A review of the Caledonian igneous rocks of the Assynt area

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Front cover

Complex cross-cutting relationships in the Loch Ailsh syenites, Glen Oykel. BGS photograph P506429.

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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.

Contents

Summary

This report describes the geology of the Caledonian igneous rocks on the Assynt Special Sheet. A review of literature is followed by a summary of preliminary field observations during 2001 and recommendations for further work.

1 Introduction and review of literature

The current state of knowledge about the Caledonian igneous rocks of Assynt has been reviewed in full by Parsons (1999) and is summarised briefly here. The Caledonian igneous rocks in Assynt include two alkaline plutonic complexes, the Loch Ailsh and Loch Borralan Complexes, together with a suite of associated minor intrusions, some of which are also of alkaline affinity.

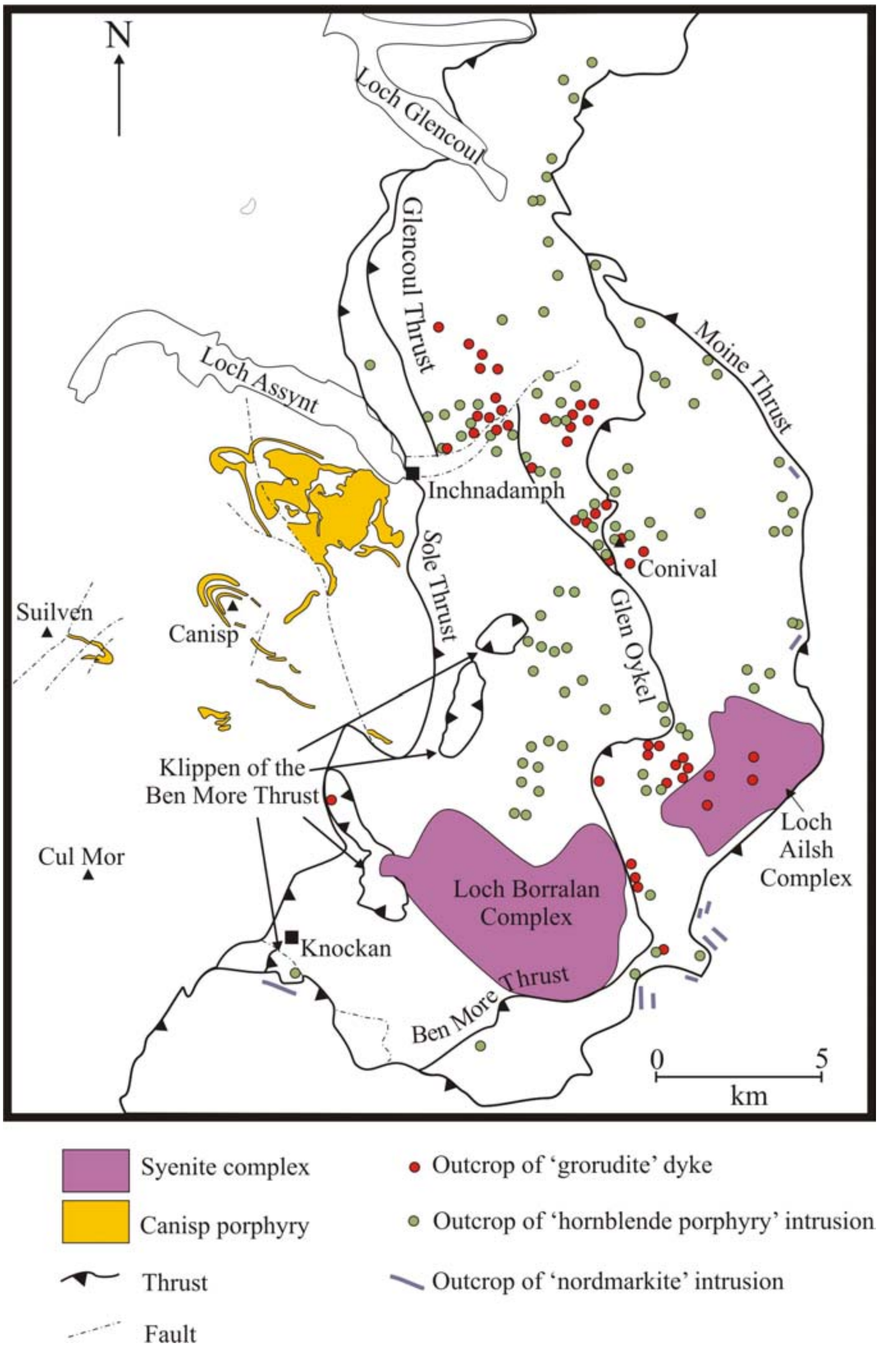

Figure 1: Sketch map of the Assynt area, showing most of the main igneous intrusions and the location of the main thrusts in the Moine Thrust Zone. The 'vogesite' sills are not included, since they have not been mapped in detail. Locations of igneous rocks from Sabine (1953) and Parsons (1999). Thrust patterns based on Peach *et al.* (1907), with modifications after Coward (1983).

EARLY WORK

The igneous rocks of Assynt were recognised during Geological Survey mapping at the end of the 19th century (Peach *et al.,* 1907), and around that time many of the unusual rocks such as borolanite were named. The existence of the Loch Ailsh and Loch Borralan syenite complexes was noted, along with the location of many minor intrusives of varying compositions. However, the six-inch Assynt Special Sheet (Geological Survey, 1965) shows the igneous rocks simply as granites and felsites. In the early part of the 20th century, these intrusions were studied in further detail by many eminent igneous petrologists (Heddle, 1883a,b; Teall, 1900; Shand, 1910, 1939).

Peach *et al.* (1907) had noted that the igneous rocks of the Assynt area appeared to pre-date all the thrust movements. This interpretation was first queried by Bailey & McCallien (1934), who noted undeformed pegmatites cutting apparently deformed syenites belonging to the Loch Borralan Complex, and suggested that the emplacement of the igneous rocks may have overlapped temporally with movement on the thrusts. This was confirmed in an important paper by Sabine (1953) in which the minor intrusions were separated into six main classes. Sabine showed that these minor intrusions were generally restricted to the area west of the Moine Thrust, but had been metamorphosed, and he concluded that their emplacement must have been roughly synchronous with thrusting. He also echoed earlier workers (Phemister, 1926; Bailey, 1935) in suggesting that the intrusion of the igneous rocks may have led to the doming of the Moine Thrust Plane, forming the Assynt culmination. More recently, Elliott & Johnson (1980) have supported this theory, noting that the intrusions and their metamorphic aureoles may have increased the competence of the glide horizons in the Cambro-Ordovician sedimentary rocks, triggering an increase in the amount of rough slip and doming.

LOCH BORRALAN COMPLEX

Most recent work on the Assynt igneous rocks has centred on the plutonic complexes. The Loch Borralan Complex was described in detail by Woolley (1970, 1973) who divided it into an earlier, silica-undersaturated ‘suite’, and a later, silica-saturated or oversaturated ‘suite’, separated by an sharp, typically irregular intrusive junction. The earlier ‘suite’ consists largely of nepheline-syenites and pseudo-leucite-syenites, together with ultramafic pyroxenites, which crop out in the poorly exposed ground southwest of the A837 road. This part of the Complex is of particular interest because it contains some of the most potassic rocks found anywhere in the world. The later ‘suite’, which is made up of quartz-syenites and feldspathic ‘perthosites’(alkali feldspar-syenites), is exposed on the higher ground around Cnoc na Sroine, and in the Allt a’Mhuilinn in the southeastern part of the complex. Woolley (1970) suggested that the early ‘suite’ has a sheet-like form, whilst the later ‘suite’ forms a plug which has punched through the earlier rocks.

The poor exposure in the Loch Borralan Complex, particularly in the earlier ‘suite’, has meant that much of the recent work is based around drilling and geophysical surveys. Matthews & Woolley (1977) recognised a magnetic anomaly between Lochs Borralan and Urigill, which was shown to be due to the presence of ultramafic rocks, forming a roughly vertical screen. These rocks were originally believed to have been formed through metasomatic processes near to the contact of the intrusive rocks with limestone country rock, but subsequent drilling (Parsons & McKirdy, 1983) has shown that the ultramafic rocks are intrusive. Parsons & McKirdy also showed that the rocks of the Loch Borralan Complex cut across the Ben More Thrust near Cam Loch, and hence concluded that the Loch Borralan igneous activity must have post-dated movement on that thrust. The Loch Borralan Complex has been dated using U-Pb methods by van Breemen *et al.* (1979) who showed that the whole sequence of intrusion occurred within the interval 430 ± 4 Ma.

Most of the recent drilling in the Loch Borralan area has been aimed at studying the economic potential of the complex. Notholt *et al.* (1985) investigated the ultramafic rocks as a potential source of phosphate (apatite) rock and showed that the intrusion contains the most significant resource of phosphate so far found in the UK. Recent drilling by the BGS Mineral Resources Programme has been aimed at studying the concentration of Platinum Group elements in the complex (P. Henney*,* pers. comm.).

It has become clear over the last twenty years or so that further drilling and excavation of the Loch Borralan Complex is necessary to fully understand the relationships between magma emplacement and the tectonic history of the area, and to elucidate the economic potential of this site. This is underlined by two recent developments in our knowledge of the Loch Borralan area. Young *et al.* (1994) described the discovery of a carbonatite, hitherto unknown, on the shores of Loch Urigill. Excavation has revealed part of this unusual igneous body, although the full extent is not known. Carbonatite is only known from one other possible location in Britain (Garson *et al.,* 1984) and so this discovery is highly significant. A second feature of interest is the relatively recently excavated quarry near Ledbeg, which provides excellent exposures of undersaturated syenites ('borolanites') cutting Cambrian country rocks (Parsons, 1999). These exposures have not been described in detail.

LOCH AILSH COMPLEX

The Loch Ailsh Complex, which crops out to the north of Loch Ailsh and is dissected by Glen Oykel, has been described in detail by Parsons (1965a,b, 1968). It is somewhat better exposed than the Loch Borralan Complex, but does not contain the same diversity of rock-types. The Loch Ailsh Complex is largely composed of syenites, including some which are so alkali-feldspar rich as to be termed 'perthosites'. Ultramafic rocks, including pyroxenites, form a roughly vertical screen in the southern part of the complex (Parsons, 1965a). This mode of occurrence is similar to that of the ultramafic rocks within the Loch Borralan Complex.

The Loch Ailsh Complex lies within the Ben More Thrust sheet, immediately underneath the Moine Thrust (Figure 1). Its temporal relationship to movement on these thrusts has been the subject of much controversy. Milne (1978) suggested that the Loch Ailsh Complex post-dated the earliest phase of deformation in the area (the Sgonnan Mór folding). However, this interpretation has been challenged by Butler (1997) who showed that the Sgonnan Mór folds may represent reactivated Precambrian structures, and that the Loch Ailsh Complex appears to pre-date all thrust-related deformation in this area. This conclusion is supported by the fact that syenites of the Loch Ailsh Complex are cut by a member of the 'grorudite' (peralkaline rhyolite) suite (Figure 2). This suite of minor intrusions only appears to occur in the Ben More and Glencoul Thrust sheets (Sabine, 1953), and so is considered to pre-date movement on the Ben More Thrust. Hence the Loch Ailsh Complex must also pre-date movement on this thrust. Halliday *et al.* (1987) have dated the Loch Ailsh syenites using the U-Pb technique and obtained a date of 439 ± 4 Ma, showing that movement on the Ben More Thrust occurred after this date.

The Loch Ailsh Complex is deformed close to the Moine Thrust, and the igneous rocks appear to pass under the thrust plane. However, it is not clear from the field relationships whether the igneous rocks were emplaced prior to any movement on the Moine Thrust, and subsequently truncated and deformed by thrusting; or whether they were emplaced following major movements on the Moine Thrust, which then acted as a roof, with late movements on the thrust deforming the igneous rocks.

MINOR INTRUSIONS

The alkaline minor intrusions of Assynt were first studied in detail by Sabine (1953) who divided them into six classes: ‘grorudite’(peralkaline rhyolite); ‘Canisp porphyry’ (porphyritic quartz-microsyenite); ‘hornblende porphyry’ (hornblende microdiorite); ‘nordmarkite porphyry’ (quartz-syenite); vogesite; and ‘ledmorite’ (melanite-augite nepheline-syenite). The old names are used below, to conform with the literature. 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. One of the most important features of the different classes of minor intrusions is their well-constrained temporal relationship to the thrusting in the area, as set out in the table below.

Intrusion class	**Structural constraint**	**Age interpretation**	**Reference**
Canisp Porphyry	Only seen W of Sole Thrust	Pre-date movement on Sole Thrust	Sabine (1953)
Vogesite	Seen in Sole, Glencoul and Ben More Thrust sheets, but not in Foreland or Moine Thrust sheet.	Pre-date all thrusting (except possibly early movements on Moine Thrust)	Sabine (1953)
	Imbricated by thrusts above Sole Thrust	Pre-date movements on the Sole Thrust system	2001 fieldwork
	One sample hornfelsed by Loch Ailsh intrusion	Older than the Loch Ailsh intrusion	Young (1989)
Hornblende porphyry	Seen in Sole, Glencoul and Ben More Thrust sheets, but not in Foreland or Moine Thrust sheet.	Pre-date all thrusting (except possibly early movements on Moine Thrust)	Sabine (1953)
	Highly sheared near Moine Thrust	Pre-date last movement on Moine Thrust	Sabine (1953); 2001 fieldwork
Grorudite	Only found in the Glencoul and Ben More Thrust sheets	Pre-date Glencoul and Ben More Thrusts	Sabine (1953)
	Cut Loch Ailsh intrusion	Younger than Loch Ailsh Complex (439 ± 4 Ma)	Parsons (1999)
	Loch Borralan complex cuts Ben More Thrust	Grorudites pre-date Loch Borralan Complex (430 ± 4 Ma)	Parsons & McKirdy (1983)
	May cut shear zones in Glencoul Thrust sheet?	Post-date some deformation	2001 fieldwork
Porphyritic Trachyte	Only found in the Glencoul and Ben More Thrust sheets	Pre-date Glencoul and Ben More Thrusts	Young (1989)
Nordmarkite	Found close to, and on both sides of, the Moine Thrust	Post-date main movement on the Moine Thrust	Sabine (1953)
	Show some metamorphism and deformation	Affected by later movements on the Moine Thrust	Sabine (1953)
Ledmorite	Occur in the Loch Borralan Complex and also as dykes in the foreland	Suggest that the intrusion of all the ledmorites post-dated movement on the Sole Thrust	Halliday *et al.*(1987)

Table 1: Relationships between the minor intrusions and thrusting in the Assynt District.

Figure 2: ‘Grorudite’ dyke cutting Loch Ailsh syenites in Glen Oykel. This is a key locality for understanding structural relationships in Assynt. BGS photograph P506430.

GEOCHEMISTRY AND DATING

Modern geochemical and dating techniques have been applied to the igneous rocks of Assynt, producing a certain amount of data, the interpretation of much of which is still rather equivocal. U-Pb zircon dates have been obtained for the Loch Borralan (430 ± 4 Ma; van Breemen *et al.,* 1979) and Loch Ailsh (439 ± 4 Ma; Halliday *et al.,* 1987) Complexes, but the minor intrusions have never been dated. As discussed above, the dates have been interpreted to show that movement on the Ben More Thrust occurred between 426 and 443 Ma, but they do not fully constrain the times of movements on the other thrusts. Freeman *et al.* (1998) have recently dated Moine mylonites, using Rb-Sr techniques, and have suggested that movement on the Moine Thrust ceased at 430 Ma. It would appear, on this basis, that the Loch Ailsh Complex entirely pre-dates thrusting.

The geochemistry of the plutonic rocks has been studied by Thompson & Fowler (1986); Halliday *et al.* (1987); and Thirlwall & Burnard (1990). These authors agreed that the syenitic magmas must have been derived by fractional crystallisation of mantle-derived parental magmas, but varying theories have been put forward as to where in the mantle those magmas originated. Thompson & Fowler (1986) noted that aspects of the syenite geochemistry, such as La/Nb ratios, are similar to those of subduction-related magmas, and postulated that the parental magmas were shoshonitic. Shoshonitic rocks are generally found above the deepest parts of subduction zones, and tend to characterise the transitional stages between active subduction and other tectonic regimes. Thompson & Fowler suggested that the source for these shoshonitic magmas was asthenospheric mantle which had been modified by the introduction of melted subducted material, but Halliday *et al.* (1987) noted that the magmatism is confined to a narrow zone and preferred to invoke a lithospheric mantle source. Thirlwall & Burnard (1990) used Nd isotope data to show that the Loch Borralan magmas could not have been generated in the ancient, sub-Lewisian lithospheric mantle, but concluded that more work would be required to fully characterise the mantle sources of the alkaline magmas of the northwest Highlands.

The chemistry of the minor intrusions has been studied by Young (1989). He showed that the minor intrusions have similar trace-element chemistries to the larger syenite Complexes, with low Nb and elevated K, Ba and Sr contents. He suggested that the lamprophyres represented parental magmas derived from a subduction-modified lithospheric mantle source, and that the more evolved minor intrusions formed by fractional crystallisation of lamprophyric magmas. However, isotope ratios are required to draw further conclusions about the sources of the minor intrusions.

2 Review of preliminary fieldwork, 2001

During preliminary field visits in 2001, the Loch Ailsh Complex and a variety of the minor intrusions were studied and some samples were collected.

LOCH AILSH SYENITES

Classic outcrops of the Loch Ailsh syenites were studied in the River Oykel at NC 3260 1274, NC 3272 1319, and NC 3269 1365. These localities are well described in the Excursion Guide to the Assynt area (Johnson and Parsons, 1979) and in the Caledonian Igneous Rocks GCR volume (Parsons, 1999). The Loch Ailsh syenites have been mapped in detail, and their geochemical and geophysical characteristics have also been studied. Remapping of the complex is not necessary, but it might be useful to investigate the deformation of the syenites – in particular in areas close to the Moine Thrust – and to collect oriented samples for detailed petrography.

MINOR INTRUSIONS

Examples of most of the main classes of minor intrusions were examined during the field visits.

Two vogesite sills were studied cutting the limestones immediately above the Sole Thrust in the Loch Assynt road section. Sill contacts are sheared and at NC 2402 2391 an offshoot from the sill is imbricated on a small scale, indicating that intrusion of the vogesites predated thrusting in the Sole Thrust Sheet.

Sills of hornblende microdiorite (‘hornblende porphyry’) were seen cutting quartzite on the ridge northwest of the Stack of Glencoul. These rocks are pale coloured, fine-medium-grained, with phenocrysts of feldspar and hornblende. A sill at NC 2853 2898 only shows shearing near the contact, whereas a second sill at NC 2862 2904 is pervasively deformed and folded. Both sills exhibit evidence of alteration in thin section, but the latter sill also shows some evidence of brittle deformation. Further sill exposures in the quartzites higher on the ridge may indicate repetition of the rock succession through imbrication. It appears that the hornblende microdiorites predate all thrusting in the area, since they are seen close to the Moine Thrust, where they are deformed, but are not seen to the east of it (Sabine, 1953). Further hornblende diorites, again showing repetition due to thrusting, cut the limestones of the Sole Thrust Sheet in Gleann Dubh near Inchnadamph.

On the slopes of Conival, around the Allt a’Choinne Mhill, abundant brick-red intrusive sheets are exposed within the quartzites of the Glencoul Thrust Sheet. These sills in places show evidence of shearing (e.g. NC 3000 2100). All those from which samples were collected are ‘porphyritic trachytes’ as described by Young (1989), with a flow texture defined by feldspar phenocrysts. At NC 2998 2094 a similar sill, which was not sampled, appears to cut across a shear zone in the quartzites, although there is also some evidence of movement along the sill contact. These sills therefore may post-date some of the deformation in the thrust zone. However, they are believed to be restricted to the Ben More and Glencoul thrust sheets and therefore are unlikely to post-date all the thrust movement. An outcrop of a true ‘grorudite’ as sampled by Young was studied at NC 3269 1365, where it cuts the Loch Ailsh syenites (Figure 2), showing that this suite is younger than 439 ± 4 Ma. More detailed mapping of the structural relationships of the porphyritic trachytes and 'grorudites' is required.

To the east of Knockan Crag, around NC 1957 0961, are abundant outcrops of irregular, lenticular, fine- to medium-grained, purplish red, closely jointed sills cutting Durness limestones in the Sole Thrust sheet. They were recognised as lenses of 'sheared felsite' by the original mappers, and cursorily mapped by Coward (1983) as a sill in limestone displaced by a couple of normal faults. A quick investigation of the well-exposed area showed that there are numerous lenses of 'felsite', which probably represent more than one irregular igneous sheet. The 'felsites' are sheared in some of the outcrops, but in places appear to cut across some structures in the limestones. There is no evidence for them continuing across the Moine Thrust and so they may be truncated by this structure. Alternatively they may have been preferentially intruded into the imbricated limestone succession. These 'felsites' were not discussed by Sabine (1953) or Young (1989) and do not appear to fit in easily with the previously identified groups of minor intrusions. In thin section, a sample from this location has the appearance of an altered 'grorudite'. If the intrusions here are 'grorudites', they are the first to be recognised below the Ben More Thrust, and this may have implications for the structural chronology. It is also possible that they are related to the Loch Borrolan Complex, and if so they may be useful in further relating the existing age data to the known structures. This area would certainly repay further mapping.

The thick 'nordmarkite' sill shown on the original map (Geological Survey, 1965) just to the south of the Uamh Mhor klippe near Knockan is not easily recognisable in the field. In the large burn at ~ NC 212 089 there is no coherent exposure of the sill, although ~ 50 cm thick veins of very coarse-grained pink syenite, associated with sheared quartz veins, are present. The syenite veins are sub-parallel to the mylonitic banding but locally show virtually undeformed igneous textures, implying that they post-date the mylonitisation. Scattered small outcrops of more typical undeformed 'nordmarkite', with pink feldspar phenocrysts in a dark matrix, occur between NC 2097 0915 and NC 2088 0916. These rocks are also associated with the pink coarse-grained syenitic material, and appear to intrude the Moine mylonites.

A fine-grained, red 'ledmorite' dyke was seen cutting Lewisian gneisses at Achmelvich. This dyke is described by Sabine (1952) and Parsons (1999) . It would be interesting to see if it is possible to follow this dyke to the SE – e.g. if it has a distinctive geophysical signature – to see if it could be linked back to the Loch Borralan Complex.

3 Recommendations for further work

There are three main areas of uncertainty relating to the Assynt igneous rocks. These are:
1) what is the temporal relationship between magmatism and thrusting?;
2) what are the sources of the magmas?
3) how were the magmas emplaced into a collisional zone?
More detailed questions within these three areas are discussed below.

WHAT IS THE TEMPORAL RELATIONSHIP BETWEEN MAGMATISM AND THRUSTING?

Much of the area underlain by igneous rocks in Assynt is poorly exposed, and so it is difficult to assess the relationships between the major igneous complexes and tectonic structures on the basis of field study.

a) The Loch Borralan Complex appears to cut rocks of the Ben More Thrust sheet (Parsons & McKirdy, 1983), but its relationship to the Sole Thrust is uncertain. It approaches fairly close to the Sole Thrust near Ledbeg, but the area is poorly exposed. Sabine (1953) described nepheline-syenite ('ledmorite') dykes in the foreland which appear to be directly aligned with the Loch Borralan Complex, and cited this as evidence that the Loch Borralan complex could not have been moved a significant distance on the Sole Thrust (supported by Halliday *et al.,* 1987). However, Coward (1985) identified minor thrusts (the Chaornaidh and Ledbeg thrusts) which had carried contact-metamorphosed limestones over unmetamorphosed Cambrian rocks. On this basis, he noted that these thrusts (and also the Sole Thrust) must post-date intrusion of the Loch Borralan Complex, and he suggested that the Loch Borralan Complex was moved approximately 30 km on the Sole Thrust. The area between Loch Borralan and the Sole Thrust requires detailed study in order to confirm Coward's work and assess whether movement on the Sole Thrust did indeed continue after 430 Ma.

b) Bailey & McCallien (1934) noted the presence of undeformed pegmatites cutting pseudoleucite-syenite ('borolanite') in which the pseudoleucite crystals have been flattened, in a quarry in the eastern part of the Loch Borralan Complex. Woolley (1973) suggested that this deformation was due to movements on the Ben More Thrust after the 'borolanites' had been emplaced, thus implying that the intrusion of the Loch Borrolan Complex overlapped temporally with movement on the Ben More Thrust. However, Elliott and Johnson (1980) have argued that the flattening is an igneous lamination. This locality requires careful mapping and petrographic study, in order to assess whether or not the Ben More Thrust could have moved after the emplacement of part of the Loch Borralan intrusion, and hence to constrain the time of movement on the thrust.

c) Both the Loch Ailsh and Loch Borralan Complexes appear to have been deformed by movements on the Moine Thrust Zone (Parsons, 1999), but Coward (1985) states that there is no evidence for late movements on the Moine Thrust in eastern Assynt. The Loch Ailsh Complex may have been intruded prior to the first movement on the Moine Thrust, but this is highly unlikely for the Loch Borralan Complex. More detailed study of the fabrics in the two Complexes, possibly including further drilling and/or excavation, should help us to elucidate the nature of movement along the Moine Thrust after the igneous rocks were intruded.

d) The temporal relationships between thrusting and emplacement of the minor intrusions can be well constrained. Detailed mapping and petrographical study of these relationships will be very important in the development of a structural chronology. Dating of the minor intrusions will be of importance in constraining further the timing of thrust movements; in particular, they should provide a maximum age for the onset of thrusting in the area.

e) Rocks of the Loch Borralan Complex appear to cut quartzites of the Cam Loch Klippe, confirming that this Complex was emplaced following movement on the Ben More Thrust. However, further work is needed to confirm that the country rocks investigated by Parsons & McKirdy (1983) do indeed belong to the Cam Loch Klippe, and that it is a klippe of the Ben More Thrust sheet. Sabine (1953) noted that the presence of a 'grorudite' dyke proved that this klippe must belong to the Ben More Thrust sheet, but Young (1989) was unable to identify a true 'grorudite' dyke in the klippe. Furthermore, sills in the Sole Thrust Sheet near Knockan may be 'grorudites', showing that this class of intrusions is not restricted to the Ben More and Glencoul Thrust sheets.

WHAT WERE THE SOURCES OF THE ALKALINE MAGMAS OF ASSYNT?

a) There are conflicting opinions about the mantle source of these alkaline magmas. The most important diagnostic tool here is isotope data, and so far this has only been published for Loch Borralan. Mike Fowler (pers. comm.) has some new and as yet unpublished data for Loch Ailsh, but the isotope systematics of the minor intrusions (including the Loch Urigill carbonatite) have never been studied. There is as yet no consensus on whether or not the igneous rocks are all derived from the same source; and if they are, whether that source is lithospheric or asthenospheric mantle. The possibility that the source region of the magmas may have covered a much wider area than the area in which we now see intrusive rocks has not been considered in detail. A particularly interesting question is whether or not the 445 Ma Batbjerg alkaline complex of East Greenland is related to the Assynt intrusions (Brooks *et al.* 1981). If it is indeed part of the same igneous suite, then these alkaline magmas were intruded over a considerably wider area than previously supposed.

b) The source of the ultramafic rocks at Loch Ailsh and Loch Borralan is still uncertain. These rocks are being studied by the BGS at present (Henney *et al.* in press). They are no longer believed to be of metasomatic origin, and Thirlwall & Burnard (1990) suggest that those at Loch Borralan may have formed through accumulation of augite, apatite and magnetite from a crystallising magma. However, the manner in which these cumulates were then emplaced as a near-vertical sheet is still under question.

HOW WERE THE ASSYNT ALKALINE ROCKS EMPLACED INTO A ZONE OF COLLISIONAL TECTONICS?

Whilst various workers have studied the possible sources of the alkaline magmas at Assynt, and their relationships to the thrust tectonics which have shaped the area, the question of how alkaline magmas were ever emplaced into a zone of compression has largely been avoided. Alkaline magmas of this type are typically intruded into areas undergoing extension, such as the present-day East African Rift or the Permo-Carboniferous igneous province of central Scotland and northern England. There are few known locations elsewhere in the world where alkaline igneous rocks have been introduced during thrusting; they are more common in post-collisional settings, the most well-known being the Roman Province of Italy (Beccaluva *et al.,* 1991).

Van Breemen *et al.* (1979) considered the problem in Assynt and suggested that continental rifting had occurred due to crustal arching, in response to compressional forces on a continental scale, and that this allowed the generation of alkaline melts in the mantle. More recent work such as that of Thirlwall & Burnard (1990) has suggested that melting of the mantle was triggered by deep subduction, but a mechanism for emplacement of mantle melts into relatively high levels in the crust under a compressional regime has not been considered. Coward (1985) has described extensional structures in Assynt which are believed to have formed during extensional collapse of the thrust wedge as it moved forward onto the weaker sediments of the foreland, and it is possible that the Loch Borralan Complex could have been emplaced in such a setting. More detailed structural mapping will be required in order to answer this question.

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