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Mineral parageneses of the sulphide ore deposits of Bergslagen metallogenic province: I. Ni-Cu deposits of southern Sweden

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Abstract

The abandoned Ni-Cu ore deposits of southern Sweden are associated with Proterozoic mafic intrusions. Their mineralogy is similar to that of Sudbury-type deposits. The dominant primary sulphides are: pyrrhotite or pyrite, pentlandite, chalcopyrite and sphalerite. Pentlandite in ores with primary pyrite has a high Ni/Fe ratio and is associated with millerite and siegenite. Secondary minerals include pyrite after pyrrhotite, bravoite replacing secondary pyrite, violarite after pentlandite. There is strong evidence that the formation of the observed violarite took place on the mine dumps during the last 40 years.

Introduction

Paragenetic investigations on sulphide occurrences of the Proterozoic metallogenic province of Bergslagen in southern Sweden were carried out in the period 1973–1986 as part of a combined research and educational project for ore-geology students of the Free University in Amsterdam. Traditionally these mineralizations were classified into four types according to their metal content and their petrogenetic position:

1. Pb-Cu-Zn ores in supracrustal rocks (Falun and Åmmeberg types),
2. W-Mo-Cu ores possibly related to acid palingenetic intrusions (Hörken and Yxsjöberg types),
3. Mo-Bi mineralization associated with pegmatites,
4. Ni-Cu ores in mafic intrusions

The present investigations on 242 occurrences revealed that only the Ni-Cu ore deposits represent a distinct class in terms of mineral parageneses, whereas the traditional classification should be radically revised for the other deposits (Zakrzewski, in prep.).

Nickel-copper sulphide ore deposits of southern Sweden provided a substantial amount of the world nickel supply in the early years of its industrial application. In the 1880s the Swedish mines were shut down because of the discoveries of ore deposits in New Caledonia and Canada. The war economy of 1914–1918 and 1939–1945 brought on the re-opening of the old mines and encouraged further exploration activities. The total production of Ni ores in southern Sweden was about 100 000 t containing 0.6–3.5 wt.% Ni, which yielded about 2000 t of metallic Ni (Grip, 1961). Almost 60% of it came from the Kleva mine in Jönköping County (actually outside the Bergslagen province), about 35% from the Kuså and Slättberg mines in Kopparberg County; a dozen of smaller mines made up the balance.

Occurrences

Geological information accumulated in the years of production and during exploration activities was summarized by Tegengren (1924), Grip (1961) and Nilsson (1984). Most Ni-Cu mineralizations of southern Sweden occur disseminated in Proterozoic gabbroid intrusions. Massive occurrences are known from the Kleva, Ruda, Frustuna and Slättberg deposits. At Kleva a central massive ore with 70–90 vol.% sulphides passes gradually into a disseminated type with 30–50 vol.% sulphides. The most favourable position for concentration of sulphides in the mafic intrusions seems to be at contacts with more leucocratic rocks: assimilated metasediments at Kleva, granites at Kuså, Gaddbo and Frustuna, and 'acid schlieren' in Ekedal (Grip, 1961). The Frustuna and Slättberg deposits are bound to altered diabases of different ages. The chemical composition of the ores, particularly the relatively high Cu/Cu+Ni ratio between 0.15 and 0.57 with an average of 0.44 (Nilsson, 1984), is consistent with the ratios observed in other deposits associated with mafic rocks (Naldrett & Cabri, 1976).

The ore mineralogy of Ni-Cu sulphide deposits of southern Sweden was investigated by Lindroth (1920) who documented the presence of pentlandite and by E. Dahlström (unpublished reports from 1941–1943, *vide* Grip 1961) who along with the most common sulphides also recognized a mineral from the linnaeite group and bravoite in ores from Kuså. This paper gives results of optical and microprobe investigations on 35 samples collected on the dumps and on drill-core specimens from Saxe and Kuså mines kindly provided by the Boliden Mineral AB. The investigated localities include the largest mines as Kleva, Kuså and Slättberg, small mines of Uvberget and Saxe (Sjögruvan) in the Smedjebäcken area, Ruda in Östergötland

Table 1. Ore minerals of the Ni–Cu sulphide deposits of southern Sweden.

	Kleva	Frustuna	Ruda	Stöpsjön	Gåstjärn	Ekedal	Uvberget	Saxe	Kuså	Slättberg
pyrrhotite	++	++	++	++	++	++	++	++	++	++
pentlandite	++	++	++	+	+	++	+	+	+	+
chalcopyrite	++	++	+	++	++	+	+	++	++	+
pyrite	+	+		+	+		+	++	+	++
sphalerite	+	+	+		+			+	+	+
siegenite	?							+	+	?
linnaeite									?	
cobaltite									?	
millerite								+		
violarite	+	+	+			+	+	+	++	+
bravoite				?				+	+	+
mackinawite	+				+			+	+	
bornite									+	
molybdenite					+					
graphite							+			
covellite				+						
marcasite	+		+	+	+		+			+
galena										++
native Bi										+
chromite									+	
magnetite	+					+			+	+
ilmenite	+	+	++		+		+	+	+	++
rutile	+	+	+	+		+	+	+	+	
goethite				+	+		+			
hematite	+		+							

County, Ekedal in Västmanland County, Frustuna in Södermanlands County, as well as two small prospects in the Filipstad area: Gåstjärn and Stöpsjön 'mines'. The ore minerals from these localities are listed in Table 1.

Mineralogical notes

Pentlandite is the most characteristic mineral of the Ni-Cu-Fe sulphide paragenesis. It occurs in two typical textural varieties. Firstly as granular chain-like veinlets and single grains up to several millimeters in diameter. They are interstitial between the pyrrhotite grains. The second variety consists of flame-like minute inclusions in pyrrhotite localized at grain boundaries or along cracks of pyrrhotite. The coarse grains of pentlandite frequently display cataclastic structure which accelerated the formation of violarite (Figs 1 and 2). Unaltered coarse-grained pentlandite was observed only in samples from drill cores from Kuså and Saxe. The microprobe analysis of pentlandite associated with pyrite and millerite from the Saxe mine (Table 2, no. 1) shows a higher Ni/Fe ratio than in pentlandite associated with pyrrhotite (Table 2, no. 2).

It should be mentioned that pentlandite was found as a minor constituent of copper-cobalt ores of Riddarhyttan and Tunaberg (Ödman, 1933) and in copper ores of Solstad (this study).

Pyrrhotite is, in most of the deposits, the dominant and the oldest sulphide. It occurs as aggregates of polygonal grains. The oxidation of pyrrhotite leads to the formation of bird's-eye textures and if more advanced, to replacement by pyrite and marcasite, or in some cases by pyrite-magnetite intergrowths. Pyrrhotite from Kuså contains up to 0.8 wt. % Ni in solid solution (Table 2).

Pyrite is a major constituent of altered ores in which it forms irregular grains replacing pyrrhotite and veinlets and infillings of small cracks in other minerals. This secondary pyrite has a porous appearence and may show darker *bravoite*-like zones enriched in Ni (Table 2), nos. 10, 11).

Primary pyrite has only been observed in ores from Saxe, in which it forms euhedral to subhedral grains. The grains are optically zoned with darker bravoite-like zones slightly enriched in Ni and/or Co (Table 2, nos. 6, 7, 8). Numerous inclusions have been observed in pyrite. They are monomineralic with chalcopyrite or pyrrhotite, or polymineralic with pentlandite-pyrrhotite, chalcopyrite-penlantdite, chalcopyrite-pyrrhotite, chalcopyrite-mackinawite, millerite-siegenite and millerite-pentlandite-siegenite.

Chalcopyrite is the main Cu-bearing mineral in the Ni-Cu ores. It occurs interstitialy within pyrrhotite, and as veinlets and stringers penetrating both pyrrhotite and pentlandite. Chalcopyrite locally forms exceptional concentrations. At Kleva massive chalcopyrite ore was mined in the upper part of the deposit (Grip, 1961). Massive up to several centimeters thick concentrations of chalcopyrite were observed in ores from Slättberg. They contain round inclusions of silicates up to several millimeters in diameter, and microscopic deformed stars of sphalerite and deformed grains of ilmenite. Replacement of ilmenite by chalcopyrite resulted in a myrmekitic intergrowth with rutile (Fig. 4A, B). In four localities chalcopyrite is associated with *mackinawite* and only at Kuså with *bornite* (Table 1).

Millerite was observed only in ores with primary pyrite in the Saxe deposit. It occurs as small droplets in pyrite and as intergrowths with pentlandite (Fig. 3). Electron-microprobe analysis (Table 2) shows traces of Fe, Cu and Co in millerite.

Siegenite was observed in the millerite-bearing ores from the Saxe deposit as a minor constituent of the primary assemblage. Electron-microprobe analysis of siegenite (Table 2) gives a nickel-rich variety with an idealized formula $(Ni, Fe)_2CoS_4$. Siegenite from Kuså is richer in Co and Fe (Table 2, No. 16). It is probable that the mineral identified microscopically as linnaeite in Kuså by Dahlström *vide* Grip (1961) is siegenite as well.

Violarite $(Ni, Fe)_3S_4$ occurs in all samples collected on the mine dumps but absent in the specimens from drill cores. It is formed by alteration of pentlandite. The replacement occurs along cracks, cleavage and grain boundaries. The small flame-like inclusions in pyrrhotite are protected against weathering and violarite developed only on the margins of pyrrhotite grains and along the cracks

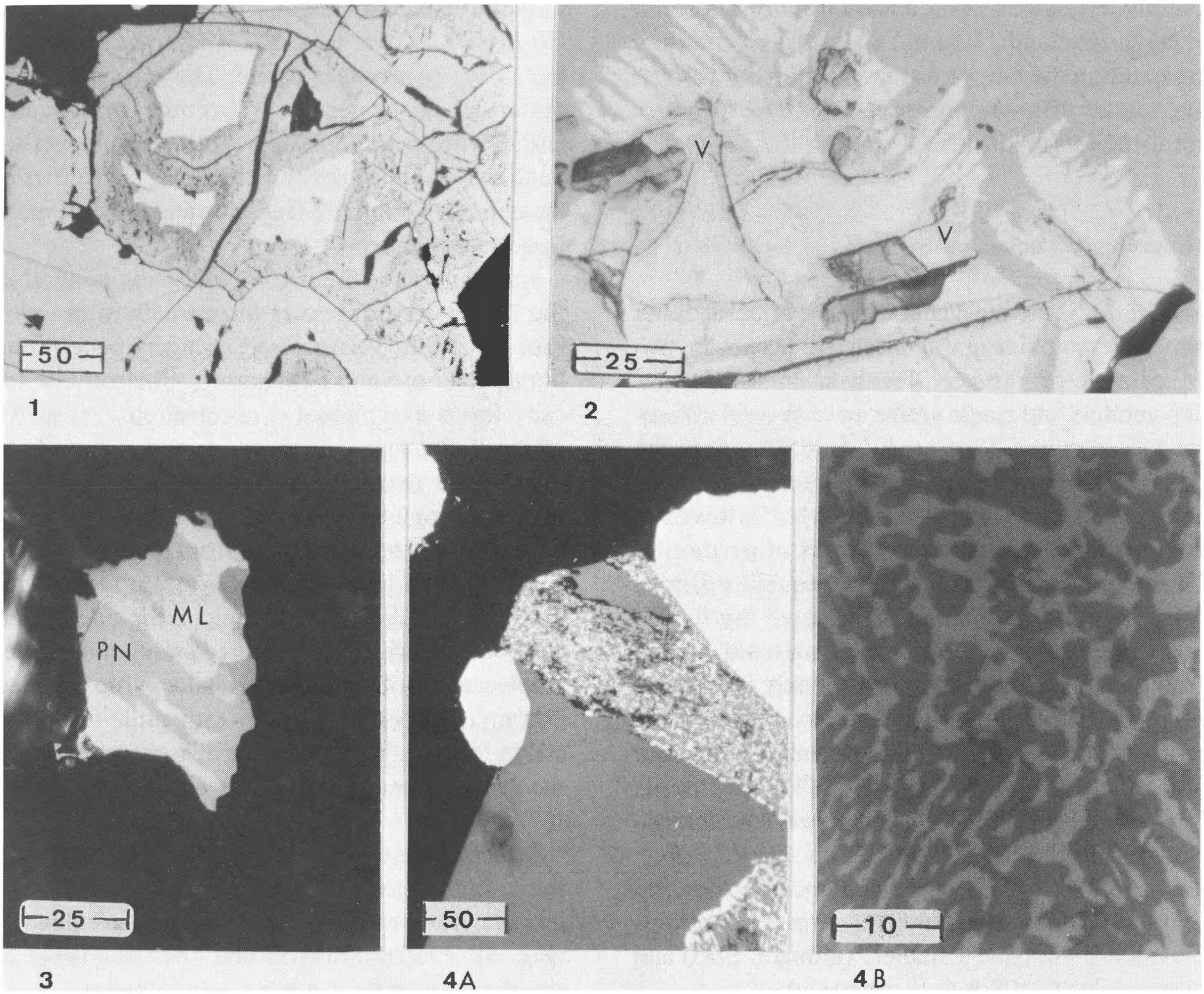

Fig. 1–4. Microphotographs of sulphide minerals from southern Sweden. Reflected light. Oil immersion. Scale bars indicate micrometers. *Fig. 1.* Relict pentlanddite in violarite. Kuså mine. *Fig. 2.* Granular pentlandite with flame-like overgrowths. Formation of violarite (V) occurs along grain boundaries and cracks. Ruda mine. *Fig. 3.* Millerite (ML) with pentlandite (PN). Saxe mine. Nickols partly crossed. *Fig. 4A.* Replacement of ilmenite by rutile with chalcopyrite. Ruda mine. *Fig. 4B.* Myrmekitic intergrowths of rutile and chalcopyrite. Ruda mine.

(Fig. 2). The porous nature of violarite resulted in typically low totals of the electron-microprobe analyses (Table 2). They indicate a slight enrichment of Co in violarite from Kuså compared to the average Co/Co+Ni ratio of 0.08 in ores from Kuså and Slättberg (Nilsson, 1984).

Sphalerite is a relatively common associate of chalcopyrite in the primary sulphide assemblage. At Slättberg sphalerite occurs in higher amounts together with *galena* and *native bismuth*. Brecciation of the Ni-Cu ores and the replacement of pyrrhotite by galena indicate that the galena-sphalerite-bismuth assemblage represents a younger phase of mineralization.

Isolated grains of *molybdenite* were observed in the Gåstjärn prospect. Baker *et al.* (1988) suggest that molybdenite belongs together with *scheelite* to a younger paragenesis. Sparse *graphite* occurs at Uvberget.*

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* *Note added in proof*: Additional microprobe investigations revealed the presence of sperrylite ($PtAs_2$) in ores from Kuså.

Oxides in the Ni-Cu sulphide deposits of southern Sweden are represented by chromite, chromian magnetite, magnetite, ilmenite, rutile, hematite and goethite. *Chromite* was only observed in the Kuså deposit were it occurs as zoned crystals with cores of chromite and rims of chromian magnetite. *Ilmenite* is the primary Ti-bearing phase that may be replaced by *rutile* and (rare) *hematite* on the rims of individual grains or along cracks. In the Stöpsjön occurrence only rutile was observed. Intergrowths of rutile and chalcopyrite (Fig. 4) suggest a replacement of ilmenite by rutile, simultaneously with the remobilization of chalcopyrite.

Genetic considerations

The mineral assemblage and their textural relations indicate that the primary oxides and sulphides incorporated in the mafic rocks were affected by retrograde metamorphism and by superficial weathering. A schematic presentation of the mineralogical evolution of the Ni-Cu ores of southern Sweden is given in Table 3.

An early oxide assemblage was followed by sulphide mineralization. In most cases the sulphide paragenesis is represented by a pyrrhotite-pentlandite assemblage. It is only in ores from the Saxe mine that primary pyrite is associated with pentlandite and millerite. The primary nature of this association is indicated by the high Ni/Fe ratio of pentlandite (Table 2) typical for pentlandite co-existing with pyrite and with millerite (Harris & Nickel, 1972). The pyrrhotite and the pyrite assemblages represent two varieties of the same phase of crystallization. In both cases the iron sulphides are the oldest phases followed by pentlandite and chalcopyrite with inclusions of sphalerite. The paragenetic position of millerite and siegenite is between pentlandite and chalcopyrite.

The galena-sphalerite-bismuth assemblage observed at Slättberg is foreign to the Ni-Cu ores as indicated by the brecciation and replacement phenomena. Its provenance is not clear. It is possible that it originated from a remobilization of an outside source. The influence of remobilization on the primary minerals also resulted in the formation of massive concentrations of chalcopyrite, the alteration of pyrrhotite into secondary pyrite and by the formation of mackinawite in chalcopyrite. Most probably the remobilization is related to retrograde metamorphism. The lack of cubanite and the occurrence of secondary magnetite-pyrite intergrowths indicate relatively low-grade metamor-

Table 2. Electron-microprobe analyses of Ni–Fe–Co sulphides from nickel-copper ores of southern Sweden in wt. %.

No	Mineral	Locality	Ni	Fe	Co	Cu	S	Total	Analyst*	Remarks
1	pentlandite	Saxe	39.4	27.0	0.53		31.7	98.63		
2		Kuså	32.9	29.8	4.17		33.1	99.97	WJL	
3	violarite	Kuså	19.4	32.5	4.63	0.05	40.7	97.28	WJL	
4		Slättberg	23.9	30.0	2.13	0.12	39.5	96.06	WJL	incl. 0.41 wt.% As
5		Slättberg	26.2	27.8	2.84	–**	39.9	96.74	WJL	
6	pyrite-bravoite	Saxe	0.3	42.2	3.2		52.4	98.1		dark zone, max. Co
7		Saxe	2.9	42.3	n.d.		53.0	98.2		dark zone, max. Ni
8		Saxe	0.8	44.4	0.4		54.3	99.9		light zone
9		Slättberg	0.5	45.5	–	–	49.6	95.6	WJL	
10		Slättberg	4.7	42.2	–	–	52.6	99.5	WJL	
11		Slättberg	9.5	37.5	0.2	0.07	52.8	100.07	WJL	
12		Kuså	–	46.3	–	–	53.0	99.3	WJL	
13	pyrrhotite	Kuså	0.8	59.8	–	–	39.6	100.2	WJL	
14	millerite	Saxe	60.3	2.7	0.43	0.59	33.1	97.12		
15	siegenite	Saxe	29.3	5.9	19.6		42.7	97.5		
16		Kuså	24.9	10.7	23.4	–	42.5	101.5	WJL	negative Pt, Sb, As

* WJL – W.J. Lustenhouwer, others – author; ** – not detected.

phism. The solutions generated at the postmagmatic stage affected some pre-existing minerals: chromite was replaced by chromian magnetite, ilmenite by rutile, and at the lowest temperatures the Ni-rich solutions formed bravoite-like zones on secondary pyrite.

Some of the bravoite zones are displaced by violarite suggesting a higher paragenetic position for bravoite. Alternatively it is possible that the Ni-bearing solutions were released during the alteration of pentlandite to violarite. Evidence for a very recent, supergene origin of violarite is provided by the fact that this mineral is present only in specimens collected on the dumps and never in sections from drill cores. The relict pentlandite shown in Fig. 1 was observed in a polished section from a specimen collected on dumps dating from the 1940s. Thus about 40 years of superficial weathering is sufficient for the replacement of more than half of the pentlandite by violarite.

Table 3. Paragenetic relations of the Ni–Cu sulphide mineralizations of southern Sweden.

Stage	Primary	Metamorphic	Supergene
phase			
I	chromite	chromian	
	magnetite I	magnetite	goethite
	ilmenite	rutile	
		hematite	
II A	pyrrhotite	pyrite II	
		marcasite	goethite
		magnetite II	
	pentlandite	bravoite	violarite
	chalcopyrite I	chalcopyrite II	covellite
		mackinawite	
		bornite	
	sphalerite I		
II B	pyrite I		
	bravoite I		
	pentlandite	bravoite II	
	millerite		
	siegenite		
	chalcopyrite I		
	sphalerite I		
III		sphalerite II	
		galena	
		native bismuth	

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