NORGES GEOLOGISKE UNDERSØKELSE

# THE NICKEL MINERALIZATION OF THE RÅNA MAFIC INTRUSION, NORDLAND, NORWAY.

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## ABSTRACT

The Råna synorogenic Caledonide intrusion in north Norway contains pentlandite+pyrrhotite+chalcopyrite+pyrite disseminations grading up to 0.8% sulfide nickel in peridotite in the northwestern part of the body. Peridotite and pyroxenite occur as bands and lenses within a peripheral zone mainly of norite, around a core mainly of quartz-norite. Crystal settling appears to have been an important process at Råna but over much of the intrusion primary structures have been severely disturbed by the later Caledonian fold phases which also involved local overthrusting: these movements resulted in infolding and thrusting of units of semipelitic and calcsilicate gneiss and black schist into the intrusion. The body has the form of an inverted, possibly truncated cone with its axis plunging northwestwards at a moderate angle.

The peridotites show no obvious systematic variation of sulfide or silicate mineralogy across strike. Locally, associated with certain deformation zones, dissemination passes into massive mobilized sulfide with up to 5% nickel. The proximity of sulfide-bearing black schists to mineralized rocks, the occurrence of graphite disseminated in peridotite and other factors, suggest assimilation of sulfur from the country rocks. Sulfur isotope studies do not, however, offer confirmation of the hypothesis that an external source of sulfur has had more than very local significance at Råna.

## INTRODUCTION

The Råna mafic intrusion lies at approximately 68°30'N, in steep mountainous terrain 20 km southwest of the iron-ore port of Narvik in north Norway (Fig.1). The present paper will give a brief description of the general geology of the complex, with a more detailed consideration of the sulfide-bearing areas - especially the main one at Bruvann (Fig.2) - and of the genetic implications involved. More comprehensive treatment of various aspects of the geology of the Råna intrusive will be forthcoming in later papers.

The information presented here results from an investigation of the Råna mass and its nickel mineralization which began in 1971 and is now approaching its conclusion. The investigation has been financed by the Norwegian steel company Stavanger Staal A/S and by the Norwegian state, and carried out mainly by the Geological Survey of Norway.

The intrusion itself has been described by Foslie (1920,1921), and the general geology of the surrounding area by Gustavson (1966,1969, 1972). The area lies within the recently published geological map-sheet Narvik (1:250,000) (Gustavson 1974).

The mass contains the only nickel deposits registered in the Norwegian Caledonides within a radius of 100 km. The region does contain many subeconomic deposits of Cu, Pb, Zn and Fe, as described by Foslie (1941, 1946,1949) and Juve (1967). Nickel exploration at Råna began during World War I and the several known deposits were investigated a number of times before the present work was initiated.

The only known major deposit is restricted to an area of approximately half a sqare km just north of the lake of Bruvann near the northwestern periphery of the intrusion where it outcrops between 400 and 500 m above sea level (Figs. 2 & 3). Prior to the present investigation a total of 7,000m was drilled in this area at various periods, and during World War II 800 m of drifting from which much of this drilling was carried out. The present investigation has, in addition to geological an geophysical mapping, entailed approximately 28,000 m of diamond drilling

## GENERAL GEOLOGY OF THE INTRUSION

The Råna mass has a surface area of over 80 sq. km and expresses positive relief in relation to the surrounding metasediments. Most of the outcropping intrusive lies above 450 m and several peaks reach over 1,300 m. The area is dissected by the north-south-running valley of ~~Rånd~~ Råndal, the lake it contains lying at 12 m above sea level.

### COUNTRY ROCK

The intrusion lies within the Caledonide orogenic belt, in rocks classified as the Narvik Group (Gustavson 1966). These consist mainly of two-mica gneisses, though thin bands of other rocks also occur, as well as frequent subconcordant pegmatites. The thin bands include amphibolite common southeast of the intrusion (Fig. 2), and red schist, a micaceous garnet-clinozoisite gneiss with traces of pyrite, which is particularly well developed in a refolded band southwest of the mass (Fig. 2). Much more common than either of these rocks are bands of varyingly hornfelsed calc silicate gneiss, up to several hundred metres thick, and occurring often on or close to the outer contact of the intrusion. This gneiss consists mainly of plagioclase+clinozoisite+hornblende+sphene+diopside+microcline ±garnet±quartz±carbonates, and also contains bands of black schist rich in graphite and pyrrhotite.

The country rocks have been affected by at least four fold phases:

1) at least one isoclinal phase, possibly two.
2) Z-folds, often with east-west axes, and with amplitudes up to the order of 100 m.
3) open folds with east-west, northeast-southwest or, less commonly, north-south axes. These folds may have wavelengths of the order of a kilometre or more.
4) monoclinal folds, generally with north-south vertical axial plane These may correspond in age to a series of north-south-oriented faults occurring at the northern and southern margins of the mass

Concepts on the geotectonics of the north Norwegian Caledonides are currently undergoing reexamination (Ramsay & Sturt 1977: Sturt & Roberts 1978: Zwaan & Roberts, in press) but it is fairly generally accepted that all but the thin autochthonous units, lowermost in the sequence, form a series of major nappes thrust a considerable distance from the northwest in two major episodes - 1) late Cambrian. early Ordovician and 2) Upper Silurian. Gustavson (1972), referring to the Silurian deformation in Nordland, states that the major period of nappe emplacement occurred post-$F_1$ and pre-$F_2$, and that the peak of regional metamorphism (garnet amphibolite facies) occurred syn-$F_1$.

The Råna intrusion appears to have been emplaced before the third fold phase under garnet-amphibolite facies (kyanite-garnet subfacies) conditions which prevailed throughout the solidification period of the mass. Evidence from the Råna area thus suggests somewhat different conclusions from those obtained regionally. Roddick (1977) dates the intrusion at 400 m.y. on the basis of Rb/Sr whole rock and mineral isochron while the country rocks give a metamorphic age of 400±16 m.y..

MAFIC AND ULTRAMAFIC ROCKS

The surface geology of the intrusion has a crudely concentric arrangement, with a peripheral zone of norite and a core of quartz-norite, both locally amphibole-bearing and both locally gabbroic, particularly the quartz-norite. The norite zone contains somewhat irregular bands and lenses of peridotite (the main host rock for the nickel mineralization at Bruvann) and pyroxenite. These rocks are not evenly disposed around the peripheral zone, but, where common, tend to occur towards the outer margin of the mass. South of the main intrusion occur two outliers: the Tverrfjell synform east of Randal and on the north side of Kvanåkertind west of the valley (Fig. 2). Neither of these appears to extend down to sea level. The Tverrfjell outlier is the only part of the intrusion in which systematic gravitational banding on scales below 100 m is common: these structures, with the exception of a few doubtful cases, are always 'right way up'.

The northern and northwestern contacts of the intrusion generally dip outwards at moderate to steep angles, while the southern and eastern contacts dip inwards under the mass at angles which are shallow to moderate in the east and southeast. The contact between the norite periphery and the quartz-norite core is distinct only where tectonic, in which case its dip is similar to that of the outer contact, except in the eastern part of the intrusion where the norite/quartz-norite contact dips outward. The geometry of the contacts suggests that the intrusion has, in a crude sense, the form of an inverted, possibly truncated, cone with an axis plunging northwestwards and exposure nearing the roof in the east. This model is supported by the results of a gravity survey (Sindre & Boyd 1977). The distribution of rock types within this framework and the nature of the magmatic gravitational structures, where not affected by later deformation, suggest that gravitational forces played an important role in the crystallization of the Råna rocks.

a) Peridotite

The most common peridotite variety found at Råna is harzburgite with 40-60% olivine ($Fo_{86-87}$ based on nine microprobe analyses), though lherzolitic and dunitic varieties also occur, and locally small amounts of plagioclase may be present. The major peridotite units in the northern and southwestern parts of the intrusion appear however to be generally homogeneous over many tens of metres, with no systematic variation readily apparent in primary characteristics.

Olivine forms grains up to 5 mm long, subidiomorphic to rounded against silicates but often idiomorphic against sulfides. Except in deformation zones and along hydrated fractures the olivine is almost always unaltered (serpentine, along irregular cracks, is rare, especially in the Bruvann area), and as yet no indication of zoning has been found. Orthopyroxene (hypersthene) occurs as primocrysts similarly to olivine, as megacrysts up to 1 cm long with rounded olivine inclusions, but most frequently as anhedral interstitial grains. Where present, augite forms megacrysts or interstitial grains similar to those of orthopyroxene. Plagioclase is always interstitial in Råna peridotites. Phlogopite is a common accessory in all peridotite varieties. The remaining primary phases, in addition to the sulfides described later, are picotite spinel, hematite, ilmenite and magnetite, all in small amounts. Secondary amphibole (uralite) in interstices is common, and in deformation zones, talc and anthophyllite.

b) Pyroxenite

This rock contains up to about 80% hypersthene in generally subidiomorphic grains up to 3 mm long, though locally as much as 6 mm. Slight marginal zoning is found, and occasionally exsolution lamellae of augite. Uralitization is common. Interstitial minerals are augite, phlogopite, plagioclase and occasionally opaque minerals. Olivine-bearing varieties occur but not commonly.

c) Norite

The term norite is used here to cover a wide range of rock types, including both primary olivine-bearing and gabbroic varieties in limited amounts. Alteration, deformation and recrystallization impose further complexities. Hypersthene occurs as subidiomorphic grains generally less than 2 mm long, rarely with exsolved lamellae of clinopyroxene and rarely zoned. Inclusions of plagioclase may be present in the hypersthene (and vice versa). Plagioclase may make up 50% of the rock and it is generally unzoned. Clinopyroxene, where present, has a mode of occurrence similar to the hypersthene. Primary amphibole is a feature of some of the norites in certain areas. Secondary amphibole and clinozoisite are common and where deformed the rock is ~~commonly~~ often recrystallized to amphiboles+plagioclase+clinozoisite±mica.

d) Quartz-norite

The quartz-norite core of the intrusion appears to be less well defined than suggested by Foslie (1941) and to be more variable internally. Plagioclase is more abundant than in the norite, and is often idiomorphic against quartz which is present in only small amounts. Clinopyroxene increases relative to orthopyroxene, and primary amphibole and biotite are present in addition to rare orthoclase. Superimposed on these variations are the effects of deformation and recrystallization, especially marked in the area of Eiterdal.

e) Later dykes and veins

These are of two main types. 1) Northeast of the Bruvann area occur thin vertical north-south-running dolerite dykes. 2) Throughout the intrusion, but especially in the southeast, occur sills of granite, trondhjemite and quartz-rich pegmatite.

STRUCTURAL GEOLOGY

Though the Råna intrusion may postdate the strongest phases of regional deformation, the effects of the later phases have locally been very pronounced. This applies particularly to the area north of a line from Bruvann to Saltvikvann and to a belt from Kvanåkertind to Eiterdal. (Fig. 2). Deformation in these areas corresponding to the regional $F_3$ movements appears to have begun with the development of segregation banding in norite/metanorite, with subsequent folding of the bands. Folding of the contact southeast of Bruvann and south of Sepmolfjell, and the development of the Tverrfjell syncline seem to date from this period. The climax of this phase of deformation involved disruption of the mass in two major areas:

1) The overthrusting of the part of the intrusion northwest of a line from Bruvann to Råna (known as the Arnesnesten block) (Fig. 3) towards the southeast. The thrust is defined by two gneiss wedges 'connected' by a series of lenses of gneiss lying in a strongly deformed arcuate zone dipping northwest at a steep angle which becomes less at deeper levels. The Arnesnesten block has a complex internal structure as a result of folding and faulting, some of this related to the overthrusting. In addition to disrupting the primary igneous structures of the block, these movements resulted in the emplacement within the block of gneiss lenses and slabs of various types including black schist (Figs. 3 & 4). Relative to most other parts of the norite periphery this area is distinguished by its high proportion of ultramafic rock to norite and by the presence of large volumes of peridotite with nickel-bearing sulfide dissemination. This is not surprising in an upthrust block, if the model of the intrusion as an inverted cone in which gravity settling has been active is correct.

2) The southern part of the intrusion was affected by the formation of synclinal structures both east and west of Råndal, those at Tverrfjell and north of Kvanåkertind eventually becoming separated from the rest of the intrusion by completely recrystallized deformation zones containing bands and pods of country rock.

The $F_4$ fold phase seen in the surrounding gneisses appears to have its analogue within the intrusion in north-south block faults common in well exposed areas on the south side of the mass, and also on Sepmolfjel and in the Arnesnesten block.

ingly complex in the southern part of the area: mineralized horizons split up and generally become weaker, and the peridotite units finger out and pass into generally noritic rocks of rapidly varying character.

Close to the base of the mineralized peridotite in this area occur accumulations of massive epigenetic sulfide with up to 5% nickel. This type of mineralization, first found at Bruvann in 1974, is now known from several localities along an east-west line (1250 N) close to the southern contact of the deposit. These locations usually have in common:

1) the presence of peridotite or other olivine-bearing rocks,
2) deformation, and
3) the presence of tectonically emplaced gneiss lenses including black schist.

Almost all of the localities show the massive sulfide occurring in connection with dissemination in peridotite.(Fig. 4).

West of the fault which dissects the Bruvann area, (Fig. 3) the situation is more complex. This part of the deposit is of a tonnage somewhat greater than that of the eastern area but it is nowhere exposed and was not discovered until 1972. The western area contains two major mineralized peridotite units which lie rather flat in the south and which increase in dip to about 45° to the northwest. The present stratigraphy, partly the result of complex deformation, is, in simplified form, from top to bottom:

Complex of interbanded norite, peridotite and pyroxenite.
Upper mineralized peridotite.
Interbanded peridotite and pyroxenite with subsidiary norite.
Lower mineralized peridotite.
Pyroxenite.
Norite (to depth drilled, approximately 400 m below sea level)

The western area has several features in common with the eastern area. In both cases the peridotites, both mineralized and unmineralized, terminate abruptly on their northern margins against a ridge of norite (under country rock in the western area). In both cases the dissemination tends to be richer and more homogeneous in the north and more discontinuous to the south.

It is thought probable that the major mineralized peridotite in the eastern part of the Bruvann area and the lower mineralized peridotite in the west were originally continuous and that the upper peridotite in the west may be a tectonic repetition of the lower one.

Typical sulfide dissemination in the peridotites at Bruvann contains: pyrrhotite (50-75%), pentlandite (10-35%), chalcopyrite (5-15%) and minute amounts of pyrite (less than 0.5% according to a detailed point count analysis by Malvik (1977)). The sulfide mineralogy of olivine-norite and pyroxenite in [illegible]

In many parts of the intrusion there are numerous subhorizontal pegmatites, individually up to 50 m thick and with a total thickness within the visible section of up to perhaps 200 m. These appear to have been emplaced along subhorizontal fractures at a late stage in the history of the intrusion, and possibly associated with the release of load pressure related to uplift.

## ORE GEOLOGY

### DEPOSITS

a) The Bruvann area.

The deposit contains a calculated 40-50 million metric tons of sulfide disseminated peridotite averaging 0.33% sulfide nickel. Restricted parts of this tonnage average as much as 0.6%, and individual analyses reach 0.8-1.0%. The deposit has approximate dimensions of 900 m east-west and 500 m north-south. It outcrops at 500 m above sea level at its eastern end and the deepest mineralized zones lie at 100 m below sea level at the western end.

In the middle of the area the deposit is cut by a northeast-southwest running hinge fault, the throw of which increases northeastwards from about 200 m close to Bruvann. East of this fault the peridotite is underlain by pyroxenite which in turn lies on norite. The base of the peridotite is rather flat-lying in north-south section and rises to the east. In the north the peridotite stops abruptly along a steep east-west contact against a ridge of norite.and is cut off in the east by faulting with upthrow to the east. Thus the norite underlying the Bruvann peridotite is thought to be equivalent to the largely noritic rocks on Arneshesten. The peridotite is also affected by various lesser dislocations. The main mineralized zone strikes east-west parallel to the rock contacts and, where not appreciably affected by deformation, as in profile 2600 E (Fig. 4), has a dip of about 45° near the surface while flattening out in depth towards the south. Above this main zone occurs a series of thinner, more tenuous zones of mineralization. A grossly simplified stratigraphy for the eastern area is, from top to bottom:

- 50-100 m: unmineralized peridotite containing thin, erratic zones of mineralization.
- 20-50 m: mineralized peridotite (the main zone).
- 0-70 m: pyroxenite.
- 150 m: norite (to explored depth).

Much of the area is complicated by deformation zones and by bodies of other rock types including gneiss whose geometric relationships are often not amenable to interpretation (Fig. 4). The situation becomes increasuously and interstitially to olivine and hypersthene but, in richer portions, has the 'net' texture described by Naldrett (1973). The pentlandite occurs for the most part as discrete, irregular grains close to or at the margins of pyrrhotite and in cracks through pyrrhotite grains. 'Flames' and lamellae of pentlandite are present in the pyrrhotite near fractures and grain boundaries but only in minor amounts – of the order of 1% (Malvik 1977). A somewhat curious feature of the dissemination is the variability of the pentlandite:pyrrhotite ratio from area to area on a polished section. The chalcopyrite also occurs as free grains marginal to pyrrhotite, but in addition is present as crack fillings cutting across other sulfides and sometimes penetrating adjacent silicates. Pyrite forms isolated idiomorphic grains in pyrrhotite. Small amounts of magnetite occur, often near the margins of olivine grains, and small amounts of intergrown hematite and ilmenite are disseminated interstitially. In common with Ramdohr (1969), the writers have found minor amounts of graphite within sulfide disseminated in peridotite. (Small amounts of graphite are also dispersed within other rocks of the intrusive at Bruvann and elsewhere).

As noted earlier, accumulations of massive ore occur locally along an east-west-running zone near the southern border of the Bruvann area, and their emplacement is apparently to some extent tectonically controlled. In most, but not all cases, this mineralization lies beneath normally disseminated peridotite and above a gneiss-like rock bearing considerable sulfide impregnation. The massive ore and the underlying impregnation have a variable Ni:S ratio, generally lower than is characteristic for the dissemination in peridotite. In certain drillholes the massive sulfide has a continuous thickness of several metres: in others it has been injected into veins from a few centimetres to several decimetres across. It would appear that the massive ore accumulated subsequent to the solidification of the peridotite and along a zone of disruption between the more homogeneous thicknesses of peridotite to the north and the more variable rock types to the south. The presence of the sulfide-rich gneissose rock beneath the massive ore may also have some genetic significance.

b) Rånbogen (Figs. 2 & 3)

This area, which lies near the northern contact of the mass, east of Råndal, has been the focus of some attention since 1915, but has never been drilled. Both norite and peridotite are commonly mineralized, though irregularly so.

In some of the norite fine, unevenly disseminated sulfide is common and in certain deformed belts this passes over into zones of massive sulfide —

These ~~In Rånbogen~~ shear zones up to several metres wide and several hundred metres long contain predominantly graphite and pyrrhotite, with small ~~(xxx~~ amounts of other sulfides, and also rounded inclusions of silicates. Thes zones may include lenses of black schist in which variable amounts of graphite and pyrrhotite are accompanied by small amounts of chalcopyrite.

Mineralization also occurs irregularly within the peridotites in Rånbogen. Two bands near the northern contact contain sulfide almost exclusively as rounded drops up to 6 mm in size. Further south weak normal dissemination is found in peridotite. Common to all mineralizatior so far known from Rånbogen are low Ni:S and Cu:S ratios (Ni:S is 1:14 or lower in the peridotites). The peridotites rarely show more than 0.25% sulfide nickel.

c) Eiterdal (Fig. 2)

This deposit lies at 300 m above sea level on a steep mountain side in the southeastern part of the intrusion. Five short exploratory adits were driven into the deposit during World War I but, because of the apparently limited extent of the mineralization and the difficulty of the terrain, little further work has been done.

The deposit occurs in olivine-norite, along the underlying, sheared contact of the intrusion - here in contact with calcsilicate rock containing black schist. Near the contact the norite is also deformed, and contains lenses of calcsilicate rock. The various types of mineralizatio include 'drop' ore and impregnation which locally passes over into more massive ore. Analyses from Eiterdal show up to 1% Ni in richer impregnation with a Ni:S ratio of 1:10.

d) Other mineralizations.

Elsewhere in the intrusion, but particularly in the northern part of the norite periphery, peridotite commonly contains weak dissemination with rarely more than 0.2% sulfide nickel. Vein sulfide with negligible contents of nickel and copper also occurs, especially in sheared areas.

CHEMISTRY 'E UNDERSØKELSE

a) Mineral chemistry

Table 1 shows the results of microprobe analyses of olivines and sulfides from mineralized peridotite at Bruvann. Sample 1 is from a zone containing 0.4% sulfide nickel and the other two from zones with 0.1% or less sulfide nickel. The pentlandites have compositions falling within the range shown to be characteristic for the assemblage pyrrhotite+pentlandite +chalcopyrite+pyrite by Harris & Nickel (1972), a systematic relationship also suggested by Graterol & Naldrett (1971). Harris & Nickel also show that the nickel contents of coexisting pentlandite and pyrrhotite are crudely proportional (see also Papunen 1970) and that the cobalt content of pentlandite varies inversely with that of nickel: the Råna data are in agreement with these conclusions. Pentlandite 'flames' in the pyrrhotite contain several percent less nickel than discrete grains.

The microprobe was also used to search for possible variations in olivine or sulfide compositions relative to grain boundaries against each other: no such variations were found. This and the textural evidence (a greater tendency for idiomorphism in olivine against sulfide than against other silicates) tend to disprove any suggestion that direct sulfurization of olivine (as suggested by Kullerud & Yoder 1965 and by Naldrett 1966, 1969) has been an important process in the Råna peridotites. The olivine analyses show a positive correlation between sulfide nickel and the percentage of nickel in olivine, as has been demonstrated statistically on natural material by Häkli (1971) and experimentally by Fleet et al.(1977).

b) Bulk sulfide chemistry

A substantial portion of the drill core material from the Bruvann deposit has been analyzed both for the total nickel content of the rock (acid soluble) and for the sulfide nickel content (bromine soluble). The difference between these two figures can be taken to represent approximately the silicate nickel content of the rock for each sample. In turn, given the peridotitic nature of the rocks and the partition coefficients for nickel between olivine and other silicates (Häkli 1971), this figure must be strongly influenced by the nickel content of the olivine. Assays from two drill holes cutting the same mineralized peridotite just over 100 m apart are shown in Fig. 5. In Fig. 5a is shown a situation similar to those described by Naldrett (1966) from the Alexo deposit and by Häkli (1971) from the Tyrvää and other deposits in Finland: in this case silicate nickel shows a background level of 0.06-0.10%, which decreases to zero in the mineralized zone which has a grade of 0.4-0.6% Ni. Fig. 5b shows a zone with similar sulfur and sulfide nickel contents but in which the silicate nickel content rises slightly, from a background level of approximately 0.1%. The only major difference in rock types between the two sections is that the mineralized peridotite in Fig. 5a is split up by two weakly to unmineralized pyroxenite zones, while the zone shown in Fig. 5b is entirely of peridotite (except where cut by a late pegmatite). The distinction between these two zones could not be explained by sulfurization unless this were a very local phenomenon.

The Ni:S ratio for mineralization at Bruvann varies from 1:2 downwards but is clustered between 1:2 and 1:5-6, with a median at approximately 1:4. This is typical of the values for nickel sulfide deposits in peridotites given by Wilson & Anderson (1959). The Cu/Cu+Ni ratio (0.2) of the Bruvann dissemination lies within the range found in deposits in ultramafic rocks (Naldrett & Cabri 1976: Rajamani & Naldrett 1978). It should here be noted that the majority of deposits for which such metal ratios are cited as characteristic are Archean (e.g. deposits of the Abitibi and Manitoba belts), and occur in host complexes which as a whole are much more mafic than the Råna mass.

It has been noted already that certain metal ratios appear to be characteristic of different parts of the intrusion. Thus, at Bruvann, where the dominant mineralization is in peridotite, the Ni:S ratio is 1:4 while in Eiterdal, in olivine norite it is 1:10 and in Rånbogen, where the mineralization is predominantly in norite, the ratio is 1:14 or less. A similar tendency with respect to rock type has been shown by Häkli (1971). This trend suggests that the sulfide magma in certain parts of the intrusion attained a degree of local homogeneity, the composition being dependent at least in part on the nature of the silicate magma present.

c) Sulfur isotope study

The presence of graphite in various rocks in the intrusion, the juxtaposition of sulfide-rich black schist with mineralized peridotite and massive sulfide, and disequilibrium features such as illustrated in Fig. 5 led the writers to suspect an external source for some of the sulfur in the deposits.

The presence of graphite in sulfide-bearing mafic intrusives has been described from the Bushveld Complex (Liebenberg 1970), Kotalahti (Haapala 1969), Hitura (Papunen 1970), the Harriman and Warren deposits in Maine (Rainville & Park 1976) and from the Water Hen Intrusion in the Duluth Complex (Mainwaring & Naldrett 1977). In a number of these cases country rock xenoliths are prominent. Sulfur isotope studies based on the difference in $^{34}S/^{32}S$ between sulfur in black schists and other metasediments and the ratio for sulfur from normal uncontaminated mantle-derived magma have been used to indicate a partly external source of sulfur for the sulfides in certain mafic intrusives (Godlevskii & Grinenko 1963:

Naldrett 1966: Liebenberg 1969: Mainwaring & Naldrett 1977).

Table 2 shows the results of sulfur isotope analyses performed on Råna samples. On the principle that investigations of the origin of sulfur in ore deposits should be based on the sulfur isotope ratio for the total sulfide content, not that of the individual minerals (Rye & Ohmoto 1974), the sulfide minerals were not separated individually. The samples consisted of more than 95% pure bulk sulfide fractions, with the mineralogy for individual rock types as described earlier. The writers have to date not found published sulfur isotope data for separated pentlandite, but data on separated mineral fractions of coexisting pyrite, pyrrhotite and chalcopyrite (Mäkelä 1974: Rye & Ohmoto 1974: Mainwaring & Naldrett 1977 and others) suggest that the degree of isotope fractionation which can be expected in this paragenesis and at high temperatures of deposition is very limited. In addition, the changes in sulfur isotope ratio so far demonstrated as due to wallrock contamination (Liebenberg 1969: Godlevskii & Grinenko 1963: Mainwaring & Naldrett 1977) are almost an order of magnitude greater than those which would be expected from isotope fractionation.

The results for dissemination in the Råna peridotites (Table 2) are closely comparable with those cited by Stanton (1972) from a number of deposits in mafic and ultramafic rocks and interpreted as indicating uncontaminated magma from a deep-seated source. This applies equally to the samples of dissemination in norite, and, though the samples from pyroxenite and massive sulfide contain slightly heavier sulfur, the difference is small and does not appear to be related to variations in the proportions of sulfide minerals.

The sulfur within the bands of black schist, both within and outside the intrusion, is on average markedly lighter than meteoritic sulfur, and are clearly lighter than the values obtained from dissemination in peridotite. The values fall within the range cited by Stanton (1972) for ancient sedimentary rocks with no volcanic component.

These results would appear to suggest that external sulfur was not a significant factor in the formation of the mineralization in the peridotite at Bruvann, nor,probably in peridotites elsewhere in the intrusion. Only very locally ( and only in samples in which graphite is clearly visible megascopically) has external sulfur had an obvious influence. A possible explanation is that country-rock sulfur was absorbed only locally, and/or at a stage at which the norite may have been in a mushy state or even after much of the mass was solid.

## DISCUSSION

A classification of ultramafic and associated mafic rocks was proposed by Naldrett & Gasparrini (1971) and later modified by Naldrett (1973) and by Naldrett & Cabri (1976). In all three papers the main emphasis is on the implications of the classification for metal deposits, especially of nickel, associated with these rocks. With more general geological considerations in view, classifications of mafic and ultramafic rocks have been published by Thayer (1960, 1971), Jackson & Thayer (1972), Thayer & Jackson (1972), Moores (1973) and Wyllie (1969). The Råna intrusion and a number of others in the Caledonides, including those of the Seiland Province (Robins & Gardner 1974), Ireland (Leake 1970: Kanaris-Sotiriou & Angus 1976) and northeast Scotland do not fall easily into any of the published classifications. This problem and many of the difficulties in interpreting the Råna mass and its mineralization arise from the fact that, though it has many of the features of the stratiform or funnel shaped intrusions occurring in stable areas, it lies in an orogenic belt and also has many of the features of the intrusions classified as alpine (Jackson & Thayer 1972). In this context the use of the terms 'stratiform' and 'concentric' (descriptive of the form of the intrusion) as opposed to 'alpine' (descriptive of present geological environment) (Jackson & Thayer 1972) seems unfortunate as also the tendency to equate 'alpine ultramafic rocks' with ophiolite (Naldrett & Cabri 1976: Garson & Plant 1973). Some related reservations on existing classifications of mafic and ultramafic rocks have been expressed by Challis (1965, 1969), Challis & Lauder (1965), McTaggart (1971), Nesbitt et al. (1970), Moore (1973), Robins & Gardner (1974) and others.

As has been described, the form of the contacts of the Råna intrusion suggest the shape of an inverted cone, possibly truncated, with its axis plunging northwestwards and the highest section of the cone, possibly near the roof of the intrusion, in the east and the deepest section in the northwest. In a very general sense the distribution of the peridotite bodies lends support for this model, as they are not frequent on the eastern rim and are most frequent along the northern and northwestern contact. Further confirmation of this model is given by the nature of the Arneshesten block which, having been thrust up from an even deeper level than those exposed elsewhere, contains not only peridotites of substantial thickness, but the only ones in the intrusion known to be significantly mineralized over large volumes. However, when considering the distribution and attitude of the individual peridotite bodies problems are encountered: the individual peridotites may be subparallel to the outer contact ( eastern Rånbogen, Tverrfjell) (Fig. 2) or discordant to it (western Rånbogen, Bruvann) (Figs. 3 & 4), some bodies changing along their length from apparently concordant to apparently discordant. So far the writers have failed to construct a model accounting for these complexities: they must, however, be related to the extensive syn- and post-intrusive defromation of the area, and complicated by the possibility indicated by the nickel-rich metal ratios from Bruvann, that some of the peridotites may have crystallized from an earlier, more mafic magma pulse.

The pentlandite-bearing sulfides at Råna are invariably within, or closely associated with olivine-bearing rocks. Though the writers do not believe that direct sulfurization of olivine has been a major process in forming the nickel mineralization at Råna, the connection between olivine-bearing rocks and nickeliferous sulfide magma is not thought to be coincidental or purely due to physical factors. Irvine (1975, 1977) has suggested the existence of a mechanism which would seem to explain satisfactorily many features of the Råna mineralization. He suggests that an increase in silica or alkalies in a magma (either by contamination or by magma mixing processes) causes a polymerization of the magma, which results in ions such as $Ni^{2+}$ with high octahedral site preference energies being preferentially expelled from the silicate liquid and into the sulfide magma. Among aspects of the Bruvann deposit explained by this process are: 1) the mineralization does not occur at the base of the peridotites and 2) the mineralization, both disseminated and massive, is almost always associated with peridotite, and to a degree may extend into adjacent pyroxenite (Fig. 5a).

A further, possibly related, mechanism is suggested by: 1) the commonly nonidiomorphic nature of olivine crystals in the peridotites( except against sulfides) and 2) the prominence of orthopyroxene in the peridotites and of orthopyroxenite in association with them - both factors pointing to a period in which olivine was being resorbed by the magma as a result of the olivine-enstatite reaction relationship. The partition coefficient $Ol^{Ni}/Hy^{Ni}$ (Häkli 1971) is such that this process, though affecting only a portion of the original volume of olivine crytallized, because it would be active more or less throughout the magma chamber, would release substantial quantities of nickel to the magma to be preferentially absorbed by available sulfide liquid.

A number of mineralogical and field geological indices suggest that part of the sulfur in the Råna mineralization was derived from black schist lenses within and around the intrusion. The sulfur isotope results seem to indicate that this process may have been active, but only locally and apparently not at a stage at which the major mineralization at Bruvann could be affected. This tends to suggest that the tectonic juxtaposition of black schist and mineralized rock seen in the Bruvann area occurred too late to have had any influence, even on the massive sulfide. Conversely, to have had more than local influence, such contamination processes would seem to require the incorporation of (xkx) country rock into the magma very early in its crystallization history.

## ACKNOWLEDGEMENTS

The writers wish to thank Stavanger Staal A/S for permission to publish the Råna material, Bård Tørdal for assistance with microprobe analyses, Astrid Hemming, Lars Holiløkk and Tore Skauge for help in preparing the figures and (x)- , - , - and - for their constructive criticism of the (xxxx) text. In the course of the exploration work at Råna many people at the Geological Survey of Norway have been involved: their help is gratefully acknowledged.

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TABLE 1 MICROPROBE ANALYSES

Olivine

| % | $SiO_2$ | MgO | FeO | NiO | Fo | No. anal. | total |
|---|---|---|---|---|---|---|---|
| 1) | 41.2 | 49.3 | 13.9 | 0.19 | 86.3 | 3 | 104.6 |
| 2) | 40.1 | 46.6 | 12.9 | 0.15 | 86.6 | 3 | 99.8 |
| 3) | 40.2 | 50.1 | 14.1 | 0.16 | 86.4 | 3 | 104.6 |

| | Weight % | | | | | Atomic % | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| % | Fe | Ni | Co | S | total | Fe | Ni | Co | S | No. anal. |
| **Pentlandite grains** | | | | | | | | | | |
| 1) | 28.3 | 36.8 | 1.1 | 34.0 | 100.2 | 22.9 | 28.3 | 0.9 | 47.9 | 2 |
| 2) | 29.8 | 34.1 | 1.5 | 32.1 | 97.5 | 24.4 | 28.7 | 1.1 | 45.8 | 3 |
| 3) | 29.0 | 34.4 | 2.3 | 32.5 | 98.2 | 24.1 | 27.2 | 1.8 | 46.9 | 2 |
| **Pentlandite flames in pyrrhotite** | | | | | | | | | | |
| 1) | 33.7 | 31.4 | 0.2 | 34.2 | 99.5 | 27.3 | 24.2 | 0.2 | 48.3 | 2 |
| 2) | 36.1 | 29.0 | 0.3 | 31.0 | 96.4 | 30.6 | 23.4 | 0.2 | 45.8 | 3 |
| **Pyrrhotite** | | | | | | | | | | |
| 1) | 58.4 | 1.33 | - | 40.0 | 99.7 | 45.2 | 1.0 | - | 53.8 | 2 |
| 2) | 61.9 | 0.04 | - | 35.5 | 97.4 | 50.0 | - | - | 50.0 | 3 |
| 3) | 59.5 | 0.59 | - | 37.7 | 97.8 | 47.3 | 0.04 | - | 52.2 | 2 |

The analyses were performed using an ARL-EMX-SM electron microprobe at the Inst. for Fysikk, Norges Tekniske Högskole, Trondheim.

TABLE 2

Summary of sulfur isotope data

| Mineralization type | No. of samples | Ave. $\delta^{34}S$ | Range of $\delta^{34}S$ |
|---|---|---|---|
| Peridotite dissemination | 11 | +0.3 | -2.5 to +1.6 |
| Pyroxenite dissemination | 1 | +2.7 | - |
| Norite dissemination | 6 | +0.7 | -0.1 to +1.6 |
| Norite diss. with graphite | 4 | -5.9 | -3.7 to -7.6 |
| Massive sulfide | 10 | +2.1 | +0.4 to +4.2 |
| Massive sulf. with graphite | 3 | -12.8 | -3.2 to -17.6 |
| Sulfide from blackschist within the intrusion | 4 | -7.4 | -3.6 to -13.6 |
| Sulfide from blackschist outside the intrusion | " | -9.0 | +1.0 to -13.5 |

The analyses were performed by Geochron Laboratories Inc., Boston. $\delta^{34}S$ is measured relative to $^{34}S/^{32}S$ for Cañon Diablo troilite.

Legends for illustrations

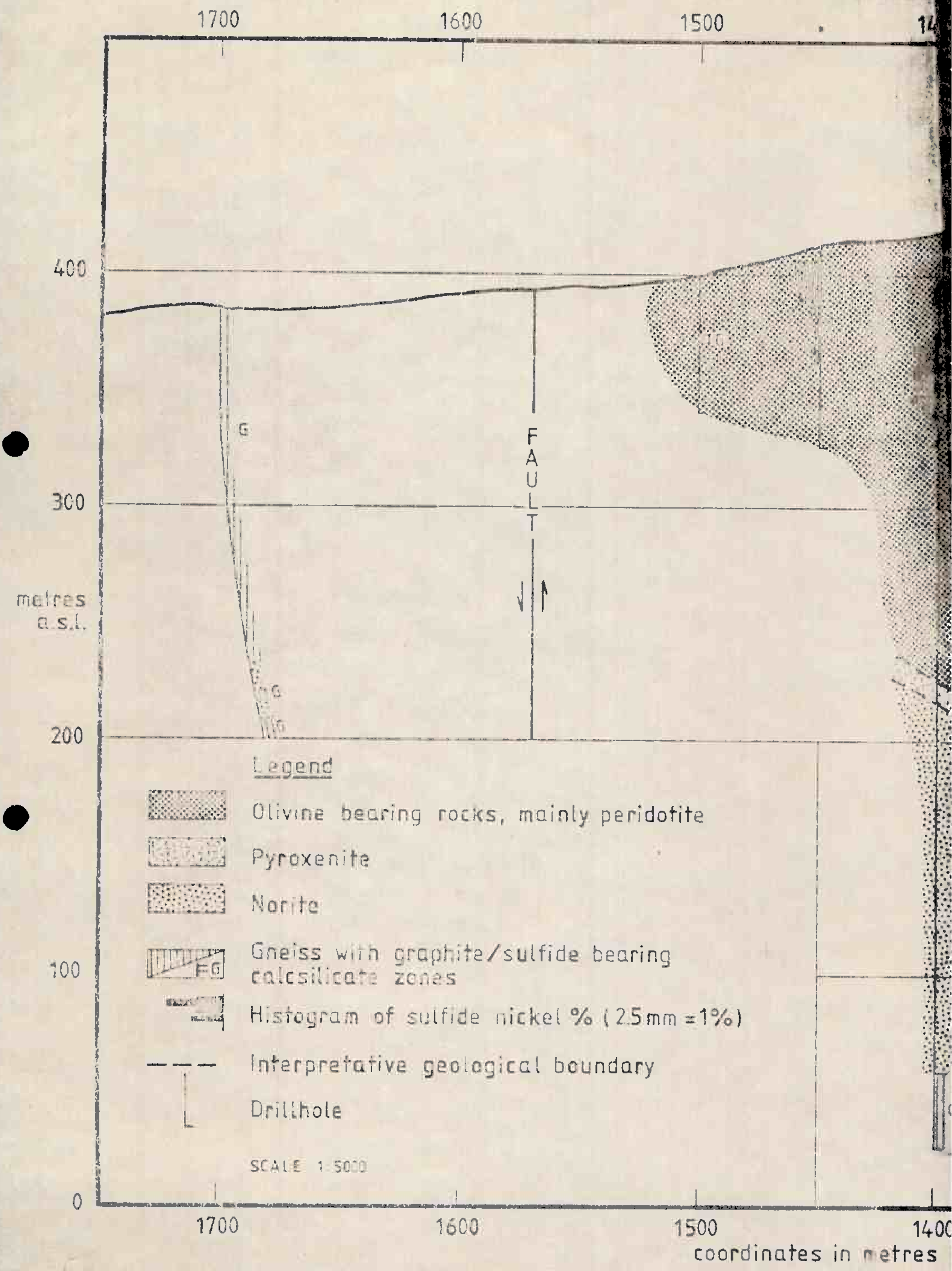
Fig. 1: Map of Norway showing the location of the Råna intrusion.

Fig. 2: Geological map of the Råna intrusion.

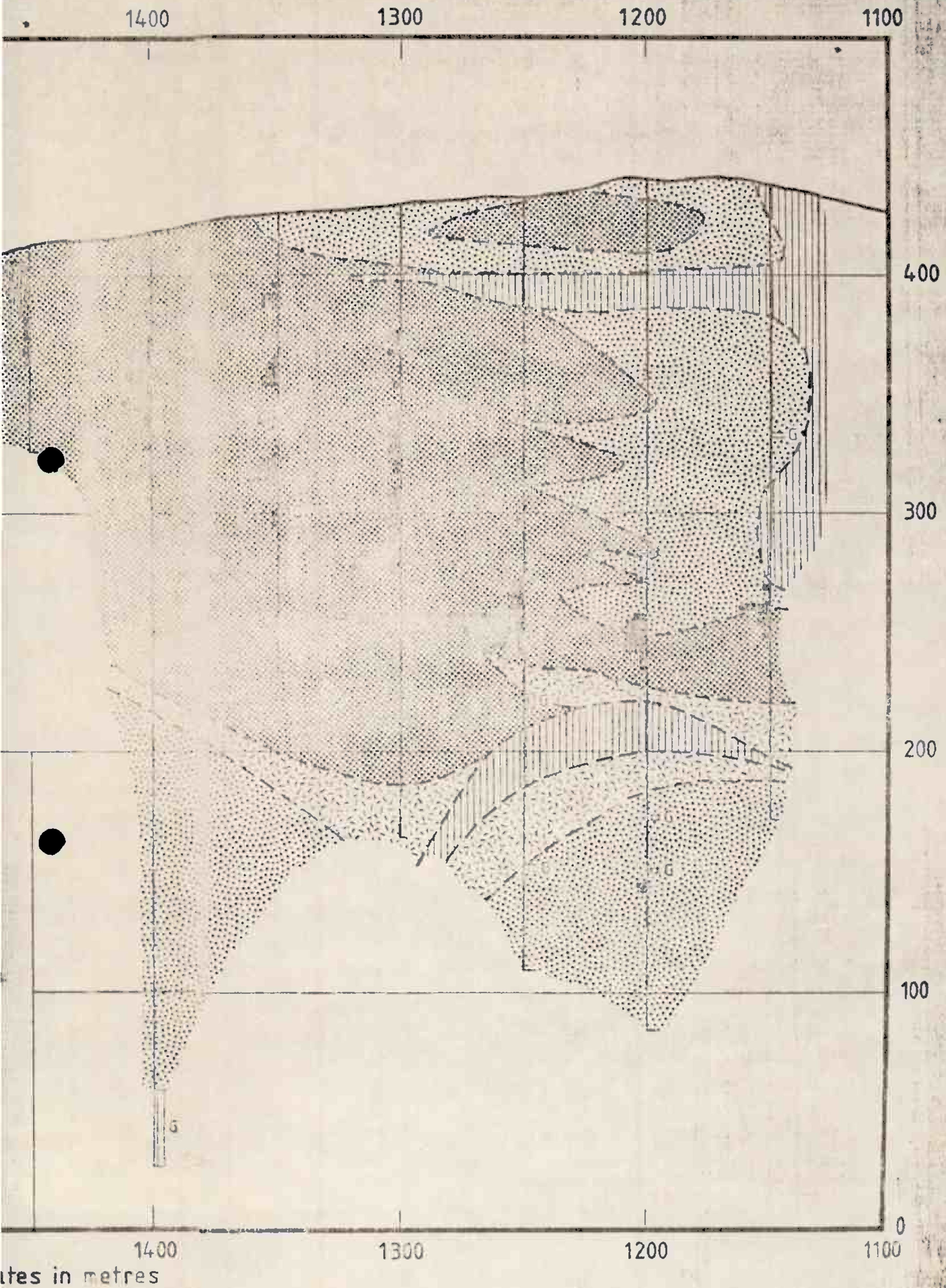
Fig. 3: Geological map of the northwestern part of the Råna intrusion.

Fig. 4: Geological interpretation of profile 2600 E in the Bruvann area: the coordinates refer to the system also used in Figs. 2 & 3.

Fig. 5: Log sheets for two core sections from the Bruvann area showing geology and analytical values: $Ni_A$ refers to acid soluble nickel and $Ni_{Br}$ to bromine soluble nickel.



1700
1600
1500
14
400
300
200
100
0
metres
a.s.l.
G
FAULT
Legend
Olivine bearing rocks, mainly peridotite
Pyroxenite
Norite
Gneiss with graphite/sulfide bearing calcsilicate zones
Histogram of sulfide nickel % (2.5mm = 1%)
Interpretative geological boundary
Drillhole
SCALE 1:5000
1700
1600
1500
1400
coordinates in metres


1400
1300
1200
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400
300
200
100
0
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G
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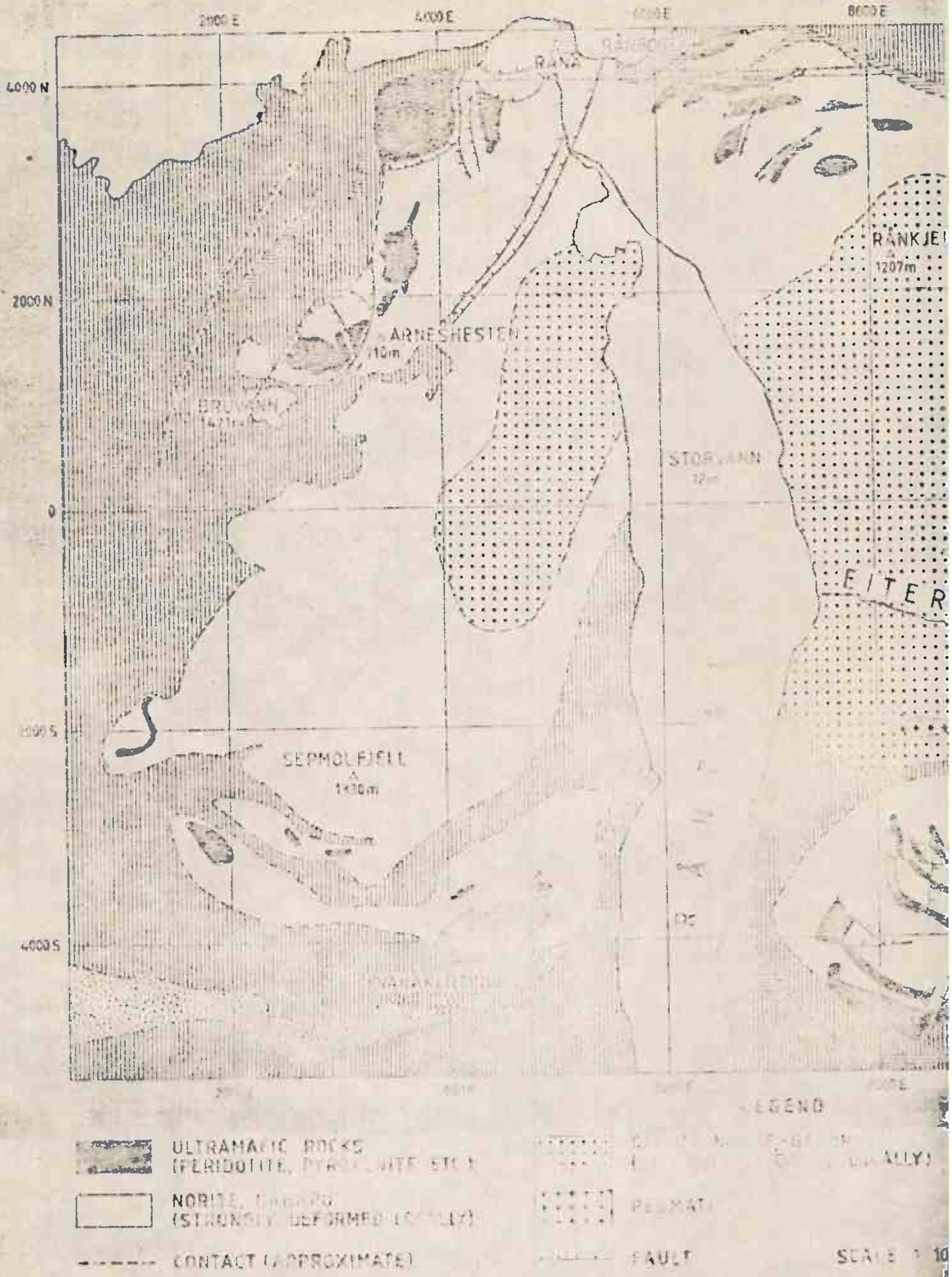
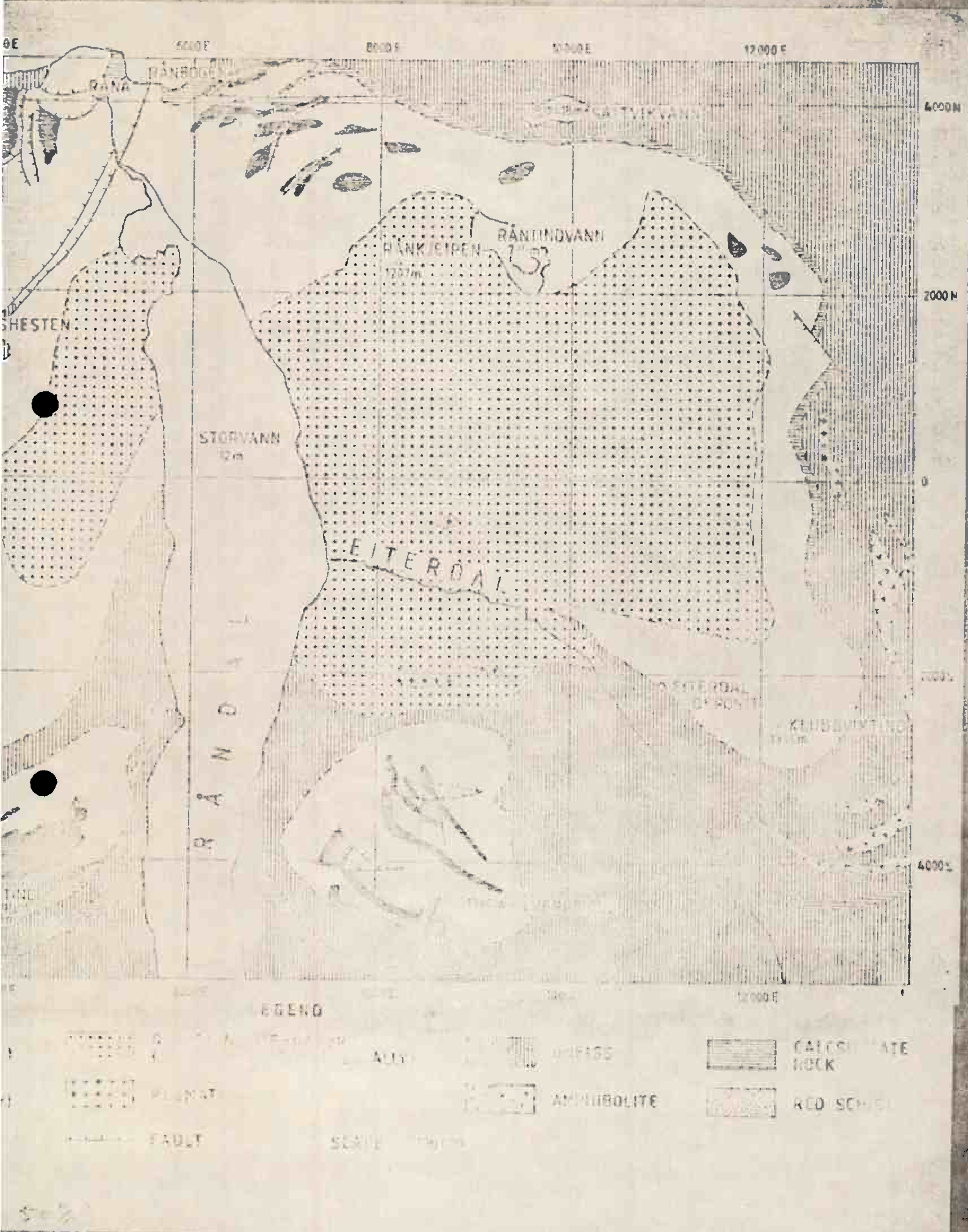
1100
tes in metres



2000 E
4000 E
8000 E
4000 N
2000 N
0
4000 S
RANA
ARNESHESTEN
SEPMOLFJELL
LEGEND
ULTRAMAFIC ROCKS
CONTACT (APPROXIMATE)
FAULT


6000 E
8000 E
10 000 E
12 000 E
RÅNA
RÅNBOGEN
4000 N
RÅNTINDVANN
RÅNKJEIPEN
1207m
2000 N
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STORVANN
12m
0
EITERDAL
4000 S
12 000 E
FAULT

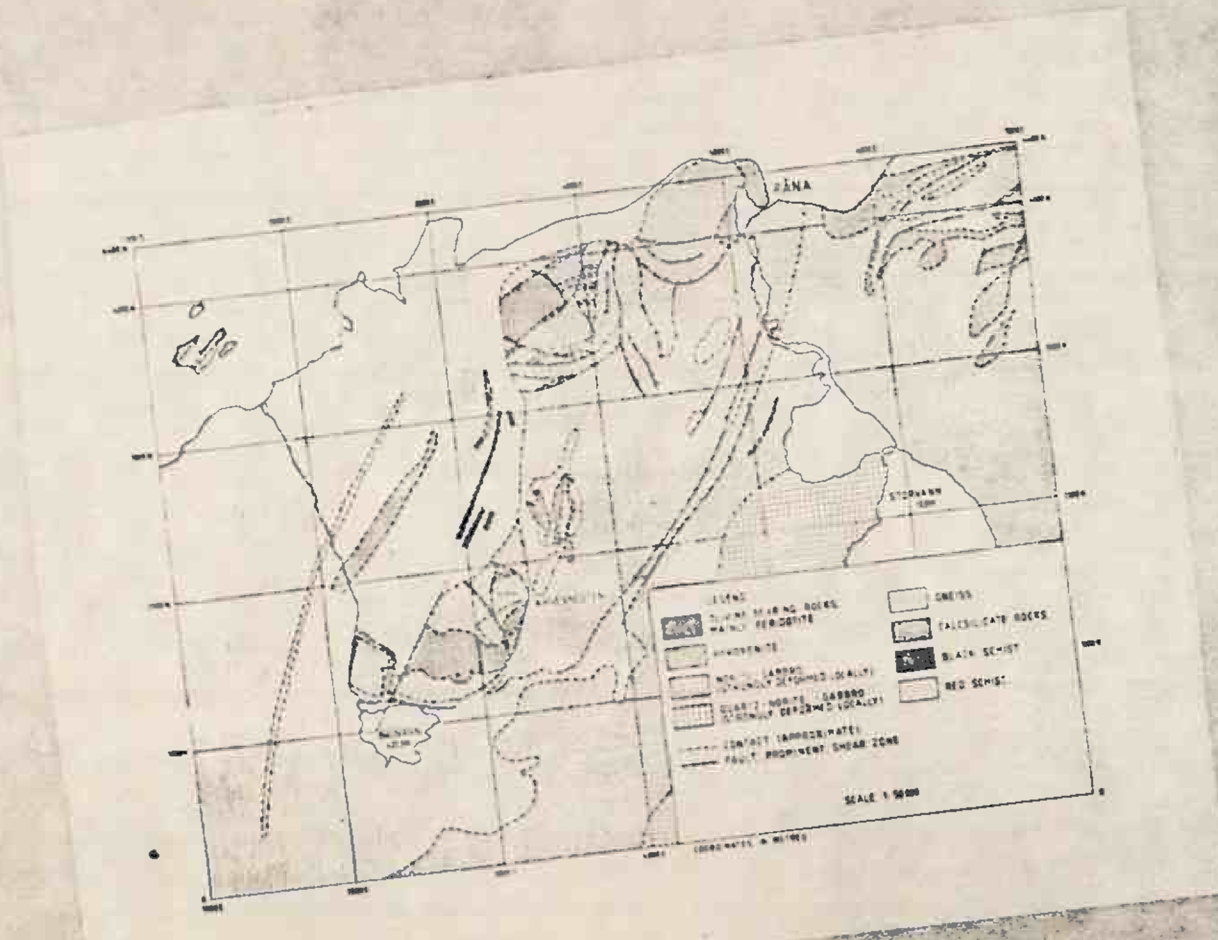

Fig. 7

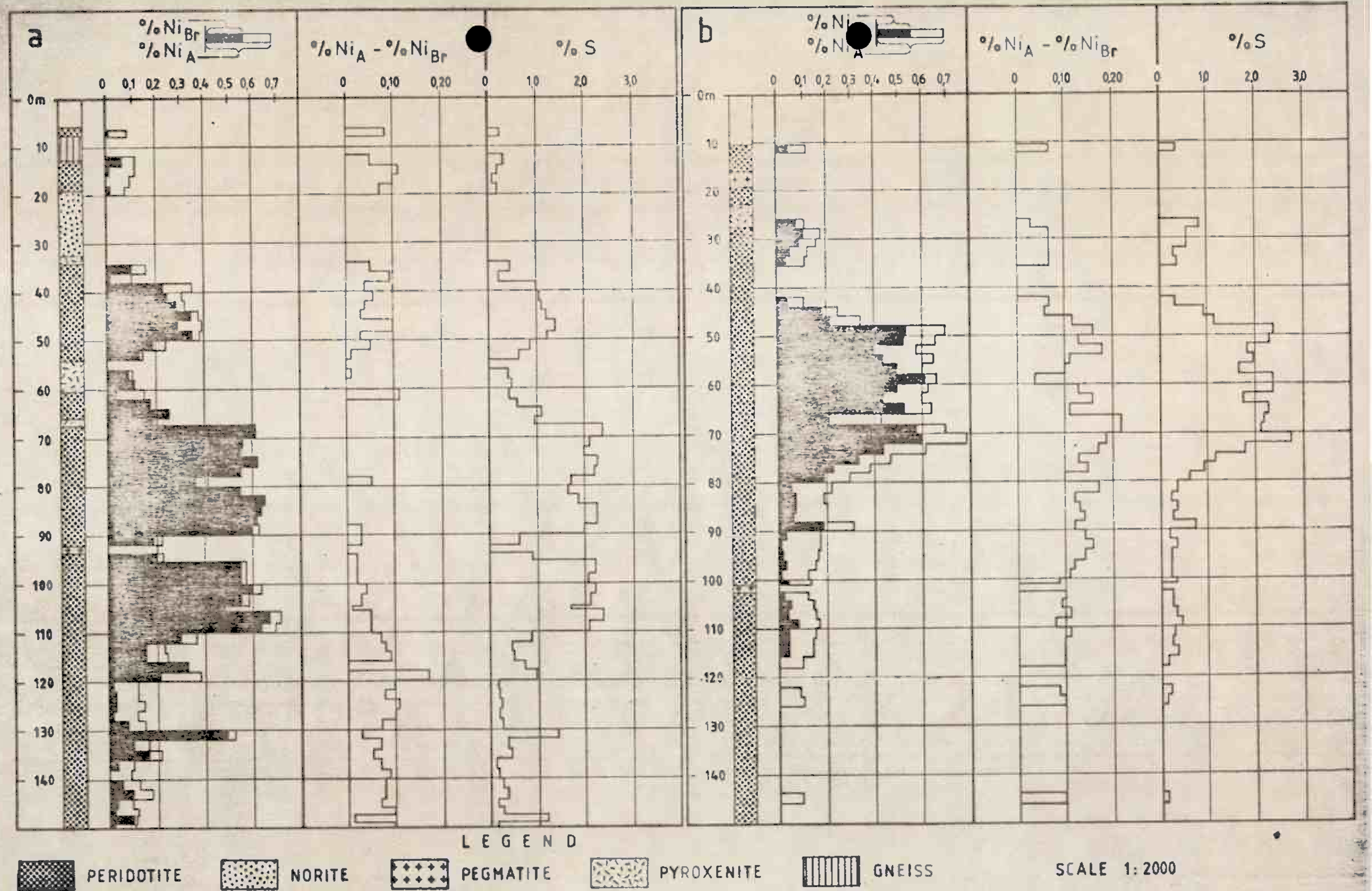


Fig. 5 (blir redusert til 50%)