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EXAMINATION OF POLISHED THIN SECTIONS FROM SAMATOSUM DEPOSIT FOCUSSING ON SULFIDE RELATIONSHIPS AND ORE GENETIC MODELS

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Introduction

An extensive suite of polished and polished thin sections was submitted by Alan Hill, Project Geologist, Minnova Inc., Box 255, Barriere, B.C. V0E 1E0. The suite had been examined previously in a predictive metallurgical study by D.J.T. Carson of Noranda (Carson, 1988). The object of the present work was to study the sulfide textures and relationships with a view to determining, if possible, the relative order of crystallization of the sulfides, and to consider evidence of exsolution, replacement, reaction, remobilization, overgrowths, etc. In addition, any conclusions bearing on the genesis of the deposit (VMS, or volcanogenic, model versus vein system model) were to be made if possible.

The suite contains a total of 96 sections of samples collected from 24 drill holes and Trench #3, from all of zones I, II, and III, and both massive and disseminated ore types. In order not to limit the effectiveness of the textural and genetic study carried out here, all sections were examined, but the descriptions are "composites", with emphasis on sections that contained illuminating relationships. No time was spent on mineral identification, since the work by Carson (1988) had adequately covered this aspect of the work. Most attention was focussed on the massive ore samples, since this is where any primary synvolcanic textures tend to be best developed and have the best chance of being preserved (the disseminated portions from the lower parts of the deposit tend to be overprinted even before cessation of volcanism, by continued hydrothermal activity).

Descriptions

Massive and Disseminated ore

-some traces of rounded (?framboidal) pyrite in RG-89-52, where it has been mostly recrystallized. However, the coarse euhedral pyrite is not everywhere an obvious overgrowth on the fine pyrite. Some framboidal pyrite was also found by Holder (1988: see her Plate 10) in a Geology 428 term project.

-however, abundant framboidal pyrite (in process of being recrystallized to coarser pyrite: see Fig. 6 of Leitch, 1981, copy enclosed) is present in RG-99-75.5, and a large area of former fine ?framboidal pyrite, now overgrown by and recrystallized to coarser euhedral pyrite, is present in RG-102-76. Fine and very fine pyrite (5-15 microns), some with spheroidal and/or atoll texture, is also present in RG-118-163.0; it appears in places to be overgrown by very coarse (1-2 mm) pyrite. Similar relations (fine pyrite, some with atoll texture, almost lost in and overgrown by much coarser pyrite) are also seen in RG-122-237/238 and to a lesser extent in RG-136-56.5 and RG-137-54.7/55: compare to Figs. 4 and 6 of Leitch (1981) for interpretation.

-distinct colloform ("spheroidal") textures of pyrite in tetrahedrite in RG-99-72. These are very similar to those described from Turkey (see Fig. 2b of Leitch, 1981; see also Leitch, 1990, Can. Mineralogist, March issue). There are also traces of ?colloform texture remaining in tetrahedrite, and atoll texture with cores of galena in tetrahedrite rims (RG-99-74).

-there are distinct vestiges left in RG-102-249 of collomorphic and radiating cockscomb texture, typical of pyrite pseudomorphs after marcasite (see Fig. 5a and d of Leitch, 1981, and similar textures from the offshore massive sulfides sketched in Leitch, 1990).

-"globular" texture of sphalerite (e.g.in RG-89-52, 105-63.5, 70.8, and also possibly RG-137-57) is suggestive of VMS type ore (the rounded shapes are reminiscent of round collomorphic balls, either from replacement of tube worm holes or otherwise: see references in Leitch, 1990). (However, where rounded sphalerite is present in a "sea" of galena, it is more likely that they are the product of deformation, by milling of the harder sphalerite in the more easily remobilized galena: see RG-108-36.9 or TR-3A.)

-similarly with pyrite (and sphalerite?) textures in 89-51.2: suggestive but not conclusive of syn-volcanic sulfide deposition.

-general cubic pyrite (e.g. RG-64-89.5) could be a later overprint; it looks different from the fine-grained pyrite. However, even this pyrite looks to be pre-metamorphic (pressure shadows around the harder pyrite of the softer galena, sphalerite and muscovite: e.g. RG-118-163.0). Also, these pyrites are <u>zoned</u>, with inclusions of galena (see photo 3 of Carson, 1988) around their margins, suggesting that the outer parts could be <u>overgrowths</u> (?this could have occurred during metamorphism). Similar overgrowths are also probably responsible for atoll textured pyrite-galena in RG-105-70.8. The anisotropy and colour variation in the euhedral pyrite (attributed by Carson, 1988 to variation in Ni content) is remarkable in this deposit and bears further investigation (it could also be due to variation in As content). In my 1981 study, I found that even in apparently optically clean, euhedral (epigenetic) pyrite, there was a "cellular" structure evident in As and Cu contents, that was distinguishable only by microprobe; I wonder if the same could be true of the Samatosum coarse pyrite.

- a definite vein origin for the coarse (0.5 cm) euhedral pyrite in RG-135-237, and probably the same for RG-137-54; these could well represent part of the vent or feeder zone for the deposit.

-some of the disseminated, but Ag-Cu-Zn-rich, ore (e.g. in RG-137-49.5, 51; as opposed to disseminated pyritic samples) is simply massive carbonate, ±quartz, with intergrown sulfides (sphalerite, tetrahedrite, chalcopyrite) that all look to have crystallized together. Again, this could be evidence to support a vein origin for the deposit, or it could be interpreted as the (lower) part of asynvolcanic deposit where epigenetic mineralization is not only possible but is usually the rule.

-a synvolcanic origin is suggested by the general banded or layered texture of much of the massive ore (and some of the disseminated ore: e.g. RG-109-141/142); this could be due to either primary deposition (or later metamorphic remobilization, by transposition of original layering into S_1). Vague remnants of a possible original colloform banding of sphalerite in chalcopyrite, but now strongly deformed, may be visible in RG-97-17.4; similarly, in RG-132-201.5, "veins" of sphalerite (and gangue) in massive chalcopyrite could represent partly transposed layers.

-there is evidence of folding of layers of tetrahedrite-sphalerite-galena-muscovite-carbonate in RG-102-80 (and 105-70, 70.8; this, combined with rare vague atoll textures of the sphalerite and tetrahedrite, suggest original layering that has been deformed. In this specimen, an earlier (?S_0) foliation may be present across the S_1 layering, as evidenced by galena and sphalerite inclusions in tetrahedrite (this foliation is not seen in the adjacent muscovite).

-the quartz and carbonate, and of course the muscovite, show evidence of a lot of strain, probably multiple since several foliations can be seen in the quartz at oblique angles.

-I am not sure what to make of the massive tetrahedrite samples (e.g. RG-64-89.5; RG-137-52.5/53.8); there are vestiges of circular structures in them, which are not, however, conclusive. I have personally not seen such high (e.g. RG-64-89.5) concentrations of, or such coarse, tetrahedrite in typical "Kuroko" (black) ore; however, the general appearance is similar - it's just that the proportions of galena and tetrahedrite are reversed from normal. (Carson, 1988, mentions abundant tetrahedrite in the Greens Creek deposit in Alaska, which is also precious-metal rich.) On the other hand, look at the difference between RG-64-89.5 and 89.9; only 40 cm apart, and the latter is tetrahedrite-rich but only disseminated (Carson's classification of 89.5 as disseminated is clearly wrong). At 89.9 m, the gangue is quartz and muscovite, possibly a highly altered ?felsic volcanic; but whether the replacement was close in timing to the volcanism (i.e. a syn-volcanic process) or much later (i.e. a quartz-vein type of deposit) is not obvious. I would favour the former on the basis of the (limited) evidence I have here. In any case, there is no reason why quartz-carbonate veining (as in RG-71-106.3) could not be part of a synvolcanic stockwork or feeder zone, at least without knowing the field relations).

-could the tetrahedrite be an overprint by continuing hydrothermal activity, or even a completely separate event, on earlier VMS sulfides? (There are rare thin stringers of tetrahedrite seen cutting sphalerite, e.g. in RG-136-58, but this and other slides contain numerous thin carbonate and/or quartz stringers also; and similar veins of tetrahedrite/galena in pyrite in RG-137-56 are clearly the result of remobilization of the softer, more easily recrystallized minerals into fractures in the brittle pyrite.)

-however, the massive coarse-grained (and I mean massive) sulfides in RG-97 are not typical of VMS; they could represent remobilized sulfides, as suggested by the monomineralic character and very coarse grain size, or sulfides from a stockwork feeder zone.

-general absence of barite in the massive, sphalerite-galena-tetrahedrite ore is a bit puzzling (yet barite is present at the original Rea Gold discovery and in the Barite zone northwest of the Samatosum deposit, and possible barite as coarse bladed crystals up to 0.5 mm long was seen in a few of the samples examined in this study, e.g. RG-102-76, RG-132-201.5).

-the significance of the albite in RG-102-75/76 is not obvious; it might suggest an orthogneiss, or intrusive (it is not from primary phenocrysts in a volcanic rock).

Discussion and Conclusions

"Exsolution" textures are best developed in the abundant chalcopyrite disease in sphalerite (see photomicrographs in Carson, 1988). Even this has been questioned in recent years (the amount of Cu in the chalcopyrite inclusions is too great to have ever fitted into the ephalerite lattice, at any temperature), and so it may be better explained as a replacement of sphalerite by Cu-rich solutions. In one sample (RG-107-23.2), the fine chalcopyrite in sphalerite could be explained as rows of inclusions that formed as chalcopyrite and sphalerite were precipitated together in layers and collomorphic shapes, which were then partially transposed into the plane of S_1 by deformation. Also, the inclusions in sphalerite are often pyrite rather than chalcopyrite (s.g. RG-99-77.6) which may also be the result of replacement, or of being included as the sphalerite was deposited (or as it recrystallized).

Most grain boundaries between different minerals (e.g. sphalerite-galena, galena-tetrahedrite, etc.) are merely mutual boundaries, and therefore are non-definitive for replacement or reaction. I see no clear evidence for reactions between any sulfides, or replacement of any sulfide by any other, although in a few instances there is rimming (usually between tetrahedrite and some other mineral, such as pyrite or chalcopyrite in RG-108-35.8; see also Carson, 1988, for photos of gersdorffite rimming tetrahedrite and chalcopyrite). The presence of arsenic- and nickel-bearing minerals such as gersdorffite and arsenopyrite in the deposit is noteworthy, and it is interesting that they should have possible reaction relationships with tetrahedrite; it raises the possibility that As and Ni addition was later than the other Fe-Cu-Zn-Pb sulfides. In particular, this might help to explain the unusual abundance of tetrahedrite compared to most VMS deposits -- although such addition need not be much later; it could also have been synvolcanic, as part of ongoing hydrothermal activity, or renewed activity.

It is not possible to tell what the "order of crystallization" is (or was): all one can see now is an order of ease of re̲crystallization. The minerals are clearly recrystallized, with the softest ones (galena, chalcopyrite, tetrahedrite) being most easily remobilized around the harder pyrite.

However, there are some indications of possible synvolcanic deposition in the most refractory material (pyrite) which resists recrystallization the most: e.g., some traces of atoll and "frog's-egg" texture, and occasional framboids, plus some colloform ("spheroidal") and radiating cockscomb texture remain. These traces are typical of the textures in VMS deposits, and the overgrowth and recrystallization textures indicate these primary textures may have been first overprinted by ongoing hydrothermal activity at the time of volcanism and then later by metamorphism and deformation. There is more remnant framboidal/colloform texture in the massive ore type of these slides than in all the Windy Craggy slides I have seen, and the origin of Windy Craggy is unquestionably VMS.

The deposit is too metamorphosed and/or recrystallized to be able to interpret genesis (VMS versus later quartz vein) confidently. In particular, one cannot stress too much the need for field relations, hand specimens (I can't even see whether a given sample is from a quartz vein or not; are there stockwork zones?), or other gross relations such as: metal zoning, tops (i.e. massive ore overlying disseminated-stockwork ore, etc.) to help in interpretation. However, my subjective reaction (after purely polished thin section examination) is that there is evidence for an original VMS origin that has been largely obliterated by later hydrothermal activity and metamorphism. This would need to be supplemented by field observations to generate more confidence in the opinion.

Sulfides have generally not (except for minor amounts in RG-106-132.9) developed typical annealing textures, or triple point junctions at 120 degrees, so characteristic of highly deformed and recrystallized deposits such as Goldstream or Sullivan. Possibly (as with the quartz, which has been strongly strained but not recrystallized), the strain rate was too high to allow readjustment by annealing (slow crystal reequilibration).

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Mineralogy and Textures of the Lahanos and Kızılkaya Massive Sulphide Deposits, Northeastern Turkey, and their Similarity to Kuroko Ores

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A distinct vertical zonation very similar to that described for the Kuroko deposits of Japan, is displayed by both mineralogy and textures of sulphides from the Lahanos and Kızılkaya massive sulphide deposits of northeastern Turkey. A deeper erosional level is exposed at the Kizılkaya deposit, so that only remnants of the massive sulphide ore zone are present. The zonation is from an upper zone of massive Cu and Zn sulphides (black and yellow ore) with fine-grained, colloform, banded, framboidal, and spherulitic textures, downwards through an intermediate zone of low Cu-Zn massive pyrite with transitional textures, to a lower zone of stockwork and impregnated pyrite displaying euhedral, zoned textures. The fine-grained and colloform pyrite of the upper zones is progressively overgrown by, and recrystallized to, the massive and euhedral pyrite of lower zones. The original textures of these deposits are best preserved by pyrite. The previous interpretation of these textures, of sulphide deposition from colloidal solutions ponded by an impermeable pyroclastic horizon, is reexamined in the light of present observations. Although ultra-fine-grained sulphides, framboids, and radially-cracked spherules could have formed by replacement of pre-existing minerals by a colloidal solution, the colloform and banded textures are indicative of growth in open spaces. It thus seems likely that the fine-grained colloform sulphides, including chalcopyrite, sphalerite, and tennantite as well as pyrite, were initially deposited on or near the surface of the sea-floor. Additional evidence for this interpretation is seen in the progressive recrystallization of the sulphide textures to massive, much coarser, pyrite in the lower zones. This recrystallization may in part be due to diagenetic and hydrothermal processes operating after formation of the original layered sulphides. These conclusions are in agreement with those reached for the similar, but larger Madenköy deposit 100 km to the east.

INTRODUCTION

In the course of a geochemical study of trace-element zonation in two Turkish massive sulphide deposits, Lahanos and Kizılkaya, a variety of textures indicative of syn-sedimentary deposition of sulphides were noted (Leitch, 1975). Colloform, banded, and spherulitic textures are displayed by pyrite, chalcopyrite,

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sphalerite and tennantite, and are similar to textures described from the Kuroko deposits of Japan. The two Turkish deposits appear to represent different, but over-lapping, erosional levels of massive sulphide deposits: at Lahanos, the main workings are in typical black and pyritic ore types, and lower levels in the mine and in drill core show a transition from massive pyrite to root-zone disseminated and stockwork pyrite. At Kızılkaya, most of the exposures are below the base of the massive pyrite zone, in the root zone. Massive black and "yellow" ore may once have existed at Kızılkaya but is now present only in two small down dropped grabens which were partially mined out in ancient times.

PREVIOUS WORK

A very detailed description of the ore mineralogy at Lahanos is given by Tuğal (1969), and a brief résumé is given in Tuğal and Phillips (1971). The mine geology has also been studied in detail by Hattie (1970). Vujanovic (1974) made a study of allthe deposits of the Eastern Pontid zone, and the reader is referred to his photomicrographs for examples of the textures found in these deposits. Earlier brief descriptions of Lahanos were made by Pollak (1961) and Schultze-Westrum (1961). The only previous widely published mineralogical descriptions of the Kızılkaya deposit is by Vujanovic (1974).

LOCAL GEOLOGIC SETTING

The area containing the deposits is situated in the Pontid tectonic zone of Turkey which is believed to have been part of a Mesozoic-Paleogene island arc running from the Carpathians and Balkans in Europe along the Black Sea coast and into the Minor Caucasus of the USSR (Gümüş, 1970; Dixon and Pereira, 1974). In particular, the deposits fall within the "Pyritic Belt" of Pejatovic (1971). Culmination of this orogen, lying north of the Anatolian massif, was in the Alpine orogeny of Oligocene time, although the Tethyan island arc system developed over a time span from Jurassic to Eocene.

A generalized stratigraphic section (after Kovenko, 1944, and Tuğal, 1969) is given in Table 1. The deposits occur in Upper Cretaceous differentiated calc-alkaline volcanics, which rest upon marine sediments of Upper Jurassic-Lower Cretaceous age. A post-mineral cover is formed by Eocene basic volcanic and flysch.

The volcanic series around the deposits consists of three main units: Lower Basic series, Lower Volcanics, and Upper Volcanics. The Lower Basic series is composed of basal spilitic and basaltic lavas. These are overlain by the Lower Volcanic dacite flows, and andesite flows and pyroclastics altered to resemble dacites, which are called the "Ore Dacite" throughout this part of northern Turkey, to as far away as Murgul. The Lahanos and Kızılkaya deposits are at the top of this "Ore Dacite", and are overlain by the Upper Volcanic series, composed of darker, more basic volcanics. This intra-to post-mineral cover comprises flows and pyroclastics of pyroxene andesite and flows of pyroxene basalt. A quartz-biotite-pyroxene monzonite porphyry intrudes both Lower and Upper Volcanic series and is also post-mineral.

The Lahanos deposit is composed of an oval lens of massive sulphides with maximum dimensions of 700 m by 400 m by 40 m thick. This lens is mainly pyritic with zones of better copper/zinc mineralization (black and yellow ore pockets, 50 m wide by 150-300 m long) in its upper parts, underlain by stockwork and disseminated pyrite. Ore reserves were estimated (Pollak, 1961) at 8 million tonnes at 40% S, 1.6% Cu, including 2.3 million tonnes of 3% Cu, 2.3% Zn. Pollak also outlined facies changes in the volcanics underlying the ore horizon; a "dacite tuff" shows greatest thickness coincident with the center of the deposit,

Table 1. Generalized stratigraphic section, eastern black sea coast (Turkey)*

CENOZOIC	Quaternary			Alluvium	
	Pliocene			Terraces, basalts.	
	Oligo-Miocene			Tuffites, marls, limestones, basalts, flysch.	"Young Basic" Series
	Eocene			Sandstones, shales, conglomerates, andesites.	"Upper Volcanic" (Basic) Series
MESOZOIC	Cretaceous	Upper	Senonian	Andesites, dacites, limestone.	"Lower Volcanic" (Ore Dacite) Series
			Turonian	Andesites, basalts, tuffs, agglomerate.	"Lower Basic" Series
		Lower	Aptian-Albian	Shales, conglomerates, sandstones, marls. (Flysch)	
			Neocomian	Marls, limestones, sandstones.	
	Jurassic	Upper	Malm	Limestones, marls sandstone, gonglomerate.	
		Lower	Lias	Sandstone, conglomerate, marls, spilites, diabasic tuffs.	
PALEOZOIC	Permo-Carboniferous			Arkosic, sandy schists, quartzites with intercalated tuffs, lavas, limestones.	
	Undifferentiated (Basement)			Mica schists, quartzites, greywackes, phyllites, marbles, greisses, granites.	

*After Kovenko (1944) and Tuğal (1969)

and an agglomerate equivalent gradually thickens outwards from the center. An area of bleaching overlies the deposit in the Upper Volcanic series, progressing inwards from propylitic alteration of mafics, to kaolinization and sericitization of feldspars, accompanied by tiny euhedra of pyrite. In the volcanics of the ore horizon, the massive sulphide and footwall stringer zones are accompanied by strong quartz/sericite/clay/pyrite alteration (Hattie, pers. comm. 1980). Dykes of purplish pyroxene andesite similar to the Upper Volcanics cut the orebody.

The geology at Kızılkaya is relatively simple: almost all outcrops are of a pre-mineral altered coarse porphyritic andesite, i.e., the "Ore Dacite" of the Lower Volcanic series, with only two outcrops of post-mineral, purplish fine porphyritic andesite of the Upper Volcanic series. The deposit occupies the summit of a ridge 3 km southeast of Lahanos, and probably represents a slightly higher section of the same important Lower Volcanic unit that contains the Lahanos deposit. An area of stockwork quartz/pyrite veins and disseminated pyrite, 1500 m long by 500 m wide, contains an elliptical central zone, 300 m by 200 m, of stronger Cu-Zn mineralization (reserves estimated at up to 10 million tonnes of 1% Cu and 1.5% Zn, over a vertical interval of 70 m; M.T.A.[1] internal report, 1974). The pyritized area is coincident with strong quartz-sericite alteration, with a central area of clay/diaspore alteration (Hattie, pers. comm. 1980).

SULPHIDE MINERALOGY

A total of 24 polished sections from Lahanos and 15 from Kızılkaya were prepared. The hypogene sulphides identified were: pyrite, marcasite, chalcopyrite, bornite, chalcocite, normal covellite, sphalerite, galena, and tetrahedrite-tennantite. Rare inclusions in pyrite of a seleniferous bismuthinite, and tetradymite (BiTeS) were also identified by microprobe. A distinct vertical zoning of minerals is evident in the Lahanos deposit, with the lower zones corresponding to the studied zones at Kızılkaya. This zoning has also been defined by Tuğal (1969), and is very similar to that of the Kuroko deposits, reviewed by Lambert and Sato (1974), as can be seen from the comparison in Table 2. In summary, the zoning is from black ores with abundant barite and base-metal sulphides (chalcopyrite, bornite, sphalerite, galena, tennantite) near the top, downwards through massive pyrite ores, to pyritic stockworks with only traces of base-metal sulphides.

Pyrite is the most abundant sulphide present, occurring in all the samples studied. Marcasite however, was only seen in one specimen of black ore from Lahanos. However, its presence, now replaced by pyrite, could be suspected in other samples from the upper zones, from relict radiating cockscomb structures (Fig. 5a) known to be typical of marcasite (Boctor et al., 1976). Tuğal (1969) also describes marcasite in the upper ore zones. Chalcopyrite is the second most abundant sulphide, being most common toward the top of the pyritic horizon. Here it is present mainly as infillings of cracks between and in pyrite grains, and locally as larger separate masses in "yellow" or black ore, or as patches of extremely fine-grained pyrite/ chalcopyrite mixtures. Bornite has a similar distribution to that of chalcopyrite, but is much less common; hypogene chalcocite and covellite are relatively rare.

Sphalerite is almost as widespread as pyrite in the samples studied, albeit normally in very small amounts. It forms almost ubiquituous, tiny (10 - 100 µm) rounded inclusions in pyrite and silicates, and shows red-brown to honey-brown pale internal reflections. Larger separate grains of sphalerite occur near the top of the massive pyritic horizon, and in black ore sphalerite is present mainly as very fine grains (5 - 25 µm). Galena is relatively uncommon in the sections studied. At higher levels in Lahanos it is present as separate grains, 100 - 500 µm across; in black ore it is coarser (0.5 mm) and commonly lies at the center of a coarse chalcopyrite mass. It appears mainly as rare inclusions with bornite in Kızılkaya specimens and specimens from lower levels in Lahanos. The only sulphosalt phase identified is tennantite, the As-rich end member of the series with tetrahedrite (range from Tn_{100} Tet_0 to Tn_{55} Tet_{45}, analyses by microprobe). It shows unusual brilliant ruby-red internal reflections where it is in very fine-grained aggregates as noted above. It also occurs in upper Lahanos zones as 0.1 - 0.2 mm irregular-shaped grains intergrown with chalcopyrite, galena, bornite, and sphalerite.

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[1] M.T.A. = Maden Tetkik ve Arama Enstitüsü (Turkish Geological Survey)

Table 2. A comparison of mineralogical and textural zoning in Kuroko and Turkish deposits*

KUROKO			EASTERN TURKEY			
Mineralogy	Textures			Mineralogy	Textures	
Sphalerite-galena Chalcopyrite-pyrite. Tetrahedrite-tennantite, enargite, argentite Gangue: barite	Massive Colloform Very fine grained Framboidal Concentric Shrinkage "Pellet"	KUROKO (Black)	"I" ↓ "II" ↓	Upper: bronite, chalcopyrite, galena pyrite, tennantite, marcasite, gold. Lower: sphalerite-galena-chalcopyrite pyrite-tennantite enargite. Gangue: barite.	Massive Colloform Very fine gr. Framboidal Concentric Shrinkage Spherulitic Botryoidal "Egg-yolk" "Radial bomb" "Shelly"	Mineralization in open space (sea floor or uncompacted sediments)
Pyrite-chalcopyrite (± sphalerite). Complex Cu, Pb, Bi, Sb, sulfosalts, bornite Gangue: barite, fluorite quartz	Massive Breccia fragments Powdery Slumps	OKO (Yellow)	"III" ↓	Pyrite-chalcopyrite Traces of bornite, Bi, Pb, Te, Se, Sb minerals (sulposalts) Gangue: dolomite	Massive Breccia fragments	
Pyrite Gangue: quartz	Massive	RYUKAKO (Pyrite)	"IV" ↓	Pyrite Gangue: quartz	Massive Breccia fragments	
Pyrite-chalcopyrite quartz stockwork	Euhedral crystals but also as colloform. Vein and disseminated.	KEIKO (Siliceous)	↓	Pyrite-chalcopyrite quartz stockwork Bornite, neodigenite and covellite as minute inclusions	Euhedral crystals Rare framboids Vein and disseminated.	Mineralization in pre-existing rock

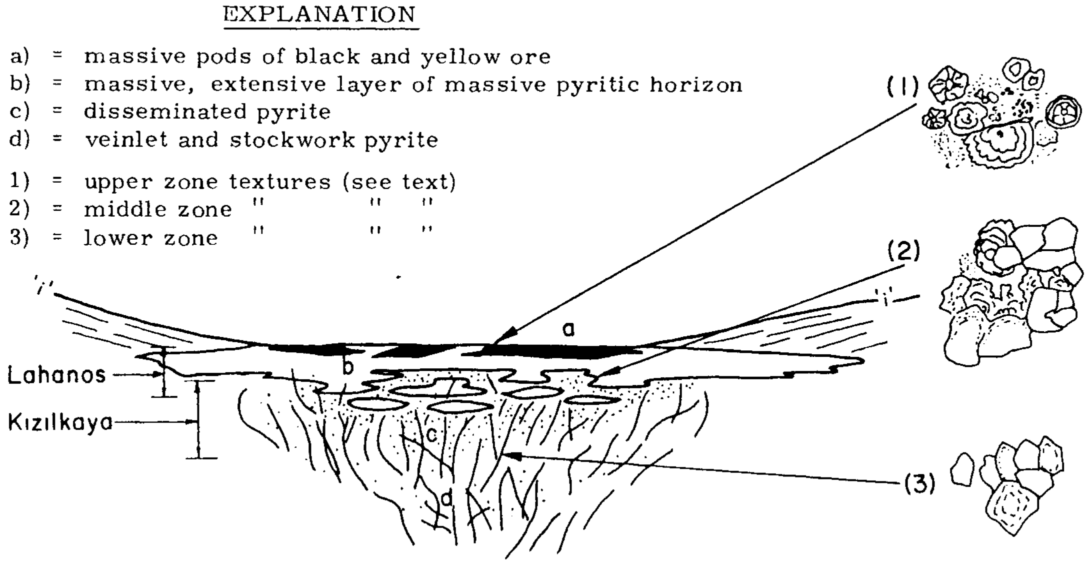
*In part from Lambert and Sato (1974) and Tuğal (1969)

No thin sections were cut, but from binocular microscope examination of hand specimens and panned concentrates, the gangue minerals quartz, sericite, carbonate, and barite were identified. Carbonate was confirmed as calcite by testing with cold dilute HCl, although dolomite was described by Tuğal (1969).

MEGASCOPIC AND MICROSCOPIC TEXTURES

In general, the Kızılkaya specimens studied display textures characteristic of the lower or "root" zones at Lahanos, demonstrating a vertical zonation of textures as well as of mineralogy. A hypothetical section to show the relative vertical positions of the two deposits is given in Fig. 1, with idealized sketches of the ore textures to be found at each level given alongside. To summarize: at the top of the Lahanos deposit "colloidal", collomorphically-banded aggregates of pyrite and base-metal sulphides, finely-banded spheroids, and spherules with radial cracking, are predominant. These "primary" or "early" textures gradually give way downward through intermediate states of overgrowth and replacement to "later" euhedral or granular pyrite, either in veins or massive. At the base of the Lahanos deposit, and in the bulk of the Kızılkaya exposures, the pyrite textures are characterized by disseminated and vein-controlled, subhedral to euhedral, and often zoned pyrite grains and aggregates. Perhaps significantly, marcasite is only noted at the top of the Lahanos deposit, and disappears downward. At the bottom of the deposit, the base-metal sulphides are much rarer, occurring as small grains with simple, smooth boundaries, and especially as minute inclusions in pyrite. Chalcocite only appears in this bottom zone, although hypogene covellite is present with bornite and chalcopyrite in the middle "coarsened" zone.

Beginning at the top, the upper zones are characterized by "colloidal" (extremely fine-grained, 1-10 μm) sulphides in aggregates of very finely-intergrown iron and base-metal sulphides (this texture is also described at Heath Steele, N. B., by Chen and Petruk (1980)). It is significant that pyrite is accompanied in these intimate mixtures by chalcopyrite and sphalerite; tennantite is less common, and galena is rare (Fig. 6a). These aggregates are often collomorphically-banded. In polished section, the collomorphic bands can be seen to be made up of fine-grained sulphides in crudely alternating layers from 10-50 μm thick. An example of this, with sphalerite in chalcopyrite, is shown in Figs. 2a) and b); a more common association is finely-banded pyrite and chalcopyrite, usually occurring in well-defined rounded balls (Fig. 5d). Round, layered, "shelly" pyrite balls with strong, finely-rhythmical banding, also contain minor chalcopyrite. The grain-size in these balls is extremely fine,


EXPLANATION

a) = massive pods of black and yellow ore
b) = massive, extensive layer of massive pyritic horizon
c) = disseminated pyrite
d) = veinlet and stockwork pyrite

1) = upper zone textures (see text)
2) = middle zone " " "
3) = lower zone " " "

Fig. 1. Hypothetical sketch section to illustrate vertical relationships in the Turkish deposits. Interface 'i' is between sea water (above) and volcanic tuffs (below). The approximate observed depth interval at both Lahanos and Kızılkaya is shown.

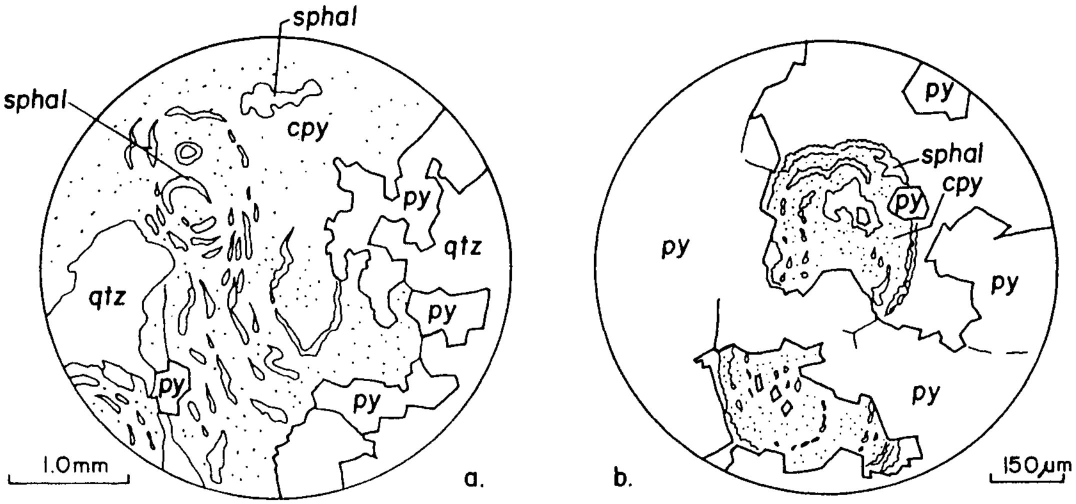


Fig. 2a and b. Original fine, primary banded aggregates of chalcopyrite, sphalerite, pyrite, cut and replaced by coarse euhedral pyrite

averaging less than 5 µm but ranging up to about 10 µm (Fig. 6b). These "shelly" balls are also noted by Love & Amstutz (1966, p. 276) when pyrite forms aggregates of above framboidal-size. The rounded spherules with radial cracks display a variety of forms (Fig. 3b), ranging from a dominant pyrite core surrounded and infilled by chalcopyrite, to polygonal pyrite masses surrounding chalcopyrite with radial and concentric chalcopyrite-filled cracks. In some aggregates (Fig. 3a) only silicate is present at the center of the spherules, thus constituting typical "atoll" textures as described by Schouten (1946a). Commonly a group of these spherules are attached to each other by a matrix of chalcopyrite. In this form (Fig. 5c) they strongly resemble the "frog's-egg" texture of Rust (1935) and textures illustrated in Schouten (1946c). Rust's photographas of his "radial bomb" textures are also strikingly similar to the radially-cracked pyrite/chalcopyrite masses from Lahanos (Fig. 5b). Such "radial bomb" textures were also described by Schouten (1946a), and they also resemble the "cracked porcelain" texture described by Lasky (1930) from the Kennecott deposit, Alaska.

The framboids in the Turkish samples appear similar to the form described by many authors (e. g. Kalliokoski, 1965; Kanehira and Bachinski, 1967; Love, 1964; Massaad, 1974; Roberts et al., 1969; Simmons et al., 1973; Sweeney and Kaplan, 1973; and Watanabe et al., 1970). The framboids seen in the present study range from 10 to 150 µm in diameter, commonly occurring in aggregates of framboids (Fig. 5c) termed "polyframboids" by Love (1971). The individual grains making up the framboids are about 1-5 µm in size.

In the middle zone of the Lahanos deposit, the textures described above are partially encroached upon, overgrown by, or recrystallized to, coarse subhedral pyrite (a similar effect was described by Johnson (1970) for Cyprus ores). The base-metal sulphides also are recrystallized and coarsened. The destruction of primary features such as framboids, colloform textures, and "colloidal" or fine grain size, proceeds through many intermediate stages (Fig. 4). In the lowermost zones, and in most of the Kizilkaya exposures, the major sulphide present is pyrite as coarse

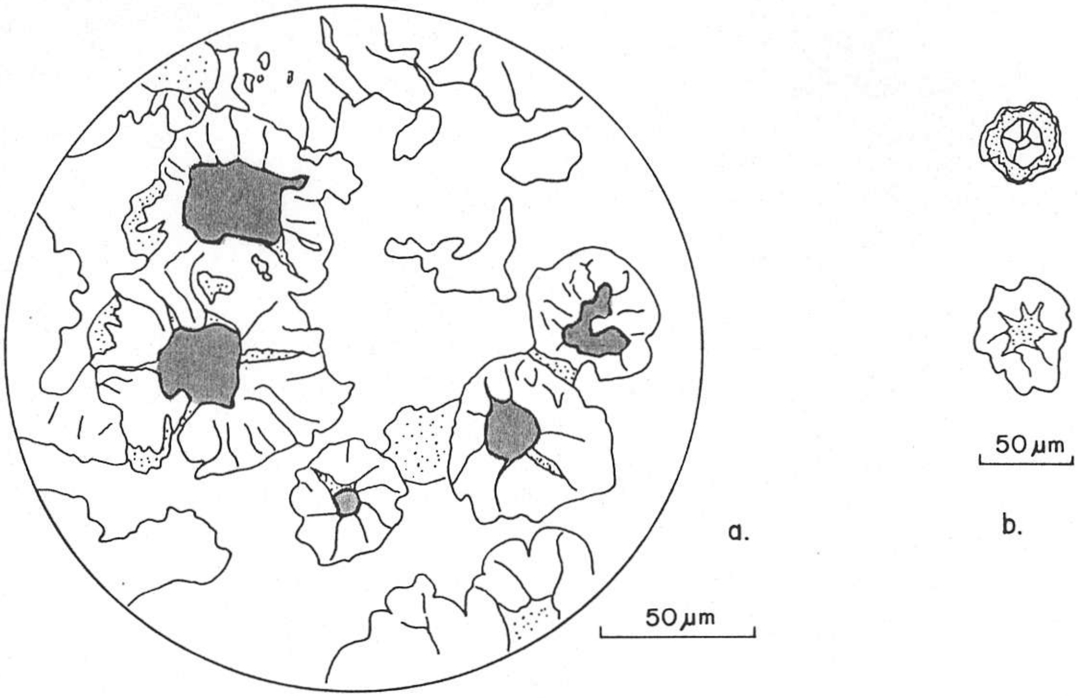


Fig. 3a Atoll textures in "radial-bomb" type pyrite aggregates. (Stipple = chalcopyrite, grey = silicate). b Radial-bomb type aggregates with either chalcopyrite (stipple) at the center, or pyrite (white)

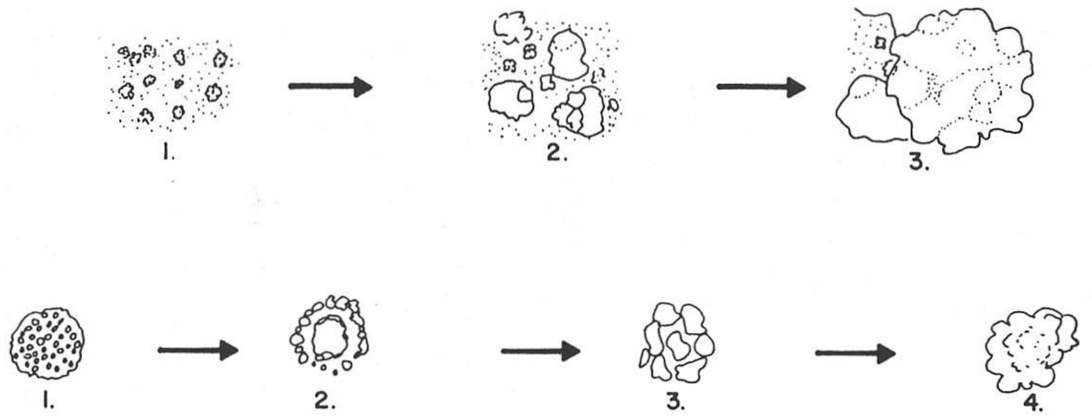


Fig. 4. Inferred stages in the recrystallization of original colloidal and framboidal pyrite (sketched from polished section). Upper: 1) Framboids in "colloidal" sea of pyrite; 2) Small areas of coarser pyrite masses; 3) Coarse pyrite, with framboidal remnants. Lower: 1) Large, homogeneous framboid; 2) Coarsening of pyrite globules; 3) Coarse, but individual blobs; 4) One large pyrite blob, with remnant circular texture

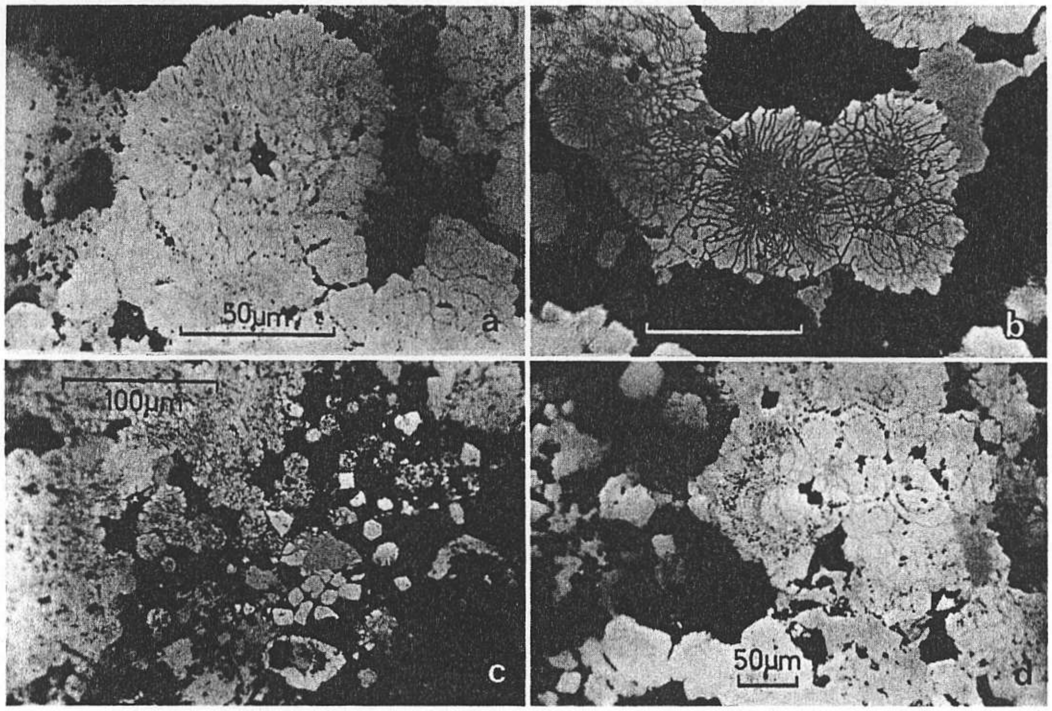


Fig. 5a Radiating cockscomb structures of chalcopyrite and sphalerite "septa" in pyrite formed after marcasite: 600x, oil. b Pyrite-chalcopyrite relationships in upper ore zones, showing "radial-bomb" texture (syneresis cracking): 600x, oil. (bar = 50 µm) c "Frog's-egg" texture of framboidal pyrite (white) in a matrix of chalcopyrite (grey): 320 x, oil. d Collomorphically-banded pyrite/chalcopyrite; note the larger masses of chalcopyrite (grey): 220 x, oil

disseminated euhedra, veins, and masses. Copper sulphides here are present almost exclusively as fine included blebs of chalcopyrite, bornite, chalcocite, and covellite. These blebs appear to have migrated towards grain boundaries as their size increased above 5 µm.

The textures of pyrite show best the transition from fine "syn-sedimentary" to coarse cross-cutting "epigenetic" (or diagenetic). The changes seen in the Lahanos specimens (Fig. 6c and d) are from: 1) areas of fine original pyrite (1-10 µm) and framboids to 2) patches of coarser pyrite still retaining their relic blebby rounded shapes, set in a groundmass of remanent fine pyrite to 3) larger rounded pyrite masses (0.1 - 1 mm across) with traces of the original framboidal shapes left, as outlined by fine silicate inclusions. Such spatially-ordered silicate inclusions pseudomorphing primary textures are to be found in almost all the specimens studied from the lower zones of Lahanos, and most of the Kızılkaya specimens. Also in these lower zones, the small inclusion blebs of base-metal sulphides are most abundant and most diverse (i.e. including bornite, tennantite, and galena as well as chalcopyrite and sphalerite) in those parts of the massive pyrite showing remnants of circular structures. This would seem to indicate that the circular structures are relics of colloform character, since the highest copper concentrations were originally associated with the collormorphic,

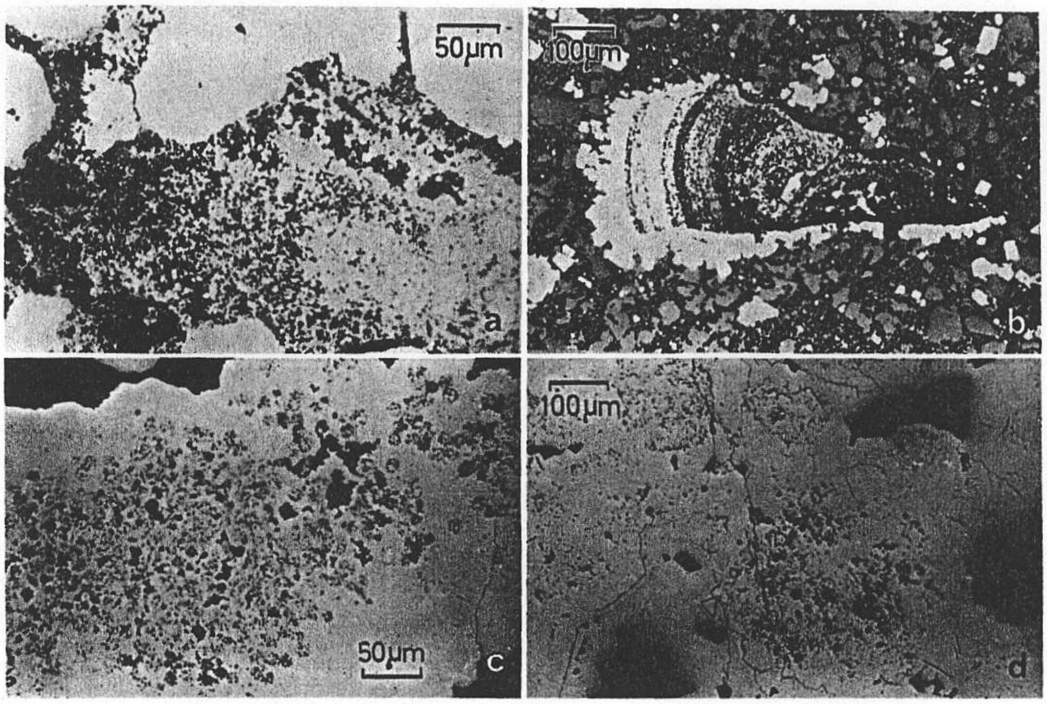


Fig. 6 a Extremely fine-grained aggregate of pyrite, chalcopyrite, sphalerite, minor tennantite being encroached upon by coarse pyrite: 220 x, oil. b Large fragment of an original collomorphic ball, broken and then incorporated into a tuff, with later euhedral pyrite overgrowth: 110 x, air. c Original framboidal pyrite being overgrown and replaced by massive pyrite: 220 x, oil. d Remnant areas of framboidal, and fine-grained or "colloidal" pyrite recrystallizing to massive pyrite: 110 x, air. Note: All photographs taken in plane polarized reflected light. White = pyrite, black = silicate

banded, rounded aggregates found higher up in the deposit. Further evidence for the recrystallization of original pyrite spherules into larger masses of homogeneous pyrite comes from electron microprobe studies of a large, smooth, optically-continuous pyrite mass in a Lahanos sample, which had a "cellular" internal pattern of "rings" of higher Cu and As in rounded or polygonal-shaped zones, rather reminiscent of the pyrite with chalcopyrite bands shown in Plate 4.

IMPLICATIONS FOR SULPHIDE FORMATION

The mineralogy and textures of the Lahanos ores have been previously described and interpreted by Tuǧal (1969). His description of the vertical zonation of mineralogy and textures compares well with the zoning pattern at Madenköy, a similar but larger volcanogenic deposit that lies some 100 km to the east (Çaǧatay and Boyle, 1977; Çaǧatay and Boyle, in press). Çaǧatay describes the top of the massive ore as being characterized by a fine, colloform texture, which gives way to coarser euhedral to subhedral textures in the lower stockwork and impregnation zones. Çaǧatay and Boyle consider a part of the euhedral pyrite to be earlier than the colloform pyrite, being overprinted by the rising solutions that debouched on the sea floor and formed the colloform sulphides. This is in essential agreement with the findings of the present study, which further suggests that ongoing hydrothermal activity may also recrystallize the massive colloform ores. At Lahanos, Tuǧal (1969) described a vertical variation in ore textures from fine-grained colloform, botryoidal and framboidal at the top of the orebody (his "Ore Zone I") to euhedral, coarse, commonly zoned pyrite crystals at the bottom in "Ore Zone IV". The textures in the upper zones were considered "primary" by Tuǧal, and he (like Çaǧatay) suggested that the colloform, fine-grained pyrite of the upper zones is of later origin than the granular pyrite, since he observed the granular pyrite to occur inside the colloform pyrite. However, the reverse is also common, if not even more characteristic, of the lower zones (Fig. 6d).

In his "Ore Zone II", Tuǧal (op. cit, p. 98) observes that "in addition to separate framboidal nuclei within an area of coarser pyrite with shrinkage cracks, relationships similar to the "radial bomb type" texture of Rust (1935) are also shown". He found that bornite, marcasite and colloform pyrite were more abundant towards the top of Ore Zone II (towards Ore Zone I). His description of Ore Zone I (p. 96) also includes the passage "colloform pyrite forms a second generation pyrite and usually surrounds the massive early pyrite. It often displasys primary botryoidal, colloidal, banded and spherulitic textures. Framboidal pyrite spheres, usually thought to be of colloidal origin, occur in isolation, and various intermediate combinations of colloform textures are seen, with a transition to textures that could be regarded as a zoned crystalline texture". Tuǧal then however concluded that such textures were indicative of a hydrothermal replacement origin for all of the sulphides. The textures observed by the author agree well with the descriptions quoted above, but quite a different depositional history of the sulphides is proposed below.

It is true that the textures observed in the upper zones of Lahanos are almost identical to those figured by Rust (1935), which he attributed to replacement of wallrocks by "precipitation from solutions of colloidal origin". A similar conclusion seems inescapable for the origin of framboids at Redruth, Cornwall (Schouten, 1946b) since they are in veins. Thus, such an origin cannot be entirely ruled out for the Lahanos sulphides. However, contrary to Tuǧal's conclusions, there appears to be evidence that the collomorphic, and very fine-grained textures were "original", i.e., syn-sedimentary, and that these textures are progressively overgrown by, and recrystallized to, coarser-grained euhedral pyrite at depth. Recrystallization may have been caused by diagenesis of sulphides deposited on and within tuffaceous volcanics forming the sea bed, and also by hydrothermal deposition during later stockwork formation in a "vent" zone below the massive sulphides. A similar conclusion was reached by Vujanovic (1974) for these textures. Also, the present interpretation is similar to that proposed for textures found in the cyprus deposits (Constantinou, 1973; Constantinou and Govett, 1972), and at Sullivan, B.C. (Morris, 1972).

Several modes of formation have been suggested for framboids, although the presence of bacteria seems to be important in most cases (Baas Becking and Moore, 1961; Trudinger et al., 1972). Framboids have been shown to form at least in part by replacement of gas-filled "vacuoles" (Rickard, 1970) or of organic debris (Love and Murray, 1963; Love and Zimmerman, 1961; Love and Amstutz, 1966), or by precipitation in free suspension from metal and sulfur in true solution at high concentrations of two to ten times the solubility product (Farrand, 1970). Thus framboids do not necessarily imply open-spaoe sulphide formation. However, they do characterize diagenetic situations, as observed in present-day sediments (Love, 1967; Berner, 1969; 1970).

It seems likely that the cracks in the radially-cracked spherules are syneresis cracks formed by shrinkage of gel-like material as it dried and solidified. However, although these textures imply deposition of sulphides from colloidal solutions, they need not imply replacement of pre-existing volcanic tuffs by sulphides from solutions of colloidal character ponded by an overlying impermeable pyroclastic horizon, as suggested by Tuğal (1969). Deposition could have been from colloidal solutions in open spaces. The formation of rounded gel-like balls of sulphide, and their later cracking upon drying and solidifying, is exactly what one would expect of sulphides deposited on the sea bed and later compacted or dewatered through diagenesis. This latter possibility is rendered more reasonable by the implications of other coexisting textures found nearby: the banded aggregates of sulphides, with separate bands of pyrite, chalcopyrite, and sphalerite, are similar to crustifications that have grown on the walls of veins (or in varioles in volcanic rocks: Ridler, R. H., pers. comm. 1980). In some samples, round, layered, shelly pyrite balls can be seen to have formed, solidified, and then been broken before being incorporated into the host volcanic tuff, and then overgrown by a subsequent layer of euhedral pyrite grains. Traces of chalcopyrite are also present between the very fine pyrite grains of these collomorphic balls. This implies that copper and iron sulphides were formed on the sea floor, were rolled around clastically and deposited as fragments within the tuffs. The layers of small euhedral pyrite grains then overgrew the broken balls in manner similar to that detailed by Ferguson et al. (1974).

Thus, even though some of the textures observed at Lahanos might have formed by replacement processes (e. g., the framboids and the radially cracked aggregates), the colloform and rounded-ball textures are indicative of open-space filling. This was the accepted dogma in the 1950's when any extremely fine-grained or colloform banded sulphides were considered to have developed as the result of flocculation of colloidal gel, and the circular forms to have been controlled by surface tension of the transporting medium (Edwards, 1954; Bastin, 1950). As such, colloform textures were considered indicative of deposition from a solution in an open-space environment. It has also been demonstrated more recently (Roedder, 1968) that radial structures can be developed from supersaturated solutions which have a rapid rate of nucleation, especially around projections or irregularites. Thus the rounded forms are mimics of pre-existing topography rather than the result of surface tension, but the original conclusions of Bastin and Edwards regarding the necessity of open space for such forms to grow in, and precipitation from suspensoids if not from colloidal solutions, are unchanged. Identical conclusions were reached by Birch (1974) in a study of ore textures of the Archean Mattabi deposit in Ontario. He described colloformly-banded sulphides including pyrite, chalcopyrite, and sphalerite, growing around and coating over projections of other grains. Interestingly, the textures of Mattabi sulphides depicted in Birch's thesis are very similar to those observed at Lahanos, with collomorphically-banded aggregates of very fine-grained sulphides, groups of framboids, shrinkage cracks, and recrystallization to and overgrowth by coarser, euhedral pyrite. Similar globular, spherulitic, and banded collomorphic textures in volcanogenic deposits attributed to "colloidal origins", are also described by Barringer at Rio Tinto in Spain (1954), by Pollock et al. (1972) at Uchi in Ontario, and by Matsukuma and Horikoshi (1970), Kanehira (1970), and Ogura (1972) in Japan. The same radial cracked, collomorphic, framboidal, atoll, and recrystallized textures have also been described by Roberts (1980) at the recently-discovered Cirque deposit in northeastern British Columbia.

It is of significance that not only pyrite is found in the very fine colloidal masses. The banded collomorphic aggregates containing rudely-alternating bands of pyrite, chalcopyrite, sphalerite, and some tennantite and galena, imply deposition of the base-metal sulphides with the pyrite. If the deposition of pyrite contemporaneous with sedimentation on the sea floor is accepted, then deposition of the base-metal sulphides would have taken place at the same time by similar processes. This is the conclusion reached for the Kuroko deposits (Kajiwara, 1970a, b; 1973a, b), and would refute at Lahanos the other commonly proposed mechanism of base-metal enrichment by addition of epigenetic Cu, Zn, Pb, etc. from hydrothermal solutions to pre-existing, syngenetic pyrite (Jenks, 1971; Robinson and Strens, 1968; Shcherba, 1971; Smirnov, 1972; Williams, 1966). Although Schouten (1964a, b, c) shows evidence that complete replacement of pyritic syngenetic textures by base-metal sulphides can be effected by solutions of appropriate composition, the occurrence together at Lahanos of extremely finely-divided intergrowths of pyrite, chalcopyrite, sphalerite and tennantite implies deposition of at least some base-metal sulphides from colloidal solutions along with the pyrite.

Additional evidence for the syn-sedimentary deposition of base-metal sulphides with pyrite is seen in the textures of the middle and bottom zones at Lahanos where the fine, banded, collomorphic, radially-cracked and framboidal textures are progressively overgrown by coarser, often euhedral or zoned pyrite, in stages that have been documented above. This coarser pyrite and the coarser aggregates of copper, lead and zinc sulphides occurring with it, appear to be indicative of diagenetic or later-stage hydrothermal recrystallization of early-formed syn-sedimentary sulphides.

Such overgrowth or recrystallization of early-formed iron sulphide has been described by several authors (e. g., Shaw and Hodgson, 1980; Chauhan, 1974; Ferguson et al., 1974). Love (1967, p. 335) describes a "later generation of sulphide surrounding and even filling in between the grains within framboids" as secondary melnikovite-pyrite', although Berner (1964) cast serious doubt on the validity of melnikovite as a distinct phase. Chauhan (1974) described a similar joining of grains in framboids by development of matrix pyrite, and development of zoned pyrite crystals from the original framboidal grains. Ferguson et al. (1974) and Boctor et al. (1976) note that marcasite may rim or crosscut pyrite in late diagenetic stages.

As support for the foregoing conclusions, it should be noted that the present-day precipitation of base metals along with iron sulphides, all of extremely fine grain size, on the sea floor near volcanic fumaroles has been reported by several workers. Honnorez (1969) and Honnorez et al. (1971) reported deposition of base metals as sulphates near a vent on the Ile de Vulcano, Sicily, followed by erosion, redeposition further away, and reduction to sulphides. De Bretizel and Foglierini (1971) noted Cu, Pb, and Zn sulphates and chlorides forming near the vent, but did not describe base-metal sulphides, and Puchelt (1971) noted only iron sulphides. Ferguson and Lambert (1972) and Ferguson et al. (1974) documented the enrichment of base metals with iron sulphides near submarine hot springs in New Guinea, but did not find any base-metal sulphides coarse enough to identify. On the other hand, both sphalerite and chalcopyrite have been positively identified with pyrite and marcasite in muds from the Red Sea Deeps (Stephens and Wittkop, 1969; Bischoff, 1969; Bischoff and Mannheim, 1969), and near vents on the Galapagos Rift (Ballard and Grassle, 1979).

Finally, it is interesting to speculate that the occurrence of the complex intergrowths of coarser-grained bornite, chalcopyrite, covellite, and chalcocite, occurring as separate masses between the larger pyrite grains, are suggestive of the supergene assemblages ascribed convincingly by Constantinou (1972) to oxidation of copper sulphides on the sea floor prior to diagenesis.

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ORE TEXTURES IN TURKISH VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN LIGHT OF EXHALATIVE SULFIDE DEPOSITS FROM AXIAL SEAMOUNT AND EXPLORER RIDGE, NORTHEASTERN PACIFIC OCEAN

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ABSTRACT

The textures displayed by volcanogenic massive sulfides from deposits in the Eastern Pontids of Turkey can be reinterpreted in the light of similar textures in massive sulfides from spreading centers in the eastern Pacific Ocean. Recently formed sulfides from the caldera of Axial Seamount and Explorer Ridge show the same radiating cockscomb structures in marcasite as do Turkish pyritic sulfides, confirming that the latter are pseudomorphous after marcasite. "Radial-bomb" textures are identical in both suites of samples, and suggest dewatering of gel-like sulfide precipitates. Collomorphically banded pyrite in the Turkish sulfides can now be inferred to have grown in the seafloor environment, by comparison with the recent sulfides. Also, round shelly pyrite "balls" apparently grew around tube-worm holes. Overprinting of these primary depositional textures by recrystallization and precipitation of later coarse euhedral pyrite also are evident in both suites, and confirm that such activity happens soon after initial precipitation.

Keywords: volcanogenic massive sulfides, textures, cockscomb, radial-bomb, collomorphic, tube-worm holes, overprinting, Turkey.

SOMMAIRE

Les textures des sulfures massifs volcanogéniques provenant des gisements situés dans la région des Pontides orientales en Turquie ressemblent beaucoup à celles qui caractérisent les sulfures massifs des rides océaniques de l'Est du Pacifique. Les sulfures formés récemment dans la caldéra du guyot Axial et le long de la crête Explorer montrent les mêmes textures radiaires en "crête de coq" dans la marcasite que les amas pyritiques turcs; ces derniers résulteraient donc d'une pseudomorphose de la marcasite. Les textures radiaires en "bombes" sont identiques dans les deux suites, et font penser qu'il s'agit d'un phénomène de déshydratation d'un précipité sulfuré colloïdal. La pyrite à bandes collomorphes dans les sulfures turcs serait une manifestation d'un milieu sous-marin, tout comme les sulfures récents. De plus, des sphères pyriteuses recouvertes de coquillages se seraient formées dans les parois des tubes d'annélides. La recristallisation de ces textures primaires de déposition et la précipitation d'une génération tardive de pyrite idiomorphe à grain grossier sont évidentes dans les deux suites, et confirment que de tels processus agissent peu de temps après la précipitation initiale.

(Traduit par la Rédaction)

Mots-clés: sulfures massifs volcanogéniques, textures, "crête de coq", bombe radiaire, collomorphe, tubes d'annélides, recristallisation, Turquie.

INTRODUCTION

Hannington's & Scott's (1988) detailed description of the mineralogy and textures of exhalative massive sulfide deposits at the Axial Seamount shield volcano in the eastern Pacific Ocean provides a wealth of new information of these deposits and insights into the genesis of their ancient analogues, volcanic-rock-associated massive sulfide deposits on land. In this regard, important comparisons and inferences have been previously made also by Oudin (1983), Oudin & Constantinou (1984), Koski *et al.* (1984), and Haymon *et al.* (1984) for sulfides formed at spreading ridges. The textures and paragenesis of sulfides in Kuroko-type deposits have been described by Eldridge (1981) and Eldridge *et al.* (1983), and their observations have been compared to similar textures in sulfides formed at spreading ridges by Koski *et al.* (1984).

Textural studies yield important information that is useful in interpreting the history of sulfides in ancient deposits. In this note, some of the textures of modern sulfides, from both Hannington's & Scott's (1988) discussion and my observations of their samples (Fig. 1), are compared to some very similar textures in two Turkish Cretaceous volcanogenic massive sulfide deposits of the Eastern Pontids: Lahanos and Kizilkaya (Leitch 1981).

Leitch (1981) described several characteristic textures of the Turkish sulfides: a) radiating cockscomb structures in pyrite defined by chalcopyrite and sphalerite "septae", b) round spherules with "radial-bomb" texture, c) collomorphically banded pyrite-chalcopyrite, d) round, layered, "shelly" pyrite balls, e) atoll textures and "frog's-egg" texture formed by pyrite framboids infilled by chalcopyrite, and f) overgrowth and recrystallization, causing destruction of original fine framboidal and collomorphic textures. Following examination of samples of modern sulfides from the Axial Seamount and Explorer Ridge, the hypotheses made in Leitch (1981) about the origin of such textures in the Turkish deposits can now

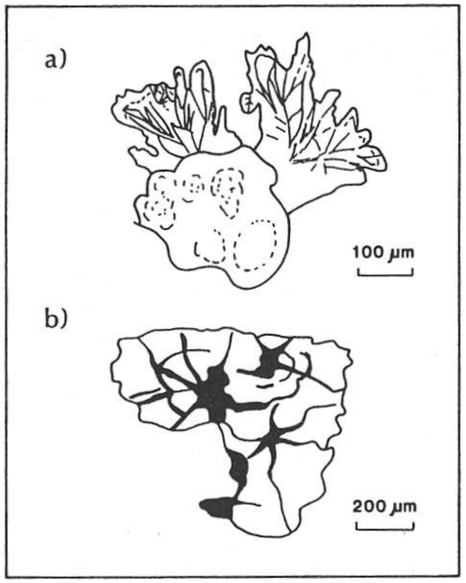

FIG. 1 a). Radiating cockscomb texture of marcasite, growing on collomorphically banded, fine-grained marcasite and sphalerite. Axial Seamount sample, reflected light, partly crossed polarizers. b). "Radially cracked" or "radial bomb" texture of marcasite in Axial Seamount sample. Plane polarized, reflected light.

be confirmed. Each of these textures is elaborated on below.

COMPARISON OF TEXTURES FROM RECENT AND ANCIENT DEPOSITS

The radiating cockscomb structures of marcasite in the Axial Seamount and Explorer Ridge samples (Fig. 1a) are identical to those in the Turkish ores (Fig. 5a of Leitch 1981). This identity confirms that the cockscomb structures in the Turkish ores probably were, as postulated, originally formed of marcasite that has now recrystallized to pyrite. In a specimen from Explorer Ridge, sphalerite also grew in the same fashion, with the "septae" in this case defined by marcasite.

"Radially cracked" textures in marcasite also present in the Axial Seamount samples (Fig. 1b) are strikingly similar to those found in the Turkish pyrite, infilled by chalcopyrite (Fig. 5b of Leitch 1981). The descriptive terms "radial-bomb" and "cracked porcelain" were in fact applied to these textures much earlier by Lasky (1930), Rust (1935) and Schouten (1946a). These authors suggested that the radially cracked spherules reflect shrinkage or "syneresis" cracking that formed as gel-like sulfide precipitates dewatered after precipitation. In the case of the Turkish samples, Leitch (1981) postulated that this dewatering may have occurred during diagenesis, but it is obvious that such changes can take place very soon after formation of the sulfides, long before burial and diagenesis.

Collomorphically banded sulfides, including pyrite, chalcopyrite and sphalerite, with the banding defined by the differing sulfides or by curved rows of gangue inclusions, also are characteristic of both sulfides on the recent seafloor (Hannington & Scott 1988, Koski *et al.* 1984, Oudin & Constantinou 1984) and in the Turkish deposits (Figs. 2a, 2b and 5d of Leitch 1981). Such banding was taken in the Turkish specimens to indicate growth in open spaces on the sea floor; this suggestion can now be confirmed with the discovery of these textures in the samples from currently precipitating sulfides (Koski *et al.* 1984). The parallelism is complete, even to the brown "melnikovite-pyrite" (Hannington & Scott 1988) at the centers of the collomorphically banded marcasite or pyrite.

An explanation can now be offered for the origin of the round layered "shelly" pyrite balls found at the Lahanos deposit in Turkey (Fig. 2; see also Fig. 6b of Leitch 1981). They are almost identical to structures in Axial Seamount samples, which originated by deposition of sphalerite and marcasite around tube-worm holes (Hannington & Scott 1988, Fig. 10a). Such a conclusion also has been drawn by Haymon *et al.* (1984) for massive sulfides formed at a Cretaceous fossil spreading ridge now preserved in the Samail ophiolite in Oman, and by Oudin & Constantinou (1984), who compared the textures of sulfides from the late Cretaceous Cyprus-type deposits found in the Troodos complex, Cyprus, to sulfides observed in recently formed deposits near the Juan de Fuca ridge (Normark *et al.* 1983), the Galapagos ridge (Law *et al.* 1981), the East Pacific Rise (Francheteau *et al.* 1979, Hekinian *et al.* 1980) and the Guaymas basin in the Gulf of California (Lonsdale *et al.* 1980, Peter & Scott 1988).

Overgrowth, recrystallization and overprinting of original framboidal and collomorphic textures by later euhedral or more massive, coarser-grained sulfides (*e.g.*, Fig. 10f of Hannington & Scott 1988) were also postulated for the Turkish deposits by Leitch (1981, Figs. 4 and 6). This process also has been proposed by many others, including Eldridge (1981), Eldridge *et al.* (1983), Oudin & Constantinou (1984) and Koski *et al.* (1984), who called the process an "intensifying hydrothermal system", causing overprinting, overgrowth, recrystallization and zoning of the sulfides. It is interesting to note the ease and rapidity with which chalcopyrite recrystallizes, even in the recent samples from the Axial Seamount and Explorer Ridge. In one of these samples, chalcopyrite varies from very fine-grained relict balls (or possibly framboids) 10 μm across on one side of the section to a smooth, even, completely recrystallized and homogeneous mass a few centimeters away. Such textures are common in the Turkish samples, with chalcopyrite almost always infilling cracks and spaces between the more brittle pyrite (Figs. 5b and 5d of Leitch 1981). This gives rise to the "frog's-egg" texture (Rust 1935) shown in Figure 5c of Leitch (1981), and to the atoll textures (Schouten 1946b) shown in Figures 3a and 3b of Leitch (1981). As would be expected from observations on the relative ease of recrystallization of sulfides (Vokes 1969), sphalerite in the Axial Seamount sulfides also shows this tendency to recrystallize, but to a lesser extent. Of course, galena would recrystallize more easily than chalcopyrite (and such was observed in the Turkish samples), but it is much less abundant than chalcopyrite in both the Turkish and the recent seafloor sulfides. The iron sulfides pyrite and marcasite, which are the most brittle, tend to preserve their original textures best.

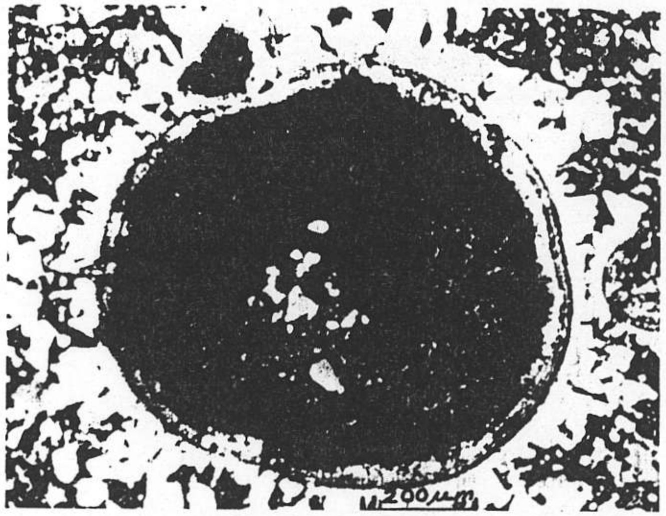

FIG. 2. Large round "shelly" pyrite ball ("ball" only in cross-section), probably formed by filling in or growing around a tube-worm hole, and overgrown by later euhedral pyrite. Sample taken from Lahanos deposit, northeastern Turkey; compare with Figure 10b of Hannington & Scott (1988).

At the Lahanos deposit in Turkey, pyrite seems to pseudomorphose earlier marcasite, and preserves the radiating cockscomb texture of the marcasite. This relation conflicts somewhat with Hannington's & Scott's (1988) observation that marcasite is later and forms at lower temperature than pyrite. The explanation preferred here for the Turkish pyritic framboids is that they formed after marcasite framboids, which are ubiquitous in the recently formed sulfides described by Hannington & Scott (1988, Fig. 10e).

Although the Turkish deposits are, strictly speaking, comparable to Kuroko deposits formed in a back-arc setting, whereas the seafloor deposits of the Eastern Pacific are comparable to Cyprus-type deposits formed at spreading centers, the textures of both are similar. This similarity has previously been suggested by Eldridge (1981) and Koski *et al.* (1984). Thus despite the differences between these two types of volcanogenic massive sulfides in their tectonic setting and metal ratios (*e.g.*, Hutchinson 1973, Franklin *et al.* 1981), the sulfides were precipitated by similar processes.

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SERPENTINIZATION IN THE ARCHEAN KOMATIITIC ROCKS OF THE KUHMO GREENSTONE BELT, EASTERN FINLAND

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ABSTRACT

Within the Suomussalmi–Kuhmo–Tipasjärvi greenstone belt of Archean age in eastern Finland, there are numerous outcrops of serpentine-bearing rocks. Petrographic and mineralogical observations have led to the recognition of three stages of mineral growth during metamorphism: I) low-grade serpentinization, with dominant lizardite I culminating in the complete transformation of magmatic olivine; II) prograde metamorphism, leading to the appearance of a new generation of olivine associated with acicular antigorite, which shows an interpenetrating texture, and III) a renewed episode of low-grade serpentinization, corresponding to a partial conversion of metamorphic olivine to lizardite II. Stages I and III correspond to the development of lizardite with a mesh texture. During each stage of mineral growth, each serpentine phase shows a specific composition. Lizardite I is characterized by the presence of Al, Mn, Ca, Na, K, Cr and Ni, whereas lizardite II appears to be highly depleted in these elements. The variability of Fe^{2+} contents in lizardite II is probably related to the compositional characteristic of the metamorphic olivine. Antigorite is characterized by an enrichment in Al, Cr and Mg linked to the breakdown of chromite during the main phase of prograde metamorphism.

Keywords: serpentinization, komatiite, greenstone belt, Kuhmo, Archean, eastern Finland.

SOMMAIRE

Au sein de la ceinture archéenne de roches vertes de Suomussalmi–Kuhmo–Tipasjärvi (Finlande orientale) affleurent de nombreuses roches dans lesquelles abondent les minéraux serpentineux. Les observations minéralogiques permettent de mettre en évidence trois stades métamorphiques: I) serpentinisation de bas degré où domine la lizardite I, aboutissant à une transformation totale de l'olivine magmatique; II) métamorphisme prograde, conduisant à l'apparition d'une nouvelle génération d'olivine et au développement d'aiguilles d'antigorite à texture interpénétrée; III) nouvelle serpentinisation de bas degré correspondant à une altération partielle de l'olivine métamorphique en lizardite II. Le premier et le troisième stade correspondent à un développement de lizardite à texture maillée. La lizardite I est caractérisée par la présence d'éléments comme Al, Cr, Ni, Mn, Ca, Na et K, alors que la lizardite II en est totalement dépourvue. Cette dernière présente des teneurs en Fe^{2+} variables, en relation avec la nature même de l'olivine métamorphique. L'antigorite est caractérisée par une grande richesse en Al, Cr et Mg; cet enrichissement est lié à la déstabilisation de la chromite au cours de l'épisode métamorphique prograde principal (stade II).

Mots-clés: serpentinization, komatiite, ceinture de roches vertes, Kuhmo, Archéen, Finlande orientale.

INTRODUCTION

Serpentinization processes have long attracted the attention of numerous investigators, and the associated literature is abundant (*Canadian Mineralogist* 17, part 4, 1979). Studies have concentrated mainly on the mineralogy and crystallography of serpentine minerals, as well as on the mode of serpentine formation in various geological settings (Wicks & Whittaker 1977). Recently, the success of chemical analyses by microprobe methods has augmented the available data-base and led to a better understanding of the geochemistry of serpentinization processes.

The Archean greenstone belt of Suomussalmi–Kuhmo–Tipasjärvi (Blais *et al.* 1977, Taipale *et al.* 1980, Piirainen 1988, Blais 1989) is particularly well suited for the study of serpentine minerals, as the ultramafic rock-types have undergone a multistage history and are composed predominantly of serpentine. The different phases of serpentinization have been related to various stages of metamorphism (Piquet 1982, Blais 1989); this insight has led to the recognition of successive textural relationships and the interpretation of geochemical mobility. The present study of serpentine minerals is based on petrographic observations as well as detailed chemical analyses of the minerals concerned. It demonstrates the participation of spinel in the development of antigorite during one stage of metamorphism.

GEOLOGICAL SETTING

The three types of lithologic units classically described in Archean "granite–greenstone" belts (Windley & Bridgwater 1971) also are recognized in the Archean terranes of eastern Finland, where outcrops can be assigned as follows: a gneissic basement containing rocks of tonalitic, trondhjemitic and granodioritic composition ranging in age from 2.86