by Shunso Ishihara and Akira Sasaki

Ore deposits related to granitic magmatism in Japan: A magmatic viewpoint

Ore sulfurs from major vein and skarn-type ore deposits in Japan containing Sn, W, Mo, Fe, Cu-Pb-Zn, Au-Ag, Sb, and Hg, show a beautiful asymmetrical pattern of negative $\delta^{34}\text{S}_{\text{CDT}}$ values in the frontal ilmenite-series granitic provinces and positive $\delta^{34}\text{S}_{\text{CDT}}$ values in the backarc magnetite-series granitic provinces. Thus, these hydrothermal ore deposits are controlled essentially by the type of felsic magmatic activities in their given provinces.

Introduction

Granitic magmatism and related hydrothermal ore deposits have been the subject of intensive study in Japan with many recent reviews. Progress up to the mid-1980s on research of granitoids and associated ore deposits was summarized by Takahashi (1985) and Shimazaki (1985a), on the occasion of the 90th anniversary of the Geological Society of Japan. Granitoid types and series were adopted at this time as a new concept in granitoid research. A special issue of Mining Geology, devoted mainly to volcanogenic Au deposits, was published in 1986 to commemorate the 200th issue of the journal (volume 36, no. 6).

The chemical aspects of magmatic evolution and deep hydrothermal fluid-rock interaction were published in a special issue of the Geochemical Journal (Urabe and Cygan, 1989). Another special issue of Mining Geology (volume 40, no. 6, 1990) contains recent studies on Jurassic granitoids in Japan and South Korea and discusses the genesis of the Kamioka Pb-Zn skarn deposits, whose related granitoids have been controversial. In a special publication, edited by Shimizu and Gastil (1990), 71 zoned plutons in Japan were cataloged (with some examples from California as well), and the mode of emplacement common to the granitoid intrusions was discussed.

With the results of these recent studies and our new data on sulfur isotopes of ore minerals in mind, we present here our view on the genesis of Japanese hydrothermal ore deposits. The ore deposits concerned are vein, skarn, and minor disseminated or porphyry types. Kuroko mineralization is described in another paper of this issue.

Felsic magmatism in Japan

In Japan, the first major magmatic cycle is the Triassic-Jurassic, I-type magnetite-series of Funatsu granitoids, Chubu district, central Japan (fig. 1). This series is granodiorite in average composition and is not accompanied by volcanism, and it has almost no related mineralization.

The next cycle is Cretaceous felsic magmatism. It is present in northern Honshu as the Kitakami granitic district and in the Abukuma granitic and metamorphic district (fig. 1). Comagmatic volcanic rocks occur only along the eastern margin of the Kitakami district. I-type, magnetite-series granitoids are overwhelming in the Kitakami district and a "quartz diorite line" may be drawn in the western part. The magnetite content of these granitoids decreases westward toward the Tanakura Tectonic Line, and I-type, ilmenite-series rocks of an average composition of granodiorite are predominant in the major part of the Abukuma district (Ishihara, 1990). Associated ore deposits are mostly skarn and mesothermal vein types containing Fe, Cu, W, and Mo, with the exception of one Pb-Zn-rich Kuroko type at Taro. The ore metals are asymmetrically zoned west to east from barren to W-Cu to Mo-Pb-Zn provinces (fig. 2).

The largest volume of granitic and coeval volcanic rocks of late Cretaceous-Paleogene age is exposed in the Inner Zone of southwestern Japan, which is defined here as an area west of the Tanakura Tectonic Line, and is called the Inner Zone batholith. In the Inner Zone batholith, the Ryoke granitic and metamorphic belts and the Sanyo and Sanin volcanic and granitic belts are distributed from the Median Tectonic Line northward (fig. 1). I-type, ilmenite-series granitoids of granodiorite in average composition, having local S-type, ilmenite-series, two-mica monzogranite, occur in the Ryoke belt. The granitic and volcanic rocks are generally I-type, ilmenite-series granodiorite and monzogranite in the Sanyo belt, but I-type, magnetite-series granodiorite and monzogranite in the Sanin belt. Many skarn and mesothermal vein deposits containing W, Mo, Sn, Cu, Pb, Zn, and F occur in the volcanic and plutonic belts. The ore elements show a distinct metal zoning of barren, W-Sn-Cu, and Mo (-Pb-Zn) provinces from south to north (fig. 2). Epithermal pyrophyllite deposits that are associated with minor gold mineralization are characteristic of the Sanyo belt.

In the middle Tertiary, the Japanese islands shifted into a new tectonic setting. This resulted in I-type, ilmenite-series granodiorite and monzogranite forming in eastern Hokkaido, and both I- and S-type granodiorite and granite intruding in the Outer Zone of southwestern Japan. The latter zone is associated with skarn and mesothermal to epithermal vein deposits containing Sn, Cu, Zn, As, and Sb. I-type, magnetite-series, volcanic and granitic rocks that have a wide range of composition (basalt to rhyolite), formed along the backarc (western) side of the island arc ("Green Tuff" region), from Hokkaido to the Ryukyu Islands and from middle-Tertiary to the present. This igneous activity was submarine in the Honshu arc during the Miocene, and it formed the Kuroko deposits. Submarine activity is now present in the Ryukyu arc, such as at the Izena hydrothermal vent that was recently discovered in the Okinawa Trough. The hydrothermal activity related to the submarine volcanism resulted in the widespread Green Tuff alteration of associated volcanics. Many small stocks are present in the Green Tuff region implying a large batholith occurring underneath the volcanic piles.

Many mesothermal to epithermal vein deposits containing Mo, Cu, Pb, Zn, Ag, Au and Mn, plus Kuroko massive sulfide deposits, occur in this volcanic and plutonic belt of the "Green Tuff" region. The portion of this region that has recently been subjected to subaer-

Sulfur content

- (Eocene)-Miocene granitoids
- Cretaceous-Paleogene granitoids
- Jurassic granitoids

Figure 1.—Distribution of Japanese granitoids and their sulfur contents. Sulfur data taken from Ishihara and others (1988). Dashed lines separate Ryoke, Sanyo, and Sanin Belts.

Figure 2.— $\delta^{34}\text{S}_{\text{CDT}}$ variation of ore sulfur of Cretaceous–Paleogene age. For the ore metal variation see Ishihara (1978). Data source: Sasaki and Ishihara (1980), Shimazaki (1985b), Shikazono (1987), and unpublished data of the authors. Open box is Kitakami district; box with bar is Abukuma district; open box with “A” is for deposits related to alkaline granitoids of Orikabe pluton in southern Kitakami district; and that with “T” is for those of the Mo-Pb-Zn province. K (in the range of rock sulfur) represents Kitakami granitoids.

Figure 5.—Distribution of major sulfide deposits in Miocene volcanic and plutonic provinces. Class 1 and 2 ore deposits (that is, the largest and second largest of Igarashi, 1979) are shown together with the larger symbols. Class 3 is shown as a smaller circle and box. Tin ores occur associated with base metal deposits at Mt. Okue, and tungsten deposits are concentrated in Yakushima Kyushu. (Igarashi and Kishimoto, 1979, and Kishimoto and others, 1979.)

Ore sulfur isotopes

Sulfur isotopic ratios of ore sulfur correlate well with those of granitoid total sulfur. The available data, mostly from composite samples, are summarized and average values for given ore deposits are shown in figures 2 and 5. Although the $\delta^{34}\text{S}_{\text{CDT}}$ of ore sulfur depends upon the mineral species of samples analyzed and the formation temperature of the ore minerals, a clear difference can be observed between the granitoid series provinces.

In the Inner Zone batholith, ^{34}S is most enriched in ores from the Mo(-Pb-Zn) Province. They have a peak at 3–4 permil $\delta^{34}\text{S}_{\text{CDT}}$ (see inset in fig. 2). Ores from the ilmenite-series granitic province are characterized by negative values and differ depending on sub-provinces. In the Chubu-Kinki subprovince, $\delta^{34}\text{S}_{\text{CDT}}$ ratios peak at –5 to –6 permil, while the ratios are concentrated around –3 to –4 permil in the Chugoku subprovince. In both western Chugoku-northern Kyushu and Uetsu-Kanto subprovinces, the ratios are biased to 0 permil.

In the Cretaceous of Abukuma and Kitakami districts of north-eastern Japan, important ore deposits are associated with magnetite-series granitoids. Yet, $\delta^{34}\text{S}$ ratios of the ore sulfur are lower than those of the Sanin belt. These ores have a peak at 0 permil (fig. 2). In detail, ore deposits related to the alkaline granitoid at Orikabe have the highest $\delta^{34}\text{S}$ ratios in the district, with ores of the Mo-Pb-Zn province having higher values than those of the W-Cu province.

Rich base metal and precious metal mineralizations occur on the backarc side of the Japanese islands, and they are related to both submarine and subaerial magnetite-series volcanic and plutonic activities, most of which are located in the "Green Tuff" region. This metallogenic province is here divided into seven subprovinces by characteristic ore elements:

Eastern Hokkaido:	<u>Au-Ag-Hg-Pb-Zn</u>
Southwestern Hokkaido:	<u>Au-Ag-Cu- Pb- Zn</u>
Northern Tohoku:	<u>Cu-Pb-Zn</u>
Southern Tohoku-Kanto:	<u>Au-Ag-Cu-Pb-Zn</u>
Fossa Magna:	<u>Au-Ag</u>
Sanin:	<u>Ag-Cu-Pb-Zn</u>
Kyushu:	<u>Au-Ag</u>

These ores have generally positive $\delta^{34}\text{S}$ values, similar to those of the Paleogene Sanin province. Whenever base metal and precious metal deposits occur, precious metal deposits have lighter $\delta^{34}\text{S}$ values than do base metal deposits (Shikazono, 1987). One interesting finding is the ^{34}S -depleted characteristic of the eastern Hokkaido, which is equivalent to the $\delta^{34}\text{S}$ value of ilmenite-series ores. This observation implies the possibility of ilmenite-series volcanic rocks in this area.

In the Outer Zone mineralized province of southwestern Japan, there are two magmatic belts. One has both S- and I-type granitoids and associated Sn-W-Cu-Sb-As mineralization and occurs in the south, while the other is an ilmenite-series, I-type andesitic belt, having related Sb-Hg mineralization, along the Median Tectonic Line. All the ore sulfur has light $\delta^{34}\text{S}$ values, and those related to S-type, ilmenite-series granitoids have the lowest values, thus correlating with rock sulfur isotopes of nearby granitoids.

Conclusions

Granitic and felsic magmatism has played a major role in metallic ore concentration in the Japanese archipelago. These hydrothermal ore deposits are mainly of the vein and skarn type, and they show distinct regional and local characteristics in the ratio of ore metals.

The most consistent framework of the ore deposits is seen in the ore sulfur having negative $\delta^{34}\text{S}$ values in the arc front and positive values in the backarc terrane. This parallelism is observed not only in so-called high-temperature-type ore deposits containing Sn, W, Mo, and base metal, but also in low-temperature-type ore deposits having Au, Ag, Sb and Hg, and it is the same as that observed in granitoids of the same provinces.

Sulfur and other major components of the hydrothermal ore deposits appear to be originated in solidifying granitic magmas in both granitic and volcanic terranes. The initial ore fluid may be modified by interaction with supracrustal rocks, even with direct host rocks in some cases (for example, Chichibu mine, Ishihara and others, 1987), and meteoric water (for example, Au-Ag deposits). Yet, essential characteristics of given metallogenic provinces are dependent upon those of granitoids in the Japanese archipelago.

Acknowledgment

Thoughtful review by Dr. J. Hedenquist, Geological Survey of Japan, is deeply appreciated.

References

- Igarashi, T., 1979, Distribution map of lead and zinc ore deposits in Japan: Geological Survey of Japan, Map Series, no. 17–2, scale 1:2,000,000.
- Igarashi, T., and Kishimoto, F., 1979, Distribution map of copper ore deposits in Japan: Geological Survey of Japan, Map Series, no. 17–3, scale 1:2,000,000.
- Ishihara S., 1978, Metallogenesis in the Japanese island-arc system: *Journal of the Geological Society*, v. 135, p. 389–406.
- , 1990, The Inner Zone batholith vs. the Outer Zone batholith in Japan—Evaluation from their magnetic susceptibility: *The University Museum, University of Tokyo, Nature and Culture*, no. 2 p. 21–34.
- Ishihara, S., Matsuhisa, Y., Sasaki, A., and Terashima, S., 1985, Wall rock assimilation by magnetite-series granitoids at the Miyako pluton, Kitakami, northeastern Japan: *Journal of the Geological Society of Japan*, v. 91, p. 679–690.
- Ishihara, S., Terashima S., and Tsukimura, K., 1987, Spatial distribution of magnetic susceptibility and ore elements, and cause of local reduction on magnetite-series granitoids and related ore deposits at Chichibu, central Japan: *Mining Geology*, v. 37, p. 15–28.
- Ishihara S., Sasaki, A., and Terashima S., 1988, Sulfur in granitoids and its role for mineralization: *Proceedings of the Seventh Quadrennial IAGOD Symposium*, E. Schweizerbart'sche Verlagbuchhandlung, p. 573–581.
- Kishimoto, F., Igarashi, T., and Shiina, N., 1979, Distribution map of gold, silver, antimony, mercury and arsenic ore deposits in Japan: Geological Survey of Japan, Map Series, no. 17–5, scale 1:2,000,000.
- Matsuhisa Y., Sasaki, A., Shibata, K., and Ishihara, S., 1982, Source diversity of the Japanese granitoids—An O, S, and Sr isotopic approach: *Abstracts of the Fifth International Conference on Geochronology, Cosmochronology and Isotope Geology*, Nikko, Japan, p. 239–240.
- Sasaki, A., and Ishihara, S., 1980, Sulfur isotope characteristics of granitoids and related mineral deposits in Japan: *Proceedings of the Fifth Quadrennial IAGOD Symposium*, Schweizerbart'sche Verlagbuchhandlung, p. 325–335.
- Shibata and Ishihara, 1979, Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of plutonic rocks from Japan: *Contribution to Mineralogy and Petrology*, v. 70, p. 381–390.
- Shikazono, N., 1987, Isotopic composition and origin of sulfide sulfur of Neogene Au-Ag and base metal vein type deposits in Japan: *Journal of the Faculty of Science, The University of Tokyo, Section II*, v. 21, no. 4, p. 239–255.
- Shimizu, M., 1986, The Tokawa batholith, Central Japan—An example of occurrence of ilmenite-series and magnetite-series granitoids in a batholith: *The University Museum, University of Tokyo, Nature and Culture, Bulletin* no. 28, 146 p.

- Shimizu, M., and Gastil, G., eds., 1990, Recent advances in concepts concerning zoned plutons in Japan and Southern and Baja California: The University Museum, University of Tokyo, Nature and Culture, Bulletin no. 2, 252 p.
- Shimazaki, H., 1985a, Recent progress of studies on metallogenesis in Japan—With special reference to the studies on the deposits of granitic affinity and on the Kuroko type deposits: *Memoirs of the Geological Society of Japan*, No. 25, p. 417–430. [In Japanese, English abstract.]
- , 1985b, Regional variation of isotopic composition of hydrothermal ore sulfur in Japan: *Journal of Faculty of Science, University of Tokyo*, Section II, v. 22, p. 81–100.
- Takahashi, M., 1985, A proposal and development of granitoid series concept: *Memoirs of the Geological Society of Japan*, no. 25, p. 225–244. [In Japanese, English abstract.]
- Urabe, T., and Cygan, G.L., eds., 1989, Special Issue—Deep crust fluid-rock interaction: *Geochemical Journal*, v. 23, no. 6, p. 269–347. □

Dr. Shunso Ishihara, born in 1934, is the Director-General of the Geological Survey of Japan (Higashi 1-1-3, Tsukuba, 305 Japan), since 1989. He was educated at Hiroshima University (bachelor's degree), Columbia University, New York, USA (master's degree), and the University of Tokyo (doctorate). His main interest has been granitoids and related ore deposits. He is known as the proposer of magnetite-series and ilmenite-series granitoids, and serves as the Secretary-General for the 29th IGC, Kyoto. In June 1991, he became the Director-General of the Agency of Industrial Science and Technology of MITI (Kasumigaseki 1-3-1, Chiyoda-ku, Tokyo, 100 Japan).

Dr. Akira Sasaki, born in 1928, is Professor of Geology, Department of Education, Ibaraki University, Mito, 310, Japan. From 1956 to 1988, he was a research geologist with the Geological Survey of Japan where he was in charge of setting up the stable isotope laboratories in the early 1970s. Prior to this he studied at the Geological Survey of Canada as a Postdoctoral Fellow from 1962 to 1965 and at the University of Alberta from 1965 to 1969 as a Postdoctoral Fellow and a Research Associate on leave from the Geological Survey of Japan. He specializes in the isotope geochemistry of sulfur and lead. His current interest is in the isotopic study of the biological sulfur cycle, especially concerning the sulfur in human bodies.