is now the SE, because the Ben More Thrust lies in the ground between. There is good evidence

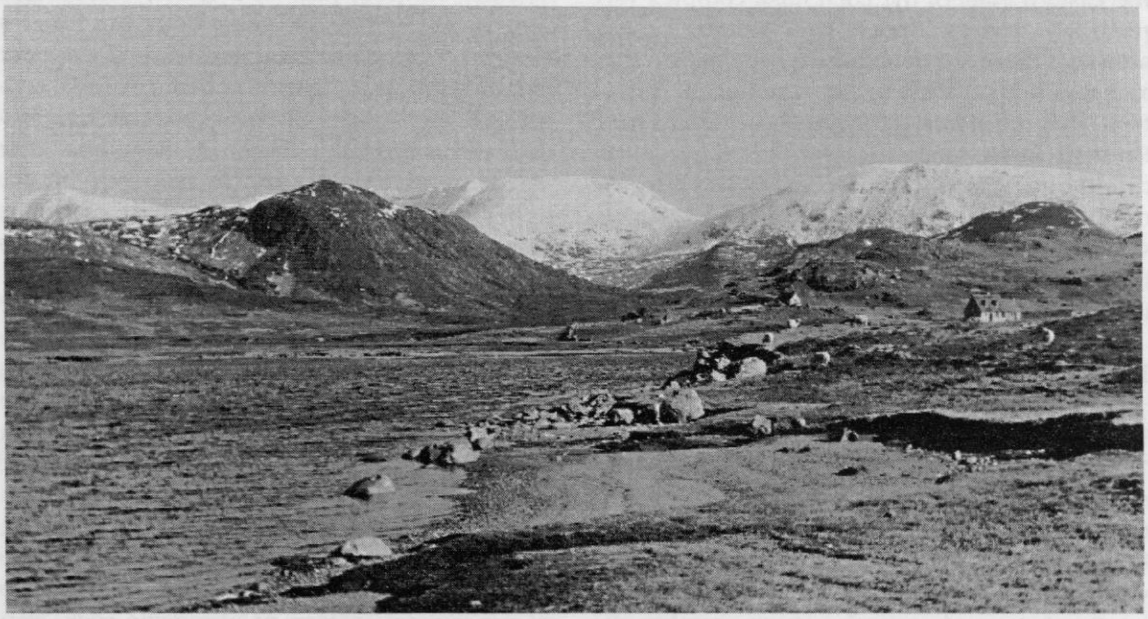

Figure 7.7 Loch Ailsh and the upper valley of the River Oykel from the south. The snow-covered ridge is Ben More Assynt (998 m), with Conival (987 m) at the extreme left. The Loch Ailsh intrusion extends from just north of the loch to the base of the eastern end of this ridge. The dark, rocky hill in the left middle distance is Black Rock, formed of syenite S3 ('perthosite'). The rough ground immediately behind the cottage is Durness Group carbonate rocks, while the low cliff in the foreground is an exposure of Moine metasedimentary rocks. (Photo: I. Parsons.)

that most units of the Loch Borralan intrusion were emplaced after the main movements on the Ben More thrust plane, because alkaline dykes of the 'grorudite' suite cut the Loch Ailsh intrusion and rocks above the Ben More Thrust only.

There is some disagreement over the age relationships between the Loch Ailsh intrusion and structures within the enclosing Ben More Nappe. Milne (1978) suggested on the basis of careful mapping that the intrusion was emplaced later than the earliest phase of deformation in Assynt, the Sgonnan Mór folding. However, Halliday *et al.* (1987) suggested that greenschist facies recrystallization in some xenolithic pyroxene syenites in the Loch Ailsh intrusion could be correlated with the Sgonnan Mór phase of folding.

The contact relationships of the Loch Ailsh intrusion, and its three-dimensional shape, are not easily defined. On Sgonnan Beag mylonitized syenite is seen against Cambrian quartzite (the Sgonnan Beag Thrust of Peach *et al.*, 1907) but the plane of movement at the exposure dips steeply in a southerly direction rather than NE, beneath the intrusion. In the ground north of Loch Sail on Ruathair, in the unnamed stream that Phemister (1926) called the 'Metamorphic Burn' (333 153), the intrusion appears to finger into Cambrian sedimentary rocks dipping to the SE, showing that it is emplaced in the rocks of the Ben More Nappe. The range of contact metamorphosed Cambrian sedimentary lithologies exposed in this stream are an instructive and valuable feature of the intrusion. In the SE of the intrusion, in the Allt Cathair Bhàn (324 122), an interpretation of the very large magnetic anomalies caused by the high magnetite content of the pyroxenites (Parsons, 1965a), showed that the contact of these rocks against Durness Group dolomitic limestones is steep.

In places, rocks of the Loch Ailsh intrusion are considerably deformed by late movements in the Moine thrust zone. Zones of mylonite occur at several localities and are well seen in the River Oykel (325 127) and at the SW corner of Black Rock (318 135). Coward (1985) considered that there was no evidence for late movements on the Moine Thrust itself in eastern Assynt. The geophysical work (Parsons, 1965a) showed that the eastern edge of the Loch Ailsh complex very probably passes under the Moine Thrust, although there are no exposures to confirm this, and it is not possible to say whether the thrust truncated the intrusion or merely acted as a roof. Feldspar in the Loch Ailsh syenites is often very turbid and coarsely exsolved, perhaps because of deuteric alteration beneath an advancing, warm Moine Nappe, and the absence of alkaline hypabyssal rocks from the Moine also suggests late movements on the Moine Thrust itself.

Description

The intrusion is about 10 km^2 in area (Figure 7.8), extending from within 750 m of the northern shore of Loch Ailsh and on either side of the Oykel valley for some 3 km. It forms several low hills (Figure 7.7), Black Rock on the eastern shoulder of Sgonnan Mór and the ridge of Sail an Ruathair, and extends up to roughly the 350 m contour on the lower slopes of Meall an Aonaich. Most of the intrusion is composed of syenites, very rich in feldspar and poor in ferromagnesian minerals (leucosyenites). Three intrusive phases can be recognized, called S1–S3 by Parsons (1965b). The syenites are all silica-saturated or oversaturated; there are minor amounts of quartz in some rocks, but nepheline has not been found. The earlier syenite units, S1 and S2, contain appreciable amounts (up to 20%) of pyroxene or alkali amphibole, but the last phase, S3, is largely the near-monomineralic alkali feldspar-syenite 'perthosite'. Contact relationships show that S1 was emplaced first, and chemically it is less evolved than S2 and S3, a feature best shown by the progressive increase in the aegirine content of the pyroxenes (Parsons, 1979). The age relationships between S2 and S3 can be seen in the centre of the complex, where the junction includes an extensive zone of mixing. The central part of S3, forming the 408 m summit of the Sail an Ruathair ridge (333 143), which Phemister (1926) suggested perhaps represented a feeder for the intrusion, is slightly richer in mafic minerals than the bulk of S3 and contains melanite garnet, titanite and thoroughly sodic clinopyroxenes (aegirine-hedenbergite), showing it to be the most evolved part of the complex (Parsons, 1979).

Pyroxene syenites ('shonkinites' of Phemister, 1926) occur at localities in the River Oykel (326 127), and in the Black Rock Burn (318 133). Phemister believed that these are entirely igneous, forming part of a lower, more mafic zone in a stratified laccolithic body, but Parsons (1968) provided chemical and textural evidence that they are partly formed of mafic material contributed by contact metamorphosed Cambro-Ordovician dolomitic limestone xenoliths. The pyroxene syenites appear to map out on the upper surface of the earlier S2 phase of syenite intrusion, suggesting that they represent a fragmented roof to this earlier phase of injection.

Ultramafic biotite-magnetite pyroxenites and hornblendites, crop out in isolated localities along the eastern margin of the complex, along the Allt Cathair Bhàn (324 122). These rocks were taken by Phemister (1926) to represent the base of a laccolith, much as Shand (1909) had suggested for the 'cromaltites' at Loch Borralan. However, the profile of the extremely large magnetic anomalies associated with the pyroxenites (Parsons, 1965a) can be explained only by a set of sub-vertical screens of ultramafic rock, also, like Loch Borralan, interposed between syenite and Durness Group limestone. The similar structural setting of the pyroxenites in these two otherwise distinctly different intrusions, and the mineralogy of the pyroxenites, led Parsons (1979) to suggest that the pyroxenite bodies are large metasomatic skarns, formed by reactions between syenite and dolomitic limestone, but at Loch Borralan later excavations clearly showed that pyroxenites were intrusive into quartzites and by analogy with Loch Borralan, the igneous origin of the very similar Loch Ailsh pyroxenites is no longer in doubt. Nevertheless the emplacement of such a rock mass, very rich in the Ca-Mg pyroxene, diopside, as a magma, is an unresolved petrogenetic problem and the reader is referred to the discussion of this in the description of the Loch Borralan GCR site.

The isolated hillock known as Sròn Sgaile in the NE corner of the complex (348 148) is composed of ultramafic hornblendic rocks at the base passing up into a more leucocratic feldspar-hornblende rock at the top. Phemister (1926) thought that this represents a section through the lower zone of his postulated stratified laccolith. The rocks have distinctive textures, particularly the presence of large plates of a green mica with a 'sieve' texture, enclosing feldspar and hornblende, and are cut by a striking network of syenitic veins with conspicuous ferromagnesian minerals. Although these rocks are undoubtedly part of the Loch Ailsh intrusion, exposure around them is so poor that their

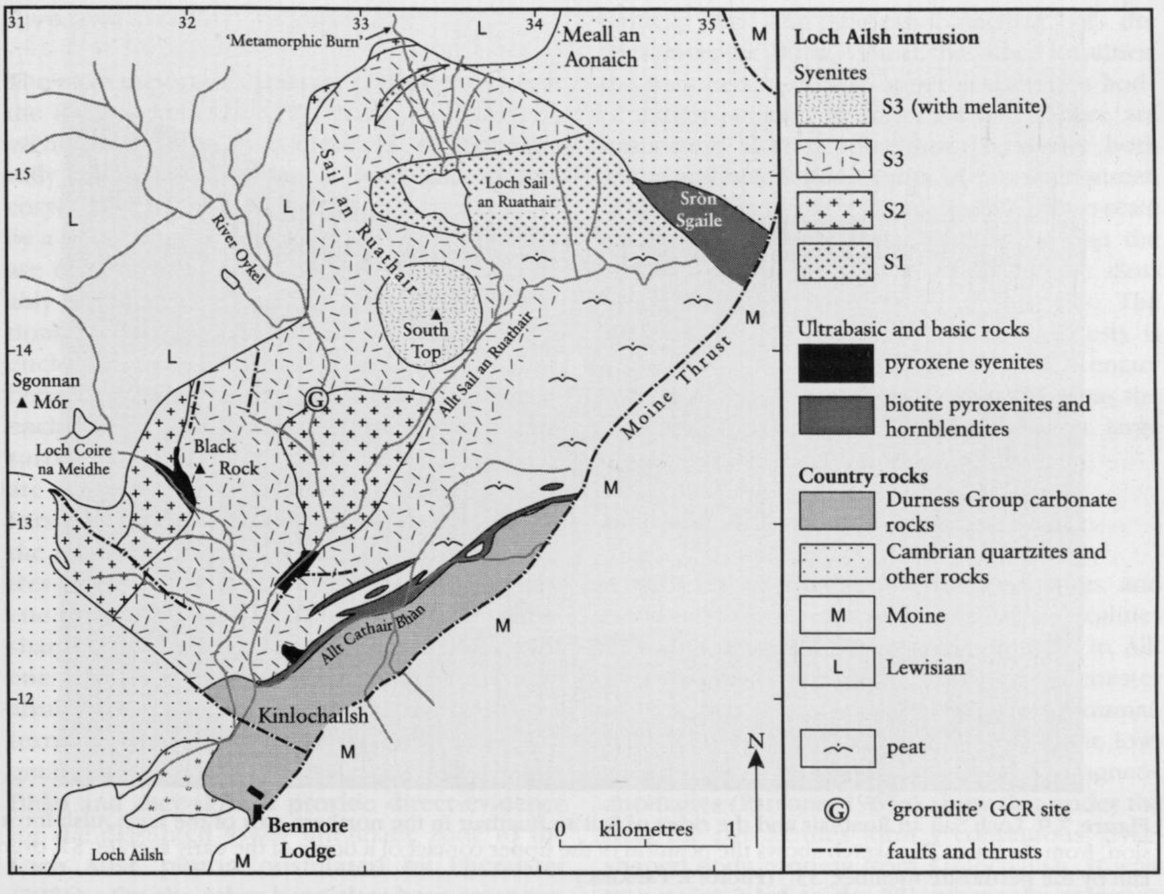

Figure 7.8 Map of the Loch Ailsh intrusion. The extent of the pyroxenites in the Allt Cathair Bhan is based largely on magnetic anomalies. (After Johnson and Parsons, 1979, fig. 15.)

structural relationships remain enigmatic. A magnetometer survey did not reveal a connection with the pyroxenites of Cathair Bhàn (Parsons, 1965a).

Syenites

The leucocratic syenites were described in detail by Parsons (1965b). Units S2 and S3 are well exposed throughout the southern part of the complex. S1 is less well exposed and crops out in Coire Sail an Ruathair. The most informative areas are those that show the inter-relationships between the units, and three critical exposures are of particular interest. At the base of the cliffs beneath the northern summit of the Sail an Ruathair ridge the junction between S1 and S3 can be examined (331 152) (Figure 7.9). S1 is coarse grained, red in colour, and has a distinct igneous lamination, shown by alignment of the slightly flattened feldspars. The S1 unit forms a dome-shaped body that does not penetrate S3 on the west side of the Sail an Ruathair ridge. The later S3 veins the earlier syenite, and encloses it as xenoliths. It is possible to demonstrate from rotation of the igneous lamination that the xenoliths have been rotated by the forceful injection of S3. This feature also shows that the lamination is igneous, and not tectonic, in origin. A screen of red syenite resembling S1 is enclosed in S3 in the central portion of the exposed section of the 'Metamorphic Burn' (see below), an interpretation confirmed by detailed work on the feldspars (Parsons, 1965b). This mass has sharp contacts, but the S3 in this section of the stream contains disseminated red feldspars which are no doubt xenocrysts from S1.

S2–S3 relationships can be seen in the central part of the intrusion around the confluence of the Allt Sail an Ruathair and the River Oykel (327

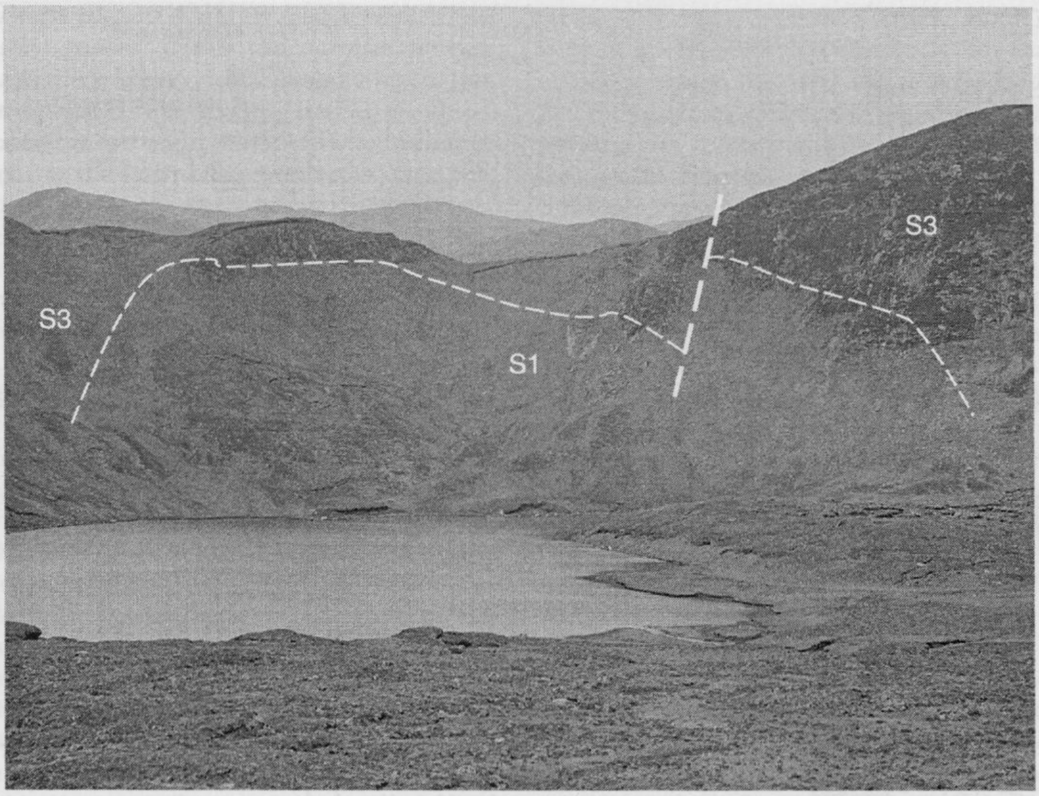

Figure 7.9 Loch Sail an Ruathair and the ridge of Sail an Ruathair in the northern part of the Loch Ailsh intrusion, from the east. The sketch shows the position of the upper contact of a dome of the early syenite, S1, overlain by the perthosite member, S3. (Photo: I. Parsons.)

130). Here there is an extensive zone of mixing between the two units, and a zone of pink xenocrysts can be mapped in the brown or grey S3 around an inner dome of S2 (Parsons, 1965b). The southern edge of this mixed zone, around the large waterfall in the River Oykel, (326 127) includes pyroxene syenite xenoliths (see next section). Rather similar relationships can be well seen in the upper section of the Black Rock Burn (318 133). Here, red xenoliths of S2 can be seen in S3, again in a zone including pyroxene syenite xenoliths. At the base of the SW cliffs on Black Rock itself (318 134) the suite is involved in a minor thrust plane, and streaking-out of xenoliths can be observed. As elsewhere in the intrusion, S2 underlies S3, but here the upper surface of S2 dips to the SE, and S2 extends on to the flanks of Sgonnan Mór.

Mineralogically, S1, S2 and S3 form an evolutionary series. The mafic mineral in most rocks is a pyroxene, those in S1 being diopsidic (calcium- and magnesium-rich), while those in S3 can have nearly 50 molecular % of the sodium-iron pyroxene component, aegirine; S2 is intermediate (Parsons, 1979). There are slight parallel changes in alkali feldspar composition, those in S1 being exceptionally rich in the albite molecule (*c.* 75 molecular %), those in S3 richer in orthoclase (*c.* 65 molecular % albite). Some facies, particularly of S2, contain a strongly pleochroic riebeckitic alkali amphibole instead of, or in addition to, pyroxene. Melanite garnet, often zoned and intergrown with titanite, appears only in the part of S3 that forms the southern summit on the Sail an Ruathair ridge (Figure 7.8). The boundaries of this variety appear to be gradational, but it contains the most evolved pyroxenes in the complex, suggesting that it was the final part of the intrusion to solidify. This part of the intrusion sometimes contains very small amounts of quartz and also muscovite. The presence of melanite together with quartz is unusual: melanite is usually present together with feldspathoids.

Pyroxene syenites – 'shonkinites'

The most important exposure of these rocks is in the River Oykel (326 127). Here, the pyroxene syenites are in the form of blocks, characteristically less than 1 m across, enclosed in leucosyenite, and the whole xenolith complex is cut by a network of leucosyenite veins. These veins are of two types, grey and red, which presumably correlate with the S2 and S3 syenite generations. The pyroxene syenite xenolith zone is enclosed by the gradational contact zone between S2 and S3. The xenoliths are therefore enclosed by mixed syenite forming the upper surface of a dome of S2 (Figure 7.8). The blocks are extremely heterogeneous (Figure 7.10, see Parsons, 1968); there are 'ultramafic clots' on the microscopic scale and up to a few centimetres across, composed almost entirely of pyroxene and/or biotite and amphibole, with either sharp or diffuse margins, enclosed in the pyroxene syenites, which are mostly diopside-biotite-alkali feldspar rocks. The 'ultramafic clots' are texturally very different, particularly in their fine grain-size, to the pyroxenites of Allt Cathair Bhàn and they do not provide direct evidence for the disrupted lower ultramafic zone to the Loch Ailsh pluton postulated by Phemister (1926). On the other hand they have great textural and mineralogical similarities to rocks occurring at syenite–limestone contacts elsewhere in the intrusion. Parsons (1968) illustrated the similarities and proposed that the pyroxene syenites represent the remains of a metasedimentary roof to S2.

Pyroxene syenites also occur as xenoliths in syenite in the Black Rock Burn (319 132 to 316 134). The S2 unit forms an inclined surface extending on to the flank of Sgonnan Mór and the pyroxene syenites are enclosed by both S2 and S3 near their interface. Xenoliths also occur under the conspicuous overhang at the SW corner of Black Rock (318 134) where they and their vein-networks are stretched and in places mylonitized in a minor thrust plane. At three isolated localities in Black Rock Burn (Figure 7.10) altered limestone xenoliths occur among the pyroxene syenites. Parsons (1968) considered this to be strong support for his hypothesis that the 'shonkinites' are not wholly igneous rocks.

A screen, about 10 m thick, of laminated pyroxene syenite, similar to those seen in the southern part of the intrusion, occurs about halfway up the exposed section of the 'Metamorphic Burn'. As at the other localities, the rock occurs on the upper surface of a body of earlier syenite, in this case S1. There are numerous altered limestone xenoliths both above and below this locality. A 5 m-wide screen of dark-green pyroxenite, and some metre-scale smaller xenoliths, occur 100 m higher up the stream. These resemble the ultramafic clots found elsewhere in the pyroxene syenites. The lowermost screen (stratigraphically highest) is attached directly to a mass of metasedimentary rock representing the Fucoid Beds, whereas the uppermost xenolith is resting against a large mass of quartzite.

Ultramafic rocks

A suite of unusual diopside pyroxenites and hornblendites is exposed at isolated localities along the eastern edge of the complex in Allt Cathair Bhàn (Figure 7.8). Although Phemister (1926) suggested that the exposures of ultramafic rocks are the sole representatives of the lowest zone of a stratified laccolith, large magnetic anomalies (Parsons, 1965a) show that under the peat the pyroxenites form a continuous, dyke-shaped body running from Kinlochailsh, at least to a point 2 km to the NE, where the magnetic anomaly dies out, probably because the rocks of

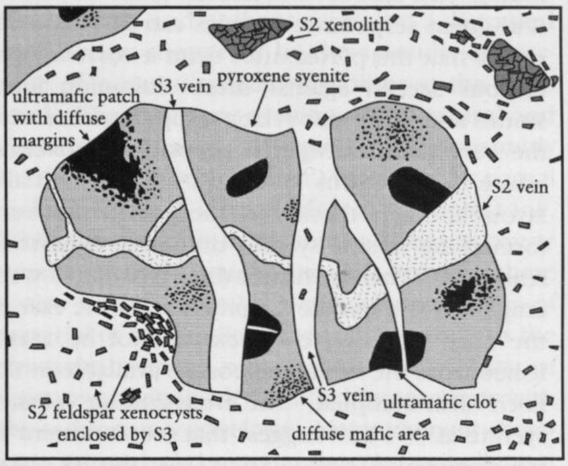

Figure 7.10 Sketch illustrating the relationships between a pyroxene syenite xenolith and feldspathic syenites in the Loch Ailsh intrusion, as seen in the River Oykel and Black Rock Burn areas. A typical xenolith would be about 1 m in length. (After Parsons, 1968, fig. 2.)

the Loch Ailsh intrusion pass under the Moine Thrust. Smaller, discontinuous lenses of ultramafic rocks are implied by the magnetic anomalies to occur in the leucosyenites to the west, and this has been confirmed by excavation.

The ultramafic rocks are deep blue-green biotite pyroxenites. They are often somewhat sheared, when the pyroxene is converted to a green-brown hornblende. The pyroxenes are close to pure diopside in composition (Parsons, 1979). Like the equivalent 'cromaltites' in the Loch Borralan intrusion, apatite is abundant, as is ilmenomagnetite, and the latter mineral leads to the very large local magnetic anomalies found over the pyroxenite members of both intrusions. The only worthwhile exposures are at 326 123, where pyroxene syenites occur to the west, and 328 123 and 334 127, where veins and screens of syenite can be seen cutting the ultramafic rocks. Parsons (1965a) presented a computer model of the profile of the magnetic anomalies found at the latter locality in which a vertical body of magnetic ultramafic rocks some 75 m thick is divided by screens of non-magnetic syenite; the depth to the base of the body must be at least 90 m. The nearest adjacent rocks to the west are mostly feldspathic syenites except for some pyroxene syenites at the south end of Cathair Bhàn. To the east are exposures of Durness Group dolomitic limestones, in the screes beneath which diopside marbles can be found. Just east of Kinlochailsh (323 120) beautiful green serpentine marbles can be found. It seems that the pyroxenites form a narrow, continuous screen against these dolomitic limestones and it was this relationship, together with the very Ca- and Mg-rich diopsidic pyroxenes, which led Parsons (1968, 1979) to initially favour the hypothesis that the pyroxenite were formed by in-situ syenite–dolomitic limestone reactions. Whether or not the pyroxenites were emplaced as a mobile magma (as was the case in the Loch Borralan complex) cannot be established from the limited exposure available in the Loch Ailsh complex. The cross-cutting veins of syenite at 334 127 suggest that emplacement of the pyroxenites pre-dated at least the S3 phase of syenite emplacement, although the possibility of rheomorphic back-veining must be considered.

Metamorphic xenolithic rocks

An excellent suite of metamorphic xenolithic rocks occur in an unnamed stream (called the 'Metamorphic Burn' by Phemister, 1926) which flows into Loch Sail an Ruathair (335 151–333 158). The exposures are important because of the evidence they afford of reactions between syenite magma and sedimentary rocks, which bears upon the origin of pyroxene syenites elsewhere in the complex, and they provide a useful instructional suite of contact metamorphic and alkaline metasomatic rocks. The igneous (and igneous-looking) rocks exposed in the stream are mostly brown 'perthosite' (S3) enclosing screens of earlier syenites, which may be correlated with S1 and S2 on the basis of colour and texture, and inclusions of pyroxene syenite and pyroxenite similar to those seen in the southern part of the intrusion. Interspersed with these are screens and xenoliths of the Cambro-Ordovician succession in correct stratigraphical order, but with Durness Group dolomitic limestones at the base of the slope, and quartzites at the top, implying a set of tongues of metasedimentary rocks more-or-less in place but dipping SE.

A log of the stream bed, starting at the lowest exposures, which occur about 400 m above Loch Sail an Ruathair, was given by Parsons (1968). At the base there are many originally dolomitic xenoliths, now diopsidic and phlogopitic calc-silicate rocks. Mafic patches can be seen in the enclosing syenites, and at certain localities individual pyroxenes can be observed apparently in the process of incorporation into the syenite. At 170 m (measured along the ground from the lowest exposures) an unusual white, melanite garnet-bearing syenite seems to be related to a large limestone xenolith, and just above here is a thick screen of red syenite (S1). At 270 m a 3 m body of fine, flinty dark-green rock with conspicuous pink feldspars and dark minerals, in contact with white or dark-grey quartzite, represents the Salterella Grit of the Cambro-Ordovician succession. Slightly above, 20 m of baked grey shale, with black streaks, represents the Fucoid Beds. Immediately in contact is a 2 m mass of dark-green pyroxenite, with micaceous patches (a 'shonkinite' of Phemister, 1926). There are also two small xenoliths of altered dolomitic limestones; which must have been moved out of their stratigraphical position by the magma. From the 308 m point upwards the syenite (S3) contains massive quartzite xenoliths that include developments of alkali amphibole, an example of the metasomatic process of fenitization. Conspicuous red feldspar xenocrysts sometimes have their long axes aligned, dipping downstream, and there are xenoliths of red syenite (probably S2). The last exposures seen before the stream flows through drift are of a pink, riebeckite-bearing syenite, probably S2.

Interpretation

The overall form of the Loch Ailsh intrusion is difficult to establish because of poor exposure in the vicinity of the contacts. Evidence that it formed a thrust sheet in its own right, as proposed by the early Survey workers (Peach *et al.*, 1907; Phemister, 1926), is not strong and it seems likely that the intrusion was emplaced in the Ben More Nappe either prior to the first folding phase in Assynt (as postulated by Halliday *et al.*, 1987) or shortly after (as proposed by Milne, 1978). This relatively early emplacement has been confirmed by the radiometric age of 439 ± 4 Ma obtained by Halliday *et al.* (1987). The ages provided by the alkaline rocks in Assynt are crucial for dating movements in the Moine thrust belt. The Loch Ailsh rocks in places are deformed (mylonitized) by late movements on the Moine Thrust, and there is geophysical evidence that the eastern contact passes under the Moine. The interfingering of syenite with a largely undisturbed sequence of altered Cambro-Ordovician sedimentary rocks, in the 'Metamorphic Burn' is consistent with a relatively gentle style of emplacement into the rocks of the Ben More Nappe. There is no convincing evidence that the intrusion is a stratified laccolith, as proposed by Peach *et al.* (1907) and Phemister (1926), although the late syenite unit S3 appears to overlie one or other of the earlier S1 and S2 units over much of the intrusion suggesting that S3 has a sheet-like form.

The eastern contact, along which a screen of pyroxenites is interposed between syenite and Durness Group dolomitic limestones, is certainly sub-vertical but the magnetic anomalies that lead to this conclusion give little information on the vertical extent of the intrusion. Like the similar pyroxenites along the southern margin of the Loch Borralan intrusion the origin of these rocks is enigmatic. The pyroxenites in the latter intrusion are definitely intrusive into quartzites and therefore certainly existed as a magma, but there are no exposures at Loch Ailsh that demonstrate that the pyroxenites have an intrusive character. It is curious that in both intrusions the pyroxenites occur only where silicate rocks and dolomitic limestone are in contact. There is no easy explanation for the extended sinuous form of the pyroxenite body if it is entirely intrusive. If it is earlier than the syenites as the cross-cutting veins of syenite superficially suggest, then it is possible that it is an incomplete section of an earlier, arcuate intrusion; alternatively if the syenite veins result from rheomorphism then it is a partial ring dyke. Whatever its structural relationships, the high temperature mineralogy requires that the pyroxenites were emplaced as a crystal mush; there is no direct evidence that they are mobilized cumulate rocks formed *in situ* from the syenite magma, as suggested by Matthews and Woolley (1977) for Loch Borralan, although this is a possible mode of origin.

The syenitic rocks were emplaced in three pulses. They were fractionated before arrival in their final resting place, and become chemically more evolved and peralkaline with time. Both the earlier members (S1 and S2) form dome-shaped bodies overlain by a final unit mostly composed of very leucocratic alkali feldspar-syenite ('perthosite', S3). The slightly more mafic, aegirine- and melanite-bearing variant forming the South Top of Sail an Ruathair is the most highly evolved member. More melanocratic, pyroxene syenites occur as xenolithic blocks at various localities; these seem to appear discontinuously on the upper surface of the earlier syenite units and perhaps represent a disrupted roof, a view supported by the sporadic appearance of metasedimentary xenoliths at the same level. The pyroxene syenites have textural and chemical similarities to syenites demonstrably (in the 'Metamorphic Burn') modified by partial assimilation of altered dolomitic limestone. While on the one hand some of the pyroxene syenites have thoroughly igneous textures, there is also strong textural evidence of assimilation of material of metasedimentary origin. Perhaps the pyroxene syenites represent an early phase of igneous activity itself modified by reactions with the sedimentary envelope. Major element chemistry, mineral chemistry and even trace-element chemistry are equivocal on this subject (Parsons, 1979; Young *et al.*, 1994).

Conclusions

The Loch Ailsh intrusion includes a suite of sodic syenites unique in the British Isles, which provide evidence for igneous fractionation processes before emplacement, and include the world type locality for 'perthosite'. The pyroxenites of the eastern margins are extremely enigmatic rocks whose extent and subsurface shape have been elucidated by geophysical means. A suite of intermediate, pyroxene syenites include rocks that have a thoroughly igneous appearance as well as types that have certainly formed by reactions between the syenite magma and dolomitic sedimentary rocks from the envelope. There are very instructive exposures illustrating contact metamorphism, alkali metasomatism (fenitization) and assimilation of a large range of Cambro-Ordovician sedimentary rocks. The structural relationships of the Loch Ailsh body, and its known age of 439 Ma, provide an important age-marker for movements in the Moine thrust zone.

LOCH LOYAL SYENITE COMPLEX (NC 610 440–670 500–670 520–560 510–560 470–590 440)

I. Parsons

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 km², 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

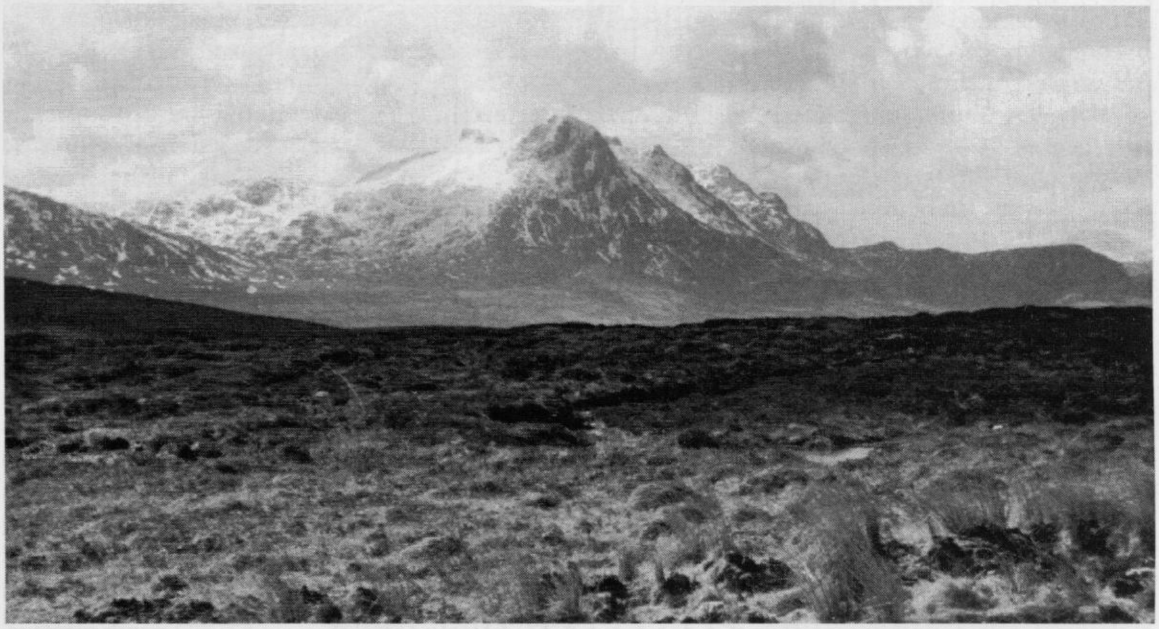

Figure 7.11 Ben Loyal (764 m) from the north. The quartz-syenite peaks rise dramatically out of the surrounding moorland underlain by Moine metasedimentary rocks. (Photo: I. Parsons.)

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 (568 495) and in the gorge of Allt Fhionnaich (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 (590 490), is exposed over some 800 × 300 m. Other large inclusions crop out on the northern and eastern slopes of Ben Hiel (595 502, 599 503, 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

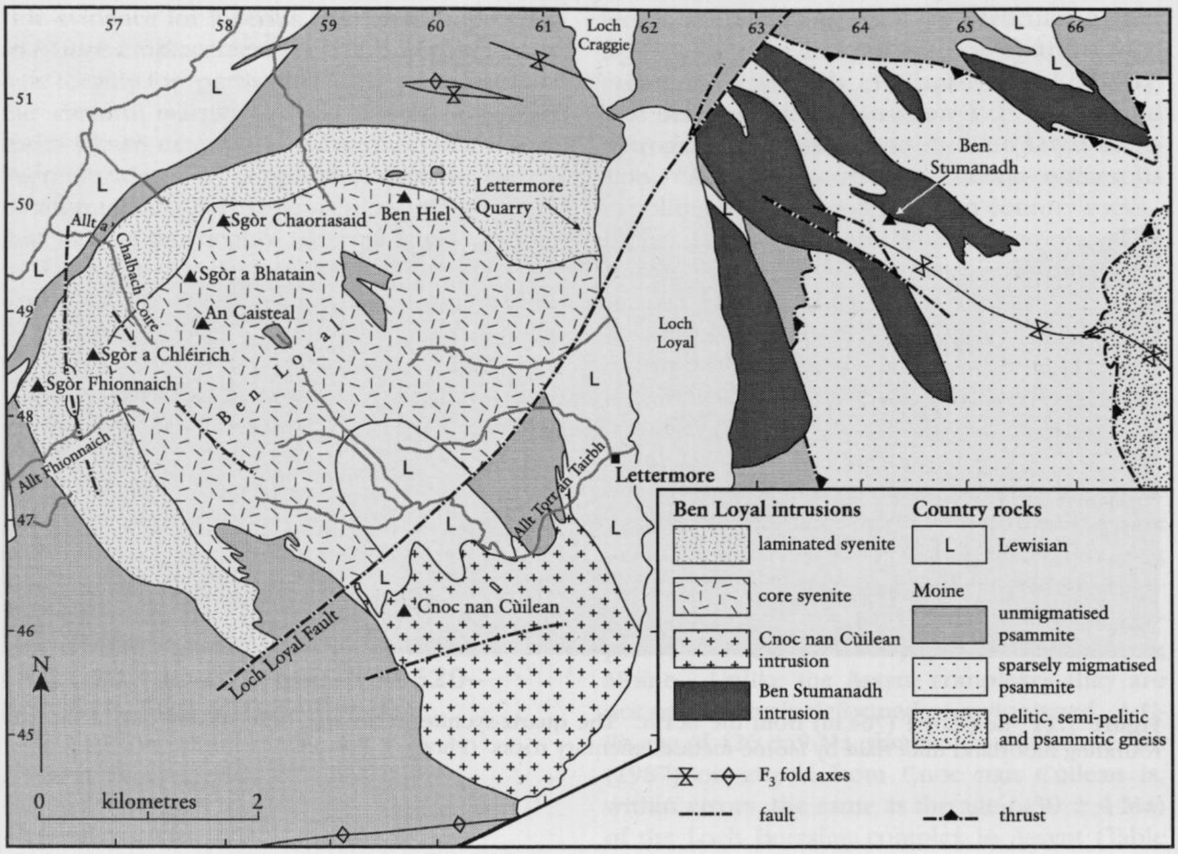

Figure 7.12 Map of the Loch Loyal syenite intrusions and their envelope rocks (compiled from Holdsworth and Strachan, in press; and Robertson and Parsons, 1974, fig. 1).

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 felsic 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 (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 (564 475), Sgòr a' Chleirich (568 485) and Allt a' Chalbhach Coire (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 (573 483).

Cnoc nan Cùilean intrusion

This pluton has an oval exposure over an area of about 3 km² 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 Torr 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 Cùilean 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 Cùilean 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 (612 473–609 469) 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 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. 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, 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 Sròn Ruadh (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 Cùilean 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.

ALKALINE MINOR INTRUSIVE ROCKS

I. Parsons

INTRODUCTION

The extensive suite of dykes and sills of alkaline and related rocks in the Assynt district are petrologically unusual in a British context, and are important representatives of the Caledonian alkaline magmatism. They extend over a considerable distance, from north of the Assynt district at Loch More (NC 330 350), to south of the Assynt Culmination in the structure known as the Achall Culmination, near Ullapool (NH 144 953, Figure 7.1). Although they are less well-known than the alkaline plutons, a glance at the Geological Survey special sheet of the Assynt district shows at once that they constitute a major part of the magmatism in Assynt. Although many of the rock types are not strictly alkaline their association in time and space with the alkaline magmatism is clear. They have very important structural and geochronological implications for understanding the evolution of the Moine thrust zone, into which many members were emplaced. The value of the minor intrusive rocks considered as a suite is greater than that of individual sites in isolation, and their relationship to the major alkaline plutons and to the individual thrust sheets, or nappes, is of critical importance. The profound implications of the alkaline rocks for the magmatic and tectonic evolution of the NW Highlands are discussed in the introduction to this chapter, and the age relationships are summarized in Table 7.1. The distribution of some of the minor intrusive rock types is shown on Figure 7.2. The reader is reminded that we are dealing with a region of very considerable crustal shortening, perhaps in excess of 100 km normal to the thrust belt if the Moine Thrust itself is included (Elliott and Johnson, 1980), and that the region involved in the alkaline magmatism must have extended from the unmoved Foreland (where nepheline-syenite dykes are found on the Atlantic coast) to a point many tens of kilometres to what is now the ESE.

The petrography, chemistry and distribution of the dykes and sills was described by Sabine (1953) who also recognized the importance of the suite as structural markers. He recognized six main petrographical types of minor intrusive rock, together with some localized varieties. The sites are grouped below according to the six rock types using the varietal and local rock names adopted by Sabine (1953), with the more usual modern equivalents given where appropriate. The different types are as follows.

1. 'grorudite' (peralkaline rhyolite, comendite)
2. The Canisp Porphyry (porphyritic quartz-microsyenite)
3. 'hornblende porphyrite' (hornblende micro-diorite, spessartite)
4. vogesite (hornblende-rich lamprophyre)
5. 'nordmarkite' (quartz-microsyenite)
6. 'ledmorite' (melanite nepheline-microsyenite)

A common introduction is provided here for each of the rock types, rather than for each individual site. The sites described are widely distributed (Figures 7.2, 7.13) and were chosen to provide examples with particularly significant structural relationships or which are relatively accessible examples of the different rock types making up the minor intrusive suite. There is one example of a probable diatreme (called a 'volcanic vent' by the early Geological Survey mappers) in Assynt. This is associated with a vogesite sill and is included in that section.

1. 'GRORUDITE' (PERALKALINE RHYOLITE, COMENDITE)

Introduction

The 'grorudites' are fine-grained acid (SiO_2 = 72–76%) peralkaline rocks for which aegirine rhyolite or comendite would be appropriate modern names. They are compositionally the equivalent of peralkaline granites and have no counterpart among the Caledonian plutonic rocks. They are therefore important in that they extend the compositional range of the Scottish Caledonian magmatism to include both strongly silica under- and oversaturated alkaline rocks, a dichotomy found in many much larger alkaline provinces. Thompson and Fowler (1986) pointed out the chemical similarity between an Assynt 'grorudite' and a comendite from the shoshonitic volcano of Lipari in the Aeolian Arc. The freshest examples may be pale-green in colour but in general they are pink or reddish-brown. The rocks are usually very fine grained and the matrix is aphanitic, although small pink alkali feldspar phenocrysts are sometimes visible. In section the rocks are characterized by phenocrysts of alkali feldspar and the sodium-iron pyroxene, aegirine, set in a quartz–feldspar matrix crowded with tiny aegirine needles. Various sub-varieties were recognized by Phemister (1926) and Sabine (1953). The reader is referred to these works for petrographical detail. 'Grorudites' are common in Assynt, particularly to the east and north of Inchnadamph (where they may be seen on the Cnoc an Droighinn GCR site (263 226), and cutting and close to the Loch Ailsh syenite intrusion (Figure 7.2). They usually occur as thin dykes (up to 1 m) but also, although less commonly, as sills, often describing a rather sinuous path through the country rocks. The examples are chosen to demonstrate the structural implications of the 'grorudite' suite.

GLEN OYKEL SOUTH (NC 327 136)

Description

The site, in slabs in the bed of the River Oykel *c.* 750 m north of its confluence with the Allt Sail an Ruathair (Figure 7.8), shows an unusually thick (*c.* 4 m) dyke of reddish-brown 'grorudite', trending E–W and cutting the S2 syenite member of the Loch Ailsh intrusion. The dyke very probably corresponds with a similar large dyke in the Allt Sail an Ruathair. This dyke is a member of a swarm that cuts both the Loch Ailsh intrusion and its envelope on Sgonnan Mór, where the dykes run undeviated across the Sgonnan Mór Syncline (Milne, 1978) and end abruptly at the Ben More thrust plane. These age relationships are discussed by Elliott and Johnson (1980).

Interpretation

The 'grorudites' are restricted to the Ben More Nappe (Figure 7.2). As this example cuts the Loch Ailsh pluton the syenites must pre-date the 'grorudites'. The pluton must therefore have moved from what is now the east on the Ben More thrust plane. As the Loch Ailsh syenite was emplaced at 439 ± 4 Ma, and the Loch Borralan syenite was emplaced after the movements on the Ben More Thrust at 430 ± 4 Ma these dates bracket both the age of movements on the Ben More Thrust and the time of emplacement of the 'grorudites'. Conclusions concerning the relationship of the Loch Borralan complex to the Ben More Thrust were reached from observed cross-cutting relationships (see the Loch Borralan GCR site report, Interpretation), but the interpretation is supported by the absence of 'grorudites' from the Loch Borralan mass. The presence of a swarm of 'grorudite' dykes cutting both the Loch Ailsh mass, and nearby Lewisian gneiss on Sgonnan Mór, was considered by Bailey (1935) to throw doubt on the existence of the Sgonnan Mór Thrust postulated by Peach *et al.* (1907).

Conclusions

The Glen Oykel South GCR site provides a thick example of a 'grorudite' dyke, an unusual rock type that is unique in the British Caledonides. At this locality it cuts the Loch Ailsh syenite, demonstrating that the Loch Ailsh intrusion was emplaced in the Ben More Nappe prior to movements on the Ben More thrust plane. The cross-cutting relationships are extremely important for the understanding of the timing, absolute and relative, of events in the Moine thrust zone.

CREAG NA H-INNSE RUAIDHE (NC 224 140)

Description

A fine-grained, red 'grorudite' dyke, about 1 m thick, striking at outcrop NNE–SSW, cuts the Cambrian 'false-bedded quartzite' in a GCR site that is also notified for structural reasons, the Cam Loch Klippe (Figure 7.2, locality 2; and see the GCR volume *Lewisian, Torridonian and Moine Rocks of Scotland*). The Lewisian–Cambrian unconformity occurs about 200 m to the SE, and is in part inverted in the lower limb of a fold that is truncated below the 'grorudite' exposure by the Ben More thrust plane.

Interpretation

The interpretation of Peach *et al.* (1907) of the structure of the Moine thrust zone in Assynt is a classic of British, and indeed world, geology. They interpreted an area of Lewisian rocks overlain unconformably by Cambrian quartzites to the east of the Cam Loch as forming an outlier, or klippe, of the Ben More thrust sheet (Figure 7.2). This interpretation has been supported by modern re-interpretations of the geology of the western part of the thrust belt in Assynt (Elliott and Johnson, 1980; Coward, 1985) although the latter author considers the eastern edge of the klippe to be a fault, not a thrust. As noted for the Glen Oykel South GCR site, 'grorudites' occur only in the rocks above the Ben More thrust plane, and the elegant and robust inter-

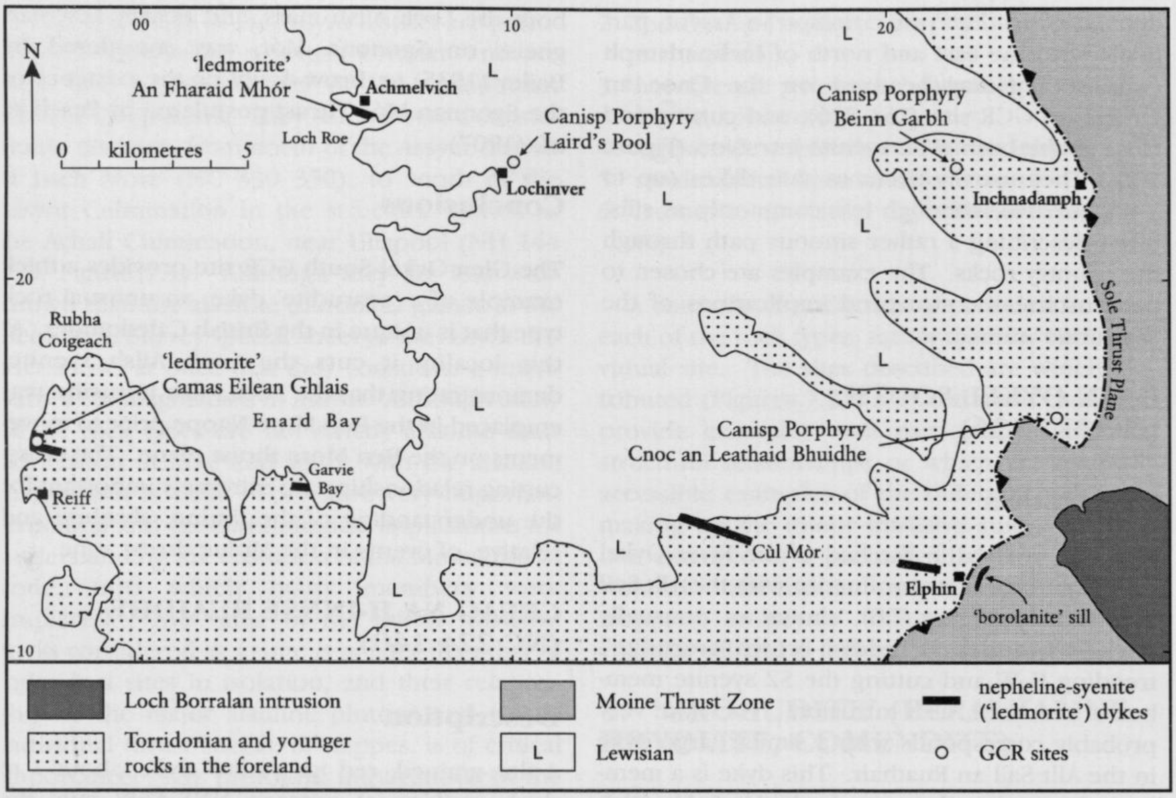

Figure 7.13 Map of western Assynt showing distribution of nepheline-syenite ('ledmorite') dykes in the Foreland and their relationship to the Loch Borralan nepheline-syenites in the Moine thrust zone. GCR sites exemplifying the 'ledmorite' dykes and the Canisp Porphyry are also shown. The full extent of the Canisp Porphyry around Beinn Garbh is shown on Figure 7.15.

pretation of Peach *et al.* (1907) is supported by the 'grorudite' at Creag na h-Innse Ruadh.

Conclusions

The Creag na h-Innse Ruaidhe GCR site demonstrates the presence of 'grorudite' in one of the outlying thrust slices (klippen) of the Ben More Nappe, providing support for the internationally well-known and historically important structural interpretation.

2. THE CANISP PORPHYRY (PORPHYRITIC QUARTZ-MICROSYENITE)

Introduction

The 'Canisp Porphyry' is one of the most striking igneous rocks in Assynt both because of its appearance in hand specimen and because of the way its sills dominate the skyline in the profiles of the well-known peaks of Canisp, Suilven and Beinn Garbh (Figure 7.14). The rock has the composition of a quartz-syenite although it is very sodic and the norm is unusually *albite*-rich. Its composition is similar to the upper quartz-syenites of Cnoc-na-Sroine in the Loch Borralan intrusion. In hand specimen the typical Canisp Porphyry is reddish-brown in colour with a fine-gained aphanitic groundmass containing well-shaped alkali feldspar phenocrysts up to 20 mm in length. These were analysed and figured by Heddle (1881) who described the rock as 'one of the most striking porphyrys of Scotland'. Paler, creamy phenocrysts are albitic plagioclase. The fine-grained groundmass consists of turbid K-feldspar, plagioclase and quartz.

The Canisp Porphyry crops out over an extensive area (Figure 7.15), one sill forming a plateau on the summit of Beinn Garbh (Figure 7.14) and then following the dip-slope of the Cambrian quartzites down its eastern flank towards Inchnadamph (Beinn Garbh GCR site). On Suilven and Canisp it forms sills, five in number on Canisp, in the Torridonian sandstones. Sabine (1953) provided a section suggesting correlations between the sills on the three mountains. It also occurs as dykes cutting Lewisian gneisses to the west, of which the most distant exposure is 12 km away from Beinn Garbh, near Lochinver, at the Laird's Pool GCR site (Figure 7.13). As Sabine (1953) noted, in view of its widespread distribution to the west of the Sole Thrust, the restriction of the Canisp Porphyry to the Foreland only is rather remarkable. In two places, on the lowest eastern slopes of Beinn Garbh, around the stream Cam Alltan (244 205) and near Loch Awe, on the Cnoc an Leathaid Bhuidhe GCR site (Figure 7.13), the Canisp Porphyry approaches close to the Sole Thrust, and although it is never seen to be truncated by the Sole it is certainly never seen in the rocks to the east.

The usual interpretation placed on the absence of Canisp Porphyry from the thrust zone (Parsons, 1979; Halliday *et al.*, 1987) is that it represents the earliest phase of magmatism in Assynt, so that its emplacement was complete before the thrust-sheets arrived. It could also be roughly synchronous with the emplacement of the Loch Ailsh pluton and the 'grorudites', albeit they were emplaced many kilometres to the east. Whatever the age relationships, there is no doubt that the source of the silica-oversaturated Canisp Porphyry magma was below the Foreland Lewisian, like that giving rise to the silica-undersaturated nepheline-syenite dykes that occur at the An Fharaid Mhór and Camas Eilean Ghlais GCR sites (Figure 7.13).

BEINN GARBH (NC 227 222)

Description

The view of Beinn Garbh (540 m) from the north, across Loch Assynt, is one of the most celebrated in British geology (Figure 7.14), showing the striking contrast between unbedded Lewisian gneisses at the base, horizontal, well-bedded Torridonian sandstones resting on them, and both being overstepped by Cambrian quartzites dipping to the east at about 15°, the so-called 'double unconformity'. The implications of the different dips has intrigued generations of students. The dips are in fact brought out by two parallel major sills, 6–20 m in thickness, of Canisp Porphyry on Beinn Garbh (Figures 7.14, 7.15), of which the upper forms an extensive plateau on the flat-lying

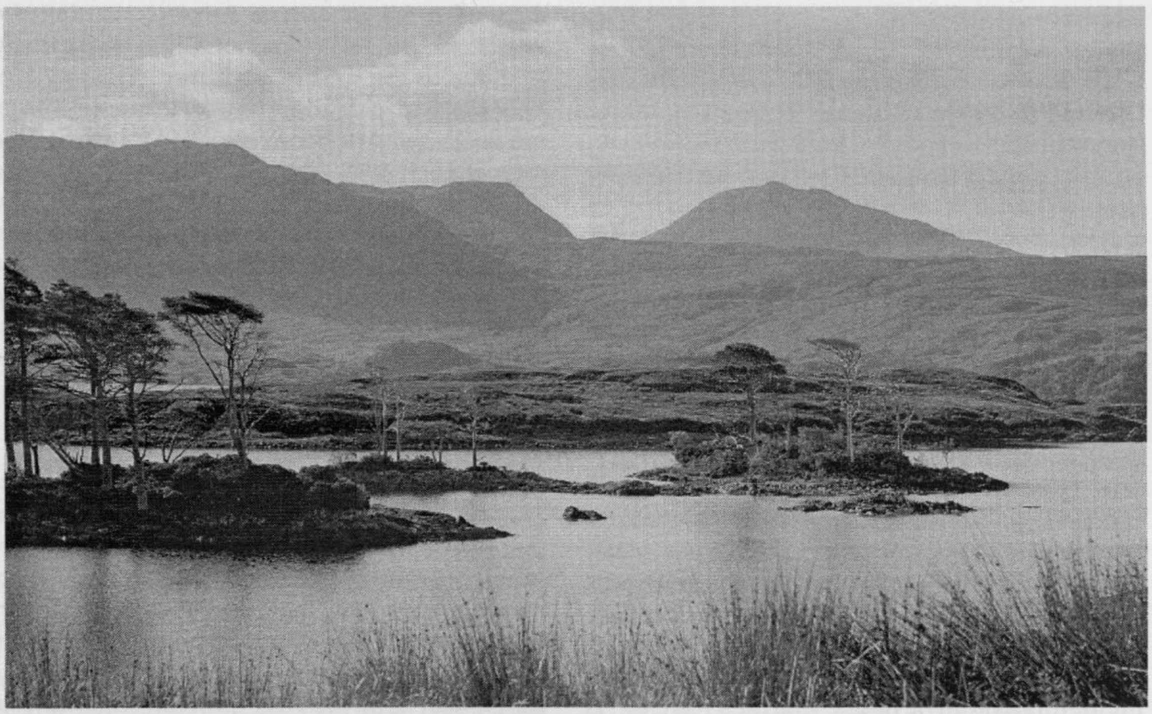

Figure 7.14 Beinn Garbh (540 m, left) and Canisp (846 m, right) from Loch Assynt. The plateau of Beinn Garbh and the steps in the skyline of Canisp are formed of sills of Canisp Porphyry. (Photo: I. Parsons.)

Torridonian sandstones and an extensive easterly-dipping exposure on the dip-slope of the Cambrian quartzites to the east, extending almost to the Sole Thrust south of Inchnadamph. There are no sills in the Lewisian.

Interpretation

The sills have clearly followed the bedding of the Torridonian and Cambrian rocks, and change dip as they cross the unconformity. The relatively slow-weathering Canisp Porphyry forms a conspicuous plateau on Beinn Garbh, and Sabine (1953, fig. 4) illustrates how the sills can be correlated with conspicuous topographical steps on Canisp.

Conclusions

Beinn Garbh is a visually outstanding GCR site providing the most extensive exposures of a unique and celebrated hypabyssal alkaline rock type, and excellent examples of the influence of rock type on topography and scenery. The outcrop of the Canisp Porphyry shows the structural control of the emplacement of the sills in the vicinity of the famous 'double unconformity' of Cambrian on both Torridonian and Lewisian rocks.

THE LAIRD'S POOL, LOCHINVER (NC 103 235)

Description

A dyke, about 4 m thick, of a red porphyritic rock with conspicuous pink K-feldspar phenocrysts up to 5 mm long, crosses the River Inver at the Laird's Pool (Figure 7.13), cutting Lewisian gneisses, and striking about 100°. The site can be reached easily along the maintained path on the south side of the river.

Interpretation

In view of the appearance and orientation of this dyke there seems every reason to correlate the rock with the Canisp Porphyry. It therefore represents the most westerly expression of Canisp Porphyry magmatism at the surface and, like the nepheline-syenite dykes farther west at Achmelvich (see the An Fharaid Mhór GCR site report, Figure 7.13) clearly shows that the alkaline magmatism was fundamentally a product of the Lewisian Foreland and the rocks beneath. The main focus of alkaline magmatism in Assynt is therefore incidentally related to the thrust belt rather than being in some way genetically connected to it. The Canisp Porphyry cuts Lewisian rocks at a number of localities in the Foreland (see Geological Survey special sheet) where it forms dykes; in the overlying sedimentary rocks it almost invariably forms sills.

Conclusions

The Laird's Pool GCR site is the most westerly example of Canisp Porphyry. Here it occurs as a dyke cutting Lewisian gneiss, which provides evidence for the widespread character of Canisp Porphyry magmatism and its relationship with the rocks of the Foreland.

CNOC AN LEATHAID BHUIDHE (NC 235 154)

Description

The exposure at this locality is poor and the main interest is in the structural implications. The Geological Survey (Peach *et al.*, 1892) mapped a sill of Canisp Porphyry cutting the Pipe Rock on the slopes of Cnoc an Leathaid Bhuidhe to the west of Loch Awe (Figure 7.15). The outcrop extends towards the Sole Thrust but is obscured in poorly exposed ground to the west of Loch Awe. There is no sign of the sill to the east of Loch Awe, where Salterella Grit, Fucoid Beds and Durness Group dolomitic limestones both above and below the Sole Thrust are exposed. Unfortunately, in the critical area, the loch itself and surrounding bog intervene so that possible truncation of the dyke by the Sole Thrust cannot be proved.

Interpretation

The relationship of this Canisp Porphyry sill to the surrounding rocks suggests, but does not prove, that its emplacement preceded all movements on the Sole Thrust. However, the very widespread development of Canisp Porphyry in the Foreland, and its complete absence from the thrust sheets to the east, strongly suggests that this phase of magmatism occurred early in the history of the alkaline magmatism in Assynt.

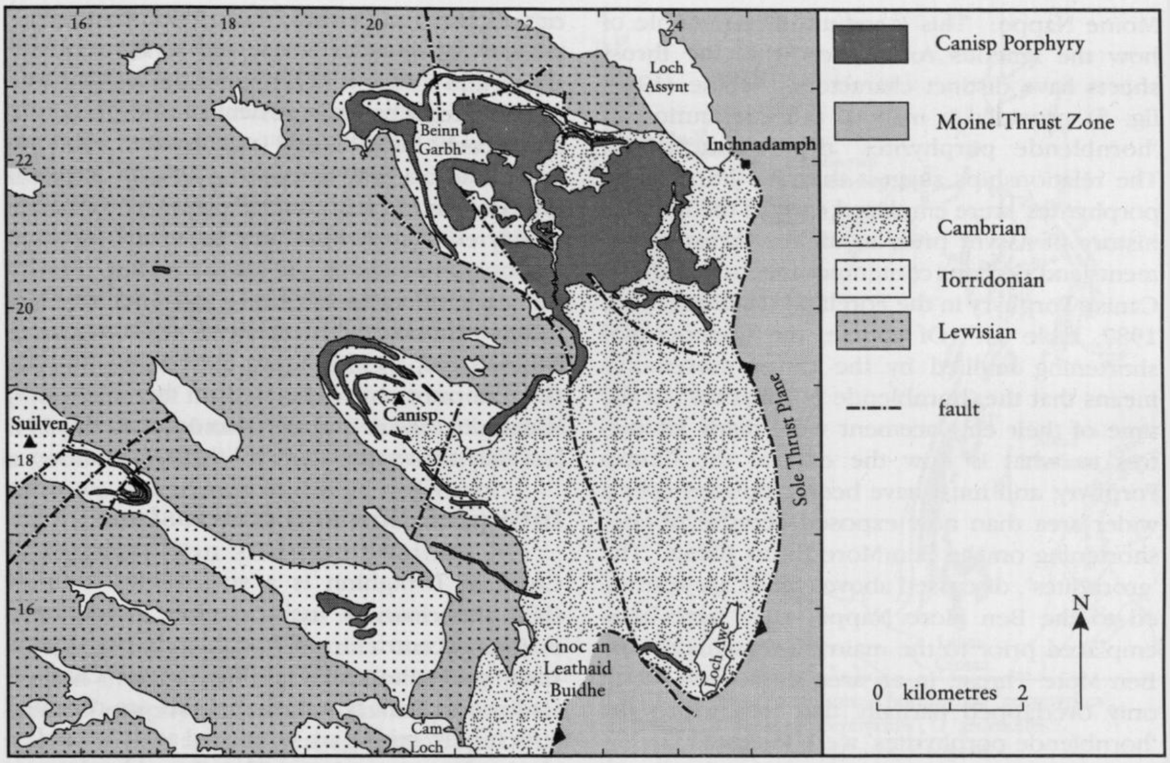

Figure 7.15 Distribution of sills and dykes of Canisp Porphyry in the Foreland. The dyke at the Laird's Pool, Lochinver, is farther to the west (see Figure 7.13). Only faults that affect Canisp Porphyry are shown. (After the Geological Survey special sheet for Assynt, 1923.)

Conclusions

The Cnoc an Leathaid Bhuidhe GCR site covers ground in which a sill of Canisp Porphyry approaches most closely the Sole Thrust from the west (in the Foreland), but is not exposed in the thrust zone to the east, providing evidence that Canisp Porphyry magmatism preceded movements on the Sole Thrust. Taken together with the absence of the porphyry from the thrust belt, this suggests that its emplacement predated all thrust movements in Assynt.

3. 'HORNBLENDE PORPHYRITE' (MICRODIORITE, SPESSARTITE)

Introduction

Hornblende-bearing microdiorites are very abundant in Assynt and were first described by Bonney (1883). The majority form sills, although in places they cut across the bedding of the sedimentary rocks, and true dykes occur only in the Lewisian gneiss. The sills are usually of the order of 1 m thick, although one intrusion into Pipe Rock on the ridge of Breabag is over 30 m thick. They have a fine-grained feldspathic groundmass containing feldspar phenocrysts up to 6 mm in size and 3 mm hornblende phenocrysts. Phenocrysts of biotite are visible in places. In section the hornblende is commonly strongly colour-zoned. The feldspar phenocrysts are usually plagioclase, but alkali feldspar also occurs. The groundmass is usually made up of small prisms of euhedral or subhedral K-feldspar and sodic plagioclase enclosed in quartz. As in many lamprophyric rocks many of the constituent minerals are commonly very altered. While the Assynt microdiorites and lamprophyres are not strictly alkaline rocks, they undoubtedly overlapped the alkaline magmatism in both space and time and their role in the petrogenesis of the syenitic rocks must be considered.

Members of this suite are common in the Sole, Glencoul and Ben More thrust sheets but they do not occur in the Foreland or in the

Moine Nappe. This is yet another example of how the igneous rocks show that the thrust sheets have distinct characters. Sabine (1953, fig. 5) provided a map of the distribution of 'hornblende porphyrites' throughout Assynt. The relationships suggest that the 'hornblende porphyrites' were emplaced early in the igneous history of Assynt prior to all the thrust movements and perhaps contemporaneously with the Canisp Porphyry in the Foreland (Halliday *et al.*, 1987, table 1). Of course, the upper-crustal shortening implied by the thrust movements means that the 'hornblende porphyrites', at the time of their emplacement were many kilometres to what is now the east of the Canisp Porphyry, and must have been emplaced over a wider area than now exposed because of later shortening on the Ben More thrust plane. The 'grorudites', discussed above, which are restricted to the Ben More Nappe, must have been emplaced prior to the main movements on the Ben More Thrust, in an area to the east which only overlapped partially that into which the 'hornblende porphyrites' were injected.

Because of their widespread distribution in Assynt, Read (1931) studied the cataclastic deformation of the 'hornblende porphyrites', following an early suggestion by Geikie (1888) that they show a progressive deformation eastward, mirroring the increase in metamorphism of the rocks generally in going from the Foreland to the Moine. Sabine (1953) revisited this problem and showed that cataclastic deformation of the 'hornblende porphyrites' is variable within the thrust belt and is most closely associated with proximity to one or other of the major thrusts.

There are many localities for viewing 'hornblende porphyrites' in the thrust belt. The GCR sites were chosen as representing intense swarms, one in an area of great structural complexity close to Inchnadamph, the other in an area with a considerable variety of hypabyssal rocks for which a map was provided by Sabine (1953).

CNOC AN DROIGHINN (NC 263 226)

Description

This is a classic region of structural complexity in Assynt, overlooking Inchnadamph (Figure 7.2), in which the Glencoul Thrust brings Cambrian quartzites over thick duplexes (imbricated lenses) of Durness Group dolomitic limestones. The reader is referred to figure 15 of Elliott and Johnson (1980), and the accompanying text, for a modern structural interpretation. Numerous 'hornblende porphyrite' sills are structurally repeated in the duplexes beneath the Glencoul Thrust, but sills were also demonstrably emplaced repeatedly at several levels in the quartzites above the thrust. They may be seen in various stages of cataclastic deformation ranging from highly sheared to unsheared. Sabine's map (1953, figure 5) records the relative amount of deformation he observed. 'Grorudite' dykes and sills also occur in this site, but only above the Glencoul thrust plane.

Interpretation and conclusions

Cnoc an Droighinn is a structurally complex GCR site close to Inchnadamph, providing a major concentration of 'hornblende porphyrite' (and 'grorudite') sills cutting various Cambro-Ordovician rock types. Some sills are repeated structurally, others are emplaced at different levels in the succession. The 'hornblende porphyrites' are clearly pre-deformational and, despite structural repetition on the lower part of Cnoc an Droighinn, they were emplaced repeatedly at various levels in the quartzites above the Glencoul Thrust. The area is an object lesson in the difficulties of achieving correlations of igneous bodies in a region which, while largely non-metamorphic, is nonetheless structurally complex. The distribution of the 'hornblende porphyrites' provides a very useful marker of relative structural displacements in the thrust belt.

LUBAN CROMA (NC 281 135)

Description

The site is a relatively accessible and representative part of a large area of barren, well-exposed ground to the north of the Loch Borralan intrusion (Figure 7.16). It is largely composed of Cambrian Pipe Rock, with some Fucoid Beds, cut by a large number of sills mainly of 'hornblende porphyrite'. Sabine (1953) provided a map of this part of Assynt which forms the basis of Figure 7.16. This shows the distribution of 'hornblende porphyrites', vogesites (see below), nepheline-syenite dykes representing outliers of the Loch Borralan mass, and a localized hypabyssal rock, which Sabine called the 'Breabag Porphyrite'. The latter occur as sills, 3–9 m thick, cropping out in a narrow belt about 5 km × 1.5 km between the Ledbeg River and the ridge of Breabag (Figure 7.16). All save one example (perhaps not *in situ*, according to Sabine) of this petrographical type occur in the Sole thrust sheet, i.e. below the Ben More Thrust. In hand specimen they have superficial similarities to fine-grained Canisp Porphyry but in section they prove to be microdiorites, with glomeroporphyritic aggregates of feldspar and phenocrysts of hornblende, set in a matrix of K-feldspar with a little quartz. Sabine's map gives a good impression of the variety of hypabyssal intrusive rocks found in this part of Assynt.

Interpretation and conclusions

The Luban Croma GCR site represents the wide variety of minor intrusions that can be demonstrated in this part of Assynt, including 'hornblende porphyrites' and a spatially restricted variety known as the 'Breabag Porphyrites'. It is possible that this variant provides a relative age-marker, because, like the 'grorudites', they must have been emplaced prior to movements on the Ben More thrust plane.

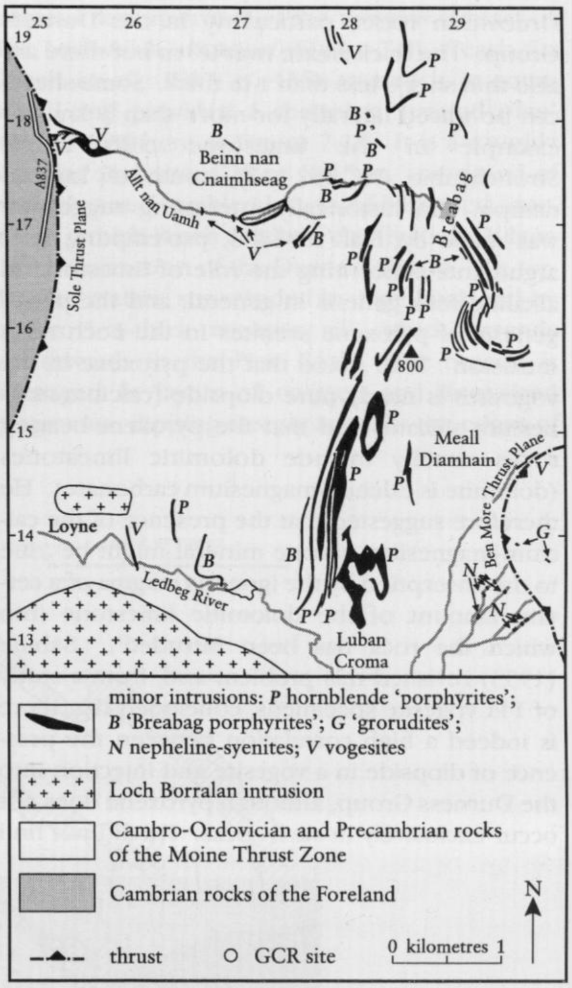

Figure 7.16 Distribution of sills and dykes between the Luban Croma and Allt nan Uamh sites, north of the Loch Borralan intrusion. (After Sabine, 1953, fig. 8.)

4. VOGESITE (HORNBLENDE-RICH LAMPROPHYRE)

Introduction

Rocks of the vogesite suite occur only in the Moine thrust belt, but are widespread in Assynt. They are found from Beinn Lice (NC 330 350) near Loch More in the north, to near Ullapool, 45 km to the SSW. A map showing the location of vogesites near Ullapool is provided by Sabine (1953, fig. 6); here they occur not far below the Moine thrust plane north and south of the Ullapool River at NH 147 958 and around NH 142 940, in an embayment structure in the Moine known as the Achall Culmination (Figure 7.1) (Elliott and Johnson, 1980), which is somewhat like a miniature version of Assynt. The structural implications of the vogesite suite in Assynt are essentially the same as those of the 'hornblende porphyrites' to which they have a similar distribution, although they tend to be most abundant in the Sole thrust sheet. Although vogesites are often altered, fresh examples include some of the most attractive rocks among the minor intrusions. Petrographically they are relatives of the 'hornblende porphyrites' but with more hornblende and in some instances diopsidic pyroxene. The hornblende phenocrysts, which may be very abundant, are characteristically 3 mm in length and are set in a finer-grained matrix of euhedral plagioclase feldspar (albite-oligoclase), alkali feldspar, hornblende and a small amount of interstitial quartz. Some contain diopsidic pyroxene in glomeroporphyritic clots 3 mm across, or as euhedral phenocrysts.

The vogesites almost all occur in the form of sills, with a few dykes mainly in the Lewisian gneiss. They are almost all emplaced in Cambro-

Ordovician rocks, particularly in the Durness Group. The thickest are over 20 m but there are also thin sheets less than 1 m thick. Some sheets can be traced laterally for more than 3 km, for example in the limestone cliffs above Stronchrubie (NC 252 192), south of Inchnadamph. An historically interesting suggestion was made by Teall in 1886, pre-empting later arguments concerning the role of limestone in alkaline rock genesis in general, and the petrogenesis of pyroxene syenites in the Loch Ailsh intrusion. Teall noted that the pyroxene in the vogesites is nearly pure diopside (calcium-magnesium silicate) and that the pyroxene-bearing rocks usually intrude dolomitic limestones (dolomite is calcium-magnesium carbonate). He therefore suggested that the presence of the calcium-magnesium silicate mineral might be 'due to the absorption by the igneous magma of a certain amount of the dolomitic limestone into which the rock has been intruded'. Sabine (1953) revisited this problem and, from a study of 141 vogesite specimens, concluded that there is indeed a high correlation between the presence of diopside in a vogesite and injection into the Durness Group, although pyroxene does not occur exclusively in such rocks. He did not find field evidence for vogesite–dolomite reactions, however. Nonetheless, the chemical composition of the vogesites is similar to that of pyroxene syenites in the Loch Ailsh intrusion. There is some strong field and petrographical evidence for the importance of magma–dolomitic limestone reactions in the genesis of at least some of the pyroxene syenites (Parsons, 1968).

ALLT NAN UAMH (NC 256 179)

Description

A thick sill of a fresh vogesite with a high proportion of large prismatic hornblendes as much as 10 mm long, set in pink feldspar, occurs close to the A837 and can be reached by a maintained path in the beautiful valley of the Allt nan Uamh, best known for its bone-caves. The locality, slightly above the fish-farm, is shown on Figure 7.16. It has hardened the Salterella Grit which forms an attractive waterfall (Figure 7.17). The sill dips gently to the east and is about 20 m thick. According to Sabine (1953) this is one of the two thickest vogesite sills in Assynt. The other is on the A837 just north of Inchnadamph.

Figure 7.17 Waterfall in Salterella Grit hardened by vogesite sill below, Allt nan Uamh (see Figure 7.16). (Photo: I. Parsons.)

Conclusions

The sill exposed in the Allt nan Uamh GCR site is a readily accessible, coarse-grained example of the most widespread hypabyssal intrusive rock type in Assynt, excellent for teaching purposes as an example of the lamprophyre family.

GLEN OYKEL NORTH (NC 312 161)

Description

This locality is in the floor of the Oykel valley about 1 km upstream of the western contact of the Loch Ailsh intrusion (Figure 7.2). Peach (in Peach *et al.*, 1907, p. 435) treated it in some detail and provided a charming 'ground plan' reproduced here as Figure 7.18. It is a roughly circular area about 22 m × 15 m, composed of variably sized jumbled blocks of hardened limestone, which Peach ascribed chiefly to the Eilean Dubh Formation of the Durness Group, in a carbonate matrix, surrounded by Pipe Rock and by a 3 to 5 m-thick vogesite sill, which extends southwards in the Pipe Rock. The breccia is arranged in layers of coarser- and finer-sized fragments, dipping steeply towards the edges of

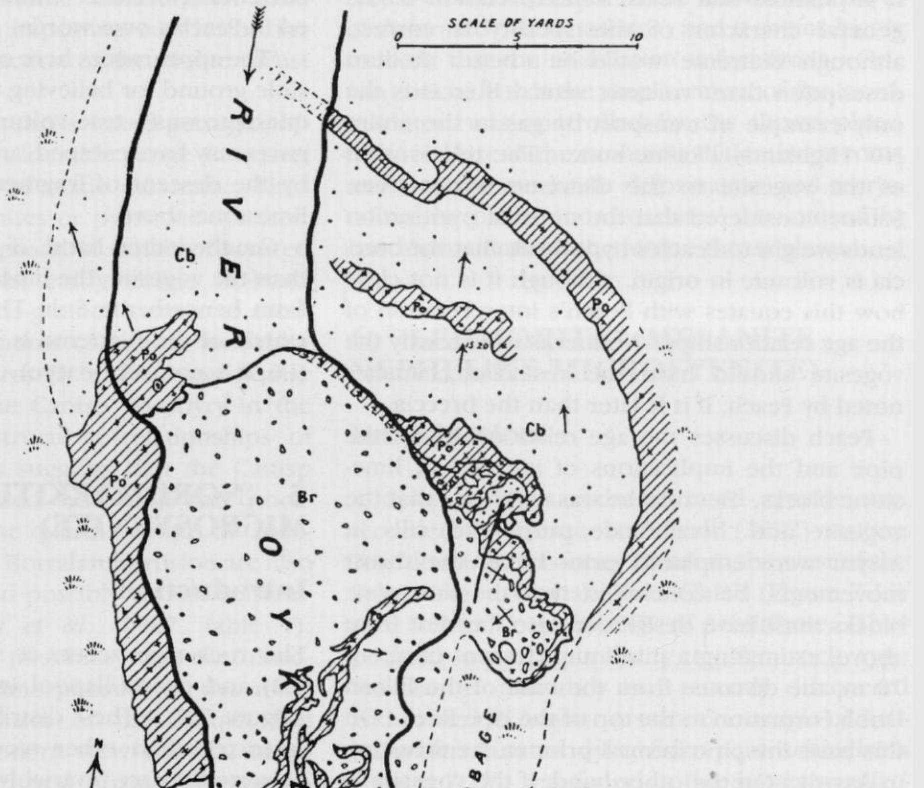

Figure 7.18 Facsimile of B.N. Peach's 'Ground Plan of possible Volcanic Vent, River Oykel, about three miles above Loch Ailsh' (from Peach *et al.*, 1907).

the depression in which the breccia lies. The breccia body has steep, clean-cut walls. The vogesite sill is emplaced in the Pipe Rock, which dips to the NE at 15–20°. According to Peach, the sill is later than the breccia, sends tongues into it, and has flowed between the limestone blocks, in some cases detaching them. A large mass of quartzite is also suspended in the vogesite. Peach noted that the vogestite is 'vesicular and slaggy' and Sabine (1953, p. 157) noted that it is very heavily pyritized where it intrudes the marble, more so than any other of the post-Cambrian sills in Assynt.

Interpretation

It is possible that Peach's interpretation of the general character of this locality is correct, although 'diatreme' would be a better modern description than 'volcanic vent'. If so it is the only example of transport by gas in the entire NW Highlands alkaline suite. The relationship of the vogesite to the diatreme is not clear. Sabine considered that the unusual pyritization lends weight to Peach's hypothesis that the breccia is volcanic in origin, although it is not clear how this equates with Peach's interpretation of the age relationships. Neither is it clear why the vogesite should have the vesicular character noted by Peach, if it is later than the breccia.

Peach discusses the age relationships of the pipe and the implications of its infill of limestone blocks. Because he was confident that the vogesite and 'hornblende porphyrite' sills in Assynt were emplaced prior to all the thrust movements, he concluded that the limestone blocks must have descended into the vent from above, estimating a minimum descent of about 70 m, the distance from the base of the Eilean Dubh Formation to the top of the Pipe Rock. On this basis the pipe formed prior to the thrusting in Assynt. On the other hand, if the vogesite is earlier than the breccia, and the shape of the body, the pyritization and the unusual vesicular character of the vogesite suggest that this may be the case, the breccia could have been emplaced later than the thrusting and could have incorporated limestone from hidden thrust sheets or from unmoved limestone beneath the Sole Thrust. The possibility, suggested by the presence of a carbonatite body near Loch Urigill (see the Loch Borralan GCR site report), that the matrix of the breccia might have been a hot carbonatite magma, can be ruled out because of recent measurements of carbon and oxygen isotopes. Both breccia fragments and matrix have identical isotopic compositions, characteristic of sedimentary carbonate rocks (K.M. Goodenough, pers. comm., 1997).

Conclusions

At the Glen Oykel North GCR site a pyritized vogesite sill is intimately associated with a jumbled mass of marble blocks, both being intruded into Pipe Rock. The structure was interpreted as a 'volcanic vent' by Peach *et al.* (1907). No other example of such a vent (or diatreme) is known in the NW Highlands alkaline suite. This is an intriguing locality of considerable historical and current importance. One hypothesis is best stated in Peach's own words:

'The appearances here observable afford plausible ground for believing that this orifice in the quartzite was a true volcanic vent, whence only gases may have escaped, and which was filled up by the descent of fragments from the walls of limestone above.'

On the other hand, if the diatreme is later than the vogesite, the limestone may have come from beneath the Sole Thrust. The carbonate matrix of the diatreme is not of igneous origin (i.e. it is not carbonatite).

5. 'NORDMARKITE' (QUARTZ-MICROSYENITE)

Introduction

This rock type occurs as sills in Assynt (Figure 7.2) and near Ullapool in the Achall structure (Figure 7.1). Their distribution is much more restricted than other types in the thrust belt because they are invariably found emplaced very close to the Moine Thrust itself, either in the Moine rocks just above the thrust plane, or in Cambro-Ordovician strata immediately below. They are thus unique in that their emplacement was apparently localized by the thrust structure itself, and in being emplaced in part in the Moine Nappe. The thickest sill, some 10 m thick, is emplaced just above the Moine Thrust at Druim Poll Eòghainn (NC 212 090) south of Knockan. Sabine (1953) reported that one of the least altered examples comes from a sill on Maol Calaisceig east of Ullapool (around

NH 144 944) and he provides a map (Sabine, 1953, fig. 6) and a detailed petrographical description. A detailed structural map of the Achall Culmination is in Elliott and Johnson (1980, fig. 22). They point out that the sill described by Sabine is slightly oblique to the foliation of the Moine rocks, so that its proximity to the Moine Thrust is to some extent fortuitous. Nevertheless the 'nordmarkites' do in general seem to be concentrated near the Moine thrust plane. The complete absence of any other members of the alkaline suite in the Moine Nappe is extremely striking and implies that the 'nordmarkites' were emplaced late in the tectonic history of Assynt (Halliday *et al.*, 1987, table 1). As many examples are considerably deformed, late movements on the Moine Thrust must have occurred. This is an important conclusion for the tectonic reconstruction of the Moine thrust zone.

The 'nordmarkite' suite is varied petrographically and there is considerable range in quartz content and content of mafic minerals. Thus some are strictly syenites or pyroxene syenites. They are usually composed of variably fractured alkali feldspar crystals, easily visible in hand specimen, set in a fine-grained matrix of alkali feldspar, variable amounts of quartz, and chlorite. The rocks are strongly alkaline and similar in composition to the Canisp Porphyry in the Foreland, but the structural relationships of these two rock types suggests that the Canisp Porphyry was emplaced early and the 'nordmarkite' sills late. The quartz-syenites of Cnoc-na-Sroine in the Loch Borralan intrusion are also chemically similar and possibly almost contemporaneous (Halliday *et al.*, 1987, table 1). Sabine discusses the possibility that the 'nordmarkites' were metamorphosed in the main regional metamorphism of the Moine, but favours the more modern view that the metamorphic changes occurred during later movements localized on the Moine Thrust.

ALLT NA CAILLICHE (NC 320 102)

Description

The Allt na Cailliche (Figure 7.2) flows into the SE corner of Loch Ailsh and can be reached easily using forestry roads. The first exposures, just above the gravel fan, are of mylonitized, almost flinty Moine rocks. Upstream from this point pink 'nordmarkite' can be seen, forming a waterfall. In the gorge above, exposures in the stream bed are of foliated and sheared 'nordmarkite' with conspicuous pink feldspars. The rock is quite mafic. The Geological Survey mapped three sills near the Moine Thrust in the Allt na Cailliche, and also at several points near the thrust plane between there and the A837.

Interpretation and conclusions

This moderately deformed and unusual alkaline rock type was clearly emplaced as a sill just above the plane of the Moine Thrust, which must lie just below the lowest exposures in the Allt na Cailliche. This close proximity to the thrust characterizes all of the known exposures of deformed 'nordmarkites', and it seems highly unlikely that the association is fortuitous. One can conclude that the emplacement of the 'nordmarkites' was controlled by the thrust plane, occurred late in the evolution of the thrust zone, and that the moderate deformation and recrystallization of the 'nordmarkites' was caused by late movements on the Moine thrust plane.

6. 'LEDMORITE' (MELANITE NEPHELINE-MICROSYENITE)

Introduction

A dyke of silica-undersaturated syenite was recorded by Horne and Teall (1892) cutting Torridonian sandstones 28 km to the west of the Sole Thrust at Camas Eilean Ghlais (Figure 7.13) near Rubha Coigeach, NW of Achiltibuie. They pointed out its similarity to the rock type 'borolanite' that they had recently discovered and named in Assynt. A second example of a silica-undersaturated dyke, from near Achmelvich (Figure 7.13), was found in the Survey's collections by Sabine (1952). He suggested that the affinities of both rocks were with the 'ledmorites' because they lacked the pseudoleucite spots that characterize 'borolanite'. The two dykes are similar in mineralogy, although the example from Coigach is coarser grained and more altered. They are largely composed of an aggregate of orthoclase and nepheline (altered to natrolite) enclosing euhedral crystals of melanite garnet, prisms of aegirine and rare deep-brown biotite. Thomsonite occurs in interstitial clusters.

These dykes are extremely important, in both a historical and a modern context. Both extend well to the west of the thrust belt and, as Sabine (1953) pointed out, are far from any extensive exposures of limestone that might have been involved in the assimilation reactions central to the 'Daly–Shand' hypothesis. The nearest Durness Group carbonate rocks would have been well above the level of the dykes if carried to the west by the thrusts. Although one might argue that the dykes were emplaced laterally from the Loch Borralan magma chamber, Sabine's arguments contributed to the eventual abandonment of the limestone assimilation hypothesis. In a modern context, the dykes show that the source of this, the most alkaline magmatism in the British Isles, lies in the high-grade Lewisian gneisses of the Foreland or in the mantle beneath.

The dykes also have structural implications. Both strike towards the Loch Borralan intrusion in its present position in the thrust zone. Although horizontal movement of the Borralan mass of a few kilometres on the Sole Thrust cannot be ruled out, it certainly seems unlikely that a large displacement has occurred. The timing of major late movements on the Sole Thrust is a contentious issue, because Elliott and Johnson (1980) and Coward (1985), on the basis of detailed mapping, suggested that the Borralan intrusion has been considerably displaced by late movements on this thrust. Coward calculated a minimum displacement of 30 km. Halliday *et al.* (1987), however, accept the evidence provided by the 'ledmorite' dykes, and consider that the main movements on the Sole Thrust must have pre-dated the emplacement of the Loch Borralan complex.

CAMAS EILEAN GHLAIS (NB 967 157)

POTENTIAL GCR SITE

Description

There are two sub-parallel dykes at Camas Eilean Ghlais (Figure 7.13), one presumably being a splay of its neighbour, striking approximately WNW. The larger can be found reasonably easily above the cliffs on the north side of this beautiful bay although, as a reddish-brown dyke cutting tilted Torridonian sandstones, it does not stand out very obviously. The presence of a high content of pink feldspars up to 2 mm in length is distinctive, however. Sabine (1953) provided a petrographical description and reported that the freshest specimens come from the more northern of the pair of dykes. An analysis was given by Horne and Teall (1892).

Sabine (1953) correlated the dykes at Camas Eilean Ghlais with a dyke at Garvie Bay (NC 039 139) and with a dyke that passes up through Lewisian into Torridonian on the NW flank of Cùl Mór (shown on the Geological Survey special sheet for Assynt at NC 140 129) (Figure 7.13). The dyke can be traced almost to Elphin (to NC 204 115) where it is less than 1 km west of a sheet of 'borolanite', an outlier of the Loch Borralan intrusion, in Durness Group carbonate rocks occurring above and to the east of the Sole Thrust. The dyke rock is very altered at this locality.

Interpretation and conclusions

The exposures in the Camas Eilean Ghlais site are at the western extremity of one of the two nepheline-syenite dykes that occur in the Foreland. These exposures of a unique dyke rock, here cutting Torridonian sandstone, demonstrate the spatial extent of the alkaline province, and tie the silica-undersaturated magmatism in Assynt firmly to the Foreland and the underlying mantle. The dyke can be traced sporadically to within 3 km of the main part of the Loch Borralan intrusion, in which it closely matches rocks of the 'ledmorite' type. Although continuity with the Loch Borralan intrusion cannot be proved directly, the alignment of this petrographically distinctive dyke with compositionally similar rocks east of the Sole Thrust, places important restrictions on the scale of displacements on this plane subsequent to the emplacement of the silica-undersaturated alkaline rocks.

AN FHARAID MHÓR (NC 060 244)

POTENTIAL GCR SITE

Description

Sabine (1952) cut a section of a dyke-rock, from the Geological Survey's collections, that had been found cutting Lewisian gneisses near Achmelvich, WNW of Lochinver (Figure 7.13). Peach *et al.* (1907) thought it was equivalent to the Canisp Porphyry found at the Laird's Pool, Lochinver (Figure 7.13), but Sabine discovered that it is a nepheline-bearing rock similar to the dykes at Camas Eilean Ghlais. Sabine (1952) provides a sketch-map of the locality, and a detailed map of the Achmelvich peninsula, showing several slightly sinuous 'ledmorite' dykes striking approximately 110°, is given by Barber *et al.* (1978). The dykes occur on the An Fharaid Mhór-Clachtoll Lewisian GCR site and an example can be found on the shore of Loch Roe (060 244). A second dyke can be reached more easily by descending a gully in the cliffs on the western side of An Fharaid Mhór (053 244), where it is about 1–2 m thick. This dyke is a fine-grained, aphanitic, pale- chocolate-brown rock that is very distinct from the enclosing gneisses. It weathers in and cannot be traced in the higher ground on An Fharaid Mhór.

Interpretation and conclusions

The An Fharaid Mhór site provides an accessible second site for this important type of nepheline-syenite ('ledmorite') dyke in the Foreland, in this case cutting Lewisian gneiss. Although rocks that may be correlated with these dykes have not been discovered between this locality and the Loch Borralan intrusion, the measured strike would extrapolate only slightly to the north of the present position of the Loch Borralan 'ledmorites'.