

The geology and mineralogy of some Fe-Cu-Ni sulphide deposits in the Bamble area, Norway

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The ore assemblages and textures displayed by some sulphide deposits associated with mafic intrusions in the Bamble area are the product of three stages of ore formation: primary orthomagmatic crystallisation, Sveconorwegian metamorphic crystallisation, and supergene alteration. Immiscible sulphide-oxide melts segregated from several contaminated noritic melts during their passive emplacement, probably during the very early stages of the Sveconorwegian Regeneration (1200–1160 Ma). At Nystein and Meikjær, primary pyrrhotite-chalcopyrite-pyrite-pentlandite ores partially recrystallised during Sveconorwegian metamorphism to sulphur-enriched, pyrite-rich secondary assemblages, locally containing millerite and nickeloan pyrite. Primary pyrrhotite-chalcopyrite-pentlandite ores at Østerå and Seljåsen remained largely unaltered during the Sveconorwegian event. The Seljåsen ores, which contain cobaltian pentlandite and accessory cobaltite, crystallised from an ultramafic-associated, cobalt-rich melt. The ores at this locality are predominantly hosted by pyroxenite, which appears to have formed as a direct response to the assimilation of siliceous country rocks during emplacement of the intrusion. Supergene violarisation is ubiquitous in all of the deposits, and in the Seljåsen ore body it has resulted in the widespread formation of cobaltian violarite.

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The supracrustal rocks and geological evolution of the Bamble area and its relation with the Telemark and Kongsberg areas of South Norway (Fig. 1) have been described by J. Bugge (1943) and Starmer (1972, 1976, 1977).

The Bamble area supracrustal rocks comprise variable quartz-plagioclase-biotite gneisses and schists, granitic and sillimanitic gneisses, meta-quartzites and amphibolites, together with subordinate bands of calc-silicate rock. The supracrustal rocks have undergone two distinct phases of metamorphic deformation and recrystallisation. The first took place under conditions of upper amphibolite facies and (locally) granulite facies grades during the later stages of the Svecofenian Orogeny (1600–1450 Ma; Milne & Starmer 1982). A second phase of metamorphism occurred during the Sveconorwegian Regeneration (1200–1160 Ma; O'Nions & Baadsgaard 1971). This was essentially a thermal metamorphism with limited structural deformation, and reached upper amphibolite facies grades only locally. A major basic intrusive event occurred during the very early stages of the Sveconorwegian Regeneration, between approximately 1200 and 1180 Ma. Numerous small stocks, lopolithic and dyke-

like bodies intruded all supracrustal lithologies at this time in both the Kongsberg and Bamble areas (Brøgger 1934, Starmer 1969, Morton et al. 1970, Brickwood 1984, Craig 1984).

The occurrence of Fe-Cu-Ni sulphide deposits associated with some of the noritic intrusions of this age in the Bamble area has long been known (Vogt 1902, A. Bugge 1922, Sinding-Larsen 1968, Morton et al. 1970, Bakken 1972, Jerpseth 1979, Ellingvåg-Pettersen 1979). The deposits, which were sporadically worked between 1859 and 1945, are all situated in the marginal parts of the host intrusions and are comparatively minor, having yielded some 10,000 tonnes of Ni in total (J. Bugge 1978).

The present study described the four largest Bamble area Fe-Cu-Ni sulphide deposits, namely those hosted by the Seljåsen, Østerå, Meikjær and Nystein intrusions (Fig. 1). Fe-Cu-Ni sulphide deposits associated with the mafic plutons in the Kongsberg area have been described by Johannesen (1974), while Dibb (1981) described Fe-Cu-Zn ores associated with (though not genetically related to) these intrusions.

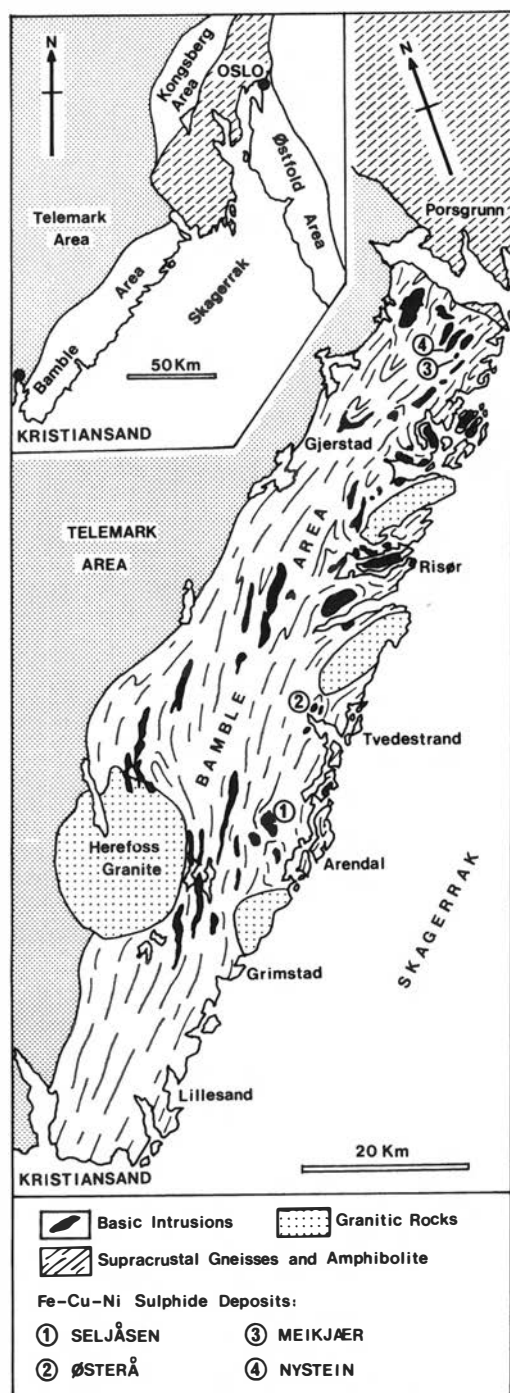


Fig. 1. Location of intrusions and ore deposits in the Bamble area.

The mafic intrusions of the Bamble area

The mafic plutons of the Bamble area which were emplaced between approximately 1200–1180 Ma are predominantly comprised of coarse-grained, plagioclase-rich mesocumulates and orthocumulates. However, the intrusive series in its entirety comprises lithologies ranging from subordinate ultramafites (including pyroxenite, picrite and peridotite) through troctolitic varieties to olivine-free gabbros and norites, and olivine-ferrogabbros (Brøgger 1934, Starmer 1969, Brickwood 1984, Craig 1984). The intrusions are alkali and iron enriched, and display transitional tholeiitic to mildly alkaline magmatic affinities. Pyroxene compositions and trends are transitional between those usually exhibited by tholeiitic and alkaline basic intrusions. Magmatic stoping was the main emplacement mechanism and may have resulted in crustal contamination of the intruded melts. Differentiation and crystallisation of the melts took place in situ under moderately high pressures and low temperatures, and at low P_{H_2O} and f_{O_2} (Brickwood 1984). In most of the intrusions, spinel and olivine (when present) crystallised first and were followed successively by plagioclase, pyroxene and Fe-Ti oxides. All of the intrusions underwent prolonged subsolidus cooling during the initial stages of Sveconorwegian metamorphism, which resulted in the widespread formation of corona textures. These textures were partially obliterated by the later amphibolitisation associated with the thermal maximum of the Sveconorwegian Regeneration (1200–1160 Ma; O’Nions & Baadsgaard 1971).

The basic intrusions of the Kongsberg area display similar petrological and geochemical characteristics to those of the Bamble area (Dibb 1981, Brickwood 1984, Craig 1984) and both intrusive series can be correlated with comparable, broadly contemporaneous magmatism in Eastern Canada and South Greenland (Patchett et al. 1978). This widespread magmatic activity is thought to have been initiated by a phase of aborted rifting prior to the ultimately successful breakup of the Proterozoic Supercontinent following the Sveconorwegian (=Grenvillian) Orogeny.

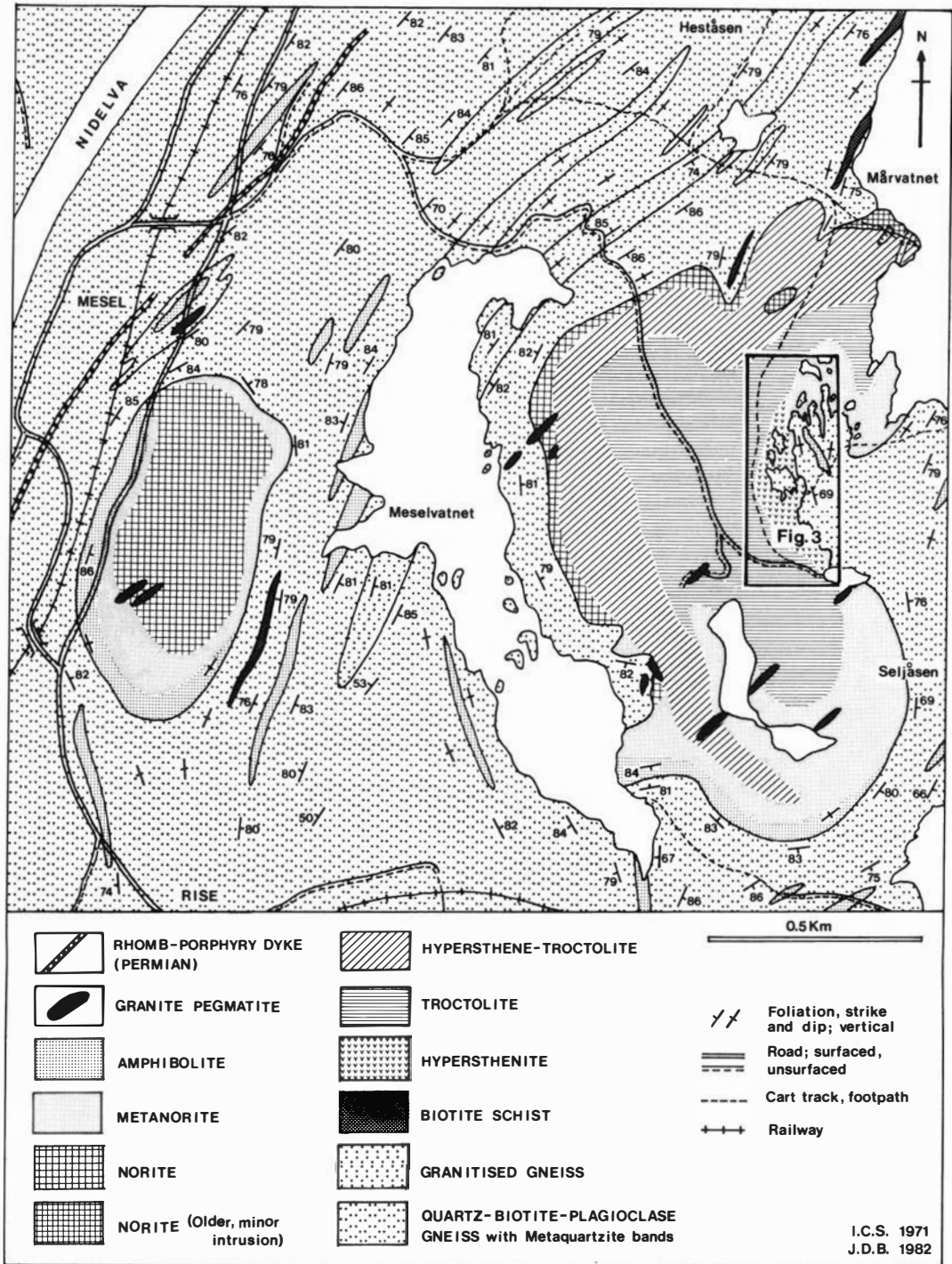


Fig. 2. Geological map of the Mesel area.

The ore deposits and host intrusions

The Seljåsen deposit

The deposit is located on the eastern margin of the Seljåsen intrusion, which lies 1.5 km east of Mesel in Aust-Agder (Fig. 2). The geology of this area has been described by Bakken (1972). The intrusion, an irregular stock-like body, has punched through the flanks of a small antiformal structure in amphibolite facies quartz-rich gneisses. The eastern margin of the intrusion interfingers in a complex manner with the adjacent gneisses. Large xenoliths of country rock occur within the pluton at this locality (Fig. 3). Small remnants of an older, minor noritic intrusion at the site of the Seljåsen pluton are preserved as xenoliths within the latter body.

The central part of the Seljåsen pluton is composed of a very coarse-grained troctolite, the primary assemblage of which consists of plagioclase (An_{61-58}) and olivine (Fo_{69-65}), together with accessory hypersthene ($Mg_{66}Fe_{33}Ca_1$), salite ($Mg_{41}Fe_{13}Ca_{46}$) and opaque, Cr-poor picotite. The troctolite displays well-developed coronas (5–19 mm thick) between olivine and plagioclase. These consist of an inner rim of prismatic bronzite ($Mg_{71}Fe_{28}Ca_1$) and an outer rim of pale green pargasite-hercynite symplectite. The primary spinel bears thick coronas of red-brown biotite or brown tschermakite-hercynite symplectite against plagioclase.

In the western part of the intrusion the troctolite grades outwards through a coarse-grained hypersthene-troctolite into a less coarse border zone composed of leuconorite and norite. Cumulus plagioclase (An_{58-51}) forms 57–80% of this rock, together with subordinate hypersthene ($Mg_{66}Fe_{33}Ca_1$) and diopside ($Mg_{44}Fe_8Ca_{44}$). Accessory magnetite and ilmenite are notably scarce throughout this lithology and the intrusion in its entirety.

In the eastern part of the intrusion, the troctolite grades over a distance of 2–3 m through troctolitic-melanorite and plagioclase-hypersthene into a marginal band of coarse-grained hypersthene. This pyroxene adcumulate is composed of hypersthene ($Mg_{67}Fe_{32}Ca_1$), together with interstitial, accessory augite ($Mg_{46}Fe_{15}Ca_{39}$), pyrrhotite and cobaltian pentlandite. Temperatures of primary pyroxene equilibration range from 815°C in the marginal norite to 1078°C in the pyroxenite (Brickwood 1984). The southern and

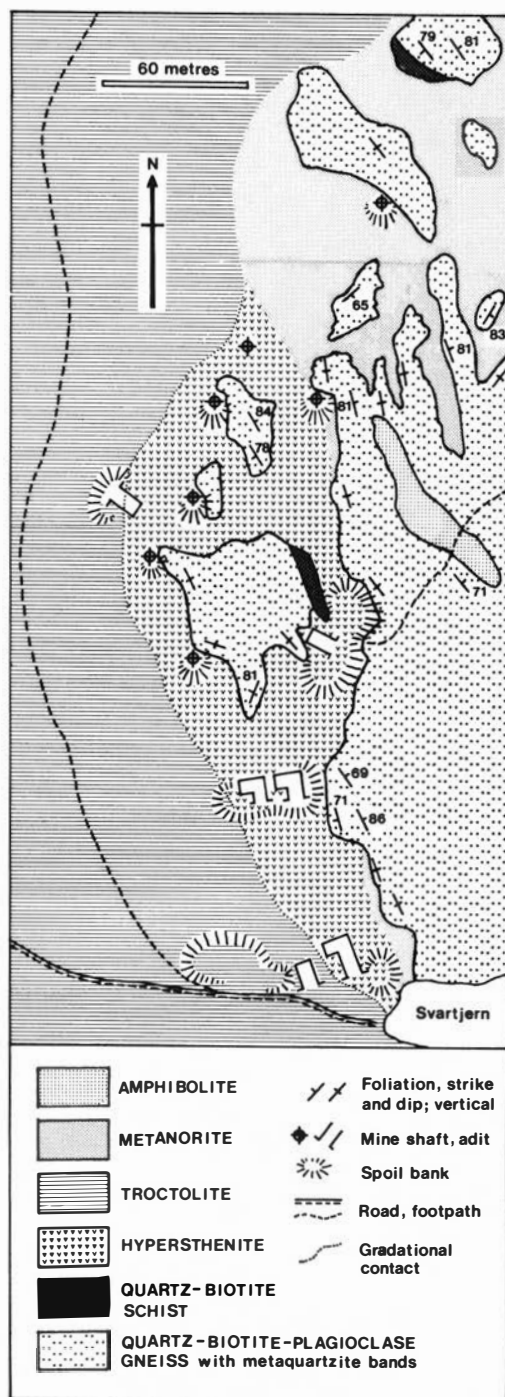


Fig. 3. Geological map of the Seljåsen mineralised zone, Mesel area.

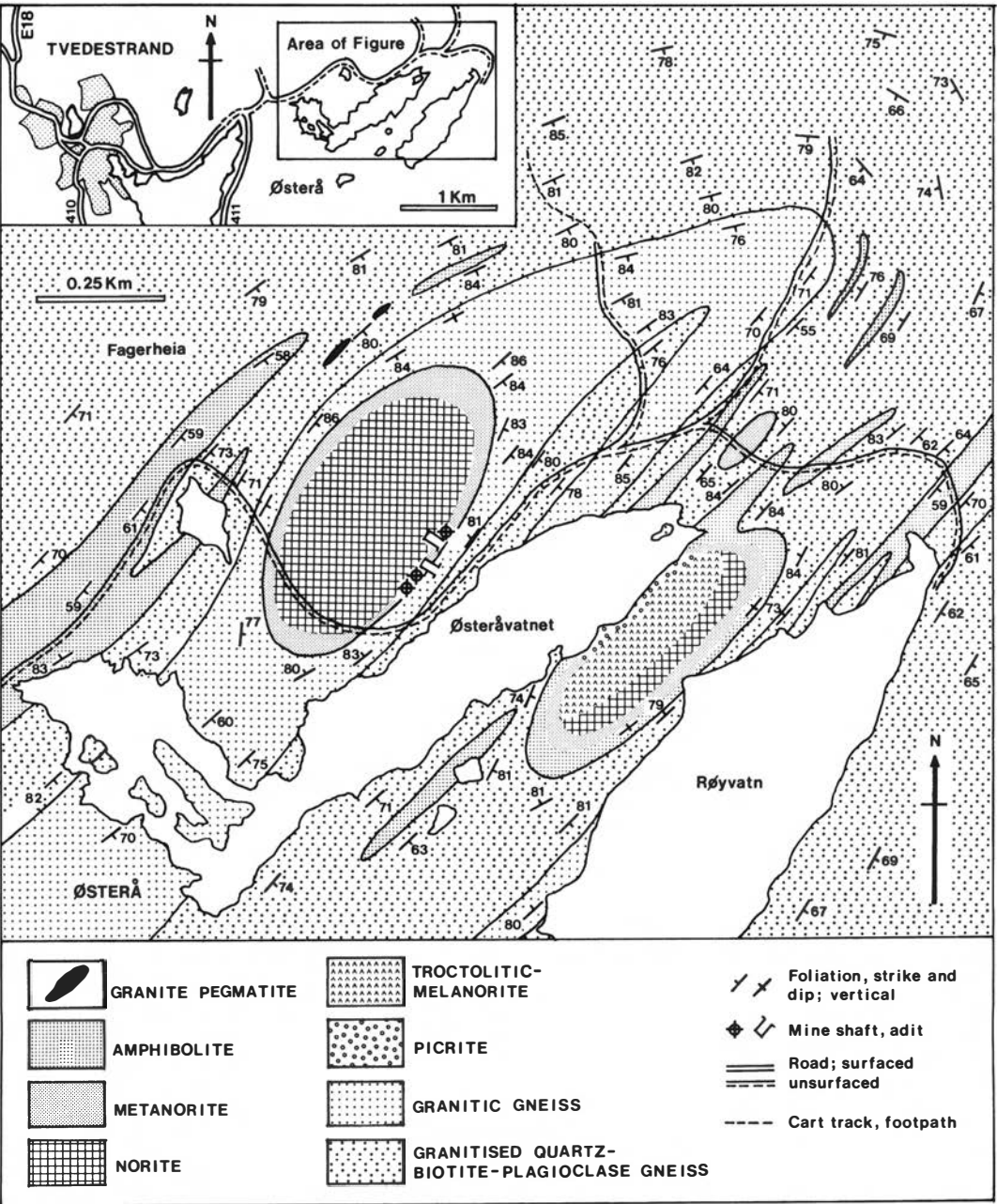


Fig. 4. Geological map of the Østerå area.

southeastern parts of the intrusion are amphibolitised but were originally noritic.

The bulk of the Fe-Cu-Ni sulphide mineralisation is contained within the pyroxenite band on the eastern margin of the pluton, but also occurs along the intrusive contact at this locality

and around the margins of the xenoliths (Fig. 3). The irregular intrusive contact would appear to have exerted a structural control over the location of the ores in addition to the lithological control.

The Østerå deposit

The deposit is situated on the southeastern margin of the Østerå intrusion, located north-east of Tvedestrand (Fig. 4). This discordant, stock-like body, together with its differentiated neighbour (the Røyvatn pluton), intrude a refolded synformal structure in amphibolite facies granitic and granitised gneisses. The Østerå pluton is composed of a coarse-grained, plagioclase-rich norite and leuconorite, displaying an ophitic to subophitic texture. The primary assemblage of this intrusive consists of plagioclase (zoned, An_{53} cores to An_{47} rims), hypersthene ($Mg_{63}Fe_{36}Ca_1$) and salite ($Mg_{40}Fe_{12}Ca_{48}$), together with accessory ilmenite and apatite. Temperatures of pyroxene equilibration lie in the range 770–810°C. Coronas (1–2 mm thick) of red-brown biotite are developed between ilmenite and plagioclase. The margins of the intrusion are sporadically amphibolitised to metanorite. The bulk of the ore in the mineralised zone is contained within the norite and metanorite.

The Meikjær deposits

Fe-Cu-Ni sulphide ores are located at the margins of several closely-spaced boss-like bodies in the vicinity of Skjilbreia in Bamble (Fig. 5a). The geology of this area has been described by Jerpseth (1979). The discordant bosses, which intrude amphibolite facies granitised gneisses, probably represent either protrusions from a larger single pluton at depth or remnants of a largely eroded intrusion. The bosses are petrologically similar, being composed of a coarse-grained norite. The assemblage of this rock, which displays an ophitic texture, consists of plagioclase (zoned, An_{70} cores to An_{58} rims), hypersthene ($Mg_{63}Fe_{35}Ca_2$) and salite ($Mg_{39}Fe_{13}Ca_{48}$), together with accessory dark green hercynite, ilmenite and apatite. Temperatures of pyroxene equilibration lie in the range 860–900°C. Relict corona textures indicate that small amounts of olivine (less than 6%) were originally present in the norite. The oxides bear coronas of red-brown biotite against plagioclase, occasionally with an outer rim of brown ferroan pargasite. The marginal parts of the bosses are amphibolitised. The bulk of the ore in the mineralised areas is contained within the marginal intrusive rocks. The irregular intrusive contacts have exerted a degree of structural control over the location of the ores.

The Nystein deposits

These deposits, which are the largest known sulphide ore bodies in the Bamble area, are located at three localities along the southeastern margin of the Nystein intrusion. Their positions are marked by the Vissestad, Nystein and Hansås Mines (Fig. 5b). The geology of this area has been described by Ellingvåg-Pettersen (1979). The semi-concordant pluton intrudes a series of amphibolite facies granitised gneisses and is composed of a coarse-grained norite to gabbro-norite. The primary assemblage of the intrusive, which displays an ophitic to subophitic texture, consists of plagioclase (zoned An_{48} cores to An_{44} rims), orthopyroxene (hypersthene/ferrohypersthene, $Mg_{49}Fe_{49}Ca_2$) and salite ($Mg_{33}Fe_{21}Ca_{46}$), together with accessory ilmenite, magnetite and apatite. Temperatures of pyroxene equilibration lie in the range 850–870°C. The oxides bear coronas of red-brown biotite or brown magnesio-hastingsite against plagioclase. The intrusion is largely amphibolitised and the original rock is exposed only in its central parts and (as indicated by ore samples) at depth in the mine workings. Most of the ore in the mineralised areas is hosted by the norite and its metamorphosed equivalents (metanorite and amphibolite).

Mining history

The Bamble area sulphide deposits were initially worked between 1859 and 1884. The Meikjær and Stoltz Mines at Skjilbreia (Fig. 5a) and the Nystein Mine (Fig. 5b) were opened again between 1915 and 1917. The Vissestad and Hansås Mines at Nystein were also worked during the latter period and were opened again during the Second World War. The combined production from the Meikjær and Nystein deposits totalled 400 tonnes of Ni and 200 tonnes of Cu (J. Bugge 1978). With the exception of the Nystein deposits (Morton et al. 1970), no details have been published of the extent and structure of the Bamble area ore bodies at depth and the present study reveals no further information on this topic, since the mine workings are no longer accessible. Sampling of ore material has consequently been limited to within the entrances to the workings and adjacent spoil heaps, and it is assumed that these samples are reasonably representative of the deposits in their entirety.

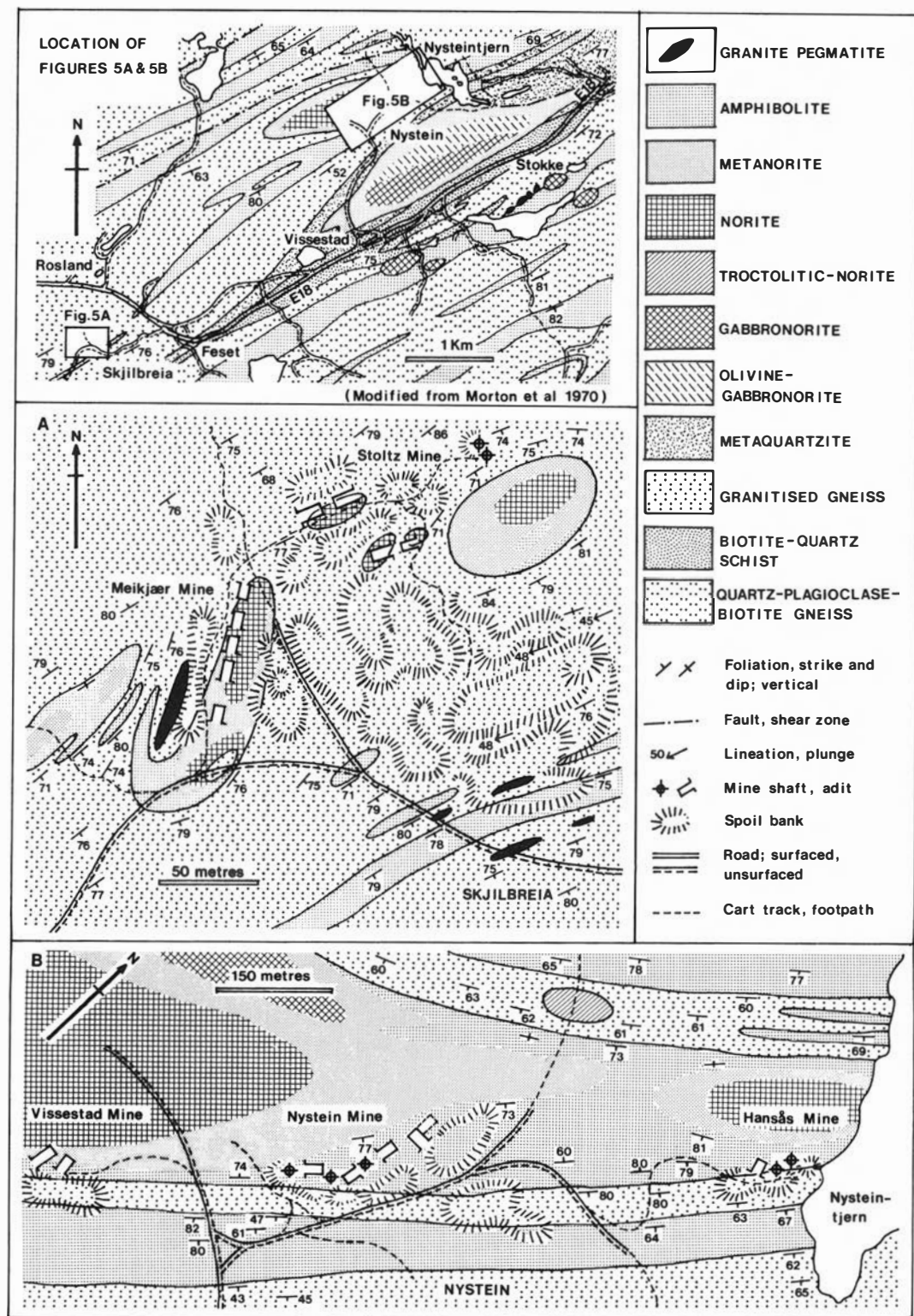


Fig. 5. Geological maps of the (A) Meikjær and (B) Nystein mineralised zones.

Sulphide distribution and mineralogy of the ores

A three-phase primary sulphide assemblage of hexagonal pyrrhotite with subordinate chalcopyrite and cobaltian pentlandite is present throughout the Seljåsen mineralised zone. The ores sporadically contain accessory magnetite, ilmenite and cobaltite. The primary sulphide assemblage of the Østerå ores consists of hexagonal and monoclinic pyrrhotite, together with subordinate chalcopyrite and pentlandite. In the unaltered parts of the Meikjær and Nystein deposits monoclinic pyrrhotite is accompanied by chalcopyrite, pentlandite and pyrite. Magnetite is a ubiquitous primary accessory phase in the Meikjær and Nystein ores, but is much scarcer in the Østerå ores.

Sulphides in the Bamble area deposits are largely incorporated in the marginal intrusive rocks. In the main mineralised zone at Seljåsen, a general gradation from disseminated to 'network' or 'matrix' ores is evident towards the outer margin of the ultramafic band, with occasional massive sulphides (less than 1 m thick) interspersed throughout. The Østerå, Nystein and Meikjær mineralised zones predominantly consist of disseminated ore, with massive sulphides only well-developed in parts of the Nystein ore bodies. In the unaltered host rocks of the deposits, sulphide-silicate textures interpreted as being of magmatic origin are well-preserved. However, in the more altered Nystein and Meikjær bodies, such textures remain only locally as pockets within metamorphosed ore.

In the richer disseminations in the Seljåsen deposit, the sulphides occur in the cumulus and intercumulus sites otherwise occupied by the primary pyroxene in the hypersthene and troctolite respectively, and frequently subpoikilitically enclose subhedral hypersthene crystals (Fig. 6a). These textures are similar to those exhibited by other ultramafic, sulphide-mineralised intrusions worldwide, such as the Mount Sholl intrusion (Mathison & Marshall 1981) and Sally Malay deposit (Thornett 1981) in Western Australia.

In weaker disseminated ores hosted by troctolite in the Seljåsen deposit, and by norite in the Østerå, Nystein and Meikjær mineralised zones, sulphides typically occur interstitially to cumulus plagioclase in the intercumulus sites otherwise occupied by primary pyroxene, frequently poikilitically enclosing the feldspar laths and imparting an ophitic texture to the ore reminiscent of the host intrusive (Fig. 6b & 6c). Such intercumulus

sulphide textures are frequently exhibited by numerous mafic host rocks in orthomagmatic deposits worldwide. More solitary, globular sulphide droplets locally occur interstitial to, and moulded around, silicate phases in the Meikjær and Nystein mineralised zones. These droplets consist of fine, granular pyrrhotite and occasionally bear partial selvages of chalcopyrite or pentlandite. These ores are more reminiscent of the 'immiscible sulphide' ores of the Sudbury deposits (Hawley 1962), as noted by Morton et al. (1970).

The higher-grade network ores and massive ores of the deposits exhibit markedly different sulphide-silicate textures to those displayed by the disseminated ores. The massive sulphides invariably contain xenoliths of the host intrusion (up to 35 mm across) or, along the intrusive contacts, similar xenoliths of country gneiss. In the latter case, there is no doubt that the sulphide ore has locally replaced the country rock, while in the marginal parts of the host intrusions, the sulphide material appears to have infiltrated and brecciated at least partially solidified intrusive rock. In the gneissose xenoliths, the silicate phases (quartz, plagioclase, K-feldspar and biotite) commonly contain fine, blebby inclusions of pyrrhotite and/or pyrite.

Minor sulphide disseminations also occur locally within the country rock gneisses around the Bamble area mineralised intrusions, but rarely persist for more than a few metres from the intrusive contact. In these host rocks the sulphides sporadically form small, granular pockets and wispy schlieren, the latter generally concordant with the gneissose foliation.

Sulphide textures show relatively little variation between the various unaltered ore types of the Bamble area deposits. Pyrrhotite predominates in all of these ores, occurring as coarse, interlocking anhedral, up to 20 mm in diameter in the larger pockets of massive ore. In the Østerå ores, hexagonal pyrrhotite occurs as subordinate relics within coarse, granular anhedral of monoclinic pyrrhotite. The monoclinic pyrrhotite in the Østerå ores had developed from fine, flame-like intergrowths within the earlier-formed hexagonal pyrrhotite, feathering out along the basal parting of the latter phase, often in association with cross-fractures.

Chalcopyrite occurs in all of the deposits as fine to coarse-grained anhedral interstitial to pyrrhotite, and in the Seljåsen ores as fine lamellae within coarser pyrrhotite anhedral. Intergrowths

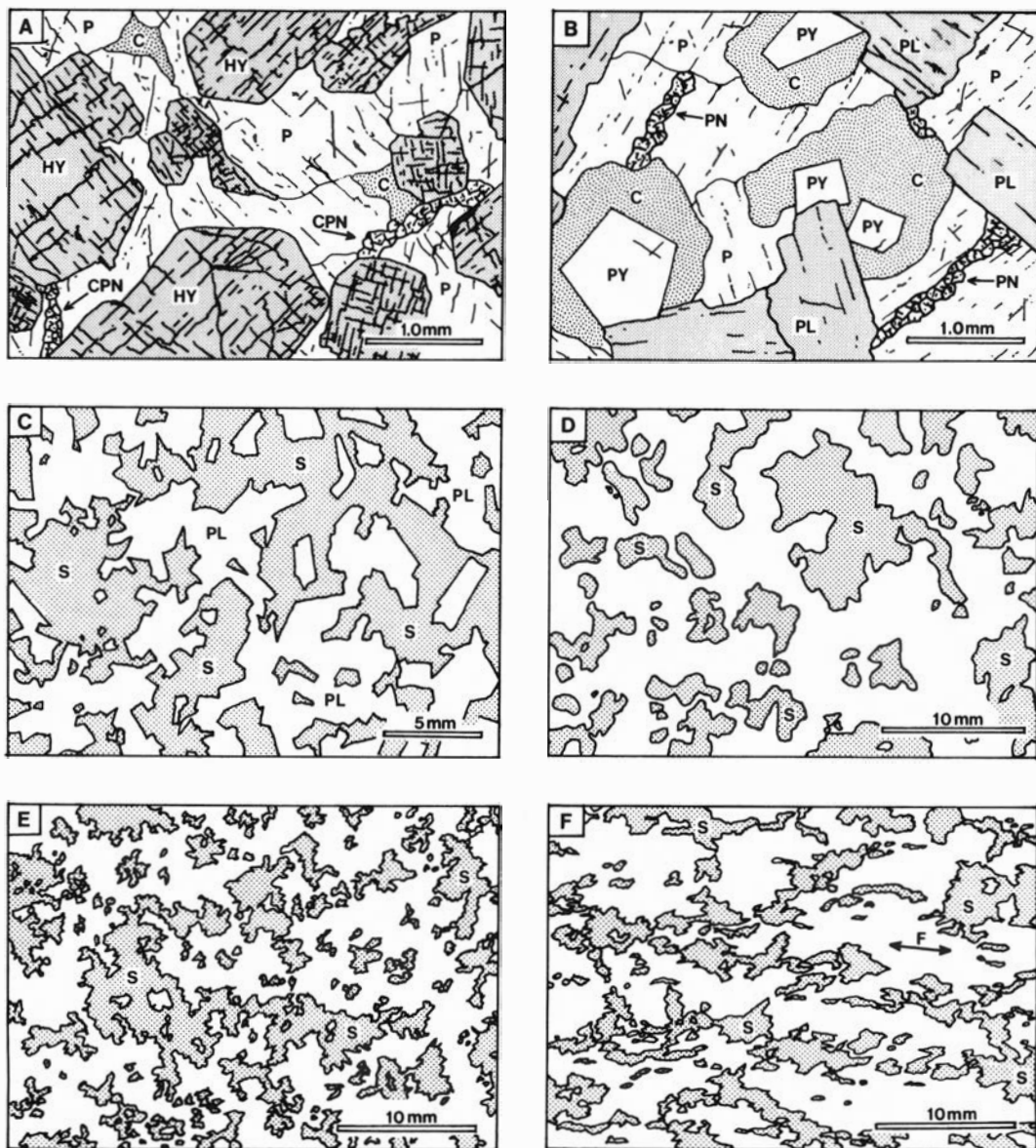


Fig. 6. Ore textures from the Bamble area sulphide deposits.

(A) Network ore, Seljåsen. Sulphide matrix encloses euhedral to subhedral hypersthene (HY) crystals., P – granular pyrrhotite, C – chalcopyrite anhedra, CPN – blocky cobaltian pentlandite (arrowed).

(B) Disseminated ore in norite, Meikjær Mine. Sulphides in intercumulus sites otherwise occupied by pyroxene and subpoikilitically enclosing cumulus plagioclase (PL). PY – euhedral pyrite, P – granular pyrrhotite, C – chalcopyrite anhedra, PN blocky pentlandite.

(C) 'Ophitic' textured primary disseminated ore in norite, Hansås Mine. Primary sulphides (S, stippled) fill intercumulus pyroxene sites and subpoikilitically enclose cumulus plagioclase (PL).

(D) Disseminated ore in metanorite, Nystein Mine. Annealed sulphides (S) interstitial to recrystallised plagioclase. Note loss of original ophitic texture.

(E) Disseminated ore in massive amphibolite, Vissestad Mine. Note the development of finer-grained, massive amphibolitic fabric, the dispersal of sulphides (S) and ragged sulphide-silicate contacts.

(F) Disseminated ore in foliated amphibolite, Vissestad Mine. Final stage of metamorphic recrystallisation, resulting in a foliated texture whereby the sulphides (S) have undergone deformation together with the metamorphic silicates.

A & B: Sketches of polished ore in reflected light, C, D, E & F: Sketches of polished ore slabs.

of chalcopyrite with cubanite or mackinawite have not been observed in any of the deposits. Pentlandite forms characteristic blocky veinlets interstitial to pyrrhotite in all of the deposits, the veinlets occasionally forming linear features within pyrrhotite anhedral, orientated (like the chalcopyrite lamellae in the Seljåsen ores) parallel to the basal parting of the former phase. Pentlandite also forms fine, flame-like exsolution intergrowths within the hexagonal pyrrhotite of the Seljåsen ores. Both fine-grained chalcopyrite and blocky pentlandite anhedral are commonly developed along sulphide-silicate contacts in all of the Bamble area deposits. In the Meikjær and Nystein ores, primary pyrite sporadically forms fine-grained, clear euhedra or subhedra, typically enclosed within, or marginal to, grains of pyrrhotite and chalcopyrite (Fig. 6b). Minute anhedral of cobaltite, apparently primary in origin, occur in the massive ores of the Seljåsen deposit, generally enclosed within pyrrhotite anhedral. Magnetite, when present, forms subrounded anhedral interstitial to the sulphide phases in all of the deposits, the anhedral commonly being located adjacent to silicate phases. Ilmenite occurs as fine, granular intergrowths within coarser magnetite anhedral, indicative of re-equilibration recrystallisation.

Metamorphic and supergene alterations

The ores hosted by the relatively unaltered Seljåsen and Østerå intrusive rocks generally retain their primary sulphide mineralogical and textural characteristics. However, the Meikjær and Nystein ores, which are locally hosted by completely recrystallised or deformed intrusive rocks (metanorite and amphibolite) have correspondingly undergone recrystallisation and/or deformation. The Vissestad Mine ore body, in particular, has almost completely recrystallised during Sveconorwegian metamorphism. In the more altered Meikjær and Nystein deposits, all gradations of sulphide textures, from primary intercumulus (orthomagmatic) to metamorphic, are represented (Fig. 6c-f). The metamorphic recrystallisation of the Meikjær and Nystein ores is characterised by the alteration of the primary sulphide assemblage to secondary pyrite-rich and magnetite-rich assemblages. Replacement textures are predominant in the metamorphosed ores and reaction-rims of chlorite are commonly developed along sulphide-silicate interfaces. Overgrowths of

secondary sulphides on metamorphic amphibole and plagioclase indicate that sulphide redistribution and recrystallisation continued at low temperatures following primary silicate recrystallisation.

The metamorphic sulphide assemblages in the Meikjær and Nystein deposits consist of pyrite-chalcopyrite-magnetite $\pm$ pentlandite. In addition, millerite is present in the recrystallised Vissestad Mine ore body. In the less altered primary ores, annealed textures (e.g. Fig. 6d) have developed from the original intercumulus sulphide textures, usually with retention of the primary sulphide assemblage. However, the metamorphic ores in the marginal amphibolitic host rocks of the deposits display markedly different textures. In these ores the sulphide-silicate contacts are extremely ragged, with sulphides occurring both as granular aggregates and as scattered, discrete xenoblasts, blebs and hair-like veins replacing silicate phases, commonly along prominent cleavages. The 'ophitic' texture of the primary ore is seen to be progressively lost with increasing metamorphism (Figs. 6b-f) and, in foliated, amphibolitic host rocks the sulphides have undergone deformation and recrystallisation together with the silicate phases and form polycrystalline schlieren and stringers concordant with the amphibolitic foliation. The sulphide aggregates in the recrystallised ores predominantly consist of fine-grained, polycrystalline pyrite, together with subordinate, interstitial xenoblasts of chalcopyrite and millerite.

Several habits are displayed by the secondary pyrite in the metamorphosed ores of the Meikjær and Nystein deposits, probably representing two or more distinct generations of pyrite growth:

- (i) Granoblastic, polycrystalline aggregates of cloudy or 'spongy' pyrite.
- (ii) Clusters of, and discrete, pyrite porphyroblasts, fine to coarse-grained and poikiloblastic with respect to tiny inclusions of chalcopyrite, magnetite and silicate phases, with individual porphyroblasts measuring up to 35 mm across.
- (iii) Fracture infilling in silicate phases (usually accompanied by magnetite).

The metamorphic pyrite thus contrasts strongly with the fine-grained, clear, sporadic euhedra of primary origin.

Metamorphic chalcopyrite forms fine xenoblasts interstitial to pyrite, replacing metamor-

phic silicates and, in some of the ores, also occurs in symplectic intergrowths with pyrite. Some pyrite idiomorphs in the recrystallised Nystein ores bear thin selvages of nickeloan pyrite. Texturally similar nickeloan pyrite occurs in the Sudbury ores in association with late, hypogene gangue minerals (Hawley 1962). The nickeloan pyrite in the Nystein ores, however, appears to have partially replaced pentlandite. Millerite forms fine, platy pseudomorphs after fine-grained pyrite and chalcopyrite in the Vissestad ore body and, like the nickeloan pyrite, is almost certainly of low-temperature, metamorphic origin. Granoblastic bands and stringers (less than 1 m in length) of secondary magnetite are ubiquitous throughout the altered Meikjær and Nystein ore bodies. Pentlandite is poorly developed in the metamorphosed ores, although a Ni-rich, S-rich variety does occur as fine-grained, blocky xenoblasts interstitial to pyrite in some of the ores.

Both the primary and metamorphic ores in the Bamble area deposits are violaritized to varying degrees. Violaritization is widespread in the massive and network ores, but is more sporadically developed in the lower-grade, disseminated ores. Varying from purple-brown to purple-grey in colour, violarite pseudomorphs both primary and metamorphic pentlandite and, more rarely, finer-grained pyrrhotite. A rare cobaltian violarite replaces the cobaltian pentlandite in the Seljåsen ores. The violarite pseudomorphs commonly display a relict octahedral cleavage after pentlandite, remnants of which are frequently preserved in the cores of the pseudomorphs. The fractured, porous and blocky nature of the violarite in the Bamble area ores indicates that it is clearly of late, supergene origin, in accordance with that in most Fe-Cu-Ni sulphide deposits worldwide (Keele & Nickel 1974, Nickel et al. 1974). Minor supergene alteration of fine, granular monoclinic pyrrhotite to pyrite and marcasite also occurs in more weathered specimens of the Meikjær and Nystein ores.

Mineral chemistry

Analytical techniques

Three-hundred and fifty-nine electron microprobe analyses of sulphides, sulpharsenides and Fe-Ti oxides from the Bamble Sector ores were performed using a Hitachi S-450 scanning electron microscope in conjunction with a Link Systems 860 energy dispersive analytical system.

Analytical conditions employed a 20kV accelerating potential, a counting time of 100 seconds and a spot diameter of about 2 μm . All analyses were performed in triplicate: the representative analyses presented in Tables 1 and 2 are the mean of three separate spot determinations on the same crystal. The relative accuracy of the system employed is approximately ± 0.5 at.% for Fe, Ni, As and S, and ± 0.2 at.% for Co and Cu. Pyrite, Co and As standards were analysed with each set of samples as a general check on accuracy. A full list of ore mineral analyses, together with analyses of silicates and oxides from the host intrusive rocks, can be found in Brickwood (1984).

Iron-titanium oxides

Magnetite and ilmenite show little variation in composition within and between the Bamble area sulphide deposits, although the primary magnetite in the Seljåsen ores contains up to 1.87 wt.% V_2O_5 . Low temperatures of equilibration (less than 500°C) were obtained for primary and secondary, coexisting magnetite-ilmenite pairs from all the deposits and indicate that re-equilibration of the oxides has occurred, in accordance with the nature of the Fe-Ti oxides in the host rocks and other intrusions of the Bamble area (Brickwood 1984).

Chalcopyrite

Chalcopyrite shows little variation in composition in all ore types (Table 1) and modes of occurrence, in accordance with the near-perfect stoichiometry usually displayed by this phase in Fe-Cu-Ni sulphide ores worldwide.

Pyrite and nickeloan pyrite

Analyses of primary and secondary, metamorphic pyrites from the Meikjær and Nystein ores display little deviation from stoichiometric MS_2 , although significant variations occur in their minor element concentrations (Table 1). The primary pyrite in both deposits is enriched in Co relative to the secondary variety. The latter, however, is enriched in Ni relative to the primary pyrite. Consequently the Ni/Co (wt.%) ratios of the primary pyrites are generally less than 0.1, but greater than 1.0 for the metamorphic pyrite. Concentrations of Cu in both varieties are uniformly low. These variations are in accord-

Table 1. Analyses of chalcopyrites, pyrites, pyrrhotites and millerites from the Bamble Sector deposits.

Sample	Element (wt.%)						Sample	Element (wt.%)					
	Fe	Ni	Co	Cu	S	Total		Fe	Ni	Co	Cu	S	Total
Chalcopyrites							Hexagonal pyrrhotites						
S102	30.25	0.06	0.00	34.39	34.88	99.68	S102	60.96	0.22	0.07	0.00	38.53	99.78
R9	30.57	0.00	0.01	34.56	34.80	99.94	S106	61.15	0.10	0.02	0.00	38.84	100.11
I14	30.39	0.08	0.00	34.47	34.86	99.80	S9	61.33	0.03	0.00	0.02	38.94	100.32
N96	30.32	0.01	0.00	34.54	34.81	99.68	R9	60.39	0.69	0.02	0.00	38.69	99.79
							R6	60.60	0.59	0.02	0.03	38.68	99.92
Primary pyrites							R8	60.51	0.56	0.09	0.00	38.58	99.74
I6	44.71	0.01	1.70	0.03	53.18	99.63							
I14	45.59	0.01	1.04	0.04	53.27	99.95	Monoclinic Pyrrhotites						
N21	44.72	0.01	1.84	0.01	53.46	100.04	R9	59.64	0.82	0.00	0.01	39.17	99.64
N29	44.89	0.04	1.22	0.01	53.56	99.72	R6	59.22	0.83	0.02	0.02	39.18	99.27
N96	45.02	0.06	0.94	0.01	53.45	99.48	R8	59.84	0.80	0.00	0.04	39.39	100.07
N101	45.20	0.00	1.27	0.01	53.24	99.72	I6	59.35	0.74	0.02	0.02	39.46	99.59
							I4	59.31	0.71	0.09	0.00	39.11	99.22
Secondary pyrites							I14	59.75	0.69	0.09	0.04	39.40	99.97
I15a	45.66	0.23	0.00	0.03	52.81	98.73	N29	59.93	0.64	0.04	0.03	39.39	100.03
I15b	45.84	0.16	0.03	0.02	52.45	98.50	N96	59.51	0.82	0.03	0.02	39.36	99.74
N18	45.96	0.69	0.07	0.00	53.16	99.88	N101	59.68	0.76	0.03	0.02	39.58	100.07
N23	45.66	0.31	0.00	0.03	53.31	99.31							
							Millerites						
Nickeloan pyrites							N24	0.47	64.88	0.00	0.10	34.39	99.84
N91	41.31	5.55	0.00	0.00	52.52	99.38	N25	0.56	65.02	0.01	0.00	34.55	100.14
N29	41.70	5.46	0.05	0.02	52.67	99.90	N18	0.61	64.67	0.00	0.06	34.04	99.38
N21	42.34	5.13	0.04	0.03	52.33	99.87	N23	0.68	64.43	0.01	0.05	34.31	99.48
N22	42.10	4.89	0.01	0.00	52.43	99.43							

Explanation of Tables 1 & 2

Seljåsen deposit

S5 – Primary disseminated ore in troctolite (hpo-cp-cpn). S106 – Primary disseminated ore in pyroxenite (hpo-cp-cpn). S9a & b, S100 – primary network ore in pyroxenite (hpo-cp-cpn). S102, S103, S105, S107 – Primary massive ore (hpo-cp-cpn-co).

Østerå deposit

R6, R8 – Primary massive ore (hpo-mpo-pn-cp). R9 – Primary disseminated ore in norite (hpo-mpo-pn-cp).

Meikjær deposits

I4 – Primary massive ore (mpo-cp-pn), Stoltz Mine. I6 – Primary disseminated ore in norite (mpo-py-cp-pn), Stoltz Mine. I14 – Primary disseminated ore in norite (mpo-py-cp-pn), Meikjær Mine. I15a & b – Metamorphic disseminated ore in metanorite (mpo-py-cp-pn), Meikjær Mine.

Nystein deposits

N18 – Metamorphic massive ore (py-cp-ml), Vissestad Mine. N20a & b – Metamorphic disseminated ore in amphibolite (py-cp-pn), Vissestad Mine. N23, N24, N25 – Metamorphic disseminated ore in amphibolite (py-cp-ml), Vissestad Mine. N21 – Primary massive ore (mpo-py-cp-pn), Vissestad Mine. N22, N29, N91 – Primary massive ore (mpo-py-cp-pn), Nystein Mine. N96 – Primary disseminated ore in norite (mpo-py-cp-pn), Nystein Mine. N101 – Primary disseminated ore in norite (mpo-py-cp-pn), Hansås Mine.

Abbreviations:

hpo – hexagonal pyrrhotite	mpo – monoclinic pyrrhotite
cpn – cobaltian pentlandite	pn – pentlandite
cp – chalcopyrite	py – pyrite
co – cobaltite	ml – millerite

ance with those noted for pyrites displaying similar textural relationships in Fe-Cu-Ni sulphide deposits worldwide (e.g. Bjørlykke 1947, Hawley 1962, Nickel et al. 1974, Craig & Higgins 1975).

In the pyrite formula, Co and Ni substitute invariably for Fe (Graterol & Naldrett 1971). Consequently the primary pyrites in the Meikjær and Nystein deposits (which contain higher total concentrations of Co + Ni than the metamorphic pyrite) are slightly depleted in Fe relative to the secondary pyrite (Table 1). The generally irregular fluctuations in the Co and Ni contents of the met-

amorphic pyrites can be correlated with the nature of their origin. Hence the pyrite which has overgrown and replaced igneous and metamorphic silicates is notably depleted in both Co and Ni, while that replacing pyrrhotite is Co-poor but relatively Ni-rich. The metamorphic pyrite enriched in Ni probably formed as a result of the dissolution of primary pentlandite. Some of the pyrite idioblasts in the annealed massive Nystein ores display Co and Ni contents comparable to those of the original pyrite, and have probably overgrown the latter.

Table 2. Analyses of pentlandites, cobaltites and violarites from the Bamble Sector deposits.

Element (wt.%)							Element (wt.%)						
Sample	Fe	Ni	Co	Cu	S	Total	Sample	Fe	Ni	Co	Cu	S	Total
Pentlandites							Violarites						
R8	28.89	36.15	1.44	0.00	32.95	99.43	R8	25.68	28.59	1.68	0.00	41.49	97.44
R9	29.11	36.46	1.20	0.00	32.61	99.38	R9	25.83	29.26	1.41	0.02	40.93	97.45
R6	29.17	36.40	1.14	0.00	32.80	99.51	R6	25.77	29.07	1.42	0.00	41.68	97.94
I14	29.10	36.57	0.96	0.04	32.62	99.27	I14	25.70	29.80	1.56	0.02	41.34	98.42
I4	28.93	36.65	0.87	0.00	32.54	98.99	I4	25.40	30.56	1.14	0.00	41.61	98.71
I6	29.30	36.51	0.74	0.04	32.96	99.55	I6	25.17	29.43	0.95	0.04	41.31	96.90
N96	28.91	36.12	1.21	0.00	32.38	98.62	N96	25.72	29.53	1.43	0.00	41.45	98.13
N29	28.58	36.79	0.67	0.00	32.51	98.55	N29	25.51	31.61	0.86	0.00	41.36	99.34
N101	29.41	37.10	0.41	0.00	32.78	99.70	N101	25.61	31.39	0.45	0.00	41.64	99.09
N20a	24.68	40.50	0.11	0.04	32.51	97.84	N20a	16.80	39.03	0.19	0.02	41.29	97.33
N20b	24.94	40.06	0.09	0.05	32.66	97.80	N20b	17.38	38.68	0.28	0.02	40.94	97.30
Cobaltian pentlandites							Cobaltian violarites						
S9a	28.36	28.01	9.95	0.00	32.69	99.01	S9a	25.23	20.68	10.91	0.01	41.22	98.05
S9b	28.22	28.57	9.66	0.02	32.80	99.27	S9b	25.26	20.49	10.82	0.00	41.34	97.91
S100	28.12	28.42	9.23	0.00	32.43	98.20	S100	25.71	19.60	11.44	0.00	40.85	97.60
S107	28.52	28.41	9.03	0.00	32.50	98.46	S107	24.45	20.57	10.60	0.02	40.71	97.35
S105	28.13	28.79	8.89	0.04	32.44	98.29	S105	25.19	20.91	9.92	0.03	41.61	97.66
S106	28.76	28.90	8.53	0.00	32.74	98.93	S106	25.74	20.62	10.08	0.03	41.10	97.57
S5	28.71	29.28	8.26	0.00	32.59	98.84	S5	25.68	21.44	10.27	0.00	41.32	98.71
Element (wt.%)							Solitary cobaltian violarites						
Sample	Co	Fe	Ni	As	S	Total	S107	20.60	19.31	16.45	0.03	40.95	97.34
Cobaltites							S105	19.80	19.85	16.34	0.06	40.73	96.78
S107	33.50	1.53	0.54	47.88	16.48	99.93	S106	19.89	20.43	16.17	0.03	40.66	97.18
S105	33.31	1.19	0.72	48.10	16.31	99.63	S103	19.86	21.44	15.58	0.04	40.90	97.82
S103	32.90	1.49	0.93	47.95	16.19	99.46	S102	24.52	19.65	12.85	0.06	41.86	98.94

The metamorphic nickeloan pyrite in the recrystallised Nystein ores contains 4.1–5.7 wt.% Ni. Concentrations of Co and Cu in this pyrite are comparable to those of the other metamorphic pyrites in the Meikjær and Nystein ores (Table 1). The nickeloan pyrite displays the stoichiometry of the Ni-poor varieties in these ores but, in accordance with most secondary pyrite, shows a tendency towards metal enrichment with S contents lying in the range 52–53 wt.% compared to the range 53–54 wt.% usually exhibited by primary pyrites. The Ni substitutes for Fe in the pyrite formula.

Pentlandite and cobaltian pentlandite

Analyses of primary pentlandites in the Bamble area ore bodies reveal significant differences in composition between the deposits (Table 2). Pentlandites with low Co contents (less than 3 wt.%) are usually Ni-rich with Fe/Ni (wt.%) ratios less than 1.0 and commonly between 0.7 and 0.9. Variations in the Fe/Ni ratio correlate with

the assemblage in which the pentlandite occurs (Graterol & Naldrett 1971, Harris & Nickel 1972). The composition of primary pentlandites from the Østerå, Meikjær and Nystein ores comply with this relationship and display Fe/Ni ratios within the range 0.76–0.81, which are typical of the pyrrhotite-chalcopyrite $\pm$ pyrite assemblage. Likewise, the Fe/Ni ratios of 0.61–0.62 exhibited by the Ni-rich metamorphic pentlandites of the Nystein ores (analyses N20a & N20b, Table 2) lie within the range characteristic of pyrite-rich assemblages. The mean Co contents of pentlandites from the Østerå, Meikjær and Nystein deposits can be correlated with the amount of pyrite in the ores. Hence the pentlandites from the pyrite-free Østerå ores are relatively Co-rich, while those from the pyrite-bearing Meikjær and Nystein ores are relatively depleted in Co, the lowest concentrations being recorded from metamorphic pentlandites in the recrystallised, pyrite-rich Nystein ores (Table 2). The metal/S ratios of primary pentlandites from the Østerå, Meikjær and Nystein deposits range between 1.124–1.150

and are metal enriched relative to stoichiometric proportions, in accordance with most pentlandite compositions (Graterol & Naldrett 1971, Harris & Nickel 1972). However, the metal/S ratios of 1.110–1.118 displayed by the Nystein metamorphic pentlandites are indicative of S enrichment.

The primary pentlandite in the Seljåsen ores is a relatively rare cobaltian variety containing 8.1–9.9 wt.% CO (Table 2). Cobalt pentlandites containing more than 20 wt.% Co are fairly common in the cobalt-arsenide ores of Finland and Canada (Kouvo et al. 1959, Petruk et al. 1969), but cobaltian pentlandites (containing 5–20 wt.% Co) are more characteristic of Ni-rich sulphide ores of ultramafic affinity in which awaruite and heazlewoodite are commonly present (Harris & Nickel 1972). The metal/S ratios of the Seljåsen cobaltian pentlandites range from 1.125–1.142 and are in accordance with those displayed by the pentlandites of the other Bamble area deposits. The Cu contents of the Seljåsen cobaltian pentlandites are uniformly low and comparable with those exhibited by the Co-poor pentlandites (Table 2).

Riley (1977) has shown that in cobaltiferous pentlandites Co replaces Fe or Ni in two separate series, thought to represent the two types of Co co-ordination in the pentlandite structure (octahedral and tetrahedral for Fe and Ni substitution respectively). The Fe/Ni (wt.%) ratios of the Seljåsen cobaltian pentlandites range from 0.98–1.02. These values are indicative of substitution of Ni by Co in the formula, and hence tetrahedral co-ordination of the Co atoms in the pentlandite structure. This is in accordance with the Fe-rich assemblage in which the Seljåsen cobaltian pentlandite occurs.

Cobaltite

Cobaltite is a common constituent of cobalt-arsenide and nickel-arsenide ores, but is rarely recorded from Fe-rich sulphide ores. Natural cobaltite is extremely variable in composition and significant amounts of Fe and Ni can substitute for Co in the formula. The Seljåsen cobaltite contains 1.19–1.83 wt.% Fe and 0.54–1.27 wt.% Ni both substituting for Co (Table 2). Nevertheless, the Co contents of this sulpharsenide (32.6–33.5 wt.%) are high in comparison, for example, with the cobaltites in the Cobalt-Gowganda deposit of Canada (which contain 25.0–31.0 wt.% Co, Petruk et al. 1972), but are in accordance with the

nature of the coexisting cobaltian pentlandite. The Seljåsen cobaltites are relatively depleted in S, with As/S ratios deviating from the stoichiometric value of 1.0 to values of 1.24–1.26, in accordance with most published analyses (e.g. Petruk et al. 1972).

Pyrrhotite

Following the method of Naldrett & Kullerød (1967), primary ore samples from the Bamble area deposits were stained using an ammonium dichromate-HCl acid solution in order to discern the possible occurrence of both the monoclinic (Fe_7S_8) and hexagonal (Fe_9S_{10}) pyrrhotite phases. In conjunction with microprobe data it was found that only hexagonal pyrrhotite is present in the Seljåsen ores, while the Østerå ores contain both varieties. The pyrite-bearing Meikjær and Nystein ores contain only monoclinic pyrrhotite.

The pyrrhotites in all the deposits show little stoichiometric deviation and display metal/S ratios $100[\text{Fe} + \text{Ni} + \text{Co} + \text{Cu}]/[\text{Fe} + \text{Ni} + \text{Co} + \text{Cu} + \text{S}]$ in accordance with the variations described for hexagonal and monoclinic varieties by Arnold (1967): generally greater than 47.2 for hexagonal pyrrhotite and less than 47.2 for monoclinic pyrrhotite. Misra & Fleet (1973), amongst other authors, have shown that the low Ni concentrations commonly displayed by natural hexagonal pyrrhotites are not necessarily characteristic of this phase, which can exhibit both low and high Ni contents when coexisting with monoclinic pyrrhotite. Analyses of pyrrhotites from the Bamble area sulphide ores are in agreement with this observation (Table 1). The coexisting hexagonal and monoclinic pyrrhotites of the Østerå ores display similarly high Ni contents, as do the solitary monoclinic pyrrhotites in the Nystein ores. In contrast, the hexagonal pyrrhotite in the Seljåsen ores displays uniformly low Ni concentrations. There are no significant variations in the Co and Cu concentrations of the pyrrhotites in the Bamble area ores.

Millerite

The metamorphic millerite in the recrystallised ores at the Vissestad Mine displays little variation in composition, with metal/S ratios ranging from 1.02–1.05, in accordance with most natural millerites (e.g. Misra & Fleet 1973), and contain 0.4–0.8 wt.% Fe substituting for Ni in the formula. Concentrations of Co in these millerites are nota-

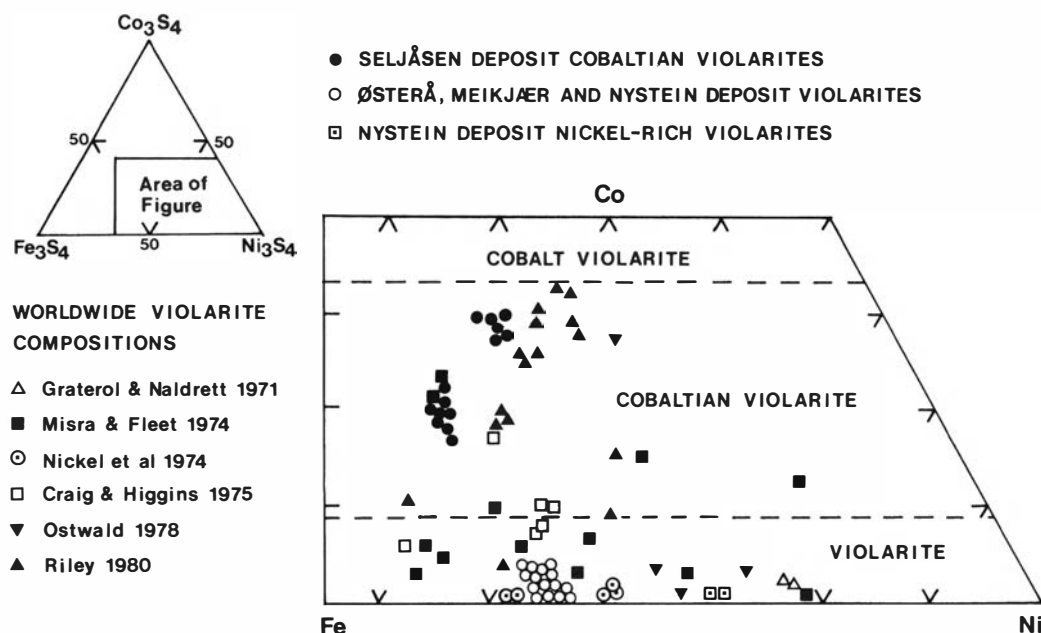


Fig. 7. Violarites and cobaltian violarites from the Bamble area and other sulphide deposits plotted with respect to wt. % Co, Fe and Ni.

bly lower than those usually recorded from primary millerite (Graterol & Naldrett 1971), and Cu contents are uniformly low (Table 1).

Violarite and cobaltian violarite

Violarite, the Fe-Ni-rich member of the thiospinel or linnaeite mineral group (M_3S_4 , where $M = Co, Ni, Fe$ or Cu), is troublesome in the beneficiation of Ni from sulphide ores, because of its tendency to pseudomorph pentlandite. The increasing recognition of violarite in Fe-Cu-Ni sulphide ore bodies worldwide has resulted in a number of studies on the genesis and compositional variations of this mineral in recent years (e.g. Arnold & Malik 1974, Hudson & Groves 1974, Keele & Nickel 1974, Misra & Fleet 1974, Ostwald 1978, Riley 1980). Natural violarites are usually S-deficient, with metal/S (atomic) ratios greater than the stoichiometric value of 0.75. Analyses of the violarites replacing pentlandite in the Bamble area ores are in accordance with this observation, displaying metal/S ratios from 0.75–0.78. These analyses (Table 2) all show low totals. Since the violarite in the Bamble area ores is mostly highly porous and fractured, these low totals are thought to have resulted from a loss of X-ray intensity during analysis. The Fe/Ni

(wt.%) ratios of violarites from the Østerå, Meikjær and Nystein ores range from 0.80–0.92, exceptions being the Ni-rich violarites pseudomorphing the metamorphic Ni-rich pentlandites in the Nystein ores, which display ratios of 0.41–0.45. The mean Co contents of violarites from these three deposits (1.5, 1.2 and 0.7 wt.% for the Østerå, Meikjær and Nystein deposits respectively) are comparable with the Co concentrations of the coexisting pentlandites previously described. The violarites exhibit uniformly low Cu concentrations (Table 2).

Violarites containing more than 5 wt.% Co are rare, occurring mainly as secondary pseudomorphs after Co-rich pentlandites. The few published analyses of cobaltian violarites show Co contents ranging from 5–19 wt.% (Hudson & Groves 1974, Craig & Higgins 1975, Ostwald 1978, Riley 1980). These Co-rich varieties are recorded from sulphide assemblages rich in hexagonal pyrrhotite or smythite. No violarite analogue to cobalt pentlandite has been noted as yet, but it is likely that a solid solution series exists between violarite and 'cobalt violarite' comparable to that of the pentlandite series.

The cobaltian violarite pseudomorphing cobaltian pentlandite in the Seljåsen ores is amongst the most Co-rich so far recorded from ore depos-

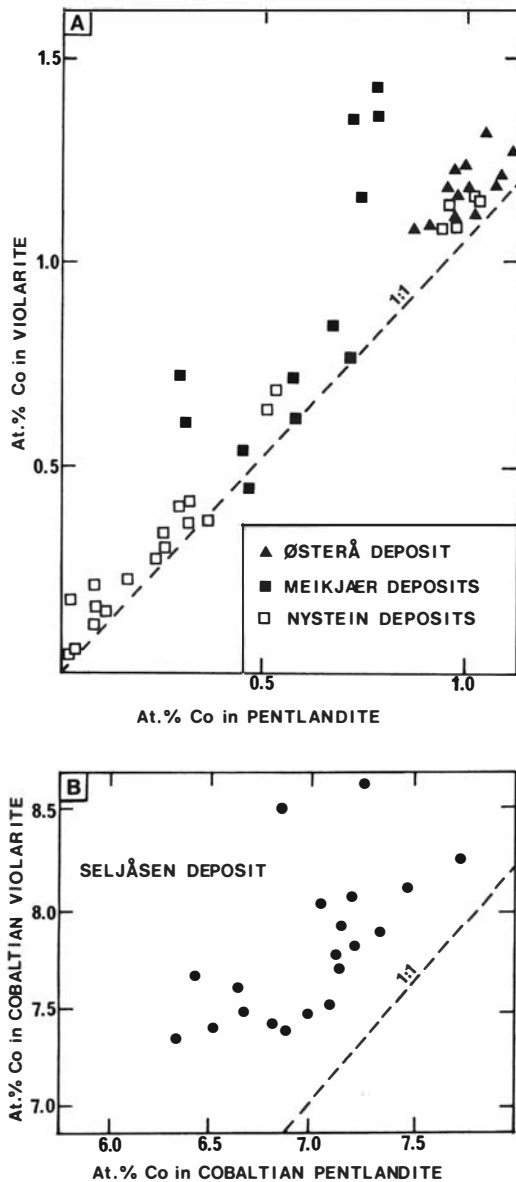


Fig. 8. Distribution of Co between coexisting (A) pentlandites and violarites, and (B) cobaltian pentlandites and cobaltian violarites from the Bamble sulphide deposits.

its worldwide (Fig. 7). The cobaltian violarite which partially replaces cobaltian pentlandite anhedra has Co concentrations ranging from 9.8–11.4 wt.%, while solitary grains (i.e. complete pseudomorphs) contain 11.8–16.5 wt.% Co (Table 2). The Fe/Ni ratios of the Seljåsen cobaltian violarites range from 0.93–1.31 and re-

flect the predominant substitution of Ni by Co in the formula. However, the more Co-rich varieties also show slight substitution of Fe by Co.

Misra & Fleet (1974), Craig & Higgins (1975) and Riley (1980) all note that coexisting pentlandites and violarites (including Co-rich varieties) exhibit a weak correlation with respect to their Co contents. The violarite invariably contains comparable or slightly greater amounts of Co than the coexisting pentlandite it replaces. Coexisting pentlandites and violarites from the Bamble area ores exhibit this relationship well, with the violarites containing up to one and a half times as much Co as the pentlandite hosts (Fig. 8).

Discussion

The Bamble area sulphide ores display primary textural and mineralogical features similar to those usually exhibited by orthomagmatic deposits of segregative origin, such as the mafic and ultramafic-associated deposits of Western Australia (e.g. Mathison & Marshall 1981, Thornett 1981). Vogt (1902), A. Bugge (1922) and Morton et al. (1970) have all noted similarities between some of the Bamble ores and the 'immiscible ores' of the Sudbury deposits (Hawley 1962). Some of the Bamble area ores also show the effects of Sveconorwegian metamorphic recrystallisation, together with more recent supergene alterations. Complete recrystallisation of the ores locally occurred in relation to changes in temperature during prograde metamorphism and post-metamorphic cooling, accompanied by deformation in some cases. The variable amphibolitisation of the Bamble area mafic intrusions and similar alteration of the ore bodies suggest that the effects of Sveconorwegian metamorphism were, however, only locally developed, both on a regional scale and on a smaller scale within individual bodies. Supergene alterations within the ore bodies are in accordance with those observed in similar deposits worldwide (eg Keele & Nickel 1974, Nickel et al. 1974).

A detailed account of the genesis of the Bamble area deposits is beyond the scope of the present work. Nevertheless, the results of the present study enable the following general points to be made:

(1) The primary characteristics of the ores are in accordance with those typically resulting from the crystallisation of immiscible sulphide-oxide

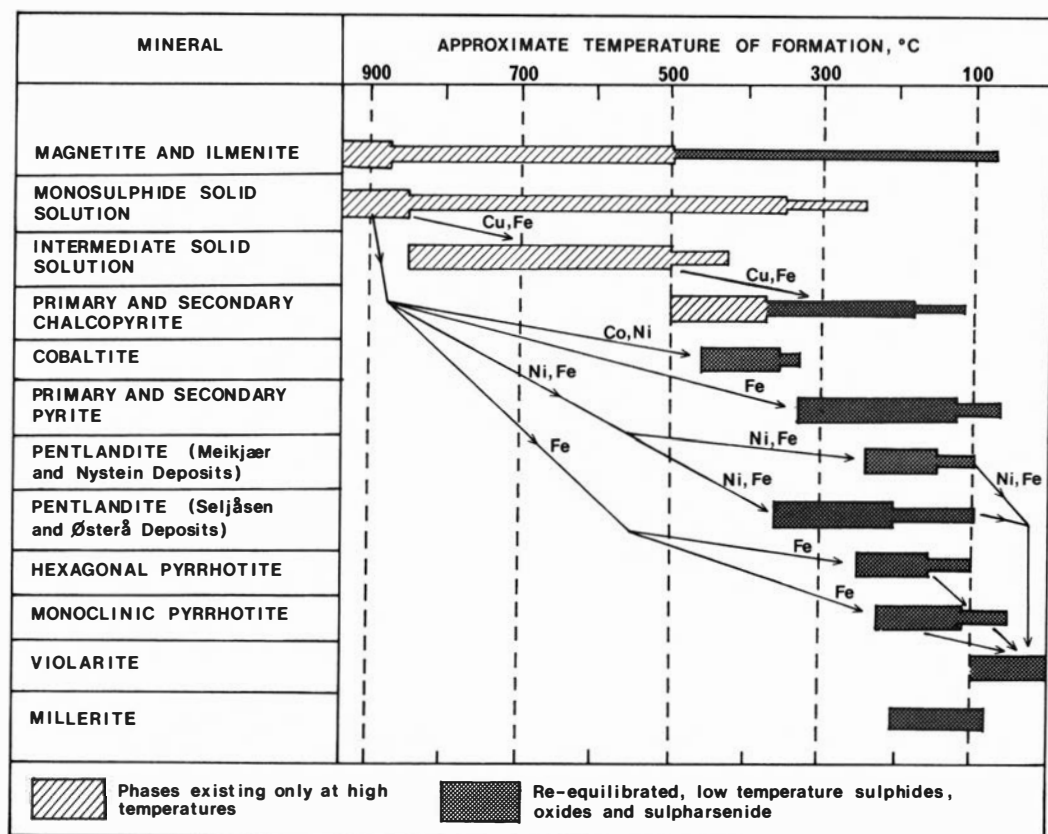


Fig. 9. Generalised paragenesis of ore minerals in the Bamble sulphide deposits.

melts segregated from mafic intrusive magmas at temperatures of 1000–800°C (Arnold 1962, Nal-drett & Kullerud 1967, Misra & Fleet 1973, 1974). Using the temperatures of primary pyroxene equilibration in the host intrusive rocks (Brickwood 1984) as a rough estimate of the temperatures at which solidification of the sulphide liquid took place, the crystallisation of mss (monosulphide solid solution) occurred at approximately 950°C in the Seljåsen deposit and at approximately 800°C in the Østerå, Meikjær and Nystein deposits.

(2) Segregation of the immiscible sulphide-oxide melts from the mafic silicate melts appears to have been aided by the conducive composition of the intruded magmas, with sialic contamination probably promoting sulphide precipitation. The composition of the mineralised Bamble area intrusives is in accordance with similar Fe-Cu-Ni sulphide mineralised bodies worldwide: they are noritic, display Fe-enrichment with fractionation

and contain S in amounts indicative of S saturation during crystallisation (Brickwood 1984). Significantly, sulphide deposits are absent from the more alkaline, gabbroic intrusions of the Bamble area, while the Ringerike sulphide deposits in the Kongsberg area are also associated with noritic intrusions (Johannesen 1974). Furthermore, the largest Fe-Cu-Ni sulphide deposits in the Precambrian of South Norway are associated with the noritic Iveland-Evje complex in the Telemark area (Barth 1947), the ores of which are notably similar to the Meikjær and Nystein ores (Bjørlykke 1947). The lack of deformation associated with the intrusion of the Bamble area mafic plutons is indicative of passive emplacement by stoping. Assimilation of supracrustal rocks (mainly highly siliceous) is thus likely to have occurred during their injection. Direct evidence of this is provided by the large, quartz-rich gneiss xenoliths in the Seljåsen mineralised zone, which undoubtedly accounts for the fixation of

the ores at this locality and the crystallisation of the local silica-rich hypersthene which hosts the bulk of the mineralisation. These features are in keeping with the observations of Haughton et al. (1974), Barker (1975), Irvine (1975) and Thorne (1981) that magma composition and salic contamination play crucial roles in the segregation of ores from mafic silicate melts.

(3) Following segregation of the immiscible sulphide-oxide melts to marginal, structurally and geochemically favourable positions during *in situ* crystallisation of the mafic intrusive magmas, relatively high-temperature solidification of trapped sulphide globules resulted in the droplet-type disseminations in the Meikjær and Nystein deposits. The sulphide liquid in the higher-grade, 'intercumulus' disseminations evidently impregnated a crystal-liquid mush and crystallised following solidification of the bulk of cumulus plagioclase, thus retaining the ophitic texture of the non-mineralised intrusive rock. In the case of the Seljåsen deposit, the sulphide liquid must have seeped into an early-formed, pyroxene adcumulate mush, displacing the silicate liquid in places (as suggested by the well-formed pyroxene crystals in some of these ores). The silicate xenoliths in the matrix ores of the deposits indicate that close to the relatively, more rapidly cooled margins of the intrusions, the sulphide liquid impregnated at least partially solidified intrusive rock and replaced the latter to some degree. The absence of chilled margins to all the mineralised plutons indicates only a slight thermal gradient across the intrusive contacts, sufficient to prevent marked migration of the sulphide liquid into the adjacent supracrustal rocks. Nevertheless, the ore material clearly, locally replaced the adjacent country rocks along the intrusive contacts, as indicated by the abraded gneiss xenoliths in the ores at these localities.

(4) On the basis of phase equilibria studies such as those of Naldrett & Kullerud (1967), and Misra & Fleet (1973), the sulphide-oxide melts from which the pyrite-bearing Meikjær and Nystein ores crystallised were enriched in S relative to those from which the pyrite-free Seljåsen and Østerå ores formed. The Seljåsen ores crystallised from a relatively Co-rich, ultramafic-associated sulphide-oxide melt. A suggested paragenesis for the crystallisation of the ores is depicted in Fig. 9. Misra & Fleet (1974) suggested that differing Co concentrations in pentlandites reflect different temperatures of formation, with higher temperatures of crystallisation resulting in higher

Co contents. The present study supports this observation, although the chemical variations displayed by the primary sulphides of the Bamble area deposits appear to indicate that the Co concentrations of pentlandite are also affected by the presence or absence of pyrite (and thus the degree of S-saturation of the melt) and its paragenetic position relative to pentlandite. The pentlandites in the primary, pyrite-bearing Meikjær and Nystein ores are notably Co-poor relative to those in the pyrite-free Østerå ores, and would appear to have crystallised following the formation of the coexisting, relatively Co-rich pyrite (Fig. 9). The exceptionally Co-rich nature of the pentlandite in the Seljåsen ores (and the presence of small amounts of cobaltite) is almost certainly a reflection of the ultramafic, relatively Co-rich intrusive silicate melt. The Seljåsen pyroxenite contains 91–188 ppm Co, compared to concentrations of 40–70 ppm recorded from the host norites of the Østerå, Meikjær and Nystein intrusions (Brickwood 1984). Thus, since cobaltian pentlandites appear to be restricted in occurrence to ores segregated from ultramafic melts, it would appear that the Co-contents of pentlandites (in orthomagmatic Fe-Cu-Ni sulphide ores) also reflect the compositional characteristics of the associated intrusive magmas in addition to the local bulk S content of the sulphide mass and temperature of crystallisation.

(5) Retention of primary sulphide assemblages in some of the annealed ores suggests that locally, within relatively impermeable pockets, the bulk composition of the sulphide masses remained stable during metamorphism. In contrast, the pyrite-rich and S enriched nature of the metamorphosed ores at Meikjær and Nystein suggest that these ore bodies underwent bulk metal (and particularly Fe) depletion during recrystallisation, the loss of Fe evidently contributing to the formation of abundant secondary magnetite and chlorite reaction rims in the amphibolised host rocks. The S-poor nature of the country gneisses adjacent to the Meikjær and Nystein deposits suggests that sulphurisation of the ore bodies is unlikely to have occurred during Sveconorwegian metamorphism.

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