DEPOSITIONAL HISTORY OF THE ORE MINERALS

W. Petruk *

Introduction

The characteristics of the ore minerals in the Cobalt-Gowganda ores, as reported and discussed on pages 108 to 231, are used to provide an interpretation of the depositional history of the ore minerals. Broader interpretations of ore genesis, based on geological features of the deposits, are given in subsequent papers of this issue.

General Characteristics of the Deposits

The ore deposits in the Cobalt-Gowganda region consist of ore veins in zones of extensively fractured Nipissing diabase, Huronian sedimentary rocks, and Keewatin volcanic rocks. Orebodies within the veins are localized by cross structures such as geological contacts, faults, and joints. The deposits occur in the various rock types within 700 feet of the Nipissing diabase contacts, and are located at specific positions with respect to basin structures formed by the diabase sheet-like bodies.

Characteristics of the Ore Minerals and their Bearing on Ore Deposition

The ores consist of arsenides, native silver, and sulphides in carbonate veins, and, to a small extent, in wall rock. The distributions and textural relations of the ore minerals show that the arsenides were the first minerals to be deposited, sulphides the last, while native silver was deposited throughout the depositional period. The arsenides indicate zoning, with nickel arsenides occurring in the parts of the veins nearest the diabase and as partial envelopes around orebodies, cobalt arsenides in the intermediate parts of the veins, and iron arsenides furthest from the diabase. This zoning of arsenides with respect to the Nipissing diabase suggests that the deposition of arsenides is genetically related to the cooling history of the diabase.

The arsenides are generally present as rosettes up to several millimeters in size. Many of the rosettes consist of nickel mono-arsenides at the cores,

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cobalt diarsenides in the intermediate parts, and cobalt and iron sulphar-senides in the outer parts. The diarsenides in the rosettes are present as prismatic crystals oriented radially around cores which indicates that the rosettes were formed by deposition of diarsenides around a nucleus. Hence the nickel-rich minerals at the cores of rosettes were the first arsenides to have been deposited, cobalt-rich ones in the intermediate parts were next, and iron-rich varieties in the outer parts were last. This depositional sequence of arsenides indicates that the composition of the ore carrier changed progressively from nickel- to cobalt- to iron-rich phases during deposition, and that the nickel arsenides were the first ore minerals to be deposited.

Some rosettes contain cobalt triarsenides and traces of cobalt sulph-arsenides at the cores, cobalt diarsenides and traces of cobalt sulpharsenides in the intermediate parts, and cobalt sulpharsenides in the outer-parts. This indicates that the ore carrier initially had a high As : S ratio. It further shows that the arsenic was continuously depleted, and the pro-portion of arsenic to sulphur was decreased during deposition. It is inter-preted that, after much of the arsenic was removed from the ore carrier by deposition of arsenides, some sulphur remained allowing for the sub-sequent deposition of sulphide minerals.

Native silver is associated with both arsenides and sulphides, but only that associated with arsenides is present in sufficient quantities to constitute silver ore. Native silver associated with arsenides is present at the cores of rosettes and as veinlets cutting arsenides and carbonates. That at the cores of rosettes occurs largely in the parts of veins that contain both nickel and cobalt arsenides (Ni-Co-As assemblage) and consistently forms a high-grade silver ore. On the other hand, native silver veinlets occur sporadically in arsenides in the parts of the ore veins beyond the Ni-Co-As assemblage, and in carbonates throughout the entire lengths of the ore veins. The association of silver to arsenides suggests that silver was a major constituent of the ore carrier and that some of it was deposited with the arsenides when the Co : Ni ratio was within a certain range (Ni-Co-As assemblage). It further shows that after this Co : Ni ratio changed within the ore carrier silver was no longer deposited with the arsenides, but instead was deposited intermittently as silver veinlets in arsenides and carbonates. This later deposition obviously occurred as proper conditions for silver deposition were reached. It is recognized that the association of silver with arsenides may be coincidental, nevertheless it provides a time-space relationship, and the resulting mineral assem-blages provide a basis for interpreting depositional conditions. These inter-pretations, however, cannot be made at the present state of knowledge.

Some antimonides are associated with the nickel arsenides and the native silver in rosettes, and all the native silver associated with arsenides contains some antimony and mercury. This indicates that some antimony was present in the ore carrier, but most of it was deposited as antimonides and silver-antimony minerals contemporaneously with the deposition of nickel arsenides and early native silver. It is interpreted that the remaining antimony and any mercury in the ore carrier were co-precipitated in solid solution in the native silver.

A very minor amount of the native silver in the ore is associated with sulphides but it occurs only in and near the parts of the veins that contain silver associated with arsenides. This silver does not contain mercury and antimony, and some of it is replaced by sulphides whereas some replaces sulphides. It is interpreted that a small amount of the silver associated with arsenides in the main veins was dissolved and then subsequently redeposited as Ag, silver sulphides, and silver sulphantimonides depending on P_s. The original mercury and antimony contaminants were effectively separated from the silver by this remobilization, and the antimony redeposited as silver sulphantimonides.

The sulphides are present as disseminated grains, masses, and veinlets in the ore veins and in late veins. Those in the ore veins occur in assemblages that can co-exist only within certain temperature intervals as described on page 229 and shown in figure 227.

Associated gangue minerals, largely carbonates, may have been deposited contemporaneously with the ore minerals, but the ore minerals were deposited under continuously changing conditions, hence the relationship between gangue and ore minerals is not clear. It is, therefore, possible that the depositional conditions for the gangue minerals were significantly different from the depositional conditions of adjacent ore minerals, but both were obviously deposited from the same ore carrier. The fact that quartz contains fluid inclusions shows that the ore carrier was a solution.

PROCESS OF ORE DEPOSITION

The characteristics of the ore minerals suggest that the ore was deposited from a complex solution. They further indicate that this solution was introduced into the rock at a fairly high temperature, but it cooled rather quickly, depositing a series of different minerals. To cool quickly the solution must have been introduced into a comparatively cold rock, and to deposit the series of different minerals the composition of the ore

solution must have changed continuously, probably by a depletion of certain elements.

A trend for the continuously changing ore depositional temperatures can be obtained by combining the indicated depositional temperatures for specific minerals with their depositional sequence. The observations can be summarized as follows :

1. The earliest minerals in the ore veins are quartz and chlorite. If the quartz studied by Scott and O'Connor (pages 263 to 271) represents early quartz, then the lowest depositional temperature (195-260°C — depending upon pressure corrections) obtained from fluid inclusion studies would represent the temperature at the beginning of mineral deposition in the veins, and the highest (285-360°C — depending upon pressure corrections) the end of early quartz deposition.

2. Pre-ore chlorite is present in the veins, hence the temperatures during ore deposition did not reach the upper stability limit for chlorite (near 600°C) (Fawcett & Yoder 1966).

3. The early ore minerals are nickel arsenides, with one of the earliest being rammelsbergite, followed closely by pararammelsbergite. It is likely that the rammelsbergite was deposited at a temperature slightly above the rammelsbergite-pararammelsbergite inversion temperature (500-590°C — depending upon impurity content) and the pararammelsbergite slightly below it.
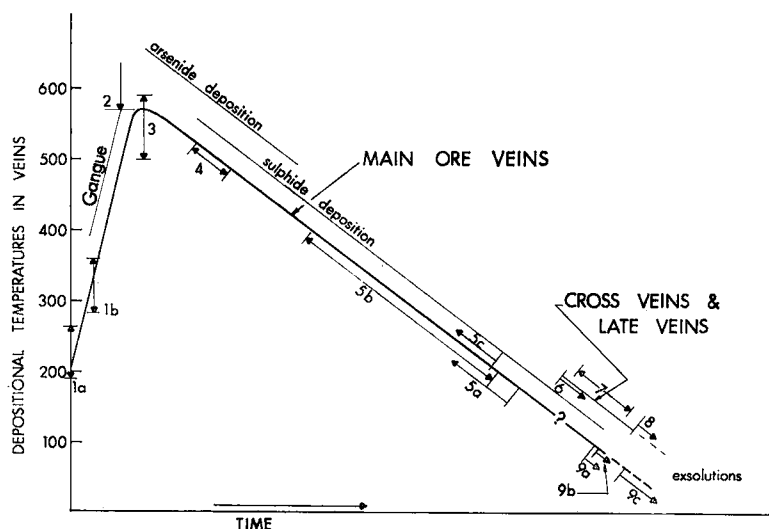

FIG. 227. Sequence of depositional temperatures for minerals in ore veins. 1a = early quartz, 1b = end of early quartz, 2 = upper stability limit for chlorite, 3 = rammelsbergite-pararammelsbergite inversion, 4 = stability field for phase A, 5a = lower argentite stability limit, 5b = stability field for silver-pyrargyrite-acanthite assemblage, 5c = galena — matildite exsolutions (lower limit for solid solution), 6 = upper stability limit for stephanite, 7 = fluid inclusions in late quartz, 8 = upper stability limit for smythite, 9 = upper stability limits for 9a mckinstryite, 9b stromeyerite and 9c stromeyerite-chalcocite exsolutions.

4. The early sulphides include exsolutions from Phase A of Craig & Kullerud (1968). Phase A is stable only between 486°C and 523°C.

5. Later sulphides in the ore veins are largely silver sulphides which include (a) cubic acanthite crystals (argentite) deposited above 176°C (Kracek 1946) (b) silver-pyrargyrite-acanthite assemblage, stable between 200°C and 400°C (Keighin & Honea 1969). (c) matildite-galena exsolutions from a solid solution stable above 215°C (Craig 1967).

6. Cross-veins and late-veins contain stephanite in the mineral assemblage. Stephanite is stable only below 197°C (Keighin & Honea 1969).

7. Fluid inclusions in late quartz from a cross-vein, studied by Taylor (1970), indicate a depositional temperature of 145°C-200°C (depending upon pressure corrections, page 270).

8. Smythite in a cross-vein, reported by Taylor (1970), stable below about 75°C.

9. Late sulphides in the main ore veins including some that are exsolved from higher temperature varieties and some that could have been deposited directly. These are (a) mckinstryite co-existing with stromeyerite, stable below 94.4°C (Skinner 1966); (b) stromeyerite, stable below 93.3°C (Skinner 1966); and (c) stromeyerite co-existing with chalcocite, stable below 67°C (Skinner 1966) but exsolved from a higher temperature phase.

These data are summarized in Figure 227.

Figure 227 shows progressively lower temperature minerals along the veins. The mechanism for depositing lower temperature minerals along a vein is not clear. Any introduction of hydrothermal solution into a cold rock would tend to warm the rock and cool the ore solution. The first wave of an ore solution would, therefore, deposit progressively lower-temperature minerals along the vein, which is indeed observed. Any continuing ore solution would be introduced along the centre of a warmed vein and, hence, would deposit higher-temperature minerals at the centre which, however, has not been observed. Thus, to continue depositing lower-temperature minerals in a vein would require introducing continuously lower-temperature ore solutions. This would be achieved if the ore solution were recycled within the ore veins, probably by convection currents. Hence minerals would continue to be deposited as the ore solution cooled until the vein became filled, until all the material was used up, or until the residual ore solution escaped from the vein. The latest minerals that would be deposited within ore veins in this manner would be low-temperature varieties, probably deposited at the temperature of the surrounding wall rock. Any residual ore solution that escaped from the ore veins at any time during deposition would have been deposited as small veins in the near-by rock. It is expected that ore solutions would escape when the open spaces in the veins were filled, which would likely be towards the end of deposition of arsenides or during the deposition of sulphides. This agrees with the observed characteristics; numerous small sulphide and arsenopyrite veins occur near the ore veins. In addition, it is possible that an ore solution travelling from its source may locally

deposit small veins before reaching the depositional site of the main ore vein. It is expected that such small veins would consist largely of nickel arsenides. One such vein was found in the Seneca mine in Casey township. This vein occurs nearer the diabase than the main ore veins in Casey township.

The veins generally occur in "nests". The characteristics of the minerals in veins from the same nest are more or less the same. On the other hand, detailed characteristics of mineral assemblages from nest to nest are slightly different although mineral assemblages from all veins in the Cobalt-Gowganda region have the same general characteristics. This indicates that the veins within a nest were deposited from the same ore solution, but veins in different nests appear to have been deposited from different fractions of similar ore solutions.

Some sulphides also occur in mineralized Keewatin interflow rocks and in the wall and country rocks. Those in mineralized Keewatin interflow rock and in Keewatin volcanic rocks are considered to be syngenetic with the deposition of the Keewatin rocks. Some of those in Huronian rocks are reworked sulphides from the Keewatin interflow rocks, and some were introduced from the ore veins. In an effort to determine whether there is any relation between ore vein sulphides and Keewatin interflow sulphides sulphur isotope ratios were determined for some sulphides (pages 391 to 395). The results show that sulphur isotope ratios for sulphides from the Keewatin interflow rocks vary from about $+ 3.8$ to $+ 6.2$ and for reworked Keewatin interflow sulphides in Huronian rocks from one spot it is $+ 0.7$. Ore vein sulphides have sulphur isotope ratios of about $+ 2.3$ to $+ 3.1$ which are similar to those of meteoric sulphur, but they also fall within the range for the interflow sulphides, hence no significant conclusions are possible from sulphur isotope data.