The Geology of the Sorjusdalen Area, Nordland, Norway

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The rocks of the Sorjusdalen area are divided into two distinct tectono-stratigraphic sequences, the lower termed the Pieske/Vasten Nappe and the upper the Gasak Nappe. The mutual contact of the nappes is imbricate in character and is marked by several distinctive lithologies and tectonic features. The Sulitjelma Gabbro was intruded across this contact resulting in intrusive relationships with both tectono-stratigraphic sequences. There are three phases of folding in the area, but only F_1 and F_2 have any significant effect on the distribution of lithologies. F_1, a phase of NE–SW trending isoclinal folds with an axial planar schistose foliation, is associated with nappe emplacement. The open, E–W trending F_2 folds deform the F_1 fabric and appear to be on the southern limb of a major F_2 synform. Medium-pressure regional metamorphism reached its peak during F_1, producing a pattern of inverted isograds; the easternmost structurally lower units are greenschist facies and the westernmost structurally highest units are middle amphibolite facies. The Sulitjelma Gabbro has a thermal aureole and yet is locally profoundly affected by regional metamorphism, indicating pre- to syn-metamorphic intrusion. The emplacement of the Gasak Nappe during F_1 was likewise syn-metamorphic and just prior to the intrusion of the gabbro. Regional correlations show that the Pieske/Vasten Nappe is merely a structurally lower level of the Gasak Nappe, and that their contact is an early slide associated with the emplacement of the Gasak Nappe.

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Introduction

The Sorjusdalen area described in this paper lies approximately 13 km north-east of Sulitjelma, spanning the border between Norway and Sweden. The Bodø-Sulitjelma region (Fig. 1) in the Central Scandinavian Caledonides lies in a tectonic depression of Caledonian cover, between the major basement culminations of the Tysfjord and Nasafjell massifs. The region has been discussed in various tectonic syntheses (Rutland & Nicholson 1965, Nicholson & Rutland 1969, Nicholson 1974, Cooper 1978). The major deformation of the area occurred during the climactic stages of the Caledonian orogeny as a result of the closure of the Iapetus Ocean during the Lower Palaeozoic and the consequent collision of the Baltic and Laurentian cratons (Wilson 1966).

The Caledonian cover consists of a sequence of metasediments, intrusives and effusives which are divisible into a series of nappes (Fig. 1) that are conjunctive in the west and disjunctive in the east (Nicholson & Rutland 1969). The varied fold structures in these rocks show a general NE-SW Caledonide trend and are polyphase in character. Using fossils found at Sulitjelma, part of

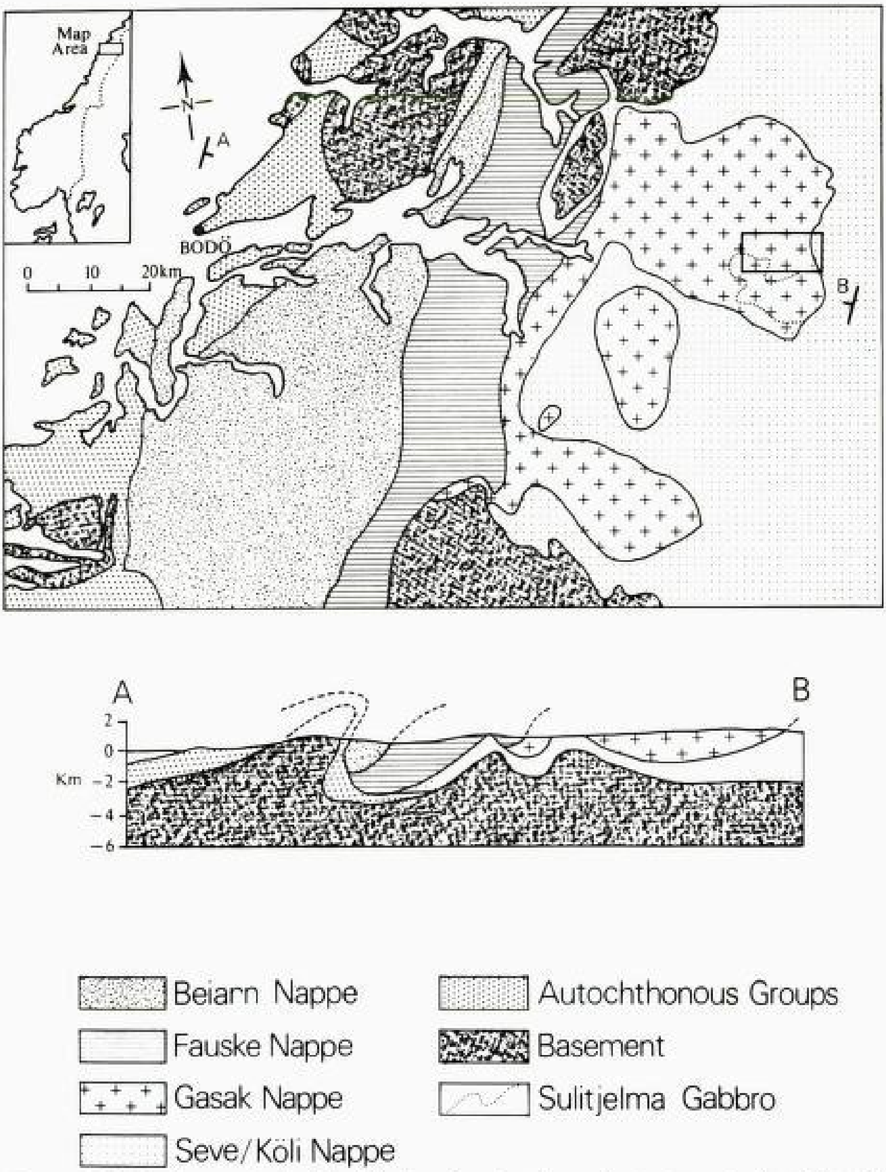

Fig. 1. Geological map of the Salta Region showing the major tectono–stratigraphic units (after Nicholson & Rutland 1969). The box locates the Sorjusdalen area.

one of the lower nappes has been dated as Middle Ordovician (Sjøgren 1900). The limits of penetrative Caledonian deformation in the basement culminations are marked by a line trending NNE-SSW (Nicholson 1974).

Since the early investigations of Sjøgren (1900) the Sulitjelma area has been considered one of the classic areas of the Scandinavian Caledonides. The tectonic and metamorphic features of the region are given an additional economic significance by virtue of the bodies of basic rocks (gabbro and amphibolite) and the stratiform pyritic ore bodies which form important parts of the rock sequence in the area (Wilson 1973).

The early investigations are reviewed in a memoir by Vogt (1927), who concluded that the gabbro and amphibolites were all part of one syn-tectonic intrusion. Kautsky (1953) challenged this interpretation based on his work on the Swedish side of the border. Kautsky divided the rocks into three allochthonous nappes, which together form the Seve Nappe complex. The highest he termed the Gasak Nappe, the middle one the Vasten Nappe and the lowest the Pieske Nappe. Kautsky interpreted the gabbro as being intruded into the Gasak Nappe and having a basal tectonic contact with the amphibolites of the Vasten Nappe. Nicholson & Rutland (1969) have fully discussed the two alternative hypotheses and concluded that Kautsky was correct in principle, but they maintained certain reservations regarding the nappe interpretation. Other discussions of the two hypotheses are given by Mason (1967) and Henley (1970). Boyle et al. (in press) present evidence for large-scale stratigraphic inversion in the Sulitjelma area and suggest a modified interpretation of the nappe structure.

The rocks in the area discussed here are divided into two sequences which, following the nomenclature of Kautsky (1953), comprise the Gasak Nappe above and to the west, and the Pieske-Vasten Nappe below and to the east. Both nappes have been intruded by the Sulitjelma gabbro. No conclusive evidence of stratigraphic way up is present in the Sorjusdalen area and hereafter the terms 'overlain' and 'underlain' are used in a purely tectono-stratigraphic sense.

This study of the stratigraphy and structure of the nappes was intended to aid the understanding of the nature of the contact between the two nappes, the timing of nappe emplacement with respect to deformation history and the timing of the gabbro intrusion.

Stratigraphy

The stratigraphy of the area is described in ascending tectonic sequence as lithological units, divided into three tectonic groups as shown on the lithological map (Fig. 2). The lowest group is the upper part of the Pieske/Vasten Nappe (Kautsky 1953) the middle one is the so-called nappe junction group and the upper one is the lower part of the Gasak Nappe (Kautsky 1953). The stratigraphy, which is diagrammatically represented in Fig. 3, indicates that the Pieske/Vasten Nappe is composed of phyllites and marbles, the nappe junction group mostly of ultramafic rocks and the Gasak Nappe dominantly of amphibolites and pelites. The Sulitjelma Gabbro, which cuts across the nappe boundaries, is described separately.

THE PIESKE/VASTEN NAPPE

The Phyllite Unit

This is a greenish chloritic phyllite with cleavage parallel to bedding, and is often kink-banded and chevron-folded. Pyritic mineralisation is locally developed on a small scale. The other main minerals present are sericite, chlorite, quartz, feldspar, calcite and biotite with accessory zircon and epidote.

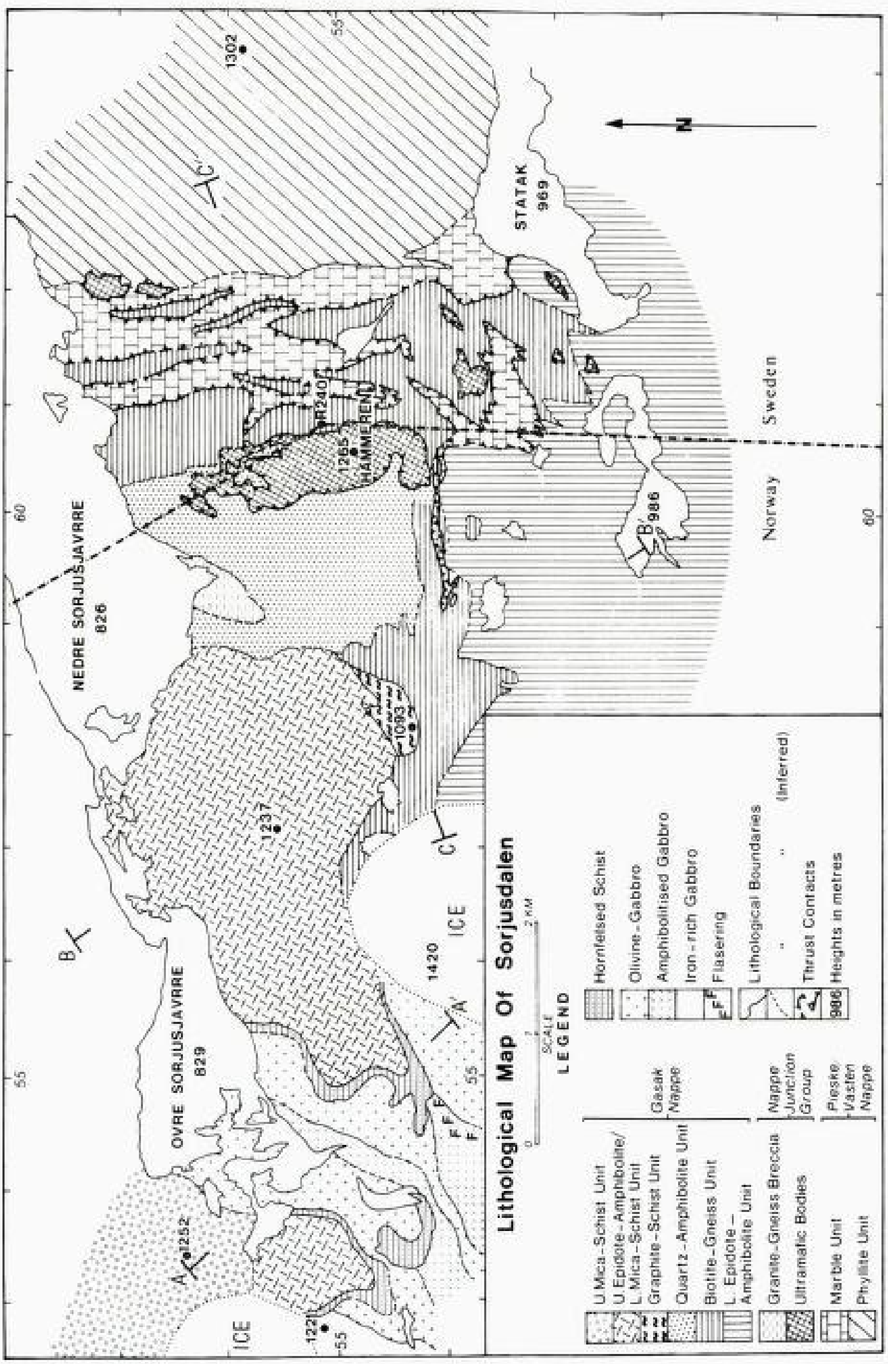

Fig. 2. Lithological map of the Sorjusdalen area.

Interbedded with the phyllite are creamy-brown calcareous, arenaceous metasediments and thin porphyritic flows of basic metavolcanics apparently thinning southwards.

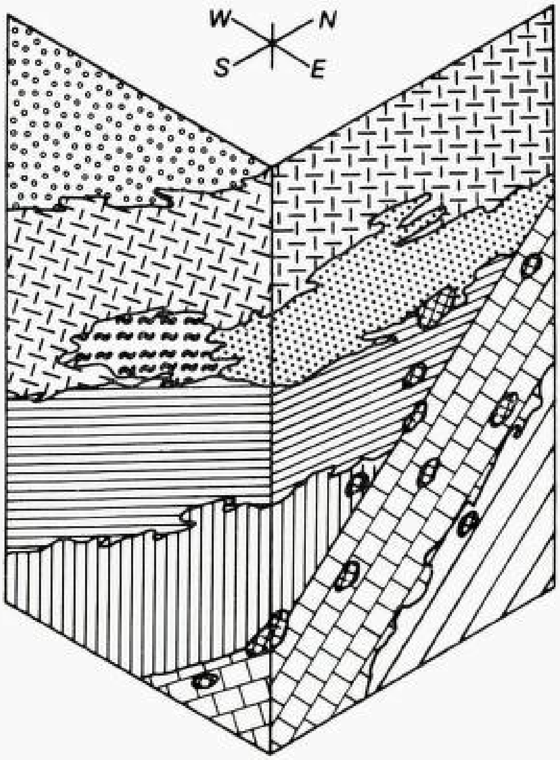

Fig. 3. Diagrammatic tectono-stratigraphy of the Sorjusdalen area. Key as for Fig. 2.

The Marble Unit

The creamy-yellow marbles vary from coarsely granular with a poorly developed planar foliation to fine grained and schistose in appearance depending on the proportions of mica and quartz present. Near their contact with the phyllite unit the marbles contain folded and boudinaged felsic bands and thick micaceous quartzites. Mineralogically the marbles comprise calcite, quartz, phlogopite, magnetite, rutile and small amounts of plagioclase.

THE NAPPE JUNCTION GROUP

Certain of the lithologies occurring in the Sorjusdalen area strongly suggest the presence of a major tectonic dislocation. These are the granite-gneiss breccia and the numerous pods of ultramafic rock. We believe that it is significant that these lithologies are broadly located between the rock sequences of Kautsky's (1953) Gasak Nappe above, and his Pieske/Vasten Nappe below.

The Granite-Gneiss Breccia

A small outcrop of the granite-gneiss breccia is present south of Nedre Sorjusjavrre; it is thought to be continuous with a far larger outcrop north of Nedre Sorjusjavrre described by Nicholson (1971).

Spheroidal blocks of granite-gneiss varying from 10 cm to 1 m in diameter are set in a finer-grained matrix of similar composition. A coarse foliation is developed, and the rock has the appearance of a metamorphosed breccia. Following Kautsky (1953) and Nicholson (1971) we interpret this rock as being a sedimentary breccia of basement gneiss clasts associated with a small area of coherent gneiss (present north of Nedre Sorjusjavrre) and associated with the basal thrust of the Gasak Nappe. One of us (I.L.F.) located a block of sheared granite-gneiss within the marble unit a short distance below the biotite-gneiss unit of Gasak Nappe.

The Ultramafic Bodies

The ultramafic bodies are found at various structural levels in the lowest parts of the Gasak Nappe and the highest parts of the Pieske/Vasten Nappe, and all show flattening in the plane of the regional foliation. The bodies generally form well-exposed topographic humps due to the hard, compact nature of the rock. Their area varies from 100 m^2 up to 150,000 m^2 in the case of Hammeren, the largest and most prominent body in the area. The dark green ultramafic rock does not developed the regional planar foliation. The mineralogy is: actinolite 60–70%, calcite 5–10%, chlorite 5–10% with talc, muscovite, plagioclase and spinel as accessories.

Associated with, and enclosing the ultramafic bodies are envelopes of altered rock derived from the original ultramafic material. Generally these consist of a coherent calcareous talc-magnetite schist, though a tectonic breccia may locally develop, as for example, around Hammeren. A typical section into an ultramafic body is as follows:

Country Rock
Calcareous talc-magnetite schist
Talc-rich actinolite schist with magnetite
Medium to coarse grained talc-actinolite rock
Fine-grained actinolite ultramafic rock.

The light-grey calcareous talc-magnetite schist is widely developed as a thin envelope enclosing the ultramafic bodies. It often contains small octahedra or larger aggregates of magnetite and occasionally becomes dark blue-grey due to finely disseminated magnetite. The mineralogy is talc, quartz, calcite and magnetite.

The tectonic breccia has a variable composition, containing blocks of ultramafic rock and carbonate, frequently fractured and veined by quartz, with a talc-rich matrix.

Within these lithologies large crystal aggregates are locally developed, for example, diopside crystals up to 5 cm long, sideritic rhombs up to 3 cm across, talc in radiating crystalline form, prismatic clinozoisite, almost perfect spheroids of pyrite and other more deformed pyrite grains.

There is no evidence of the presence of thermal metamorphic aureoles around the bodies, and we consider the alteration envelopes described above to represent a dynamic metamorphic aureole. We therefore suggest that the bodies were tectonically emplaced in the solid state, their movement being facilitated by the lubricating nature of their aureoles. The bodies are therefore allochthonous with respect to the host nappes and were probably derived from the tectonic break-up of a larger ultramafic mass.

THE GASAK NAPPE

The Lower Epidote-Amphibolite Unit

The lower epidote-amphibolite is medium grey in colour, compositionally banded and fine grained with occasional coarser patches. A planar schistose foliation is usually developed parallel to the compositional banding. Numerous pale green lenses of epidote and occasional pale brown lenses of carbonate occur, flattened in the plane of the foliation. The local presence of matrix carbonate causes the development of solution pits. The rock contains hornblende 50–60%, sodic andesine 25–30%, quartz 10%, opaques 5% and calcite 0–5%. The mafic and felsic minerals occur in discrete bands and within the former the hornblendes have a strong preferred orientation.

The Biotite-Gneiss Unit

The biotite-gneiss is a well-foliated rock with alternating discrete bands 2–3 mm wide of felsic and mafic minerals. Small red almandine garnets (1–2 mm) are common. The mineralogy is biotite 30–40%, quartz 25–30%, sodic plagioclase 15–20%, muscovite 10–15%, garnet 0–5% and kyanite 0–2%; accessory minerals include tourmaline and opaques. The garnet and kyanite form post-tectonic porphyroblasts that truncate the micas of the gneissose foliation. In its outcrop east of Hammeren the biotite-gneiss contains numerous quartz and feldspar augen. Here it is less homogeneous than in the western outcrop, with some mineralized horizons which are discussed in detail in the section on mineralisation.

The Quartz-Amphibolite Unit

This rock is dark green-grey, fine grained amphibolite with a well-developed planar foliation. Almond-shaped lenses (amygdaloidal?) of quartz, feldspar or calcite and small pyrite cubes are common. At the southern contact with the biotite-gneiss unit the amphibolite becomes very schistose, whereas at the contacts with the calcareous talc-magnetite schist it is apparent that localised Fe/Mg metasomatism has occurred during regional metamorphism. The mineralogy is hornblende 80%, quartz 5–10% and plagioclase 5–10%, with accessory epidote, pyrite, calcite and secondary chlorite. The amphiboles show a high degree of preferred orientation, and also show uneven extinction indicating post- or syn-crystallisation stress.

Within the quartz-amphibolite, lenses 100×100 – 500 m of metafelsitic rock occur. There are complex interveining and mixing relationships between the two lithologies and reaction rims around xenoliths can be observed, suggesting that the unit was originally igneous.

Nicholson (1971, p. 157) included these rocks, by extrapolation, within his granite-gneiss breccia. We believe that the granite-gneiss breccia thins southwards across Nedre Sorjusjavrre, only occurring as a small outcrop and that the quartz-amphibolite unit (presumably not present north of the lake) should be considered as a separate lithology.

The Graphite Schist Unit

The graphite schist is a black, well-foliated, rusty-weathering rock composed principally of graphite and pyrite. This presumably indicates sedimentation under strongly reducing conditions producing a black mud rich in FeS and organic matter. Nicholson (1971, p. 156) notes the presence of the graphite schist in the area, but it is more discontinuous than he implies.

The Upper Epidote–Amphibolite Unit

The rock is medium grey and fine-grained with a strong planar foliation which is often crenulated. Compared with the lower epidote–amphibolite it contains fewer epidote lenses and more carbonate lenses, some of which are very large. In areas of high matrix carbonate content the rock becomes mottled grey and brown with numerous solution pits. The mineralogy is: hornblende 60–75%, (with a marked preferred orientation), quartz 15–25%, plagioclase 5–10%, epidote 0–5% and calcite 0–5%.

The Lower Mica Schist Unit

The lower mica schist unit occurs as small concordant bands within the upper epidote–amphibolite on the northern slopes of hill 1237. The schist is well-foliated, fine/medium-grained and varies from grey to dark grey in colour with some coarser mica flakes and clusters of red garnets. The matrix carbonate content must be locally quite high as solution pits are often observed on weathered surfaces. However, the carbonate is not seen in the available thin-sections, which contain biotite 35–40%, quartz 10–20%, plagioclase 5–15% and opaques. The micas have a marked preferred orientation and are concentrated into discrete bands.

The Upper Mica Schist Unit

The field appearance of this rock is very similar to the lower mica schist unit; it has been reported by Mason (1967)to contain kyanite, but none was observed in the field or in the thin-sections studied.

THE SULITJELMA GABBRO

The north-western corner of the Sulitjelma Gabbro outcrops within the Sorjusdalen area. The gabbro is layered, and in the field is divisible into four major facies; olivine–gabbro, amphibolitised gabbro, flaser gabbro and iron-rich gabbro. The flaser gabbro is more commonly found at the gabbro/schist contact, while the other three facies occur as broadly E–W trending bands parallel to Sorjusdalen.

Olivine–Gabbro

A detailed account of the olivine–gabbro facies can be found in Mason (1971), with which our own petrological observations concur. Contacts with the amphibolitised gabbro are gradational, with amphibole replacing olivine over a distance of 8–10 m. The contact with the country rocks is primary.

Amphibolitised Gabbro

The amphibolitised gabbro contains plagioclase (An_{45-55}), cummingtonite, clinozoisite and small amounts of chlorite and pale-brown biotite. Locally the amphibole is green hornblende in place of cummingtonite. The amphiboles tend to form large aggregates of small fibrous grains with larger crystals sometimes developed in the centres. Many specimens retain relict ophitic textures, and occasionally relict pyroxene and olivine occur. The amphibolitisation is the result of processes similar to those which formed the corona structures described by Mason (1971), but occurred later as water was introduced during regional metamorphism. The amphibolitised gabbro occurs as two broad layers sandwiched between layers of olivine gabbro, and is concordant with primary igneous banding. The development of amphibolitisation thus appears to have been controlled by the layered nature of the intrusion. Shear zones are localised within the amphibolitised gabbro indicating preferential failure within this layer.

Flaser Gabbro

The word 'flaser' is used to describe rocks in which crystal lineation is developed. There are both amphibole- and olivine-rich flaser gabbros and there is no visible mineralogical difference between the flasered and non-flasered facies. In the amphibolitised gabbro where the flasering phenomenon is best developed, segregation of the amphibole and plagioclase has occurred and preferred orientation is pronounced even in the plagioclase layers. Plagioclase seems to be more resistant to the deformation, although the plagioclases are slightly fractured, well rounded and sub-spherical to elliptical. The olivine gabbros behave in a similar fashion, crystals becoming strained and elongate during flasering. However, the olivine tends to fragment into anhedral aggregates. The flasering facilitates movement of water and subsequent recrystallisation to an amphibolitised gabbro; however, this does not always occur and some rare flasered olivine gabbros are preserved. The formation of the flaser rocks occurred during the regional metamorphism, primarily in the later stages due to hydration as the gabbro cooled.

Iron-rich Gabbro

The sulphide enriched facies occurs on the western margin of the Sorjusdalen area. Its contact is concordant with the other primary layering within the gabbro. Some smaller localised bodies also occur. The presence of such enrichments suggests the possibility of economic Cu–Ni cumulus mineralisation within the Sulitjelma gabbro. Details of the textures and compositions of the opaque minerals are given in the mineralisation section.

Deformation history

The Caledonian deformation within the two nappes and the intervening nappe junction group consisted of three phases of folding of varied importance, style

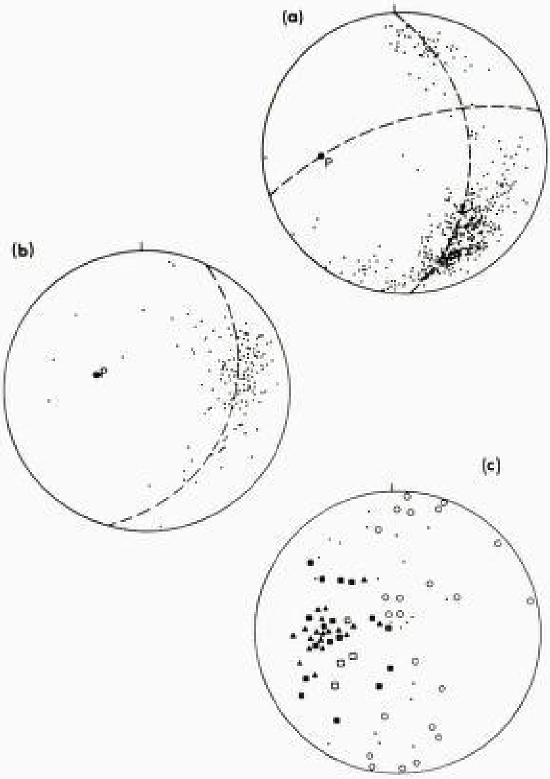

Fig. 4. (a) Stereogram of poles to S_1 in the Gasak Nappe, P is the pole to the best fit π circle, and the great circle containing P the approximate orientation of the axial plane; (b) stereogram of poles to S_1 in the Pieske/Vasten Nappe, P is the pole to the best fit π circle; (c) stereogram of F_1 minor fold axes ·, F_2 minor fold axes ■, F_3 minor fold axes ∘, mineral lineations ▲, and boudin neck directions □.

and distribution, with the later formation of small shear zones and areally important faults. Coeval with the first fold phase (F_1) regional metamorphism occurred at greenschist facies in the east, rising steadily to lower amphibolite facies in the west and producing the regional foliation (S_1).

FOLDING

Within the area three distinct phases of folding can be recognised by their different styles, scales and their relationship to S_1. Folds ascribed to the earliest of these phases, termed F_1, are present throughout the area, although in the western and central parts they are strongly modified by subsequent F_2 folding. The F_1 folds are isoclinal with approximately N–S axes and axial planar foliation (S_1) produced during the coeval regional metamorphism. Within the phyllite unit, where the effects of F_2 are negligible, S_1 is preserved in its original orientation, striking N–S with a dip of 60° to the west (Fig. 4b). F_1 minor folds are common in the eastern part of the area, but in the central and western sectors they are comparatively rare (Fig. 5). They are predominantly isoclinal to tight and have a random orientation (Fig. 4c). Application of the techniques of Ramsay (1967, p. 450) for removing the effects of later deformations does not, however, produce a concentration of data. Major F_1 folds are best displayed east of Hammeren where the biotite–gneiss unit and the marble unit are isoclinally interfolded (Fig. 7).

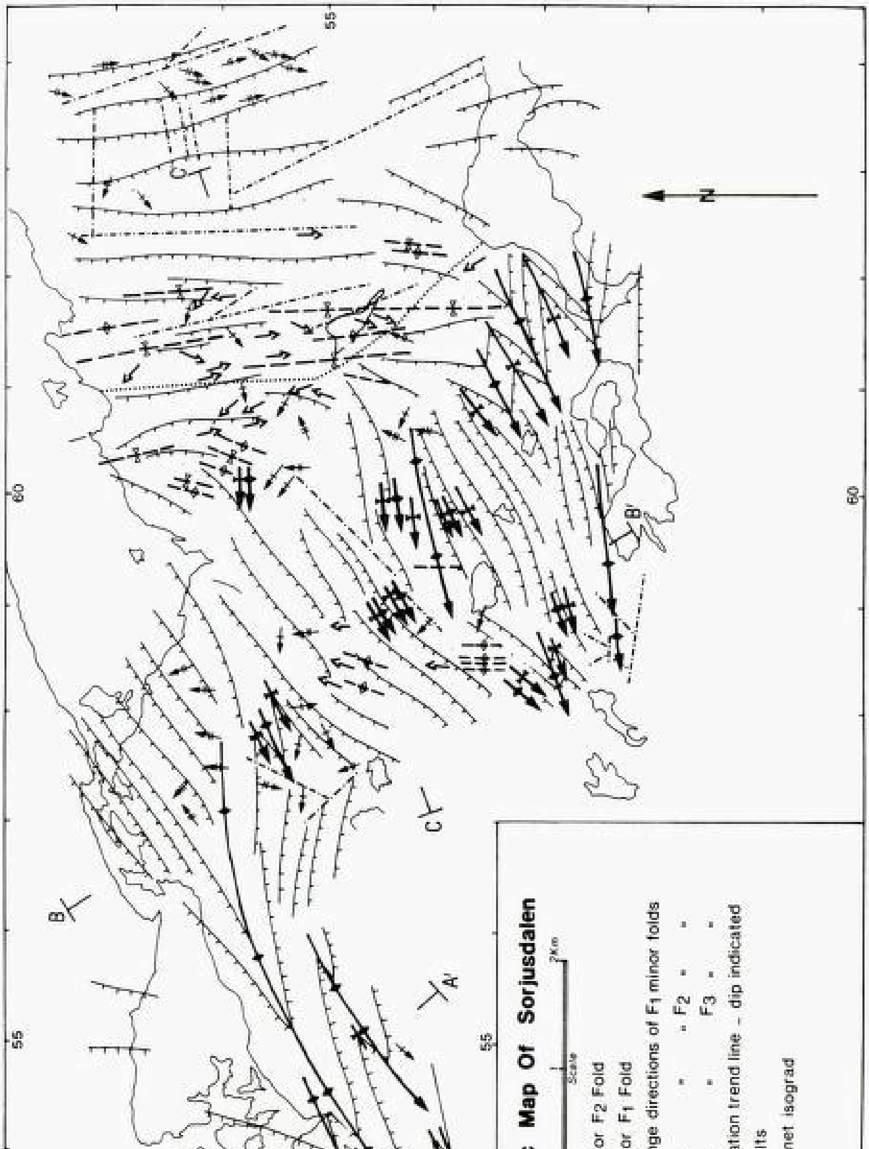

Fig. 5. Tectonic map of the Sorjusdalen area.

F_2 folds are present at all structural levels and deform S_1 in an open asymmetric style on E–W fold axes without development of an axial planar cleavage. F_2 folding appears to die out eastwards, being completely absent in the phyllite unit, thereby causing the areal swing in S_1 (Fig. 5). Southern limbs dip approximately 65° to the south-west; the spread of data for the northern limbs, however, suggests a curved profile with dips varying from 60° to the north-west to 70° to the north-north-west. Fold axes plunge 50° to the west and the axial planes strike 075° with a dip of 70° to the north-north-west (Fig. 4a). F_2 minor folds are common, frequently displaying S and Z symmetries related to their position on larger F_2 structures. They vary considerably in style but always fold S_1 and usually plunge west (Fig. 4c). The largest and best example of an F_2 fold in the area occurs on the ridge just to the south of Øvre Sorjusjavrre (Fig. 5). The symmetry of the major F_2 folds indicates that the area is situated on the southern limb of a regional F_2 synform. Boudinage apparently developed during F_2, the boudin neck directions being broadly parallel to the F_2 fold axes (Fig. 4c), however, much of the boudinage has a chocolate-tablet structure and it is difficult to discriminate between the effects of F_1 and F_2. A mineral lineation is developed apparently parallel to the F_2 axes, but there is no evidence to support a metamorphic event during F_2; it is therefore considered to be an F_1 lineation. In the central part of the area F_1 and F_2 folds are superimposed producing interference patterns.

Major F_3 folds are not recognised in the area, but minor folds occur which are not obviously compatible with the known geometries of F_1 and F_2 structures, and therefore are assumed to be F_3. In the amphibolitic units these are often ptygmatic in style but in the phyllite unit chevron folding and kinking of S_1 has occurred on gently southward plunging axes (Fig. 4c).

METAMORPHISM

One main phase of regional metamorphism is recognised in the area, broadly coeval with the F_1 fold phase and producing S_1. From east to west there is a general increase in metamorphic grade rising from the chlorite zone up to the kyanite zone.

The easternmost part of the phyllite unit is in the chlorite zone, the proportion of chlorite relative to sericite increasing westwards. The marbles contain the first occurrence of green biotite, but this has no bearing on the location of the biotite isograd. As the contact of the marble with the biotite–gneiss unit is approached knots of acicular amphibole and epidote appear. The garnet isograd can, however, be fixed with comparative certainty (Fig. 5). Moving west from the garnet isograd the biotite/chlorite ratio changes from 7.0 to 25.0 and muscovite appears at the expense of sericite. The amphibolites which occur in the almandine zone contain calcic oligoclase, garnet, green hornblende and epidote, an assemblage which indicates epidote–amphibolite facies metamorphism (Miyashiro 1973). A kilometre or so to the west of the garnet isograd, kyanite begins to appear as small grains but the position of the kyanite isograd cannot be located accurately. The biotite within the pelitic rocks becomes brownish green and tourmaline appears. The amphibolites within the kyanite zone contain a similar assemblage to that in the almandine zone except that the plagioclase present is a sodic andesine. This is the highest grade of regional metamorphism present in the area.

The S_1 fabric developed during the metamorphism varies from phyllitic through schistose to gneissose, with no evidence of an earlier fabric preserved in the porphyroblasts. The garnet porphyroblasts are idioblastic, inclusion-free and truncate the S_1 foliation. The kyanite porphyroblasts have similar relationships to the S_1 foliation, and both garnet and kyanite porphyroblastesis is therefore regarded as post-S_1 and hence post-F_1. The plagioclase porphyroblasts are somewhat ragged but clearly contain inclusions of mica that parallel the external foliation. It is concluded that although the regional metamorphism was broadly coeval with F_1, the highest grade in fact post-dates F_1.

During metamorphic retrogression and cooling, a large number of quartz veins seem to have formed at various times. Their relative chronology can be deduced in relation to the fold phases, one set forming post-F_1 pre-F_2, another post-F_2 pre-F_3, and the youngest set post-F_3. The rocks must have cooled down considerably by F_2 times as no evidence of diaphthoresis is apparent, even in F_2 hinges.

The effect of regional metamorphism on the gabbro has been to produce amphibolitisation. However, as noted earlier regional metamorphic effects are incomplete, and certain parts of the gabbro retain their primary mineralogy. In agreement with Mason (1971) it is thought that this is probably due to the availability and mobility of water during the metamorphism of the gabbro. The gabbro shows the effects of regional metamorphism but it also has a thermal aureole preserved as a hornfelsic envelope varying in width from 30 to 40 m and dying out gradually as shown by the progressive appearance of the regional foliation.

SHEAR ZONES AND FAULTS

Shearing and faulting occur at all structural levels, cutting and therefore post-dating all the above-mentioned structural elements. There is, however, no apparent relationship between the shear zones and the faults. The shear zones cause sharp changes in strike of schistosity, and have occasionally developed sigmoidal tension gashes infilled by quartz. Thin-sections taken near the shear zones show post-crystallisation strain effects.

The faults shown on the tectonic map (Fig. 5) are not directly detectable in the field by displacement of foliation or juxtaposition of lithologies. However, fractures are readily seen on the available aerial photographs and help to explain several apparent paradoxes of structural trend (Fig. 5). The faulting is thought not to be coeval with the shearing, as the former is a brittle fracture compared with the more ductile development of the shear zones.

Mineralisation

Mineralisation of both magmatic and sedimentary origins occur within the area. Magmatic mineralisation is represented by the occurrence of the pentlandite–pyrrhotite association together with magnetite and chalcopyrite in the gabbro and by magnetite–pyrite–pyrrhotite–chalcopyrite–chromite mineralisaton in

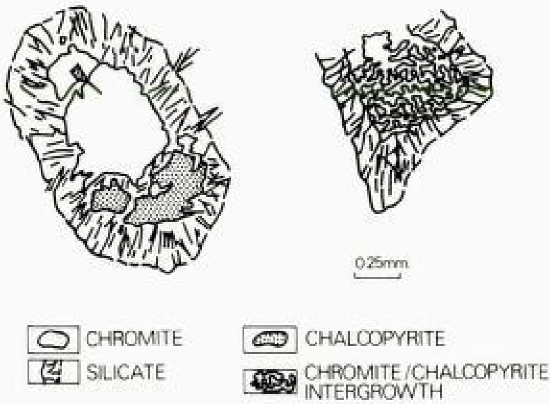

Fig. 6. Ore mineral textures from the Sorjusjavrre ultramafic body (620571).

bands within the ultramafic pods. Sedimentary mineralisation is represented by minor concentrations of pyrite, with rare chalcopyrite, within the biotite–gneiss unit and by pyrite–graphite in the graphite schist unit.

Evidence for the presence of a nickel-bearing monosulphide liquid at certain stages during the crystallisation of the gabbro magma is provided by the occurrence of the rusty weathering iron-rich facies. The opaque minerals are located in the interstices of the silicate cumulus fabric making up approximately 20% by volume of the rock. The opaque minerals occur in the following relative proportions pyrrhotite (with alteration products) 80%; magnetite 10%; chalcopyrite 5% and pentlandite <2.5%. The pentlandite was shown by electron probe microanalysis to be a cobaltian pentlandite with the following composition:

Fe 30.3%, Co 3.3%, Ni 35.1%, S 29.8%.

Within the two largest ultramafic bodies, Hammeren and the body just to the south of Nedre Sorjusjavrre, mineralisation involving chromite, chalcopyrite, pyrite and cobaltian pyrite occurs. The mineralisation in the Sorjusjavrre body (620571) occurs as crude bands of small grains (0.5 mm) dispersed through the fibrous rock. Individual bands are 3–4 mm thick, and the texture appears to be the result of the cataclasis of larger grains. In polished section chromite forms 10–15 modal % of the rock, occurring as large grains with decussate boundaries in intimate association with chalcopyrite (Fig. 6). Electron probe scans across several chromite grains produced an average figure of 4–6% Cr. Pyrite and cobaltion pyrite are dominant, however, occurring as large (1–2 mm) sub-angular to rounded grains.

Within the biotite–gneiss unit, to the north-east of Hammeren, there occurs a distinctive and unique horizon of about 1 m thickness, composed of approximately 80% garnet, 10% quartz and feldspar and accessory chlorite, biotite, carbonate and magnetite. This lithology is pink in colour, very fine-grained and is pervasively dissected by fine fracture veinlets filled by quartz and carbonate. At the time of mapping this horizon was considered to represent an anomalously iron–alumina-rich sedimentary intercalation.

Since 1973, investigations carried out in the Grong region of the Central

Norwegian Caledonides (Halls et al. 1977) have revealed a striking similarity between the Sorjusjavrre garnetite and certain volcanogenic exhalative (chemical–sedimentary) horizons which commonly occur within the volcano-stratigraphy of the Skorovas area near Grong. In the Skorovas area, laminated horizons of pink garnetite and epidotite, laterally gradational into hematite/magnetite cherts, occur above and stratigraphically peripheral to the Skorovas massive sulphide orebody. Such iron–aluminium–calcium rich horizons are considered to be the concentrated products of precipitation under appropriate physio-chemical conditions from fluids rich in elements leached from submarine extrusives, following exhalation and dispersal of the fluids into the submarine environment. Pink spessartite-rich horizons of similar appearance have been reported from the Trondheim region by Oftedahl (1967).

In the Sulitjelma region, garnetite horizons have recently been found associated with pillow lavas of the Sulitjelma amphibolite (A. Boyle, pers. comm. 1978), being essentially very similar both in field appearance and petrography to the exhalative garnetite horizons of the Grong region. Geological evidence thus suggests that the garnetite horizons within the Sulitjelma amphibolite are exhalative in origin and similarly there is little doubt that the Sorjusjavrre garnetite is exhalative.

Discussion

THE TIMING OF GABBRO INTRUSION

The presence of a thermal aureole around the gabbro together with regional metamorphism of the gabbro indicates that intrusion of the gabbro occurred syn-metamorphically. The mineral assemblages described from the units adjacent to the gabbro indicate a minimum pressure of 5 kb and temperatures in excess of 500°C (Winkler 1974). The temperature of the gabbro during and immediately preceding intrusion must have been considerably higher than that of the country rocks. The metamorphism of the gabbro, mainly flasering and amphibolitisation, occurred during the latter stages of the regional metamorphism as the gabbro slowly cooled to a temperature at which water could enter, because as shown by Mason (1971, p. 137) the metamorphism is isochemical apart from H_2O.

REGIONAL SIGNIFICANCE OF THE SORJUSDALEN AREA

The division of the lithological units into the Gasak Nappe above the nappe junction zone (from here on referred to as the Hammeren slide) and the Pieske /Vasten Nappe beneath follows the interpretation of Kautsky (1953). Recently, major stratigraphic inversions in the Sulitjelma area have been recognised and used to reinterpret the structure and stratigraphic relationships of the area (Boyle et al. in press). The inversions are largely based on pillow lavas and require the interpretation of the Gasak Nappe as a fold-nappe with an extensive inverted limb of which the sequence east of Hammeren is a part. The granite–gneiss breccia and the ultramafics are considered by Boyle et al. (in press) to occupy the core of the fold-nappe. Such an interpretation presents difficulties, for as the evidence presented above suggests an early slide is present in the Hammeren area. A further problem is that the stratigraphy west of Hammeren does not repeat that found to the east and thus it is difficult to accept that Hammeren occupies the core of a large fold-nappe. Boyle et al. (in press) appreciate the latter point, correlating the rocks west of Hammeren with those of the Duoldagop area (Fig. 8), known to belong to a structurally higher level of the Gasak Nappe. They do not, however, insert the early slide in the Hammeren area that this stratigraphic argument would appear to require.

The correlation of the rocks west of Hammeren with those of the Duoldagop area must be questioned for two reasons. The first is the presence in the biotite–gneiss unit of the banded exhalative garnetite described earlier which is similar in appearance to the garnetiferous horizons of the Vaknahelleren schist described by Boyle et al (in press, Fig. 1) as 'commonly graphitic, manganiferous or keratophyric'. This correlation is supported by the presence of the graphite schist unit on the northern contact of the biotite gneiss unit. The second point is that many of the rocks west of Hammeren are amphibolitic and locally display igneous characteristics. It is therefore possible to correlate the biotite gneiss, graphite schist, quartz amphibolite and lower epidote–amphibolite units with the Sulitjelma Amphibolite Group. The upper epidote–amphibolite and the lower and upper mica schist units are, however, correlated with the rocks of the Duoldagop area. This substantially reduces the amount of stratigraphy cut out by the Hammeren slide, necessitating only the removal of the marble and phyllite units. If the correlation with the Sulitjelma Amphibolite Group is refuted a major slide of even greater displacement must be postulated.

A consequence of these correlations is that an early synclinal fold must be proposed in the Hammeren area (Fig. 8) similar to that demonstrated south of Duoldagop by Boyle et al. (in press). Also, a second slide must be inserted to account for the juxtaposition of the above synclinal structure and the structurally higher rocks of the Gasak Nappe which form hill 1237. This strengthens the analogy with the structure south of Duoldagop.

The stratigraphy requires that both of these slides must cut out early anticlinal closures to which the proposed syncline is complementary. These relationships are indicated on the cross-section X–Y (Fig. 8). The Hammeren slide must be accepted in view of the stratigraphic arguments presented. The other structures, however, are speculative and the interpretation presented here is not unequivocal. The units attributed to the Pieske/Vasten Nappe are therefore structurally lower elements of the Gasak Nappe, and the nappe junction units regarded by Kautsky (1953) as marking the base of the Gasak Nappe in fact represent a slide within the Gasak Nappe. This revised interpretation does not prejudice the conclusion of Boyle et al. (in press) that the Gasak Nappe is a fold-nappe but modifies it to accord with the stratigraphic relationships.

THE HAMMEREN SLIDE

The Hammeren slide is very complex (Fig. 7 C-C') but, significantly, no

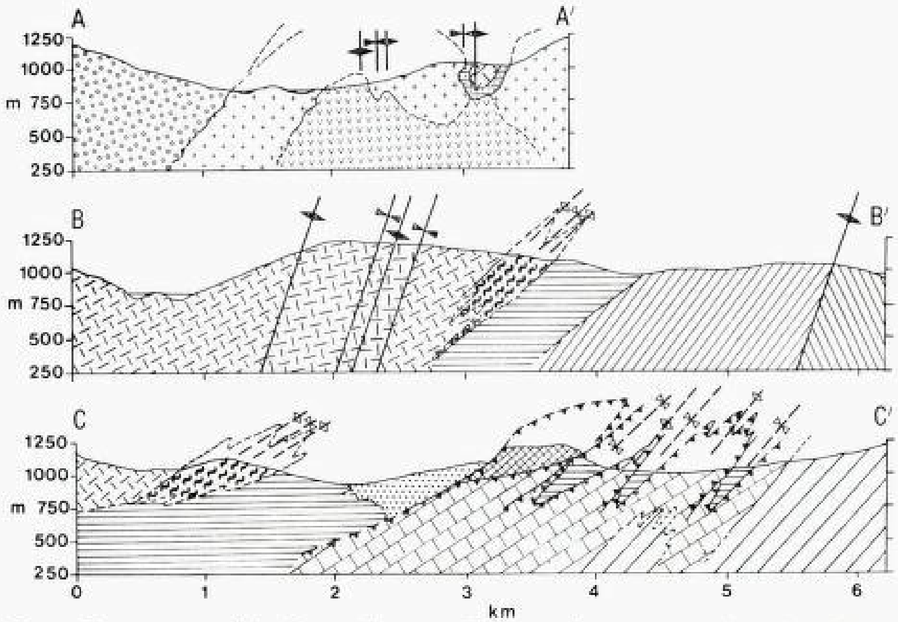

Fig. 7. Cross-sections of the Sorjusdalen area. The lines of section are indicated on Fig. 2.

evidence of mylonitisation is present. Evidence of high tectonic strain is often preserved in the lithological units in contact with the marble unit. Slices of the biotite–gneiss unit occur within the marble, indicating anastomosis of the slide (Fig. 7 C-C'). The complex structures within the marble beneath the slide zone suggest that a great deal of flow has occurred in the marble, which was presumably in a highly ductile state.

In the field, the Hammeren slide is marked by the change from one lithological sequence to another and by the very characteristic lithologies described previously. These include the ultramafic bodies and the granite–gneiss breccia. The envelope of calcareous calc–magnetite schist surrounding the ultramafic bodies is thought to be a dynamo–metamorphic alteration of the ultramafic rock and would act as an excellent lubricant suggesting solid emplacement of the ultramafic bodies (Heard & Rubey 1966). The bodies are therefore the remnants of a larger ultramafic body fragmented and tectonically emplaced during the development of the Hammeren slide.

The granite–gneiss breccia has been correlated by Nicholson (1971) with similar rocks on the basement gneiss of the Nasafjell culmination who considered that: ". . . its discovery adds weight to the proposals that the Sorjusvann assemblage also is of basement origin . . ."; the implication being that the breccias formed uncomformably on the basement (not necessarily on the Nasafjell culmination) together with the overlying comformable sequence prior to emplacement as part of the Gasak Nappe. The rocks now in contact with the granite–gneiss breccia have been tentatively correlated with the Sulitjelma Amphibolite Group. The regional stratigraphy, however, requires that in a conformable sequence the Pieske marble and the Furulund and Sjønstå Groups

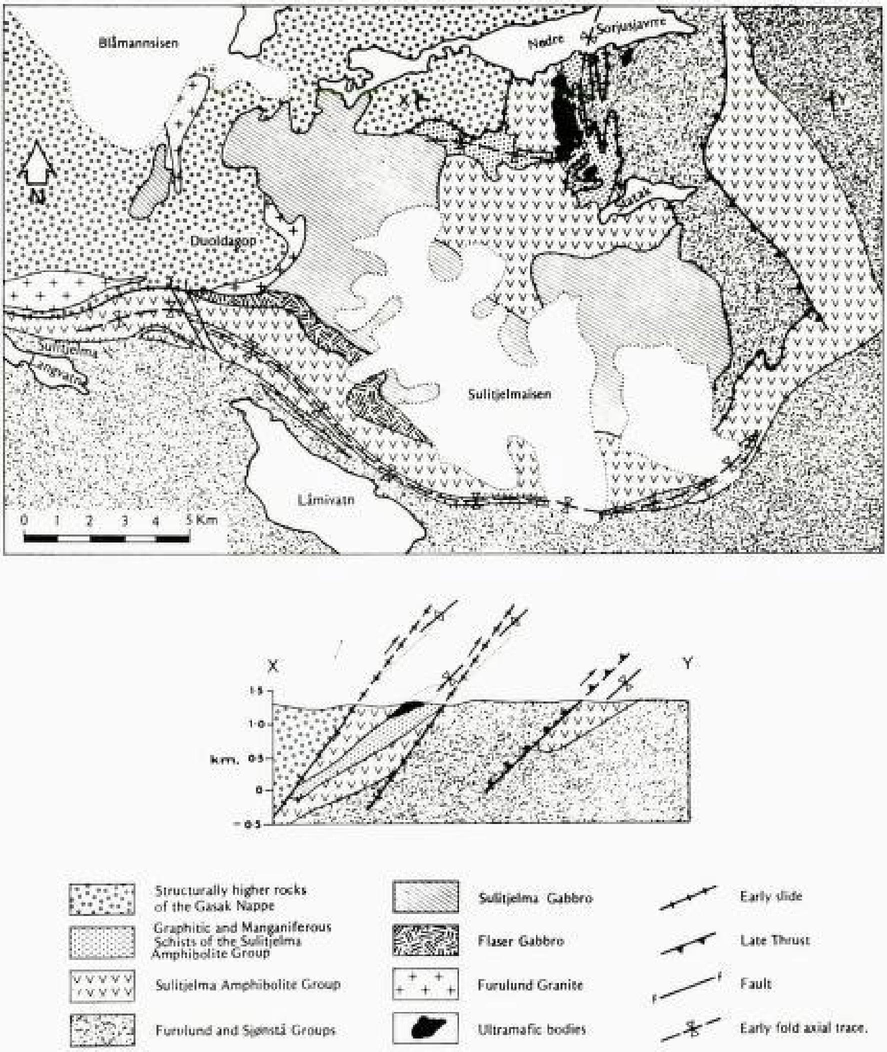

Fig. 8. Speculative geological map of the Sulitjelma district based on that of Boyle et al. (in press).

should separate the two (Nicholson & Rutland 1969). It must be concluded, therefore, that the Hammeren slide is an imbricate tectonic slide within the Gasak Nappe.

All the lithological units were involved in F_1 folding and the coeval S_1 foliation has overprinted the Hammeren slide. This, together with the ductile style of the slide, suggests development during the early stages of F_1 deformation.

TIMING OF NAPPE EMPLACEMENT

It is known from other studies in the Nordland region that nappe emplacement occurred during F_1 deformation (Nicholson & Rutland 1969, Wells & Bradshaw 1970). The association of the development of the Hammeren slide with F_1

deformation in the Sorjusdalen area therefore suggests both were linked with the emplacement of the Gasak Nappe. This is supported by the conclusions of Boyle et al. (in press) who point out that the Gasak Nappe is a fold-nappe emplaced during the earliest deformation phase.

Following Henley (1970) and Mason (1971) we attribute the inversion of metamorphic grade in the area to the syn-metamorphic nature of the large Sulitjelma Gabbro which must have supplied a considerable amount of heat to the country rocks. The regional trend of increasing metamorphic grade westwards must not, however, be forgotten, and we believe that even if the thermal effects of the gabbro were removed there would still be a general westward increase in grade. The effect of the thermal energy supplied by the gabbro has been to enhance and exaggerate this trend. The gabbro must have been intruded after the emplacement of the Gasak Nappe and the associated development of the Hammeren slide as there is no evidence to suggest that these early structures affect the gabbro.

Henley (1970) made a detailed examination of the area to the south-east of Sulitjelma and concluded that the nappe emplacement is syn-metamorphic. However, he noted that the observed penetrative fabric was created by a flattening modification (his D_2) of an earlier schistosity axial planar to isoclinal folds (his D_1). We equate our F_1 fold phase with Henley's D_1, and suggest that subsequent (D_2) flattening, which we have been unable to differentiate as such, may have produced the congruency of structure and the fabric above and beneath the Hammeren slide.

We conclude that the Gasak Nappe was emplaced syn-metamorphically, at or just prior to the metamorphic peak, with the intrusion of the gabbro occurring shortly afterwards. The nappe is internally disrupted by the anastomosed Hammeren slide which is further complicated by the ultramafic bodies which were tectonically emplaced as the slide developed during the translation of the Gasak Nappe. Considering the nature of the deformation occurring at this time the Gasak Nappe must be regarded as a disjunctive fold-nappe of considerable size.

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