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Sphalerite geobarometry of some metamorphosed sulphide ore deposits in Finland

by Ragnar Törnroos

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SPHALERITE GEOBAROMETRY OF SOME METAMORPHOSED SULPHIDE ORE DEPOSITS IN FINLAND

by
RAGNAR TÖRNROOS

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The sphalerite geobarometer has been applied to 14 metamorphosed sulphide ores in Proterozoic schists of Finland.

In the Vihanti ore zone, the Outokumpu area and the Tampere schist belt the model pressures appear to be very similar i.e. 5–7 kb. An exceptional low model pressure of 1–2 kb was shown in the northwestern part of the Vihanti ore zone, in the prospect at Pattijoki. Low model pressures of 1.4–3 kb were also encountered in some parts of the Sotkamo prospect whereas in the prospect as a whole the values vary from 1.4 to 6.3 kb. In the Orijärvi–Kimito leptite belt the model pressures of the prospect at Attu were 3.4 kb and in the ore deposits at Aijala–Metsämonttu 4.8–5.8 kb. At Riikonkoski in the Kittilä greenstone belt the sphalerite geobarometer failed. Previous measurements from Pahtavuoma (4.0 ± 1.5 kb) may, however, also be applied to Riikonkoski.

The clustering of re-equilibrated sphalerites at a lower iron content, suggests that a second hydrothermal event at a temperature below 300°C took place in the Vuohtojoki–Vihanti region within the Vihanti ore zone.

Key words: geologic barometry, sphalerite, mineral deposits, metamorphism, P-T conditions, Proterozoic, Finland.

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INTRODUCTION

One of the major challenges facing petrologists is how to develop methods that can be used to estimate the temperature and pressure at which the minerals in rocks have crystallised.

During the last two decades, considerable attention has been paid to geobarometry and geothermometry. Most of the geobarometers are based on elemental partitioning between silicate or oxide mineral pairs in rocks of low- to high-metamorphic grade. Only a few deal with sulphides, and the results obtained are not always encouraging. Hence, it has been difficult to estimate the pressure conditions that prevailed during the metamorphism of sulphide ores.

Within its limitations the sphalerite geobarometer (Scott & Barnes 1971) has proved to be a very useful tool for the sulphide petrologists. The refractory character of sphalerite makes this geobarometer especially useful in determining the pressure of metamorphism in ore deposits.

Most Finnish sulphide ores are metamorphosed, and they should therefore be suitable for studies related to experimental data on the system Zn-Fe-S and to the application of the sphalerite geobarometer.

The aim of this study is to apply the sphalerite geobarometer to Finnish sulphide deposits and to compare with each other the pressure of metamorphism (peak of metamorphic pressure) of the various sulphide ore deposits and zones in Finland. Of the 15 occurrences studied, all but one (Ylöjärvi) are of the massive strata-bound type.

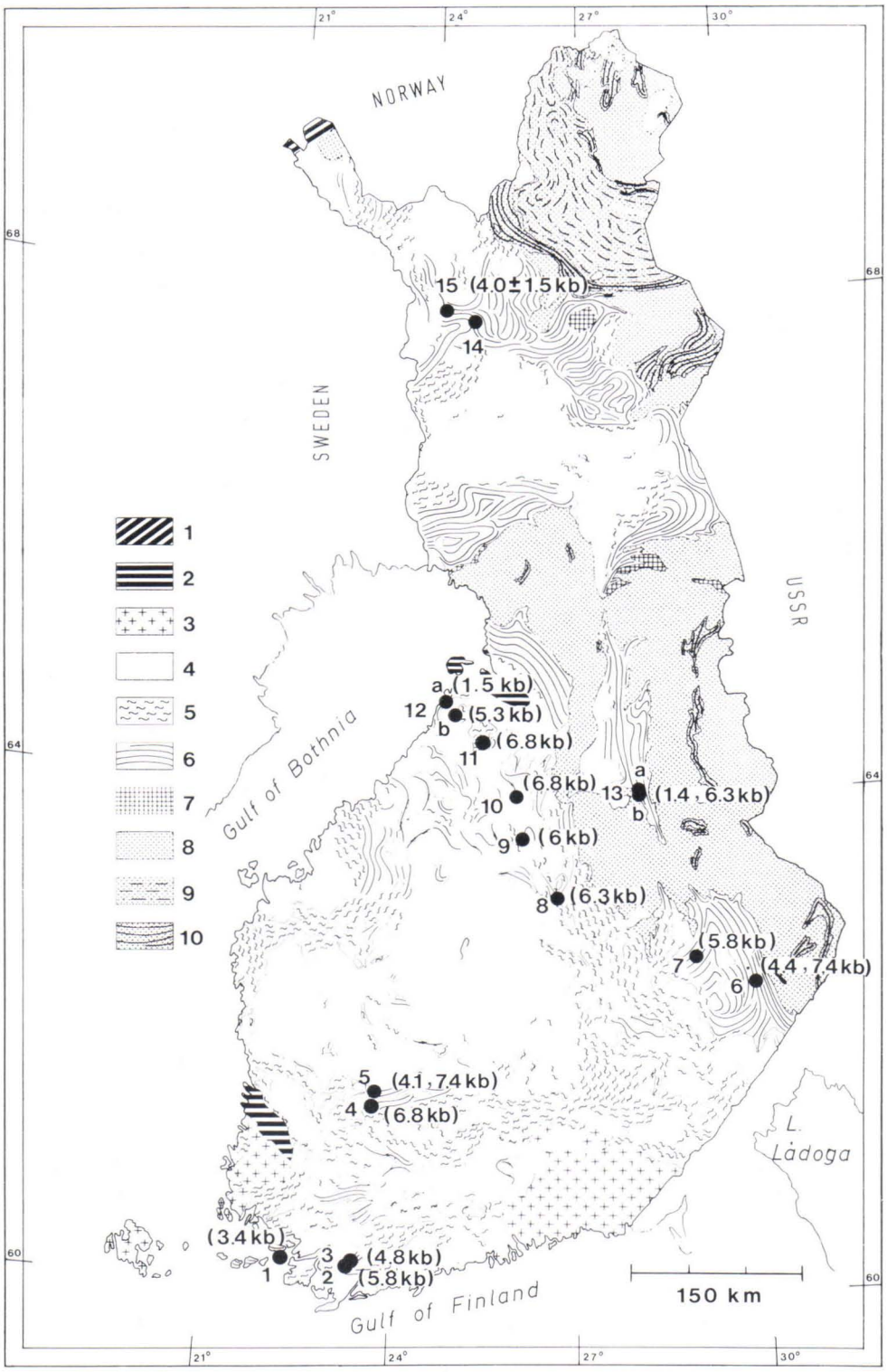
THE MAIN GEOLOGICAL FEATURES

General geology

With the exception of a minute Caledonidic formation in the northwestern corner of Finnish Lapland and some small alkaline rocks and carbonatites in northern Finland that belong to the Kola alkaline province (~ 300–500 Ma) (Vartiainen & Woolley 1974), the bedrock in Finland (1300–3100 Ma) is of Precambrian age and is part of the Baltic or Fennoscandian shield. The Finnish Precambrian has been reviewed by Simonen (1960, 1971 and 1980) and Eskola (1963). According to these authors, the Finnish bedrock is composed predominantly of two crustal provinces: the Archean basement complex and the Proterozoic rocks.

The oldest part (2600–3100 Ma), the Archean basement, covers large areas of eastern and northeastern Finland (Fig. 1). The rocks consist of: 1) extensive areas of granite gneisses; 2) long, narrow schist and gneiss zones, including volcanites of greenstone belt type, which are surrounded and penetrated by granitoidic rocks of about the same age; 3) the granulite area, a high grade metamorphic region in the northeastern area of the country. The granulites have been subjected to metamorphism by the younger Svecokarelidic orogeny.

Stabilisation of the basement was followed by igneous activity resulting in the emplace-


21°
24°
27°
30°
68
64
60
NORWAY
SWEDEN
USSR
Gulf of Bothnia
Gulf of Finland
L. Ladoga
15 (4.0±1.5 kb)
14
a (1.5 kb)
12
b (5.3 kb)
11 (6.8 kb)
10 (6.8 kb)
13 a (1.4, 6.3 kb)
b
9 (6 kb)
8 (6.3 kb)
7 (5.8 kb)
6 (4.4, 7.4 kb)
5 (4.1, 7.4 kb)
4 (6.8 kb)
(3.4 kb)
1
3 (4.8 kb)
2 (5.8 kb)
1
2
3
4
5
6
7
8
9
10
150 km

ment of the carbonatite complex of Siilinjärvi about 2600 Ma ago and the Early Proterozoic layered mafic intrusions about 2450 Ma ago (Patchett *et al.* 1981).

The Archean rocks disappear to the southwest under the Proterozoic rocks where they were partly remobilised during the Svecokarelidic orogeny (2200–1800 Ma). The main phase of folding and metamorphism occurred about 1900–1800 Ma ago. This orogeny generated two different schist zones: The Karelidic and the Svecofennidic schist zones.

The Karelidic schists extend from southeastern Finland to Lapland and constitute an epicontinental-miogeosynclinal facies series. The epicontinental lithosome, known as the Jatulian sequence, consists of quartzites and mafic volcanites. This sequence is overlain by the Kalevian schists composed of geosynclinal metasediments, phyllites, mica schists and mica gneisses of flysch type. The oldest section of the Karelides, the Lapponium in northern Finland, is composed of mafic volcanites and metasediments.

The Svecofennidic schist zone of southern and western Finland consists mainly of metasediments and metavolcanites of eugeosynclinal facies type. During the Svecokarelidic orogenic movements the Karelidic and the Svecofennidic schists were widely penetrated by orogenic plutonites, mainly granodiorites and granites.

The Svecokarelidic orogeny was followed by a period of cratonisation, during which the crust was intruded by rapakivi granites (1700–1550 Ma) and diabases. The youngest group of the Precambrian in Finland comprises unmetamorphosed Jotnian sediments (1300–1400 Ma) deposited in graben structures, and Postjotnian diabases (1250–1275 Ma).

Ore geology

The majority of the Finnish economic ore deposits are associated with the Proterozoic metasediments and plutonic rocks. Some small iron showings without economic value, the nickel occurrences at Suomussalmi and Kuhmo and the small molybdenum deposits at Mätäsvaara and Aittojärvi, are the only ones found in the Archean basement (Kahma 1973, 1978; Kahma *et al.* 1976; Kokkola & Penttilä 1976 and Frietsch *et al.* 1979).

The Proterozoic pre-Svecokarelidic mafic layered intrusions, which extend discontinuously from Kemi in the west to the Soviet border in the east, contain some interesting deposits and showings (Piirainen *et al.* 1974): The Kemi chromite ore in an ultramafic layer in the western end of the intrusion belt; the Mustavaara vanadium deposit in a magnetite gabbro; the PGE-showing at Konttijärvi (Vuorelainen *et al.* 1982); and the low-grade nickel-copper showings close to the basal contact of the Porttivaara intrusion in the

Fig. 1. Main crustal units of the Finnish bedrock with location of the mineral deposits investigated and in brackets the mean model pressures of the sphalerite geobarometer. Key: 1, Caledonian schists; *Middle Proterozoic rocks:* 2, Jotnian sediments; 3, rapakivi granites; *Early Proterozoic formations:* 4, plutonic rocks; 5, migmatites; 6, schist belts; 7, layered mafic intrusions; *Archean rocks;* 8, granite gneisses; 9, granulite complex; 10, schist belts. After Kahma *et al.* (1976).

1. Attu
2. Aijala
3. Metsämonttu
4. Nokia
5. Ylöjärvi
6. Hammaslahti
7. Outokumpu
8. Säviä
9. Pyhäsalmi
10. Vuohtojoki
11. Vihanti
12a. Pattijoki
b. Pattijoki, Ylipää
13a. Sotkamo, Kolmisoppi
13b. Sotkamo, Kuusilampi
14. Riikonkoski
15. Pahtavuoma

eastern part of the mafic belt. The Koitelainen cromite deposit in central Lapland belongs to the same group.

The majority of the deposits are, however, sulphide ores. Some nickel-copper sulphide deposits are also associated with mafic and ultramafic plutonic rocks, whereas most of the copper, zinc, cobalt and lead sulphide ores are located in the schists.

According to Kahma (1978), about 80–90 per cent of the mined sulphide ores and known reserves in Finland are located in deposits in the »Main Sulphide Ore Belt» (Kahma 1973). Kahma (*op. cit.*) includes the Vihanti ore zone, the Outokumpu ore district and the Kotalahti nickel-copper ore zone in this belt which runs roughly along the boundary between the two main crustal provinces of the Finnish Precambrian, the Archean and the Proterozoic rocks, from Lake Ladoga in the east to the Gulf of Bothnia in the west.

This boundary also marks the position of a major shear zone characterised by wide drag folds upon steep axes and by traces of repeated brecciation (Tuominen *et al.* 1973).

Some Cu-Zn sulphide deposits occur in the Kittilä greenstone complex, which is part of the Karelidic schist zone in northern Finland. According to Gaál *et al.* (1978) and Silvennoinen *et al.* (1980), the Kittilä greenstone belt is Archean in age. Several massive stratabound Cu-Zn-Pb sulphide deposits and showings are encountered in the Orijärvi area in the Svecofennidic schist zone in southern and western Finland (Latvalahti 1979). In the Ahlainen–Kylmäkoski nickel belt the deposits are associated with ultramafites (Häkli *et al.* 1979). The Korsnäs lead ore has been interpreted as a carbonatite deposit (Isokangas 1978) and the Virtasalmi copper ore deposit represents a deposit of the contact pneumatolytic type (Hyvärinen 1969).

The sulphide ores of the Outokumpu district are associated with black schists, serpentinite, carbonate and quartz rocks. This folded and narrow zone forms an intercalation in the Svecokarelidic micaceous schists (Huhma & Huhma 1970). The Sotkamo Ni-Cu-Zn deposits occur north of the Outokumpu district in the Kainuan schist belt. These are large but low-grade sulphide impregnation deposits in black shists and black skarns (Aho 1979, Ervamaa & Heino 1980).

THEORETICAL BACKGROUND TO THE SPHALERITE GEOBAROMETER

Evolution of the Zn-Fe-S system as a geobarometer

Sphalerite has the ability to take up appreciable amounts of FeS in solid solution. Pure colourless sphalerite is very rare in nature. Most sphalerites contain iron and traces of other elements and hence they may occur in divers colours. It has also been shown that the colour of sphalerite is dependent on the stoichiometry (Craig & Scott 1974). Darker sphalerites may not necessarily be rich in iron, rather they may be deficient in total metal.

After investigating the system Zn-Fe-S, Kullerud (1953) proposed its use as a geothermometer. Provided that equilibrium conditions exist between free pyrrhotite and the amount of FeS dissolved in the sphalerite lattice at the time of formation, the amount of FeS in the sphalerite will be dependent only on the temperature and pressure. Extensive use has since been made of the sphalerite geothermometer, but not, however, without problems, and some peculiar findings have

resulted in additional investigations and refined data. Thus, Barton and Kullerud (1957, 1958) showed that the phase relations are highly complicated, and later, Barton and Toulmin (1966) pointed to serious errors in the phase diagrams published for the system Fe-Zn-S. They also stated that the system is much more sensitive to pressure than was earlier supposed and that it could possibly be used as a geobarometer.

In 1967, Boorman pointed out that the solvus of sphalerite in equilibrium with pyrite and pyrrhotite at normal pressure is vertical at a constant composition of 20.8 ± 0.5 mole-% FeS from 580°C to the hexagonal-monoclinic pyrrhotite inversion temperature.

Other investigations showed disagreements as to the FeS content of sphalerite in the three-phase assemblage sphalerite-pyrite-pyrrhotite (Barton & Toulmin 1966, Scott & Barnes 1967, Chernyshev & Anfilogov 1968, Chernyshev *et al.* 1968 and Einaudi 1968).

Scott and Barnes (1971) discussed complications in the use of the system Fe-Zn-S as a geothermometer. According to them, »the FeS content of sphalerite, even in equilibrium with pyrrhotite, is not useful in geothermometry without data on the sulphur fugacity f_{S_2} at the time of deposition». Instead they adopted and extended the theory, first developed by Barton and Toulmin (1966), of the sphalerite geobarometer. They give experimental isobars for the three-phase system sphalerite – pyrite – pyrrhotite in the temperature range 300°–700°C.

These data have since been refined (Scott 1973, 1976, Brown & Lovering 1973, Scott *et al.* 1977). Lusk and Ford (1978) extended experimentally the sphalerite geobarometer to 10 kb and found sphalerite at this pressure to have a constant composition of 10.3 ± 0.5 mole per cent FeS from 420° to 700°C. Scott (1976) described briefly the theory behind the sphalerite geobarometer: »The FeS content of sphalerite is a function of temperature (T), pressure (p) and FeS activity (a_{FeS}). The a_{FeS} is not necessarily dependent on p and T, and for geobarometry must be buffered by one or more iron sulphide phases».

Later (Scott *et al.* 1977) demonstrated that, theoretically hexagonal pyrrhotite alone can act as a buffer because the relations between a_{FeS}, pyrrhotite composition (X^{po}_{FeS}), and T are known and are independent of p (Toulmin & Barton 1964). In practice, pyrrhotite can undergo compositional changes on cooling (Genkin 1971), which, together with the high value of the T coefficient of the a_{FeS}–X^{po}_{FeS} relations usually makes such a geobarometer of little use. However, when a_{FeS} is buffered by divariant assemblages of the Fe-S system, such as pyrite + pyrrhotite, retrograde variation in pyrrhotite composition is not important.

In 1977 Scott *et al.* assumed that the sphalerite + pyrrhotite assemblage could be used as a geobarometer in metamorphic terrains if: 1) temperatures of sulphide equilibration during metamorphism were known, and 2) one could be sure that the pyrrhotite had not been subjected to retrograde compositional alteration.

Brown *et al.* (1978), however, demonstrated that sphalerite grains in metamorphic terrains are often heterogeneous, mostly with chalcopyrite exsolutions. These sphalerites give a wide range of pressures, and the exsolutions are probably an indication of reequilibration of the system. In the opinion of Brown *et al.* (*op. cit.*), the sphalerite geobarometer should therefore be used with caution if based on a few samples or on heterogeneous material.

According to equations 1 and 2 given by Barton and Toulmin (1966), contaminants may affect the geobarometer only if they enter in appreciable amounts into sphalerite or pyrrhotite and change either the partial molar volume of FeS in sphalerite ($\bar{V}^{sp}_{FeS}$) or the activity of FeS (a_{FeS}) in the system. The

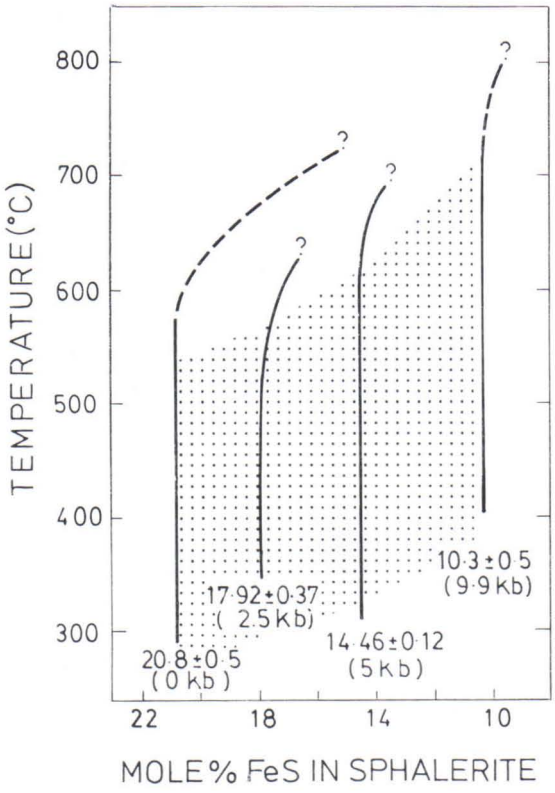


Fig. 2. T-X projection onto the FeS-ZnS join of the sphalerite + hexagonal pyrrhotite + pyrite solvus isobars. Temperature-independent portion is indicated by the shaded area. Modified after Lusk and Ford (1978).

trace amounts of cobalt and nickel in natural pyrrhotites and the solid solution of manganese and cadmium in sphalerite have been shown to have no measurable effect on the pressure dependence of FeS in sphalerite (Craig & Scott 1974). Of the remaining elements, only copper presents a problem in the use of the sphalerite geobarometer (Hutchison & Scott 1981).

Natural sphalerites normally contain less than 0.5 wt per cent copper in solid solution (Wiggins & Craig 1980), but sphalerite commonly has what appears to be chalcopyrite exsolutions, suggesting a more extensive solid solution between sphalerite and chalcopyrite at higher temperatures (Hutchison & Scott 1981). According to them, the question is whether or not the dissolved copper and exsolved chalcopyrite have affected the sphalerite – pyrite – pyrrhotite phase relations as applied to geobarometry.

Hutchison and Scott (1981) found that the presence of chalcopyrite in ores should not affect the sphalerite geobarometer over its temperature-independent portion, because the solubility of copper in sphalerite is low below 650°C in the four-phase assemblage sphalerite-chalcopyrite-pyrite-pyrrhotite. Sphalerite that is heterogeneous in FeS and which contain chalcopyrite blebs in excess of the amount that can reasonably be accounted for by an equilibrium process of solubility and subsequent exsolution should be avoided in applying the geobarometer.

Fig. 2 shows the isobars (Lusk & Ford 1978) of sphalerite composition along the pyrite +

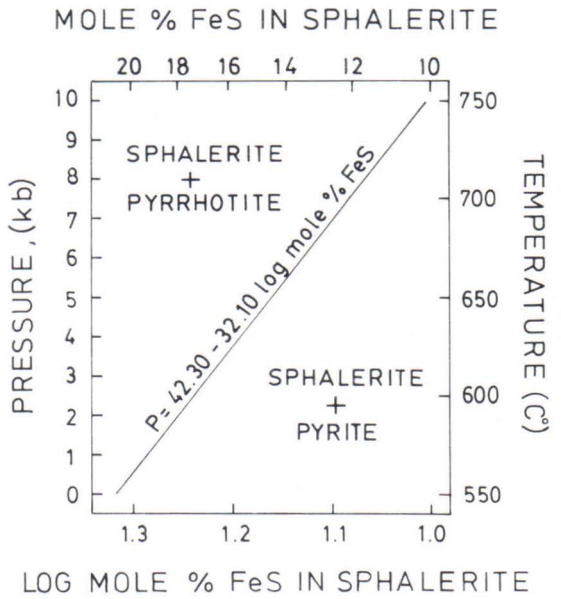


Fig. 3. Pressure-log mole per cent FeS projection onto the FeS-ZnS join of the temperature-independent portions of the sphalerite + pyrite + hexagonal pyrrhotite solvus isobars. Temperature scale gives the upper limit of the temperature-independent portion. After Hutchison and Scott (1981).

hexagonal pyrrhotite buffer. For the temperature-independent region of the sphalerite geobarometer, Hutchison and Scott (1981) have expressed the pressure dependence (in kb) of the composition of sphalerite in equilibrium with pyrite and pyrrhotite as p = 42.30−32.10 log mole-% FeS (Fig. 3).

The Fe-S system

One problem in applying the results of the analyses to the geobarometry of the sphalerite – pyrite – pyrrhotite assemblage is the ascertaining of whether or not the bulk composition of the nonrefractory pyrrhotite has changed in response to postmetamorphic alteration events.

In Fig. 4 a simplified picture of the phase relations of the Fe-S system is given. Although detailed phase relations of the system are more complex (Craig & Scott 1974, Power & Fine 1976) than shown in Fig. 4, a few pertinent features explain both the occurrence and the texture of natural pyrrhotite phase assemblages.

At high temperatures, the pyrrhotite phase field is occupied by a single solid solution, hexagonal $Fe_{1-x}S$, extending from stoichiometric FeS to compositions richer in sulphur than those of the monoclinic pyrrhotite along its solvus with pyrite. This hexagonal phase also extends to lower temperatures, but with a more restricted compositional range. With decreasing temperature, iron-rich, high-temperature pyrrhotites encounter a solvus between troilite and hexagonal pyrrhotite, whereas sulphur-rich ones either encounter a solvus separating hexagonal pyrrhotite from monoclinic pyrrhotite or intersect the solvus with pyrite forming a pyrite + pyrrhotite assemblage.

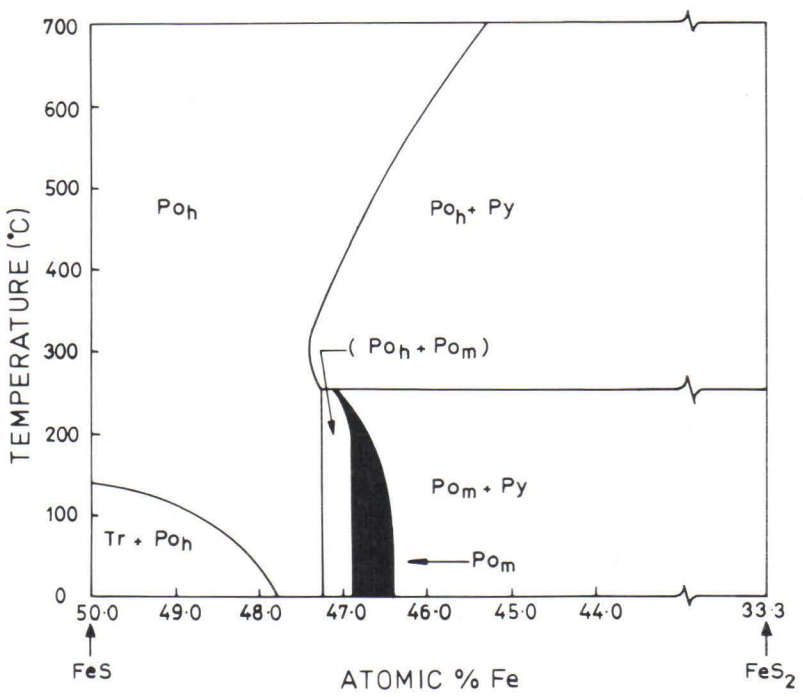


Fig. 4. Simplified relations in the central portion of the Fe-S system. Hexagonal pyrrhotite (Po_h), monoclinic pyrrhotite (Po_m), pyrite (Py), troilite (Tr). Modified after Scott *et al.* (1977).

Postmetamorphic alteration of iron sulphide has been noted (e.g. Desborough & Carpenter 1965, Nickel *et al.* 1974). This process may produce a variety of complex secondary metastable assemblages through the extraction of iron and/or addition of oxygen or sulphur to the primary mineral phases (cf. Einaudi 1971). In more advanced stages, oxidation and/or loss of iron leads to the formation of pyrite, marcasite, and ultimately of magnetite or hematite.

APPLICATION OF THE THEORY

Application of the sphalerite geobarometer as described in the previous chapter, is subject to some constraints. In the present study the conditions had to meet the following five criteria:

1) Sphalerite must have equilibrated with pyrite + high-temperature hexagonal pyrrhotite. Seen under the microscope, the sphalerite grains analysed should, therefore, be in mutual contact with pyrite + pyrrhotite.
2) The temperature of formation or metamorphism must be higher than the abrupt reversal in the slope of the pyrite + hexagonal pyrrhotite (265°C at 1 bar) and lower than the upper limit of the temperature-independent region (see Fig. 2).
3) Precise microprobe analyses of sphalerite are necessary. An uncertainty of ± 0.5 mole-% FeS corresponds to ± 400–500 bars.
4) Heterogeneous grains and grains that host chalcopyrite exsolutions are deleted.
5) Grains containing other elements in such amounts that the ($\overline{V}^{sp}_{FeS}$) is affected are deleted.

In the present study, Mn was excepted from the last restriction in some measurements from the manganese-rich deposits of Pattijoki and Sotkamo. This will be discussed in a later chapter.

EXPERIMENTAL

Sample selection

Most of the samples used in this study were collected from old drill cores in the ore bodies. Polished sections of the specimens were first carefully examined under the microscope for the association of sphalerite, pyrite and pyrrhotite with clear mutual boundaries. Sphalerites with abundant exsolutions of chalcopyrite were avoided. To distinguish monoclinic pyrrhotites from hexagonal ones, a thin film of a magnetic colloid was applied to the samples (cf. Scott 1974, p. 5–18). The magnetic colloid would attach itself to the magnetic monoclinic modification and under the microscope the two phases are then easily distinguishable.

Checking the structural form of pyrrhotite by X-ray diffraction is a more reliable procedure, but it was not appropriate in the present work because of the practical difficulty of picking the very small pyrrhotite grains from a polished section and X-raying them.

Microprobe analyses

The samples selected as described above were then vacuum coated with a thin layer of carbon (~ 200 Å) and analysed with a JEOL JXA-733 Super Probe. At least four points per grain were measured three times for a fixed interval of 10 sec. The background counts were collected on both sides of the line. The data were processed with a standard ZAF on-line correction program (ZAF: Z = atomic number correction coeff., A = adsorption correction coeff., F = fluorescence correction coeff.). The accelerating voltage was set at 15 kV and the probe current at 100 nA. The standards for the sphalerite measurements were natural sphalerite for Zn and Cd, natural troilite for Fe and S, natural alabandite for Mn and natural chalcopyrite for Cu. The x-ray lines used were L_α for Cd and K_α for the others.

THE SULPHIDE ORES STUDIED

The Vihanti ore zone

The Vihanti ore zone is situated in the northwestern part of the Svecokarelidic orogenic belt (cf. Fig. 1, points 8–12), which crosses Finland from northwest to southeast from the Gulf of Bothnia to Lake Ladoga. The zone is significant for its zinc deposits but it also contains copper and lead (Huhtala 1979).

Two mines, Vihanti and Pyhäsalmi, are currently operative in the area. There are also three other deposits of importance that constitute a reserve of potential ores for future use. In addition, several smaller occurrences are known in the area (Isokangas 1978).

The sulphide showings are mainly located in volcanites, although some occur in metasediments of detrital origin in which tuffite beds indicate volcanic activity. These ore deposits and showings are interpreted as massive strata-bound sulphide ores related to submarine volcanism (Huhtala 1979, Mikkola 1980).

The ore deposits and showings are characterised by the mineral associations sphalerite – pyrrhotite – pyrite – chalcopyrite – galena, pyrite – pyrrhotite, and sphalerite – chalcopyrite – galena. The mutual abundances of the sulphides vary from one deposit to another. In the NW part, especially in Vihanti, the amount of sphalerite is greater, whereas in the SE, iron- and copper-sulphides predominate.

The assemblage sphalerite + pyrite + pyrrhotite is met with in all of the deposits, however, and thus the application of the geobarometer is feasible.

According to Rouhunkoski (1968), Aho (1977) and Huhtala (1979), the bedrock, which is characterised by strongly metamorphosed sediments and volcanic schists related to the Svecokarelidic orogeny, is intruded by plutonic rocks of varying composition.

The orogeny has intensely folded and broken up the supracrustal formations into separate schist blocks, which are embedded in or surrounded by plutonic massifs. They intersect the schists and form migmatites with them (Salli 1965, Rouhunkoski 1968). Metamorphism has almost completely obliterated the primary structures of the rocks. Locally primary structures are, however, preserved, allowing the country rocks of the orebodies to be recognised as volcanogenic rocks (lavas,

tuffs, tuffites) and argillaceous sediments with tuffaceous components. These rocks, altered in the course of hydrothermal processes combined with the volcanic activity that produced the sulphide ores, were metamorphosed into sericite schists, cordierite gneisses, sillimanite gneisses and various cordierite-, garnet- and anthophyllite-bearing rocks (Huhtala 1979).

Vihanti

Lithology

The Lampinsaari ore complex (11) has been described by many authors (e.g. Mikkola 1963, Rouhunkoski 1968 and Huhtala 1979). The bedrock of the Vihanti area consists of gneisses of sedimentary or volcanic origin, and of intrusive granitic, granodioritic and gabbroic rocks. The ore complex consists of zinc, pyrite and disseminated copper ore bodies and a uranium-apatite showing. The host rocks of the sulphide ore complex (dolomite, skarn and felsic metavolcanites) form a long zone surrounded by the regionally predominant mica gneisses (Rauhamäki *et al.* 1978).

Lithologically the complex can be divided into arenaceous rocks comprising cordierite gneiss, quartzitic rocks and black schists; and into calcareous rocks, comprising dolomite and skarn rocks. Mafic and felsic dyke rocks also exist. The quartzitic rocks and black schists are currently interpreted as volcanites (Rauhamäki *et al.* 1978).

According to Rouhunkoski (1968), the cordierite gneisses are rather coarse grained and poorly foliated and they contain cordierite, quartz, plagioclase, mica (phlogopite), iron sulphides and minor K-feldspar, sillimanite, apatite, zircon, rutile and titanite. Some anthophyllite is occasionally present. Calcite and skarn minerals occur in the dolomite rock. The skarn rocks generally contain diopside and tremolite with variable amounts of quartz, plagioclase, phlogopite, carbonate, baryte and sulphides. Tourmaline, scapolite, garnet, apatite, titanite, graphite and zircon are occasionally met with, and in some varieties corundum, pleonast, forsterite, sapphirine, anhydrite and fluorite occur.

The uranium- and apatite- bearing horizon is encountered near the hanging wall of the Lampinsaari ore zone. This horizon is composed of overlapping lenticular layers of apatite-bearing dolomite and skarn, and apatite-quartz-plagioclase gneiss (Rehtijärvi *et al.* 1979).

Sphalerite geobarometry

The results of the sphalerite analyses are given in Table 1, and the FeS contents of sphalerites are presented in the form of histograms in Fig. 7. The FeS contents range from 11.7 to 13.7 mole per cent, giving a pressure estimate of 8.0 to 5.8 kb with a mean of 6.8 kb for the Vihanti ore. The coexisting minerals cordierite + sillimanite in the cordierite gneisses indicate a temperature of over 630°C (cf. Winkler 1974). According to Rouhunkoski (1968, p. 81) the temperature did not reach 700°C and the pressure was in the order of 2 kb. Rehtijärvi *et al.* (1979) show, however, that the temperature of metamorphism inside the ore was in the order of 400°C (cf. discussion on p. 26). The temperature estimated is therefore within the allowed temperature range of the sphalerite geobarometer (Fig. 5 p. 24).

Pyhäsalmi

Lithology

The Pyhäsalmi (9) ore body is conformable with its environment and occurs in a sericite schist zone of the Ruotanen schist belt (Helovuori 1979), which is a part of the Svecokarelides. The schists trend almost north-

south with either vertical or steep eastward dips. In the east the schists are bordered by a dome-like granite gneiss that is obviously a highly altered part of the Archean basement. In the west, the schists are bordered by a younger porphyric granite.

The ore deposit is composed of a massive pyrite ore that contains variable amounts of chalcopyrite and sphalerite, with galena, arsenopyrite, magnetite and fahlore as accessories. The gangue consists mainly of quartz and baryte. For a more detailed description of the massive Zn-Cu sulphide deposit and the surrounding schists see the paper by Helovuori (1979).

Sphalerite geobarometry

Unfortunately only one specimen in which the sphalerite was in triple junction with pyrite + hexagonal pyrrhotite was available. The sphalerite geobarometer failed. It gave an anomalously high pressure of > 10 kb ($\sim 4-6$ mole-% FeS), which is out of the question for this deposit and beyond the limits of experimental calibration of the barometer. On the other hand, a sphalerite grain totally encapsulated in pyrite (cf. p. 27) gave a model pressure of 6.0 kb (13.5 mole-% FeS, see Table 2).

Vuohtojoki

Lithology

According to Oivanen (1962) and Huhtala (1979), the predominant rock types are biotite-plagioclase gneiss with local hornblende-bearing parts, and leptite, which consists of a variety of volcanic material within sediments. Thin layers of volcanogenic amphibolite are also present in the zone. The plutonic rocks consist of gneissoid oligoclase granites, granites, unakites, quartz diorites and gabbros. Also present are diabase, plagioclase porphyrite, uralite porphyrite and granitic pegmatite dykes.

The ore deposits (10) occur in alteration zones in the sedimentogenic rocks. The main minerals in the alteration zone are quartz, cordierite, biotite, anthophyllite, sillimanite, garnet, andalusite and muscovite. The accessories are zircon, apatite, titanite, rutile, baryte, gahnite and fluorite. The ore bodies include disseminations and massive parts in cordierite gneiss. Sphalerite is ubiquitous.

Sphalerite geobarometry

The Vuohtojoki deposit consists of several ore bodies, denoted A, B,... deposit. The iron content of the sphalerite varies. In the A deposit the mole-% FeS ranges from 11.1 to 14.5, corresponding to a pressure of 8.8–5.0 kb. In the D deposit the range of FeS content is 12.3–14.3 mole-% (7.4–5.4 kb) and in the H deposit 13.9–15.3 mole-% (5.6–4.3 kb). As seen in Fig. 7, the frequency maximum is at 12.5–13.0 mole-% FeS, corresponding to a pressure of 6.8 kb. Some specimens, especially those with lower Fe content from the B and C deposits (see Table 1 and Fig. 7), indicate a pressure of 10 kb or over. These specimens contain abundant pyrrhotite largely altered into a monoclinic variety. The monoclinic varieties were identified by microscopic examination of the specimens treated with magnetic colloid.

The garnet of the alteration zone is almandine-predominant and, according to Winkler (1974), the mineral assemblage cordierite + sillimanite + almandine indicates that the pressure reached ~ 5 kb and the temperature ~ 630°C. Andalusite is, however, occasionally present, suggesting somewhat lower pressures in some parts of the alteration zone. The given T and p values plot on the border of the upper temperature limit of the sphalerite geobarometer (Fig. 5a).

Säviä

Lithology

The ore deposit at Säviä (8) is situated beneath a lake. According to Aho (1977) and Huhtala (1979), the ore occurs in a schist zone trending from north to south and consisting mainly of volcanogenic mafic and intermediate rocks. To a lesser extent, felsic rocks, tuffs, tuffites and metasediments of detrital origin are also met with. The schists are clearly banded and veined and are migmatitic in appearance. Metamorphism has altered the rocks into cordierite–anthophyllite gneiss, hornblende–cummingtonite gneiss and amphibolite with appreciable garnet and sillimanite. Cummingtonite–hypersthene gneisses are also present. According to Laitakari (1968), the cordierite gneisses contain varying amounts of cordierite, quartz, biotite, plagioclase, anthophyllite, garnet and sillimanite and, as minor constituents, zircon, rutile, spinel and apatite.

The ore deposit occurs in the schist zone in association with cordierite gneisses. The main ore types are copper ore and zinc ore. The copper ore contains pyrite + pyrrhotite together with chalcopyrite. The zinc ore is a rather massive pyrite and pyrrhotite ore with sphalerite bands. The ores have been remobilised by regional metamorphism, giving rise to secondary cross-cutting structures.

Sphalerite geobarometry

The sphalerite compositions (Table 1) range from 12.5 to 14.9 mole-% FeS, with more iron in the middle parts of the ore and less at the margin.

The mineral assemblage (hypersthene – cordierite – sillimanite – garnet) of the country rock indicates that the peak of metamorphism reached a high grade. This stage was, however, followed by retrograde metamorphism (Makkonen 1981). The garnet close to the ore is a rather Mn-rich almandine (Aho 1977) and cannot therefore be used to estimate the temperature and pressure of metamorphism (cf. Winkler 1974 p. 209).

The garnet in the surrounding cordierite gneisses and amphibolites is suitable though, and, according to Makkonen (*op.cit.*), the temperature and pressure, based on Fe + Mg partitioning in the mineral pair cordierite – garnet in these rocks, are 550°–650°C and 7–8 kb, respectively.

The sphalerite geobarometer indicates 6.3 kb (see Fig. 7) for the pressure of metamorphism of the ores. The difference between the two pressure estimates (7–8 kb and 6.3 kb) is not large. The pressure may, however, have been somewhat lower in the ore. Structurally the ore deposit is a joint fissure that was filled with remobilised ore minerals during metamorphism; hence, it should be expected that the pressure in the ore is lower than in the wall rock.

Pattijoki

Lithology

At Pattijoki (12) in the Raahe–Paavola area in the northwesternmost part of the Vihanti ore zone two small showings occur in Proterozoic schist. Nykänen (1959) divided the schists into two main structural units, the Saloinen–Pattijoki schist zone near the coast of the Gulf of Bothnia and the more intensely metamorphosed NW-SE striking Revonlahti–Paavola zone in the east of the area. The schist zones are separated by intrusive rocks.

The rocks in the Revonlahti–Paavola zone are strongly migmatised veined mica gneisses containing cordierite, almandine, andalusite and straurolite. Medium-grade metamorphism is indicated by the assemblage diopside–tremolite–calcite in the calcareous rocks. The small prospect of Ylipää (12b) (in

the parish of Pattijoki) is situated in a long narrow tongue stretching westwards from the main schist zone.

The prospect at Pattijoki (12a) is situated in the Saloinen–Pattijoki schist zone. The schists are rather well-preserved volcanogenic, calcareous and argillaceous rocks. The main minerals in phyllites and mica schists are biotite, quartz and plagioclase. The accessories are graphite, titanite, magnetite, apatite, tourmaline and zircon. Hornblende, tremolite and carbonate also occur occasionally. The mineral assemblages biotite-hornblende-plagioclase and diopside-tremolite-calcite reveal that the recrystallisation generally took place at medium-grade (amphibolite facies) metamorphism. In places, however, the recrystallisation took place at relatively low temperature (Nykänen 1959), especially in fault- and shear zones where the mineral assemblage epidote–albite–chlorite often occurs. According to Vaasjoki (1956), the ore mineralisations are restricted to pyrrhotite-bearing phyllite–mica schists with calcareous interlayers. Minor sphalerite-bearing veins with alabandite, galena and chalcopyrite may also occur. Rhodonite is a common constituent in the calcareous layers. A fine carbon pigment and some coarser graphite are met with in the calcareous and dark argillaceous layers (Veltheim 1954).

Sphalerite geobarometry

The metamorphic grade suggested by the sphalerite geobarometer at Pattijoki is in conflict with the mineral paragenesis of the surrounding rocks (cf. Fig. 7). The iron content of the sphalerite at Pattijoki is 21.7 to 17.8 mole-% (0–2 kb) whereas the small prospect in the veined gneisses at Ylipää (parish of Pattijoki) gives 13.9–14.3 mole-% FeS (5.6–5.2 kb). The Pattijoki showing belongs to the Saloinen–Pattijoki schist belt, whereas Ylipää belongs to the Raahe–Paavola schist belt. The high Mn content of the rock at Pattijoki manifests itself, not only in the presence of alabandite and rhodonite, but also in the high Mn content (8 wt-%; Törnroos 1982) of the sphalerite. In contrast, the Mn content of the sphalerite from Ylipää is low (0.3 wt-%). The influence of Mn on the sphalerite geobarometer is not known, but it seems that the presence of this element may cause errors. The results obtained must therefore be accepted with caution.

Sotkamo

Lithology

Two deposits, Kolmisoppi (13a) and Kuusilampi (13b), are located about 5 km from each other at the Sotkamo, Talvivaara prospect (13 in Fig. 1) (Ervamaa & Heino 1980). The ores are in black schists of the Kainuan schist belt, which is part of the Karelides. According to Heino and Havola (1980), the lowest part of the Kainuan schists consist of Jatulian quartzites that were sedimented on Archean gneisses. The Jatulian quartzites are overlain by impure quartzites interlayered with mica schists. Uppermost in the sequence are Kalevian mica schists. The ore-bearing black schists and the mica schists with black schist interlayers occur in the sequence between the impure quartzites and the Kalevian mica schists.

Younger metadiabase dykes crosscut the gneiss complex and the schist belt. Serpentinites and talc–magnesite schists have also been encountered in several places (Heino & Havola *op. cit.*).

The main minerals in the black schists are

quartz, biotite, graphite and sulphides. Minor amounts of rutile, chlorite, feldspar, apatite, garnet, tourmaline and epidote are also encountered, and in places the garnet is very abundant. The sulphides include alabandite, sphalerite, pyrite, pyrrhotite, chalcopyrite and pentlandite (Aho 1979). The main minerals in the quartzites are quartz and sericite. The accessory minerals are biotite, apatite, zircon and titanite. In the upper quartzites there are random tremolite, carbonate, biotite, chlorite and sericite. Diopside- and garnet-bearing skarn layers are also encountered in the quartzites.

Primary sedimentary structures are still visible, and the sulphides often occur as very fine-grained primary dissemination together with graphite. In places, however, metamorphism has remobilised the sulphides. Thin agate veinlets associated with alabandite indicate low-temperature hydrothermal events, at least in some parts of the deposits.

Sphalerite geobarometry

As seen in Fig. 7, the FeS contents of the sphalerites in the Kolmisoppi prospect are clustered roughly around two maxima (~ 13.5 ~ 15.0 mole-% and ~ 16.5 ~ 19.0 mole-% corresponding to ~ 4.5 ~ 6.0 kb and ~ 1.3 ~ 3.2 kb). The iron contents given in Table 1 show that the sphalerite grains of specimen 11738 should be divided into two groups: low-iron and high-iron grains. This will be discussed in a later chapter. At Kuusilampi there is only one frequency maximum (Fig. 7), and the iron content ranges from 13.6 to 15.6 mole-% FeS (corresponding to 5.9–4.0 kb). The Mn content of the sphalerite is also high here (4–5 wt-% Mn) (cf. Pattijoki). No high-temperature minerals have been met with. The iron content of a sphalerite from outside the ore body of Kuusilampi was found to be 12.5–13.0 mole-% (or 6.9 kb), or somewhat higher than the values inside the ore.

Outokumpu

Lithology

The geology of the Outokumpu (7) district has been discussed in numerous papers. For more detailed geological descriptions, see Peltola (1960, 1980), Huhma and Huhma (1970), Gaál *et al.* (1975), Koistinen (1981) and Treloar *et al.* (1981).

There are several ore deposits and showings in the Outokumpu district. The rocks in the area are Karelidic schists separated from the Archean basement in the east by an unconformity (Peltola 1980). In the western part of the schist area there is a long narrow zone, the Outokumpu zone, that consists mainly of serpentinites, skarns, calcareous black schists and quartz rocks – the »Outokumpu quartzites».

The Outokumpu zone is bordered by black schists that grade into quartz rocks and serpentinites towards the middle of the zone. In many places the serpentinite lenses are rimmed by dolomite, skarn and quartzite. Green skarns containing chrome-bearing minerals (diopside, tremolite, uvarovite, eskolaite, chromite, etc.) occur as reaction products between carbonate and silicate rocks (Huhma & Huhma 1970). The quartzites contain thin intervening layers of cordierite-anthophyllite rocks that often include phlogopite, almandine and staurolite (Gaál *et al.* 1975).

The ore bodies and prospects are located in the Outokumpu zone and are embedded in

quartz rocks near the contact of serpentinite.

According to Koistinen (1981), the ores within the Outokumpu zone are deformed and metamorphosed strata-bound massive sulphide deposits associated with mineralised stockworks. Two ore types occur: massive pyrite or pyrrhotite Cu-Co-Zn and disseminated nickel-pyrrhotite ores. The massive ores occur in quartzites, skarns and carbonate rocks extending into black schists or mica schists. The characteristic minerals are pyrite, pyrrhotite, chalcopyrite, sphalerite and cobalt pentlandite. The disseminated nickel ores in stockwork and in cordierite–anthophyllite (-staurolite-garnet-spinel) -bearing rocks occur within intercalated quartzite and skarn and in the chloritic amphibole rocks that are marginal to serpentinite.

Three deposits are currently being mined. The mines in operation are Keretti, Vuonos and Luikonlahti.

Sphalerite geobarometry

The most frequent iron contents in sphalerite from the Outokumpu area cluster at 13.5 to 15.3 mole-% (Fig. 7), corresponding to a pressure of 6.0 to 4.3 kb. The sphalerite contains ca. 2 wt-% Mn, except for one sample that had a low Mn content (0.6 wt-%) and an Fe content of 12.8 mole-% or 6.8 kb (Table 1).

Gaál *et al.* (1975) have discussed the metamorphism of the Outokumpu area on the basis of the mineral assemblage in the adjacent rocks. The presence of cordierite, almandine + staurolite and the three polymorphs of Al_2SiO_5 (kyanite-andalusite-sillimanite) indicate pT conditions around the triple point (~ 6 kb and ~ 600°C according to studies by Althaus 1967 and Richardson *et al.* 1969, cited by Winkler 1974). On the other hand, recent temperature and pressure estimates from Outokumpu based on element partitioning in co-existing minerals in a cordierite–anthophyllite – (+ cummingtonite) – almandine-staurolite rock give 550° + 50°C and 3.5 ± 1 kb (Treloar *et al.* 1981) that is, values close to the experimentally determined Al_2SiO_5 triple point by Holdaway (1971) (~ 4 kb and ~ 500°C). The range of model pressure (4.3–6.0 kb) obtained by the sphalerite geobarometer is consistent with the foremention pressure estimates for the wall rock.

Hammaslahti

Lithology

The Hammaslahti mine (6), about 55 km southeast of Outokumpu (cf. Fig. 1), is situated in Karelidic schists. According to Kahma (1973) and Isokangas (1978), the deposit lies at the western margin of a syncline associated with a zone of impure arkose and greywacke that forms an interbed in Kalevian phyllite. Quartzite, black schists and arkosite occur as intercalations in the phyllite. There are also carbonate concretions in the phyllite. Staurolite, andalusite and garnet are met with as porphyroblasts. The arkosite shows a marked variation in the abundance of feldspar and quartz.

Hyvärinen *et al.* (1977) suggest that the sulphides were originally synsedimentary but that they were later remobilised by regional metamorphism and concentrated in transversal shear zones. According to Isokangas (1978), the deposit shows a breccia structure in which the sulphides occur as veins and stockwork in arkosite. The intensity of mineralisation varies from one part of the deposit to the other, ranging from a high-grade breccia ore to a low-grade impregnation.

The main and almost only ore minerals are chalcopyrite and pyrrhotite, although in the northernmost part of the ore sphalerite and pyrite are also fairly abundant.

Sphalerite geobarometry

The sphalerite geobarometry gives a pressure of 7.4 kb (cf. Fig. 7), range 5.7–8.7 kb (13.9–11.2 mole-% FeS, Table 1) for the northernmost part. In one specimen, where the sphalerite grains are totally encapsulated in pyrite, the FeS content is 14.7–15.6 mole-%, corresponding to a pressure of 4.8–4.0 kb (Table 2).

The rocks have not been markedly affected by regional metamorphism, but they have been exposed to intense dynamometamorphism (Isokangas 1978), which may explain the unusually high pressure.

According to Hyvärinen *et al.* (1977), fluid inclusion studies have demonstrated that the metal components deposited as sulphide minerals at temperatures exceeding 310°C.

Orijärvi–Kimito zone

Lithology

The Orijärvi–Kimito zone in southwestern Finland (1–3 in Fig. 1), contains numerous small polymetallic showings. The belt belongs to the east-west trending part of the Svecofennidic schists occurring along the coast of the Gulf of Finland. In lithology and structure these schists are comparable to the leptites in central Sweden. The area has long been an object of geological interest. Comprehensive descriptions of the area have been given by Eskola (1914, 1915 and 1950), Tuominen (1957) and Latvalahti (1979).

The schist zone consists mainly of leptites i.e. ancient acid volcanics and volcanic sedimentary rocks rich in quartz and feldspar. Depending on the grain size, the rocks are called hälleflinta, leptite or leptite gneiss (Latvalahti 1979). Volcanogenic leptites predominate in the Orijärvi–Aijala area and on the island of Kimito. Amphibolites and calcareous schists are also present in this zone. The leptite beds are bordered by Perniö (Bjärnå) granite in the west and north and by granodiorites and more mafic intrusive rocks in the south and southeast.

The leptite zone, which may extend westwards as far as Attu (1), includes the sulphide occurrences of this area (Orijärvi–Attu). The sulphide ores are complex Cu-Pb-Zn ores in either skarn rocks or felsic metavolcanites and are often associated with cordierite-anthophyllite rocks. Latvalahti (1979) regards these rocks as the metamorphic equivalent of the alteration pipes of volcanic-exhalative deposits. Eskola (1914) described the deposits as epigenetic and considered that the ore constituents derived from granodioritic intrusions whose hydrothermal fluids induced magnesia metasomatism around the intrusive bodies.

The principal ore deposits are the Aijala (3) Cu-Zn deposit, the Metsämonttu (2) and Attu (1) Zn-Pb deposits and the Orijärvi Zn-Cu deposit. The Aijala–Metsämonttu and Orijärvi deposits have been mined out, and the only ore showing that currently appears to be of economic significance is the Zn-Pb deposit on the island of Attu in Pargas.

Sphalerite geobarometry

The barometer gives a total pressure of 3.2 to 4.2 kb (16.5–15.4 mole-% FeS) for Attu, in the western part of the leptite belt; the values for the Aijala–Metsämonttu area vary from 4.1 to 7.3 kb (15.5–12.3 mole-% FeS), the

most frequent iron contents indicating 4.8 kb for Aijala and 5.8 and 4.3 kb for Metsämonttu (cf. Fig. 7).

Dietvorst (1982), who has discussed the grade of metamorphism on the island of Kimito, between Attu and the Aijala–Orijärvi area, gives a temperature and pressure of 560° ± 25°C and 3.0 ± 0.5 kb, respectively, for the muscovite-quartz zone and 670° ± 25°C and 4 ± 0.5 kb for the cordierite – K-feldspar zone. He based his pressure estimates on the Mg/Mg + Fe ratio of cordierite in the K-feldspar-bearing gneisses by using the experimental data of Holdaway and Lee (1977) on the breakdown reaction of cordierite + K-feldspar to biotite + sillimanite + quartz. The temperature determinations were based on the experimental calibration of the partitioning of Fe and Mg between garnet and biotite as reported by Ferry and Spear (1978).

The element partitioning in the cordierite-garnet pair gives a pressure of 5.1 to 5.5 kb and a temperature of ~ 750° to ~ 790°C for Attu (Schellekens 1980). The mineral pair occurs in the cordierite – K-feldspar zone mentioned by Dietvorst (1982).

Latvalahti (1979) supposed that the pT conditions of regional metamorphism in the Aijala–Orijärvi area were roughly 3 kb and 650 ± 30°C. She based her estimates on the reaction muscovite + quartz → K-feldspar + sillimanite and on the presence of andalusite together with sillimanite in the cordierite–sericite mica gneisses.

The Tampere (Tammerfors) schist belt

The Tampere (Tammerfors) schist belt (4–5 in Fig. 1), which is part of the Svecofennian formations, includes several small sulphide showings. The schist belt trends from west to east and is penetrated by plutonic rocks. In the north, the schist belt is bordered by the granitic batholith of central Finland; southwards, it grades into the more strongly metamorphosed schists of southern Finland. In the west, the schist zone is cut by the quartz- and granodioritic Hämeenkyrö plutonic massif, which was emplaced in the schist zone during the Svecokarelidic orogeny (Simonen 1952).

Although most of the sulphide showings in the area are of no economic value, two of the deposits, the gold-copper deposit at Haveri and the copper-tungsten deposit at Ylöjärvi, have been exploited. In Haveri, there is no sphalerite, but the assemblage sphalerite + pyrite + hexagonal pyrrhotite is encountered at Ylöjärvi and at a small prospect at Nokia.

Ylöjärvi

Lithology

The Ylöjärvi deposit (5), which has recently been described by Himmi *et al.* (1979), is located at the western end of the Tampere schist belt. The sequence begins with phyllites and mica schists surrounded by more coarse-grained psammitic feldspar schists. The upper part is composed of volcanics, tuffites and thin intercalations of volcanic rocks, porphyrites and porphyries.

Adjacent to the deposit the predominant rock type is tuffite with agglomeratic horizons. Thick beds and lenses of porphyrites are encountered between the tuffites. The formation is cut by the Hämeenkyrö granodiorite, which brecciates the volcanic rocks with an intensity varying from incipient fracturing to total fragmentation. The host rock

of the Cu-W ore is a pipe-shaped tourmaline breccia, with a matrix composed of tourmaline, quartz and apatite. Also present are arsenopyrite, chalcopyrite, pyrrhotite, pyrite, scheelite and, more rarely, molybdenite, sphalerite, galena and bismuth. According to Himmi *et al.* (1979), the volcanics attained their current mineral composition through regional metamorphism. The brecciation is attributed to explosive discharges of hot gases (explosive breccia). This took place twice at different explosive pressures. Because the deposit is in the immediate vicinity of the Hämeenkyrö granodiorite massif Himmi and his associates suggest that the mineralising fluids derived from this massif.

Sphalerite geobarometry

At Ylöjärvi the sphalerite contains 14.8–16.2 mole-% FeS and 11.6–12.5 mole-% FeS giving a pressure of 4.7–3.5 kb and 8.2–7.1 kb. The conflicting results are probably due to the extreme crystallisation conditions that prevailed during the formation of the pipe breccia. This will be discussed in a later chapter.

Nokia

Lithology

At Nokia (4) a small sulphide showing in black schists and skarn rocks interbedded in phyllites has been submitted to prospecting (Marmo 1957). According to Marmo *(op. cit.)*, the main sulphide-schist zone is comparatively narrow but long. The main sulphide is pyrrhotite that occurs as a very fine dissemination. Sphalerite, chalcopyrite and pyrite are common, and occasionally linneite has been met with. Pyrrhotite, sphalerite and pyrite occur in different generations: the primary, which is apparently sedimentary, and the younger, which is a product of remobilisation. The phyllites contain quartz, biotite, muscovite, chlorite, graphite, plagioclase and small amounts of cordierite and, in quartzitic layers, andalusite.

Sphalerite geobarometry

The sphalerite grains had to be carefully selected. Only a few samples contained sphalerite grains appropriate for geobarometry. The FeS contents of these grains were 12.5–13.5 mole-%, corresponding to 7.1–6.0 kb (cf. Fig. 7 and Table 1).

Riikonkoski–Pahtavuoma

Lithology

Both occurrences are situated in the western part of the Kittilä greenstone belt in central Finnish Lapland (14–15 in Fig. 1). The area has three main geological formations: 1) the Lapponium group of Archean or Proterozoic schists; 2) the Proterozoic Kumpu formation; and 3) the felsic plutonic rocks of western Lapland.

The Lapponium includes schists (phyllite, mica schists, greywacke, quartzite, skarn) and greenstones (Mikkola 1941). According to Simonen (1980), the complex is Proterozoic (Svecokarelidic) in age, but Gaál *et al.* (1978) and Silvennoinen *et al.* (1980) maintain that it is Archean.

The greenstones consist of metamorphosed volcanogenic and sedimentogenic rocks. They are overlain by sedimentogenic schists, with volcanogenic and detrital sediments often intermingled. The phyllites, mica schists, amphibole schists and greywackes are of sedimentary origin and display abundant primary structures referring to the flysch type of sedimentation (Inkinen 1979).

The most important plutonic rocks are the syenite intrusion at Äkäslompolo in the western margin and the Hetta granite in the north. Other intrusions in the schist zone include albite gabbros, albite diabases and albitites.

The ore showings at Pahtavuoma are stratiform but brecciated and lie in metasediments, mostly phyllite, at the contact with the greenstone (Mäkelä 1977, Inkinen 1979).

Sphalerite geobarometry

The temperature and pressure of formation for Pahtavuoma (15) were estimated by Latvalahti (1973) on the basis of the chemical composition of the gersdorffite-cobaltite solid solution, the sphalerite geobarometer, the sulphur-arsenic ratio and the d_{131} value of the arsenopyrite. Her results suggest that in the main crystallisation phase (chalcopyrite, sphalerite, pyrrhotite) the temperature was 360° to 425°C and the total pressure 4.0 ± 1.5 kb.

The Riikonkoski prospect (14) (Nenonen 1975) is situated in the southern part of the greenstone area (Fig. 1). The ore showings are in brecciated phyllites or their contacts and in the neighbourhood of the albitites.

Several ore showings exist. The main minerals are pyrite, pyrrhotite and chalcopyrite. Sphalerite, too, is occasionally encountered in some of the showings. The sphalerite seems to be of two generations: the earlier crystallised together with the other sulphides, whereas the later consists of thin sphalerite veinlets cross-cutting the matrix. The sphalerite grains, which optically seem to be in equilibrium with pyrite and pyrrhotite, have an FeS content of 12.9–14.9 mole-%, corresponding to a pressure of 6.7–4.6 kb. The younger sphalerite grains have an FeS content of 14.4–18.7 mole-%, but they are not in contact with the pyrite and pyrrhotite. As shown in Fig. 7, the iron content of this sphalerite fluctuates considerably and gives no definite pressure estimate.

DISCUSSION

The influence of temperature on the pressure determinations.

As has been pointed out (Figs. 2 and 3), the sphalerite geobarometer is applicable in a limited temperature region only. For accurate pressure determinations, it is important to know whether or not the temperature of formation or metamorphism of the ore deposits exceeded the temperature limits.

Temperature and pressure determinations on some of the ore deposits investigated in this work are compiled in Fig. 5b. With the exception of Pahtavuoma (15) (see below), these data are mainly based on wall-rock silicate mineral assemblages.

As shown by the figure (points K a–b and 7 a–b), determinations on the same object by different methods may give widely divergent results (cf. below).

Some comments are appropriate on the three earlier pT estimates for the Orijärvi–Kimito belt (see p. 21 and Fig. 5b). The temperature and pressure estimates for Attu (1) by Schellekens (1980) and for Kimito (K in Fig. 5b) by Dietvorst (1982) are based on the partitioning of Fe and Mg between the minerals cordierite and garnet in cordierite-bearing gneisses. This partitioning is dependent on temperature and pressure, and experiments and thermodynamical calculations have been carried out to calibrate the geothermometer and geobarometer, (see, for instance, Currie

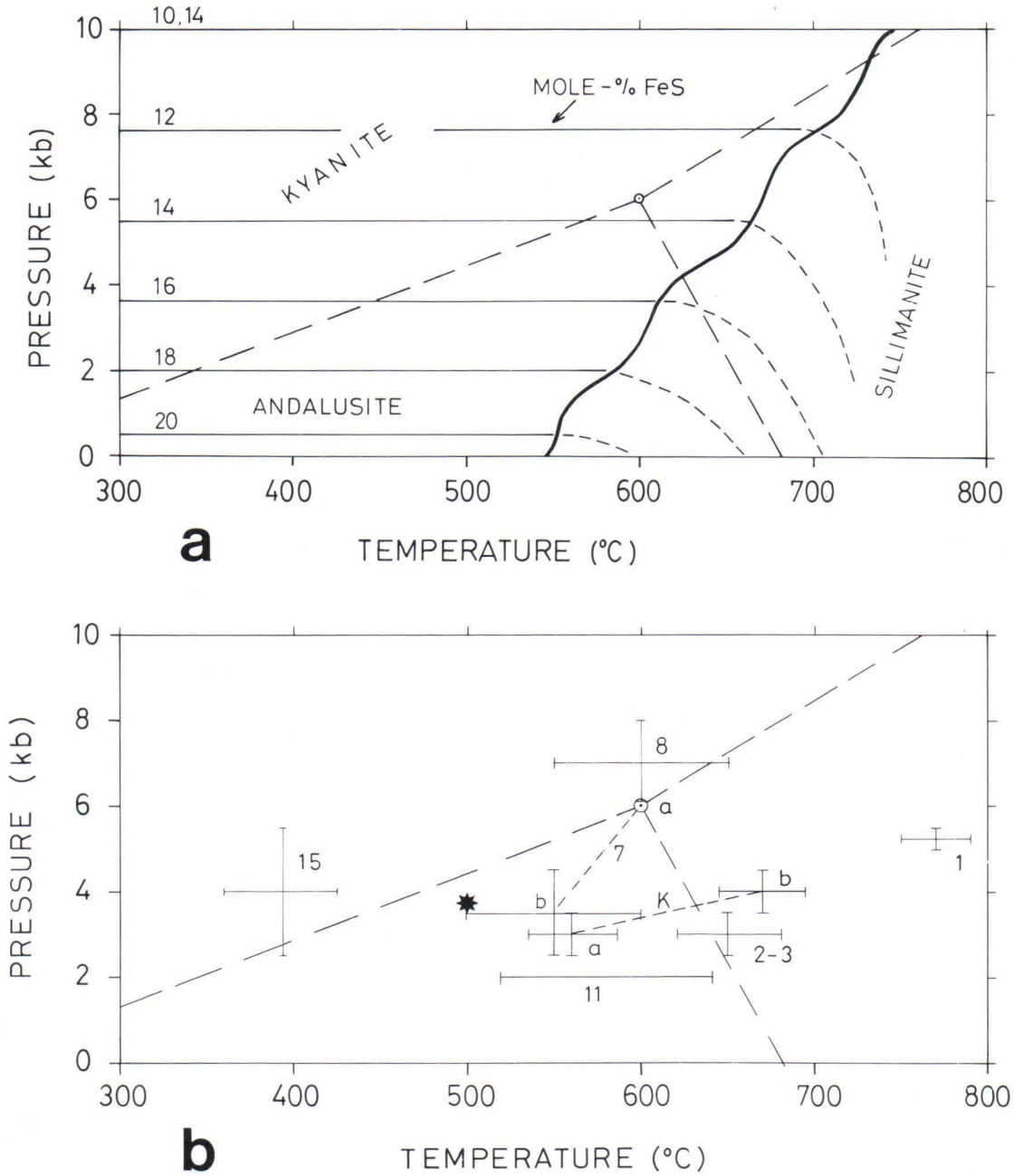


Fig. 5. a) pT projection of sphalerite isobars from Fig. 2 superimposed on the Al_2SiO_5 diagram of Winkler (1974). Wavy line marks the upper limit of the temperature-independent portion of the sphalerite geobarometer.

b) pT diagram as in a), showing plots of available temperature and pressure data compiled from earlier papers dealing with areas around some Finnish sulphide ores. 1 = Attu (Schellekens 1980); 2–3 = Aijala–Metsämonttu area (Latvalahti 1979); K = the island of Kimito between Attu and Aijala–Metsämonttu (Dietvorst 1982); 7 = Outokumpu area (a = Gaál *et al.* 1975, b = Koistinen 1981); 8 = Säviä (Makkonen 1981); 11 = Vihanti (Rouhunkoski 1968); and 15 = Pahtavuoma (Latvalahti 1973). Point 15 refers to the ore; the other points to the wall rock. ✸ = denotes the Al_2SiO_5 triple point after Holdaway (1971).

1971, Hensen 1971, Hensen & Green 1973, Hutcheon *et al.* 1974, Thompson 1976, Holdaway & Lee 1977, Lee & Holdaway 1977 and Perchuk 1977). The various methods have, however, produced conflicting results (Currie 1974, Holdaway 1976). Holdaway (*op. cit.*) also doubts if the present state of knowledge justifies the application of partition coefficient data to natural cordierite-garnet compositions.

The temperature of 758° to 788°C (p = 5.1–5.5 kb) determined for Attu by Schellekens (1980) is the highest reported (see Fig. 5b point 1). A temperature as high as this would need a marked reduction in the pressure indicated by the sphalerite geobarometer (cf. Figs. 2 and 5a). As shown by Fig. 5a, such a reduction would give a negative pressure for Attu and hence, would not be meaningful. In his estimates, Schellekens employed the results of Currie (1971). If, however, the calculations had been made with the data by Perchuk (1977), the temperature would have been reduced to 610°–645°C, which is more in accordance with the measurements of Dietvorts (1982) from the island of Kimito some kilometres to the east of Attu (670° ± 25°C and 4 ± 0.5 kb).

The temperature (~ 630°C) estimated for Attu with the method by Perchuk (1977) and the pressure derived from the sphalerite data (~ 3.5 kb) plot on the border of the upper temperature limit of the sphalerite geobarometer (Fig. 5a), and would not necessarily entail temperature corrections of the sphalerite data. If, on the other hand, Dietvorst's data are applied to the sphalerite of Attu, the pressure would be reduced to 2–3.5 kb (cf. Fig. 5a), that is, it would be about 1 kb less than estimated for the surrounding rocks.

Latvalahti (1979) based her temperature and pressure estimates in the Aijala–Metsämonttu area (2–3) on the reaction muscovite + quartz → K-feldspar + Al_2SiO_5 + H_2O, and on the fact that andalusite and silimanite occur together. Muscovite decomposes at 650° ± 30°C (Winkler 1974 p. 86), and the occurrence of andalusite + sillimanite indicates that the pressure was lower than 5 kb (2–4 kb, Winkler 1974 p. 86). This is nearly the same as that reported by Dietvorst for Kimito. The pressure given by the sphalerite geobarometer is, however, 4.8–5.8 kb. Reduction with the aid of Dietvorst's temperature would lower the pressure to 3.5–4.5 kb at the most.

Temperature and pressure determinations published earlier for Säviä (8) and Outokumpu (7) are also based on the cordierite–garnet assemblage in cordierite–anthophyllite–almandine rocks (Makkonen 1981, Koistinen 1981). The results depend on the method used. Koistinen gives 550°C ± 50°C and 3.5 ± 1 kb for Outokumpu. Makkonen has established that the results by Thompson (1976), Holdaway and Lee (1977) and Perchuk (1977) are consistent with each other, whereas the method by Currie (1971) gives too high a temperature and a somewhat lower pressure. According to the results by Makkonen (1981), the temperature was 620° ± 30°C in cordierite–garnet–anthophyllite rock and 585° ± 35°C in cordierite–garnet–sillimanite rock.

The cordierite–anthophyllite–almandine + Al_2SiO_5 rocks are present throughout the Vihanti ore zone. The mineral assemblages are fairly similar, and so it seems reasonable to assume that the pT conditions were also similar throughout the area.

The temperature and pressure for the Pahtavuoma ore (Latvalahti 1973) were determined using the ore minerals sphalerite, arsenopyrite and the pair gersdorffite–cobaltite. The results suggest a relatively low temperature of formation, viz. 400°C (point 15 in Fig. 5b).

Lower temperature of formation of the ore is also indicated by sulphur isotope investigations. The archives of the Geological Survey of Finland contain sulphur isotope data on the Säviä ore deposit. The measurements

were made by Dr M. Mäkelä in the sulphur isotope laboratory at the Technical University of Helsinki. The data give a mean of 480°C when based on the experimental data of Kajiawara and Krouse (1971) on the sulphur isotope fractionation between sphalerite-pyrite, sphalerite-pyrrhotite and pyrite-pyrrhotite. This result indicates that the »quenching» temperature of the sulphides was lower than that of the wall rocks.

Sulphur isotope data are also available on the foot wall of the Vihanti ore deposit (Rehtijärvi *et al.* 1979). They report a mean of 400°C for the sulphide crystallisation, or nearly the same as that at Säviä. At Outokumpu, data on the isotopic fractionation between coexisting sulphides indicate temperatures of ~ 350°C (Mäkelä 1974). »The sulphur isotopic composition of coexisting sulphides may result either from simple equilibrium isotope effects or from depositional isotope effects followed by partial or complete equilibrium during metamorphism» (Mäkelä *op. cit.* p. 34). He warns that the value given above »can only be accepted as a statistical value indicating the temperature at which the isotopic equilibrium was reached». »Indirectly it may be considered to be representative of temperatures associated with the regional metamorphism undergone by the ore deposits».

On the basis of the decrepitation of secondary fluid inclusions in the ore-bearing microfractures, Hyvärinen *et al.* (1977) suggest that the metal components deposited at Hammaslahti (6) as sulphides at temperatures not less than 310°C.

A comparision between the temperatures from elemental partition between silicate minerals in wall rock and the temperatures from ore (sulphur isotope data, fluid inclusions and the data on Pahtavuoma) indicate a lower temperature of formation for the ores. The present author is of the opinion that, some of the temperature estimates given in other works on these deposits or areas are slightly too high.

Hence, it may be assumed that the temperature of metamorphism in the ores was within the allowed range of sphalerite geobarometry, as shown in Fig. 2.

This assumption is consistent with the investigations by Scott *et al.* (1977) on the Broken Hill deposits in Australia. They propose that the initial cooling from the peak metamorphic temperature to the final »setting» temperature of the sulphide was nearly isobaric. They based the final setting temperature on the sulphur isotopic fractionation between sulphide minerals.

The pyrrhotite problem

Before sphalerite can be used as a geobarometer, it is essential to confirm that it is equilibrated with pyrite and high-temperature hexagonal pyrrhotite. Indirect evidence for the equilibration of pyrrhotite at relatively high temperatures was discussed on the foregoing pages. As in some of the ore deposits investigated, the sphalerite geobarometer may give too high a pressure.

Scott and Kissin (1973) have demonstrated experimentally that FeS activity (a_{FeS}) is inversely proportional to sulphur fugacity (f_{S_2}). The iron content of sphalerite equilibrated with monoclinic pyrrhotite is therefore lower than that of sphalerite in equilibrium with hexagonal pyrrhotite.

Evidence exists that sphalerite may change its composition during cooling, even together with pyrrhotite + pyrite. During the cooling of an assemblage of sphalerite, hexagonal

pyrrhotite and pyrite, monoclinic pyrrhotite forms at a temperature of ~ 254°C at 1 bar and ~ 290°C at 5 kb. This formation implies an increase in f_{S_2}, and, in accordance with the results mentioned above, it is presumed that the composition of sphalerite also changes.

Monoclinic pyrrhotite occurs typically as a secondary alteration product along grain boundaries and fracture planes. As the secondary alteration proceeds, a residual core of primary hexagonal pyrrhotite remains surrounded by rims of monoclinic pyrrhotite. In more advanced stages, oxidation (high f_{O_2}) or loss of iron, or both, leads to the formation of pyrite, marcasite and, ultimately, of magnetite or hematite (Scott *et al.* 1977). Such oxidation may also affect the sphalerite and lead to Fe depletion.

Bristol (1979) found that, in rocks with abundant monoclinic pyrrhotite (inverted from high-temperature hexagonal pyrrhotite), sphalerite appeared to be anomalously poor in iron, giving excessive pressure estimates. Reequilibration of sphalerite has also been reported by Groves *et al.* (1975) from some nickel deposits in Western Australia; by Ethier *et al.* (1976) from the Sullivan ore body in Southwestern British Columbia; by Brown *et al.* (1978) from the Ruttan mine in Manitoba, Canada; by Boctor (1980) from the Bodenmais ore in Bavaria; and by Hutchison and Scott (1980) from some sulphide ores in the Swedish Caledonides and the U.S. Appalachians. Hutchison and Scott (*op. cit.* pp. 66–67), however, interpret the problem differently. As in Finnish sulphide deposits, monoclinic pyrrhotite is observed only as a product of the secondary alteration along fractures and grain boundaries. This suggests that »primary metamorphic» hexagonal pyrrhotite had not completely reacted when the temperature decreased. If this is true, then it is unlikely that the more refractory sphalerite would have completely reequilibrated at a low temperature. The occurrence of low-iron sphalerites is, however, undeniable, as may be seen in Fig. 7 and as is suggested by the authors mentioned above. Barton *et al.* (1980) (cited by Hutchison & Scott 1980) suggest that, at low temperature, an assemblage of sphalerite + pyrrhotite supersaturated with respect to pyrite, could lead to low-iron sphalerites. According to Groble *et al.* (1979), it is evident that, in order to flux the sphalerite, the low-temperature process must have taken place in the presence of a fluid phase because the kinetics of a solid-state reaction are far too slow.

Hutchison and Scott (1980 p. 59) comment on the use of the geobarometer as follows; »Successful application of the sphalerite geobarometer to metamorphosed sulphide ores is dependent upon the ability of user to discriminate between preserved equilibrium assemblages, if present, and those which are in disequilibrium or have retrograded to a low temperature condition». In their study of massive sulphide ores in the Swedish Caledonides and the U.S. Appalachians, Hutchison and Scott (*op. cit.* p. 59) found that »sphalerites which are totally encapsulated within metablastic pyrites represent preserved high pT-equilibrium assemblages».

Hutchison and Scott *(op. cit.)* denote such »totally encapsulated sphalerites» (A) sphalerites. As (B) sphalerites they denote sphalerites in triple junction (in mutual contact) with pyrite and hexagonal pyrrhotite. The results on the (A) and (B) sphalerites in the study by Hutchison and Scott (*op. cit.*) show, however, very small differences and only a slight depletion (about 0.5 mole-%) of the FeS in sphalerite. The resulting model pressure is too high by 400 to 500 bar.

(A) sphalerites were found in some of the specimens used in the present work. The data are given in Table 2, but they are too few to permit a statistical analysis. Nevertheless, the iron content in many grains appears to be slightly higher than in those in the triple junc-

tion ((B) sphalerite). In some cases, however, the reverse is true, inferring higher pressures than do the sphalerites of the type-B assemblages. For these, Hutchison and Scott (*op. cit.*) suggest that the reactions giving rise to such products occurred at lower temperatures, and that the grains thus record a later event(s).

The present work deals mainly with (B) sphalerites and, with the forementioned comments by Hutchison and Scott, in mind, the present author is of the opinion that there should not be any serious errors as long as the grains investigated (type-B sphalerites) are carefully selected.

Monoclinic pyrrhotite (inverted from a high-temperature hexagonal variety) has been encountered in many of the Finnish ores dealt with in the present study. In all of the specimens giving an estimated pressure of over 8 kb, the primary hexagonal pyrrhotite is more or less inverted into the monoclinic modification. In such an assemblage the sphalerites are denoted as (C) sphalerites (Table 1, marked with m). There are, however, also some ores in which no appreciable iron depletion is observed in the (C) sphalerite, and the pressure estimates are well within the range given by the hexagonal assemblage of the same occurrence (see discussion below). A characteristic trend is for small sphalerite grains to be poorer in iron than coarser grains by about 1 to 2 wt-% Fe as measured at Säviä (8) and Vuohtojoki (10). Scott (1976) also considered that the reequilibration of the sulphides with a coarser grain size during reduced pressure was unlikely on kinematic ground. Small grains may also be formed through exsolution or they may totally recrystallise during later events.

The histograms in Fig. 7 show the FeS contents of the sphalerites that are in contact with either hexagonal or monoclinic pyrrhotite in the Finnish occurrences investigated. The data on the monoclinic assemblages appear to be more spread, whereas those on the hexagonal assemblage give more distinct peaks.

Estimated pressures and type of metamorphism

At Vuohtojoki (10) the sphalerite in contact with monoclinic pyrrhotite (type C sphalerite) clearly record a higher pressure (see Fig. 7) than do the (B) sphalerite. This is the only deposit investigated in this work in which the (C) sphalerite data are conspicuously clustered (10–12.5 mole-% FeS). Such a distinct peak may indicate later activity, most probably hydrothermal, that gave rise to reequilibrium reactions at lower temperature (under the lower temperature limit of the sphalerite geobarometer (see Fig. 3)). Such hydrothermal activity could be related to deformation movements, magmatic activity or a new metamorphic phase (cf. Groble *et al.* 1979, Hutchison & Scott 1980). A slight clustering may, however, also be seen on the Vihanti (11) data in the same range (10–12.5 mole-% FeS), although the scarcity of the measurements makes such an assumption precarious. At both Säviä (8) and Nokia (4) there is no essential difference between the data on sphalerite (triple junction) in contact with either hexagonal or monoclinic pyrrhotite.

The temperature determined on the fluid inclusion at Hammaslahti (6) corroborates a later hydrothermal event. During deformation at high pressure, massive sulphides are incompetent and it is unlikely that sufficient porosity of permeability exists in the ores to permit widespread migration of fluids. Only later, at a much lower confining pressure, do the aqueous fluids become mobile and able to

penetrate the massive sulphide ores through grain boundaries and fractures, thereby producing a number of retrograde changes (Plimer 1976). If the temperature then decreases sufficiently monoclinic pyrrhotite will form.

In the Ylöjärvi (5) deposit, there seem to be two types of sphalerite (Fig. 7). Sphalerite is very sparse at Ylöjärvi and only six (B) and three (A) sphalerite grains were measured; hence, the statistics are poor. The Ylöjärvi ore, which is within a tourmaline breccia pipe in the contact zone of the Hämeenkyrö granodiorite massif, was mineralised in connection with brecciation processes (explosive breccia) (Himmi *et al.* 1979). As discussed on page 22, Himmi *et al. (op. cit.)* suggest a brecciation in two stages: First an explosive discharge of hot gases followed by gas flow. Then, after the discharge, pressure was reduced, and the feeding channel was blocked until an increase in gas pressure caused a new explosion, now at a lower explosive pressure.

If equilibrium was reached under such conditions, the two types of sphalerite in Ylöjärvi may refer to the variation in the pressure conditions of the brecciation processes. The maximum temperature that prevailed in the breccia cannot be estimates. Sharp but totally silicified layers of fragments and the fact that the cores of the fragments and the wall rock in the contacts are unaltered suggest a rather high temperature but one of short duration.

Although tentative, the numbers of the estimated pressures (~ 7.5 kb and ~ 4 kb, see Fig. 7) indicate a two-stage event of formation for the Ylöjärvi breccia.

The samples from Nokia (4) had only six grains in contact with hexagonal pyrrhotite. The others plotted in Fig. 7 were in contact with monoclinic pyrrhotite. The pressure of the peak of regional metamorphism in the Tampere schist belt, as given by measurements in Nokia, was 6–7 kb.

For Säviä (8), Vuohtojoki (10), Vihanti (11) and probably Pattijoki (12b) (Ylipää), the pressure estimates are within 6–7 kb (Fig. 7). The (A) sphalerites in these deposits give model pressures within the range of the (B) sphalerites. At Pyhäsalmi (9), however, one (A) sphalerite measurement indicates a pressure of 6 kb, whereas the other gives > 10 kb, as do the sphalerite in the triple junction (cf. Tables 1 and 2).

This suggests that the peak pressures of metamorphism during the formation of the various ores in the Vihanti ore zone and in the Tampere schist belt were very similar, about 6–7 kb.

The Outokumpu zone is represented by the data on the Keretti ore body alone (7). The pressure of 5–6 kb is, nearly, the same as that estimated for the Vihanti zone.

The manganese-rich sphalerites from Pattijoki (12a), Sotkamo (13) and Outokumpu (7) pose a special problem (see Fig. 7). At Sotkamo (Kuusilampi) (13b) and Outokumpu the metamorphic pressures are about the same, whereas at Kolmisoppi (13a), as at Pattijoki, low-pressure portions are also encountered.

The schists at Outokumpu and Sotkamo are very alike. The manganese content of the sphalerites is high, 2 wt-% at Outokumpu and 4–6 wt-% at Sotkamo. The only other deposit where sphalerite shows such high manganese contents is Pattijoki (up to 8 wt-%). At Pattijoki and Sotkamo alabandite occurs together with the other sulphides. As discussed by Törnroos (1982), the alabandite was formed at Pattijoki and Sotkamo in the presence of manganese in very reducing environments. Such reducing conditions also favour the formation of black schists, which are present in both areas. The results given by the (A) sphalerites from Outokumpu and Pattijoki (see Table 2) are not different from those given by the forementioned B-type sphalerites in these occurrences. Sphalerites from the Ylipää prospect at Pattijoki give the same pressure

as do those at Outokumpu and Kuusilampi and in some parts of Kolmisoppi.

The formations at Sotkamo and Outokumpu and in some instances at Pattijoki as well show many similarities to each other. The deposits are bordered by or within black schists. At Outokumpu and Sotkamo the ores are associated with a black schist-serpentinite-carbonate-quartz rock assemblage. The grade of metamorphism is, however, different: low to medium at Sotkamo and medium at Outokumpu. The sphalerite contains unusually high contents of manganese. Alabandite is present at Pattijoki and Sotkamo, and problably at Outokumpu as well (Y. Vuorelainen pers. comm.).

It has been demonstrated that small amounts of contaminants in sphalerite do not affect the geobarometer (cf. p. 10). What the case would have been if the manganese content had risen as high as it has at Outokumpu, Sotkamo and Pattijoki, is not known. There might have been a reduction in the model pressure estimates. Because the influence of manganese is unknown, the pressure estimates for these deposits should be accepted with caution.

The lowering of the model pressure at Pattijoki and Sotkamo, however, seems to be too great to be wholly attributed to manganese. It is always possible that low-pressure regimes exist in these deposits.

A regime with such low pressure may be very small in size. The black schists of Sotkamo have undergone tectonisation that has caused lamellae and brecciation in the primary sediments. The breccia is partly filled with remobilised sulphides. In such regimes the pressure is likely to vary substantially from place to place. The grains analysed from specimen 11738 (cf. p. 18) are from remobilised sulphides of this kind. The assemblage sphalerite-pyrite-pyrrhotite is present, but pyrite predominates. Because of tectonisation, it is quite possible that equilibrium was not reached in some places. Under these conditions, the f_{S_2} may not have been completely buffered. Hence, the differences may be due to either disequilibration or variation in f_{S_2} and/or total pressure.

A comparision between pressure estimates on the silicates at Outokumpu (Koistinen 1981) and the sphalerite geobarometer (3.5 ± 1 kb versus 5.8 kb) sheds no light on the problem with manganese. On the other hand, the model pressures for Outokumpu and the Vihanti zone, as given by the sphalerite geobarometer, are practically the same. This seems to suggest that the pressure metamorphism in the ore at Outokumpu differs from that in the surrounding rocks.

The Hammaslahti (6) ore deposit occurs in rocks that, being only slightly affected by regional metamorphism, are intensely deformed (Isokangas 1978), i.e. exposed to cataclastic metamorphism. In other words, although the temperature was low, the pressure may have been high. A high model pressure, such as 7–8 kb at Hammaslahti, may therefore be consistent with the above concept. The sphalerites encapsulated in pyrite gave low model pressures, e.g. 4.0–4.8 kb.

In the Orijärvi–Kimito zone, the data on Attu (1) cluster at 3 kb whereas those on Aijala (3) and Metsämonttu (2) are more spread. At Aijala and Metsämonttu the pyrrhotite inversion to monoclinic modification is more evident. Data on (C) sphalerites are few, and they give clear and anomalously high model pressures (Fig. 7) as does the (A) sphalerite at Aijala (see Table 2). The pressures given by the (A) sphalerites from Metsämonttu range from 4.4 to 6.5 kb, which is slightly (0.5 kb) less than those given by the (B) sphalerites, or in accordance with the suggestion on p. 27.

The sparse occurrence of sphalerite means that the results from Riikonkoski (14) are less reliable. The few grains found are more or less heterogeneous, and the data must be considered with caution. Latvalahti's (1973)

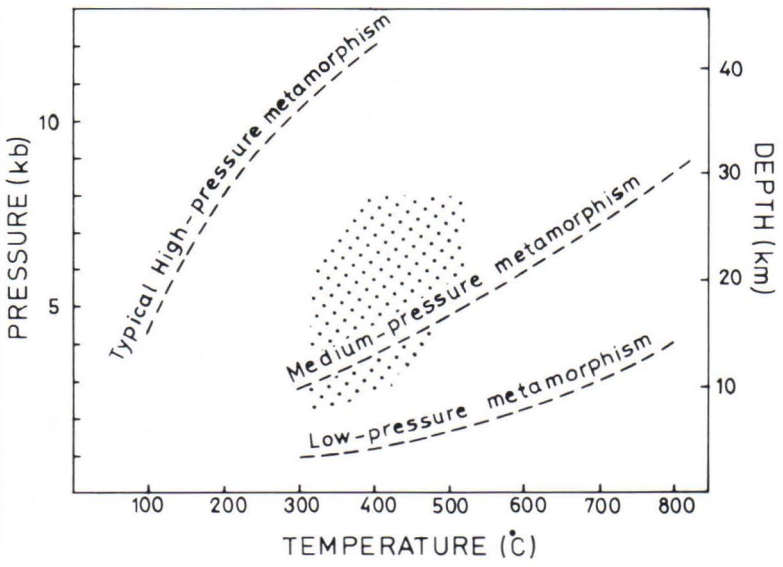


Fig. 6. pT diagram showing the main types of metamorphism after Miyashiro (1973). The shaded area represents the suggested model pressure-temperature conditions of metamorphism in the sulphide ores.

estimate of 4 ± 1.5 kb for Pahtavuoma (15) may be accepted for Riikonkoski as well. As was pointed out on page 23, Fig. 7 shows that the sphalerite geobarometer is of little or no use at Riikonkoski. The data are spread over the entire barometer range, clearly owing to differences in the a_{FeS} and f_{S_2} during regional metamorphism, i.e. equilibrium was not reached.

Characteristic of regional metamorphism is the depth at which a given temperature is attained. According to Miyashiro (1973), there are three main types of metamorphism: low-pressure, medium-pressure and high-pressure (Fig. 6). As a characteristic mineral of the low-pressure type he mentions andalusite commonly accompanied by biotite, cordierite, staurolite and sillimanite. Kyanite is typical of the medium-pressure type and is frequently accompanied by biotite, almandine, staurolite and sillimanite.

In the majority of Finnish Precambrian rocks metamorphism is of the low-pressure type (Simonen & Vorma 1978). According to these authors, the Karelian schist belt as a whole was metamorphosed at a lower metamorphic grade than were the Svecofennidic schists. The Karelides near the Archean basement were metamorphosed under conditions of greenschist facies. Otherwise the conditions of low-pressure amphibolite facies prevailed. In the Svecofennides the metamorphism took place mainly under conditions of low-pressure amphibolite facies, and in some places under conditions of granulite facies.

Most of the sulphide ore deposits investigated in this study belong to the Svecofennides. The ore deposits of Hammaslahti (6), Outokumpu (7), Sotkamo (13) and Riikonkoski–Pahtavuoma (14–15) belong, however, to the Karelides.

The model pressures derived by the sphalerite geobarometer indicate a pressure that corresponds to a lithostatic load of 15 to 30 km (Fig. 6). If it is accepted that the »setting» temperature of the sulphides was 310°–500°C (cf. p. 26), then the type of metamorphism suggested for the ores is slightly above the medium-pressure type (shadowed area in Fig. 6).

CONCLUSIONS

Pyrrhotite is a problematic mineral in sphalerite geobarometry as applied to some sulphide deposits in Finland. It is mostly inverted from the hexagonal high-temperature form to the monoclinic low-temperature form, sometimes depleting sphalerite from FeS. The possibility also exists, especially in occurrences submitted to tectonic movements or brecciation, that equilibrium is not reached and that the f_{S_2} is not completely buffered.

Therefore the sphalerite geobarometer has to be used with caution, and equilibrium conditions must be fulfilled. Carefully selected sphalerite grains in triple junction (sphalerite + pyrite + hexagonal pyrrhotite in mutual contact with each other) give reliable results.

It has been established that the pressure estimates of Finnish ores by the sphalerite geobarometer are roughly compatible with the pressure conditions of the peak of metamorphism estimated with the aid of certain silicate minerals in associated rocks. The sulphide ores have undergone medium-pressure metamorphism. Sometimes, however, the pressures measured on the ores are somewhat lower than those estimated for the surrounding rocks, suggesting that the ore minerals were accumulated in the pressure minima.

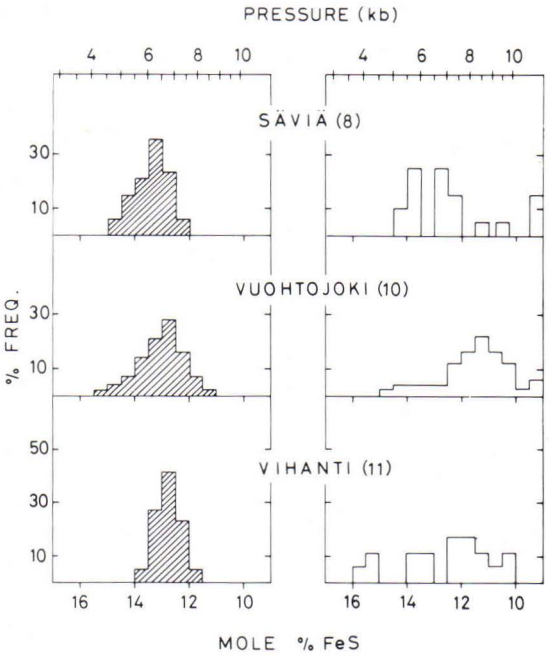
Fig. 1 indicates that the pressures of metamorphism were generally similar in the Vihanti ore zone (points 8–12), the Outokumpu ore district (7) and the Tampere (points 4–5) schist belt, or 6–7 kb. In the Svecofennidic schists in southern Finland and in the Karelides in Lapland the pressure of formation was somewhat lower (3–5 kb). The high manganese-bearing sphalerites at Pattijoki (12a) and Sotkamo (13) give a considerably lower model pressure (1–3 kb). The influence of marked manganese contents on the sphalerite geobarometer has not yet been studied.

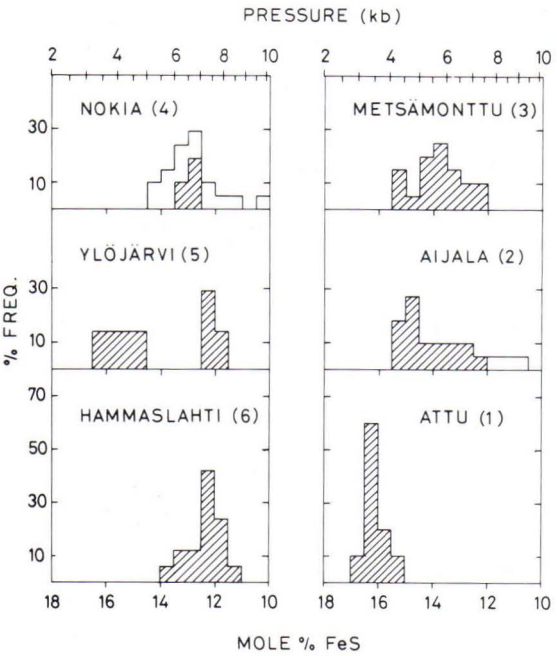
Most of the ores were formed at the boundary of medium- to high-grade metamorphism, at the very limit of the temperature-independent region of the sphalerite geobarometer.

The temperature estimates exhibit large variations, depending on the method used. It should therefore be assumed that during metamorphism the ores were formed at temperatures below the upper temperature limit of the sphalerite geobarometer; hence, corrections due to temperature are not needed.

In the Vihanti ore zone the grade of metamorphism may be low at Pattijoki in the northwest, rising to medium grade towards the southeast. The mean model pressures for the ores in the zone are: 1–2 kb (12a) (Mn-rich sphalerite) and 5.3 kb (12b) for Pattijoki, 6.8 kb for Vihanti (11) and Vuohtojoki (10), 6 kb for Pyhäsalmi (9) and 6.3 kb for Säviä (8). With the exception of Pattijoki, they are all very similar.

The clustering of the data on (C) sphalerites (in contact with monoclinic pyrrhotite) suggests that, after the main metamorphic stage in the Vihanti–Vuohtojoki region, events, most probably hydrothermal, took place, giving rise to re-equilibration reactions at temperatures below 300°C.





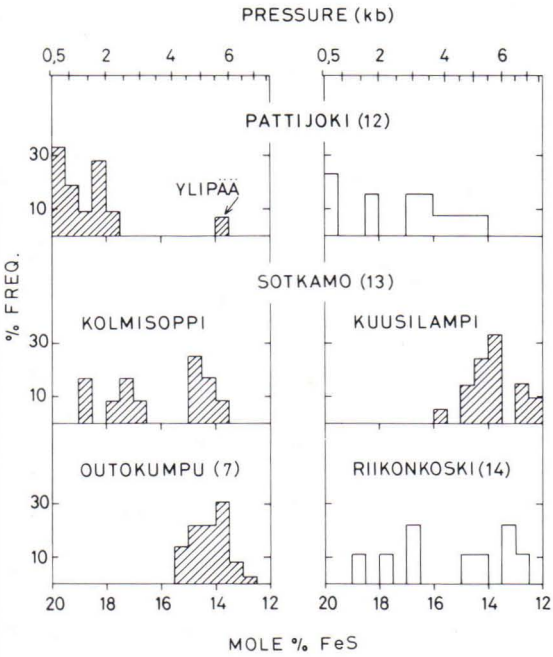


Fig. 7. Frequency histograms of the FeS content of sphalerites in contact with pyrite + hexagonal pyrrhotite (shaded) or monoclinic pyrrhotite (open).

Table 1. Application of the sphalerite geobarometer to the assemblage sphalerite + pyrite + pyrrhotite (h = hexagonal, m = monoclinic, A, B . . . = different deposits within the Vuohtojoki ore).

Location	Sphalerite data				grains	Sample No. Comments	
	mole-% FeS		p (kb)				
	mean	range	mean	range			
Attu (1)	15.5	15.4–15.6	4.1	4.0–4.2	3	R133/106.5	h
	16.3	16.1–16.5	3.4	3.2–3.6	7	/130.5	h
Aijala (2)	14.8	14.5–15.1	4.7	4.6–4.9	3	P-6910	h
	14.6	14.5–14.7	4.9	4.8–5.0	2	P-6913	h
	12.8	12.3–13.3	6.8	6.2–7.3	3	P-6913	h
	13.3	12.8–13.8	6.2	5.7–6.8	3	P-7108	h
	14.5	13.7–15.3	5.0	4.3–5.7	3	P-9060	h
	15.1	14.6–15.5	4.5	4.1–4.9	3	P-9060	h
	15.1		4.5		1	P-9067	h
	14.3		5.2		1	P-9111	h
	6.6	6.2– 7.1		>10	2	P-9098	m
	4.2	3.6– 4.8		>10	2	»	m
	11.3	10.8–11.8	8.5	7.9–9.1	3	»	m
Metsämonttu (3)	13.1	12.2–13.9	6.4	5.6–7.4	4	P-6411	h
	13.4	13.0–13.8	6.1	5.7–6.5	2	P-6417	h
	14.0		5.5		1	P-6442	h
	14.0	13.7–14.3	5.5	5.2–5.8	2	P-6444	h
	14.4	14.3–14.5	5.1	5.0–5.2	2	P-6446	h
	12.9	12.5–13.9	6.6	5.6–7.1	3	P-6447	h
	15.1	14.9–15.3	4.5	4.3–4.6	3	P-6452	h
	13.6	13.1–14.1	5.9	5.4–6.4	2	P-6454	h
	15.5		4.1		1	P-6454	h
	7.1	6.2– 7.8		>10	3	P-6454	m
Nokia (4)	12.8	12.7–13.0	6.7	6.5–6.9	3	2899	h
	12.9	12.5–13.5	6.6	6.0–7.1	3	2990	h
	12.5		7.1		1	2905	m
	13.2	12.4–14.0	6.3	5.5–7.2	3	2991	m
	13.8	13.5–14.1	5.7	5.4–6.0	3	2998	m
	11.0	10.2–11.5	8.9	8.3–9.9	3	3015	m
	13.7		5.9		1	3024	m
	13.4	12.7–14.5	6.1	5.0–6.9	3	3026	m
Ylöjärvi (5)	16.0	15.8–16.2	3.7	3.5–3.8	2	2118	h
	15.1	14.8–15.3	4.5	4.3–4.7	2	»	h
	12.1	11.6–12.5	7.5	7.1–8.2	2	»	h
Hammaslahti (6)	11.9	11.2–12.7	7.8	6.9–8.7	9	9717	h
	12.1		7.5		1	9718	h
	12.3	12.1–12.9	7.3	6.7–7.5	3	9719	h
	12.4	12.4–12.4	7.2	7.2–7.2	2	9720	h
	13.5	13.1–13.9	6.0	5.7–6.4	3	9721	h
Outokumpu (7)	14.6	14.4–14.9	4.9	4.6–5.2	2	P-10107	h
	14.3	13.5–15.3	5.3	4.3–6.1	3	P-10117	h
	14.5	13.9–15.0	5.1	4.6–5.6	4	P-10170	h
	13.8	13.5–14.2	5.7	5.4–6.0	2	P-10121	h
	12.8		6.8		1	P-8822	h

Table 1. cont.

Location	Sphalerite data: mole-% FeS mean	mole-% FeS range	p (kb) mean	p (kb) range	grains	Sample No. Comments	
Säviä (8)	14.1	13.7–14.4	5.4	5.1–5.8	3	9026	h
	12.9	12.5–13.4	6.6	6.1–7.1	2	9028	h
	12.8		6.8		1	9038	h
	13.3	13.1–13.5	6.2	6.0–6.5	3	9041	h
	13.3	12.5–14.0	6.3	5.6–7.1	8	9042	h
	14.2	13.8–14.7	5.3	4.8–5.7	3	9209	h
	13.9	13.8–14.1	5.6	5.4–5.8	2	9210	h
	13.1	12.7–13.5	6.4	6.0–6.9	8	9221	h
	14.0	13.1–14.8	5.5	4.8–6.4	4	9222	h
	14.6	14.1–14.9	5.0	4.7–5.4	2	9261	h
	13.7	13.0–14.5	5.8	5.0–6.5	2	9206	h
	12.7	12.5–12.9	6.9	6.6–7.1	2	8955	m
	13.4	12.1–14.1	6.1	5.4–7.5	10	8956	m
	13.6		5.9		1	8994	m
	12.6		7.0		1	9015	m
	10.1	9.4–12.1	~10	7.4–>10	6	9219	m
Pyhäsalmi (9)	4.7	3.9– 6.2	>10		3	21509	h
Vuohtojoki (10)	13.2	13.0–13.4	6.3	6.2–6.5	4	5919 D	h
	12.5	12.3–12.8	7.1	6.8–7.4	2	5920 D	h
	13.7	13.4–13.8	5.9	5.7–6.1	2	5923 D	h
	12.9	12.5–13.3	6.7	6.3–7.1	3	5930 D	h
	12.6	12.3–13.0	7.0	6.6–7.4	5	5931 D	h
	13.0	12.5–13.2	6.5	6.3–7.1	8	5932 D	h
	13.1	12.7–13.6	6.4	5.9–6.9	4	5934 D	h
	12.3	12.0–12.6	7.3	7.0–7.7	2	5971 A	h
	14.4	13.9–14.8	5.2	4.7–5.6	3	6093 H	h
	13.6	13.1–14.5	6.0	5.0–6.4	5	6094 A	h
	13.3	12.2–14.0	6.2	5.5–7.4	3	6095 A	h
	14.8	14.2–15.3	4.8	4.3–5.3	3	6097 H	h
	13.8	13.0–14.3	5.7	5.2–6.5	3	6145 D	h
	12.0	11.6–12.3	7.7	7.3–8.1	2	6148 A	h
	13.5	13.3–13.7	6.0	5.8–6.2	2	6310 D	h
	12.2	11.8–12.5	7.5	7.1–7.9	3	6746 A	h
	11.7	11.1–12.1	8.0	7.5–8.8	3	6749 A	h
	10.1	10.1–10.1		~10	2	5902 B	m
	10.8	10.2–11.3	9.2	8.6–9.9	6	5971 A	m
	9.0	8.9– 9.3		>10	4	6018 A	m
	13.2	12.9–13.6	6.3	5.9–6.7	6	6021 D	m
	11.6	10.5–12.6	8.2	7.0–9.5	6	6026 C_1	m
	11.5	10.7–12.1	8.2	7.5–9.3	8	6031 C_1	m
	10.0	9.4–10.4	>10	9.7–>10	6	6035 C_1	m
	11.3	11.2–11.4	8.5	8.4–8.6	3	6094 A	m
	10.1	9.0–10.9	>10	9.0–>10	3	6095 A	m
	10.9	10.4–11.7	9.0	8.0–9.7	5	6099 H	m
	13.9	12.9–14.7	5.6	4.8–6.6	4	6145 D	m
	10.9	10.5–11.1	9.0	8.8–9.5	3	6148 A	m
	14.3	13.9–14.7	5.2	4.8–5.6	4	6311 D	m
	12.1	11.6–12.5	7.6	7.1–8.1	3	6314 B	m
	11.0	10.7–11.2	8.9	8.6–9.3	5	6328 A	m
	11.9	11.5–12.2	7.8	7.4–8.3	7	6748 A	m
	10.9	10.2–11.5	9.0	8.3–9.9	6	6750 A	m

Table 1. cont.

Location	Sphalerite data mole-% FeS mean	range	p (kb) mean	range	grains	Sample No. Comments	
Vihanti (11)	12.9	12.7–13.2	6.6	6.4–6.8	2	2317	h
	12.8	12.6–13.0	6.8	6.6–7.0	2	2318	h
	12.9	12.5–13.3	6.7	6.3–7.1	2	2343	h
	12.7	12.3–13.0	6.9	6.6–7.3	4	2355	h
	13.2	13.0–13.4	6.3	6.1–6.5	3	2367	h
	13.2	12.6–13.7	6.4	5.8–7.0	2	2612	h
	12.2	11.7–12.5	7.4	7.1–8.0	4	2618	h
	12.7	12.4–13.0	6.9	6.6–7.2	3	2621	h
	14.4	13.0–15.9	5.2	3.7–6.5	3	2238	m
	11.6	11.3–11.9	8.1	7.8–8.5	3	2316	m
	11.9	11.5–12.2	7.8	7.5–8.2	2	2317	m
	11.1	10.2–12.2	8.8	7.5–9.9	4	2322	m
	10.9	10.5–11.1	9.0	8.8–9.5	3	2367	m
	13.4	13.0–13.8	6.1	5.7–6.5	3	2612	m
Pattijoki (12a)	17.6		2.3		1	3776	h
	21.0	20.3–21.7	0	0.0–0.3	2	3771	h
	18.0	17.8–18.2	2.0	1.8–2.1	2	3865	h
	18.3	18.1–18.4	1.8	1.7–1.9	2	6265	h
	18.2		1.8		1	6267	h
	18.1	18.0–18.1	2.0	1.9–2.0	2	6269	h
	19.1	18.6–19.6	1.2	0.8–1.5	4	6271	h
	19.7	19.0–20.6	0.8	0.2–1.3	6	6273	h
	14.6	14.2–15.2	4.9	4.4–5.3	3	3861	m
	20.1	18.0–22.2	0.5	0–2.0	2	3917	m
	16.9	16.9–16.9	2.9	2.9–2.9	2	6266	m
	16.2		3.5		1	6267	m
	16.1	15.9–16.4	3.5	3.4–3.7	2	6269	m
	18.6		1.6		1	6270	m
	20.2	20.2–20.3	0.4	0.3–0.4	2	6271	m
Pattijoki (12b) (Ylipää)	14.1	13.9–14.3	5.4	5.2–5.6	3	5431	h
Sotkamo,	14.6	14.4–14.8	4.9	5.1–4.7	3	11738	h
Kolmisoppi (13a)	17.0	16.8–17.5	2.8	3.0–2.4	3	11738	h
	18.0	17.4–18.6	2.0	1.6–2.5	5	11740	h
	14.3	13.7–14.9	5.2	4.6–5.8	4	11744	h
Kuusilampi (13b)	12.7	12.4–13.0	6.9	6.5–7.2	5	11790 (outside ore)	h
	14.6	13.6–15.6	4.9	4.0–5.9	8	11746	h
	14.1	13.8–14.4	5.4	5.1–5.7	4	11749	h
	14.3	13.7–14.9	5.2	4.6–5.8	4	11752	h
Riikonkoski (14)	13.3		6.3			12288	
	17.4	17.0–17.7	2.5	2.2–2.8	2	12288	
	18.7		1.5		1	196	
	16.5		3.2		1	196	
	14.4		5.1		1	196	
	13.9	12.9–14.9	5.6	4.6–6.7	3	10059	

Table 2. Application of the sphalerite geobarometer to sphalerite grains encapsulated within pyrite. (D and C_1 as in Table 1).

Location	Sphalerite data mole-% FeS	p (kb)	grains	Sample No.
Aijala (2)	11.1	8.8	1	P-9060
Metsämonttu (3)	13.1–13.8	5.7–6.5	2	P-6444
	15.2–16.3	3.4–4.3	3	P-6447
	14.7	4.9	1	P-6452
	13.3	6.2	1	P-6454
Nokia (4)	12.1	7.5	1	2899
Ylöjärvi (5)	8.2	>10	1	2064
	3.9	>10	1	2080
	13.5	6.0	1	2127
Hammaslahti (6)	14.7–15.6	4.0–4.8	3	9721
Outokumpu (7)	12.8–13.5	6.1–6.7	2	P-10130
Säviä (8)	12.9	6.6	1	9206
	14.0	5.5	1	9209
	13.0–16.0	3.7–6.5	2	9210
Pyhäsalmi (9)	13.5	6.0	1	51
	5.5	>10	1	21509
Vuohtojoki (10)	13.3	6.2	1	6021 D
	13.5	6.0	1	6087 C_1
Vihanti (11)	12.9–15.3	4.3–6.7	2	2322
	13.8–14.0	5.5–5.7	2	2612
Pattijoki (12a)	19.6	0.8	1	5811

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