The Husfjord Plutonic Complex, Sørøy, Northern Norway

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The Husfjord area of Sørøy is underlain by a plutonic complex which has been emplaced into Vendian to Cambrian metasediments during the Finnmarkian phase of the Caledonian orogeny.

The metasedimentary envelope of the complex consists mainly of a sequence of psammites, pelites, semipelites, calc-silicate schists and marbles, which have undergone prolonged regional metamorphism and two principal episodes of deformation. The regional metamorphic event commenced before the first folding episode, reached its peak in the almandine-amphibolite facies between the deformation episodes, and waned during the second period of folding. The various members of the igneous complex were emplaced synchronously with these metamorphic and tectonic events, and thermal metamorphic effects produced by some members have been superimposed upon those of the regional metamorphism.

The earliest intrusion, the Husfjord metagabbro, was emplaced towards the end of the first deformation episode, and has been affected by the highest grades of regional metamorphism. A suite of diorites, monzonites and quartz-syenites was emplaced during the second deformation episode, and these have only suffered low-grade regional metamorphism. The Husfjord metagabbro and the diorite – monzonite – quartz-syenite complex were emplaced essentially by a mechanism of permissive intrusion. The latest members of the igneous complex were the Vatna gabbro and a number of minor intrusions including perthosite sheets, basic dykes, and nepheline-syenite-pegmatites. The gabbros are thought to have had their genesis in a long-lived mantle diapir in the asthenosphere above a subduction zone dipping eastwards beneath the Baltic plate. The diorite – monzonite – quartz-syenite suite developed from a dioritic magma which was generated deep in the crust by the fusion of pelitic material by the heat of metamorphism and the mantle diapir. Metamorphic mineral parageneses in pelitic hornfelses indicate that the development of the Husfjord plutonic complex took place at depths greater than 20 km.

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Introduction

Sørøy is an island off the coast of West Finnmark, near the town of Hammerfest (Fig. 1). The Husfjord area, in the southeast of Sørøy, comprises a plutonic complex, mainly gabbros and diorites, whose emplacement and subsequent deformation and metamorphism are associated with events of the Caledonian orogeny.

The Husfjord igneous complex has been intruded into Vendian (Eocambrian) to Cambrian metasediments which constitute the major part of Sørøy and which have been described by Ramsay & Sturt (1963), Appleyard (1965), Roberts (1968a, 1968b), Holland & Sturt (1970) and Ramsay (1971a). The metasediments are part of a regionally extensive stratigraphic succession and occur within the Kalak Nappe Complex of the northern Norwegian Caledonides (Sturt et al. 1975, Ramsay & Sturt 1977, Binns 1978, Sturt et al. 1978, Roberts & Sturt 1980). The geology of neighbouring parts of West Finnmark has been described

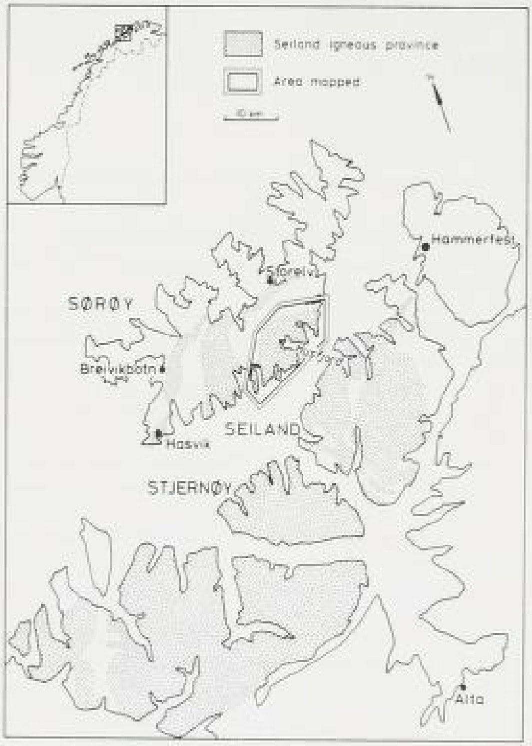


Fig. 1. Map showing the area mapped, in its setting within the Seiland igneous province.

by Holtedahl (1918), Holmsen et al. (1957), Strand (1960), Ball et al. (1963), Reitan (1963) and Hooper & Gronow (1970), and a discussion of the Caledonian nappe sequence and the timing of orogenic deformation and metamorphism of Finnmark has been gived by Sturt et al. (1975, 1978). Norges Geologiske Undersøkelse has produced a geological map (Roberts 1974) and an aeromagnetic map (N.G.U. 1971), both on the scale 1:250 000, and Brooks (1970) has made a gravity survey of West Finnmark. Ramsay (1973) indicated a possible plate tectonic setting for the region.

A number of igneous bodies have been emplaced into the metasediments of Sørøy (Fig. 1). The Storelv gabbro has been described by Sturt & Taylor (1972) and Stumpfl & Sturt (1965), and the latter authors made a mineralogical and geochemical comparison with the Breivikbotn gabbro. Aspects of the Hasvik gabbro have been studied by Sturt (1969), Gardner (1972) and Robins & Gardner (1974). Near Breivikbotn is an alkaline complex which has been described by Sturt & Ramsay (1965). The igneous rocks of Sørøy form the northern-most part of the Seiland petrographic province; most of the rocks in this province are basic or ultrabasic, and some exhibit layering. Accounts of various parts of the province have been given by Strand (1952), Barth (1953, 1961), Krauskopf (1954), Oosterom (1954, 1956, 1963), Heier (1961, 1964, 1965), Ball et al. (1963), Hooper (1971), Robins (1972, 1973, 1974, 1975), Bennett (1974), Gardner & Robins (1974), Robins & Gardner (1974, 1975), Robins & Takla (1979), Robins & Tysseland (1979) and Sturt et al. (1980).

N. & W. SØRØY[1]	N.E. SØRØY[2]	S.E. SØRØY[3]
Hellefjord Schist Group	Hellefjord Schist Group	Phyllitic schists
Åfjord Pelite Group Falkenes Marble Group	Falkenes Limestone Group	Calc-silicate schists with marbles
Storelv Schist Group	Storelv Schist Group Transitional Group	Garnet-mica schists
Klubben Psammite Group	Klubben Quartzite Group	Psammites and semi-pelites

Fig. 2. Comparative metasedimentary successions of Sørøy. 1. Ramsay & Sturt 1963, Ramsay 1971a, Ramsay & Sturt 1973a. 2. Roberts 1968a. 3. Speedyman, this paper.

The present paper is an account of the plutonic complex in the Husfjord area of Sørøy, and its material has been derived from a Ph. D. thesis presented at the University of London (Speedyman 1968). Mapping was done using aerial photographs on a scale of 1:15,000.

I. The Country Rocks

A. Stratigraphy and Petrography

The Husfjord igneous complex is bounded by the sea in the southeast, but to the northwest has an envelope of metasedimentary country rocks which have been overturned by folding. The earliest intrusion is the Husfjord metagabbro, and its intrusive contact is preserved along the northwestern margin of the complex. This metagabbro is a discordant sheet-like body, its margin slightly transgressing the stratigraphic succession of the country rocks (geological map, Plate I).

The generalized stratigraphic succession is as follows:

Youngest	phyllitic schists
	calc-silicate schists with marbles
	garnet-mica schists
Oldest	psammites and semipelites (migmatized in part)

The succession in other parts of Sørøy and West Finnmark has been described by Ball et al. (1963), Ramsay & Sturt (1963), Sturt & Ramsay (1965), Roberts (1968a), Ramsay (1971a), and Ramsay & Sturt (1973a), and the succession in the Husfjord area is similar. A probable correlation with some of these areas is presented in Fig. 2.

The only fossils recorded in Sørøy are archaeocyathids in impure limestones of the Falkenes Marble Group, which are considered to be Lower to early Middle Cambrian in age (Holland & Sturt 1970). This provides, for this region, a lower age limit to the Caledonian orogeny, a protracted event punctuated by several phases of magmatic activity. The youngest igneous intrusion within the late-D_2 Breivikbotn alkaline complex of west Sørøy is a syenite dyke, giving an upper Rb/Sr age limit of 490 ± 27 Ma (recalculated to $\lambda\,^{87}Rb = 1.42 \times 10^{-11}a^{-1}$) to the orogeny (Sturt et al. 1978). This major orogenic phase, of late Cambrian to early Ordovician age, is called the Finnmarkian.

The lowest members of the succession are fine-grained feldspathic psammites and semipelites; the former are greyish-white to buff with small reddish-brown garnets, while the latter contain abundant large garnets overgrowing and replacing biotites. These rocks have undergone extensive migmatization along a broad belt having its maximum intensity at the northern end of Kobbefjord.

Above these rocks are grey and rusty weathering, garnet-mica schists, often containing quartzose bands and streaks, probably due to metamorphic segregation. Small red garnets and retrogressive muscovite overprint kyanite, sillimanite and early biotite. In the upper part of the group are occasional calc-silicate schists containing actinolite which occur as bands and lenses within the semipelites; towards the top the psammites and semipelites are of less importance, and the calc-silicate schists become more abundant, forming a gradation into the overlying group.

The overlying calc-silicate schists are mainly well-bedded and fine-grained, with numerous pale greenish actinolite-rich bands. Interbedded with these schists, near the base of the group, are occasional diopside marbles which occur as long tectonic lenses, each several tens of metres in length and about ten metres in thickness, elongated parallel to the general layering of the rocks.

The phyllitic schists are light grey, well-banded, flaggy rocks, some feldspathic and slightly micaceous, while others are rich in biotite and poikiloblastic muscovite.

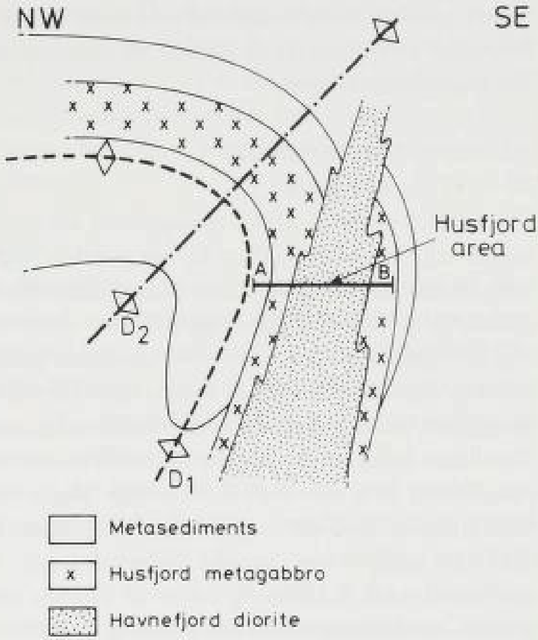
B. Tectonics

Structures belonging to two complex and protracted episodes of Finnmarkian deformation are recognized in the metasediments. In the Husfjord area, the general attitude of the metasedimentary layering is due principally to the second phase of folding.

The first deformation episode (D_1) in Sørøy is characterized by large-scale recumbent folding in which movement was towards the east and southeast (Ramsay & Sturt 1963, Roberts 1968a, Ramsay 1971b), and the metasediments in the Husfjord area all lie on one limb of a large D_1 fold. The earliest D_1 minor folds are tight to isoclinal, lying within the general metasedimentary layering, and the axes of these folds are curved within their axial planes. A detailed analysis of noncylindrical folds on Sørøy has been given by Ramsay & Sturt (1973a, 1973b). These D_1 folds are refolded by later folds, and are cut by amphibolitized basic sheets.

In the second major episode (D_2) folds of more open style were formed, and these tend to have orthorhombic or monoclinic symmetry (Ramsay & Sturt 1963). They generally have axial trends close to those of the D_1 structures, and in the case of the monoclinic folds the eastern- or southeastern-facing limbs are often slightly

Fig. 3. Simplified NW-SE cross-section across the Husfjord area showing the relationship between the major intrusions and the major structures. Line of section A–B shown on Plate I. After Speedyman 1972.



overturned. The metasediments of the Husfjord area lie within one of these steep, overturned, southeast-facing limbs. The D_2 folding had two main phases, and in the Husfjord area there was considerable igneous activity during and after the earliest D_2 movements. Late D_2 folding was responsible for the present arcuate form of the igneous complex and its envelope, and the latest D_2 deformation at the end of the regional metamorphism was brittle.

The major structures of Sørøy have been discussed by Sturt & Ramsay (1963), Roberts (1968a), Ramsay (1971b) and Ramsay & Sturt (1973a), the Falkenes Marble proving a useful marker horizon in elucidating the structure of the island. Relics of the Falkenes Marble occur as trains of rafts within the igneous complex of Husfjord, where the stratigraphic succession youngs towards the southeast, away from the major D_1 fold axial trace.

The emplacement of the Husfjord igneous complex spanned the period of time between the waning stages of D_1 and the latest phases of D_2 The complex has two major plutons: the Husfjord metagabbro which was intruded discordantly along the upper limb of a large recumbent isoclinal D_1 fold, and the Havnefjord diorite which was emplaced into the steep overturned limb of a major D_2 fold which refolded the D_1 isocline and the Husfjord metagabbro (Fig. 3).

II. The Igneous Complex

A. Field Relationships

The Husfjord igneous complex comprises major plutonic intrusions, principally gabbros and diorites, and a number of minor intrusions, including monzonites, quartz-syenites, basic dykes and perthosite sheets (Plate I). These bodies have been emplaced at various times during the development of the Finnmarkian stage of the Caledonian orogeny.

1. HUSFJORD METAGABBRO

Facies of the metagabbro

The outcrop of the Husfjord metagabbro, the earliest intrusion, runs in an arc from southwest to northeast (Plate I), but much of the central zone is now occupied by later intrusions. The gabbro is a melagabbro which has undergone metamorphism and is fairly uniform, although there are some slight variations.

The typical gabbro is fine- to medium-grained but is sporadically coarser-grained, a primary feature of the gabbro. There is also a finer-grained facies which sometimes has a poorly formed foliation subparallel to the margin of the gabbro. This latter facies is not near the contact, but mainly in the central part of the body, particularly in a zone rich in later thin coarse-grained diorite sheets which have been intruded into the metagabbro. This foliation is a fluxion texture, suggesting that the gabbro was intruded synchronously with slight tectonic movement associated with the waning stages of D_1; the similar, contemporaneous Storelv gabbro, to the north, also has a strong D_1 foliation (Sturt & Taylor 1972). This zone of finer-grained, slightly foliated gabbro provided structural weakness into which the thin coarse-grained diorite sheets were later readily emplaced.

In the southwest the metagabbro is variably contaminated by metasediment, developing a gabbronoritic facies containing metasediment rafts. In places the gabbro is extremely contaminated, forming xenolithic norite, as seen to the north of Kobbefjord and on the Fella peninsula. In Kobbefjord, where the country rocks are migmatized psammites and semipelites, this noritic facies, developed along the marginal zone, is a fine-grained rock containing dark brown garnets. It is extremely xenolithic, inclusions varying from large rafts of migmatite several metres long to small fragments of psammite.

The contact between the norite and the country rocks consists of a zone about a metre wide in which the rocks are a mixture of contaminated garnetiferous norite and assimilated migmatite. Away from the contact the garnets, which are abundant in the neighbourhood of xenoliths in the marginal zone, diminish in both number and size, and it is clear that the formation of garnet was associated with the assimilation of aluminium-bearing semipelites by the gabbroic magma. Several features of this xenolithic norite are similar to those of the contaminated norites of Aberdeenshire (Read 1935, 1936, Read et al. 1965, Gribble 1967, Gribble & O'Hara 1967), although there is an absence of cordierite and more garnet in the Husfjord rocks, presumably due to greater pressures. On the Fella peninsula the garnetiferous norite is similar to that in Kobbefjord, but the rafts are mainly of hornfelsed psammite, semipelite and calc-silicate schist.

The Husfjord metagabbro contains sporadic lenses and layers of troctolite, ranging up to about 5 m in length, elongated parallel to the trend of the gabbro sheet. Usually the lenses are isolated and dispersed throughout the gabbro, but there is one horizon on Husfjordnes in which there is a swarm of closely packed tectonic lenses of troctolite within a zone of D_2 shearing. Husfjordnes is the only locality where continuous troctolite layers have been found, usually only a few centimetres in thickness. One layer dipping steeply to the north is graded, having a sharp ultramafic upper margin and grading downwards into leucocratic rock and if this represents primary gravitational layering it would confirm that the gabbro sheet has been inverted by D_2 folding.

Metasedimentary rafts and xenoliths

As well as the noritic facies, the normal metagabbro contains a number of large elongate rafts and small xenoliths of metasediment, particularly in the north, though here the gabbroic magma was not contaminated by the inclusions. The rafts, generally a few tens of metres in length, include marbles, mica schists and psammites, while the xenoliths, which are usually less than a metre in length, are of mica schist, calc-silicate schist and psammite.

The largest and most abundant of the rafts consist of bluish-grey marble, and although these sometimes occur as isolated bodies they usually appear as groups or trains of rafts composed of several individuals. Occasional rafts of mica schist, up to a few tens of metres in length, have provided weaknesses in the metagabbro, for they are almost invariably intruded by later sheets of coarse-grained quartz-syenite. On Ramnes the metagabbro contains xenoliths and rafts of migmatized psammite and semipelite. The migmatization postdated the emplacement of the gabbro, for the latter has undergone extensive feldspathization and veining by quartzofeldspathic material derived from partial anatexis of the metasediments. In the northwestern part of Havnefjordfjell the marginal zone of the metagabbro is rich in small metasedimentary xenoliths, sometimes only a few centimetres in length. Thes are of several different lithologies including psammite, semipelite, calc-silicate schist, basic hornfels, and blocks of acid pegmatite. They are usually angular and sharp-margined, and are randomly orientated with different rock-types brought into juxtaposition with one another.

The trains of metasedimentary rafts form a relict stratigraphy through both the Husfjord metagabbro and the Havnefjord diorite, a large fine-grained diorite which has been emplaced into the central part of the metagabbro sheet (Plate I). The marble rafts form a good marker horizon, and these occur well within the metagabbro body near to the Havnefjord diorite in the southwest, but close to the outer margin of the metagabbro in the northeast. The trend of these rafts is approximately parallel to the general strike of the country rocks outside the pluton. The preservation of this relict stratigraphy across a large part of the metagabbro sheet is a result of the emplacement mechanism discussed below.

Early intrusions

The finer-grained foliated facies of the Husfjord metagabbro has been susceptible to feldspathization and the introduction of dioritic material. The diorites are coarse-grained pyroxene-mica diorites with a fluxion texture and generally occur as parallel sheets less than a metre in width (Fig. 4), although some irregular veins are present. Many have been sheared and jointed during D_2, and the large-scale orthogonal swing in the regional strike of the country rocks, due to the late D_2 movements, is reflected by a similar swing in strike in these early diorite sheets.

The foliated facies of the Husfjord metagabbro has also been prone to feldspathization in the neighbourhood of the dioritic sheets. The metagabbro contains streaks and bands replete with feldspar porphyroblasts which are always elongated parallel to the foliation of the metagabbro. In some cases the porphyroblasts are relatively dispersed and the borders of the feldspathized areas are diffuse, while in others the porphyroblasts are closely spaced and the margins of the bands of feldspathization are sharply defined.

The emplacement of the diorites postdates the feldspathization since they cut across the feldspathized patches, but it is possible that the two events were closely linked in time, the feldspathization being a precursor to the diorite intrusion. Petrography shows that the diorite intrusion followed the peak of the regional metamorphism, whilst it is likely that the feldspathization could have been associated with higher grades of the regional metamorphism. The zones containing diorites have been prone to shearing, probably due to internal failure in the metagabbro during D_2 folding along planes of weakness formed by these diorite sheets. Sometimes only the diorites have been sheared, but locally the metagabbro is also affected.

Late intrusions

A complex of diorites, monzonites and quartz-syenites, of variable grain-size, was emplaced into the central zone of the Husfjord metagabbro. The largest body is the fine-grained Havnefjord diorite, which thermally metamorphosed the Husfjord metagabbro, the width of the aureole being 300–400 m. The metagabbro becomes more amphibolitic in the neighbourhood of the diorite, and sometimes feldspar porphyroblasts develop, occasionally containing minute inclusions of mafic minerals in their cores. Some of the early coarse diorite sheets in the metagabbro occur within the aureole of the Havnefjord diorite, and these have also been amphibolitized. There is no evidence in the metagabbro that the Havnefjord diorite caused any marked deformation of its envelope during its emplacement.

A number of perthosites have been emplaced into one of the more intense shear-zones in the Husfjord metagabbro around the margin of the Vatna gabbro. They are pink or cream coloured, varying in grain-size from fine to coarse, and ranging in size from sheets tens of metres thick to small irregular streaks and veins only a few millimetres wide. The mechanism of emplacement of these perthosites has been discussed in detail by Speedyman (1973).

Emplacement

The distribution of the metasedimentary rafts provides the clue to the emplacement mechanism of the gabbro sheet. This mechanism must account for the preservation of a relict stratigraphy in the rafts within the metagabbro. It must also explain the presence of metasedimentary rafts in the metagabbro near to the Havnefjord diorite, well away from the gabbro's outer contact.

The raft distribution suggests that on emplacement the gabbro sheet bifurcated,

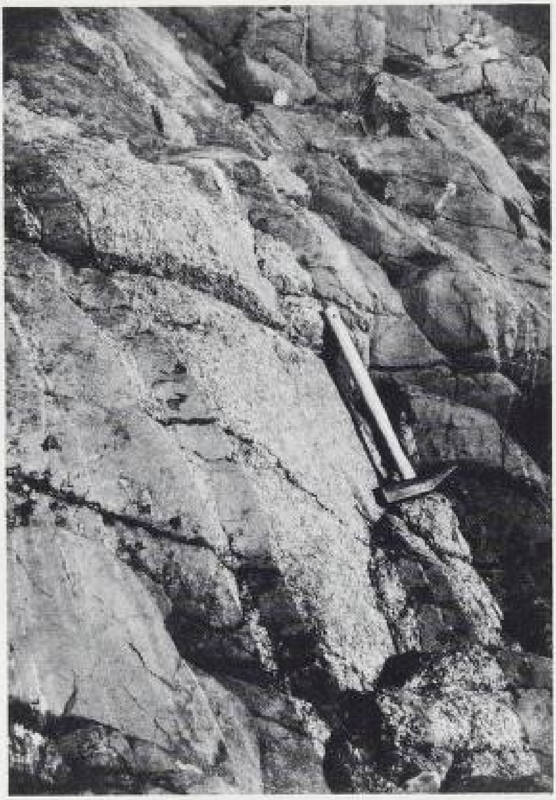


Fig. 4. Early diorite sheets in the Husfjord metagabbro. Husfjord.

preserving a large central lenticular region predominantly of country rock, consisting of large screens of metasediment alternating with sheets of gabbro (Speedyman 1972). This central lenticular complex is now occupied by the Havnefjord diorite, accounting for the general alternation of metagabbro and metasediment rafts within the diorite. The emplacement of the gabbro was syntectonic, associated with the last stages of the D_1 folding, and Speedyman (1972) considered that the intrusion of the Husfjord gabbro was by a mechanism of syntectonic permissive emplacement.

2. HAVNEFJORD DIORITE

This is a large, fairly homogeneous body of fine-grained pyroxene-mica diorite, emplaced into the central zone of the Husfjord metagabbro (Plate I).

It has not undergone the high-grade regional metamorphism that affected the metagabbro, and thus postdates the peak of the regional metamorphic event. Its outcrop is arcuate, about 12 km in length and nearly 2 km in width at its centre, and takes the form of a sheet, both contacts dipping towards a northwesterly direction.

The diorite is almost invariably aphyric and is fairly uniform in grain-size throughout, although sometimes near the margins, particularly the southern, there are zones parallel to the contact in which the diorite is slightly porphyritic exhibiting a fluxion texture.

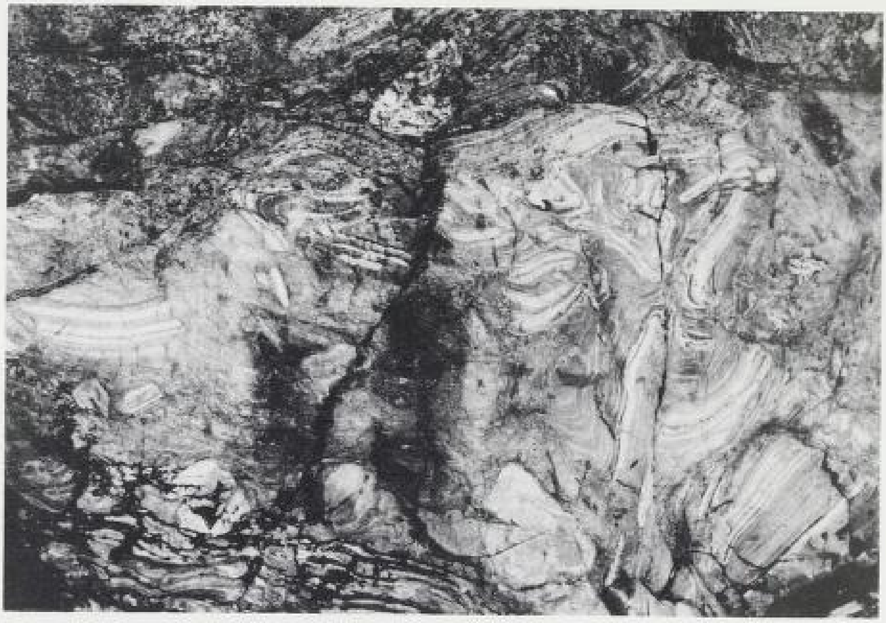


Fig. 5. Mobilized hornfels in a metasediment raft in the Havnefjord diorite. Havnefjord.

Rafts and xenoliths

A common feature of the Havnefjord diorite is the occurrence of numerous inclusions, varying from occasional xenoliths a few centimetres long to numerous large rafts up to several tens or hundreds of metres in length. The xenoliths are of metasediment but the rafts consist of various lithologies including metagabbro, psammite, semipelite, basic schist and marble. The rafts occur throughout the diorite, but the various rock-types are restricted to different zones, reflecting a relict stratigraphy comparable with that of the country rocks. The small xenoliths mainly occur near the northern margin, and are not obviously related to the rafts.

The metagabbro rafts are of the order of a few metres or tens of metres in length, and are lenticular, with their longest axes parallel to the margins of the diorite. Occasionally they contain early diorite sheets and zones of feldspathization, and have been thermally metamorphosed.

Much of the central part of the Havnefjord diorite, especially to the north of Husfjord, is occupied by planar rafts of psammite, rusty-weathering semipelite and basic schist, ranging from a few metres long up to about 1 km in length and 200 m in width. They are orientated parallel to the margins of the diorite, and sometimes occur as trains which trend in this direction. The layering in the rafts is parallel to the raft margins, which are usually subvertical or dipping steeply to the north.

In some places D_1 minor folds are refolded by D_2 folds, indicating that the diorite emplacement postdates at least the beginning of D_2. The margins of the rafts are fairly sharp, and there is no significant assimilation by the diorite. The spatial arrangement of rafts of similar composition indicates that they are close to

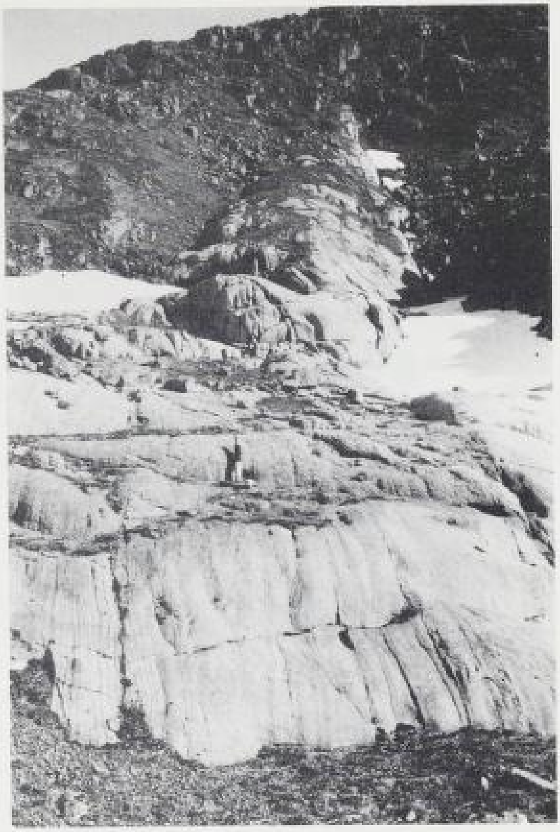


Fig. 6. Marble raft in the Havnefjord diorite. Havnefjordfjell.

their original pre-diorite positions, since a relict stratigraphy can be traced across the body. The size of many rafts also indicates that they have probably not changed their positions very much. The psammitic and semipelitic rafts are very abundant in the central zone of the diorite, and here sporadic metagabbro rafts occur between and parallel to the metasedimentary raft trains. Away from the central zone, and particularly towards the south, the metasedimentary rafts decrease in size and number, and the frequency of metagabbro rafts increases.

In one large raft hornfelsed metasediments have become mobilized by the diorite, and form broken and deformed blocks in a dioritic matrix (Fig. 5). The blocks have sharp margins, sometimes with leucocratic reaction rims, and the diorite in the neighbourhood of these mobilized hornfelses has been net-veined by quartzofeldspathic material, the source of which appears to be the metasediment.

The northern limit of the rusty-weathering semipelitic rafts is fairly clearly defined, and to the north of this the Havnefjord diorite contains occasional rafts of marble. Most of these are large, often many tens of metres in length (Fig. 6), and are elongated parallel to the trend of the psammite and semipelite rafts and the diorite contact.

Fig. 7. Steep northward-dipping contact between monzonite (left) and Havnefjord diorite. Havnefjordfjell.

Fig. 8. Feldspathization of metasediment near quartz-syenite sheet. Havnefjord.

A few randomly-orientated psammite and semipelite xenoliths occur in the northern part of the diorite. These are almost invariably partly assimilated by the diorite, and their margins are generally diffuse, sometimes only remaining as dark schlieren. Locally, tight isoclinal D_1 folds have been preserved in the xenoliths. Such small, highly-digested xenoliths must have been brought up by the diorite from deeper levels.

Emplacement

As in the case of the Husfjord metagabbro, the distribution of the rafts within the Havnefjord diorite provides the key to its emplacement mechanism. The preservation of a relict metasedimentary stratigraphy throughout the diorite must be explained, and the presence of metasedimentary rafts within the diorite at such a great distance from the metasediments of the country rocks must be accounted for. Moreover the alternation of metagabbro and metasediment rafts across the diorite must be explained.

As already mentioned, when the Husfjord gabbro was emplaced it bifurcated forming a central lenticular region consisting of sheets of gabbro alternating with metasediment screens. It was into this sheeted screen complex that the Havnefjord diorite was emplaced synchronously with late D_2 folding (Speedyman 1972). Both metagabbro and metasediment were incorporated as rafts, and the pre-existing sheeted nature of the screen complex resulted in the alternation of metagabbro and metasediment rafts. This also explains the relict stratigraphy and the preservation of the metasediments within the heart of the diorite so far from the country rocks. Like the Husfjord metagabbro, the Havnefjord diorite is considered to have been intruded by a mechanism of syntectonic permissive emplacement (Speedyman 1972).

3. MONZONITES

The Havnefjord diorite and in some places the Husfjord metagabbro have been intruded by a number of coarse-grained pyroxene-mica monzonite sheets (Plate I). These vary in width from a few metres to many tens of metres, the largest having a length of about 1,5 km, although it is likely that many of the smaller ones link up with longitudinally adjacent ones beneath the present erosion surface. The sheets dip steeply towards the north (Fig. 7), and their trends are subparallel to the margins of the Havnefjord diorite and its metasedimentary rafts.

The contacts of the monzonites against their host are always sharp, but there is no chilling, and the monzonites commonly contain hornfelsed blocks of Havnefjord diorite at their margins.

The monzonites are frequently located adjacent to metasedimentary rafts in the Havnefjord diorite, although in some cases the rafts have been completely enveloped by the monzonites. A common feature of the monzonites, whether or not they are associated with rafts, is the presence of small metasediment xenoliths. Psammitic xenoliths usually have fairly well-defined margins, but pelitic and semipelitic inclusions are generally diffuse, and have been extensively assimilated by the monzonite, forming vague schlieren. In some places semipelitic horizons in the larger xenoliths can be traced along strike from normal metasediment through stages of progressive assimilation until they become indistinguishable from monzonite.

4. QUARTZ-SYENITES

These occur as sheets, a few metres in width, emplaced into the Havnefjord diorite, the Husfjord metagabbro, and occasionally the country rocks (Plate I), but their age relative to the monzonites is uncertain in the field. They are coarse-grained, and some contain numerous small reddish garnets. These quartz-syenites are usually associated with metasedimentary rafts which have sharply defined margins, but there are none of the small digested xenoliths characteristic of the monzonites.

In the neighbourhood of the quartz-syenites, the Husfjord metagabbro and the metasediments have generally been extensively feldspathized, the latter being much more prone to this than the former. Feldspar porphyroblasts up to about 2 cm in length are randomly orientated, and in some places the feldspars are relatively sparse, whereas in others they are very dense (Fig. 8). The feldspathization is sometimes so dense that the rock begins to resemble the quartz-syenites, and it is possible that the relationship between the quartz-syenites and the feldspathization is comparable to that between the early diorite sheets in the Husfjord metagabbro and the feldspathization associated with them.

5. VATNA GROUP

The Vatna gabbro occupies the area around Vatna, and makes contact with the Husfjord metagabbro to the north and west (Plate I). It has not undergone the amphibolite-grade regional metamorphism which has affected the metagabbro, and it causes the formation of a metamorphic aureole in the latter. It comprises a number of facies, mostly olivine-bearing, having various grain-sizes, but with a general tendency for the rocks in the southern part to be finer-grained, and in places a fluxion texture is developed. Dioritic patches are fairly common, especially near its western margin and these, together with granular pyroxene-hornfels inclusions, are probably relics of Husfjord metagabbro and its associated diorites. The Vatna gabbro has metamorphosed the Husfjord metagabbro, the aureole being about 1 km wide to the west but narrowing to a few hundred metres in the north. The metagabbro becomes variably amphibolitized, and in places there are feldspar porphyroblasts.

Southward-dipping sporadic and variable layering is present in the gabbro. Two types occur: one is a gradation in grain-size, and the other is a gradation in the proportion of mafic minerals present. In the former, olivine-gabbro with an ophitic texture gradually passes up into a coarser-grained variety before reverting rapidly to the finer-grained facies; the mineralogy remains the same throughout and units are about 0.5 m thick. The second type of layering is fine-scaled with units 0.5–2.0 cm in thickness, and is defined by variation in the ratio of plagioclase to pyroxene, olivine and opaque minerals across the units. In many cases layers are well defined and continuous for many metres, varying little along the strike, whereas in others the layers are diffuse and discontinuous laterally. Although many of the units grade from mafic up to felsic, the direction of grading is often conflicting in neighbouring units. The graded units are not generally adjacent to one another, but are usually separated by several centimetres or metres of homogeneous olivine-gabbro.

Inclusions and veins

Inclusions are fairly common in the gabbro, especially around Vatna; they tend to occur in zones, individual inclusions ranging up to a few tens of centimetres in length. Sometimes they are randomly orientated, and neighbouring ones are frequently of different rock-types. The most common type is a finer-grained facies of the host-rock itself, and these are generally elongate and aligned parallel to the attitude of the fluxion structure in the host. They are autoliths, representing an early phase in the emplacement of this facies of the Vatna gabbro complex, and their origin may be similar to the inclusions in the hypersthene-gabbro of Ardnamurchan, described by Wells (1953).

At Vatna the gabbro commonly has a streaky appearance with bands and veins of coarse pink-weathering feldspathic material. These are parallel to the autoliths and fluxion structure, and some have sharp margins while others are diffuse and mix with the gabbro. The veins and streaks are of perthite, and in those cases where they merge with the gabbro the latter is pink-weathering and in thin-section is seen to be a mixed rock containing both olivine and antiperthitic feldspar. Thus it appears that this facies of the Vatna gabbro had an alkali magma associated with it, either during or shortly following its emplacement.

The gabbro contains a few veins rich in opaque minerals, principally magnetite, which occur mainly in the streaky antiperthitic facies. Their attitude is parallel to the perthosite veins, dipping steeply south, suggesting that an ore body may exist beneath Sørøysund. It is significant that the 1:250 000 Hammerfest aeromagnetic map produced by Norges Geologiske Undersøkelse (1971) shows a magnetic maximum over the Vatna area.

Intrusions

Minor intrusions are abundant in the Vatna gabbro, and include perthosite sheets, basic dykes and nepheline-syenite pegmatites. The perthosites consist almost entirely of hair-perthite, are variable in grain-size from fine to medium, weather to a pink or yellowish colour, and form large sheets up to several tens of metres in width trending NW-SE. In many cases the ends of the sheets are diffuse and merge with pink-weathering antiperthite-gabbro. There is a gradation from olivine-gabbro through antiperthitic olivine-gabbro and melaperthosite to practically pure perthosite, and it appears in places that the perthosite and olivine-gabbro magmas must have become mixed at the time of emplacement; the perthosite may, in fact, be a late fraction of the alkaline olivine-gabbro magma. It is possible that the perthosites were emplaced before the Vatna gabbro was completely solid, so that those parts of the perthosite sheets in contact with the gabbro became mixed with the neighbouring crystallizing host. Pitcher & Read (1960) have described dykes in the Donegal Granite which display mixing of granite and dyke material at their margins and a merging of textures, and which are considered by these authors to have been emplaced into an embryonic joint system in the granite before the latter was entirely solid. The Vatna perthosites have many features in common with the Donegal dykes, and may have had a similar mode of emplacement.

The Vatna gabbro and perthosites are cut by numerous basic dykes, mainly amphibolites, some of which are porphyritic. They range in width from about 10 cm to 2 m, although a distinctive white-spotted olivine-leucogabbro reaches several tens of metres in width. At Vatna a few nepheline-syenite pegmatites have been emplaced into the gabbro. They are invariably sheared, having provided planes of weakness in the massive gabbro along which shearing could take place during the late D_2 brittle deformation, the intensity of the shearing being variable, even within a single body. Feldspars form broad elliptical-sectioned augen, while nephelines form long, sinuous, streaked-out granulated augen, and shearing has also causes the formation of small overturned isoclinal folds. Similar features in western Sørøy have been described by Sturt (1961).

B. Petrography

1. HUSFJORD METAGABBRO

Facies of the metagabbro

The Husfjord metagabbro is essentially a clinopyroxene-gabbro (Table 1) which has been variably amphibolized during the regional metamorphism. The main facies is fine- to medium-grained, typically has a relict subophitic texture, and is sometimes slightly foliated. As a result of regional metamorphism, plagioclase has

Table 1. Modal analyses of the facies of the Husfjord metagabbro.

Mineral	1 36/3A	2 36/139E	3 36/119C	4 36/141A	5 05/38B	6 38/5A	7 46/11A	8 05/34B	9 11/47F	10 56/1A	11 60/47F	12 60/47G	13 60/47H
Qu	–	–	0.5	–	–	–	–	0.3	–	–	–	–	–
Plag	33.2	35.4	44.3	52.6	45.4	34.1	40.6	31.7	77.3	58.2	51.9	37.4	65.8
Cpx	13.7	6.6	2.8	13.5	22.7	2.4	9.5	–	5,4	–	–	–	–
Hyp	–	–	–	0.3	1.8	–	–	–	4.4	3.9	16.7	20.7	21.2
Hbl	46.3	52.7	42.2	29.4	23.0	–	–	–	0.8	2.1	2.8	3.0	2.5
Act	–	–	–	–	–	60.6	43.4	64.9	–	–	–	–	–
Bi	3.2	3.1	7.6	2.8	5.6	0.8	3.7	0.4	4.6	10.7	3.4	3.4	5.6
Sph	0.5	0.3	0.6	–	0.1	0.8	0.3	2.1	–	–	–	–	–
Ap	0.1	0.1	0.2	0.2	0.2	0.4	0.4	0.3	0.5	0.4	0.8	0.7	1.0
Opaq	3.0	1.8	1.8	1.2	1.2	0.9	2.1	0.3	7.0	2.9	4.6	5.3	3.6
Gnt								–	–	21.7	19.8	29.5	0.3
Zir								–	–	0.1	–	–	–

1–2, fine-grained facies; 3–5 coarse-grained facies; 6–8, actinolitic facies; 9, contaminated facies; 10–13, noritic facies. Based on 3,000 points per thin-section.

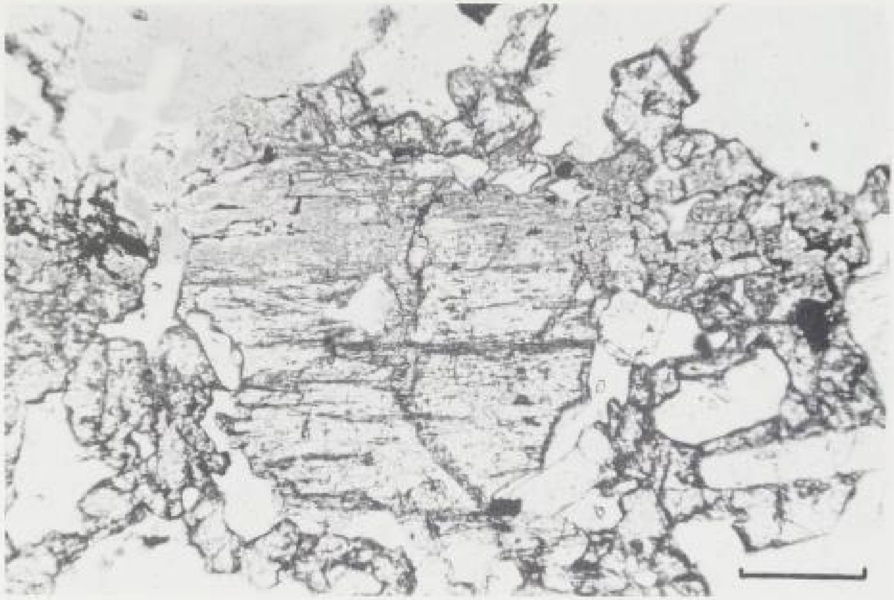


Fig. 9. Garnet corona around hypersthene; note clear zone of quartz. Noritic facies of the Husfjord metagabbro. Plane polarized light. Bar scale = 0.1 mm.

recrystallized and clinopyroxene has become partially altered to green amphibole. Hypersthene occasionally occurs in this facies, (Table 1), but is less prone to amphibolitization than the augite. There are two generations of biotite; early laths altering to hornblende, and later large fresh crystals which have developed retrogressively from both hornblende and early biotite.

In the noritic facies the only pyroxene is strongly pleochroic hypersthene. Ragged biotite laths form from some of the hypersthenes, and there is usually a narrow zone of quartz between the two minerals with vermicular inclusions of quartz in the biotites as a result of the reaction. Corona textures are ubiquitous in this facies, the most common being rims of granular garnet around hypersthene generally with a clear zone of quartz between the two (Fig. 9). These garnet rims also occur around hypersthenes which have altered to biotite containing vermicular quartz inclusions, and where garnet overgrows biotite it sometimes inherits the vermicular quartz inclusions from the biotite, indicating that the formation of garnet is secondary, postdating the metamorphic alteration of hypersthene to biotite. Garnet coronas around orthopyroxene in noritic and related rocks, often with an intermediate zone of quartz, have been described by many workers (Brøgger 1934, Shand 1945, Gjelsvik 1952, Friedman 1955, Murthy 1958, Reynolds & Frederickson 1962, Engels & Vogel 1966, Frodesen 1968, Glaveris 1970, Griffin 1971, Griffin & Heier 1973, and Whitney & McLelland 1973). Although some of these authors believe the reactions to be deuteric, the majority consider them to be metamorphic. In this facies garnet also occurs as large porphyroblasts, particularly at the contact with the country rock migmatites where the norite is strongly contaminated by metasediment. The close association of garnet formation with assimilated metase-

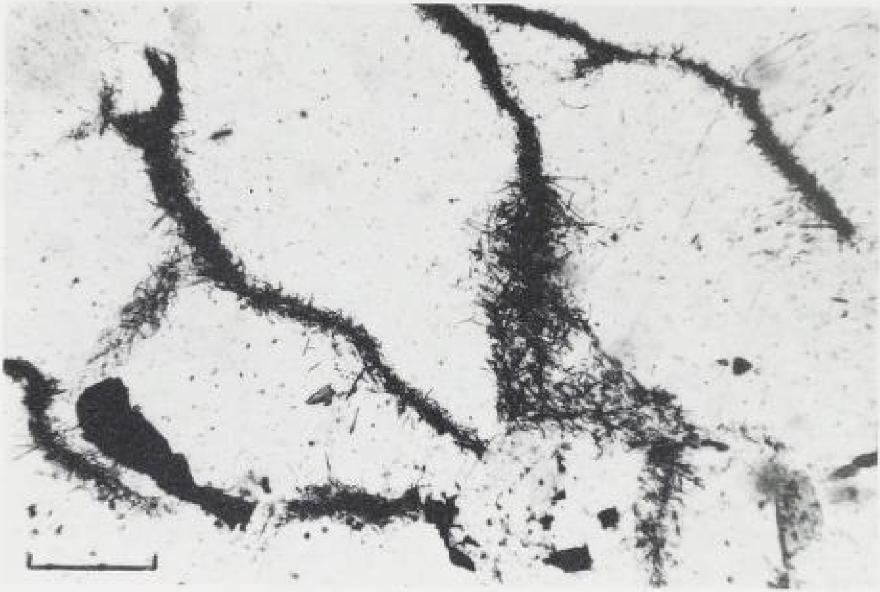


Fig. 10. Fibrolite along feldspar grain boundaries. Migmatized psammite raft in the Husfjord metagabbro, Ramnes. Plane polarized light. Bar scale = 0.1 mm.

diment is not a primary feature, as a result of direct contamination, but a secondary one. It is due to the metasediment providing excess aluminium, creating chemical metastability in the more contaminated parts of the norite which became stabilized during metamorphism by the formation of garnet.

The Husfjord metagabbro has been thermally metamorphosed by the Havnefjord diorite. Towards the contact pyroxene, which has already been slightly altered to amphibole during the regional metamorphism, becomes progressively more amphibolitized, and although it is almost completely replaced by amphibole a relict subophitic texture is preserved. Plagioclase is sodic andesine, and there are sporadic porphyroblasts of antiperthitic oligoclase.

Metasedimentary rafts and xenoliths

The marble rafts consist mainly of coarsely recrystallized calcite forming a subequigranular mosaic in which rounded grains of diopside are common, and small amounts of alkali feldspar, quartz, garnet and idocrase are sometimes present. The thin calc-silicate horizons have a fine-grained granular texture, and consists of diopside, calcite, quartz and feldspar. Locally, the metagabbro adjacent to the marble rafts contains a few anhedral buff-coloured garnets, due to contamination. In the mica schist rafts garnets overprint the folded D_1 schistosity, but have themselves undergone D_2 deformation, with secondary biotite forming along cracks in the porphyroblasts. The psammite and semipelite rafts have been migmatized after being enveloped by the metagabbro. The psammites are quartzofeldspathic, with varying amounts of biotite, sillimanite and garnet, the last sometimes forming large porphyroblasts which are altering to fibrolite and

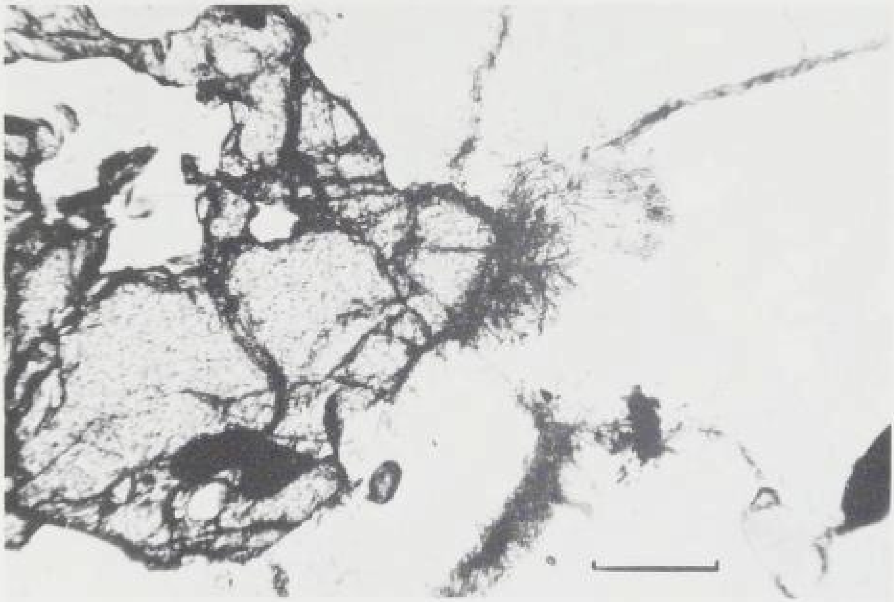


Fig. 11. Fibrolite nucleating on garnet porphyroblast. Migmatized psammite raft in the Husfjord metagabbro, Ramnes. Plane polarized light. Bar scale = 0.1 mm.

opaques, especially at their margins. Along nearly all the grain boundaries between adjacent alkali feldspars, and between alkali feldspar and quartz are aggregates of fibrolite (Fig. 10), a mineral which also nucleates around the margins of garnet porphyroblasts (Fig. 11). The growth of this fibrolite appears to be related to the migmatization, and its significance is discussed in Part III. In the semipelites quartz and alkali feldspar form a subequigranular mosaic, often with biotites along grain boundaries, and some horizons contain garnet which is breaking down to late regrogessive biotite.

Four principal lithologies are presesented in the small xenoliths: psammite, semipelite, calc-silicate schist and basic hornfels. The psammites consist mainly of quartz which, together with a few plagioclase grains, forms a fine-grained mosaic. A relict early foliation is preserved by layers of biotite, garnet, opaques, kyanite, sillimanite and rutile. Kyanite is in the process of altering to sillimanite, and fan-shaped aggregates of fibrolite needles nucleate on garnet. In the semipelites a hornfelsic texture overprints a relict schistosity, the main minerals being plagioclase, biotite, garnet and quartz. The principal mineral in the calc-silicate schists is diopside, occurring as rounded grains, which together with plagioclase forms a granular hornfelsic texture overprinting an early regional metamorphic fabric. Tremolite, quartz and poikiloblastic biotite form a D_2 schistosity, and enclose the rounded grains of diopside and plagioclase. The basic hornfelses represent basic metasediment inclusions, and have a fine-grained granoblastic texture consisting of orthopyroxene and plagioclase, the former beginning to alter retrogressively to amphibole and biotite. In xenoliths in the noritic facies, orthopyroxenes are rimmed by garnet.

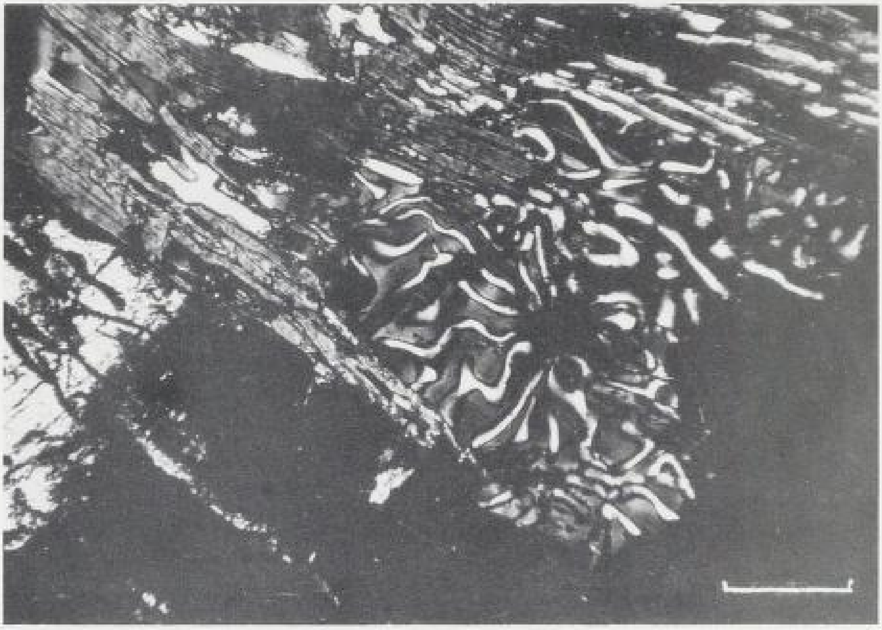


Fig. 12. Biotite with vermicular quartz associated with myrmekite developing from alkali feldspar. Early diorite intrusion in Husfjord metagabbro, Husfjord. Crossed polars. Bar scale = 0.1 mm.

Early intrusions

These are pyroxene-mica-diorites, containing a little alkali feldspar, in which hypersthene and phenocrysts of plagioclase tend to have a preferred orientation parallel to the sheet margins. At the contacts between hypersthene and alkali feldspar biotite often forms at the expense of hypersthene. The biotite usually contains vermicular inclusions of quartz, and this symplectite is frequently closely associated with the development of myrmekite from alkali feldspar (Fig. 12). This is a late metamorphic effect, discussed in Part III. Hornfelsing of the metagabbro by the early diorites postdates the peak of the regional metamorphism, since the regional metamorphic texture and mineralogy are overprinted by a fine-grained granoblastic texture of rounded grains of hypersthene, clinopyroxene and andesine. In places the early diorites have been metamorphosed by the Havnefjord diorite; hypersthene is pseudomorphed by turquoise-green amphibole having a diablastic texture with small rounded blebs of quartz, and this amphibole in turn is regrogressed to biotite containing vermicules of quartz.

2. HAVNEFJORD DIORITE

This is a pyroxene-mica-diorite, sometimes monzodioritic, with a fine-grained subequigranular xenomorphic texture, in which the principal pyroxene is usually hypersthene (Table 2). Although generally non-porphyritic, it occasionally has feldspar phenocrysts which tend to be aligned in a fluxion structure, particularly in the marginal zone. These phenocrysts consist of antiperthite and sometimes perthitic alkali feldspar, the latter generally bordered by myrmekite. When

Table 2. Modal analyses of the Havnefjord diorite

Mineral	36/92B	36/117C	36/126A	36/159B	36/233C	38/48A	05/58A
Qu	–	–	–	2.9	–	0.3	–
Kfeld	37.2	3.5	4.7	0.8	49.7	6.2	5.5
Plag	37.6	59.1	49.6	67.6	21.9	43.5	67.2
Hyp	17.2	23.8	10.8	13.4	15.4	14.7	15.6
Cpx	–	2.5	18.5	–	–	23.2	1.6
Bi	3.6	6.6	12.4	7.8	5.8	6.1	1.7
Hbl	1.8	–	0.8	0.1	0.3	0.2	0.3
Ap	0.2	0.2	0.3	0.9	1.4	0.7	1.3
Zir	–	–	–	0.1	–	–	0.2
Opaq	2.4	4.3	2.9	6.4	5.5	5.1	6.6

3,000 points per thin-section.

diopsidic augite occurs it is often being altered to green hornblende, which in turn is altering to retrogressive poikiloblastic biotites containing vermicular quartz. At contacts with the later monzonite sheets, the Havnefjord diorite is frequently hornfelsed, developing a fine-grained granoblastic texture, mainly consisting of hypersthene, diopside and plagioclase.

Rafts

Some rafts are of recognizable metagabbro, variably hornfelsed, but hybrids are often developed in which the diorite has been contaminated by metagabbro inclusions, forming a rock of intermediate character. These hybrids have a xenomorphic texture like that of the diorite, but the mineralogy has similarities with that of the metagabbro in that the principal pyroxene is clinopyroxene, although some hypersthene does occur, and the opaque minerals are the same as in the metagabbro.

At the margins of the psammite and semipelite rafts a hornfelsic texture develops in which quartz and perthite form polygonal grains, with decussate biotites. Thermal metamorphic garnets overgrow and form from biotite and kyanite, and diffuse relics of radiating kyanite prisms remain in the garnet (Fig. 13). In some rafts, regional metamorphic garnets have become unstable at the raft margins during hornfelsing, and all stages in their pseudomorphing by aggregates of fibrolite, iron oxide, and sometimes biotite can be observed. Some of the more pelitic schists have been slightly feldspathized and contain occasional perthite porphyroblasts.

Basic schist rafts have become two-pyroxene hornfelses due to the thermal effects of the diorite. Hypersthenes are usually large and poikiloblastic with so many inclusions of plagioclase that a diablastic texture develops, similar to the sieve-textured porphyroblastic hypersthenes in sedimentary xenoliths in the hypersthene-gabbro of Ardnamurchan (Wells 1951). Plagioclase is poikiloblastic and appears to be becoming more basic during hornfelsing; the excess silica that cannot be incorporated into the more calcic plagioclase is exsolved as vermicular quartz inclusions (Fig. 14). Long poikiloblastic biotites having a preferred orientation overgrew the pyroxene and plagioclase during regional metamorphism.

Fig. 13. Radiating relict kyanite prisms within garnet. Semipelite raft in Havnefjord diorite, Havnefjord. Plane polarized light. Bar scale = 0.2 mm.

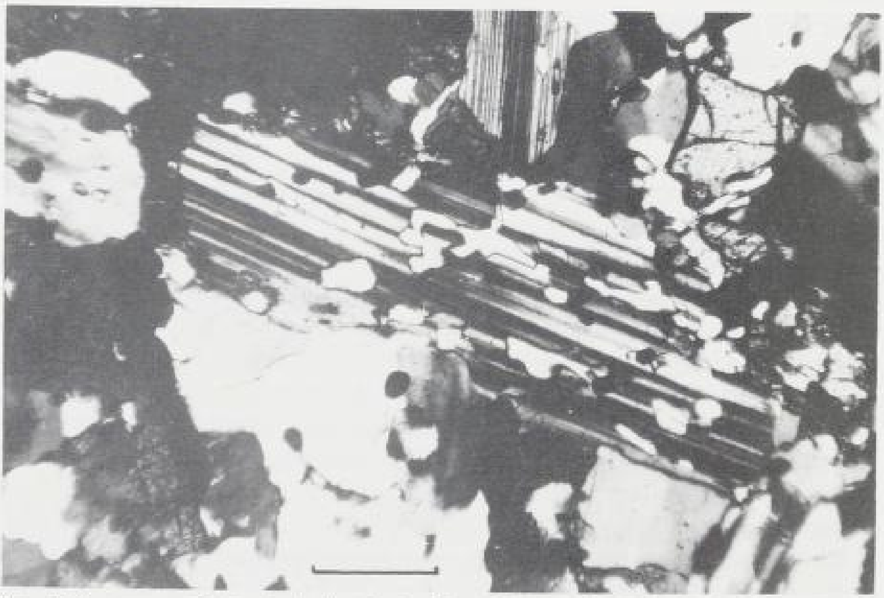


Fig. 14. Quartz vermicules in plagioclase. Basic schist raft in Havnefjord diorite, Havnefjord. Crossed polars. Bar scale = 0.2 mm.

In the marble rafts calcite forms a subequigranular mosaic with fairly straight grain boundaries, and diopsides, apatites, alkali feldspars and opaques occur as interstitial grains. The calc-silicate horizons in the marbles consist of diopside, andesine, opaques and rarely zircon.

Table 3. Modal analyses of the monzonites

Mineral	36/112B	36/237A	36/301A	36/301B	38/18B	38/38A	38/48E
Qu	1.4	–	–	–	–	1.2	–
Kfeld	21.3	32.6	29.6	17.5	50.5	37.8	35.2
Plag	50.6	54.5	53.5	64.4	22.7	43.1	51.5
(Myrm)	–	–	–	–	–	1.9	0.8
Hyp	18.7	7.0	13.0	12.9	13.3	8.9	7.7
Bi	3.6	3.5	1.5	1.7	9.0	4.9	2.3
Hbl	0.5	0.7	0.6	0.2	0.5	0.1	0.2
Ap	–	0.2	0.3	0.5	0.7	–	–
Zir	–	–	–	0.1	–	0.1	–
Opaq	3.9	1.5	1.5	2.7	3.3	2.0	2.3

7,000 points per thin-section.

3. MONZONITES

These are coarse-grained pyroxene-mica-monzonites, are sometimes monzodioritic (Table 3), and have a porphyritic xenomorphic texture in which the pyroxene is strongly pleochroic hypersthene. Biotite, commonly containing vermicules of quartz, frequently envelops hypersthene and sometimes forms from it. Anhedral phenocrysts of perthite and anti-perthite are generally randomly orientated but sometimes form a crude fluxion texture, and the perthite phenocrysts are commonly lobed by myrmekite.

Xenoliths

These range from blocks a few tens of centimetres in length to small fragments distinguisable within a single thin-section, and many are partly assimilated by the monzonite. They are principally semipelites, but there are also some basic hornfelses.

In the semipelites a granoblastic hornfelsic texture is developed with polygonal grains of alkali feldspar, usually hairperthite, and ragged decussate biotites, although a relict schistosity is sometimes preserved. Towards the contacts with the host, biotite is replaced by fibrolite and iron oxides, but in some rocks large fresh poikiloblastic biotites have grown during the waning stages of the regional metamorphism. At some contacts biotite is altered to small hypersthenes, and as the contact is crossed hypersthenes and feldspars gradually become coarser and the amount of biotite decreases until the rock resembles the monzonite.

The basic hornfelses are mostly of metasediment but a few are of Husfjord metagabbro. They have a fine-grained granoblastic texture, generally consisting of hypersthene, labradorite, decussate opaques, and sometimes biotite and clinopyroxene. At the contacts hypersthenes are often large and poikiloblastic, approaching in size those in the host monzonite, and hypersthenes in the monzonite near the xenoliths tend to be very strongly pleochroic suggesting contamination by the metasediment. It appears that these hornfelses too are being converted to monzonite at their margins; further evidence for this transition is described below.

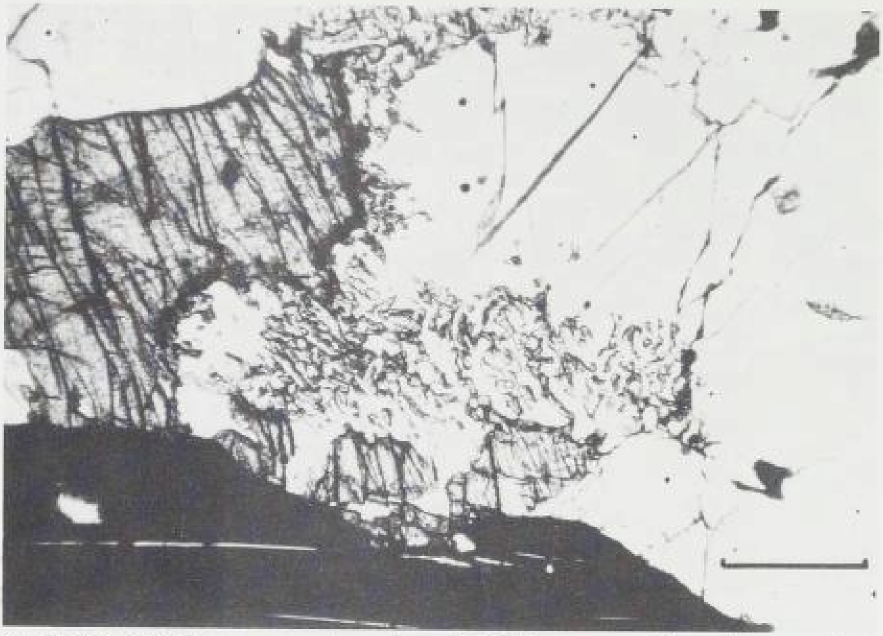


Fig. 15. Vermicular clinopyroxene at hypersthene-alkali feldspar contact. Monzonite next to a basic hornfels xenolith, Havnefjordfjell. Plane polarized light. Bar scale = 0.4 mm.

Symplectites and coronas

These develop in the monzonite next to those xenoliths which are being assimilated. Symplectites form next to the basic hornfels inclusions, whereas coronas occur in the neighbourhood of the semipelitic xenoliths. In both cases chemical instability, apparently as a result of the presence of xenoliths, is indicated.

The symplectites are confined to boundaries between hypersthene and alkali feldspar, the hypersthene becoming frittered with the development of diopside-oligiclase symplectites (Fig. 15). The formation of these is associated with contamination by basic xenoliths, since hypersthene and alkali feldspar are stable together away from the xenoliths. Another phenomenon occurring in the monzonite next to the basic hornfels xenoliths is the presence of opaque inclusions, sometimes vermicular, within hypersthene. These are magnetite and ilmenite, and as the former does not normally occur in the monzonite contamination by the xenoliths is suggested. In the basic hornfels xenoliths themselves small hypersthenes also contain opaque inclusions, often vermicular, closely resembling those in the monzonite hypersthenes. At contacts with xenoliths the monzonite contains large, strongly pleochroic hypersthenes containing a number of small separate inclusions of opaque, each of which resembles the inclusions within the small hornfels hypersthenes (Fig. 16). The large monzonite hypersthenes appear to have formed by the amalgamation of a number of hornfels hypersthenes, each retaining its central opaque inclusion, and under cross-polars the large monzonite hypersthenes are seen to consist of aggregates of small domains. Furthermore, in places the actual annexing of a small hornfels hypersthene to a large monzonite

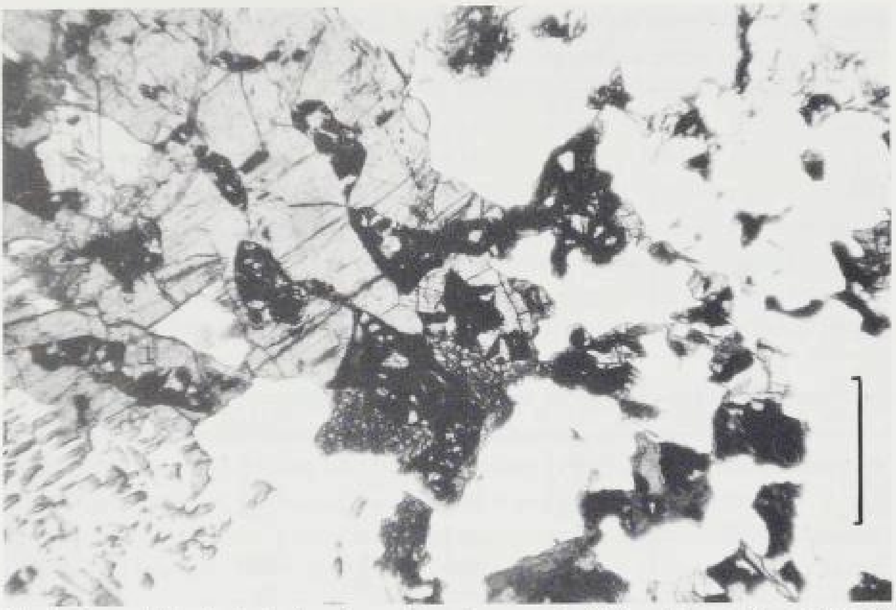


Fig. 16. Iron oxide inclusions in large hypersthene in monzonite (left) and in small hypersthenes in hornfels. Contact of basic hornfels xenolith in monzonite, Husfjord. Plane polarized light. Bar scale = 0.4 mm.

hypersthene, with opaques along the join, can be seen (Fig. 16). Thus some of the minerals in the monzonite appear to have developed from the hornfelsic material which it assimilated.

Coronas involving several minerals form in the monzonite in the neigbourhood of some of the semipelitic xenoliths. Opaques have reaction coronas of dark green hornblende or hypersthene against plagioclase, and sometimes a double corona is formed with hypersthene on the inside against the opaque mineral and hornblende outside against the plagioclase. Some opaques have narrow coronas of granular, colourless garnet against plagioclase, and sometimes there is a shell of hypersthene between the garnet and the opaque. Garnet also forms narrow coronas around some biotites, while other biotites are rimmed by dark green hornblende. The coronas are not ubiquitous, even in the vicinity of semipelitic xenoliths, but occur in irregular fine-grained patches which appear to be assimilated inclusions. The semipelitic hornfels xenoliths themselves sometimes have corona textures very similar to those just described but on a finer scale, particularly the rimming of biotites and hypersthenes by garnet. In addition, some of the more pelitic hornfelses contain green spinel which have coronas of hypersthene or garnet, or both, with garnet on the outside. These coronas in the xenoliths must have formed during hornfelsing, and the fine-grained patches in the monzonite where coronas occur are diffuse relics of assimilated metasediment. Similar symplectites and coronas in the immediate vicinity of xenoliths have been described from the Insch norite of Aberdeenshire (Read 1966). Read considered that the xenoliths were being converted directly into norite by assimilation, and that the norite in the neigbourhood of xenoliths developed as a result of contamination by the hornfelses.

Table 4. Modal analyses of the quartz-syenites

Mineral	38/52A	38/56C	48/29B	03/15C
Qu	22.3	19.6	2.2	9.4
Kfeld	45.4	62.5	47.1	33.0
Plag	20.6	12.7	32.8	39.0
(Myrm)	1.2	–	–	–
Bi	9.3	3.6	17.7	16.0
Musc	0.2	1.5	–	2.2
Hbl	0.2	–	–	–
Ap	0.4	–	–	–
Zir	0.1	0.1	0.2	0.3
Opaq	0.3	–	–	0.1

Mineral	38/13A	38/56C	48/8B	46/4A	46/17A
Qu	6.1	28.1	7.0	11.5	3.0
Kfeld	66.5	37.7	72.7	60.6	40.5
Plag	15.8	20.3	7.8	12.9	33.2
(Myrm)	0.8	–	0.7	0.5	–
Bi	9.7	7.3	10.3	11.6	18.0
Musc	0.4	1.4	0.5	0.2	–
Gnt	0.2	1.2	0.4	1.3	4.8
Ap	–	–	–	0.1	0.1
Zir	0.2	0.2	0.2	1.0	0.2
Sph	–	3.0	–	–	–
Rut	–	–	0.3	–	–
Opaq	0.3	0.8	0.1	0.3	0.2

7,000 points per thin-section.

4. QUARTZ-SYENITES

These coarse-grained quartz-syenites sometimes grade into quartz-monzonite or granite (Table 4), and have a porphyritic xenomorphic texture. Phenocrysts are usually of perthite, commonly with myrmekite developing at their margins, although some are of sodic andesine. A few quartz-syenites contain small anhedral garnets, some of which are altering to biotite; the significance of these garnets is discussed in Section D.

Associated with the quartz-syenite is a coarse feldspathization which affects both the Husfjord metagabbro and its metasedimentary rafts. The metagabbro contains xenoblastic alkali feldspar porphyroblasts, rimmed by myrmekite, and its plagioclase has recrystallized to a polygonal mosaic of sodic andesine. The pyroxenes have completely altered to actinolite and biotite, some of the latter being chloritized. Metasedimentary rafts also contain xenomorphic feldspar porphyroblasts in a matrix of quartz and biotite.

5. VATNA GABBRO

In the southern fine-grained facies, which generally have xenomorphic textures, the principal mafic minerals is pale greenish-buff augite which tends to have blebs and fine schiller needles of opaques, and in places is altered to biotite. Rounded fresh olivines and basic labradorites are sometimes elongated parallel to one another forming a fluxion texture. The northern coarse-grained facies in places exhibits ophitic textures, in which augite containing opaque schiller lamellae is slightly altering to brown hornblende. Some of the coarse rocks contain olivines which generally have narrow coronas of hypersthene or fibrous cummingtonite.

Inclusions and veins

Inclusions are of two kinds: autoliths and xenoliths. The autoliths are inclusions of fine-grained early marginal facies of the gabbro enclosed within the main body, and have a strong fluxion texture. They have the same mineralogy as typical fine-grained facies Vatna gabbro, but are finer grained. The xenoliths comprise a variety of lithologies, mainly coarse-grained pyroxenites but also brown amphibolites.

At Vatna the gabbro contains small irregular veins and streaks of coarse pink perthite which usually merge gradually into normal gabbro. In the transitional lithology the olivine-gabbro becomes progressively enriched in hair-antiperthite, which itself becomes perthite as the veins are approached. The antiperthitic streaks in the gabbro occasionally have mafic aggregates containing considerable amounts of opaque minerals. These aggregates consist of rounded grains of clinopyroxene, olivine, apatite, antiperthite and large euhedral zircons, with the opaques being interstitial. These opaques, principally magnetite but also ilmenite, pyrite, pyrrhotite and chalcopyrite, are often rimmed by biotite where they make contact with antiperthite.

Intrusions

The perthosites are composed almost entirely of hair-perthite, accessory minerals including aegerine-augite, diopside, hypersthene, hornblende, apatite and zircon; the hypersthene is strongly corroded and variably pseudomorphed by iddingsite. The rock has a xenomorphic texture, with perthite grains having highly sutured margins. These sutures become quite complex so that neighbouring crystals are interlocked, and early stages in the development of swapped rims (Voll 1960) can be seen. At the margins of most perthite grains, especially where incipient swapped rims are forming, the perthite lamellae peter out and a single-phase zone occurs; this also happens around some of the inclusions within the perthites. Both the highly sutures margins and the marginal zones indicate that the perthosites have undergone some recrystallization during waning stages of the regional metamorphism.

The basic dykes vary greatly in grain-size but the majority are fine-grained and ophitic textures are common. Some are non-porphyritic whereas others have phenocrysts of zoned plagioclase. Augite, which also sometimes forms phenocrysts, commonly contains opaque schiller lamellae and shows incipient alteration to brownish hornblende and biotite.

The nepheline syenite pegmatites consist primarily of alkali feldspar and nepheline with sporadic sodic plagioclase and mafic minerals such as hornblende and biotite. They have been extensively sheared, and various stages through mortar textures up to a true mylonite can be observed. Nepheline was the mineral least resistant to shearing, and lenses of sericitized nepheline streaked out along the foliation are common.

Table 5. Chemical analyses of the Husfjord metagabbro

Major elements	1 36/1A	2 36/3A	3 36/54A	4 36/11F	5 36/11G	6 11/64A	7 60/47H	8 36/118F	9 36/225A
SiO_2	48.35	47.50	48.20	46.93	47.54	46.40	46.47	50.93	49.56
TiO_2	2.31	2.42	1.72	2.32	2.10	2.35	3.45	2.05	2.28
Al_2O_3	16.85	15.87	17.44	16.31	16.69	16.94	16.30	18.21	16.27
Fe_2O_3	2.21	2.64	1.53	2.30	2.87	2.36	1.02	3.35	3.67
FeO	8.52	8.70	8.49	9.07	7.09	8.03	15.16	7.28	8.88
MnO	0.11	0.11	0.10	0.11	0.09	0.09	0.17	0.09	0.11
MgO	6.34	6.53	6.94	7.52	7.28	6.04	3.12	4.24	6.48
CaO	10.19	10.98	10.84	9.30	9.86	11.87	7.27	6.44	6.86
Na_2O	3.40	3.02	2.74	2.12	2.90	3.23	3.40	3.29	2.34
K_2O	1.24	0.73	0.92	2.45	1.13	0.71	1.20	2.43	2.27
P_2O_5	0.15	0.17	–	0.15	0.14	0.16	0.29	0.10	0.08
H_2O^+	0.71	0.68	0.56	0.67	0.95	0.59	0.81	1.03	2.33
H_2O^-	0.11	0.07	0.08	0.10	0.29	0.17	0.19	0.12	0.19
	100.49	99.42	99.56	99.35	99.74	98.94	98.85	99.56	101.32
CIPW norms									
q	–	–	–	–	–	–	–	–	0.07
or	7.33	4.20	5.38	14.07	6.50	4.20	7.09	14.07	13.42
ab	23.96	23.71	22.05	15.79	24.02	19.45	28.77	28.01	19.80
an	27.05	26.42	31.58	26.71	28.13	29.63	25.67	26.77	27.19
ne	2.61	1.09	0.71	1.21	0.42	4.27	–	–	–
di	18.37	20.75	17.27	13.98	15.06	22.97	7.27	3.13	5.15
hy	–	–	–	–	–	–	4.09	14.41	23.34
ol	12.41	11.52	14.89	16.49	14.08	9.41	16.25	1.30	–
mt	3.20	3.83	2.22	3.33	4.16	3.42	1.48	4.84	5.32
il	4.39	4.60	3.27	4.41	3.99	4.46	6.55	3.89	4.33
ap	0.35	0.39	–	0.35	0.32	0.37	0.67	0.23	0.19

1–3, fine-grained facies; 4–6, coarse-grained facies; 7, noritic facies; 8–9, feldspathized metagabbro
Analyst: the writer, by XRF

C. Chemistry

1. HUSFJORD METAGABBRO

Chemical analyses of the Husfjord metagabbro are presented in Table 5 and it can be seen that, except for the contaminated noritic facies and the two slightly feldspathized specimens, they are nepheline-normative. Total alkalies are plotted against silica in Fig. 17A, showing that the metagabbro falls in the alkaline field of Irvine & Baragar (1971). The two specimens of feldspathized metagabbro, however, have slightly higher values of silica and alkalies.

In northern Sørøy there are two gabbro sheets, the Storelv and Breivikbotn gabbros, which have several field, mineralogical and chemical characteristics similar to the Husfjord metagabbro (Stumpfl & Sturt 1965, Sturt & Taylor 1972). These are plotted on Fig. 17A for comparison with the Husfjord metagabbro; although they have a greater scatter for points they too fall mainly in the alkaline field.

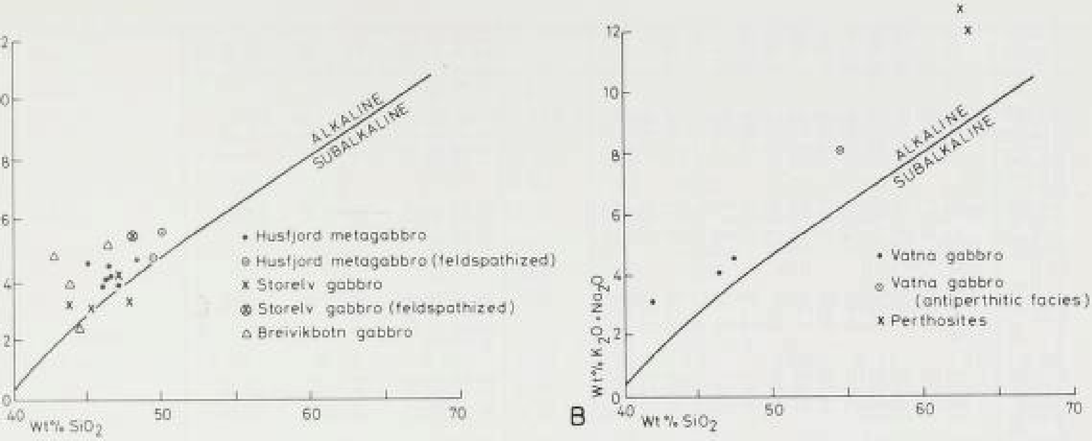


Fig. 17. Plot of total alkalies v. silica. A. Husfjord metagabbro, and the Storelv and Breivikbotn gabbros (data from Stumpfl & Sturt 1965). B. Vatna gabbro and perthosites. Alkaline/subalkaline boundary from Irvine & Baragar (1971).

Table 6. Chemical analyses of the Vatna gabbro and perthosites

Major elements	1 11/29I	2 07/25D	3 07/25G	4 11/38K	5 11/1C	6 11/25A
SiO_2	47.58	46.78	42.67	54.55	63.46	63.26
TiO_2	1.78	2.93	4.81	1.91	0.26	0.44
Al_2O_3	22.17	16.66	15.31	17.57	18.66	19.10
Fe_2O_3	1.56	2.62	1.45	1.80	0.56	0.47
FeO	6.18	8.64	12.41	8.30	1.31	1.53
MnO	0.08	0.12	0.12	0.12	0.02	0.03
MgO	4.08	6.42	7.21	1.67	0.84	0.06
CaO	11.52	11.30	11.17	5.18	1.41	1.44
Na_2O	4.20	3.46	2.73	6.01	6.55	7.42
K_2O	0.28	0.64	0.34	2.01	5.39	5.30
P_2O_5	0.18	0.16	0.42	0.09	–	–
H_2O^+	0.55	0.61	0.70	0.58	0.98	0.15
H_2O^-	0.57	0.12	0.16	–	0.21	0.16
	100.24	100.36	99.50	99.79	99.65	99.36

CIPW norms						
or	1.65	3.78	1.95	11.88	31.56	30.97
ab	24.28	21.73	9.70	47.43	55.59	54.03
an	40.82	28.04	25.23	15.03	5.19	2.57
ne	6.10	4.09	7.30	1.86	–	4.55
di	12.41	21.91	22.47	8.01	1.44	3.60
wo	–	–	–	–	–	0.16
hy	–	–	–	–	1.68	–
ol	8.29	10.35	15.25	7.96	0.93	–
mt	2.26	3.80	2.10	2.61	0.81	0.68
il	3.38	5.56	9.14	3.63	0.49	0.84
ap	0.42	0.37	0.97	0.21	–	–

1–3, Vatna gabbro; 4, Vatna gabbro, antiperthitic facies; 5–6, perthosite.
Analyst: the writer, by XRF

Table 7. Chemical analyses of the diorite – monzonite – quartz-syenite suite

Major elements	1 36/99A	2 36/116A	3 36/117C	4 36/233C	5 36/237A	6 38/1A	7 38/18B	8 38/38A	9 38/13A	10 38/31A	11 38/56C	12 46/4A	13 48/8B	14 48/29B	15 03/15C
SiO_2	54.60	48.69	52.77	51.55	55.31	56.54	58.32	56.96	69.51	63.44	59.52	63.91	65.35	63.39	67.06
TiO_2	1.16	2.27	1.89	2.35	1.44	1.38	1.09	1.36	0.53	0.81	1.27	0.95	0.73	0.90	0.57
Al_2O_3	18.78	17.61	19.90	19.40	18.56	18.40	18.88	17.45	15.94	17.34	16.23	16.61	18.02	18.23	16.38
Fe_2O_3	1.32	2.25	1.26	1.18	1.31	1.91	1.20	1.31	0.35	1.18	2.09	0.87	0.36	0.58	0.44
FeO	7.27	8.11	8.59	10.46	6.76	4.94	4.86	6.59	2.23	3.35	5.60	4.47	2.64	2.95	2.93
MnO	0.11	0.15	0.15	0.17	0.11	0.08	0.07	0.11	0.03	0.06	0.10	0.05	0.02	0.04	0.05
MgO	3.17	5.29	3.23	2.24	1.61	2.48	1.55	2.24	0.92	1.49	2.41	1.47	1.37	1.52	1.08
CaO	6.91	11.34	7.25	5.81	5.00	4.93	4.15	4.17	1.94	1.34	2.78	2.05	2.64	2.17	1.65
Na_2O	4.28	2.39	2.97	2.53	4.20	3.79	3.94	3.68	2.76	3.15	3.41	2.75	3.78	2.89	2.58
K_2O	1.47	1.11	2.08	3.87	4.22	4.42	5.19	4.89	5.33	6.51	5.13	6.32	5.12	6.67	6.17
P_2O_5	0.09	0.14	–	–	–	0.06	0.05	0.06	–	–	–	0.02	–	–	0.01
H_2O^+	0.45	0.76	0.39	0.58	0.60	0.95	0.50	0.69	0.71	0.96	0.61	0.18	0.71	1.04	0.85
H_2O	0.11	0.14	0.11	0.08	0.14	0.12	0.17	0.13	0.04	0.12	0.21	0.09	0.06	0.19	0.17
	99.72	100.25	100.36	100.22	99.26	100.00	99.97	99.64	100.29	99.75	100.36	99.74	100.80	100.57	99.94
CIPW norms															
q	0.79	–	–	–	–	5.99	1.42	1.90	21.55	7.89	8.12	12.38	18.89	13.97	20.53
or	7.98	6.74	12.29	19.15	20.86	17.08	27.60	29.37	31.14	37.76	27.42	33.39	19.86	28.84	34.10
ab	36.22	22.76	30.46	25.64	34.82	32.07	31.14	33.34	28.52	33.09	28.85	27.50	31.99	29.70	25.55
an	28.05	30.48	32.00	26.49	19.43	22.18	15.23	17.41	9.33	6.70	13.10	9.69	13.10	10.77	7.92
ne	–	–	–	–	0.39	–	–	–	–	–	–	–	–	–	–
cor	–	–	–	0.06	–	0.26	–	–	0.48	0.99	0.44	0.98	2.00	2.71	2.26
di	2.35	15.75	3.31	–	3.05	–	3.09	1.15	–	–	–	–	–	–	–
hy	16.83	2.00	4.92	7.68	–	11.14	12.64	9.04	5.65	7.59	12.35	9.99	6.78	7.71	7.04
ol	–	–	10.84	9.23	8.14	–	–	–	–	–	–	–	–	–	–
mt	1.91	3.26	1.83	1.71	1.87	2.70	1.86	1.64	0.51	1.55	2.91	1.15	0.52	0.84	0.64
il	2.20	4.31	3.59	5.49	2.73	2.62	2.58	2.07	0.93	1.50	2.41	1.79	1.39	1.69	1.08
ap	0.21	0.32	–	–	–	0.14	0.14	0.12	–	–	–	0.05	–	–	0.02

1–4, Havnefjord diorite; 5–8, monzonite; 9–15, quartz-syenite.
Analyst: the writer, by XRF

Table 8. Partial chemical analyses of mineral separates of coexisting feldspars in the diorite – monzonite – quartz-syenite suite

Alkali feldspar	1 36/117C	2 36/233C	3 36/237A	4 38/18B	5 38/38A	6 38/56C	7 38/13A	8 38/31A	9 46/4A	10 48/8B
CaO (wt %)	3.29	1.22	2.18	0.96	2.25	1.57	0.28	0.40	0.22	1.48
Na_2O	2.55	1.87	2.60	1.62	2.60	2.50	1.92	1.92	1.67	2.80
K_2O	8.55	13.48	10.20	11.52	9.68	8.80	13.10	12.00	14.60	8.37
Ba (ppm)	2300	4300	7250	4200	5550	2100	5100	3700	4550	9100
Rb	60	140	120	140	130	180	325	210	250	170
Sr	500	575	540	500	535	430	425	395	405	635
Plagioclase										
CaO (wt %)	9.04	9.12	8.19	7.40	8.26	4.50	2.65	4.14	3.44	3.85
Na_2O	5.84	6.15	6.50	6.41	6.47	5.17	3.57	5.06	4.81	5.45
K_2O	0.62	0.50	0.57	0.78	0.50	0.88	1.15	0.58	1.22	0.95
Ba (ppm)	530	200	140	530	95	590	510	100	440	570
Rb	14	–	2	11	2	24	57	14	22	32
Sr	650	580	540	500	580	420	210	280	280	460

1–2, Havnefjord diorite; 3–5, monzonite; 6–10, quartz-syenite.
Analyst: the writer, by XRF

Robins & Gardner (1974, 1975) have divided the Seiland petrographic province into subprovinces, in which there is a general trend from early subalkaline gabbros through transitional rocks to later alkaline gabbros. The Breivikbotn, Storelv and Husfjord gabbros are included in the pre-D_2 subalkaline subprovince by Robins & Gardner. The chemical data, however, suggest that these early gabbros are fairly alkaline, lying chemically (but not temporally) between the pre-D_2 tholeiitic Hasvik gabbro of southwestern Sørøy and the late-D_2 Rognsund clinopyroxene-gabbro on Seiland (Robins & Gardner 1974).

2. VATNA GABBRO

Chemical analyses of the Vatna gabbro and its associated perthosites are presented in Table 6. This gabbro is strongly nepheline-normative which, together with a plot of total alkalies against silica (Fig. 17B), indicates its alkaline nature. The antiperthitic facies plots in an intermediate position between the normal facies and the perthosites.

On Seiland a syn-D_2 syenogabbro with associated perthosites may be approximately contemporaneous with the Vatna gabbro, and the two gabbros have been placed in a transitional (high-K tholeiite) subprovince by Robins & Gardner (1975).

3. DIORITE – MONZONITE – QUARTZ-SYENITE SUITE

Whole rock analyses of the diorite – monzonite – quartz-syenite suite, for both major and trace elements, are presented in Table 7, and partial analyses of coexisting feldspars in this suite in Table 8. The analyses were carried out by the author using X-ray fluorescence (and classical wet methods for the determination of FeO and H_2O). The chemistry of this suite suggests that these rocks may form a petrogenetic series, as discussed below.

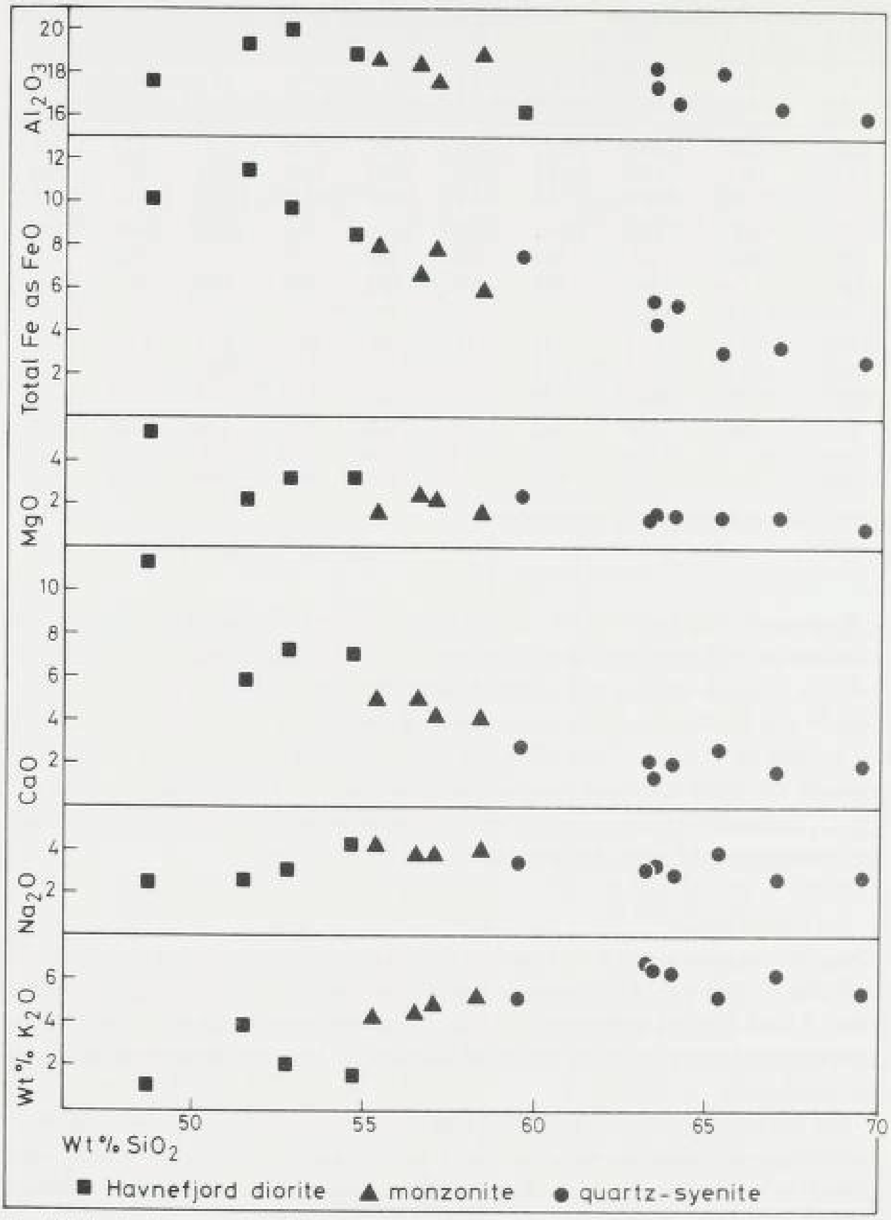


Fig. 18. Harker diagram of the diorite – monzonite – quartz-syenite suite.

Whole rock analyses

The chemical data for the diorite – monzonite – quartz-syenite suite are presented on a Harker diagram (Fig. 18), and various triangular diagrams (Fig. 19). These show a progressive trend from fairly basic Havnefjord diorite, through monzonite, to relatively acid quartz-syenite. MgO, FeO and CaO decrease in absolute amounts (Fig. 18), but remain in fairly constant proportion with respect to each other (Figs.

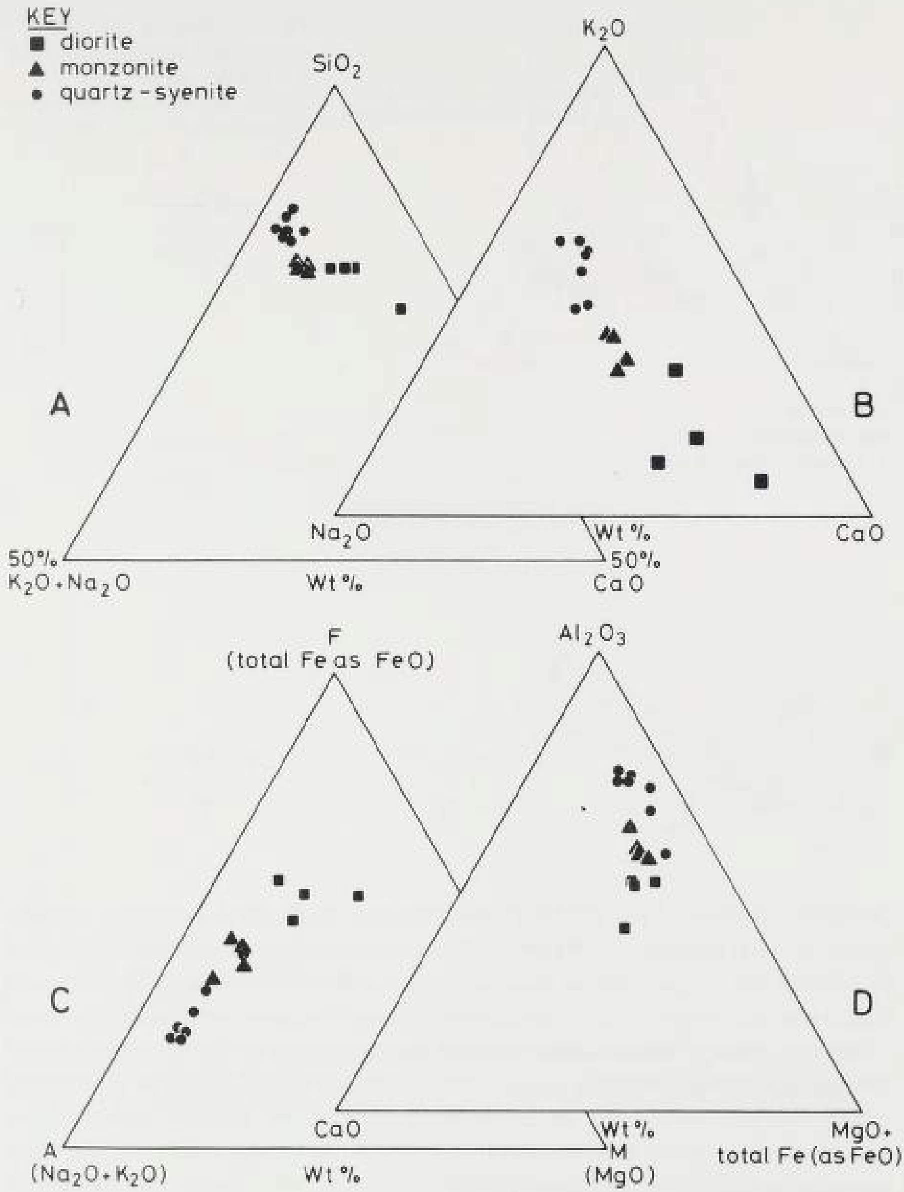


Fig. 19. Plots of the diorite – monzonite – quartz-syenite suite. A. System SiO_2 – (K_2O + Na_2O) – CaO. B. System K_2O – Na_2O – CaO. C. AFM diagram. D. System Al_2O_3 – CaO – (MgO + total Fe).

19C & D) while there is a corresponding increase in SiO_2 and the alkalies (Fig. 19A), with the K/Na ratio progressively increasing (Fig. 19B). The AFM diagram (Fig. 19C) shows that as alkali enrichment takes place the Fe/Mg ratio remains constant at about 3, with no Fe-enrichment during differentation. Although care must be taken while interptreting trends in AFM diagrams (Robinson & Leake 1975), all these various trends suggest that this suite of rocks may form a

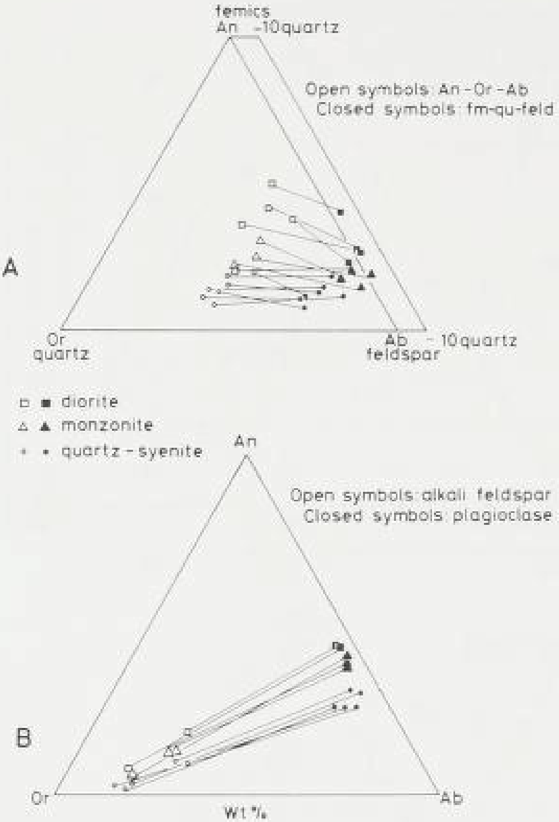


Fig. 20. Plots of the diorite – monzonite – quartz-syenite suite. A. CIPW norms after Larsen (1938). B. Coexisting feldspars in the system An – Or – Ab.

petrogenetic series. Field evidence confirms that both the monzonites and the quartz-syenites postdate the Havnefjord diorite, but there is no evidence in the field to indicate the relative ages of the monzonites and quartz-syenites. The chemical data, however, suggest that the quartz-syenites are the latest members of the suite.

An expression of the saturation of the series is given by the CIPW norms plotted on a triangular diagram (after Larsen 1938) presented in Fig. 20A. The Havnefjord diorite lies just within the undersaturated field in the femics-quartz-feldspar system showing that it is quite a silica-poor diorite, but later members of the series are entirely within the oversaturated field.

Feldspar analyses

The whole rock trend away from calcium towards the alkalies is reflected in the major elements in coexisting feldspars in the diorite – monzonite – quartz-syenite suite (Fig. 20B).

The variations of trace elements with respect to each other in alkali feldspars are sympathetic with those in the corresponding coexisting plagioclase, and these trends are presented by plotting total concentrations of Ba, Rb and Sr in the coexisting feldspars against each other (Figs. 21A–C). During evolution of the series absolute amounts of Ba and Rb increase while Sr decreases, and there is an

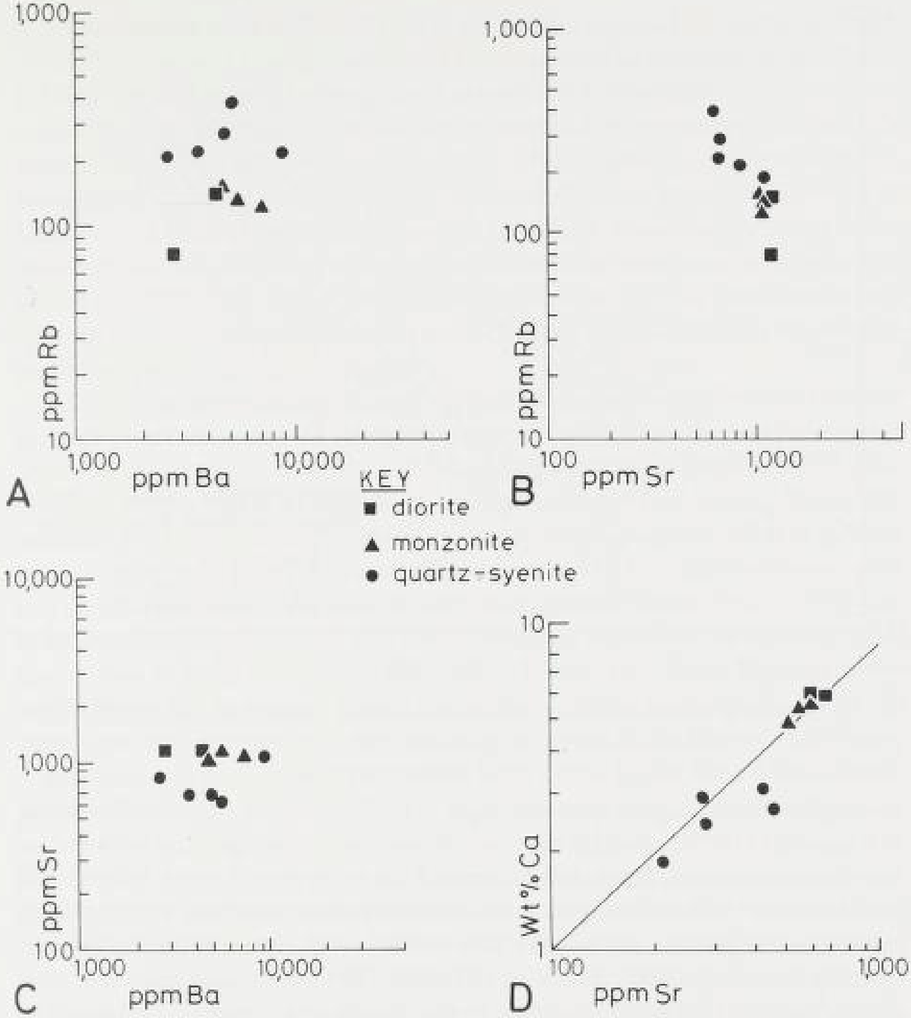


Fig. 21. Graphs of the diorite – monzonite – quartz-syenite suite. A. Total Rb v. total Ba in coexisting feldspars. B. Total Rb v. total Sr in coexisting feldspars. C. Total Sr v. total Ba in coexisting feldspars. D. Ca v. Sr in plagioclase. Squares – diorite, triangles – monzonite, circles – quartz-syenite.

increase in the radios Rb/Sr, Ba/Sr and Rb/Ba, indicating that Rb is concentrated in the later members and Sr in the earlier rocks.

Similar trends are reported for the Rb/Sr ratio by Sen et al. (1959) and Taylor et al. (1968), and for the Rb/Ba ratio by Herz & Dutra (1966) and Taylor et al. (1968), and are due to the incorporation of Rb in late phases because of its large ionic radius and low charge. The Ba/Sr ratio is more problematical in that El Bouseily & El Sokkary (1975) describe an increase in this ratio with fractionation, while others report decreases (Heier & Taylor 1959, Taylor & Heier 1960, Heier 1962). The latter authors point out that Ba has a slightly lower electronegativity than Sr and forms a more ionic bond, apparently favouring its entry into lattice sites before Sr. Nockolds & Allen (1953) on the other hand maintain that Ba is

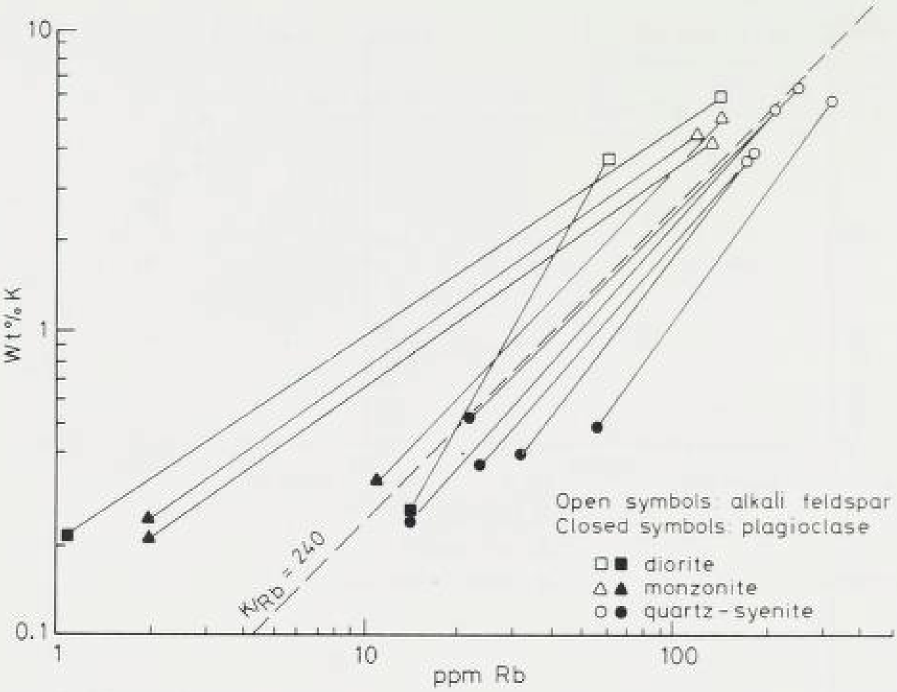


Fig. 22. Graph of K v. Rb in coexisting feldspars in the diorite – monzonite – quartz-syenite suite.

not depleted in the magma until late stages in a differentiation sequence. According to Ringwood (1955), provided that the difference in electronegativity between two ions does not exceed 1, Goldschmidt's rules of diadochy should apply. In the presnt case it seems that the difference in electronegativity between Ba and Sr is insufficient to prevent the smaller ionic radius of Sr from taking Precedence, ensuring early entry for Sr. According to Smith (1974), Sr tends in general to enter plagioclase while Ba tends to remain in the crystallizing liquid. Sr replaces K in alkali feldspar as well as ca in plagioclase, whereas Ba only significantly replaces K in alkali feldspar, and thus Sr has affinities for plagioclas and Ba for alkali feldspar (Sen 1960). Therefore in a suite of rocks as those under discussion, in which alkali feldspar becomes progressively more dominant with evolution, an increase in the Ba/Sr ratio is to be expected. This is supported by the fact that in granitic rocks there is a weak positive correlation between Ba/Sr ond Or content, and that syenitic rocks in alkali feldspar have unusually high Ba/Sr ratios (Smith 1974).

Each of the trace elements Ba, Rb and Sr have been plotted against K, Na and Ca. The most significant trends are the behaviour of Sr in plagioclase, and variations in K/Rb ratios in coexisting feldspars. With differentation of the diorite – monzonite – quartz-syenite suite absolute values of Sr and Ca in plagioclase fall, with the Ca/Sr ratio remaining almost constant at about 100 (Fig. 21D). The constant, linear relationship between these elements has been commented on by Herz & Dutra (1966), and the value of the average partition coefficient for the

Husfjord rocks is close to the 120 for granodiorites reported by Kolbe & Taylor (1966). In basic rocks the Sr content of plagioclase rises as Ca content falls (Butler & Skiba 1962), while Sr has its greatest abundance in plagioclase in intermediate rocks (Wager & Mitchell 1951), and the Sr content falls sympathetically with Ca in acidic rocks (Sen et al. 1959, Hall 1967). This is because calcic plagioclase is less efficient than sodic plagioclase at extracting Sr from the melt (Korringa & Noble 1971). Another factor is that acid rocks contain more alkali feldspar which removes from the magma some of the Sr which would otherwise go into plagioclase (Sen et al. 1959, Hall 1967, El Bouseily & El Sokkary 1975). This accords well with the trends of the Husfjord suite, in which alkali feldspar plays an increasingly important part during differentation.

K/Rb ratios for coexisting feldspars in the diorite – monzonite – quartz-syenite suite are presented in Fig. 22. There is an enrichment in Rb both in absolute terms and with respect to K with differentiation, the series having an average K/Rb ratio of about 240, a figure in agreement with the average K/Rb ratio for normal igneous rocks (Taylor et al. 1956), although the possible range of values in igneous rocks is quite wide (Herz & Dutra 1966, Shaw 1968). In a differentiation series it is common for the K/Rb ratio to drop during fractionation (Smith 1974) due to the late incorporation of Rb into the K lattice site because of the relatively large ionic radius of Rb (Nockolds & Allen 1953, Taylor et al. 1956, Taylor & Heier 1960, Heier 1962, Herz & Dutra 1966, Shaw 1968, Taylor et al. 1968). In agreement with this principle, the coexisting feldspars in the diorite – monzonite – quartz-syenite suite show a progressive drop in the K/Rb ratio with differentiation.

Summary

In summary it can be stated that the chemical trends exhibited by both the whole rock and the feldspar analyses indicate that the diorite – monzonite – quartz-syenite suite forms a petrogenetic series. This suite was emplaced just after the peak of the regional metamorphism and its petrogenesis is associated with that event, as discussed below.

D. Petrogenesis

The members of the Husfjord igneous complex span a time interval from late-D_1 (Husfjord metagabbro) to syn-D_2 (Vatna gabbro and its associated alkaline rocks). During this interval the Finnmarkian orogeny reaches its structural and metamorphic peak, and the complicated igneous history is closely related to the development of the orogen.

In this part of the Seiland province, intrusive igneous activity evolved from low-K tholeiitic magmas through high-K calc-alkali and possibly transitional high-K basaltic magmas to alkali olivine basalt, and finally highly differentiated alkali magmas and carbonatites (Robins & Gardner 1975). This general chemical trend in the development of the Seiland igneous province is linked by Robins &

Gardner to a long-lived mantle diapir complex in the asthenosphere above a subduction zone dipping eastwards beneath the Baltic plate, and becoming progressively steeper with time. This mantle diapir would have been the source of the essentially basic and ultrabasic Seiland plutonic complex, the upper part of which has been displaced to the southeast by nappes which decapitated the mantle diapir (Ramsay 1973). The root of the diapir may underlie S. W. Sørøy where there is a high positive gravity anomaly approaching 100 mgal (Brooks 1970). This positive anomaly, indicating the presence of mafic and ultramafic rocks, is thought to continue southwestwards along the coast of Lofoten (Brooks 1970).

The Husfjord metagabbro is a product of the first phase of magmatic activity associated with the mantle diapir, late in D_1 Field, mineralogical and chemical characteristics of the Storelv and Breivikbotn gabbros of Sørøy (Stumpfl & Sturt 1965, Sturt & Taylor 1972) indicate that these are probably contemporaneous with the Husfjord metagabbro. The later Vatna gabbro and its associated syenitic rocks, however, are likely to be coeval with the syn-D_2 syenogabbros of Seiland (Robins & Gardner 1975).

The emplacement of the mantle diapir into the crust would have caused considerable heating of the metasedimentary pile. It is significant that the peak of the regional metamorphism was closely followed by the emplacement of the diorite – monzonite – quartz-syenite complex, and this suite was probably generated from lower crustal material fused by the heat of metamorphism and the mafic mantle diapir.

Gastil (1975) considers that magmas from the mantle intruded into the crust overlying a subduction zone could cause the generation of welts of tonalitic magma, from which plutons might arise. Dioritic magmas generated by anatexis of crustal rocks would possibly be in the form of crystal mushes under conditions of normal regional metamorphism, but would contain a higher proportion of liquid if additional heat is introduced by the emplacement of basic or ultrabasic magmas in the region (Wyllie 1977). In the Husfjord area considerable additional heat was introduced by the rising mantle diapir which was the parent of the abundant basic and ultrabasic plutons of the Seiland province. The volume of melt which can form by anatexis is also dependent upon the quantity of water available, which is essentially controlled by the amount of hydrous minerals, such as biotite and amphibole, in the crustal rocks (Fyfe 1973); these minerals are abundant in the schists of the Sørøy succession. One of the products of the breakdown of biotite on melting of paragneisses can be hypersthene (Büsch et al. 1974), which is the main mafic mineral in the Havnefjord diorite and monzonites, and the extensive breakdown of biotite to form pyroxene lowers the solidus temperature of the gneiss (Büsch et al. 1974). The intrusive hypersthene-tonalites in the Rio de Janeiro region are thought by Leonardos & Fyfe (1974) to represent extreme products of progressive melting of lower crustal rocks. Hoschek (1976) found that a gneissic assemblage of biotite,plagioclase and quartz began melting between 650° and 725°C at 4 kb P_{H_2O}, according to the composition of the plagioclase, although these temperatures would be lower at higher P_{H_2O}, and Lappin & Hollister (1980) produced a tonalitic melt by melting a hornblende-plagioclase-biotite-quartz gneiss between 675° and 750°C at 6–8 kb P_{H_2O}.

Wyllie (1977) suggests that dioritic plutons can result from the more refractory components during crustal anatexis, the more siliceous and alkali-rich volatile-bearing fractions producing smaller bodies of granitic rocks at higher levels. Studies of the system Ab-An-Or-SiO_2-H_2O by Presnall & Bateman (1973) confirm that it is possible to produce a suite of granitic rocks, as in the Sierra Nevada batholith, by fractional crystallization of a parental dioritic magma produced by equilibrium fusion at the base of the crust (Presnall 1979). The Husfjord monzonites and quartz-syenites are small, late, coarse-grained bodies produced by fractionation of the dioritic magma, and developed as late-stage pegmatitic fluid-rich phases, probably due to vapour saturation at points where crystallization of the diorite was more advanced (Whitney 1975). This could explain their common occurrence alongside the larger metasedimentary rafts in the diorite where cooling and slight contamination would promote crystallization. The small diffuse xenoliths in the diorite and monzonites may represent relict metasedimentary material which had resisted melting (Presnall & Bateman 1973, White & Chappell 1977). Experimental work on the fusion of sediments shows that the melting curve of shales is only about 20°C higher than the minimum melting curve of granite in the presence of water, and assuming a geothermal gradient of about 30°C/km, shales would melt in the depth range of 20–25 km (Wyllie & Tuttle 1960, 1961). It is deduced from the mineral paragenses of the Husfjord rocks that the approximate depth of the regional metamorphism at its peak was greater than 20 km, and the temperature in excess of about 620°C; temperatures at greater depths where the dioritic magma developed would have been higher.

If shales are completely melted they would produce magmas of intermediate composition but which have different chemical characteristics from melts produced from igneous parents by fractionation (Wyllie & Tuttle 1961). The main difference is that rocks formed from fused shales are richer in aluminium, and this can sometimes cause the crystallization of aluminous phases (Wyllie & Tuttle 1961). Members of the diorite – monzonite – quartz-syenite suite are plotted on Fig. 23, and compared with average diorites and monzonites (Nockolds 1954) and with the Plauen quartz-syenite (Johannsen 1932). Each group of rocks from Husfjord is, on the whole, more aluminous than its equivalent from the literature, suggesting that they may have originated from the melting of metasediments. This relatively high aluminium content may account for the presence of occasional garnets in some of the quartz-syenites, for the occurrence of garnet in granitic rocks is considered by Green (1976) to suggest an origin by equilibrium fusion of pelites. The fact that garnet rather than cordierite has formed indicates that the depth of generation of the magma from metasedimentary material was in the order of 25 km or more (Green 1976), although the presence of Mn can lower this a little Green 1977). The average of 235 shales (Pettijohn 1949) is also plotted on Fig. 23, and this falls very close to the average composition of the whole diorite – monzonite – quartz-syenite series, which must represent the bulk composition of the parent material of the suite. Thus the diorite – monzonite – quartz-syenite

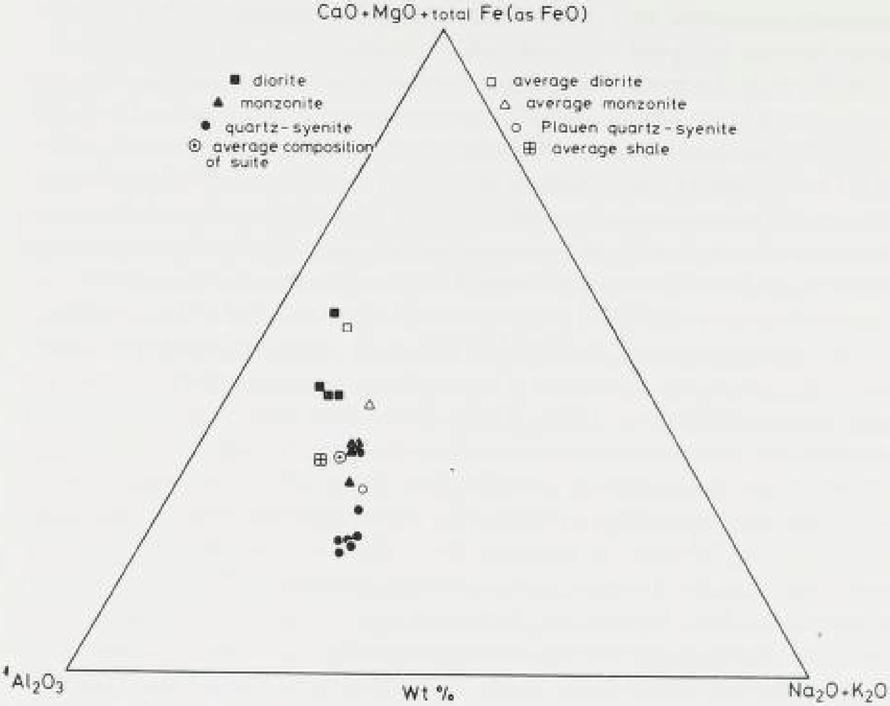


Fig. 23. Composition of the diorite – monzonite – quartz-syenite suite compared with average igneous rocks and shales. Average of 50 diorites and 46 monzonites from Nockolds (1954), Plauen quartz-syenite from Johannsen (1932), and average of 235 shales from Pettijohn (1949).

series could have been generated by fusion of metasediments at about 25 km depth in the crust at the peak of the regional metamorphism, with additional heat being provided by the rising mantle diapir above the subduction zone.

III. Metamorphism

The rocks of the Husfjord area have undergone two major episodes of Finnmarkian deformation, D_1 and D_2; the regional metamorphism began during D_1, increased to its peak between D_1 and D_2, and waned during D_2. Thus the character of the metamorphism varied from being syntectonic during the more intense deformation phases, to essentially static between D_1 and D_2, and superimposed upon this regional metamorphism were thermal metamorphic effects of some of the igneous intrusions. These metamorphic phases are discussed below chronologically, and the relationships between the metamorphic, tectonic and igneous events are summarized in Fig. 24.

The earliest D_1 fabric recorded is a weakly developed schistosity, which is folded around later isoclinal D_1 minor folds. The mineralogy and textures formed in the metasediments during the syn-D_1 metamorphism have been destroyed in places

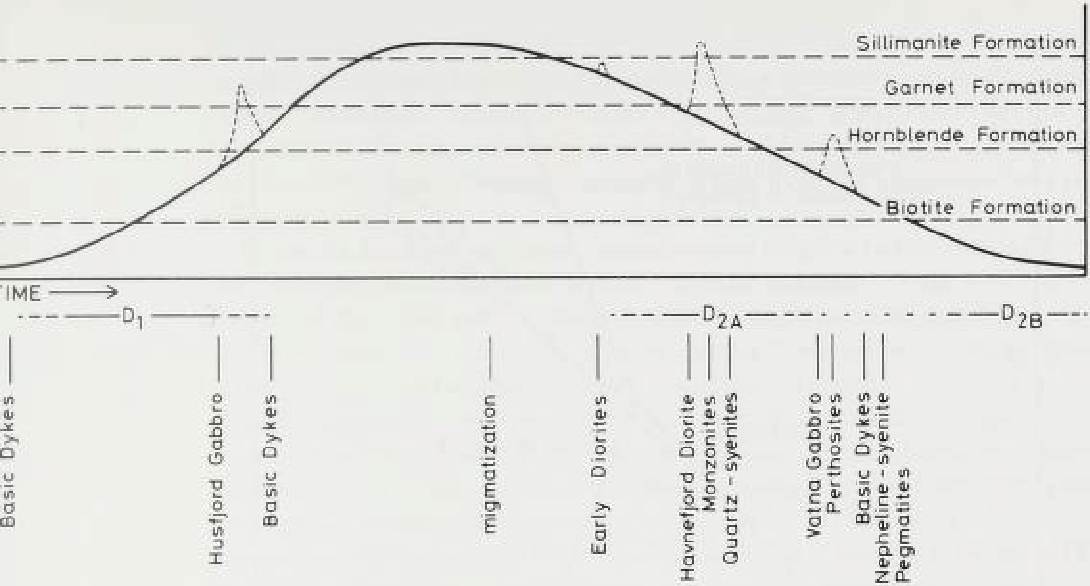


Fig. 24. Diagrammatic summary of the metamorphic, tectonic and igneous events in the Husfjord area during the Caledonian (Finnmarkian) orogeny. Solid temperature curve represents regional metamorphism; dotted temperature curves represent thermal metamorphisms superimposed upon regional metamorphism.

by thermal metamorphism by the Husfjord metagabbro, and in many cases the hornfelsic texture has been overgrown by a later regional metamorphic fabric.

The regional metamorphism reached its peak in the sillimanite-almandine subfacies of the almandine-amphibolite facies (Turner & Verhoogen 1960), between the two major episodes of deformation. This period of static recrystallization in the country rocks is characterized by development of porphyroblasts of garnet, kyanite and sillimanite. Garnet overgrows the D_1 schistosity, and is occasionally augened by the D_2 foliation; in some cases rotation has occurred. Fibrolite has nucleated on some garnets during progressive metamorphism, while other later garnets have formed retrogressively from kyanite and biotite. Kyanite and sillimanite appear to coexist stably in many rocks, suggesting that the prevailing conditions were near those at the kyanite/sillimanite boundary, although reaction between the polymorphs was sluggish. In the Husfjord metagabbro clinopyroxene has altered to green hornblende, with a concomitant decrease in the An-content of the plagioclase. The psammites and semipelites of the country rocks in the southwest have undergone migmatization associated with the peak of the regional metamorphism. In the most intensely migmatized parts fibrolitic sillimanite sometimes occurs along alkali feldspar grain boundaries (Fig. 10), and appears to be related to the migmatization. These fibrolites could either form from ions migrating along grain boundaries, or from constituents which were derived from the neighbouring crystals; the latter seems more likely for three reasons. First, fibrolite is essentially restricted to feldspar/feldspar contacts; second, fibrolite needles commonly penetrate into the neighbouring grains; and third,

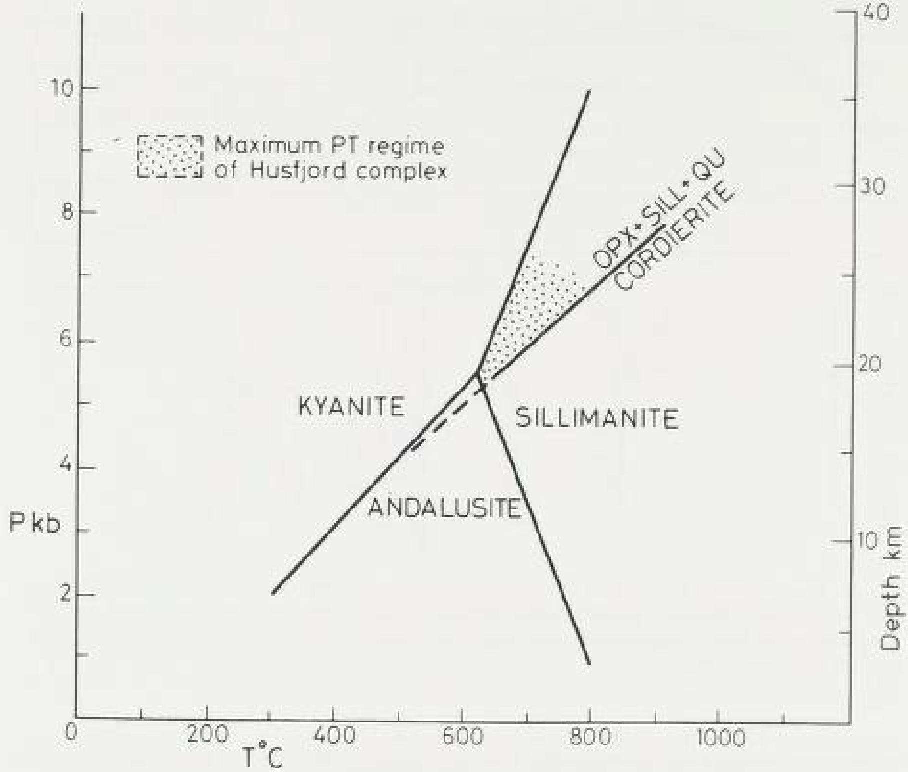


Fig. 25. Stability fields of Mg-cordierite (Newton et al. 1974) and the Al_2SiO_5 polymorphs (Richardson et al. 1969). Depth scale after Wyllie (1979).

fibrolite is occasionally involved in myrmekitic intergrowths which have formed between alkali feldspar and plagioclase. Sturt (1970) has described the development of fine-grained sillimanite at feldspar/feldspar boundaries, usually associated with myrmekite, in the aureole of the syn-orogenic Hasvik gabbro, in southwestern Sørøy. He proposed that these formed from exsolution of excess Si and Al from the feldspars, and suggested that the location of sillimanite nucleation at certain sites may be influenced by the level of thermal stress set up in the minerals during metamorphism.

After the Husfjord metagabbro had been amphibolitized during regional metamorphism, it was locally thermally metamorphosed by the early pyroxene-mica diorites. The diorites themselves have not been amphibolitized, and clearly postdate the peak of the regional metamorphism. The Havnefjord diorite has metamorphosed the Husfjord metagabbro up to the hornblende hornfels facies, and many of the metasedimentary rafts in the diorite have been hornfelsed at their margins, particularly the semipelites. In many cases, the D_2 schistosity has been obliterated, while in others it remains as a relict texture only discernible by the presence of biotite-rich bands. Regional metamorphic garnets have broken down to fibrolite, biotite and iron oxides, and the absence of new garnet indicates that the temperature of regional metamorphism had dropped beneath that of the garnet isograd by this time. The monzonite sheets thermally metamorphose the neighbouring Havnefjord diorite, in which a fine-grained granoblastic hornfels of hypersthene, clinopyroxene and plagioclase is developed. Hornfelsic textures also develop in the metasedimentary xenoliths within both the monzonites and the quartz-syenites.

While the diorite – monzonite – quartz-syenite complex and the Vatna gabbro were being emplaced the regional metamorphism continued to wane, so that by the end of D_2 it had reached greenschist facies conditions. The members of the diorite – monzonite – quartz-syenite suite and the Vatna gabbro, therefore, show a low grade of metamorphism, while retrogressive alteration is evident in the Husfjord metagabbro and some of the country rocks and metasedimentary rafts. In the calc-silicate schists of the country rocks the granular hornfelsic texture produced by the thermal effects of the Husfjord metagabbro has been overprinted by a regional metamorphic texture and mineralogy. In the Havnefjord diorite and monzonites, hypersthenes are sometimes in the process of altering to biotite where they make contact with alkali feldspar, and a similar phenomenon occurs in the early diorites within the Husfjord metagabbro. These biotites generally contain vermicular inclusions of quartz (Fig. 12); similar textures, in which biotite/quartz symplectite has developed at the expense of hypersthene, have been described by Sederholm (1916). The Vatna gabbro is only slightly metamorphosed with olivines scarcely altered and augites sometimes fringed by a little biotite. The perthosites show early stages in the development of swapped rims at the boundaries of perthite grains.

Discussion

The inter-relationships between the regional metamorphism and the thermal metamorphic effects of the intrusions show that the emplacement of the Husfjord plutonic igneous complex was protracted, and took place synchronously with metamorphic and structural events during the Finnmarkian phase of the Caledonian orogeny.

The regional metamorphic mineral parageneses indicate that pressures continued to be relatively high throughout the period of metamorphic recrystallization. The absence of andalusite and the coexistence of kyanite and sillimanite, the former sometimes in the process of altering to the latter, indicate that pressures were in excess of the aluminium silicate triple point at 5.5 kb (Richardson et al. 1969), representing a depth of about 20 km (Wyllie 1979), see Fig. 25.

Temperatures during the thermal metamorphism caused by the Havnefjord diorite, which was emplaced soon after the peak of the regional metamorphism into already hot rocks, must have exceeded 622°C (Richardson et al. 1969) since sillimanite was formed in the hornfelses. Although the composition of the rock may have had some control over the formation of cordierite, the absence of cordierite from these hornfelses is probably mainly due to high pressures. Fig. 25 shows the upper pressure stability limit of anhydrous Mg-cordierite (Newton et al. 1974), although this stability is lowered as Fe replaces Mg (Holdaway & Lee 1977). Cordierites in pelitic hornfelses usually contain a considerable percentage of the Fe molecule (Leake 1960), so the stability limit shown in Fig. 25 should be taken as a maximum for the present situation. At higher pressures, instead of cordierite, orthopyroxene, sillimanite and quartz would form (Newton et al. 1974), an assemblage which is present in the pyroxene-hornfels xenoliths within the Havnefjord diorite. This cordierite reaction curve forms an upper temperature limit within the sillimanite field for the thermal metamorphism ascribed to the intrusion of the Havnefjord diorite.

As deduced from the metamorphic mineral parageneses, Fig. 25 shows the approximate peak of the PT regime that must have prevailed in the environment of the Husfjord plutonic complex during its emplacement.

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GEOLOGICAL M
RAMNESTIND
KOBBEFJORD
STRANDTIND
KOMAGFJORD
RAMNES
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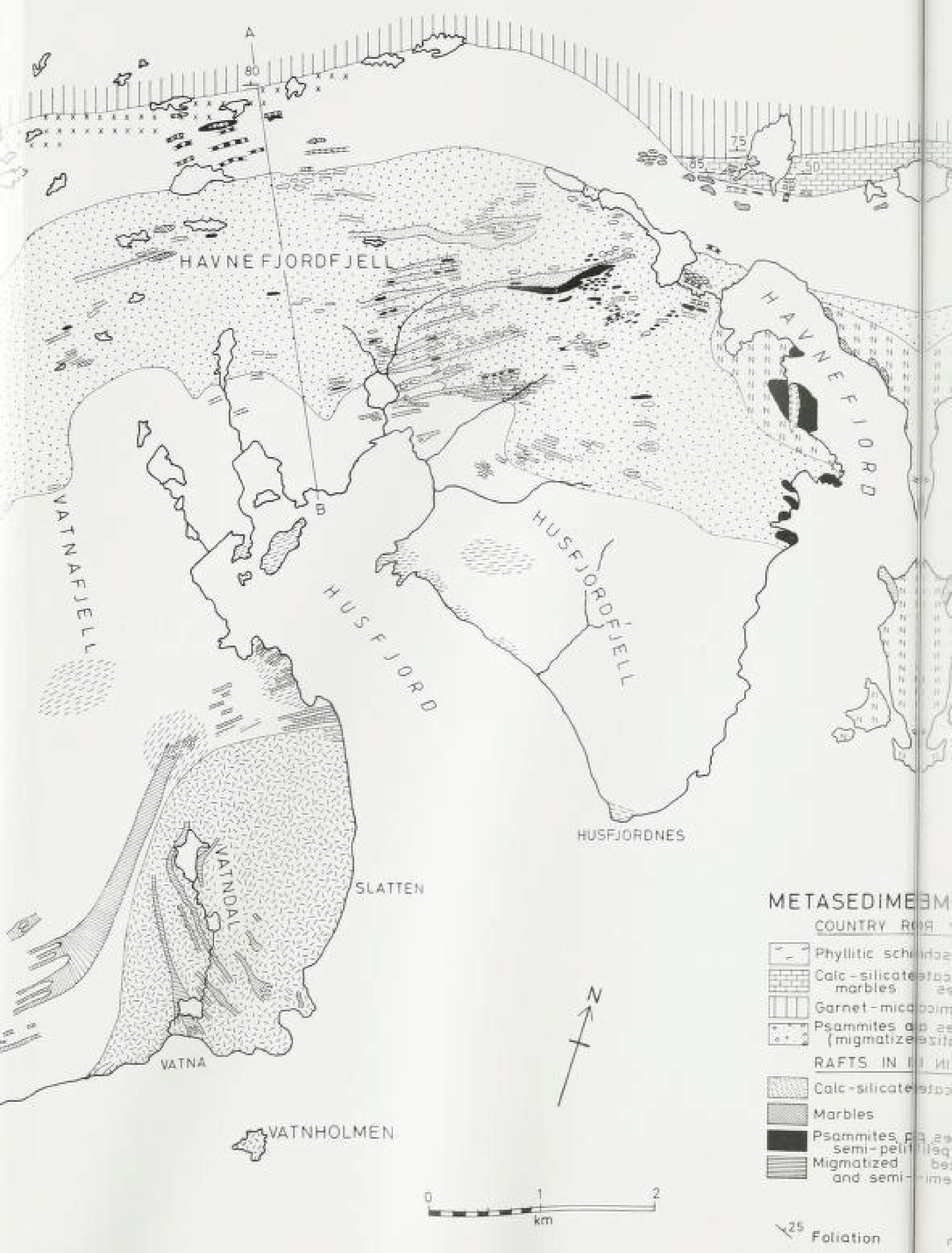
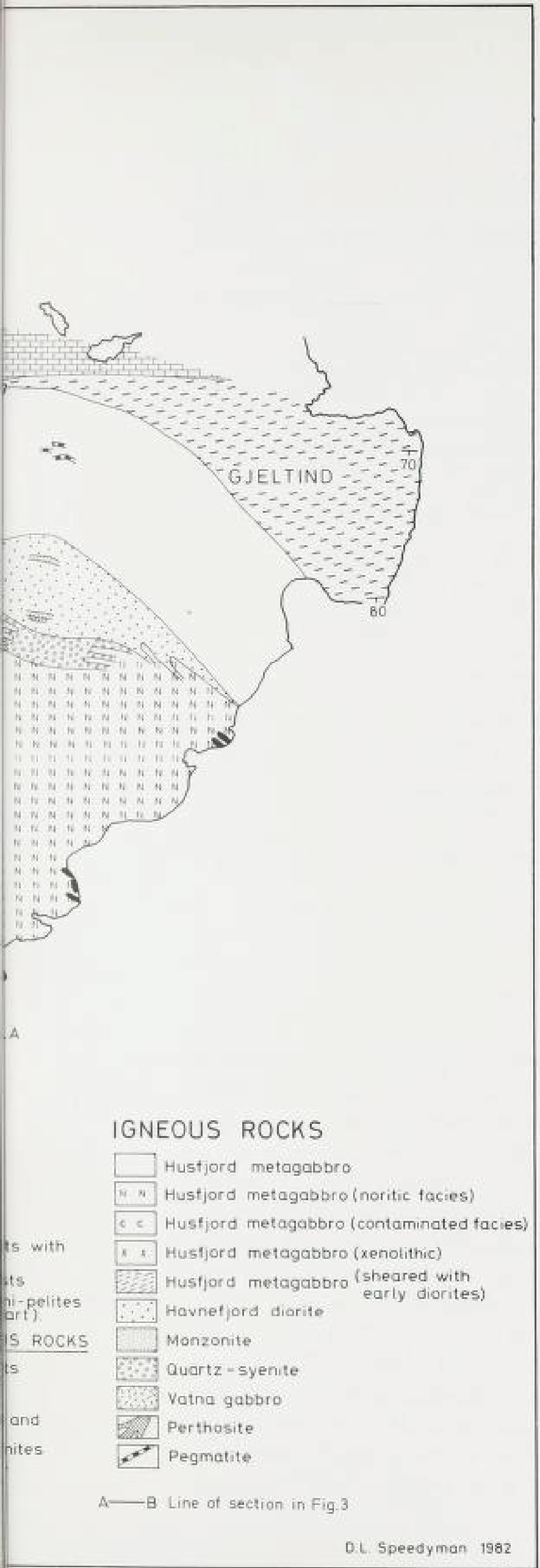
MAP OF THE HUSFJORD AREA, SØRØY




GJELTIND
70
80
IGNEOUS ROCKS
Husfjord metagabbro
Husfjord metagabbro (noritic facies)
Husfjord metagabbro (contaminated facies)
Husfjord metagabbro (xenolithic)
Husfjord metagabbro (sheared with early diorites)
Havnefjord diorite
Monzonite
Quartz-syenite
Vatna gabbro
Perthosite
Pegmatite
A——B Line of section in Fig.3
D.L. Speedyman 1982