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The Caledonian minor intrusions of the Assynt region

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Front cover

View of Beinn Garbh across Loch Assynt. The summit region of Beinn Garbh is formed by a thick sill of Canisp Porphyry.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) Moine Thrust Project, as part of the revision of the Assynt Special Sheet. Mapping of the Assynt area was carried out from 2001 to 2003 by Maarten Krabbendam, Roger Key, Graham Leslie, Kathryn Goodenough, Elizabeth Pickett, Sue Loughlin and Tom Bradwell, and the whole team contributed to mapping and collection of samples from the minor intrusions.

Contents

Figures

Summary

This report provides a full description of new mapping, petrographical and geochemical studies of the minor intrusions of the Assynt area of the Northwest Highlands. These intrusions were studied in detail by Sabine (1953) but since then little has been published on them, although a PhD study was carried out by Young (1989). The minor intrusions are divided into six main groups, each of which is described in detail.

1 Introduction

The main syenite intrusions within the Moine Thrust Belt in Assynt (the Loch Ailsh and Loch Borralan plutons) are well known (for reviews see Goodenough, 2002 and Parsons, 1999). However, the area also contains a widespread, but less well understood suite of 'minor' intrusions, including sills and dykes that range in composition from peralkaline rhyolites to lamprophyres. These minor intrusions extend from Loch More, north of Assynt, to the Achall valley near Ullapool. They are most abundant in the Assynt area, where they are found in the undisturbed Foreland to the west of the Moine Thrust Belt, in the Assynt Culmination of the Moine Thrust Belt, and in the Moine Schists within a few kilometres east of the Moine Thrust. The Moine Thrust Belt in Assynt comprises four main thrusts, separated by thrust sheets that are named after the thrust at the base of the sheet (Figure 1). The structural geology of this area has been described in detail elsewhere (e.g. Coward, 1983, 1985; Elliott and Johnson, 1980) and is not discussed further in this report.

The stratigraphical sequence of the Foreland to the Moine Thrust Belt was established by Peach et. al. (1907), and has been recently reviewed by Park et al. (2002). The oldest rocks in the area belong to the Lewisian Gneiss Complex, and these are overlain in turn by the Torridonian sandstones and by a Cambro-Ordovician sedimentary sequence that largely comprises quartzites and limestones.

The Assynt minor intrusions were first mentioned by some of the early surveyors (e.g. Teall, 1907; Phemister, 1926). However, the first detailed study was that of Sabine (1953) who divided them into six classes: 'grorudite'(peralkaline rhyolite); 'Canisp Porphyry' (porphyritic quartz-microsyenite); 'hornblende porphyrite' (hornblende microdiorite); 'nordmarkite porphyry' (quartz-syenite); vogesite; and 'ledmorite' (melanite-augite nepheline-syenite). These classes were reviewed and described in more detail by Young (1989), who distinguished some of the intrusions previously classified as 'grorudites' as porphyritic trachytes, and divided up some of the other suites.

One of the most important features of the different classes of minor intrusions has always been considered to be their well-constrained temporal relationship to the thrusting in the area, as summarised by Parsons (1999). However, recent mapping work in the area (2001 – 2003) has raised certain questions over some of the generally accepted theories, and has led to a re-appraisal of our understanding of some of these minor intrusions. In this report, the field relations of the main suites of minor intrusions are described in some detail, together with new petrographical and geochemical studies. The rocks of the ledmorite swarm have not been studied in detail during the current BGS mapping project and so are not discussed further here; Parsons (1999) summarises the current understanding of the ledmorite intrusions.

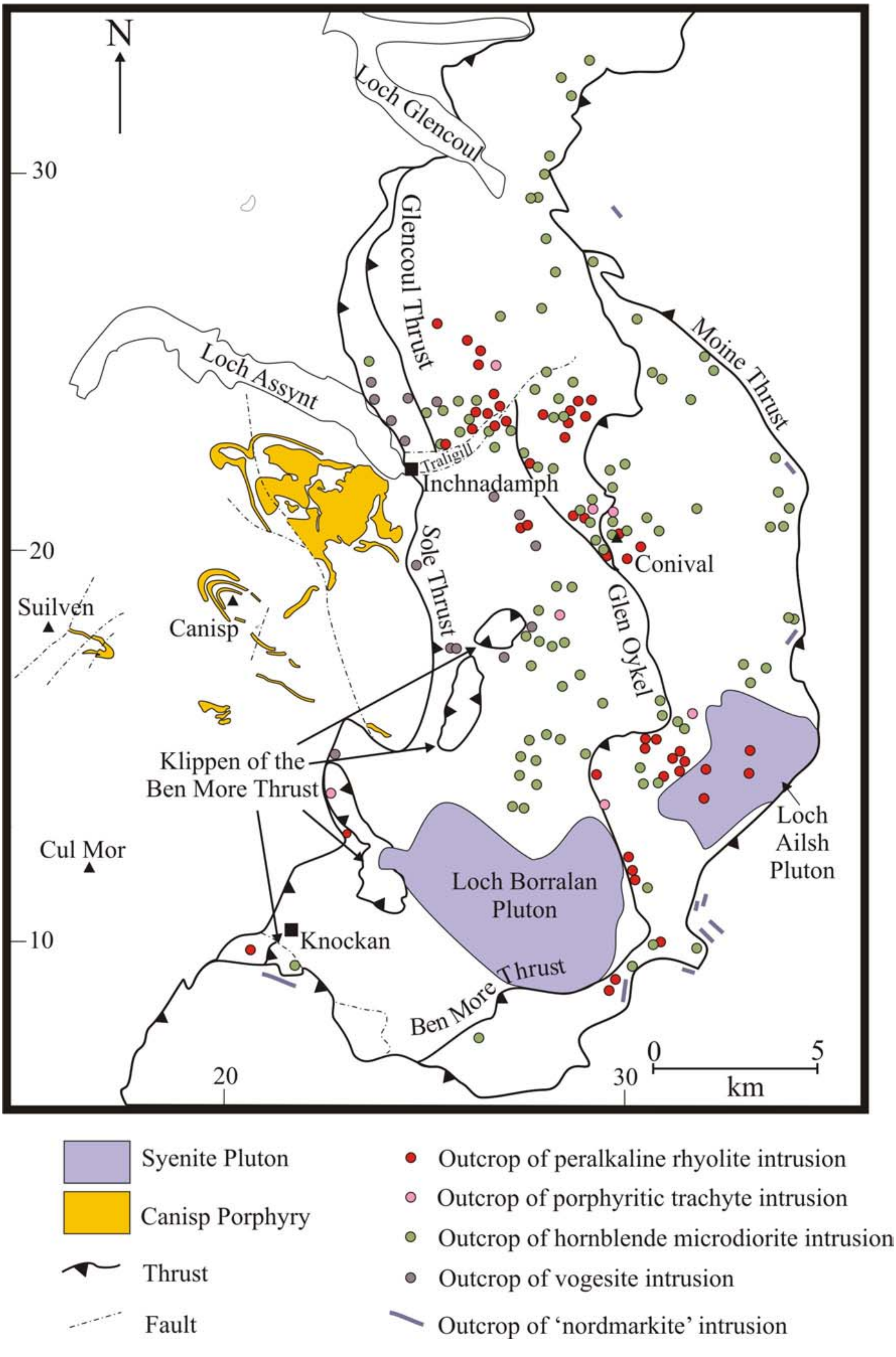

Figure 1: Sketch map of the Assynt Culmination, showing the approximate distribution of the main groups of intrusive rocks. Thrust patterns from Peach et al. (1907), modified after Coward (1983). Locations of minor intrusions from Sabine (1953), modified after Young (1989) and recent BGS mapping. Note that this is not a comprehensive map of all the minor intrusion localities.

2 Field relationships of the minor intrusions

2.1 CANISP PORPHYRY SILLS

The Canisp Porphyry is a distinctive porphyritic quartz-microsyenite, first mentioned by Heddle (1881), and described by Sabine (1953) and Young (1989). It is easily recognised in hand specimen by the presence of large zoned feldspar phenocrysts up to 2 cm across, together with smaller green pyroxene phenocrysts, in a red, fine-grained quartzofeldspathic groundmass. The type area for the Canisp Porphyry is on Beinn Garbh [NC 227 222], on the south side of Loch Assynt, where it forms two major sills in Cambrian quartzites and Torridonian sandstones. The upper sill, which is up to 50 m thick, is well exposed on the summit plateau and eastern dip slope of the hill. In general it lies parallel to the bedding in the country rocks, but in places is clearly transgressive. The Beinn Garbh sills can be correlated with exposures on Canisp and Suilven (Sabine, 1953). The Canisp Porphyry also occurs as dykes cutting the Lewisian Gneiss Complex, including an easily accessible exposure in the River Inver near Lochinver [NC 103 235] (Parsons, 1999).

The distribution of the Canisp Porphyry as shown on the original maps was assessed during the 2003 field season and is considered to be generally accurate, although it is likely that the extent of outcrop in the poorly exposed Loanan Valley [NC 245 205] is rather smaller than originally shown. A previously unmapped Canisp Porphyry dyke cuts Torridonian sandstone (Applecross Formation) on the northern shore of Loch Assynt [NC 2279 2459]. This dyke is approximately 30 cm wide, north-south trending, and can be traced for about 10 m from the loch shore to the point where it is concealed beneath the peat.

The Canisp Porphyry has only been recognised in the Foreland to the Moine Thrust Belt, approaching close to the Sole Thrust but never being seen east of it, and is generally considered to pre-date movement in the Moine Thrust Belt (e.g. Parsons, 1999).

2.2 ASSYNT VOGESITE SWARM

The Assynt vogesites are hornblende-rich lamprophyres, generally medium to coarse grained and weathering green to grey in colour. They consist of phenocrysts of hornblende up to 2 mm long in a mafic hornblende-feldspar matrix. Young (1989) divided the vogesites into melanocratic and leucocratic types according to their content of hornblende phenocrysts. He also recognised the presence of a biotite-bearing minette at Skiag Bridge on the north shore of Loch Assynt [NC 2445 2320]. However, the extent of the different lamprophyre types has not been mapped out and thus they will be grouped together as the Assynt Vogesite Swarm on the new map.

The vogesites are widespread in the Assynt region and beyond, having been recognised from Loch More in the north to Ullapool in the south (Sabine, 1953), although they are most common in the dolomitic Durness limestones of the Sole Thrust Sheet. They only occur within the Moine Thrust Belt and have not been seen in the Foreland or to the east of the Moine Thrust. Young (1989) noted that vogesite intrusions are hornfelsed close to the Loch Ailsh Pluton and thus concluded that the vogesites pre-date this pluton.

During 2001 fieldwork, two vogesite sills were studied cutting the limestones immediately above the Sole Thrust on the north side of Loch Assynt. The sill contacts are sheared and at [NC 2402 2391] an offshoot from one sill is imbricated on a small scale.

During 2002 fieldwork, vogesites were chiefly studied in the Allt nan Uamh and the Traligill Valley, and in stream sections in between. Of particular interest is a thick vogesite sill that is exposed some two hundred metres above the waterfall in the Allt nan Uamh [NC 256 179], with excellent exposures in undercuts along the river banks. At both [NC 2582 1774] and [NC 2593 1770], narrow shear planes can be seen cutting across the vogesites. These shear planes have a strike of approximately 025º and dip at 20º – 30º towards the south-east. They are marked by fine lines of bleached, sheared rock, with slickenslides on some surfaces. In some places the vogesite below the shear planes is conspicuously altered, showing a pale green colour. At NC [2593 1770], segregations of pink, coarse-grained felsic rock with black amphibole needles that are up to over 1 cm long can be seen within the vogesite (Figure 2), possibly associated with the shear plane. The largest segregation is approximately 50cm by 50 cm and forms a protrusion from the river bank. Contacts between the two rock types are fairly sharp but there is no clear evidence of chilling. Sabine (1953) noted the presence of an alkali microsyenite associated with vogesite in Strath Kanaird, and this may be a similar association.

Figure 2: Felsic segregation in vogesite, Allt nan Uamh. BGS photo P513570.

The vogesite sills are clearly deformed by thrust movements within the Assynt Culmination and so were intruded prior to the main period of thrusting. Young (1989) concluded that the vogesites are the most primitive and also the earliest of all the minor intrusions in the Assynt area and this seems reasonable, since there is no evidence that they post-date any of the other intrusions.

2.3 HORNBLENDE MICRODIORITE SWARM

The Assynt hornblende microdiorite intrusions were originally described by Bonney (1883) and Sabine (1953) as 'hornblende-porphyrites', and the more modern name has been adopted relatively recently (Parsons, 1999). They consist of phenocrysts of feldspar up to about 5 mm long, with smaller hornblende phenocrysts, in a fine-grained feldspathic groundmass. Young (1989) suggested that the hornblende microdiorites north of the Traligill valley can be distinguished from those to the south on the basis of groundmass variations, but again this distinction cannot be mapped on the ground.

The hornblende microdiorites are common across much of the Assynt Culmination, typically forming sills rather than dykes. They are not found in the Foreland or east of the Moine Thrust. Sabine (1953) studied the deformation state of these intrusions and showed that they are sheared adjacent to all the major thrusts, but that they are most intensely deformed close to the Moine Thrust. This relationship can be easily studied on the slopes west of the Stack of Glencoul [NC 290 287], where hornblende microdiorites show evidence of increasingly pervasive shearing and deformation approaching the Moine Thrust.

The structural relationships of the hornblende microdiorites are particularly clear in the quartzites above the Glencoul Thrust on Cnoc an Droighinn, north of Inchnadamph. A 10 m-thick sill, with abundant phenocrysts of feldspar and hornblende up to 5 mm across in a feldspathic matrix, is exposed just 20 m above the thrust plane at [NC 2565 2275]. About two hundred metres east of that location two hornblende microdiorite sills, each approximately 5 m-thick and north-trending, cut Pipe Rock adjacent to a fence line. The sills can be traced northwards, until they are cut off by a minor thrust carrying Pipe Rock in its hanging wall

(Coward, 1982). The western sill in particular can be traced continuously from [NC 2582 2268] as far as [NC 2583 2300], where it is clearly truncated.

Higher on the slopes of Cnoc an Droighinn, hornblende microdiorites are exposed in close association with peralkaline rhyolites. At [NC 2662 2289], in the vicinity of a lochan, all the sills can be seen to be folded. The peralkaline rhyolite clearly cuts the hornblende microdiorite at one point.

Northeast of Cnoc an Droighinn, hornblende microdiorite sills are common in the Basal Quartzite west of Loch nan Cuaran. Around [NC 2889 2382], a large mass of hornblende microdiorite, some 200 m across, interfingers with the Basal Quartzite. The central part of the hornblende microdiorite mass consists of a north-west trending sheet, about 5 m thick, which contains abundant megacrysts of hornblende that are typically more than 2 cm long, in a leucocratic matrix. This megacrystic material does not appear to be repeated elsewhere. This hornblende microdiorite mass is thus probably a single large intrusion, possibly composite, with irregular contacts with the surrounding Basal Quartzite. To the south of the main intrusive mass, a sill of hornblende microdiorite is clearly folded by an anticline in the Basal Quartzite [NC 2893 2365].

Farther south, on Creag Mhor Fuaran nan Each, abundant hornblende microdiorite (and peralkaline rhyolite) sills in Basal Quartzite are folded in a major syncline that has been mapped accurately by Coward (1982).

The field relationships of the hornblende microdiorites on the north side of the Traligill valley clearly indicate that these intrusions were formed prior to thrusting within the Glencoul Thrust Sheet, since they are folded by structures considered to be syn-thrusting (Coward and Potts, 1985) and truncated by thrusts.

Hornblende microdiorites are also common south of the Traligill valley, on the Breabag ridge, where they form sills that are chiefly intruded into the Cambrian quartzites. The majority of sills are no more than a few metres thick. A notable exception lies on the south ridge of Breabag, around [NC 2822 1370], where the original map shows a wide and irregular area underlain by ‘felsite’. This area seems to represent a single sill of hornblende microdiorite that, even taking into account the probable effects of folding, must be a few tens of metres thick.

Sabine (1953) described a spatially restricted variety of hornblende microdiorite that he termed ‘Breabag porphyrite’. In hand specimen, these intrusions look similar to the Canisp Porphyry, with phenocrysts of feldspar in a red matrix. However, both Sabine (1953) and Young (1989) noted that, unlike the Canisp Porphyry, the ‘Breabag porphyrites’ contain hornblende phenocrysts. For the purpose of mapping, therefore, these intrusions are grouped with the hornblende microdiorites. A good example of a ‘Breabag porphyrite’ can be seen at [NC 2769 1679], on the west slopes of Breabag.

2.4 PERALKALINE RHYOLITE SWARM

Sabine (1953) recognised the presence of a group of red felsites in Assynt and termed them ‘grorudites’ since they closely resemble the grorudites from Norway described by Brögger (1894). They are red or green in colour, with small white to pink feldspar phenocrysts up to about 4 mm across. Sabine described three types of ‘grorudite’ in Assynt: a fine-grained type; an aegirine-rich type from the Sail an Ruathair ridge above Loch Ailsh; and a more varied ‘Inchnadamph’ type. He also stated that the ‘grorudites’ only occur in the Glencoul and Ben More thrust sheets.

Young (1989) divided the red felsite group into ‘grorudites’ and porphyritic trachytes, the latter always having a flow texture in the groundmass (see section 2.5). Young recognised that Sabine’s ‘fine-grained’ type represented the chilled margins of ‘Inchnadamph’ type sills and instead suggested a more detailed division of the ‘grorudites’ based on detailed phenocryst mineralogy. In particular, he distinguished two very different groups to the north and south of

Traligill. To the north, the 'Cnoc an Droighinn type' have feldspar phenocrysts up to 5 mm across, and rare aegirine augite phenocrysts, in a green to red groundmass. To the south, around Loch Ailsh, are much more variable intrusions with phenocrysts including feldspar, quartz, green aegirine augite and blue sodic amphiboles. Young showed that his 'grorudites' are truly peralkaline, having acmite in the norm, and Parsons (1999) suggested the modern name peralkaline rhyolite.

On Cnoc an Droighinn, there are no peralkaline rhyolites below the Glencoul Thrust, but they appear as thin discontinuous dykes in the Pipe Rock almost immediately above the thrust at [NC 2567 2266] and at [NC 2588 2242]. Thin (1-2 m) sills are seen higher on the slopes at Cnoc an Droighinn and at least one example can be traced from [NC 2629 2304] to [NC 2662 2289]. These peralkaline rhyolites have a brick-red, fine-grained matrix with pink, tabular feldspar phenocrysts typically 2-3 mm long. At [NC 2661 2286], two peralkaline rhyolite sills are quite clearly folded by an anticline in Basal Quartzite. The sills are then cut off by a fault, marked by a gully and a steep wall of quartzite, a short distance to the northeast at [NC 2663 2291]. These sills are roughly parallel to a set of hornblende microdiorite sills, but the peralkaline rhyolites can be seen at one point [NC 2661 2286] to cut across the margin of one of these sills, which is foliated at the margin. The peralkaline rhyolite is chilled against the hornblende microdiorite and the contacts are sharp with no signs of magma mingling, showing that the peralkaline rhyolite is younger than the hornblende microdiorite. However, it is clear from the folding of the peralkaline rhyolite sills that they also pre-date thrusting in the Glencoul Thrust Sheet.

Peralkaline rhyolites are also seen cutting the Basal Quartzites on Creag Mhor Fuaran nan Each [NC 2795 2195]. Here again they form sills 1-2 m thick, are associated with hornblende microdiorites, and are folded in a major syncline (as mapped by Coward, 1982). Contact relationships with the hornblende microdiorites are not seen in this area.

A thick, brick-red, peralkaline rhyolite sill occurs on the slopes of Cnoc Chaornaidh to the south of Loch Ailsh. It cuts limestones that originally mapped (Peach et al., 1907) as being above the Ben More Thrust, although the course of the thrust here is uncertain due to poor exposure. Christie (1963) suggested that the Ben More Thrust cuts across the peralkaline rhyolite sill, but it seems highly unlikely that the thrust would place two such unusually thick sills adjacent to each other, and so this suggestion for the line of the thrust can be discounted. The south-western end of the major sill of peralkaline rhyolite is well exposed on a crag just above the A837 at [NC 298 084]. This sill is reddish in colour, coarse grained, and composed largely of quartz and alkali feldspar. It can be traced north-eastwards through scattered outcrops as far as [NC 3085 0940], although it is in places offset by late faults. The lower contact of this sill with Salterella Grit is exposed at [NC 2979 0837] and again a finer grained facies with small feldspar phenocrysts is seen at this margin. Similar, thinner peralkaline rhyolites are seen parallel to, and above and below this main sill.

Sills of brick-red peralkaline rhyolite that have not been previously mapped occur in the limestones below Cnoc nan Uamh in Gleann Dubh, within the Sole Thrust Sheet. These may be comparable with the peralkaline rhyolite sills seen in limestones of the Sole Thrust Sheet near Knockan as described by Goodenough (2002). The intrusions are best seen in the stream west of Cnoc nan Uamh [NC 2755 2046], where two sills each one metre thick have sharp contacts against eastward-dipping limestones (Figure 3). These sills can be traced as far as [NC 2756 2053], and one sill can be seen a short distance north on the lip of the sinkhole above Uamh an Uisge, at [NC 2760 2057]. At this locality the intrusion appears to be approximately 1 m thick and trends roughly east-west. It has sharp, but irregular contacts with the limestone; xenoliths of limestone appear to be included within the margin of the intrusive sheet, and narrow veins of red igneous rock a few centimetres thick are seen in the limestone below the contact. Outcrops of peralkaline rhyolite are also seen on the northern slopes of Cnoc nan Uamh [NC 2775 2053] and [NC 2780 2052], and are probably the continuation of the sheet at Uamh an Uisge. This sheet is not exposed higher on Cnoc nan Uamh and is interpreted to be cut off by the Cnoc nan Uamh thrust. The presence of this peralkaline rhyolite apparently beneath the level of the Glencoul

Thrust does not fit with the previously mapped relationships of this group of intrusions, and disproves Sabine's contention that these intrusions only occur above the Glencoul and Ben More thrusts.

Figure 3: Peralkaline rhyolite sill cutting limestones on the slopes of Cnoc nan Uamh. BGS photo P515168

Field relationships show that the peralkaline rhyolites are younger than the hornblende microdiorites, and the folding of the peralkaline rhyolites by thrust-related folds on Cnoc an Droighinn and Creag Mhor Fuaran nan Each clearly shows that these intrusions pre-date thrusting within the Glencoul Thrust Sheet. However, since one intrusion is seen cross-cutting the Loch Ailsh syenites in the River Oykel at [NC 3269 1365] (Parsons, 1999) the peralkaline rhyolites must be younger than the syenites which are dated at 439 ± 4 Ma (Halliday et al., 1987).

2.5 PORPHYRITIC TRACHYTE SWARM

The porphyritic trachytes were described by Young (1989) as forming a series of sills along the Cnoc an Droighinn – Breabag axis. They form brick-red sills that are not easily distinguished from the peralkaline rhyolites in the field, but can be recognised in thin section since they have a groundmass that consists almost entirely of alkali feldspars, orientated to give a flow direction.

Young (1989) recognised the presence of a sill of porphyritic trachyte on Cnoc an Leathaid Bhig, in the Cam Loch Klippe [NC 2260 1430]. A 1 m wide dyke of red porphyritic trachyte cuts Basal Quartzite a short distance away [NC 2244 1384] and the two may be related. Another heavily weathered porphyritic trachyte sill, approximately 5 m thick, occurs on the north-eastern shore of Cam Loch [NC 2559 1305], where it cuts Pipe Rock just below the Cam Loch Thrust. Porphyritic trachytes from Cnoc an Droighinn and Breabag Tarsuinn were also described by Young (1989).

During the present study, further examples of porphyritic trachytes have been identified in the Allt a'Choinne Mhill stream on the slopes of Conival. One such sill [NC 2999 2076] is intruded into mylonitic quartzite adjacent to the Ben More Thrust, but largely retains its igneous texture, although foliated along the margins.

Another brick-red porphyritic trachyte dyke, approximately 1 m wide, is seen cutting foliated Torridonian sandstone just above the Ben More Thrust on the southern slopes of Sgonnan Mor at [NC 2955 1387] (Figure 4). Although it is impossible to see whether or not this intrusion cuts across the thrust due to lack of exposure, it clearly cross-cuts a foliation that is considered to be related to thrusting. Evidence from these localities therefore suggests that the porphyritic trachytes were intruded towards the end of, or following, movement on the Ben More Thrust, and may perhaps have been localised along it.

Figure 4: Red porphyritic trachyte dyke cutting foliated, pale grey Torridonian sandstone, Sgonnan Mor. BGS photo P531551.

2.6 NORDMARKITE SWARM

These rocks were termed 'nordmarkitic rocks' by Sabine (1953) following on from terminology used by Phemister (1926). Sabine (1953) noted that these intrusions crop out close to the Moine Thrust plane and described them as being composed of fractured feldspar plates cemented mainly by chlorite and finer grained feldspar, with or without quartz, and always showing some degree of deformation. Sabine (1953) provided several strands of evidence that he considered as indicating a post-Cambrian, probably 'inter-thrustal' age for these intrusions. This evidence included the point that 'nordmarkitic rocks' only occur close to the Moine Thrust plane, but were considered to crop out on both sides of it, and the similarity in chemical composition between these rocks and the syenites of Loch Borralan. This led to general acceptance of the view summarised by Parsons (1999) that the 'nordmarkitic' intrusions were emplaced late in the tectonic history of Assynt, and were deformed by late movements on the Moine Thrust. Parsons (1999) also noted that these sills are quartz-microsyenites; the term nordmarkite is retained for this swarm in order to distinguish these intrusions from other quartz-syenites in Assynt.

A number of the nordmarkite localities described by Sabine have been revisited. Two significant quartz-microsyenite sills were recognised at these localities; one in the Allt na Cailliche, above Loch Ailsh [NC 320 101] and one near Knockan [NC 209 092], both cutting mylonitised Moine rocks a short distance above the Moine Thrust. The sill in the Allt na Cailliche is well exposed in the river valley (Figure 5), whereas the Knockan sill is less well exposed. Both sills have clearly been strongly deformed, and have mylonitic fabrics at their margins. Sheets of mylonitised psammite, often several centimetres thick, are enclosed within the margins of the sill. The sill contacts are parallel to the fabric within the sill, which is also parallel to that within the surrounding Moine mylonites.

Figure 5: Quartz-microsyenite sill of the Nordmarkite Swarm in the Allt na Cailliche. BGS photo P513459.

A third quartz-microsyenite sill has been recognised cutting Moine schists in a stream draining into Loch nan Eircill [NC 3071 2851], some distance from the Moine Thrust. At this locality (Figure 6), an intrusion with pink feldspar phenocrysts up to 5 mm across in a sheared dark grey matrix is associated with a more mafic igneous rock.

Figure 6: Quartz-microsyenite sill of the Nordmarkite Swarm in stream draining into Loch nan Eircill. BGS photo P515154.

Only one member of the Nordmarkite Swarm has been recognised west of the Moine Thrust; this is a highly sheared sill cutting Durness limestone *beneath* the Moine Thrust on Cnoc Chaornaidh [NC 3010 0832] (Figure 7), a locality that was not mapped by Sabine. Several 'leaves' of the sill can be recognised, indicating that it has been repeated several times by the imbrication that can be mapped in the area.

Figure 7: Sheared quartz-microsyenite sill of the Nordmarkite Swarm sill cutting limestone, Cnoc Chaornaidh. BGS photo P531461.

On the southern slopes of Cnoc Chaornaidh, where Sabine mapped a series of sills, there are scattered outcrops of Moine mylonite. Some of these contain crystals of pink alkali feldspar, but there is no clear evidence to suggest that they might be considered as igneous intrusions.

Sabine also described sheared 'nordmarkitic' sills cutting Moine schists in the Allt nan Sleogh [NC 322 097] and cutting rocks *below* the Moine Thrust plane at Loch Sron na Luime [NC 348 216] and in the Allt Carn nan Conbhairean [NC 350 175]. Despite careful study of the exposures in these streams, no intrusions belonging to the Nordmarkite Swarm have been recognised. However, there are samples of quartz-microsyenite sills in the BGS collection (sample numbers 9768, 9769, and 38664; collected by Phemister and/or Sabine) that are described as having come from these localities, and so it may be the case that the sills are so intensely sheared that they are not easily recognisable in the field. All the localities mentioned above are represented by at least one thin section.

The balance of evidence, including the samples in the BGS collection and the sill at Cnoc Chaornaidh, indicates that nordmarkite intrusions occur on both sides of the Moine Thrust plane. However, their intense state of deformation clearly shows that they were deformed during ductile movement on the thrusts. It would thus appear that these intrusions were emplaced *during* the period of thrusting – possibly at a time when the Moine mass had been moved a considerable distance to the west, but ductile deformation was still ongoing, perhaps prior to other movements in the Moine Thrust Belt. It is quite clear that this suite of intrusions was not emplaced after the cessation of ductile deformation in the Assynt area (cf Parsons, 1999).

3 Petrography of the minor intrusions

3.1 CANISP PORPHYRY SILLS

The Canisp Porphyry is characterised by large (up to 1.5 cm) euhedral feldspar phenocrysts in a fine-grained groundmass that is composed of alkali feldspar crystals less than 0.1 mm across, micropoikilitically enclosed by quartz plates up to 0.5 mm in size (Sabine, 1953). The feldspar phenocrysts include both albites and microperthites, although both types have mantles of sericitised albite. Some larger phenocrysts are composed of aggregates of several feldspar crystals. Pale green pyroxene phenocrysts are also present; these are up to 3mm long, euhedral and concentrically zoned, from diopside cores to aegirine-augite rims. Tabular biotite phenocrysts up to 3 mm long also occur, and are commonly altered to chlorite (Young, 1989). Young (1989) described small idiomorphic phenocrysts of titanite, although these are rare or absent in many of the samples in the BGS collection. However, euhedral apatites up to 0.5 mm long are common.

3.2 ASSYNT VOGESITE SWARM

Sabine (1953) grouped all the Assynt hornblende lamprophyres together as a single group of vogesites, which were subsequently divided by Young (1989) into melanocratic and leucocratic vogesites (see Section 2.2).

Young (1989) described the melanocratic vogesites as consisting of approximately 50% mafic minerals in a felsic groundmass, with phenocrysts of both pyroxene and hornblende occurring in all samples and plagioclase phenocrysts in some. The groundmass is composed of an interlocking mass of irregular grains of alkali feldspar, up to 3 mm across, and often sericitised. The hornblende phenocrysts vary in size from 1 to 7 mm in differing samples, and are usually subhedral. Hornblendes in some samples show excellent concentric zoning.

The pyroxene phenocrysts show variable degrees of alteration. In a sample from the Allt nan Uamh, they form colourless, euhedral crystals up to 1mm long, but in many other samples the pyroxenes are represented by clusters of euhedral crystals that have been extensively altered to chlorite-rich aggregates. Calcite is present in all the pyroxene-bearing vogesites, and in many places appears to be replacing primary minerals or forming vein fills. Young (1989) suggested that all the calcite is magmatic, but in at least some of the samples it seems to be associated with late-stage alteration. The sample from the Allt nan Uamh is unusual in that it appears to contain little or no late-stage calcite, and also in that it contains biotite plates.

Young distinguished his leucocratic vogesites on the basis of the sparcity of hornblende phenocrysts, and the fine-grained nature of the groundmass. However, study of the BGS specimens suggests that both these attributes are quite variable across the spectrum of the Assynt vogesites, and that the vogesites would be more easily divided on the presence or absence of pyroxene. The leucocratic vogesites contain phenocrysts of hornblende up to about 4 mm long, in a groundmass composed mainly of plates of plagioclase. Calcite is absent, as is pyroxene; plates of biotite, typically altered to chlorite, occur infrequently.

3.3 HORNBLENDE MICRODIORITE SWARM

The hornblende microdiorites are strongly porphyritic, with phenocrysts of feldspar and hornblende occurring in a fine-grained feldspathic groundmass (Sabine, 1953). The feldspar phenocrysts include both microperthite crystals up to 3 mm across, and albite crystals which are commonly larger. They are typically sericitised, and aggregates of several crystals are common. Many of the crystals show oscillatory or complex sector zoning. Hornblende phenocrysts commonly range in size from 0.5 to 3 mm long, and are often zoned. Plates of altered biotite are also present in places.

Young (1989) described two types of groundmass in the hornblende microdiorites, both consisting of small crystals of alkali feldspar and plagioclase, the difference essentially being in the presence or absence of quartz plates enclosing the feldspar crystals.

3.4 PERALKALINE RHYOLITE SWARM

A variety of peralkaline rhyolites have been studied during the current project, including examples from Cnoc an Droighinn, Cnoc nan Uamh, Cnoc Chaornaidh, Glen Oykel, and Knockan (see section 2.4). These are all similar in appearance to the ‘Cnoc an Droighinn’ type of Young (1989). They have a fine-grained groundmass, with feldspar phenocrysts up to 5 mm across that have typically been largely recrystallised to coarse perthitic aggregates. Euhedral phenocrysts of aegirine-augite and titanite are found in some samples. The groundmass consists of fine-grained quartz and feldspar crystals, and in places contains stubby needles of aegirine.

Young suggested that the peralkaline rhyolites south of Traligill are very variable. He described coarse-grained examples from Sgonnan Mor, with feldspar phenocrysts up to 7 mm across. These phenocrysts are generally aggregates of coarsely microperthitic alkali feldspar, but with patches of albite and microcline. Other peralkaline rhyolites from the Sgonnan Mor - Loch Ailsh area were noted by Young to have quartz and/or sodic amphibole phenocrysts. However, these features have not been observed in peralkaline rhyolites collected during the current mapping project.

3.5 PORPHYRITIC TRACHYTE SWARM

The porphyritic trachytes contain phenocrysts of albite up to 7 mm long, in a fine-grained groundmass that consists almost entirely of aligned laths of alkali feldspar. Young (1989) did not find any samples with unaltered mafic phenocrysts, but irregular aggregates of opaque oxides may represent pseudomorphs after original mafic phases.

3.6 NORDMARKITE SWARM

The rocks of the Nordmarkite Swarm are medium- to coarse-grained quartz-(micro)syenites, with sericitised phenocrysts of alkali feldspar (largely perthite, but also including microcline and albite) in a medium-grained groundmass. The phenocrysts are in places up to 5 mm long, but more commonly 1-2 mm, and in places show signs of strain such as kinked twins. Small (up to 1 mm) phenocrysts of clinopyroxene (augite) are also seen in some samples. The groundmass typically consists of quartz and feldspar with augite, biotite, chlorite and calcite, plus accessory zircon and sulphides. In many of the quartz-microsyenite samples, particularly those taken from the margins of sills, the groundmass shows a strong penetrative fabric that wraps the K-feldspar phenocrysts. In comparison with less strained parts of the sills, the crystals within the groundmass in strained samples have undergone a pronounced grain size reduction, to about a half or a third of their original size. In many strained samples the fabric wraps the alkali feldspar phenocrysts in an asymmetric manner, and strain-shadows filled by quartz occur adjacent to some alkali feldspar phenocrysts. This fabric is in places cut across by later calcite veins. In general, the fabric in the sheared quartz-microsyenites is indicative of significant amounts of ductile deformation, comparable to that in the mylonitised Moine country rocks.

4 Geochemistry of the minor intrusions

Bulk-rock samples of most of the different types of minor intrusions, with the exception of the quartz-microsyenites of the Nordmarkite Swarm, were analysed for major and trace elements, and rare earth elements (REE), by Young (1989). Selected further samples of peralkaline rhyolites, porphyritic trachytes and quartz-microsyenites have been recently analysed as part of the current BGS Moine Thrust Project (Appendix 1). Analyses were carried out by X-ray fluorescence (XRF), using the standard procedures employed by the analytical labs at BGS Keyworth.

All available major element data, including those from Young (1989), for the Assynt minor intrusions have been plotted on a total alkalis vs. silica (TAS) variation diagram (Figure 8). The classification fields are taken from Gillespie and Styles (1999). It should be noted that the TAS diagram is primarily used for the classification of fine-grained rocks, and due to the presence of phenocrysts in the majority of these minor intrusions, it may not be appropriate for classification in this case. In particular, lamprophyric rocks can never be named on the basis of a TAS diagram. However, the main groups of minor intrusions in Assynt can be readily identified and separated from each other using this diagram.

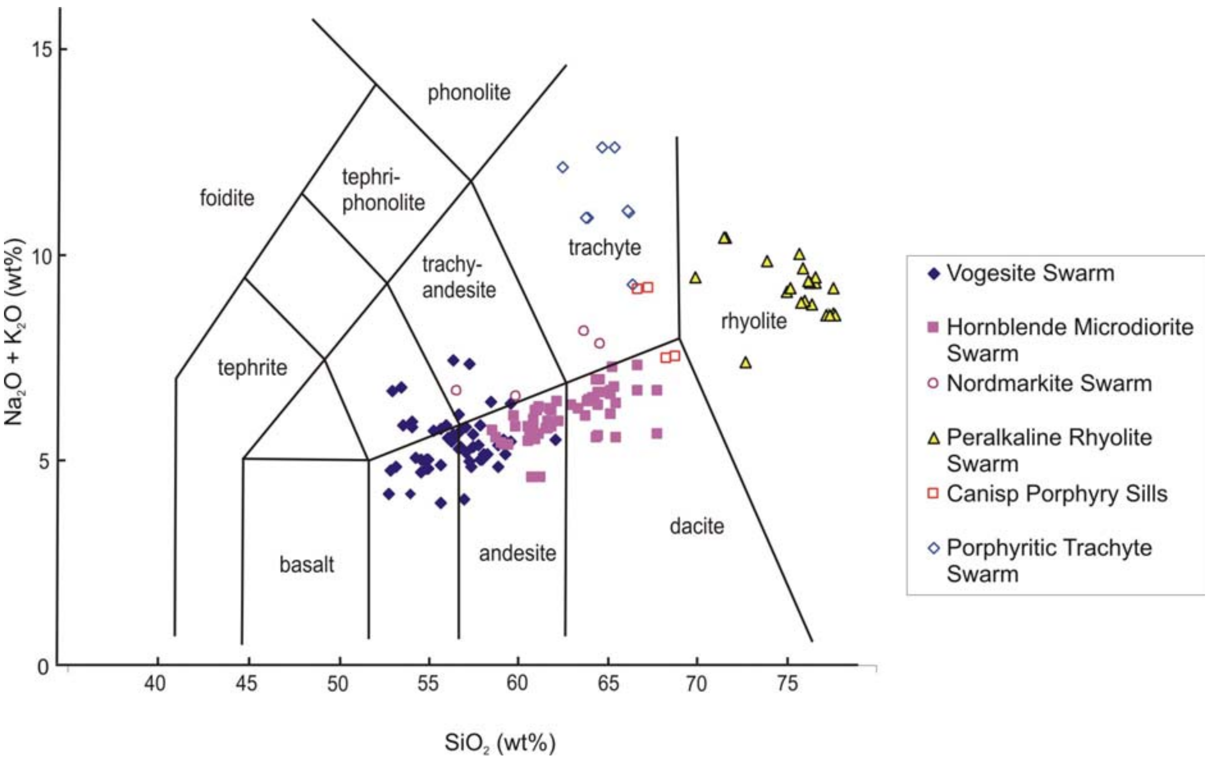

Figure 8: Total alkalis vs. silica diagram for the Assynt minor intrusions

Young (1989) noted that in general the Assynt minor intrusions show a tendency for alkali enrichment with increasing fractionation, with a corresponding depletion in Fe_2O_3 $_{tot}$, MnO, MgO, CaO and TiO_2. He used major element modelling techniques to show that the hornblende microdiorites could have been formed from the melanocratic vogesite magma, through simple crystal fractionation of hornblende, clinopyroxene, forsteritic olivine and Fe-Ti oxides. He also noted that the porphyritic trachytes are alkali enriched in comparison with members of the hornblende microdiorite swarm that have similar SiO_2 contents (Figure 8), and suggested that this might indicate derivation from different parental magmas, albeit possibly with the same primitive mantle source. This conclusion may also be applied to the members of the Nordmarkite Swarm. Leucosyenites from the Loch Borralan Pluton are similarly enriched in alkalis (Thirlwall and Burnard, 1990) and plot close to the porphyritic trachytes on the total alkali - silica diagram; this raises the possibility that the porphyritic trachytes represent offshoots of the Loch Borralan Pluton. The formation of the peralkaline rhyolites was considered by Young (1989) to be more complex, as discussed below. It should be noted that the peralkalinity index (molar (Na_2O + K_2O)/Al_2O_3)) of the peralkaline rhyolites averages about 1; that is, some of them are not truly peralkaline.

The trace element characteristics of the minor intrusions are illustrated on primitive mantle-normalised spider diagrams (Figure 9). These spider diagrams only show the subset of trace elements measured by Young (1989); note that a wider range of elements are available for the new data obtained for this project. The vogesites, hornblende microdiorites and quartz-microsyenites all have very similar patterns, with a clear Nb trough and relatively high Ba and Sr contents. These features are characteristic of many Caledonian igneous rocks across the Northern Highlands, including lamprophyres (Canning et al*.,* 1998); members of the appinite suite (Fowler and Henney, 1996); and syenites (Thompson and Fowler, 1986). The presence of a Nb trough on the spider diagram is generally considered to indicate the presence of subduction-derived material in the mantle source of the magmas, and Thompson and Fowler (1986) have shown that the geochemistry of most igneous rocks of the Northern Highlands is similar to that of subduction-related shoshonitic suites.

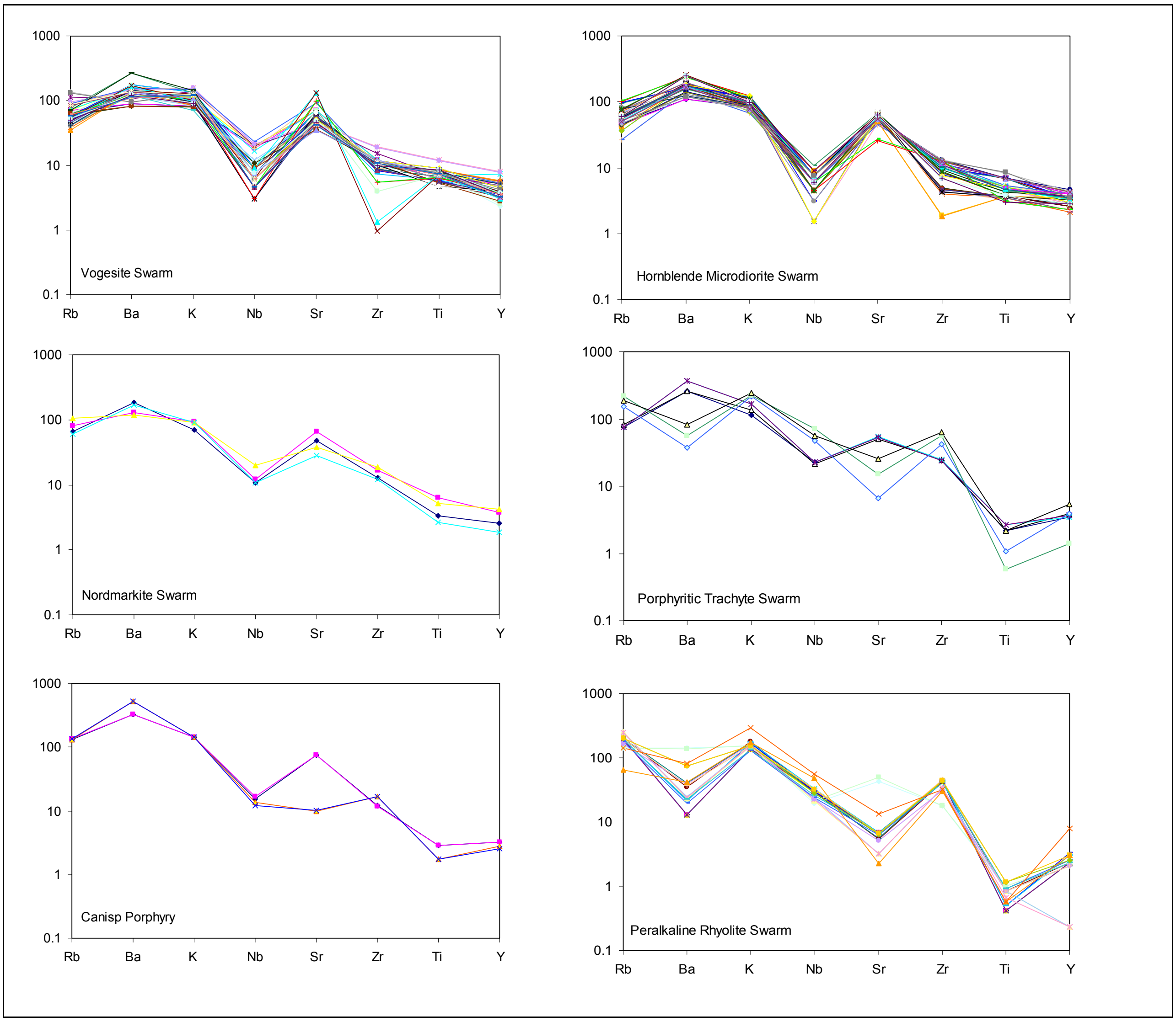

Figure 9: Primitive mantle-normalised spider diagrams for the Assynt minor intrusions. Data from Young (1989) and this project. Normalising values from McDonough and Sun (1995).

The more evolved minor intrusions show a wider range in their trace element patterns. The patterns for the Canisp Porphyry are similar to those of the hornblende microdiorites, with a variation in Sr contents that is probably due to varying amounts of feldspar phenocrysts in the rock. The majority of the porphyritic trachytes and peralkaline rhyolites have substantially lower Ba and Sr contents than the more mafic rocks, and do not have such a pronounced trough at Nb. Thompson and Fowler (1986) suggested that the peralkaline rhyolites were potentially formed through fractionation of alkali feldspar, clinopyroxene, Fe-Ti oxide, apatite, titanite and allanite from the syenite magmas. However, the peralkaline rhyolites occur throughout Assynt and are not spatially associated with the major syenite bodies. Furthermore, Thompson and Fowler (1986) studied La/Nb ratios, which do not tend to vary significantly during fractional crystallisation, and showed that the majority of syenites and other Caledonian igneous rocks in the Northern Highlands have very high La/Nb ratios (> 5). Young (1989) did not measure La, but data obtained as part of the current project indicate that La/Nb for the peralkaline rhyolites and porphyritic trachytes ranges from 0.3 to 3.2. Derivation of the peralkaline rhyolites through fractionation of a syenite magma thus seems to be unlikely.

Young (1989) preferred to link the peralkaline rhyolites to the other members of the minor intrusion suite. He noted that the Ba and Sr depletion in the peralkaline rhyolites relative to the other minor intrusions could be explained by the fractionation of plagioclase from an evolving hornblende microdiorite magma, but that it was necessary to call on the presence of a peralkaline fluid phase to explain the higher contents of Nb and Zr. Although the mineralogy of the peralkaline rhyolites is now largely anhydrous, Young pointed out that the internal morphology of the feldspar phenocrysts, with original plagioclases almost entirely replaced by alkali feldspar, provides further evidence of the existence of a fluid phase in the magma.

The geochemical data above seem to suggest that the majority of the Assynt minor intrusions were formed from a mantle source that contained subduction-related material. Primitive shoshonitic magmas were generated through melting of this source, and the most mafic vogesites probably represent the closest approximation to the parental magmas for the more leucocratic vogesites and the hornblende microdiorites. It is possible that the magmas from which the major syenites were formed were derived from a similar source. The peralkaline rhyolites may have been formed through fractionation of the mafic vogesite parental magma, combined with the presence of a peralkaline residual fluid, as suggested by Young (1989); but it is also possible that they may be derived from an entirely different parent. The source of the porphyritic trachytes is also uncertain; although in some ways they are geochemically similar to the Loch Borralan leucosyenites, they have the elevated Nb and Zr contents also seen in the peralkaline rhyolites. This question is only likely to be resolved with petrogenetic isotope study (Nd, Sr, possibly Pb).

5 Dating of the minor intrusions

Five samples of the minor intrusions have been submitted to the National Isotope Geoscience Laboratories (NIGL) for U-Pb dating of zircons under the BGS-NIGL programme. One sample of peralkaline rhyolite from Cnoc an Droighinn proved not to contain a sufficient quantity of zircon for dating. Two samples of the Nordmarkite Swarm, one from the Allt na Cailliche sill (KG41) and one from the Cnoc Chaornaidh sill (KG49), will be dated. These dates will be extremely useful as they may provide an important time marker for thrusting. Dating of samples from the Canisp Porphyry (sample KG23, from Beinn Garbh) and the Hornblende Microdiorite Swarm (KG45, from Cnoc an Droighinn) should constrain the onset of thrusting.

6 Summary and Conclusions

The minor intrusions of the Assynt area can be divided into seven main swarms, of which one (the Ledmorite Swarm) has not been discussed here. The three most widespread of these are the Vogesite Swarm, the Hornblende Microdiorite Swarm, and the Peralkaline Rhyolite Swarm. Examples of these three swarms occur throughout the Assynt Culmination between the Moine Thrust and the Sole Thrust, but are not seen in the Foreland or to the east of the Moine Thrust. Field relationships show that all three swarms were intruded prior to movement on the thrusts in the Moine Thrust Belt, and also that the peralkaline rhyolites are younger than the hornblende microdiorites.

The other three swarms have more restricted areas of outcrop. The Canisp Porphyry forms major sills and rare dykes in the Foreland, but is not seen within the Moine Thrust Belt. Sills and dykes of the Porphyritic Trachyte Swarm are most commonly seen close to the Ben More Thrust and at some localities appear to cut foliations that are considered to be related to thrusting, raising the possibility that these intrusions may have formed at a later stage, during or after movement on the thrusts in the Moine Thrust Belt. Finally, sills of the Nordmarkite Swarm are seen on both sides of the Moine Thrust and appear to be localised along it. These rocks are heavily deformed and in places mylonitised, indicating that they were emplaced following the first movement on the Moine Thrust but prior to the last ductile movements.

The Assynt minor intrusions show a range in their geochemistry from the most mafic rocks (vogesites) through dioritic rocks to trachytes and rhyolites. Some of the rhyolites are just peralkaline, but the majority of the minor intrusions are calc-alkaline in nature. The majority can be related by fractionation of a parent equivalent to the most primitive vogesites, although production of the peralkaline rhyolites would require the introduction of a peralkaline fluid (Young, 1989). The porphyritic trachytes are enriched in alkalis in comparison with the other minor intrusions. Taken together with the field relationships, this indicates that they may represent a separate pulse of magmatism, possibly related to the later syenites at Loch Borralan.

The trace element patterns for all the minor intrusions show the characteristics of magmas derived from a subduction-influenced source, such as high Ba and Sr and low Nb contents. It is considered that the parental magmas for the Assynt minor intrusions were shoshonitic, as suggested by Thompson and Fowler (1986) for the syenite magmas.

Appendix 1 Geochemical data

Major elements wt%	Quartz-micro syenite **KG 33 (N4144)**	Quartz-micro syenite **KG 34 (N4145)**	Quartz-micro syenite **KG 36 (N4147)**	Quartz-micro syenite **KG 46 (N4157)**	Porphyritic trachyte **KG10 (N3253)**	Peralkaline rhyolite **KG40 (N4151)**	Peralkaline rhyolite **KG43 (N4154)**	Porphyritic trachyte **KG67 (N4721)**	Porphyritic trachyte **KG71 (N4725)**
SiO_2	63.73	56.62	59.92	64.61	64.78	75.79	72.69	65.46	62.58
TiO_2	0.40	0.76	0.63	0.32	0.13	0.07	0.07	0.07	0.26
Al_2O_3	15.33	15.89	14.46	15.71	19.15	13.20	13.62	18.85	20.01
$Fe_2O_{3\ t}$	3.58	7.04	7.63	3.37	2.15	0.62	1.63	1.28	2.35
MnO	0.08	0.14	0.07	0.08	<0.01	<0.01	0.01	0.02	0.07
MgO	1.98	3.98	2.81	1.80	0.08	0.09	0.36	0.11	0.19
CaO	3.31	6.01	2.72	2.38	0.03	<0.01	0.49	0.17	0.90
Na_2O	6.50	4.44	4.36	5.63	7.44	4.64	0.32	7.19	6.27
K_2O	1.68	2.25	2.20	2.21	5.22	4.23	7.07	5.45	5.91
P_2O_5	0.19	0.33	0.31	0.15	0.01	<0.01	0.01	<0.01	0.02
LOI	2.46	1.81	4.18	2.87	0.62	0.53	3.18	0.70	0.73
Total	99.24	99.27	99.29	99.13	99.61	99.17	99.45	99.30	99.29
Trace elements ppm									
Y	11	16	18	8	17	13	34	6	23
Nb	7	8	13	7	31	32	37	47	37
Sr	958	1295	743	567	132	45	266	297	505
Rb	39	48	63	36	93	39	85	132	112
Zr	133	173	199	128	438	321	334	596	663
Ni	19	32	20	23	<1	<1	<1	<1	<1
Ba	1210	864	782	1113	246	273	546	373	540

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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