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A Kuroko-Type Polymetallic Sulfide Deposit in a Submarine Silicic Caldera

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Manned submersible studies have delineated a large and actively growing Kuroko-type volcanogenic massive sulfide deposit 400 kilometers south of Tokyo in Myojin Knoll submarine caldera. The sulfide body is located on the caldera floor at a depth of 1210 to 1360 meters, has an area of 400 by 400 by 30 meters, and is notably rich in gold and silver. The discovery of a large Kuroko-type polymetallic sulfide deposit in this arc-front caldera raises the possibility that the numerous unexplored submarine silicic calderas elsewhere might have similar deposits.

Kuroko-type polymetallic sulfide deposits, as described from the Miocene rocks of the Hokuroku district in northern Honshu, Japan, are formed on the sea floor and genetically related to silicic submarine volcanoes (*1*). Heat from magma reservoirs beneath these volcanoes forms convecting hydrothermal systems that leach heavy metals from shallow crustal rocks. As they rise through fissures or volcanic conduits, hot aqueous fluids carry these metals to the sea floor, where they precipitate polymetallic sulfide deposits as they encounter cold seawater. Kuroko-type deposits in ancient rock sequences are important sources of Cu, Zn, Pb, Ag, and Au that have been exploited economically in many countries (*2, 3*).

Here, we describe a major Kuroko-type deposit in Myojin Knoll Caldera, which is located 400 km south of Tokyo (Fig. 1). This is one of nine Quaternary submarine silicic calderas lying on the front of the Izu-Ogasawara Arc (*4*). The caldera rim, 520 to 880 m below sea level, is about 7 km in diameter; its floor is 4 by 3 km and it ranges in depth from 1350 to 1400 m. The caldera's collapse volume is about 18 km^3. The age of the caldera is not yet known. The steep caldera wall exposes a variety of unaltered deposits, including rhyolite lava flows and domes, breccias, and thick sequences of bedded and nonbedded pumice containing 71 to 74 weight % SiO_2 and <1 weight % K_2O. A postcaldera rhyolite dome rises 300 m above the caldera floor (*5*).

Box and gravity cores collected in 1986–1989 provided the first indication of hydrothermal sulfide mineralization (*6*). Anomalous concentrations of methane (to 11 nmol/kg) and manganese (to 170 nmol/kg) in the water column about 300 m above the caldera floor implied that hydrothermal fluids were being emitted locally (*7*). A manned submersible program, begun in 1991, has so far involved 23 dives into the caldera.

The deposit extends from the flat caldera floor at 1360 m to a depth of about 1210 m on the sloping talus at the foot of the eastern caldera wall (Fig. 2). The deposit lies above the interpreted trace of the caldera boundary fault, and its underlying hydrothermal system is probably contained largely within the debris-filled caldera collapse conduit. The caldera-related magma reservoir at depth provides the heat that drives the system, and the collapse conduit connecting this reservoir with the caldera provides a pathway for ascending hydrothermal fluids. The deposit bears no obvious relationship to the postcaldera rhyolite dome, whose center lies more than 2 km to the west.

The exposed part of the sulfide mass, which we call the Sunrise deposit, is at least 400 by 400 m in plan view. Submersible-based sounding profiles along the 1350-m contour and three traverses crossing this contour (Fig. 2) indicate that it rises an average

Table 1. Selected minerals identified in the Sunrise deposit.

	Active chimneys	Inactive chimneys	Mounds, massive and layered	Disseminated in tuff breccia
Anhydrite	*			
Barite	*	*	*	*
Cerussite		*		
Chalcopyrite	*,†	*,†	*	*
Covellite		*	*	*
Galena	*,†	*,†	*	*
Jordanite	*	*		
Marcasite	*	*	*	*
Native arsenic	*			
Native sulfur	*			
Orpiment	*			
Pearceite				*
Pyrargyrite				*
Pyrite	*,‡	*,‡	*,‡	*,†,‡
Realgar	*			
Sphalerite	*,§,‖	*,§,‖	*	*
Tennantite	*	*	*	*
Tetrahedrite	*	*	*	*
Wurtzite	*			

*Present in euhedral to anhedral forms. †Colloform. ‡Pelletal. §Columnar. ‖Dendritic.

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of 30 m above the surrounding caldera floor. The deposit is topped by at least four nearly continuous ridges running northwest to southeast, which are composed of dozens of overlapping and coalesced sulfide mounds. Small fissures on some mounds parallel the azimuth of the ridges. In places, the lower parts of tall chimneys have coalesced with neighboring chimneys to form spectacular castellated walls. Areas between the ridges and chimneys are covered by brecciated massive sulfides, hydrothermal manganese oxide, and muddy sand. The cross section of one mound reveals internal layering consisting of brecciated massive sulfide overlaid by silica-cemented pumice and capped by a layer rich in chalcopyrite and pyrite.

Normal faults, striking northeast to southwest and roughly paralleling the nearby caldera wall, cut the deposit and produce conspicuous scarps (Fig. 2); some are more than 15 m high. More than a hundred chimneys were observed, and about 70% of them appeared to be inactive. Active ones emitted black smoke or shimmering water at a maximum measured temperature of 278°C. Deep-sea mussels, bythograeid and galatheid crabs, barnacles, large actinians (sea anemones), and gastropods were observed near many of the active chimneys.

Selected minerals identified in four facies of the Sunrise deposit and chemical analyses of 37 samples are presented in Tables 1 and 2, respectively. No Au-bearing minerals were observed under optical and scanning electron microscopes with high magnification. However, the association of Au with Zn suggests that Au exists as unresolvable, submicrometer-sized particulates within sulfides, mainly sphalerite.

Compared with other modern and ancient volcanogenic sulfide deposits from different tectonic settings, the Sunrise deposit has high values of both Au and Ag (Table 3). The Au contents of the Myojin Knoll samples are not as high as the Au contents of those from Suiyo seamount, which lies 400 km to the south along the Izu-Ogasawara arc, but the Ag and Pb contents are much higher. This enrichment may reflect a thicker and more mature crust beneath the northern part of the arc (*8*). Available analyses show that the Sunrise deposit is significantly richer in Au and Ag than an average Kuroko deposit (*2*).

Analysis of 26 liquid-rich two-phase inclusions (averaging 10 μm across) in two cleavage-free barites (*9*) from a pyrite-rich brecciated massive sulfide imply that the minerals were formed at temperatures of 180° to 290°C (mean, 228°C) and 230° to 330°C (mean, 271°C) and from moderately saline fluids with NaCl equivalents of 2.9 and 3.5 weight %, which is close to and slightly higher than that of seawater. The variable homogenization temperatures might reflect changes in the mixing ratios of the hydrothermal fluid and seawater at the time of barite precipitation or variations in the temperature of these fluids with time. The sulfur isotopic values δS (per mil relative to CDT standard)

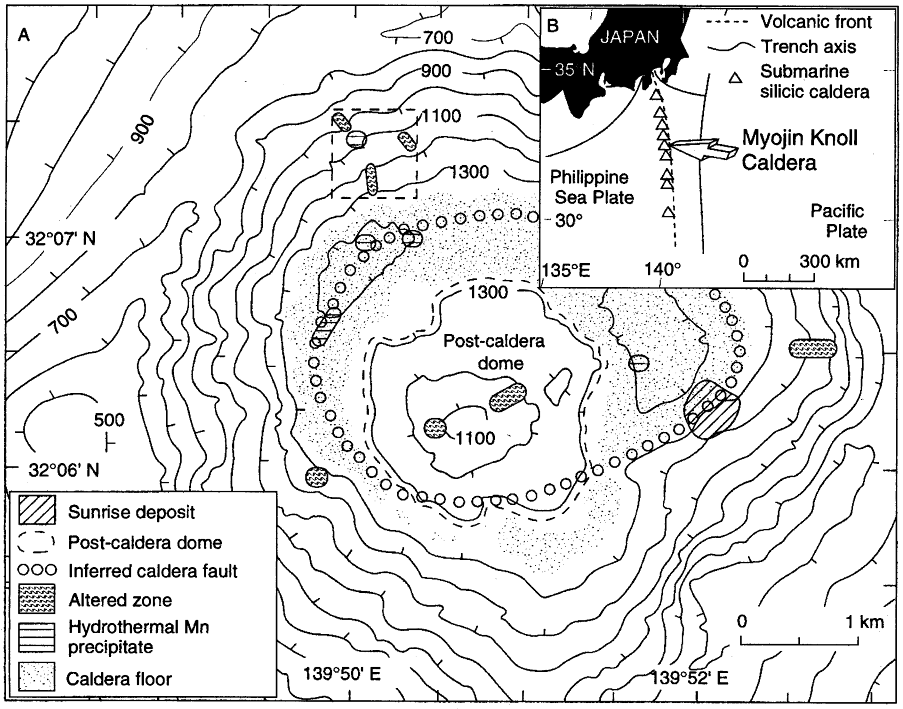

Fig. 1. (**A**) Bathymetric map of Myojin Knoll Caldera, showing relationship of the Sunrise deposit to selected caldera features. Dashed rectangle on the northwestern caldera wall encloses an active hydrothermal field containing sulfate chimneys, barite- and sulfide-bearing tuff breccias, and Mn precipitates. Contour interval, 100 m. (**B**) Location map. Data for submarine silicic calderas (north to south) are as follows: Omurodashi (34°33′N, 139°27′E), Kurose Hole (33°24′N, 139°40′E), Shin-hachijo (32°42′N, 139°45′E), Higashi-aogashima (32°27′N, 139°55′E), Myojin Knoll (32°06′N, 139°51′E), Myojinsho (31°53′N, 139°59′E), Sumisu (31°28′N, 140°03′E), Minami-sumisu (31°15′N, 140°05′E), and Torishima (30°30′N, 140°16′E).

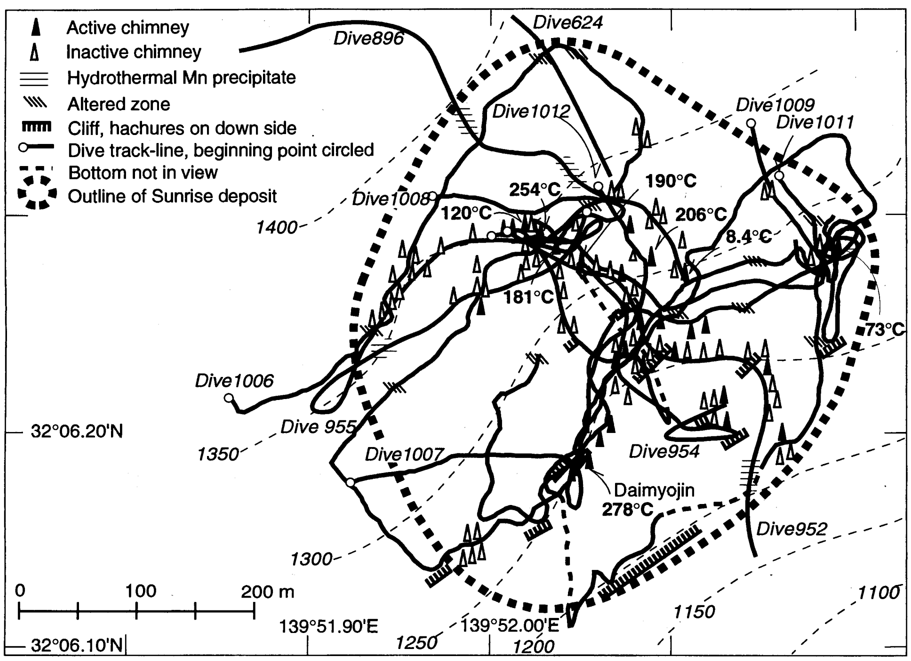

Fig. 2. Map of the Sunrise deposit. Hydrothermal fluid temperatures are shown at selected chimneys; the highest observed temperature, 278°C, was measured at the top of a 30-m-high sulfide chimney informally called Daimyojin ("Big Myojin"). Contour interval, 50 m.

Table 2. Average content (expressed as parts per million or percent) of selected metals and SiO_2 in 37 hydrothermal sulfide samples from the Sunrise depost.

	Au* (ppm)	Ag* (ppm)	As* (ppm)	Sb* (ppm)	Cd† (ppm)	Cu† (%)	Pb† (%)	Zn† (%)	Fe* (%)	Ba* (%)	SiO_2† (%)
Sulfide chimney											
Chalcopyrite-rich conduit wall (N = 2)	2.5	83	745	33	6	26.70	0.08	0.34	25.30	0.10	0.11
Sphalerite-rich interior and conduit wall (N = 22)	31.0	1609	7,366	5,759	2991	2.94	3.64	33.90	6.45	4.03	4.31
Anhydrite-rich rind (N = 1)	3.5	180	1,300	380	102	0.29	0.87	3.79	3.42	8.50	0.33
Silica-rich rind (N = 1)	2.9	36	1,800	210	28	0.12	1.42	1.36	0.99	9.90	49.40
Layered sulfide (N = 1)	0.8	100	330	65	145	24.60	0.03	1.77	21.20	0.70	16.00
Brecciated massive sulfide (N = 4)	4.0	75	1,575	130	62	11.92	0.04	0.82	30.50	0.07	8.55
Disseminated sulfide (N = 6)	5.1	1447	2,228	658	401	2.40	0.22	8.85	7.92	23.26	21.06
Maximum	49.0	4530	19,000	28,000	8930	30.70	11.00	52.10	32.30	45.50	49.40
Average (N = 37)	20.0	1213	5,044	3,564	1858	5.54	2.27	21.89	10.48	6.70	8.68

*Analyses (dry basis) by neutron activation. †Analyses (dry basis) by inductively coupled plasma emission.

Table 3. Average content (expressed as parts per million or weight %) of selected metals in samples from the Sunrise deposit compared with other modern sea-floor deposits and an average Kuroko massive sulfide deposit.

	Au (ppm)	Ag (ppm)	Cu (weight %)	Fe (weight %)	Zn (weight %)	Pb (weight %)	Refs.
Arc-front							
Sunrise deposit (N = 37)	20.0	1213	5.5	10.5	21.9	2.27	This study
Suiyo seamount (N = 11)	27.7	190	11.9	14.6	20.6	0.77	*(14)*
Back-arc basin							
Izena cauldron (N = 14)	4.7	2806	2.0	10.3	20.9	11.49	*(15)*
Lau (N = 46)	3.8	178	5.2	10.6	21.6	0.38	*(16)*
Midocean ridge, slow spreading							
TAG (N = 31)	2.9	80	7.8	24.0	11.1	0.04	*(17, 18)*
Snake Pit (N = 36)	2.0	87	9.2	34.4	6.2	0.05	*(18, 19)*
Midocean ridge, intermediate to fast spreading							
Explorer (N = 48)	0.8	124	3.4	26.8	5.0	0.11	*(18)*
Axial seamount (N = 16)	4.7	175	0.3	4.9	18.8	0.36	*(18)*
East Pacific Rise, 13°N (N = 6)	1.2	80	6.0	23.0	14.8	0.08	*(20)*
Galápagos (N = 17)	0.1	17	4.7	28.7	0.8	0.01	*(21)*
Average Kuroko deposit	0.5	50	1.5	15	3	1	*(2)*

of four euhedral chalcopyrites from massive sulfides and one euhedral chalcopyrite from a chimney conduit fall within a narrow range from +5.0 to +5.5 per mil. Equivalent values of two euhedral pyrites from massive sulfides are +6.0 and +7.6 per mil, which exceed the range of sulfur values of quaternary volcanic rocks from the Izu-Ogasawara arc (+2.7 to +5.8 per mil) (*10*).

Because δS values of precipitated sulfide minerals are not significantly different from those of aqueous sulfide in hydrothermal solution at the estimated solution temperature (180° to 330°C) (*11*), the main source of sulfide sulfur is likely the hot volcanic rocks that host the hydrothermal system. It is possible, however, that a minor part of the aqueous sulfide was produced by reduction of seawater sulfate during deep circulation through hot volcanic rocks. The δS value of a barite (+21.0 per mil) is close to that of seawater sulfate (+21.0 ± 0.2 per mil) (*12*), which suggests that the barite sulfur originates from local seawater.

Given the Sunrise deposit's exposed dimensions, and assuming an average bulk density of 1.9 g/cm^3 (*13*), its mass is about 9×10^6 metric tons, which makes it larger than 80% of the 432 deposits listed in a tabulation of Kuroko mining districts worldwide (*3*). The deposit is situated in the dynamic environment of a caldera, however, where sedimentation is rapid. Submersible observations in areas adjacent to the deposit show the caldera floor to be blanketed with nonmineralized lithic debris and pumice shed from the steep caldera wall. The surface of the Sunrise deposit, especially the most active areas near its center, consists almost entirely of massive and brecciated sulfides, which suggests that it may be growing upward at a rate sufficient to keep its upper surface virtually free of caldera floor sedimentation. Depending on the age and past vigor of the caldera's hydrothermal system, a large part of the Sunrise deposit may be concealed beneath caldera floor debris.

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