THE NICKEL MINERALIZATION OF THE RÄNA MAFIC INTRUSION,
NORDLAND, NORWAY

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ABSTRACT

The Räna 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, 0.087% copper and approximately 0.11% cobalt. The Räna intrusion consists of a peripheral zone of norite containing bands and lenses of peridotite and pyroxenite, and a core mainly of quartz norite. The Räna 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 folding and thrusting of units of semipelitic and calc-silicato gneiss and black schist into the intrusion. The body has the form of an inverted, possibly truncated cone with its axis plunging northwestward at a moderate angle. There are problems in placing the Räna 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 Räna.
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 ± quartz ± 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± 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.

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 Kvanåkerfjord 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
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 Râna 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 Râna body.

The most common variety of peridotite found in the intrusion is harzburgite with 40–60% olivine (Fo_{80-87} based on nine microprobe analyses of samples from Bruvann), though herzolitic 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,
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 mesocumulate 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-bear-

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**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 Rândal, those at Tverrfjell and north of Kvanåkertino becoming separated from the rest of the intrusion by deformation zones containing bands of country rock.

The F1 phase of folding seen in the surrounding gneisses seems to correspond to the north-south faults common in well-exposed areas on the south side of the mass, and also on Sepmoljell 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 olivine 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 sections 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 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 Ramdoth (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 Rånboen (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 Rån 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 Rån 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 Håkli (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 $^{34}$S/$^{32}$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 chloropyrite (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 mantle-derived magma have been used to indicate a partly external source

<table>
<thead>
<tr>
<th>Mineralization type</th>
<th>No. of samples</th>
<th>$\delta^{34}$S</th>
<th>Range of $\delta^{34}$S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peridotite dissemination</td>
<td>11</td>
<td>+ 0.3</td>
<td>-2.5 to + 1.6</td>
</tr>
<tr>
<td>Pyroxenite dissemination</td>
<td>1</td>
<td>+ 2.7</td>
<td>-</td>
</tr>
<tr>
<td>Norite dissemination</td>
<td>6</td>
<td>+ 0.7</td>
<td>-0.1 to + 1.6</td>
</tr>
<tr>
<td>Norite dissemination with graphite</td>
<td>4</td>
<td>- 5.9</td>
<td>-3.7 to -7.6</td>
</tr>
<tr>
<td>Massive sulfide</td>
<td>10</td>
<td>&lt; 2.1</td>
<td>+0.4 to + 4.2</td>
</tr>
<tr>
<td>Massive sulfide with graphite</td>
<td>3</td>
<td>-12.8</td>
<td>-3.2 to -17.6</td>
</tr>
<tr>
<td>Sulfide from blackschist within the intrusion</td>
<td>4</td>
<td>- 7.4</td>
<td>-3.6 to -13.6</td>
</tr>
<tr>
<td>Sulfide from blackschist outside the intrusion</td>
<td>7</td>
<td>- 9.0</td>
<td>+1.0 to -13.5</td>
</tr>
</tbody>
</table>

The analyses were performed by Geochron Laboratories Inc., Boston. $\delta^{34}$S is measured relative to $^{34}$S/$^{32}$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 & Gasparini (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 Wylie (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 northwestward and with 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 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 Seland province by Gardner & Robins (1974). The partition coefficient OI/H2O (Håkli 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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