Quartz Simultaneously Precipitated with Kuroko Ores

In the Uwamuki No. 4 Deposit, Kosaka Mine*

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Abstract: Quartz is the only silica mineral in black, yellow and siliceous ores of the Uwamuki No. 4 (Kuroko) deposit, Kosaka mine. Intimate textural relationship between quartz and sulfide minerals in Kuroko ores suggests that these minerals were precipitated simultaneously. Filling temperatures, T, of fluid inclusions in quartz from the siliceous ore (MARUTANI, 1977) can be fitted by:

\[ T (°C) = 289.7 + 0.2159y \]

where y represents vertical distance in meters from estimated sea bottom at the time of siliceous ore mineralization. The steep thermal gradient within siliceous orebody may be a consequence of mixing between ascending hydrothermal solution and down-circulating cool sea water. Net contamination of sea water is computed to be less than 25%.

Contents of quartz and barite in six black ores are measured. The ratios quartz/sulfides and barite/sulfides show excellent parallel relation. Mixing of cool and oxygenic sea water with discharged hydrothermal solution causes both decrease in temperature and introduction of sulfate ion. Consequently, quartz and barite precipitate simultaneously with sulfide minerals in black ore. Common occurrence of bipyramidal quartz in black ore indicates that the quartz grew up in open space. Besides, the grain size of quartz increases towards the margin of the black orebody. It will be ascribable to gradational slow cooling of the discharged hydrothermal solution on sea floor.

Introduction

Kuroko deposit is characterized by its remarkable mineralogical and compositional zonation from base to top of the orebody. Chalcopyrite and pyrite are concentrated at the base of the massive sulfide ore lens to form yellow ore. And the upper half of the massive sulfide orebody consists of black ore in which sphalerite, galena and barite are enriched.

There have been arguments on mechanism of such mineralogical zoning in the massive ore. At first, FUKUCHI (1902) discussed that the zoning could be explained as the result of the progressive change in initial chemical compositions of the ascending hydrothermal solution. Alternative explanation of the mineralogical zoning is; differential precipitation of minerals from a hydrothermal solution along certain physico-chemical gradient during mineralization (KAIJWARA, 1973a,b; ICHIKUNI, 1975; SHIKAZONO, 1976). SATO (1972, 1973), LAMBERT and SATO (1974), LARGE (1977), and URABE and SATO (1978) explained that the zonation of metal sulfides within the massive sulfide orebody was caused by progressive change in solution chemistry by the mixing of hydrothermal solution with sea water. These models including KAIJWARA'S (1973a,b) and SHIKAZONO'S (1976) ones are based on the experimental or extrapolated solubility data of sulfide minerals. However, the solubility of sulfide minerals essentially depends on many parameters like temperature, pH, fO2, total dissolved sulfur, and chemical composition of the solution. Therefore, proposed mechanisms of mineral zoning and chemistry of the hydrothermal solution of Kuroko deposit involve many uncertainties. For example, estimated concentration of copper in the ore-forming solution differs remarkably among many workers, i.e., 0.0086 ppm (KAIJWARA, 1973a), about 6 ppm (SATO, 1971; LARGE, 1977), and 220 ppm (SHIKAZONO, 1976).
On the contrary, solubility of quartz in acid or intermediate hydrothermal solution does not primarily depend on pH, chloride concentration, gas fugacity, presence of other colloids or suspended materials, and total pressure, but depends only on temperature (Holland, 1967; Krauskopf, 1956). Dissolved silica exists dominantly as mono-silicic acid H$_4$SiO$_4$ (e.g. Krauskopf, 1956) and complexes containing soda-silica or sulfur-silica are not necessarily of major significance (Crerar and Anderson, 1971). Solubility of quartz in water at elevated temperature was measured by many investigators (Kennedy, 1950; Kitahara, 1960; Morey et al., 1962; Crerar and Anderson, 1971) and they coincide in their results very well each other (Crerar and Anderson, 1971). Therefore, quartz content in black ore is useful to solve the behavior of ascending hydrothermal solution at the site of Kuroko mineralization.

Description of Used Samples

Six ore specimens were collected from the Uwamuki No. 4 ore deposit of the Kosaka mine (Fig. 1). The geology and ore deposit of the ore body are given elsewhere (Kawabe and Masubuchi, 1974; Oshima et al., 1974; Urabe, 1974b; Urabe and Sato, 1978), and only brief descriptions are given below. There are three pairs of black and siliceous orebodies in the Uwamuki No. 4 deposit (Urabe and Sato, 1978). Used samples are exclusively taken from lower (LO) black orebody. The lower black orebody has a sedimentary siliceous ore or "siliceous chimney" at its central part (Urabe and Sato, 1978).

Besides, a minor orifice of hydrothermal solution is observed at the northern part. Both the "siliceous chimney" and the minor orifice change into cylindrical network siliceous orebodies, or siliceous ore pipe, in their lower part (Fig. 2). These orebodies can be traced downwards more than 100m into white rhyolite dome (Kawabe and Masubuchi, 1974).

Sample A was collected at level L –34m. Quartz fills up the grain boundary of sphalerite, galena, pyrite and chalcopyrite. This sample coincides with the ore near the siliceous chimney.

Sample B was collected at level L –28m. Chalcopyrite is the most dominant sulfide mineral and the ore will be designated as yellowish black ore.

Samples C and D were collected at the same locality (L –28m). Sample C is massive and compact black ore but sample D is black ore with clastic texture.

Sample E is the ore at the very point of the minor orifice of the hydrothermal solution
Fig. 2 Geologic section of the Uwamuki No. 4 deposit along line (A)–(A') in Figure 1. Cross-hatched area denotes siliceous chimney and hatched area is siliceous ore pipe in which strong silicification is observed. See Urabe and Sato (1978) for detail.

Table 1 Brief descriptions of used samples and analytical results.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Vertical Distance from Hanging-wall</th>
<th>Descriptions</th>
<th>Total wt. (g)</th>
<th>Quartz (g)</th>
<th>Barite (g)</th>
<th>Sulfides (g)*</th>
<th>Qtz/ Sulfides</th>
<th>Barite/ Sulfides</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (7241301)</td>
<td>0.5m</td>
<td>Silicified black ore at the boundary between siliceous chimney and black ore.</td>
<td>27.01</td>
<td>3.2560</td>
<td>0.102</td>
<td>23.65</td>
<td>0.138</td>
<td>0.431 x 10^-2</td>
</tr>
<tr>
<td>B (70Y0505)</td>
<td>4 - 5m</td>
<td>Massive, coarse-grained black ore rich in chalcopyrite (yellowish black ore). Compact black ore which stands for common black ore. No sedimentary textures.</td>
<td>78.06</td>
<td>0.0378</td>
<td>0.008</td>
<td>78.01</td>
<td>0.465 x 10^-3</td>
<td>0.103 x 10^-3</td>
</tr>
<tr>
<td>C (70Y1307)</td>
<td>2.5m</td>
<td>Black ore showing slightly reworked texture. Barite forms radial aggregates.</td>
<td>69.05</td>
<td>0.1187</td>
<td>12.139</td>
<td>56.79</td>
<td>0.209 x 10^-2</td>
<td>0.214</td>
</tr>
<tr>
<td>D (70Y1310)</td>
<td>0.8m</td>
<td>Black ore just above a minor orifice at northern part of the deposit.</td>
<td>34.77**</td>
<td>0.1166</td>
<td>16.123</td>
<td>18.34</td>
<td>0.636 x 10^-2</td>
<td>0.879</td>
</tr>
<tr>
<td>E (7241306)</td>
<td>ca. 2m</td>
<td>Fine-grained compact black ore at northern part of the deposit.</td>
<td>51.61</td>
<td>0.5659</td>
<td>18.550</td>
<td>32.49</td>
<td>0.174 x 10^-3</td>
<td>0.571</td>
</tr>
<tr>
<td>F (7241111)</td>
<td>2.5m</td>
<td></td>
<td>84.10</td>
<td>0.2853</td>
<td>0.527</td>
<td>83.29</td>
<td>0.343 x 10^-2</td>
<td>0.633 x 10^-2</td>
</tr>
</tbody>
</table>

* Including small amount of clay minerals.
** This sample contains 0.1903 gram of silicified volcanic rock fragments. The rock fragments are not included in quartz fraction.
at level L – 40 m (See also Fig. 2).

Sample F stands for the black ore distant from the siliceous chimney. Samples C, D and F belong to “common” black ore. Additional descriptions of the ore samples are given in Table 1.

**Analytical Procedures and Results**

Six ore samples are crushed and sized to 60 mesh under, and digested by conc. nitric and hydrochloric acids until sulfide minerals decompose entirely. Residue is washed repeatedly by hot water and then by carbon disulfide to remove sulfur. Obtained mixture of barite and quartz is treated by heavy liquid (methylene iodide; D = 3.3) to separate these two minerals each other. Preliminary semi-quantitative X-ray Fluorescence Analysis by use of Rigaku Geigerflex IKF-3064 indicates that every sample contains 0.1 wt.% of Al₂O₃ which is apparently ascribed to clay minerals. However, clay minerals are decomposed or washed away during the above procedures. And silica in clay minerals should have been removed as well. Separated fractions of barite and quartz are weighed to calculate the ratios among barite, quartz and sulfide minerals in the ore.

**Results and Discussion**

**Quartz in Black Ore**

The ratios quartz/sulfides and barite/sulfides are given in Table 1 and plotted in Figure 3. The ore near the outlet of ascending hydrothermal solution (Samples A and E) is found to contain relatively high amount of quartz. Quartz content in common black ores (Sample C, D and F) is higher than that in chalcopyrite-rich ore (Sample B). Such a tendency can be observed also in the Uchinotai deposit of the Kosaka mine (TATSUMI and OSHIMA, 1966) and the Uwamuki-group deposits (OSHIMA et al., 1974). For example, black and yellow ores in the Uchinotai deposit contain 2.3 and 1.1 wt.% of SiO₂, and they do 0.9 and 2.2 wt.% of (Al₂O₃ + CaO + MgO + Na₂O + K₂O + SO₃), respectively (TATSUMI and OSHIMA, 1966). Therefore, net quartz content in black ore is estimated to be larger than that in yellow ore.

Separated quartz crystals are carefully examined under a binocular microscope (Table 2). Length of the quartz prisms increases towards the margin of the stratiform orebody, while opaque inclusions (sulfides?) decrease in their number. To know the true grain size of the quartz in common black ore, sample C was “rapped” by hammer into blocky pieces and was served for the same analytical procedures as mentioned above. Both prismatic and anhedral crystals of quartz are observed
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Plate 1. Photographs showing the variation in crystal form of quartz from the Uwamuki No. 4 deposit. (a) "pine cone" like aggregates of quartz in sample A. (b) prismatic crystal with two pyramids at both ends (bipyramidal habit) in sample C. (c) clear anhedral quartz in sample C.

and the grain size of the latter crystals reaches up to 2 mm in diameter.

Hexagonal prismatic quartz crystal which is terminated by both rhombohedrons (bipyramidal form) is common in samples A to C (Plate 1). This crystal form strongly suggests that the quartz crystal grew freely in open space, from hydrothermal solution.

Quartz in Siliceous Ore

Silica mineral in black, yellow, and siliceous ores is exclusively low-quartz (Urabe, 1974b). Microscopic observation indicates that quartz in ferruginous chert has inverted textures due apparently to opal or amorphous silica (Urabe and Sato, 1978). However, neither the inverted opal nor chalcedonic quartz is found in black, yellow and siliceous ores of the Kuroko deposit. Besides, quartz is the only silica mineral in the alteration halo of the Kuroko deposit (M. Utada, oral communication). Therefore, it is concluded that quartz is the only primary silica mineral which is precipitated from ascending hydrothermal solution.

Marutani (1977) measured filling temperature of about 370 fluid inclusions in quartz from siliceous ore of the Uwamuki No. 4 deposit. His results are graphically reproduced in Figure 4. Observed steep thermal gradient within the siliceous orebody appears to be the result of mixing between ascending hydrothermal solution and sea water which has down circulated into the volcanic pile (Marutani, 1977). The thermal gradient in the siliceous orebody is fitted to be;

Fig. 4. Vertical change in filling temperature of fluid inclusions in quartz from the siliceous orebody of the Uwamuki No. 4 deposit, after Marutani (1977). Data at levels L-145, -160 and -170m are obtained from drill core samples. Dotted lines indicate the observed range of variation. B.S.O. and Y.S.O. denote sphalerite-galena rich siliceous ore and chalcopyrite-pyrite rich siliceous ore, respectively.
\[ T (\text{°C}) = 289.7 + 0.2159Y \quad \ldots (1) \]

where \( Y \) represents depth in meter from sea bottom at the time of mineralization. Because of this rapid cooling of the ascending hydrothermal solution, over-saturated silica would be precipitated as quartz to form the siliceous orebody (Fig. 2).

A certain degree of caution is necessary when we apply the Marutani’s (1977) data to the problem of ore deposition of the Uwamuki No. 4 deposit, for the time relation between quartz precipitation and ore deposition is not yet clarified. However, intimate association of quartz and sulfide minerals in the siliceous orebody strongly suggests that the deposition of these two phases proceeded more or less simultaneously during ore deposition. So, we assume hereafter that the observed filling temperatures represent the temperatures of formation of the ore deposit.

Because of the inferred steep thermal gradient, the down circulating sea water will be rapidly heated with minor change in its chemistry. The heated sea water mixed with ascending hydrothermal solution will bring both decrease in temperature and change in chemistry of the hydrothermal solution. The temperature of a mixed solution of two different NaCl aqueous solutions, \( T_{\text{mix}} \), can be simply approximated by,

\[ T_{\text{mix}} = \frac{T_1 W_1 + T_2 W_2}{W_1 + W_2} \quad \ldots (2) \]

(SATO, 1972)

where \( T_1 \) and \( T_2 \) are the initial temperature of solution 1 and 2, and \( W_1 \) and \( W_2 \) are the weight of the solution 1 and 2, respectively. Rearranging the equation 2, we obtain;

\[ T_{\text{mix}} = \frac{T_1 + T_2}{1 + r} \quad \ldots (3) \]

\[ r = \frac{T_{\text{mix}} - T_1}{T_2 - T_{\text{mix}}} \quad \ldots (4) \]

where, \( r = \frac{W_2}{W_1} \). Here we assume that an ascending hydrothermal solution which is represented by inclusion fluid in quartz from lowest part of the siliceous orebody (L = 170m) had mixed with heated sea water which passed down into tuff breccia to produce a mixed hydrothermal solution. Designating the solution 1 and 2 as ascending hydrothermal solution and sea water, respectively, we get the following relation between \( r (= W_{\text{sea water}} / W_{\text{ascending solution}}) \) and \( T_2 \) (temperature of heated sea water) from equation (4) as;

\[ r = -\frac{290 - T_2}{290 - T_{\text{mix}}} = \frac{30}{290 - T_{\text{mix}}} \quad \ldots (5) \]

Here we assumed that the temperature of mixed solution is the same as filling temperature of fluid inclusions in quartz from uppermost part of the siliceous orebody (L = 40m). Figure 5 represents the plot of \( r \) vs. \( T_2 \). Because the ascending hydrothermal solution will always attain equilibrium with quartz in the siliceous orebody, the maximum temperature of the heated sea water is calculated to be 136°C (See Appendix for detail). If we assume that the heated sea water dissolves 100 ppm of silica, the maximum value for \( T_2 \) becomes to be 163°C. Fraction of incorporated sea water will be in any event less than 1/4. When normal oceanic water is heated to temperatures around 150–200°C, anhydrite begins to precipitate from it (e.g. Bischoff and Dickson, 1975). Therefore, lack in an-
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hydrite and gypsum in footwall rocks of the Uwamuki No. 4 deposit supports the idea that temperature of the penetrating sea water did not exceed ca. 150°C.

Behavior of Ascending Solution on Sea Floor

When the ascending hydrothermal solution reached sea water-rock interface, mixing will advance, in other words, the mixing ratio \( r = \frac{W_{\text{sea water}}}{W_{\text{ascending solution}}} \) increases rapidly. If we again assume that the hydrothermal solution just below the sea bottom has a temperature of 290°C and is saturated with quartz, its silica content is calculated to be 556 ppm (See Appendix).

It is reasonable to assume that the sea water during the Miocene age had a similar chemical composition with present-day normal oceanic water, and silica concentration in Miocene sea water is estimated as 2.9 ppm after Turekian (1969). The relation between \( r \) and silica concentration in mixed solution (\( M_{\text{mix}} \)) can be obtained by;

\[
M_{\text{mix}} = \frac{556 + 2.9r}{1 + r} \quad \ldots (6)
\]

The relation between \( M_{\text{mix}} \) and \( r \) is illustrated in Figure 6 together with the solubility of quartz at corresponding temperature. Silica concentration in mixed solution is always higher than that in solution which is in equilibrium with quartz.

It is indicated by measurement on iron content in sphalerite that reduced sulfur is the dominant species in the ore-forming hydrothermal solution of the Uwamuki No. 4 deposit (Urabe, 1974a). On the other hand, oxidized sulfur is assumed to predominate in the Miocene sea water. Experimental evidence by Malinin and Khtarov (1969) suggests that kinetics of equilibration of dissolved sulfate and sulfide species are very sluggish below 200°C. Sulfur isotope study on sulfide and sulfate (barite) minerals also supports this conclusion (Kajiwara, 1971, Sakai et al., 1970). Therefore, incorporated sea water sulfate will persist during the mixing between

![Fig. 6 SiO₂ concentration in mixed solution as a function of mixing ratio r (curve (A)). Temperature of the mixed solution is also given. Curve (B) denotes the solubility of SiO₂ in aqueous solution at the calculated temperature. See Appendix.](image-url)
Mineralogy:

Fig. 7  Barium concentration in mixed solution as a function of the degree of mixing r (curve (A)). Initial barium concentration in ascending solution was taken from ICHIKUNI (1975). Calculated solubility of barite in the mixed solution is given in curve (C) employing the tabulated data of HELGESON (1969). See text.

Sea water and hydrothermal solution. Curve (B) in Figure 7 shows the change in SO$_4^{--}$ concentration in the mixed solution with varying sea water/hydrothermal solution ratio at the site of black ore deposition, by use of equation A–2. ICHIKUNI (1975) estimated concentration of barium in the Kuroko-forming solution as $1.46 \times 10^{-4}$ mole/Kg. H$_2$O. Concentration of barium ion in normal oceanic water is $1.5 \times 10^{-7}$ mole/Kg. H$_2$O (TUREKIAN, 1969) and is about 1000 times smaller than the former. Calculated concentration of barium ion in the mixed solution (curve (A) in Fig. 7) is much higher than the equilibrium concentration of barium (curve (C)) which is estimated by combining the concentration of sulfate ion (curve (B)) and tabulated activity products of barite from HELGESON (1969).

Consequently, it is concluded from Figures 6 and 7 that quartz and barite precipitate simultaneously during the mixing of issued hydrothermal solution and sea water on the sea floor. In proportion as the ratio quartz/sulfide increases the ratio barite/sulfide rises and vice versa (Fig. 3). This proportional relation between quartz and barite contents supports the above conclusion, because the increase in sulfate ion and decrease in temperature have one-to-one correspondence. Fluid inclusion study on barite in black ore (e.g. TOKUNAGA and HONMA, 1974) indicates that black ore was formed at temperatures between $100\degree$C and $200\degree$C. Therefore, it is likely that precipitation of barite, sulfides and quartz continued until the hydrothermal solution was cooled to these temperatures by incorporated sea water.

Estimated solubility of sphalerite at $200\degree$C in 1 molal NaCl solution with $\sum S = 10^{-2}$ molal, Na/K = 10, and pH = $4.9 - 5.6$ is $9.8 \times 10^{-3} - 3.9 \times 10^{-4}$ ppm (Data after HELGESON, 1969). Here, pH is assumed to be a range in which sericite and quartz are stable, because these two minerals are common in the black ore. Sphalerite will be precipitated simultaneously with quartz and barite by cooling of the hydrothermal solution, for, more
than 99% of zinc should precipitate until temperature of the solution becomes 180°C according to the solubility data by HELGESON (1969).

Accordingly, we come to a conclusion that boundaries among siliceous chimney, yellow ore (yellowish black ore) and black ore are not the time-planes but isopleth planes. In fact, the boundary between siliceous chimney and black ore in the Uwamuki No. 4 deposit is irregular in its shape and is sometimes nearly perpendicular to the upper surface of the black orebody. The low quartz content in yellow ore may suggest that the precipitation of chalcopyrite occurred by neutralization of the hydrothermal solution by sea water without accompanying large temperature decrease.

It is interesting that the morphology and grain size of quartz crystals change systematically towards the outer part of the ore body (Table 2). The "pine cone" like aggregates of quartz in the siliceous chimney will be a consequence of rapid quenching of discharged solution. And the gradual increase in grain size of prismatic quartz towards the margin of the ore deposit will be ascribable to gradational slow cooling of the discharged solution on sea floor. Unfortunately, it is difficult to construct a precise model for the mixing behavior on the basis of the morphology and grain size of the quartz crystal, because our knowledge on crystal growth is not yet satisfactory.

The dynamic mechanism of mixing of two solutions is still necessary to discuss. Since NaCl equivalent concentration in the inclusion fluid from the Uwamuki No. 4 deposit never exceeds 4.5 wt.% (MARUTANI, 1977; MARUTANI and TAKENOUCHI, 1977), the density of the mixed solution is always lower than that of normal sea water at 20°C according to SATO (1972). Then the hydrothermal solution which has flowed out the orifice will float up in the same manner as was suggested at the Uchinotai-higashi deposit (URABE and SATO, 1978). However, the distribution of the precipitated minerals is likely to be limited, for the crystallization of these minerals will occur at relatively early stage of mixing (in other words, the time when the ratio \( r \) is not yet large) as was suggested before.

**Volume of Ore Solution**

The volume of the ore-forming hydrothermal solution can be estimated from the quartz content in black ore as follows; average quartz content in normal black ore (Samples C, D and F in Table 1) is 0.28 wt.%, and total amount of quartz in the black orebody is evaluated to be 1400 tons, because the total reserve of the black orebody of the Uwamuki No. 4 deposit is estimated to be ca. 500,000 tons. Quartz in the siliceous chimney is calculated similarly to be 6,000 tons, and total amount of quartz in the sedimentary part of the deposit becomes to be 7,400 tons. If we again assume that the dissolved silica (556 ppm) will precipitate entirely as quartz, total tonnage of discharged hydrothermal solution is estimated to be ca. 1.3 \( \times 10^7 \) tons. As was mentioned previously, a part, say half, of the dissolved silica is fixed as clay minerals, and the obtained value may be a minimum value. As the total amount of copper in black orebody of the deposit is ca. 12,500 tons, copper content in the hydrothermal solution discharged onto sea floor is evaluated to be a few hundreds ppm. This value is in general harmony with the experimental solubility of chalcopyrite by CRERAR and BARNES (1976) under the physico-chemical conditions assumed above.

**Conclusions**

1. Quartz is the only silica mineral in black, yellow and siliceous ores.
2. Prismatic quartz with bipyramidal habit is common in black ore. This crystal form strongly suggests that the quartz in black ore grew up in open space.
3. The grain size of quartz increases monotonously towards the margin of the black orebody of the Uwamuki No. 4 deposit, accompanying its morphological change.
4. The ratios quartz/sulfides and barite/sulfides show proportional relation in sedimentary ores of the Uwamuki No. 4 deposit.

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*1 Rough estimate by the present author on the basis of geologic section of the deposit.
In other words, in proportion as the ratio quartz/sulfides increases the ratio barite/sulfides rises and vice versa. Quartz/sulfides ratio is extremely high at the solution outlet onto sea floor and is low at yellow ore zone.

5. Mixing of cool sea water with discharged ascending solution caused both temperature lowering and introduction of sulfate ion. These are the reasons why quartz and barite precipitate simultaneously with sulfide minerals. Chalcopyrite in yellow ore may be precipitated due to neutralization of hydrothermal solution by mixing with sea water.

6. If we assume that the filling temperature of fluid inclusions in quartz is identical with the formation temperature, net contamination of sea water at the site of mineralization of siliceous orebody is less than 25%.

7. Black ore is precipitated at relatively early stage of mixing of discharged hydrothermal solution with sea water.

8. The minimum amount of ore-forming hydrothermal solution responsible for black orebody of the Uwamuki No. 4 deposit is ca. \(1.3 \times 10^7\) t in which a few hundreds ppm of copper will dissolve.

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Appendix

Experimentally measured solubility of quartz in water along three-phase subcritical curve (KENNEDY, 1950; KITAHARA, 1960; MOREY et al., 1962; Siever, 1962; CRERAR and ANDERSON, 1971) can be fitted satisfactorily by the following equation (CRERAR and ANDERSON, 1971);

$$
\log (\text{ppm SiO}_2) = 3.3105 + 0.25293 X - 0.32168 X^2
$$

where, $X = 1000 \frac{1}{T} (°K)

On the basis of equation (A-1), decrease in quartz solubility caused by cooling of solution is calculated to be $3.60 \pm 0.02$ ppm per unit degree between $320°$ and $290°C$.

SiO$_2$ content in mixed solution, $M_{mix}$, is given by,

$$
M_{mix} = \frac{M_1 + M_2 r}{1 + r}
$$

where, $M_1$ and $M_2$ are the SiO$_2$ content in ppm in hydrothermal solution and admixing sea water, respectively. Rearranging the equation (A-2), we obtain,

$$
r = - \frac{M_1 - M_{mix}}{M_2 - M_{mix}}
$$

Substitute the equation (A-2)' into equation (3), we get,

$$
T_2 = T_1 - \frac{M_1 - M_2}{M_1 - M_{mix}}
$$

Here we assumed that $T_{mix} = T_1 - 1$.

Assuming that the ascending hydrothermal solution was cooled by unit degree by sea water, $(M_1 - M_{mix})$ should be smaller than $3.6$ ppm. If the value is larger than $3.6$ ppm, dissolution of quartz will occur. Substituting the following values into equation (A-3), $T_2$ is calculated to be; $T_1 = 320°C$ ("Formation" temperature of siliceous ore at level ~170 m)

$$
M_1 = 665 \text{ ppm (SiO}_2 \text{ concentration in solution saturated with respect to quartz at 320°C)}
$$

$$
M_2 = 2.9 \text{ ppm (SiO}_2 \text{ concentration in normal oceanic water after TUREKIAN (1969))}
$$

$T_2 \leq 136°C$

Corresponding value of $r$ becomes less than about 0.2, according to Figure 5.
小坂鉱山，上向第四鉱床中の石英

浦辺 徹 郎

要旨：表記鉱床中の黒鉱，黄鉱，珪鉱中のシリカ鉱物は石英のみで，硫化鉱物と同時沈殿したものと考えられ
る。黒鉱鉱石中には両亜石英がごく普通に見られ，その大きさは鉱流の噴出中心から外側へ向かうにつれて增大
する。また石英／硫化鉱物の比と重晶石／硫化鉱物の比
は正の相関を示す。石英の水溶液中の溶解度は主として水溶液の温度のみの関数であるので，下記の二つの比の関
の正比例関係は，冷たく，硫酸イオンに富んだ海水と上昇してきた鉱液との混合により説明可能である。