

THE NICKEL MINERALIZATION OF THE RANA MAFIC INTRUSION, NORLAND, NORWAY

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ABSTRACT

The Råna synorogenic Caledonide intrusion in north Norway contains one known nickel deposit of significance, Bruvann. The mineralization consists of pyrrhotite + pentlandite + chalcopyrite + pyrite, occurring interstitially to olivine and orthopyroxene in peridotite and grading up to 0.8% sulfide nickel. Locally, associated with certain deformation zones, interstitial sulfide dissemination passes into massive mobilized sulfide with up to 5% nickel. Reserves are 43 million metric tons with 0.33% sulfide nickel, 0.08% copper and approximately 0.015% cobalt. The Råna intrusion consists of a peripheral zone of norite containing bands and lenses of peridotite and pyroxenite, and a core mainly of quartz norite. The Råna mass thus has a gross stratigraphy that conforms to the pattern of many layered intrusions, but, over much of the intrusion, primary structures have been disturbed by the later Caledonian fold phases which also involved local overthrusting; these movements resulted in an infolding and thrusting of units of semipelitic and calc-silicate gneiss and black schist into the intrusion. The body has the form of an inverted, possibly truncated cone with its axis plunging north-westward at a moderate angle. There are problems in placing the Råna intrusion within existing classifications of mafic intrusions. The peridotites show no obvious systematic variation of sulfide or silicate mineralogy across strike. The presence of sulfide-bearing black schists on or close to the contacts of the intrusion and emplaced within it along shear zones and the occurrence of graphite within sulfide disseminated in peridotite 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.

SOMMAIRE

L'intrusion synorogénique Calédonienne de Råna (Norvège septentrionale) ne contient qu'un seul gisement nickelifère important, celui de Bruvann. Les sulfures pyrrhotite + pentlandite + chalcopyrite + pyrite, associés interstitiellement à l'olivine et l'orthopyroxène de la péridotite, contiennent jusqu'à 0.8% de nickel. Dans certaines zones de

déformation, les disséminations interstitielles passent à des sulfures massifs remobilisés dont la teneur atteint 5% Ni. Le gisement possède des réserves de 43×10^6 t de sulfures à 0.33% Ni, 0.08% Cu et $\sim 0.015\%$ Co. L'intrusion comprend une zone de norite avec des lits et des lentilles de péridotite et de pyroxénite, autour d'un noyau de norite quartzifère. Stratigraphiquement, elle ressemble *grosso modo* à nombre de complexes stratiformes, mais en beaucoup d'endroits, les structures primaires ont été dérangées par les plissements et les chevauchements Calédoniens. Des lambeaux de gneiss semi-pélitiques à calc-silicates et des schistes noirs pris dans ces plissements, ont été enfouis au sein de l'intrusion. Le massif se présente sous forme d'un cône renversé, peut-être tronqué, dont l'axe s'enfonce légèrement vers le nord-ouest. L'intrusion de Råna n'est pas facile à classer dans les schémas courants. Les péridotites ne montrent aucune variation minéralogique évidente, ni en sulfures ni en silicates, perpendiculairement au litage. Les schistes noirs à sulfures observés au contact de l'intrusion ou à l'intérieur de celle-ci le long de zones de cisaillement, ainsi que le graphite décelé dans les disséminations de sulfures, semblent indiquer une assimilation de soufre des roches encaissantes. D'après une étude des isotopes du soufre, pareil apport de soufre d'une source externe n'a été qu'un phénomène local insignifiant.

(Traduit par la Rédaction)

INTRODUCTION

The Råna mafic intrusion lies at approximately $68^{\circ}30'N$, 20 km southwest of the iron-ore port of Narvik in northern Norway (Fig. 1). This paper will give a brief description of the general geology of the complex, with a more detailed consideration of the sulfide-bearing area at Bruvann (Fig. 2), the only known major deposit in the intrusion, and of the genetic implications involved. The information presented here results from an investigation of the Råna mass and its nickel mineralization begun in 1971. The investigation has been financed by a steel company, Stavanger Staal A/S, and by the Norwegian state, and carried out mainly by the Geological Survey of Norway.

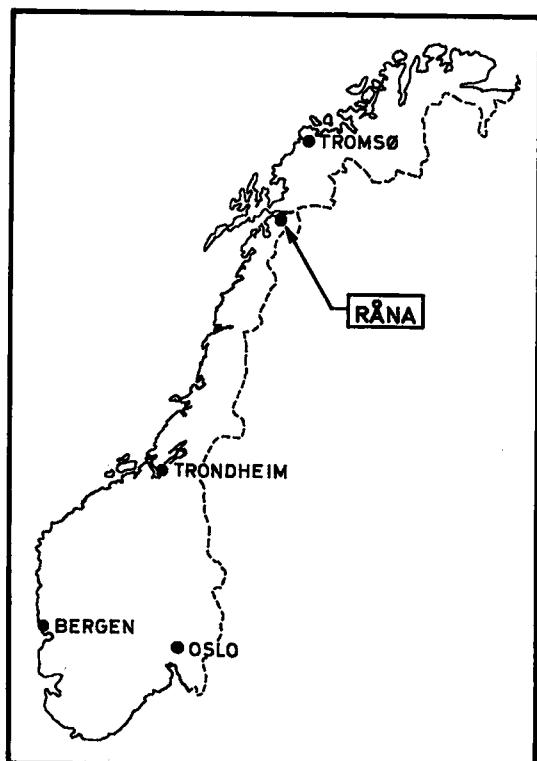


FIG. 1. Map of Norway showing the location of the Råna intrusion.

The intrusion has been described by Foslie (1921), and the general geology of the surrounding area by Gustavson (1972); see also references therein. The area lies within the recently published 1:250,000 geological map-sheet Narvik (Gustavson 1974). The mass contains the only nickel deposits discovered in the Norwegian Caledonides within a radius of 100 km, though the region does contain many sub-economic deposits of Cu, Pb, Zn and Fe.

The Bruvann deposit is restricted to an area of approximately half a square km near the northwestern periphery of the intrusion, where it outcrops between 400 and 500 m above sea level (Figs. 2, 3). A total of 7,000 m had been drilled in this area up to 1960. The present investigation, in addition to geological and geophysical mapping, has entailed 28,500 m of drilling.

GENERAL GEOLOGY OF THE INTRUSION AND ITS ENVIRONS

Country rock

The intrusion lies within the Caledonian oro-

genic belt, in two-mica gneisses classified as the Narvik Group (Gustavson 1972 and earlier papers). These gneisses include thin units of variably hornfelsed calc-silicate gneiss up to several hundred m thick and commonly occurring on or close to the outer contact of the intrusion. These units consist mainly of plagioclase + clinozoisite + hornblende + sphene + diopside + microcline + garnet \pm quartz \pm carbonates, and also contain bands of black schist rich in graphite and pyrrhotite.

The country rocks have been affected by at least four phases of folding including nappe emplacement at an early stage. The Råna intrusion appears to have been emplaced before the third phase of folding under garnet-amphibolite facies conditions that prevailed throughout the solidification period of the mass. This is indicated by the presence of orthopyroxene \pm amphibole + amphibole/spinel symplectite coronas in olivine-plagioclase bearing rocks of the intrusion and by the assemblage garnet + hornblende + plagioclase in rocks within shear zones in the norite. Roddick (1977) dated the intrusion at 400 m.y. on the basis of Rb/Sr whole rock and mineral isochrons; 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 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. At least locally the norite can be shown to intrude the ultramafic rocks; whether this is due to synmagmatic disturbance or to emplacement in separate magma pulses is not yet known. South of the main intrusion are two outliers, one on Tverrfjell east of Råndal, and the other on the north side of Kvanåkertind west of the valley (Fig. 2). The Tverrfjell outlier is the only part of the intrusion in which regular banding on scales below 100 m is common; these structures, which include cross- and graded bedding, are always 'right way up', with the exception of a few dubious cases. Elsewhere in the intrusion banding other than the gross zonation already described is rare.

The northern and northwestern contacts of the intrusions generally dip outward at moderate

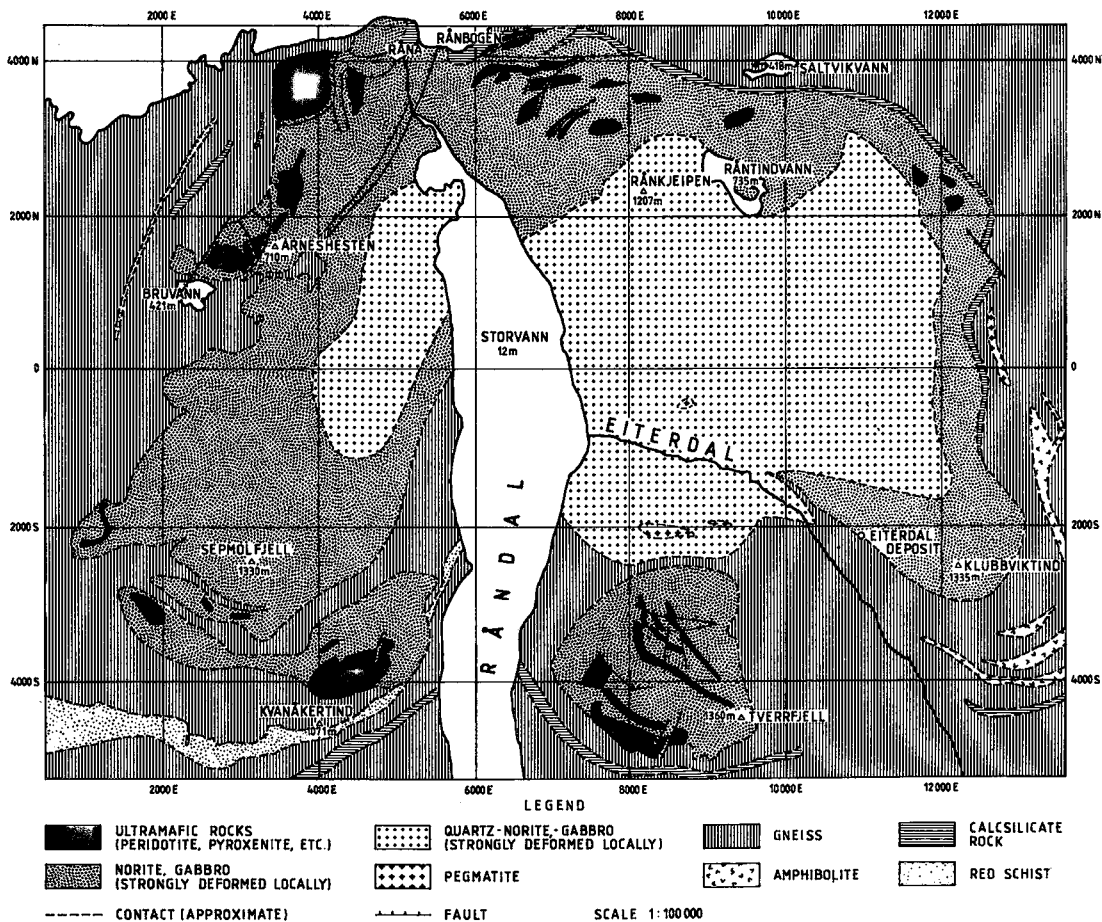


FIG. 2. Geologic map of the Råna intrusion.

to steep angles, whereas the southern and eastern contacts dip inward under the mass at angles that are shallow to moderate in the east and southeast. The contact between the norite periphery and the quartz-norite core is distinct only where it is tectonic, in which case its dip is usually similar to that of the outer contact. However, in the eastern part of the intrusion the norite/quartz-norite contact dips outward. The geometry of the contacts and gravity data (Sindre & Boyd 1977) suggest that the intrusion has the approximate form of an inverted, possibly truncated cone with an axis plunging north-westward and with exposure nearing the roof in the east. The distribution of rock types within this framework and the nature of the magmatic banding, where not affected by later deformation, suggest a gross stratigraphy similar to that of many well-described layered intrusions emplaced in cratonic environments. Because of

the complex and often contrasting nature of the Råna structures and because of published reservations on the classical cumulus theory (Campbell 1978), judgment is reserved as to the exact processes involved in producing the internal variations of the Råna body.

The most common variety of *peridotite* found in the intrusion is harzburgite with 40–60% olivine (FO_{66-87} based on nine microprobe analyses of samples from Bruvann), though lherzolitic and dunitic varieties also occur; locally, small amounts of interstitial plagioclase may be present. In the usage of Wager *et al.* (1960), the bulk of the peridotite is olivine ortho- or mesocumulate, though olivine-hypersthene orthocumulate and locally olivine adcumulate are present. Poikilitic intercumulus orthopyroxene, less commonly augite and phlogopite, and rarely plagioclase are present. The remaining primary phases, in addition to the sulfides described later,

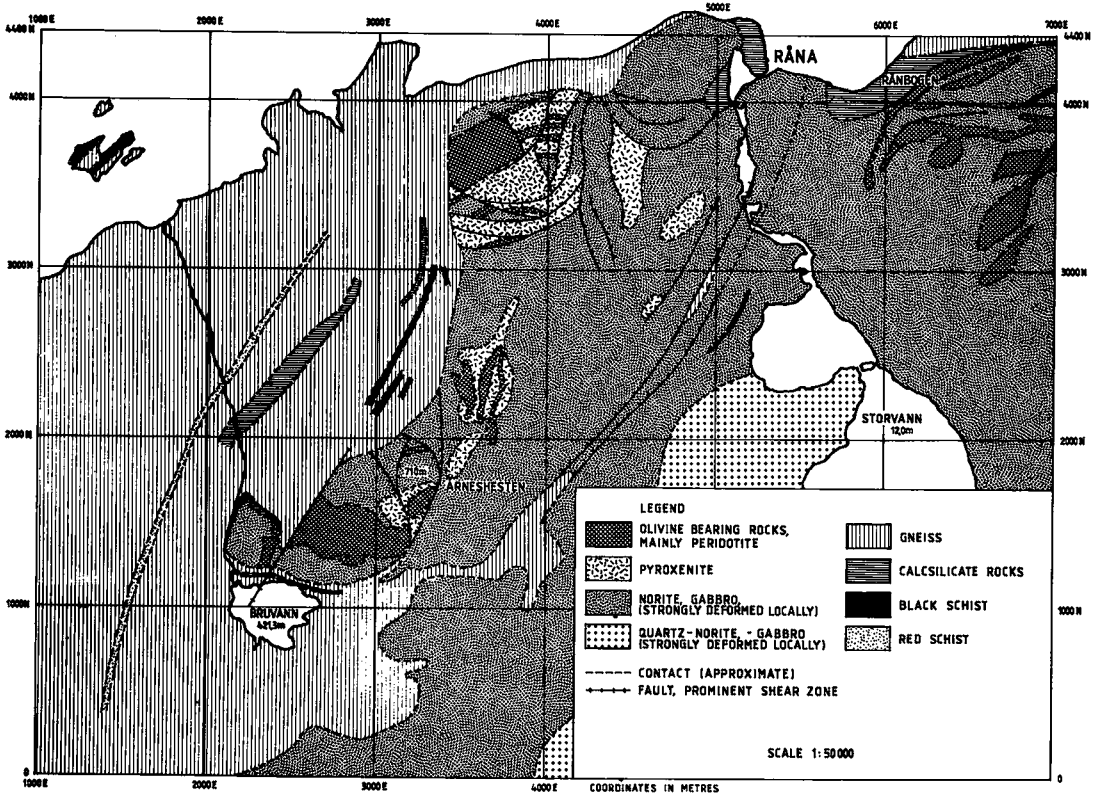


FIG. 3. Geological map of the northwestern part of the Råna intrusion.

are picotite spinel, hematite, ilmenite and magnetite, all in small amounts. Where olivine has originally abutted against plagioclase, coronas are developed as mentioned earlier. Olivine shows a greater tendency to idiomorphism against sulfides than against silicates, being often rounded and internally corroded in the latter case. Talc and anthophyllite are common in deformation zones.

The *pyroxenite* is generally an ortho- or meso-cumulate with up to about 80% hypersthene; adcumulate textures occur locally. The intercumulus material consists of augite, phlogopite, plagioclase and occasionally, opaque minerals. Olivine-bearing varieties occur, but usually as a transition to peridotite. The hypersthene shows slight marginal zoning and may contain augite exsolution lamellae.

Norite is used here to cover a wide range of rock types, including limited amounts of both primary olivine-bearing and gabbroic varieties. Alteration, deformation and recrystallization impose further complexities. The rock is, where fresh, generally a hypersthene-

plagioclase heteradcumulate (adcumulus plagioclase), commonly with strong lamination of the cumulus laths of orthopyroxene and plagioclase. The hypersthene may be zoned, and only rarely contains exsolved lamellae of clinopyroxene. Hypersthene and plagioclase may contain inclusions, one of the other. Clinopyroxene, where present, has a mode of occurrence similar to that of 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 generally recrystallized to amphiboles+plagioclase+clinozoisite±mica. Where olivine-bearing, the norite may contain some disseminated nickeliferous sulfide. Olivine-free norite may contain some sulfide, but essentially nickel-free. Locally non-nickeliferous sulfide occurs together with graphite as small blebs or streaks in deformed norite.

The *quartz-norite* core of the intrusion appears to be less well-defined than suggested by Foslie (1921), and to be more variable internally. Plagioclase is more abundant than in

the norite, and is commonly idiomorphic against quartz, 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.

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, probably began 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 synform seem to date from this period. The climax of this phase of deformation involved disruption of the mass along two major zones: (1) The overthrusting of the part of the intrusion known as the Arneshesten block northwest of a line from Bruvann to Råna (Fig. 3) towards the southeast. The thrust is defined by a strongly deformed arcuate zone that dips steeply northwest and becomes less steep at deeper levels. The Arneshesten block has a complex internal structure due to folding and faulting, some of which is related to the overthrusting. In addition to disrupting the primary structures of the block, these movements resulted in the emplacement within the block of lenses and slabs of country rock 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

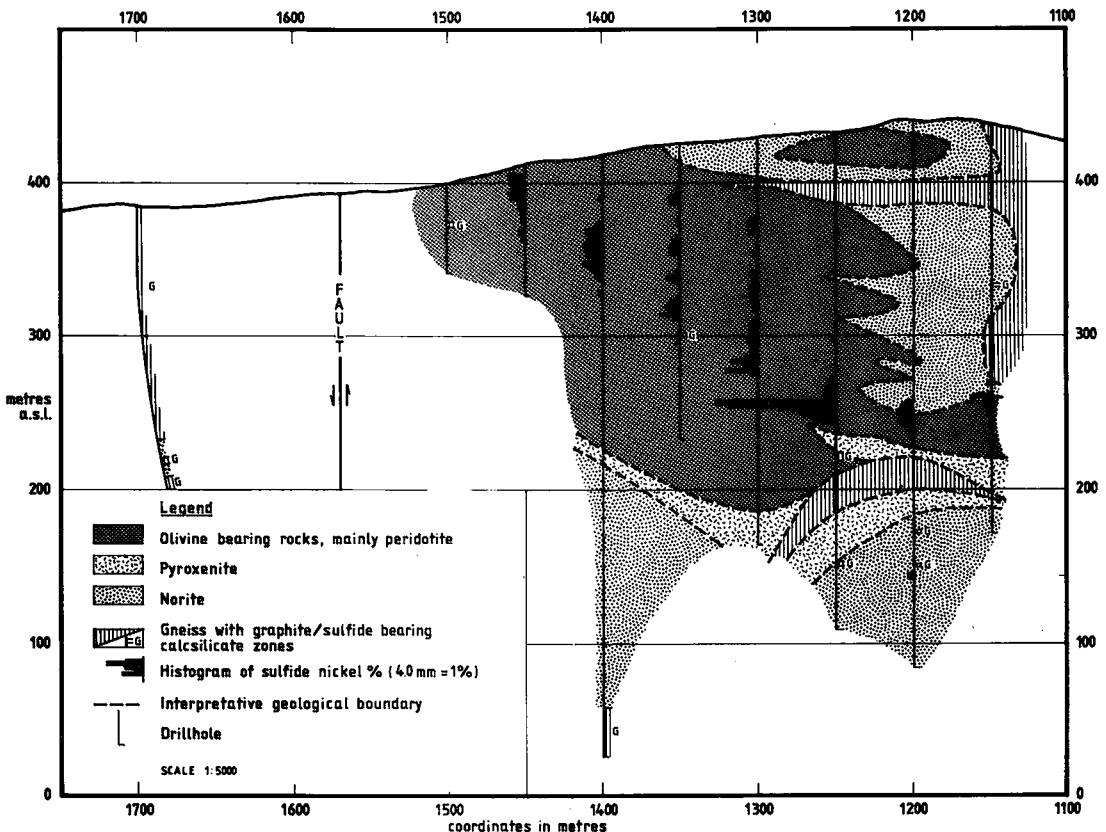


FIG. 4. Geological interpretation of profile 2600 E in the Bruvann area; the coordinates refer to the system also used in Figures 2 & 3.

ing sulfide dissemination. This is not surprising in an upthrust block, if the model of the intrusion suggested earlier 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 becoming separated from the rest of the intrusion by deformation zones containing bands of country rock.

The F_4 phase of folding seen in the surrounding gneisses seems to correspond to north-south faults common in well-exposed areas on the south side of the mass, and also on Sepmolfjell and in Arneshesten block. Subhorizontal pegmatites emplaced late in the history of the mass occur in many parts of the intrusion.

ORE GEOLOGY

The Bruvann area

The deposit contains a calculated 43.6 million metric tons of sulfide-bearing peridotite averaging 0.33% sulfide nickel, 0.08% copper and *ca.* 0.015% cobalt (cutoff was taken as 0.15% sulfide nickel). Restricted parts of this tonnage average as much as 0.6%, and individual analyses reach 0.8%. These figures are based on analysis of the sulfide content (bromine soluble) of 2 m core sections. The deposit has approximate dimensions of 900 m east-west and 500 m north-south. In the middle of the area it is cut by a northeast-southwest hinge fault (downthrow to the west), the throw of which increases northeastward 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 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 it 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 main mineralized zone, which lies in peridotite, strikes east-west parallel to the rock contacts. Where deformation is least, as in profile 2600E (Fig. 4), it has a dip of about 45° near the surface, flattening out in depth towards the south. Above this main zone occurs a series of thinner, less continuous zones of mineralization. Pyroxenite interbanded with mineralized peridotite commonly contains interstitial sulfide of lower grade than the average for the mineralized peridotite. Sparse mineralization also occurs locally in oli-

vine norite. A simplified stratigraphy for the eastern area is, from top to bottom: 50–100 m of unmineralized peridotite with thin, erratic mineralized zones and pyroxenite bands; 20–50 m of mineralized peridotite (the main zone) with thin pyroxenite bands; 0–200 m of unmineralized peridotite, 0–70 m of pyroxenite and 150 m of 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 southern part of the area is more complex; mineralized horizons weaken and disappear and the peridotite units finger out and pass into generally noritic rocks of rapidly and irregularly 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 intersections usually have in common a proximity to peridotite, or other olivine-bearing rocks with disseminated sulfide (Fig. 4), and location in zones of deformation.

West of the fault that dissects the Bruvann area (Fig. 3) the situation is more complex. This part of the deposit has a greater tonnage than the eastern area. It is nowhere exposed and was not discovered until 1972. The western area contains two major mineralized peridotite units that lie rather flat in the south and generally increase in dip to the northwest. The present stratigraphy, partly the result of complex deformation, is, in simplified form, from top to bottom: 50–250 m of complex, irregularly interbanded norite, peridotite and pyroxenite; 50–100 m of upper mineralized peridotite with thin pyroxenite bands; 40–100 m of interbanded peridotite and pyroxenite with subsidiary norite; 20–100 m of lower mineralized peridotite; 60–120 m of unmineralized peridotite; 0–50 m of pyroxenite, and 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 terminate abruptly to the north 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 weaker or absent in the south. The major mineralized peridotite in the eastern part of the Bruvann area and the lower mineralized peridotite in the west were probably

originally continuous; 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 (50–70%), pentlandite (10–35%), chalcopyrite (5–15%) and minute amounts of pyrite, <0.5% according to a detailed point-count analysis by Malvik (1977). The sulfide mineralogy of olivine norite and pyroxenite in the area is similar. The mineralization occurs discontinuously and interstitially to olivine and hypersthene but, in richer portions, has the 'net' texture described by Naldrett (1973). Pentlandite occurs mainly 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 associated with grain boundaries, but only in minor amounts, of the order of 1% of the total pentlandite (Malvik 1977). Chalcopyrite occurs mainly as free grains marginal to pyrrhotite, but also as crack fillings cutting across other sulfides and locally penetrating adjacent silicates. Pyrite forms isolated idiomorphic grains in pyrrhotite. Small amounts of magnetite occur, commonly near the margins of olivine grains; intergrown hematite and ilmenite occur interstitially. In common with Ramdohr (1969), the writers have found minor amounts of graphite within sulfide disseminated in peridotite.

As noted earlier, accumulations of massive ore occur locally along an east-west-trending zone 50–100 m north of the southern border of the Bruvann area, and their precise location is apparently to some extent tectonically controlled. In most cases, this mineralization lies beneath interstitial sulfide in peridotite and above a zone of rock with variable amounts of sulfide and fragments of altered, foliated mafic rock. In certain drillholes the massive sulfide may be several m thick; in others it has been injected as veins from a few cm to several dm across. The massive ore seems to have 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 sheared rock beneath the massive mineralization may reflect the accumulation of the massive sulfide in dilations within or irregularities on a deformation zone. Note that this mineralization has been intersected at three localities only and that these differ to an extent that makes generalization difficult.

Other areas of mineralization

Other areas of the intrusion contain mineralization of lesser significance. In Rånbogen (Figs. 2, 3), sulfides are present in smaller amounts as blebs and as interstitial dissemination in peridotite, as interstitial dissemination in norite and as massive sulfide with graphite in dilations along shear zones. Common to all these mineralizations are low Ni:S ratios.

The Eiterdal deposit (Fig. 2) contains mineralization in olivine norite along the underlying sheared contact of the intrusion, here in contact with calc-silicate rock containing black schist. The norite contains lenses of country rock and several types of mineralization including 'bleb' sulfide and interstitial mineralization transitional into more massive sulfide.

ANALYTICAL DATA

Composition of sulfide minerals

Preliminary microprobe determinations suggest that the pentlandites have compositions falling within the range characteristic for the assemblage pyrrhotite+pentlandite+chalcopyrite+pyrite (Harris & Nickel 1972, Graterol & Naldrett 1971). Pentlandite 'flames' in the pyrrhotite contain several percent less nickel than discrete grains and also considerably less cobalt.

The microprobe was also used to search for variations in olivine or sulfide compositions relative to olivine-sulfide grain boundaries; no such variations were found. This and the textural evidence (a greater tendency for idiomorphism in olivine against sulfide than against other silicates) suggest that direct sulfurization of olivine (Kullerud & Yoder 1965, Naldrett 1966, 1969) has not been an important process in the Råna peridotites.

The Ni:S ratio for disseminations in peridotite at Bruvann varies from 1:2 downward 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 massive sulfide has a Ni:S ratio of less than 1:5. The Cu/(Cu+Ni) ratio at Bruvann, 0.2, lies within the range found in deposits in ultramafic rocks (Naldrett & Cabri 1976, Rajamani & Naldrett 1978). The majority of deposits for which such metal ratios are cited as characteristic occur in host complexes that as a whole are much more mafic than the Råna mass (e.g., deposits of the Abitibi and Manitoba belts).

Certain metal:sulfur ratios seems to be

characteristic of different parts of the intrusion. At Bruvann, where the dominant mineralization is in peridotite, the Ni:S ratio is 1:4; 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 correlation with rock type has been shown by Häkli (1971). This trend suggests that the sulfide magma occurring in various 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.

Sulfur isotope study

The presence of small amounts of graphite in various rocks in the intrusion, the juxtaposition of sulfide-rich black schist with mineralized peridotite and massive sulfide, and variable Ni:S ratios led the writers to suspect an external source for some of the sulfur in the deposits. Graphite has been described from other sulfide-bearing mafic intrusive bodies: 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 $^{34}\text{S}/^{32}\text{S}$ between sulfur in black schists and other metasedimentary rocks and sulfur from normal uncontaminated mantle-derived magma have been used to indicate a partly external source

of sulfur for the sulfides in certain mafic intrusive complexes (Godlevskii & Grinenko 1963, Naldrett 1966, Liebenberg 1969, Mainwaring & Naldrett 1977).

Table 1 shows the results of sulfur isotope analyses performed on Råna samples. On the assumption 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 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 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 samples from Råna peridotites (Table 1) resemble those cited by Stanton (1972) for 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; the samples from pyroxenite and massive sulfide contain slightly heavier sulfur but the difference is small and does not seem related to variations in the proportions of sulfide minerals.

The sulfur in the bands of black schist, both within and outside the intrusion, is on the average markedly lighter than meteoritic sulfur, and is clearly lighter than the values obtained for disseminated sulfide in peridotite. The values fall within the range cited by Stanton (1972) for ancient sedimentary rocks with no volcanic component. These results suggest that external sulfur was not significant in the formation of mineralization in the peridotite at Bruvann, or 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 corollary of this conclusion is that some of the graphite (*e.g.*, the flakes of graphite found in interstitial sulfide in peridotite) must clearly

TABLE 1. SUMMARY OF SULFUR ISOTOPE DATA

Mineralization type	No. of samples	Ave. $\delta^{34}\text{S}$	Range of $\delta^{34}\text{S}$
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 dissemination with graphite	4	- 5.9	-3.7 to - 7.6
Massive sulfide	10	+ 2.1	+0.4 to + 4.2
Massive sulfide 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	7	- 9.0	+1.0 to -13.5

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

be of an early or primary magmatic nature, whereas locally it has probably been derived from the country rock with some sulfur.

DISCUSSION

A classification of ultramafic and associated mafic rocks was proposed by Naldrett & Gasparri (1971) and later modified (Naldrett 1973, Naldrett & Cabri 1976). All three papers emphasize 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 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 (Ashcroft & Munro 1978, Boyd & Munro 1978), 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 that occur in stable areas, it lies in an orogenic belt and also, at least locally, has many of the features of the intrusions classified as alpine (Jackson & Thayer 1972), *e.g.*, tectonite fabrics, metamorphic and igneous layers, discordant and irregular banding, poor continuity of banding and dykes of mafic rock (at Råna, norite intruding earlier formed rock types). 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 is 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 (1969), Challis & Lauder (1966), Nesbitt *et al.* (1970), Moore (1973), Robins & Gardner (1974) and others.

The form of the contacts of the Råna intrusion suggests the shape of an inverted cone, possibly truncated, with its axis plunging north-westward and with the highest section of the cone, possibly near the roof of the intrusion, in the east and the deepest section in the north-west. In a very general sense the distribution of

the peridotite bodies lends support to this model: they are not common on the eastern rim but are mostly found along the northern and northwestern contact. Further confirmation of this model is given by the nature of the Arneshesten block which, having been upthrust, represents the deepest level exposed in the mass and contains not only peridotites of substantial thickness, but also the only ones in the intrusion known to be significantly mineralized over large volumes. The individual peridotites, however, may be subparallel to the outer contact (eastern Rånbogen, Tverrfjell) (Fig. 2) or discordant to it (western Rånbogen, Bruvann) (Figs. 3, 4), some bodies apparently changing along their length from concordant to discordant. The writers have failed to construct a model accounting for all these complexities; however, these must be related to the extensive syn- and postintrusive deformation of the area.

The nickeliferous sulfides at Bruvann (and elsewhere at Råna) are invariably within or closely associated with olivine-bearing rocks. However, the mineralization does not occur systematically at or near the upper or lower margins of the peridotites. In addition, the massive nickel-bearing mineralization is generally close to 'net' texture sulfide, but it constitutes only a small fraction of the total mineralization. Thus it seems likely that the magma from which the peridotites began crystallizing was not saturated in sulfur, that sulfur saturation was attained while olivine and locally a smaller amount of hypersthene were accumulating, and that the sulfide subsequently accumulated as part of the material interstitial to the cumulus phases. The further observation that olivine shows a tendency to idiomorphism where it abuts against interstitial sulfide while being more rounded or even internally resorbed against interstitial silicate suggests that olivine accumulated rapidly (possibly having nucleated close to the floor of the magma chamber) and was resorbed to form orthopyroxene, mainly after accumulation, through reaction with intercumulus liquid (the Bowen-Anderson reaction).

The direct cause of the attainment of sulfur saturation is not clear. The isotope data tend to discount any major role for country-rock sulfur. Irvine (1975, 1977) has suggested the existence of a mechanism that may explain several features of the Bruvann mineralization: an increase in silica or alkalis in magmas of certain compositions (either by assimilation or by magma-mixing processes) reduces sulfur solubility (resulting in formation of an immiscible sulfide magma) and causes a polymeriza-

tion of the silicate magma (which would produce orthopyroxene instead of olivine). Ions such as Ni^{2+} with high octahedral-site-preference energies are then preferentially expelled from the silicate liquid and partition into the sulfide magma. Some evidence for multiple influxes of magma at Råna may lie in the recurrence of thick peridotite layers and in the intrusive relationship, at least locally, of norite to the ultramafic rocks. Late- and postmagmatic deformation complicates the reconstruction of events. That the bulk of the mineralization at Bruvann lies in peridotite and not in pyroxenite could be taken as evidence against the theory but, on the other hand, once sulfur saturation is attained, it can perhaps be assumed that the sulfide magma would accumulate more rapidly than orthopyroxene; the mineralized peridotite, particularly in its upper reaches, is interbanded with pyroxenite which is also mineralized to some extent.

The Bowen-Anderson reaction probably caused partial resorption of cumulus olivine to produce intercumulus orthopyroxene. That this reaction may take place between cumulus crystals and intercumulus liquid has been advocated in the case of the Stillwater complex by Jackson (1961) and in the case of rocks of the Seiland province by Gardner & Robins (1974). The partition coefficient Ol^{Ni}/Hy^{Ni} (Häkli 1971) is such that this process, though affecting only a portion of the original amount of olivine crystallized, would recycle substantial quantities of nickel to the silicate magma because it would affect a large volume of olivine. Where sulfide magma was present interstitially, it would absorb this nickel preferentially with respect to crystallizing orthopyroxene. The effect of this process would be enhanced if: (1) there was expulsion of intercumulus liquid from olivine cumulates formed before sulfur saturation, and (2) intercumulus sulfide magma had, because of its greater density, intimate contact with a greater volume of olivine than that against which it ultimately solidified, *i.e.*, if sulfide magma percolated downward through a pile of cumulus olivine crystals displacing intercumulus silicate magma. These processes may have contributed to the relatively high nickel content of the Råna sulfides.

A number of factors suggest that part of the sulfur in the Råna mineral deposit was derived from black schist lenses within and around the intrusion. The sulfur isotope data 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 country rock into the magma very early in its crystallization history.

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REFERENCES

- ASHCROFT, W.A. & MUNRO, M. (1978): The structure of the eastern part of the Inch mafic intrusion, Aberdeenshire. *Scot. J. Geol.* 14, 55-79.
- BOYD, R. & MUNRO, M. (1978): Deformation of the Belhelvie mass, Aberdeenshire. *Scot. J. Geol.* 14, 29-44.
- CAMPBELL, I.H. (1978): Some problems with the cumulus theory. *Lithos* 11, 311-323.
- CHALLIS, G.A. (1969): Discussion on the paper "The origin of ultramafic and ultrabasic rocks" by P.J. Wyllie. *Tectonophys.* 7, 495-505.
- & LAUDER, W.R. (1966): The genetic position of "Alpine" type ultramafic rocks. *Bull. Volc.* 29, 283-306.
- FOSLIE, S. (1921): Field observations in Northern Norway bearing on magmatic differentiation. *J. Geol.* 29, 701-719.
- GARDNER, P.M. & ROBINS, B. (1974): The olivine-plagioclase reaction: geological evidence from the Seiland petrographic province, northern Norway. *Contr. Mineral. Petrology* 44, 149-156.
- GARSON, M.S. & PLANT, J. (1973): Alpine type ultramafic rocks and episodic mountain building in the Scottish Highlands. *Nature Phys. Sci.* 242, 34-38.
- GODLEVSKII, M.N. & GRINENKO, L.N. (1963): Some data on the isotopic composition of sulfur in the sulfides of the Noril'sk deposit. *Geochem.* 35-41.

- GRATEROL, M. & NALDRETT, A.J. (1971): Mineralogy of the Marbridge No. 3 and No. 4 nickel-iron sulfide deposits. *Econ. Geol.* 66, 866-900.
- GUSTAVSON, M. (1972): The Caledonian mountain chain of the southern Troms and Ofoten areas. III. Structures and structural history. *Norg. Geol. Unders.* 283.
- (1974): Geologisk kart over Norge, berggrunnsgeologisk kart – Narvik, 1:250 000. Norg. Geol. Unders.
- HAAPALA, P.S. (1969): Fennoscandian nickel deposits. In *Magmatic Ore Deposits* (H.D.B. Wilson, ed.), *Econ. Geol. Mon.* 4, 262-275.
- HÄKLI, T.A. (1971): Silicate nickel and its application to the exploration of nickel ores. *Geol. Soc. Finland Bull.* 43, 247-263.
- HARRIS, D.C. & NICKEL, E.H. (1972): Pentlandite compositions and associations in some mineral deposits. *Can. Mineral.* 11, 861-878.
- IRVINE, T.N. (1975): Crystallization sequences in the Muskox intrusion and other layered intrusions. II. Origin of chromitite layers and similar deposits of other magmatic ores. *Geochim. Cosmochim. Acta* 39, 991-1020.
- (1977): Origin of chromitite layers in the Muskox intrusion and other stratiform intrusions: a new interpretation. *Geol.* 5, 273-277.
- JACKSON, E.D. (1961): Primary textures and mineral associations in the Ultramafic Zone of the Stillwater complex, Montana. *U.S. Geol. Surv. Prof. Pap.* 358.
- & THAYER, T.P. (1972): Some criteria for distinguishing between stratiform, concentric and alpine peridotite-gabbro complexes. *Int. Geol. Congr.* 24th, 2, 289-296.
- KANARIS-SOTIRIOU, R. & ANGUS, N.S. (1976): The Currywongaun-Doughruagh syntectonic intrusion, Connemara, Ireland, *J. Geol. Soc. London* 132, 485-508.
- KULLERUD, G. & YODER, H.S., JR. (1965): Sulfide-silicate reactions and their bearing on ore formation under magmatic, postmagmatic and metamorphic conditions. In *Symposium on Problems of Postmagmatic Ore Deposition II*, *Geol. Surv. Czechoslovakia, Prague.*
- LEAKE, B.E. (1970): The fragmentation of the Connemara basic and ultrabasic intrusions. In *Mechanism of Igneous Intrusion* (G. Newall & N. Rast, eds.), *Geol. J. Spec. Issue* 2, 103-122.
- LIEBENBERG, L. (1969): *The Sulphides in the Layered Sequence of the Bushveld Igneous Complex*. Ph. D. thesis, Univ. Pretoria, Pretoria, South Africa.
- (1970): The sulphides in the layered sequence of the Bushveld igneous complex. In *Symposium on the Bushveld Igneous Complex and other Layered Intrusions* (D.J.L. Visser & G. von Gruenewaldt, eds.), *Geol. Soc. S. Afr. Spec. Publ.* 1, 108-207.
- MAINWARING, P.R. & NALDRETT, A.J. (1977): Country-rock assimilation and the genesis of Cu-Ni sulfides in the Water Hen intrusion, Duluth complex, Minnesota. *Econ. Geol.* 72, 1269-1284.
- MÄKELÄ, M. (1974): A study of sulfur isotopes in the Outokumpu ore deposits, Finland. *Geol. Surv. Finland Bull.* 267.
- MALVIK, T. (1977): Mineralogisk undersøkelse av bulkkonsentrat av Råna Ni-malm. Unpubl. Rep., Norges Tekniske Høgskole, Trondheim.
- MOORE, A.C. (1973): Studies of igneous and tectonic textures and layering in the rocks of the Gosse Pile intrusion, Central Australia. *J. Petrology* 14, 49-80.
- MOORES, E.M. (1973): Geotectonic significance of ultramafic rocks. *Earth-Sci. Rev.* 9, 241-258.
- NALDRETT, A.J. (1966): The role of sulfurization in the genesis of iron-nickel sulfide deposits of the Porcupine District, Ontario. *Can. Inst. Mining Met. Trans.* 69, 147-155.
- (1969): Discussion of papers concerned with sulfide deposits. In *Magmatic Ore Deposits* (H.D.B. Wilson, ed.), *Econ. Geol. Mon.* 4, 359-365.
- (1973): Nickel sulfide deposits — their classification and genesis, with special emphasis on deposits of volcanic association. *Can. Inst. Mining Met. Trans.* 76, 183-201.
- & CABRI, L.J. (1976): Ultramafic and related rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. *Econ. Geol.* 71, 1131-1158.
- & GASPARRINI, E.L. (1971): Archean nickel sulfide deposits in Canada: their classification, geological setting and genesis with some suggestions as to exploration. In *Symposium on Archean Rocks* (J.E. Glover, ed.), *Geol. Soc. Aust. Spec. Publ.* 3, 201-226.
- NESBITT, R.W., GOODE, A.D.T., MOORE, A.C. & HOPWOOD, T.P. (1970): The Giles Complex, central Australia: a stratified sequence of mafic and ultramafic intrusions. In *Symposium on the Bushveld Igneous Complex and other Layered Intrusions* (D.J.L. Visser & G. von Gruenewaldt, eds.), *Geol. Soc. S. Afr. Spec. Publ.* 1, 547-564.
- PAPUNEN, H. (1970): Sulfide mineralogy of the Kotalahti and Hitura nickel-copper ores, Finland. *Ann. Acad. Sci. Fennicae Ser. A. III*, 109.
- RAINVILLE, G.D. & PARK, W.C. (1976): Nickeliferous pyrrhotite deposits, Knox County, southeastern Maine. In *Studies in New England Geology* (P.C. Lyons & A.H. Brownlow, eds.), *Geol. Soc. Amer. Mem.* 146, 319-347.
- RAJAMANI, V. & NALDRETT, A.J. (1978): Partitioning of Fe, Co, Ni and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits. *Econ. Geol.* 73, 82-93.

- RAMDOHR, P. (1969): *The Ore Minerals and their Intergrowths*. Pergamon, Oxford.
- ROBINS, B. & GARDNER, P.M. (1974): Synorogenic layered basic intrusions in the Seiland petrographic province, Finnmark. *Norg. Geol. Unders.* 312, 91-130.
- RODDICK, J.C. (1977): Age of the Råna massif, north Norway. *Fifth Eur. Colloq. Geochron. Cosmochron. & Isotope Geol. Pisa* (Abstr.).
- RYE, R.O. & OHMOTO, H. (1974): Sulfur and carbon isotopes and ore genesis: a review. *Econ. Geol.* 69, 826-842.
- SINDRE, A. & BOYD, R. (1977): Tyngdemålinger, Råna, Ballangen, Nordland. *Norg. Geol. Unders. Rap.* 1538 (Unpubl.).
- STANTON, R.L. (1972): *Ore Petrology*. McGraw-Hill, New York.
- THAYER, T.P. & JACKSON, E.D. (1972): A classification of igneous rocks by their history of crystallization and emplacement. *U.S. Geol. Surv. Prof. Pap.* 800-B, 79-83.
- WAGER, L.R., BROWN, G.M., & WADSWORTH, W.J. (1960): Types of igneous cumulates. *J. Petrology* 1, 73-85.
- WILSON, H.D.B. & ANDERSON, D.T. (1959): The composition of Canadian sulfide ore deposits. *Can. Inst. Mining Met. Trans.* 62, 327-339.
- WYLLIE, P.J. (1969): The origin of ultramafic and ultrabasic rocks. *Tectonophys.* 7, 437-455.

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