The Caledonides of the British Isles—reviewed. 1979. Geological Society of London.

Caledonian minor intrusions of the N Highlands of Scotland

D. I. Smith

SUMMARY: Three major suites of minor intrusions cut the Caledonian rocks north of the Great Glen fault. (1) *The amphibolite suite* was intruded between D_1 and D_2 deformations as a swarm of dolerites (locally gabbroic) trending sub-parallel to the fold belt. (2) *The microdiorite suite*, consisting of a wide variety of rock types, was emplaced during the closing phases of Caledonian tectonism principally in the southern part of the area. Early members were locally involved in the final phase of folding and metamorphism. The majority, however, occur as sheared sheets occupying easterly dipping planes which transgress all the Caledonian fold structures. These sheared intrusions exhibit a variety of internal fabrics, the geometry of which indicates that they were recrystallised under an ESE, subhorizontal maximum stress. Over most of the N Highlands, the recrystallised mineral assemblages belong to the greenschist facies metamorphism, but in the south an area of amphibolite facies has been defined. This is believed to reflect a residual Caledonian temperature gradient. (3) *The minette suite*, centred on the Ratagain granite is a post tectonic dyke swarm which marks the end of igneous activity in the N Highlands Caledonides. Members of the swarm are widely dispersed throughout the Moine and are also present in the foreland rocks west of the Moine thrust. Variations in K–Ar ages from these dykes may relate to differential uplift or to the continuing presence of a local Caledonian thermal high.

The area considered lies between the Moine thrust and the Great Glen fault. In the south-western part of the region the Caledonian minor intrusions are particularly well developed and the igneous sequence has been firmly established by cross–cutting relationships in the field. No intrusions cut the Old Red Sandstone cover and the basal conglomerates, which are at least partly of lower Old Red Sandstone age, are rich in fragments derived from the Caledonian intrusives.

The minor intrusions are mainly parallel–sided dykes and sheets, or well delineated small bosses. Pegmatite veins, regional networks (vein complexes) of granitic rocks, and migmatitic complexes are not considered here except where they provide age relationships between certain of the older suites described. The post Cambrian alkaline minor intrusions of Assynt are also excluded (Parsons this volume).

Whereas south of the Great Glen fault dense swarms of dykes are known to be related to several of the major granitic complexes (Wright & Bowes this volume), the minor intrusions in the N Highlands are poorly known and were generally thought to be sparse, but west and northwest of Fort William large numbers have been mapped by the I.G.S. This account demonstrates how the igneous rocks relate spatially and temporally to the Caledonian metamorphism and deformation and in particular how they can be used as an aid to the understanding of the late tectonic and thermal history of the Caledonides of northern Scotland.

The sequence of minor intrusions and their

TABLE 1: *Relative ages of major and minor intrusions in SW Inverness–shire*

BASAL OLD RED SANDSTONE		
	MINOR INTRUSIONS	MAJOR INTRUSIONS
POST-TECTONIC	MINETTE SUITE	RATAGAIN
POST- TO LATE-TECTONIC	Felsic porphyrite-MICRODIORITE-Appinite suite	ROSS OF MULL STRONTIAN
	Early felsic porphyrite suite of Cluanie	CLUANIE
	LATE CALEDONIAN PEGMATITE SUITE	
SYN- TO PRE-TECTONIC	AMPHIBOLITE SUITE	

ages relative to the major granitic intrusions is given in Table 1. Most of the intrusions shown, both major and minor, have been K–Ar dated but the results are not compatible with the age relations established in the field. It may be that the time span occupied by the complete igneous sequence, apart from the amphibolite suite, was too short to be differentiated by the techniques used. Other factors, however, such as regional lateral variations in country rock temperatures, variable thickness of cover and, or, its rate of removal due to differential uplift, may also have influenced the apparent discrepancies in the ages so far obtained. Provisionally, the minor intrusions can be divided, as in Table 1, into the post tectonic *minette* suite, the post to late tectonic *microdiorite* suite (preceded by the early felsic porphyrite suite of Cluanie), and the syn to pre-tectonic *amphibolite suite*.

The minette suite

Members of this suite, although not numerous, are widely distributed and have long been recognised throughout the N Highlands from the Ross of Mull in the south to Achmore Point in the

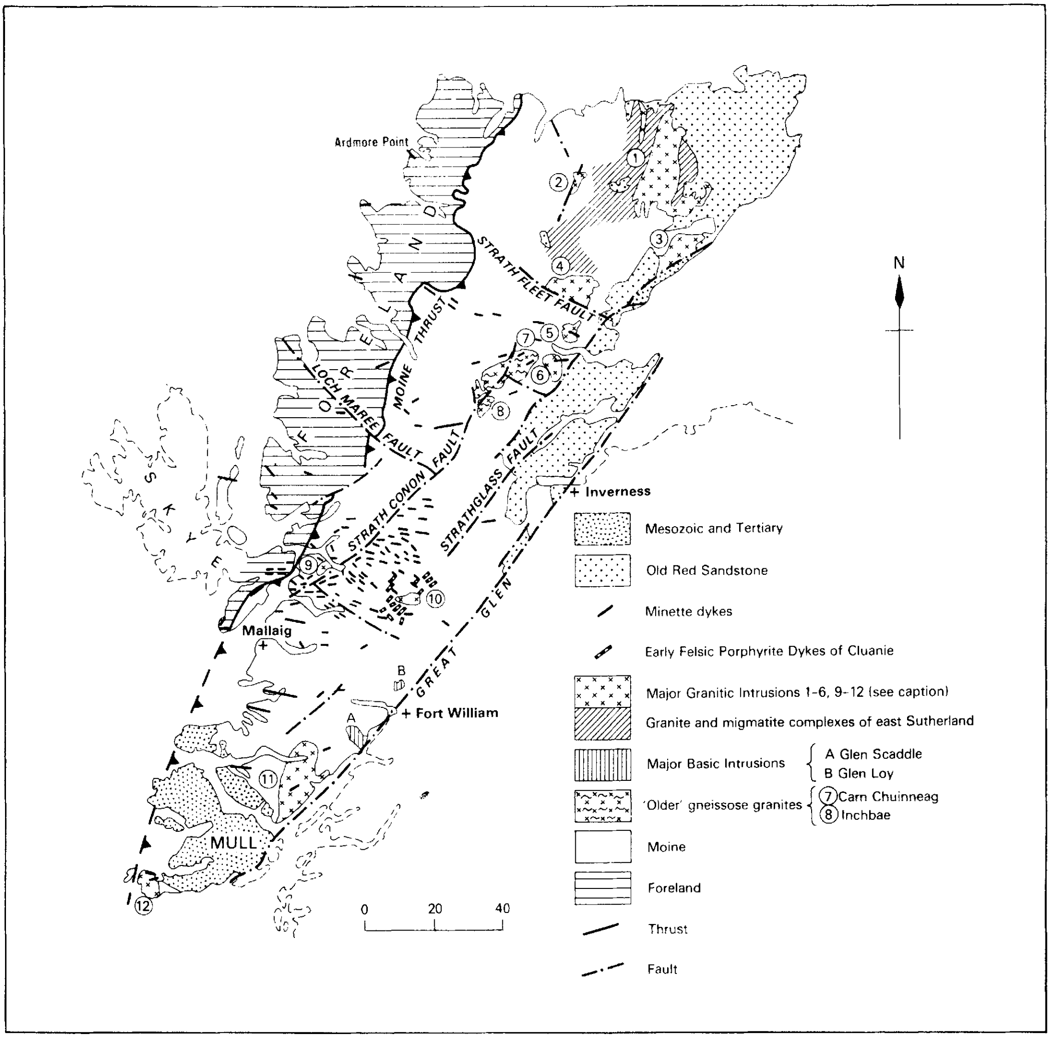

FIG. 1. Distribution of minette dykes and early felsic porphyrite dykes of Cluanie. Granites: 1. Strath Halladale, 2. Strath Naver, 3. Helmsdale, 4. Rogart, 5. Migdale, 6. Fearn, 9. Ratagain, 10. Cluanie, 11. Strontian, 12. Ross of Mull.

north. They have been variously described as 'mica-trap', 'red lamprophyre' or simply 'lamprophyre' and some confusion has existed as to their age and their relationship to minor intrusions of other suites. In respect to age, the minette dykes and related types cut most of the granites and have been found as pebbles in the basal conglomerates of the Old Red Sandstone outlier in Strath Rannoch [NH 380 750] (Peach *et al.* 1912 p.113). Near Loch Garve [NH 400 600] however, two small patches of basal Old Red Sandstone breccia are cut by sills, which although somewhat altered, show certain affinities with the minettes (Horne & Hinxman 1914 p.53). These relationships have been confirmed by the author but since no other examples of minettes cutting Old Red Sandstone strata have been detected, it is suggested that, either the deposition of the Garve basal conglomerates was earlier than elsewhere, or the period of intrusion overlapped the phase of uplift and erosion which also probably varied from place to place. Either or both explanations seems more reasonable than invoking two separate phases of dyke intrusion as some writers have proposed (Soper & Brown 1965).

The second problem concerns the relationship between the minettes and the older microdiorite suite. It arose because members of both suites were encountered in the Carn Chuinneag district, the first area within the northern Highland Caledonides where these intrusions were described in detail (Peach *et al.* 1912). The lamprophyric dykes were thought at that time to belong to a single series divisible into three groups; normal lamprophyres i.e. typical minettes with unmodified igneous minerals and textures; sheared lamprophyres representing altered members of the first group with retrogressed mineral assemblages and marginal fractures and foliation; and lamproschists, thoroughly schistose sheets in which all traces of original igneous character is obliterated.

It is now known that the lamproschists are low grade foliated members of the microdiorite suite and are not derived from the younger unrelated minettes but are cut by them. This is consistent with the observation that lamproschist xenoliths are present in fresh unaltered minettes (Read 1926). The sheared lamprophyres are probably altered and slightly crushed members of the minette suite affected by post Lower Old Red Sandstone movements which locally produced overthrusting towards the northwest (Armstrong 1977).

Characteristically the minettes are vertical, parallel–sided dykes with sharp, chilled edges. They have an average thickness of about 3 m but can often be traced intermittently for several kilometres. They are typically rich in megacrysts of corroded colour–zoned biotite and colourless or pale green clinopyroxene, and more rarely, serpentinised olivine. Pale brown hornblende is also frequently present and where this is the dominant ferromagnesian mineral the dyke may be classed as vogesite. A detailed petrographic description of the dykes is given by Read *et al.* (1926) who drew attention to the fact that they commonly carry inclusions derived from the Lewisian gneiss below the Moine which could provide valuable evidence of the character and composition of the concealed basement.

As can be seen on Fig. 1 the dykes extend westwards across the Moine thrust and cut the Lewisian and Torridonian rocks of the foreland. One example, on Skye occurs as a sill lying in the plane of the thrust. The sheet is somewhat crushed, suggesting that although the thrust existed prior to intrusion it has been subsequently reactivated (Peach *et al.* 1910). This observation does not necessarily invalidate the general impression that the period of dyke emplacement post dated the Caledonian movement on the thrust. The late crushing could be of the same period as the post lower Old Red Sandstone thrusting mentioned above or even movement resulting from the emplacement of the nearby Tertiary igneous centre on Skye. Several other examples of minette dykes following pre–existing fractures and being affected by later movements are known. Faulted lamprophyres with inclusions of crush–rock have been recorded from the Strath Fleet fault (Soper 1963) where there is independent evidence of pre– and post Old Red Sandstone cataclasis. It is interesting to note that this fault marks the northeast edge of the Assynt culmination, while the southwest margin is defined by a local concentration of thick minette dykes, presumably intruded along fissures, which extend almost across the full width of the Moine outcrop. E-W dykes, apparently displaced by the Strath Glass fault, change orientation to a NE trend along a parallel satellite fault and carry inclusions of previously fractured schist (Horne & Hinxman 1914). The most striking example of this use of pre–existing planes of weakness is seen at Ratagain where the minettes can be truly classed as a dyke swarm. Centred on the Ratagain complex and associated with thick dykes of felsite and porphyrite, the minettes cut a zone of indurated breccias and cataclasites related to early movements on the Strathconon

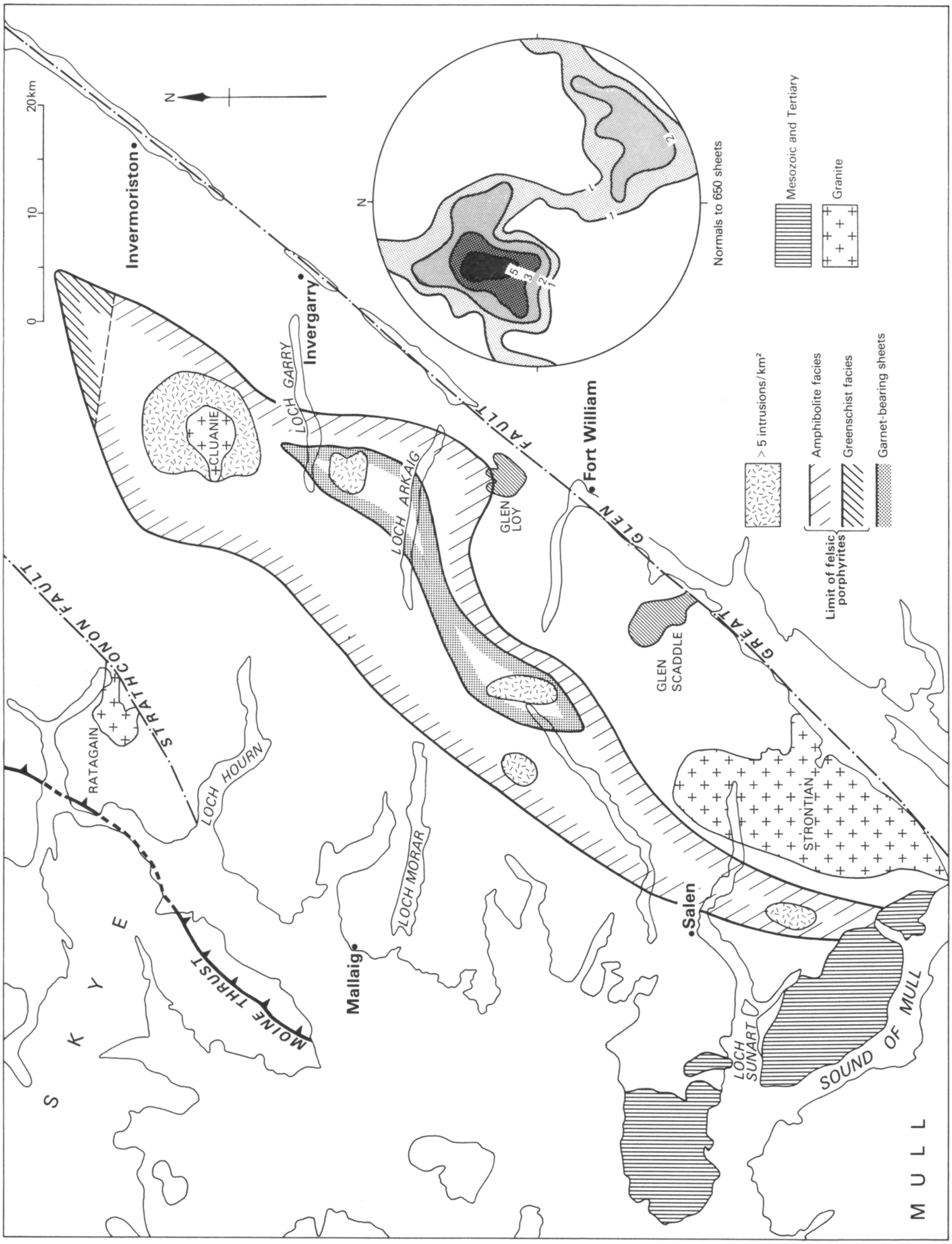

FIG. 2. Distribution, orientation and metamorphic grade of felsic porphyrite intrusions.

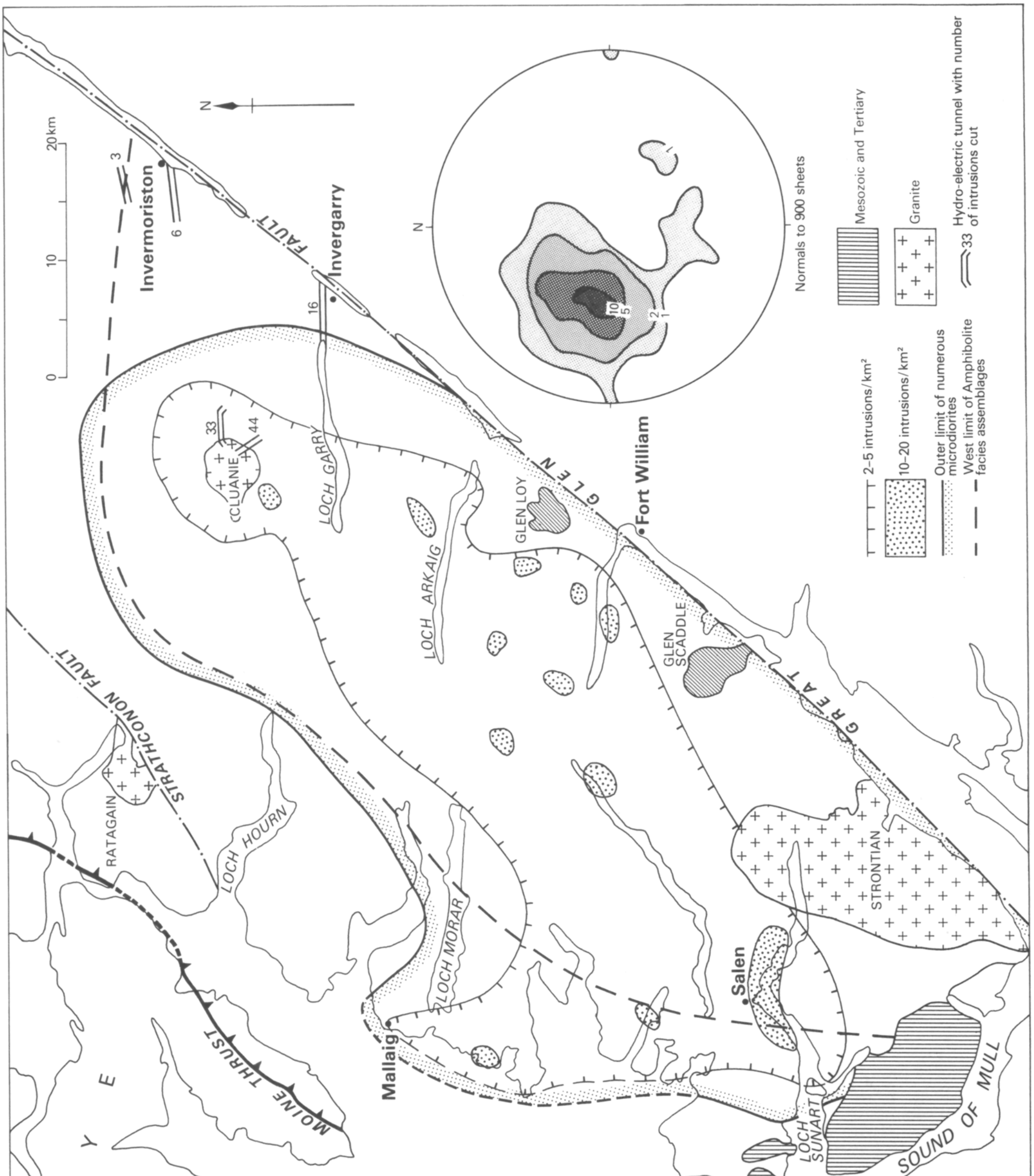

FIG. 3. Distribution, orientation and metamorphic grade of microdiorite intrusions.

fault but the swarm as a whole can be shown to be displaced in a sinistral sense by about 6 km on either side of the fault. In addition, although the general trend of the dyke swarm is NW it is apparent from the map that in the proximity of the fault a number of dykes appear to be guided by pre–intrusion fractures running parallel to the plane of the fault.

The only consistent age relationship shown by the dykes of the Ratagain swarm is that the porphyrites are the youngest members. Several examples of minette cutting felsite and of felsite cutting minette have been recorded and the same relationships appear to exist in the smaller swarm of similar dykes associated with the Ross of Mull granite.

The microdiorite suite

As with the minette suite a nomenclature problem arises with the microdiorite suite, different names and groupings having been used in different places at different times. The term microdiorite suite is used here because in W Inverness–shire and N Argyll (Figs. 2 and 3) where the suite as a whole is best developed, microdiorite is by far the most abundant type. Petrographically the suite consists of a continuous transition from leucocratic felsic porphyrite through quartz microdiorite to microdiorite, and thence through mafic microdiorite to a variable appinitic group consisting mainly of hornblende diorite. The felsic porphyrites have been referred to as 'acid porphyrites' and 'trondhjemite–porphyrite' (Leedal 1952), the microdiorites have been generally classed as lamprophyre, foliated lamprophyre and lamproschist, while appinite in the N Highlands has been employed as a 'sack' name for a suite of coarse grained hornblende–bearing rocks of granitic, dioritic and ultrabasic composition. In the Strontian area, hornblende lamprophyres, often foliated, were recognised as fine-grained members of the 'Appinite Suite' (MacGregor & Kennedy 1932).

In view of the (more correct) previous usage of lamprophyre for the post Caledonian minette and vogesite dykes, and the fact that it has also been used as a general name for much younger Permo–Carboniferous camptonite–monchiquite dykes, it is therefore suggested that microdiorite suite or microdiorite–appinite suite is used for this group of late Caledonian minor intrusions. In general microdiorite equates with lamprophyre as formerly used and foliated microdiorite with foliated lamprophyre and lamproschist.

The age of the microdiorite suite in relation to the major granitic rocks in Table 1 is unequivocal. They freely cut the Cluanie granite but are cut by veins extending from the Strontian complex, as well as occurring as inclusions within the granite. No members of the suite intersect the Ross of Mull granite but several examples of microdiorites cutting the adjacent Moine schists and hornfelsed along with them, are known.

Felsic porphyrite

The only reliable age relationship within the microdiorite suite is that the more acid members, the felsic porphyrites and leucocratic quartz microdiorites, consistently cross–cut the more basic types. Petrographically a majority of the felsic porphyrites are porphyritic microgranodiorites with phenocrysts of complex oscillatory–zoned albite–oligoclase up to 4 mm across. Dark brown biotite occurs as large single crystals or elongate, spindle–shaped aggregates, while hornblende, when present, forms bright green prisms up to 2 mm in length. Biotite and hornblende may both appear in the fine grained granoblastic groundmass but the dominant constituents are quartz, potash feldspar and acid plagioclase in equal proportions of about 30% each.

Fig. 2 is a plot of the distribution of felsic porphyrites prepared from about 650 separate intrusions, few of which are greater than 1 m in thickness. They lie in a fairly narrow zone extending from 20 km northeast of the Cluanie granite southwestwards to disappear below the Mesozoic and Tertiary cover rocks along the Sound of Mull. The intrusions vary in orientation but the stereoplot shows a preferred inclination of 40° towards the southeast. Minor intrusions of this group have not been recorded in the N Highlands outwith the area of Fig. 2 but the thinner sheets superficially weather like a psammite and are notoriously difficult to detect, especially where they are concordant to the dominantly psammitic Moine host rock. Their distribution may therefore be greater than is known at present. The same remark applies to the eastern limit of felsic porphyrites shown on Fig. 2. Isolated sheets are found farther east, almost as far as the Great Glen fault, and both basic intrusions of Glen Loy and Glen Scaddle are cut by members of the swarm. Most of the felsic porphyrites have a recrystallised granoblastic groundmass and exhibit an oblique internal schistosity of aligned biotite and, or, hornblende which wrap around the rotated remnants of zoned plagioclase phenocrysts. 'Spongy' garnets of undoubted metamorphic origin are a common occurrence in the core region of the zone, but northwards from the Cluanie granite, epidote, green mica and carbonate minerals become increasingly more common and a transition to a greenschist facies mineral assemblage appears to take place.

Microdiorite

The relatively small size of the microdiorite intrusions (average thickness about 1 m) together with the large number involved (over 3000) makes their representation in a conventional manner a matter of some difficulty. Fig. 3 has been prepared therefore in spite of the obvious limitations imposed by variation in degree of exposure and quality of mapping extending over a period of fifty years. Microdiorites are present in quantity on the well-exposed coastal sections south of Mallaig and are found eastwards as far as the Great Glen fault. A reliable limit can be drawn outwith which they are virtually absent, except in the west where the boundary must lie offshore. The inner limit of 2–5 intrusions per km^2 is less certain while some of the areas of high concentration, 10–20 intrusions per km^2, are obviously the sites of well-exposed sections. Nevertheless, the general disposition of the boundaries is probably correct. Along the almost continuously exposed north shore of Loch Sunart for example, the number of intrusions per kilometre rises from zero just east of the Tertiary lavas, to a maximum of twenty around Salen, and falls to less than ten at the west edge of the Strontian granite. No intrusions cut the granite, and across the fairly well-exposed section between the east edge of the granite and the Great Glen fault only two microdiorites have been detected. Further support for the general reliability of the map is supplied by the numbers of intrusions encountered in hydro-electric tunnels. The two tunnels on the east and southeast sides of the Cluanie granite cut through 33 and 44 intrusions respectively; the one from Loch Garry to the Great Glen, which crosses the outer limit of numerous intrusions, intersected 16 sheets, while in the two tunnels at Invermoriston, well outside the limit, only 3 and 6 intrusions were found. The concentration of microdiorites in this southwestern part of the N Highlands, as compared with the remainder of the area where a very limited number of 'lamproschists' have been mapped, also receives support from tunnel evidence. In the 65 km of hydro-electric tunnels driven, mainly in central Ross-shire, a mere six examples of microdiorite were recorded.

If the good west coast exposures on Fig. 3 are ignored then the main zone of microdiorites can be seen to roughly coincide with that for the felsic porphyrites, extending from north of the Cluanie granite southwestwards to the north end of the Strontian granite and thence across Loch Sunart before finally passing below the Mesozoic and Tertiary rocks of the Sound of Mull. The microdiorites can be subdivided into three distinct groups.

Igneous microdiorites. Intrusions with original, unmodified, igneous mineral assemblages are most common in the coastal region south of Mallaig but occur intermittently across the full width of the zone eastwards to the Great Glen fault. They consist essentially of subhedral tablets of zoned andesine, and hornblende (both of which may occur as phenocrysts) together with biotite and subordinate interstitial quartz and K feldspar. Many intrusions, especially the thicker and slightly coarser ones, exhibit a mottled appearance due to the segregation of the felsic and mafic constituents which when well developed gives the rock a net-veined appearance.

Metamorphosed microdiorites. In a fairly restricted zone between Loch Arkaig and Loch Garry microdiorite sheets are found which cut the banding in the Moine metasediments and show crenulated margins which are folded along with the adjacent country rock (Lawrie 1961). Internally a strong planar, completely recrystallised, fabric defines a steeply inclined or vertical oblique cleavage with a consistent orientation trending NW parallel to the axial planes of the marginal folds and the ubiquitous local F_3 folds in the Moine country rock. Feldspar phenocrysts in these microdiorites are flattened and recrystallised in the plane of the cleavage, and thin pegmatite veins, which are rectilinear in the country rock, become ptygmatically folded where they cross the microdiorites. These intrusions are consistently cut by granitic veins of the Glen Garry vein complex (Fettes & Macdonald 1978) and all the evidence indicates that in this area the microdiorites were deformed under fairly ductile conditions shortly after their intrusion, and before the end of Caledonian tectonism.

Sheared microdiorites. These are by far the most abundant members of the swarm and are present throughout the area of Fig. 3 apart from that occupied by the metamorphosed microdiorites described above. They occur as parallel-sided sheets ranging in thickness from several metres down to a few millimetres with an average value of about 1 m. The majority occupy a set of well developed penetrative joint planes sharply discordant to the Moine banding inclined at 35–40° towards the ESE as shown by the prominent maximum on the stereoplot in Fig. 3. A less well defined conjugate set dips northwest at 40°. Many of the structures seen in these intrusions bear a striking resemblance to those described by Watterson for a dyke suite in south Greenland (Watterson 1968). A characteristic feature of both suites is the presence of an internal sigmoidal schistosity. The orientation of this fabric relative to the sheet margins, for the N Highlands suite, is dictated by the orientation of the sheet and the principal stress direction. In almost all cases the internal fabric is inclined more steeply than the intrusion so that, when viewed looking north, easterly–dipping sheets show a sinistral sense of movement (i.e. 'overthrust' westwards) while a dextral sense is typical of those inclined towards the west ('overthrust' eastwards). No corresponding fabrics exist in the country rocks and it appears that the intrusions have acted as narrow zones of low resistance and have been deformed by simple shear in the manner described recently by Davidson & Park (1978). Insufficient measurements of internal fabrics have been made to analyse the stress system accurately but the few that are available indicate a sub–horizontal principal stress direction trending 110°. No significant body rotation of the sheets has occurred but most horizontal intrusions are gently folded about axes trending 0–20°, a feature consistent with the stress direction deduced above. The intensity of shearing and its distribution in the intrusions is, in part, related to the thickness of the sheets. Thin ones are schistose throughout, the fabric making a small angle, often less than 5°, with the edge of the intrusion. In sheets of average thickness (1 m) the fabric is present across the full width but changes angle from 5–10° close to the contact of 30–35° in the centre. In thicker sheets shear is concentrated at the margins and the fabric commonly dies out or is very weakly developed internally. Such heterogeneity is partly a function of sheet thickness but the strong ductility contrast between country rock and intrusion may induce a boundary layer effect causing curvature of the fabric into near parallelism with the contact (Watterson 1968, p. 89). Grain size and compositional variation may also play a part, the finer edges deforming and recrystallising more readily than the interiors. The concentration of shear strain close to the contacts might also indicate the intrusions were solid and uniformly cool. If a temperature gradient towards a warmer centre existed at the time of shear, deformation might be expected to be higher in the central zone (type 7 of Davidson & Park 1978), and no examples of this have been found. The general rigidity of the intrusions during deformation is further indicated by the presence in some of them of included strips of country rock which are folded, with the schistosity in the sheet being axial-planar to the folds (cf. Watterson 1968, p.27). The deformation of the net–veined igneous microdiorites is of particular interest. When weakly deformed, sheets of this type usually show a marginal schistosity only. As deformation increases fabrics are preferentially developed in the mafic patches and along discrete shear planes which penetrate the interior of the intrusion. Continued shear produces a flattening of the net–veins which can simulate tight folds with the schistosity lying parallel to the 'axial planes' (cf. Johnson & Dalziel 1966). Although the net–veining often appears to be accentuated in the deformed sheets there is no evidence to suggest that it is the result of filter–pressing as proposed by Watterson for the Greenland dykes (Watterson 1968).

The schistosity planes within the microdiorites usually contain a prominent extension lineation defined by spindles of biotite aggregates and, or, aligned amphiboles. Its orientation within the fabric plane is variable, depending upon the orientation of the intrusion but in the most common ESE–inclined sheets it plunges down dip and signifies the maximum principal strain. Both the schistosity and the lineation are locally crenulated in some intrusions. These minor folds have variable axial planes but fairly constant axes with trends of 0–20°, the plunge varying according to the orientation of the sheet. In most cases the fold clusters are located near local irregularities in the sheet walls and give the impression of accommodation structures formed by continuous deformation of the schistosity.

Theoretically for simple shear, the angular difference between the wall of the intrusion and the internal schistosity, measured in the plane normal to the fabric–wall intersection should be directly related to the amount of displacement across the sheared intrusion (Ramsay & Graham 1970). Reliable markers which could be used to measure displacements directly are not common in the Moine country rocks and apparent displacements can be produced depending upon the sense of opening of the fissure occupied by the intrusion. For reasons given below it is believed that the fissure opening was achieved by vertical uplift, and hence, by selecting intrusions cutting vertical country rock the possibility of pre–shear displacement is largely avoided. On this basis a number of measurements were made and always the actual displacement of clearly identifiable markers was found to be much greater than could be accounted for by the intrusion wall–fabric angle, suggesting that late stage translation has taken place along the surfaces of the intrusions. Direct support for this interpretation has been found at a number of localities where different country rock lithologies with vertical banding are aligned one above the other separated by thin sheets with intense internal fabrics lying sub-parallel to the sheet walls. Such relationships indicate that either the imposed stress reached a critical value which could not be accommodated by the internal fabric, and brittle fracturing has taken place at the sheet margins, or the fissile edges of the sheets have been preferentially used as thrust planes by a later, unrelated event.

It is not intended here to give a detailed petrographic account of the development of the sheared microdiorites, but a number of the more important aspects will be summarised. The complete sequence can frequently be studied in a single intrusion ranging from a normal igneous core region, through intermediate stages, to a thoroughly recrystallised schistose margin. Most importantly, no cataclastic fabrics have been recognised in any of the several hundred thin sections examined; recrystallisation, evidently having kept pace with the rate of deformation. The fabric varies from highly inhomogeneous and lenticular, in the case of flattened and recrystallised net-veined intrusions; through variable slightly inhomogeneous examples where the original intrusion was porphyritic and the hornblende is replaced by spindle-shaped clusters of biotite and the plagioclase has recrystallised into lenticular aggregates of polygonal grains; to homogene-

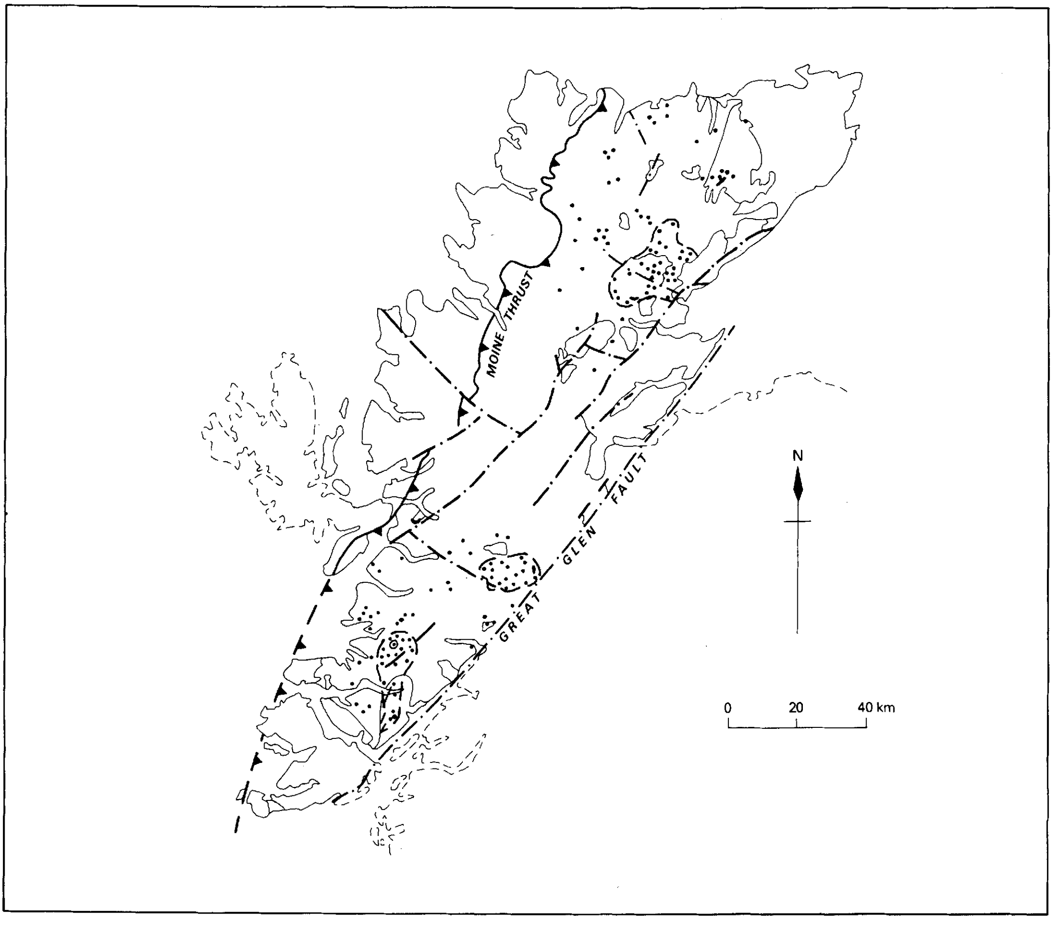

FIG. 4. Distribution of appinitic and ultrabasic bodies.

ous penetrative fabrics derived from even grained non-porphyritic original igneous textures.

In the area of Fig. 3 two distinct mineral assemblages can be readily recognised. Outwith the area enclosed by a line running across Loch Sunart near Salen, northwards through Loch Morar and the head of Loch Hourn, *all* the microdiorite intrusions show either unmodified igneous assemblages or recrystallised assemblages typical of the greenschist facies, i.e. albite-pale green mica-actinolite-epidote and carbonate. A detailed description of a type example of this group from the west coast south of Mallaig is given by Lambert (1959) who classed it as an epidiorite. North of Loch Hourn the facies boundary turns and trends eastwards where it coincides with the change in grade noted in the felsic porphyrites. Further east the position of the boundary is less certain since there are few sheared intrusions in that area, but those that do occur suggest that it reaches the Great Glen at Loch Ness just north of Invermoriston. All the examples of foliated microdiorites to the north in central Ross-shire (lamproschists) are of greenschist facies. Within the boundary and covering the greater part of the present area, all sheared intrusions have an amphibolite facies mineral assemblage. Original zoned plagioclase is homogenised on recrystallisation to calcic oligoclase, bright green hornblende is the characteristic mafic mineral, and in the highest grade opaque ore is replaced by sphene. The significance and possible interpretations of this facies boundary will be discussed in the concluding section of the paper.

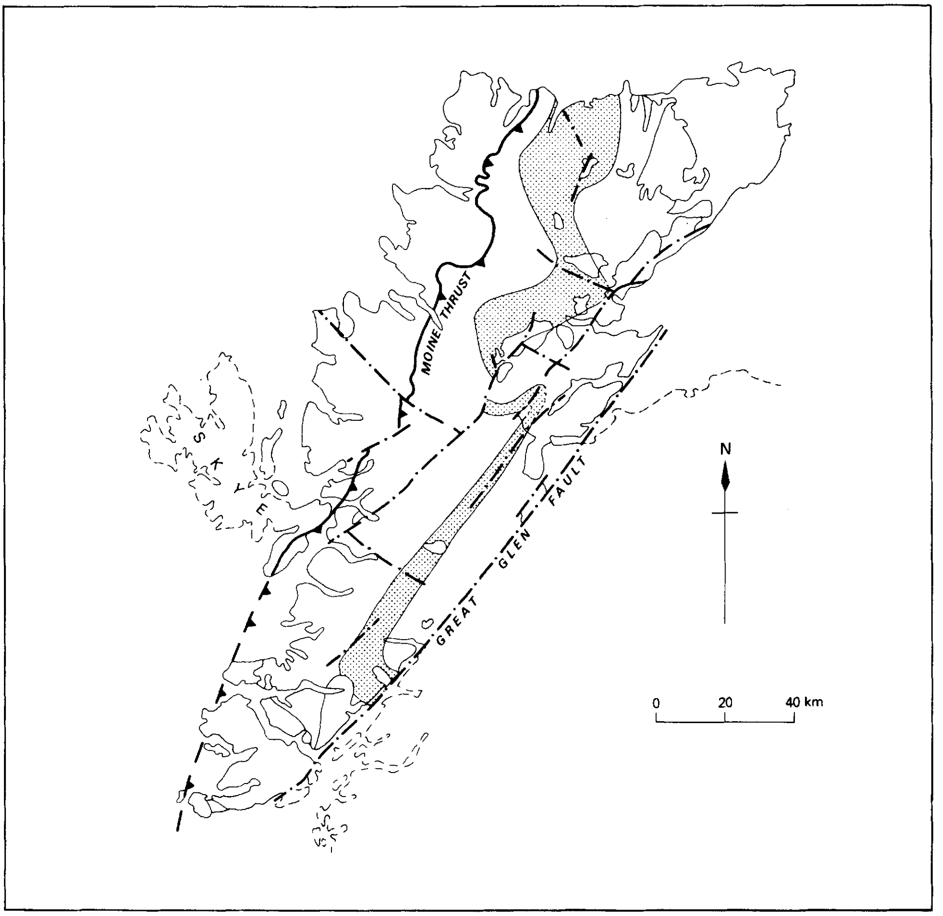

FIG. 5. Zones of metadolerites and metagabbros.

Appinite

In the N Highlands the term appinite has been used in a somewhat imprecise manner to encompass a variety of hornblendic rock types with a broad range in composition. In W Inverness-shire it was originally employed as a 'suite' name and included the microdiorites described above (MacGregor & Kennedy 1932). As the mapping progressed, however, and the extended petrographical nature of the suite became apparent, with microdiorites and felsic porphyrites predominating, the use of appinite became more restricted and is now confined to the coarse grained mafic diorites mainly occurring as thick sheets and small bosses. As can be seen on Fig. 4 appinites of this type show a marked concentration within and to the north of the Strontian granite. The majority are hornblende-rich and a few are pyroxene-bearing but genuine ultrabasic varieties are comparatively rare and are restricted to the area of Ben Gair [NM 790 750]. Although the appinites are undoubtedly older than the Strontian granite, their exceptional size and abundance in its vicinity suggests a genetic relationship (Sabine 1963).

MacGregor & Kennedy (1932) proposed a correlation between the Strontian appinites and a similar suite of rocks in Sutherland (the Ach'uaine Hybrids of Read) and this has been generally accepted (Read 1961). Fig. 4 gives an indication of the close spatial relationship between these rocks and the Rogart granite and serves to emphasise the many similarities which exist between that igneous complex and the one at Strontian. The virtual completion of the mapping of the N Highlands has borne out Phemister's observation (1960) that appinitic minor intrusions appear to be absent in the central part of the region. In one area, however, west of Invergarry, a notable concentration of pyroxene-bearing appinites, together with some ultrabasic, olivine-bearing types, has been found. It may be significant that this is also an area of intense granitic veining, slightly younger in age than the appinites (Fettes & Macdonald 1978), but there is no evidence in this area of a major plutonic body such as those of Strontian or Rogart.

The early felsic porphyrite suite of Cluanie

Preceding the microdiorite suite, and cut by them, a restricted swarm of acid dykes was intruded in the immediate vicinity of the Cluanie granite (Fig. 2). About 100 intrusions have been mapped, mainly dykes, aligned NE-SW and varying in thickness from two to five metres. Although they are found close to the margin of the granite, and are presumably genetically related to it, none are seen to cut the granite itself and a few are penetrated by aplitic veins extending into the country rock from the last phase of the main granite body.

The dykes are distinguished from the younger felsic porphyrites by their greater abundance of large (up to 5 mm) oscillatory-zoned phenocrysts of acid plagioclase and smaller subsidiary phenocrysts of biotite and hornblende. Being earlier, they have been subjected to the same shearing stress as the younger intrusions and commonly show a weak foliation and a recrystallised plagioclase-quartz-rich groundmass.

The amphibolite suite

These rocks include all the minor hornblendic types variously classified as 'pre-foliation intrusions and igneous rocks', 'older basic intrusions and igneous rocks' or 'metamorphosed igneous rocks in the Moine Series'. They are described in all the Geological Survey Memoirs of the N Highlands as epidiorites, amphibolites or hornblende schists occurring as isolated boudins, small bosses, and sills varying from less than one to as much as 100 m in thickness. In places these early amphibolites have been obviously confused with members of the microdiorite suite and with infolded or upthrust slices of hornblendic Lewisian basement rocks. Additionally, in the absence of contrary evidence, a metasedimentary or metavolcanic origin must also be considered thus excluding them from the category of Caledonian minor intrusions. Some of these difficulties were recognised at the time of the original mapping but no subdivision or classification of the amphibolites was attempted and it was generally assumed that they belonged to a single suite of basic intrusives. Sufficient examples were cited of intrusions with margins which cut the bedding and, or, lithological banding in the country rocks, and were subsequently tectonised and metamorphosed together with the Moine, to state with a reasonable certainty that at least one important period of intrusive igneous activity took place at an early stage in the history of the N Highland Caledonides.

In Fig. 5 two zones have been drawn delimiting those amphibolites which on field or textural evidence are believed to be of igneous origin. The southern zone forms a remarkably straight feature over 100 km long between the northern end of the Strontian granite and the Strathglass fault, and separates two contrasting amphibolite provinces. To the west, amphibolites are restricted to the pelitic–rich rocks of the Glenfinnan division where they occur as small isolated boudins with a massive, coarse grained texture characterised by the presence of large garnets. They are never seen to be intrusive and this fact, together with their restricted stratigraphical range, and association with calc silicate rocks, suggested a sedimentary origin (Johnstone *et al.* 1969). However, Winchester (1976), on geochemical grounds favoured an igneous origin resulting from a period of minor tholeiitic intrusion contemporaneous with a first phase of presumed Caledonian metamorphism. No amphibolites have been found in the rocks of the Morar Division in this southern area but farther north, in Ross–shire, Winchester has recorded thin sheets in Morar Division pelites which he ascribes to minor igneous activity contemporaneous with the deposition of the Morar Division sediments.

To the east of the zone, the Moine psammites of the Loch Eil Division, between Fort William and the Cluanie granite, are intruded by numerous sheets of fine grained hornblende schist. They are normally less than 3 m thick and concordant, but many examples of slightly transgressive sheets are also present. Both types appear to have been involved in all the deformational events which affect their host rocks. All traces of original igneous minerals and textures have been obliterated and the usual assemblage is a greenish–blue amphibole − andesine − quartz ± garnet ± biotite. Where garnet is absent epidote is invariably present. Sphene is the most common accessory mineral and occurs either as rims to ilmenite or as fairly large well formed crystals.

Within the limits of the southern zone numerous bosses and sills of undoubted intrusive igneous origin are encountered cutting both the Glenfinnan and Loch Eil Division Moines and the Ardgour granitic gneiss which locally marks the junction. The preservation of undeformed, sub–ophitic textured cores in the larger bodies is partly a function of their size, but relatively thin sheets which cross–cut the earliest fabric in the schists and granitic gneiss are not uncommon. A comprehensive account of the relationships at one locality is given by Peacock (1977) which includes evidence for the existence of hornblende schists in the granitic gneiss prior to the intrusion of the main suite of metadolerites and metagabbros. Abrupt changes in trend are apparent at both ends of the southern zone, towards the Strathconon fault in the north and the Great Glen fault in the south. The significance of these deflections will be discussed later but it is interesting to note here that the southern termination encloses the major basic complex of Glen Scaddle which was originally described as an epidiorite (Bailey 1916).

In marked contrast to the southern zone, the northern one, extending from Carn Chuinneag to the north coast, is conspicuously sinuous following round the large, late–stage cross–folds which affect the full width of the Moine outcrop. Amphibolites are extremely rare to the west of the zone but within it large meta–igneous bosses and transgressive intrusions are common. Some cut the Carn Chuinneag granitic gneiss and are sufficiently undeformed to have been originally classed as dolerite (Peach *et al.* 1912). Farther north intrusions preserving ophitic textures and clouded igneous plagioclase crystals have been described (Read *et al.* 1925) and the sequence of deformation from doleritic–textured cores, through epidioritic zones, (i.e. totally recrystallised but undeformed), to schistose margins was recognised as analagous to that seen in the Scourie dykes cutting the Lewisian (Read 1931, p.85). On the north coast of Sutherland, and traceable for about 15 km is the 'Ben Hope sill', the largest intrusion known of this amphibolite suite. No detailed description of the sill has been published but it is highly garnetiferous, at least 100 m thick, transgressive, and post dates the episode of interleaving of the Moine and Lewisian basement. Much of the ground to the east of the zone is occupied by the granite–migmatite complexes of east Sutherland. Amphibolites occurring within the complexes have been extensively modified and commonly exhibit retrogressive mineral assemblages with biotite replacing hornblende accompanied by the development of prehnite, epidote and chlorite (Read 1931, p.134–6). In contrast, immediately north of the Rogart granite and just outwith the migmatite belt, there occur the only recorded examples of amphibolites containing metamorphic diopside (Read *et al.* 1925, p.17). It is perhaps significant that these localities lie within a regional high grade sillimanite zone (Winchester 1974).

Discussion

The three suites of minor intrusions described above are important in their own right as significant igneous episodes in the magmatic history of the N Highland Caledonides. In addition, however, their relationships to the metamorphic rocks of the fold belt provide valuable information on the tectono–thermal history of this portion of the Caledonides particularly during its closing phases. For the purpose of this discussion it is assumed that each of the three suites constituted a single, relatively short–lived igneous event.

Age sequence

The intrusions of the main *amphibolite suite* post dated the emplacement of Lewisian slices into the Moine rocks of Sutherland, the intrusion of the Carn Chuinneag granite and the formation of the Ardgour granitic gneiss (Peacock 1977). They occur in a northern zone which transgresses the boundary of the Morar and Glenfinnan divisions and a southern zone which cuts across the junction of the Glenfinnan and Loch Eil divisions. If the boundaries of the divisions are tectonic, as has been claimed, (Tanner *et al.* 1970, Dalziel 1966), then their juxtaposition clearly pre–dated the time of amphibolite intrusion. Widespread examples of individual intrusions cross–cutting the oldest fabric in the Moine country rocks show that the suite post dated the first phase of regional deformation. In terms of isotopic dating, the only reliable lower and upper limits of the period of intrusion are provided by the age of the Carn Chuinneag granite, *c*.560 Ma and the late Caledonian pegmatite suite *c*.450 Ma. The intrusions of the *microdiorite suite* began in the Loch Garry area during the last phase of regional Caledonian folding and reached its climax when folding had ceased and when deformation was restricted to movement on discrete planes. Microdiorites intruded along these planes were sheared and recrystallised. These sheared microdiorites cut the 450 Ma pegmatites and are older than the Strontian and Ross of Mull granites. The age of the latter, *c*.420 Ma (Beckinsale & Obradovich 1973), and the contention that it is younger than the Moine thrust may indicate a correlation between the shearing of the microdiorites and the late–stage movements on the thrust plane.

The relationships between the *minette suite* and the rocks of the fold belt indicate that the region had stabilised and that Caledonian deformation had ceased when these dykes were intruded. They thus provide an important time marker for the closure of the N Highland deformation and an attempt to date this event radiometrically is currently in progress.

Regional stress

The attitude of regional stress patterns has been deduced from the reorientation of deformed dyke swarms, and from the orientation of internal fabrics within the dykes (Escher *et al.* 1975, Davidson & Park 1978). Applying similar techniques, and assuming that the meta–dolerite and meta–gabbro zones of the N Highlands originated as linear features, it is evident that their deformation has followed two markedly different paths. In the north, large scale open cross–folds are the dominant structures. In contrast, the southern zone has remained linear apart from the abrupt folds at either end, the sense of which give the impression that they are related to sinistral displacements on the Strathconon and Great Glen faults.

On a more restricted scale the original stress direction at the time of deformation of the folded members of the microdiorite suite had a NE trend which coincides with the direction of the early felsic porphyrite dykes of Cluanie. The sheared microdiorites on the other hand appear to have been intruded during a period of uplift or NE-SW elongate doming. A low vertical stress combined with a high relict or applied horizontal WNW-ESE stress controlled the orientation of shear joints and continued to operate after intrusion with the igneous sheets acting as planes of low resistance and deforming by ductile shear in a more competent matrix of massive Moine country rock. The preponderance of easterly–dipping planes implies a stacking up towards the west and a consequent increase in vertical load. This may account for the fact that the succeeding minette suite, although oriented parallel to the same maximum stress, take the form of dykes with a horizontal minimum stress trending roughly NNE-SSW.

Regional metamorphic facies

The stable amphibolite facies assemblages of the amphibolite suite and the complete absence of relict igneous pyroxene, even in the centres of the most massive and undeformed bodies, is consistent with the general conclusions (Fettes this volume) that the greater part of the N Highland Caledonides evolved under amphibolite facies conditions.

One of the most important facts to emerge from the examination of the microdiorite suite is the existence of a boundary within which sheared intrusions contain recrystallised amphibolite facies assemblages. It has been argued (Johnson & Dalziel 1966) that these recrystallised assemblages result from autometamorphism with the shearing effects initiating the recrystallisation. While it is conceded that shearing probably took place before the intrusions had cooled completely, it is difficult to envisage how such a mechanism could cause a regional variation between amphibolite and greenschist facies assemblages as shown on Fig. 3. The simplest explanation would appear to be that the country rocks were at a higher temperature within the zone of amphibolite facies-sheared intrusions than elsewhere in the N Highlands (cf. Dearnley 1967). It must be emphasised, however, that this does not imply that the country rock temperature lay within the amphibolite facies field at this time but was almost certainly lower. That is, the distribution of recrystallised assemblages reflects the degree to which the cooling rate of the dykes was controlled by the regional temperature gradients. Evidence for this may be seen near Glenfinnan [NM 923 195] where transgressive sheets of both the amphibolite and microdiorite suites are present. The former have massive garnetiferous centres and schistose margins in which amphibole is partially retrogressed to biotite and accompanied by epidote and carbonate. Nearby sheared microdiorites of comparable size and orientation show no signs of marginal retrogression. If, as seems likely, the schistose edge of the amphibolite developed at the same time as the fabric in the microdiorites, these relationships indicate that the older amphibolites were at a lower temperature than the adjacent microdiorites at the time when the latter were sheared.

Whether the region of amphibolite facies microdiorites represents a residual Caledonian thermal high, in keeping with the conclusions of Watson (1964), or a local zone of reheating is not known, but the magmatic continuity from the folded microdiorites through to the sheared intrusions favours the former interpretation.

If this warm 'core margin' was still in existence during the period of intrusion of the minette dykes it could explain the variation in ages obtained from members of this suite. The K–Ar results so far show a decrease in apparent age as the swarm is traced eastwards from Ratagain towards the Cluanie granite, which may relate to differential uplift of separate blocks or to a waning regional thermal gradient.

Major lineaments

The 'Quoich-line' (Clifford 1957) marking the junction of the Glenfinnan and Loch Eil divisions, extends from the Strontian to the Cluanie granite. It operated as a fundamental large-scale structure throughout the period of the N Highland Caledonides, and may have acted as a plane of décollement locally upthrusting the more mobile and migmatitic Glenfinnan rocks (Dalziel 1966). It is the zone along which the Ardgour granitic gneiss was either generated or emplaced. In addition it also appears to have controlled the intrusion of the southern zone of meta-dolerites and meta-gabbros and is the zone along which the felsic porphyrites and microdiorites are concentrated. At a late stage, the extension of the line towards the northeast, is expressed by the presence of the Strathglass fault along which movement has taken place after the deposition of the post tectonic Old Red Sandstone sediments.

ACKNOWLEDGEMENTS. This paper is largely based on mapping by past and present members of the Highlands and Islands Unit of I.G.S. I thank in particular Mr G. S. Johnstone, Drs J. D. Peacock, F. May, D. J. Fettes and J. R. Mendum for their helpful discussion. This paper is published by permission of the Director of the Institute of Geological Sciences.

References

ARMSTRONG, M. 1977. The Old Red Sandstone of Easter Ross and the Black Isle. *In The Moray Firth area Geological Studies*. Inverness Field Club.

BAILEY, E. B. & MAUFE, H. B. 1916. *The geology of Ben Nevis and Glen Coe*. Mem. geol. Surv. U.K.

BECKINSALE, R. D. & OBRADOVICH, J. D. 1973. Potassium-Argon ages for minerals from the Ross of Mull, Argyllshire, Scotland. *Scott. J. Geol.* **9**, 147–56.

CLIFFORD, T. N. 1957. The stratigraphy and structure of part of the Kintail district of southern Ross-shire. *Q. J. geol. Soc. Lond.* **113**, 57–92.

DALZIEL, I. W. D. 1966. A structural study of the granitic gneiss of Western Ardgour, Argyll and Inverness-shire. *Scott. J. Geol.* **2**, 125–52.

DAVIDSON, L. M. & PARK, R. G. 1978. Late Nagssugtoquidian stress orientation derived from deformed granodiorite dykes north of Holsteinsborg, West Greenland. *J. geol. Soc. Lond.* **135**, 283–89.

DEARNLEY, R. 1967. Metamorphism of minor intrusions associated with the Newer Granites of the Western Highlands of Scotland. *Scott. J. Geol.* **3**, 449–57.

ESCHER, A., ESCHER, J. C. & WATTERSON, J. 1975. The reorientation of the Kangâmiut Dike Swarm, West Greenland. *Can. J. Earth Sci.* **12**, 158–73.

FETTES, D. & MACDONALD, R. 1978. Glen Garry vein complex. *Scott. J. Geol.* **14**, 335–58.

HORNE, J. & HINXMAN, L. W. 1914. *The geology of the country round Beauly and Inverness*. Mem. geol. Surv. U.K.

JOHNSON, M. R. W. & DALZIEL, I. W. D. 1966.

Metamorphosed Lamprophyres and the Late Thermal History of the Moines. *Geol. Mag.* **103,** 240–49.

JOHNSTONE, G. S., SMITH, D. I. & HARRIS, A. L. 1969. Moinian Assemblage of Scotland. *Am. Ass. Petrol. Geol. Mem.* 12, 159–80.

LAMBERT, R. ST. J. 1959. The mineralogy and metamorphism of the Moine Schists of the Morar and Knoydart Districts of Inverness-shire. *Trans. R. Soc. Edinb.* **63,** 553–88.

LAWRIE, T. R. M. 1961. *Scottish Highlands and Islands.* Mem. geol. Surv. Summ. Prog. for 1960, 45–7.

LEEDAL, G. P. 1952. The Cluanie Igneous Intrusion, Inverness-shire and Ross-shire. *Q. J. geol. Soc. Lond.* **108,** 35–63.

MACGREGOR, A. G. & KENNEDY, W. Q. 1932. *The Morvern–Strontian Granite.* Mem. geol. Surv. Summ. Prog. for 1931. Part II, 105–19.

PEACH, B. N. HORNE, J., WOODWARD, H. B., CLOUGH, C. T., HARKER, A. & WEDD, C. B. 1910. *The geology of Glenelg, Lochalsh and South-East part of Skye.* Mem. geol. Surv. U.K.

——, GUNN, W., CLOUGH, C. T., HINXMAN, L. W., CRAMPTON, C. B. & ANDERSON, E. M. 1912. *The geology of Ben Wyvis, Carn Chuinneag, Inchbae and the Surrounding Country.* Mem. geol. Surv. U.K.

PEACOCK, J. D. 1977. Metagabbros in granitic gneiss, Inverness-shire, and their significance in the structural history of The Moines. *Rep. Inst. Geol. Sci.*, No. 77/20.

PHEMISTER, J. 1960. *Scotland: The Northern Highlands.* Br. reg. Geol.

RAMSAY, J. G. & GRAHAM, R. H. 1970. Strain variation in shear belts. *Can. J. Earth Sci.* **7,** 786–813.

READ, H. H., ROSS, G. & PHEMISTER, J. 1925. *The geology of the country around Golspie, Sutherlandshire.* Mem. geol. Surv. U.K.

——, ——, PHEMISTER, J. & ROSS, G. 1926. *The geology of Strath Oykell and Lower Loch Shin.* Mem. geol. Surv. U.K.

——, 1931. *The geology of Central Sutherland.* Mem. geol. Surv. U.K.

——, 1961. Aspects of Caledonian Magmatism in Britain. *Lpool Manchr Geol. J.* **2,** 653–83.

SABINE, P. A. 1963. The Strontian Granite Complex, Argyllshire. *Bull. geol. Surv. Gt Br.* No. 20. 6–42.

SOPER, N. J. 1963. The structure of the Rogart igneous complex, Sutherland, Scotland. *Q. J. geol. Soc. Lond.* **119,** 445–78.

—— & BROWN, P. E. 1965. Late Orogenic Events in the Northern Part of the Moine Nappe. *Geol. Mag.* **102,** 285–95.

TANNER, P. W. G., JOHNSTONE, G. S., SMITH, D. I. & HARRIS, A. L. 1970. Moinian Stratigraphy and the Problem of the Central Ross-shire Inliers. *Geol. Soc. Am. Bull.* **81,** 299–306.

WATSON, J. 1964. Conditions in the metamorphic Caledonides during the period of late-orogenic Cooling. *Geol. Mag.* **101,** 457–65.

WATTERSON, J. 1968. Plutonic development of the Ilordleg area, South Greenland: Part II: Late-Kinematic basic dykes. *Meddr Grønland* **185,** 3, 104 pp.

WINCHESTER, J. A. 1974. The zonal pattern of regional metamorphism in the Scottish Caledonides. *J. geol. Soc. Lond.* **130,** 509–24.

——, 1976. Different Moinian amphibolite suites in northern Ross-shire. *Scott. J. Geol.* **12,** 187–204.

D. I. SMITH, I.G.S., Murchison House, West Mains Road, Edinburgh 9.