Some Ore Textures Involving Sphalerite from the Furutobe Mine, Akita Prefecture, Japan*

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Abstract: Observations of doubly-polished, uncovered thin sections of Kuroko from Furutobe reveal a paragenesis of great complexity. Sphalerite crystals up to 2 mm across show finely detailed growth banding, and the crystals occur both as broken fragments in "moved" ore and as later fillings between clasts. The "moved" ore exhibits a variety of sphalerite types (including coarse crystals as well as fine-grained aggregates) as clasts showing that coarse crystals did exist prior to the synsedimentary slumping. Growth of large crystals seems incompatible with rapid deposition on the sea floor, therefore an alternative model is suggested. The initial deposits were derived from submarine hot springs and consisted of very fine-grained sulfides with silica and barite. With continued supply of hot fluid the lower part of the sulfide deposit covering the vent became heated, and solution and reprecipitation occurred below an upper, less permeable "blanket." Deposits formed on slopes slumped repeatedly yielding graded beds with coarse sphalerite and other sulfides incorporated in a melange of finer ore and gangue fragments.

Much of the sphalerite exhibits a fine "dusting" of chalcopyrite that appears to have developed subsequent to the growth of the host sphalerite, probably by a process of replacement, not of exsolution.

Introduction

In recent years the Miocene Kuroko deposits of Japan have become recognized almost universally as synsedimentary, hydrothermal deposits formed essentially at the seawater-sediment interface (Tatsumi and Watanabe, 1971; Ishihara, 1974; Lambert and Sato, 1974). They appear to be prototypes for many stratabound massive sulfide ores found in older rocks throughout the world. Many careful studies of the Kuroko deposits have revealed significant features regarding these fascinating ores, but not all questions are yet satisfactorily answered. Previous studies specifically of the Furutobe mine include: Taguchi and Lu (1966). Tanaka and Lu (1969), and Tanaka et al. (1974).

In 1970 I had the opportunity, through the kindness of the Mitsubishi Metal Corporation, to visit briefly and collect a few specimens from the Furutobe mine. Some of the textures revealed in my small collection are startling and, even more surprising, apparently have not been described in the voluminous and otherwise comprehensive Japanese literature. Perhaps the reason for this lack is that most, if not all, previous workers relied entirely on standard thin sections, polished sections, and hand specimens, whereas I used uncovered, doubly-polished thin sections. Sphalerite has an index of refraction of about 2.4, but bonding media for thin sections usually have indices of refraction in the 1.5 to 1.6 range. Therefore, unless both the upper and lower surfaces are polished, so much light is scattered from the rough sphalerite surfaces that very important features go undetected. In our laboratory we use a single microscope set up for simultaneous reflected and transmitted light, and control the illumination by means of separate, foot-operated switches. The color plates show typical kuroko from Furutobe as paired reflected and transmitted light photographs. The wealth of information available to viewers of doubly polished sections is apparent from the figures. I will discuss here only some of the more spectacular textures revealed in these samples.
Description of Textures

The observations described below were made principally on sphalerite. Other minerals may also possess informative textures, but only sphalerite has the broad range of chemical and optical properties that make a study such as this one possible.

The crystal size of sphalerite can be large. Plates I-1 and II-1 show crystals as much as a millimeter across, and other crystals as much as 2 millimeters across are present in my samples. Considerably larger crystals have been reported (see Ishihara, 1974).

A wide variety of sphalerite is present, as is shown in the illustrations. In particular, the transmitted-light photographs reveal strikingly contrasting characteristics, even for materials that appear superficially similar in reflected light.

Many previous studies (see Ishihara, 1974) have clearly recognized extensive intradepositional slumping that creates the clastic "moved" ore and also develops the widespread graded beds of ore and gangue, with or without wallrock components. When viewed at even lower magnification than illustrated, e.g., 10 × or less, the different types of sphalerite serve to identify different clasts of sulfide ore. Many of the clasts are also recognizable by distinctive mineral associations with or without sphalerite. A complex, fragmented "stratigraphy" of intricately banded sphalerite is displayed in the Furutobe samples, but the clastic nature of the samples produces a discontinuous record that would be far more tedious to reconstruct than my collection of specimens warrants. Another potential difficulty is the probability that any single stratum of sphalerite may undergo facies changes as it is traced through the ore zone.

The different varieties of sphalerite can occur in close juxtaposition in such a way that they must have originated separately and been brought together physically by the slumping process after crystallization (note especially Plate I-2). A very significant fact is that coarse, well-crystallized sphalerite occurs both in clastic fragments (Plate I-4) and as open-space fillings between fragments. The coarse sphalerite in the clastic fragments presumably formed in some earlier open space.

Some of the sphalerite clasts appear to be "primitive" (Plates I-1 and I-2) because they show little growth morphology, appear to be made up of many small crystals, and contain numerous ragged inclusions of galena, pyrite, chalcopyrite, and tetrahedrite. These may be the closest thing to the initial, sphalerite-bearing sediment preserved in my samples.

Although no new measurements have been made in the course of this study, it is likely that many of the fluid inclusion studies reported in the literature for the black ore (for an excellent summary see Tokunaga and Honma, 1974) were based on the coarse, recrystallized sphalerite and that the coarse sphalerite in the clasts was not distinguished from the
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coarse sphalerite filling vugs between clasts. It would be surprising if any of the “primitive” sphalerite had been studied for inclusions, as such sphalerite is usually too fine grained and too opaque for good optical examination (see Plates I–1 and I–2).

Much of the sphalerite suffers from the “chalcopyrite disease”, a feature common to many hydrothermal deposits (P. M. Bethe and P. B. Barton, Jr., unpublished research). This malady has several symptoms, the most common of which is the development of a fine “dusting” of \( \leq 1 \) micrometer-sized chalcopyrite inclusions in solid sphalerite. It begins along grain boundaries and cracks and spreads into the adjacent crystals (Plates I–2, II–1, II–2). Eventually, it may spread sufficiently to make the entire grain appear “smoky” (Plates I–3, II–3). Often the more iron-rich sphalerite is preferentially attacked (as may be the case shown in Plate II–1), but the generally low iron content of Kuroko sphalerite does not permit this aspect to develop very well. Another symptom is the generation of such high concentrations of fine chalcopyrite that the sphalerite becomes opaque, even in sections only 20 micrometers thick; frequently irregularly patches of colorless sphalerite are intimately intergrown with the opaque material (Plates I–3, II–3). Finally, some grains of sphalerite show vermicular, myrmekite-like intergrowths containing 2 to 20 micrometer inclusions of chalcopyrite (Plate II–4).

Observations of the “chalcopyrite disease” in hydrothermal ores from Creede, Colorado, U.S.A., show that it develops subsequent to the crystallization of the sphalerite grain under attack. It appears to be a reaction of copper in solution with FeS in sphalerite and may be associated in time with the replacement of pyrite by chalcopyrite, but documentation of this relation requires more work. Some of the sphalerite-chalcopyrite features are all too easily confused with exsolution textures, but I have found no chalcopyrite exsolved from sphalerite at Furutobe.

Another significant feature is the presence of hydrothermal leaching and regrowth of sphalerite (Plates II–1, II–2). This phenomenon is common in conventional hydrothermal ores, but was a surprise in the black ore part of a Kuroko deposit because its mode of deposition (Tatsumi and Watanabe, 1971; Sato, 1972) suggests rapid, irreversible precipitation (see Barton et al., 1963, for a discussion of equilibrium). Other minerals may also show resolution, but sphalerite is uniquely suited to show evidence of such activity because of its clearly visible growth banding.

A final observation is one that carries little value for interpretation but may be of use in unraveling the microstratigraphy of these ores. Sphalerite associated with tetrahedrite very often shows a characteristic blotchy red color that appears to be due to fine tetrahedrite disseminated within the sphalerite. The color appears (Plates I–4, II–2) to be the same as that given by light passing through larger tetrahedrite crystals, and the eye soon learns to distinguish the “tetrahedrite red” from the yellows, oranges, reds and browns that accompany different iron contents in the sphalerite. Yui (1971) has already shown that the Kuroko tetrahedrite can be com-

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Plate II. Photomicrographs of sphalerite from the Furutobe mine. As in Plate I, Each microscope field is shown in transmitted (A) and reflected (B) light. The mineral descriptions are as in Plate I

Plate II–1: Fragment of sphalerite crystal showing probable hydrothermal leaching followed by the addition of fine chalcopyrite (width 1 mm).

Plate II–2: Deep hydrothermal etching of banded sphalerite followed by regrowth of colorless sphalerite. The earlier sphalerite is highlighted by a slight case of the “chalcopyrite disease” (width 0.5 mm).

Plate II–3: Intensive chalcopyritization of an initially banded sphalerite. The outer bands received a light dusting of chalcopyrite whereas the central area yielded a bimodal assemblage of clear sphalerite containing large patches of sphalerite so impregnated by chalcopyrite that they are opaque (width 1 mm).

Plate II–4: Vermicular chalcopyrite intergrowths with colorless sphalerite overgrown by faintly banded white to yellow sphalerite (width 1 mm).
positionally variable; thus the use of tetrahedrite composition as a correlation tool for tetrahedrite-bearing sphalerite seems very promising.

Discussion

In this section I shall discuss the implications of my observations to the mode of formation of the bedded black ore, and perhaps by implication to the bedded yellow ore also; neither the gypsum nor the vein and stockwork ores will be considered.

There are five alternative modes of origin to which the textural observations pertain: (1) replacement of pre-existing sedimentary or volcanic rocks, (2) precipitation of ores containing banded sphalerite in veins, followed by eruption of materials from the walls of the veins onto the sea floor, (3) precipitation at very low temperatures directly from fluids as they emerged from the sea floor, (4) crystallization directly from fluids as they emerged from the sea floor, the ore being essentially in its present form without extensive recrystallization, and (5) precipitation at very low temperature (0–20°C) directly from fluids as they emerged from the sea floor followed by, or perhaps associated with, the development of a thin “blanket” (perhaps the ferrugineous cherty layer) under which high temperature (200–250°C) recrystallization processes occur. I will now discuss each of these alternatives in the light of the textural observations.

(1) The heterogeneous arrays of clasts so well displayed in the individual specimens of the Furutobe black ore provides a few more drops in the ocean of evidence that precludes the simple replacement of pre-existing rocks as a tenable hypothesis for the bedded ores.

(2) The proposal by Clark (1971) that the ores originated through the eruption of submarine, hydrothermal veins could account for the polymictic nature of the clastic ores, but such an origin is unlikely because of the frequent nearly complete lack of gangue or wallrock inclusions with the sulfides. Further-

more, the consistent stratigraphic separation of the black and yellow ore would appear to be unlikely for even one ore body, let alone the several tens of stratified ore bodies having nearly identical characteristics.

(3) The existence of extensive alteration of rocks stratigraphically and structurally above ore (see several excellent papers in Ishihara, 1974) suggests that a continued input of heat from depth following deposition might result in a local thermal buildup and associated recrystallization of initially fine-grained ore. It might also produce the high-temperature, saline fluid inclusions. Unfortunately, this alternative is inconsistent with the broken crystals of banded sphalerite found in “moved” ore. Good crystals had to exist prior to slumping and formation of graded ore beds. Post-ore tectonic fracturing is no answer because the crystals are found in graded beds, not tectonic breccias. Also, the heterogeneous arrays of sphalerite could not have originated in the same place at the same time; they had to have formed separately and then be brought together by the same process that broke the solid crystals of sphalerite.

(4) Sato (1972) has thoughtfully appraised the consequences of mixing seawater with saline hydrothermal fluids emerging from the sea floor. He proposed that the Kuroko deposits formed by hot, saline, hybrid, hydrothermal—seawater fluids that were at first less dense than bulk seawater and formed a local convecting plume in which sulfides and gangue precipitated. On further mixing, the hybrid solution became more dense than seawater and sank to the bottom, depositing ore near the source vents. The sphalerite crystals shown in the Plates are so complex and so coarse that they surely could not have developed in the short time required for a solution to evolve from vent to depositional site on the sea floor in Sato’s model. Moreover, the crystals are neither skeletal nor doubly

* Whether the hydrothermal portions of the fluids were of magmatic origin, as advocated by Sato (1972), or of seawater heated by deep circulation, as preferred by Ohmoto and Rye (1974), is not of importance to the present discussion.
terminated as one might expect of crystals grown in a convecting plume. Primary sedimentary or very early diagenetic ore minerals in such modern marine environments as Vulcano near Sicily (Honnorez et al., 1973) or the saline deeps of the Red Sea (Degens and Ross, 1969), or even the older deposits such as the Kupferschifer, show very fine-grained ore textures that contrast greatly with my samples of black ore.

(5) The last alternative, involving crystallization beneath a thin "blanket," was suggested to me by D. E. White in 1970, and although the hypothesis is not yet a polished, it does appear to present no irresolvable problems. The coarse sphalerite must have formed either by the recrystallization (by solution and reprecipitation) of an earlier, primary, syn-sedimentary precipitate, or by the introduction of a fresh, hot, saline, hydrothermal fluid into a previously formed mass of fine-grained sulfide. The crystals grew both before and after the multiple periods of slumping recorded in the ore.

A hydrothermal fluid of only moderate salinity emerging at the sea floor must cool quickly (Sato, 1972), and bottom waters in modern thermal areas associated with spreading centers (Lowell and Rona, 1976; Corliss and Ballard, 1977) have temperatures of less than 20°C. Therefore, a thermal and mechanical "blanket" is needed to permit temperatures to rise to 250°C to permit crystal growth so close to the sea floor that slumping or other disruption of the "blanket" can allow crystals to be spread out over the sea floor, not just once, but repeatedly. As long as the column of seawater exerts pressure sufficient to prevent boiling, the sulfide-plus-hot-water mass below the "blanket" is probably mechanically stable because of its high density. However, the "blanket" must be impermeable enough to prevent extensive intermixing of seawater and hydrothermal fluid. One might expect to find thin, widely dispersed, metal-rich layers that had originated from the fallout of hot fluids, which must have escaped from the ore mass during periods of slumping, but to my knowledge, none have been reported. One also wonders why parts of the "blanket" are not recognized in the "moved" or graded ore. Perhaps the "primitive" sulfide, noted earlier, or the ferruginous cherty layer are parts of the "blanket." One might also ask of whether the thermal regime below the "blanket" might not tend to redistribute the sulfides and gangues according to their solubilities in a very local convecting system having a steep thermal gradient. Such a process could contribute significantly to the diminution of porosity in the uppermost horizons and might help explain the hydrothermal leaching of sphalerite, the powdery nature of some of the yellow ore, and the distribution of metals within the bedded ore.

**Perspective**

This paper is based on a brief study of only a few specimens from a single deposit. I have no reason to suspect that Furutobe is atypical, but until more studies of this sort are made farreaching conclusions are necessarily tentative.

It is tantalizing to surmise that detailed microstratigraphic studies of sphalerite and associated minerals might provide a base for answering questions such as: How did the temperature and salinity vary with space and time during the formation of these ores? Are such variations systematic or random? If systematic, are all ore bodies in the same mine recording the same events? Do all Kuroko deposits show similar trends? What were the fundamental reasons for the change upward in an ore body from Fe to Cu to Zn to Pb? Only additional investigations can resolve these questions; I hope that this report may encourage, and suggest an additional dimension for, such studies.

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References


秋田県古遠部鉱山における亀亀鉱鉱を含む鉱石の組織

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