Ring Structures, Resurgent Cauldron, and Ore Deposits in the Hokuroku Volcanic Field, Northern Akita, Japan*

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Abstract: Ring dikes, normal faults, central uplift, and slumping structure are considered to be the key factors of the submarine resurgent cauldron. In the east Odate area, there occurs a ring distribution of post-Kuroko dacites and epithermal ore deposits around the central Otaki quartz diorite. Vein-type and Kuroko deposits are distributed almost along the half of the ring. There also occur submarine slumping structures. The estimated subsurface structure indicates the central uplifting and marginal depression in the inside of ring dacites. Those phenomena are interpreted as the fossil submarine resurgent cauldron in the Miocene age with the intermediate scale of about 8 kilometers in horizontal diameter, associated with the genesis of Kuroko deposits and epithermal veins. A structural model of the relationship between the processes of a cauldron formation and ore genesis is proposed.

Introduction

Many cauldrons are accompanied with hydrothermal mineralization (e.g. San Juan, Steven et al., 1974; British Columbia, Barr et al., 1976). Many studies have indicated the close relationships between volcanogenic or volcanoplutonogenic sulfide ore deposits and the formation of calderas, especially resurgent cauldrons (Smith and Bailey, 1968, p. 642-643; Steven, 1969; Burbank and Luedke, 1968; Steven et al., 1974; Koidé and Bhattacharji, 1975a; Bethke et al., 1976; Casadevall and Ohmoto, 1977). Most well known mineralizations associated with volcanic depression in Japan are seen in areas around the Ikuno mine (Maruyama, 1957) and Ashio mine (Imai, 1966). Imai (1966) indicated that many ore veins in Japan are related to magmatic upheaval or cauldron subsidences.

When H. Ohmoto proposed the submarine caldera theory of Kuroko genesis in his visit to Japan in December 1976, many Japanese geologists were impressed by his proposal. Spatial relationship between a graben structure and Kuroko deposits was first stressed by Kinoshita (1944, p. 41), who suggested that the Kuroko deposits occur along the margin of N–S trending graben. But he denied the genetical relation between graben and deposits as well as syngenetic chemical precipitation model of Kuroko deposits. After the revival of the syngenetic theory of Kuroko deposits (Horiyoshi, 1960; Hayashi, 1960), a large basinal structure (Fig. 1) was proposed for the Hokuroku district where occur many Kuroko deposits. It was named “Hokuroku Basin” (Sakazaki et al., 1965; Ohtagaki, 1966). They emphasized the margin of the Miocene basin to be important for Kuroko mineralization. Fujii and Yoshida (1968) presented an alternative hypothesis that up-and-down block movement bounded by N–S and E–W faults controlled localization of Miocene ore deposits of the Hokuroku basin including some Kuroko deposits. Tatsumi et al. (1970) compiled the metallogenic features of the Japanese volcanogenic ore deposits and concluded that the genesis of Kuroko is closely related to the large scale basins in the Green Tuff belt. Subsequently, the “Hokuroku Basin” was interpreted anew as a volcanicogenic collapsed...
Fig. 1 Distribution of the post-Kuroko igneous rocks and ore deposits in northern Akita. Possible five ring structures are predicted within the “Hokuroku basin” (see Fig. 5).

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Ring Distribution of Post-Kuroko Magmatism

The sedimentary and igneous history of the east Odate area is simply shown on Figure 2 by the pre-Kuroko and Kuroko substages (the Yukisawa formation, including of the Kuroko deposits at the upper part) of the Nishikurosawa stage, and the post-Kuroko, Onnagawa stage (the Kagoya and Shigenai formations in the ascending order). The Nishikurosawa and Onnagawa stages are the standard stages of the northeast Japan in Miocene age. Epithermal ore veins occur in the dacitic or andesitic volcanic intrusions and tuffs of the intermediate to upper Shigenai formation of post-Kuroko time (Fig. 2).

Thick dacitic volcanics are widely distributed in the Hokuroku district. It is newly found in the east Odate area that the distribution of dacitic volcanics of the post-Kuroko stage has a ring structure of the scale of 8 kilometers in diameter surrounding of the
Otaki quartz diorite which is located in the central part of the east Odate area (Fig. 3). The ring dacites are composed of partly lavas and partly intrusives. Many ore veins exist in and around this ring dacites. These ore veins are apparently of post-Kuroko stage and were formed probably shortly after the intrusion of the ring dacites.

The dacite masses near the central Otaki quartz diorite in the ring are also considered to have intruded at the post-Kuroko stage according to the recent field survey (T. Takahashi, personal communication). Structures of the Miocene strata indicate the central uplift but marginal depressions in the inside of the ring structure (Fig. 3). This ring structure could be a resurgent cauldron.

Many slumping structures occur in the clastic sediments of the post-Kuroko Onnagawa stage in the inside of the ring structure (Fig. 4a). Some normal faults along the margin of the inner part of the ring support the existence of a marginal depression zone. The time-sequence of emplacement of rocks and sediments were observed. Most dacitic intrusions vertically and sharply cut the wall rocks. Tuff breccias near the dacitic shallow intrusions or lava include many dacitic irregular fragments accompanied with large (occasionally lenticular) fragments of mudstone and shale. Those tuff breccias of post-Kuroko Shigenai stage (TFB6 & TFB7 in Fig. 2) are thought to be formed almost simultaneously with dacitic eruption. On the eastern part of this area, the source of dacitic activity is estimated to be at the site of Nakayama dacite (Fig. 4), because the fragments of the tuff breccia become smaller away from the dacite.

The Otaki quartz diorite is considered to have intruded after the Shigenai dacitic magmatism because the quartz diorite body cut those dacitic volcanics of the upper post-Kuroko Shigenai formation (TFB6), and mudstone and basalt of the post-Kuroko Kagoya formation (TFB4 and BST2). But some fragments of the quartz diorite were found in the intermediate part of the upper post-Kuroko Shigenai tuff breccia (TFB7), so that the quartz diorite might have solidified before the TFB7 activity. Because of the existence of pisoliths and moluscan fossils in the pumiceous tuff (PTF), the submarine environment in this area might have become...
shallower after the ring-volcanism.

The Kuroko deposits distribute near to the ring structure but shifts a little to the southeast from the ring distribution of post-Kuroko epithermal ore veins.

Subsurface Structure

It is difficult to know the subsurface geology in detail because of the lack of the outcrops of the pre-Kuroko stage rocks at the surface. However, the underground geology down to depth of about 500 meters below sea level can be estimated in the east half of the east Odate area because of the existence of the data from many drill holes. In the central part of the east half of the east Odate area, there occur a few Kuroko deposits of intermediate scale called Fukazawa ore deposits (the estimated crude ore amounts to about 3 million tons). The profiles are shown in Figure 4b.

Fuji et al. (1968) reported that rocks on the western area from the Ishinosawa river (Fig. 4) belongs to the pre-Kuroko stage, Yukisawa formation. Tanimura et al. (1974) also considered the inner part of the ring structure as an uplifted zone. But after the detailed geological field works, the rocks in this area are found to belong to the post-Kuroko Kagoya and Shigenai formations (T. Ito, personal communication; Ishikawa et al., 1976).

Most of the Kuroko ore bodies except for the Shinsawa in the northern part of the east Odate area are concealed under the ground. The line of the profile, B–B' which is roughly tangential to the distribution of the dacites, show nearly flat structure under the Kuroko horizon K–K' (Fig. 4). The line A–A' which cuts the ring structure indicates the “marginal depression” and the “central
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Fig. 4b  Geological sections of the eastern part of the Otaki cauldron along A-A' and B-B' lines in Fig. 4a. K-K' implies the horizon of Kuroko deposits. The rock units are shown by symbols illustrated in Fig. 2. Note a great thickness change of the pre-Kuroko units; TFB3, TFB2 and DAC1. The eastern part of A-A' and southeastern part of B-B' belong to the Komaki ring structure, which shows also the marginal depression.

uplift.” Before the time of the Kuroko deposition, a large quantity of dacitic magmas had intruded and erupted. The first depression zone of Smith and Bailey model (1968) was possibly formed at this time. The sediments in the lower Kagoya formation of the earlier post-Kuroko stage have some features of slumping, but those in the upper part of the Kagoya formation have little evidence of slumping and consist of a regular alternation of thin mudstone and tuff layers.

In the southern part of the profile, B-B', there occurs a local depression formed the Shigenai stage of later post-Kuroko stage. Lower Shigenai formation has many features of slumping while the upper part has few. The distribution of the Kagoya basalts (BST2) of the post-Kuroko stage shifts a little to the east from the ring distribution of post-Kuroko epithermal ore veins, as well as Kuroko deposits. The basalt (BST2) distributes out the ring dacites on the eastern part and southeastern part, that is, over the Fukazawa Kuroko deposits and at Kuzuhara area (Fig. 4). On the western part, basalt occurs nearby the No. 10 ore veins (Edate mine, Fig. 1) in the inside of the dacite ring.

Slumping structures of the post-Kuroko stage probably indicate the structural movements. The flow directions of the slumping indicate the directions of flanking, or trend of depression or uplifting. The trend is mostly concordant with the estimated central uplift and marginal depression stated above (see Fig. 4a). The development system of the east
Odate area could be mostly similar to the development model of the resurgent cauldrons of Smith and Bailey (1968).

Discussions

The brief descriptions mentioned above indicate that the Miocene structure of the east Odate area is possibly interpreted as a submarine resurgent cauldron. The scale of this ring structure which is ca. 8 kilometers in diameter is smaller than the scale of the so-called Hokuroku basin which amounts to 30 kilometers in diameter. Some other ring structures in Miocene age are also found in the Hokuroku district, which are similar in size to that in the east Odate area (Fig. 1). LANDSAT (satellites) image also indicate local circle-like structures (Fig. 5). Ishikawa et al. (1976) considered that several “Kuroko volcanos” whose magma reservoirs were assumed to have about 10 kilometers in diameter were distributed in the “Hokuroku Basin” at the middle Miocene age. One of the “Kuroko volcanoes” associated with the Fukazawa ore deposits, roughly accords with the site of the author’s resurgent cauldron of the east Odate area. However, they did not mention about any ring structure or collapsed zone (caldera). Their “Kuroko volcano” is rather a type of dome-volcano.

Fig. 5  LANDSAT image (left) and Bouguer anomalies (right) of northern Akita. Dashed line, major fault. Five Miocene ring structures (thick line with A through D) are inferred from the photograph, Bouguer anomalies and geological data (see ring dacite of Fig. 1). The Bouguer data after Inoue et al. (1973).
The authors propose that the resurgent cauldrons of the scale of about 10 kilometers in horizontal diameter, as the size of a unit magmatism, are directly related to the generation of the post-Kuroko ore veins and also Kuroko deposits in the Hokuroku district rather than the large “Hokuroku Basin” or large caldera which is amount to ca. 20 to 30 kilometers in diameter. But the magnitude of the magma reservoir is much smaller horizontal section: possibly one or a few kilometers in diameter according to Koide (1978). In fact, the horizontal scale of the rock body of the Otaki quartz diorite is amount to be the size of about 1 kilometer X 5 kilometers in horizontal section (Fig. 3).

Smallest scale of dacite or rhyolite domes nearby the Kuroko deposits may probably be closely related to the Kuroko mineralization (Horikoshi, 1969), but in the Fukazawa ore deposits there are not any lower domes closely associated with the ore bodies. These smallest dacite or rhyolite domes looking like lava domes intrude along rim fault zones of a cauldron.

Some geologists indicated that the Miocene structure of northeast Japan was a “geosynclinal trough” (Kitamura, 1959) and maximum marine transgression occurred at the upper Nishikurosawa formation (Matsuda et al., 1967). Inoue (1969) called the arrangement of Kuroko as the “Kuroko belt” and considered that the depth of the sea water in the “Kuroko belt” were amount to over 500 meters below sea level at the time of the Kuroko deposition. The deepest trough is located to the west of the Hokuroku district, that is along the Japan Sea Coast (Fujii, 1974). At the time after the Onnagawa stage (post-Kuroko), the Hokuroku district was one of the peripheral basins of a graben-dome system of the northeast Japan (Fig. 6). If we could neglect the scale problem, the structural settings of the Hokuroku district are very similar to the San Juan volcanic field, southwestern Colorado (Kouda and Koide, 1978). But it is notable that the scale of the San Juan is more than five-fold of the scale of the Hokuroku volcanic field.

The resurgent cauldron of the east Odate area is one of the smaller size cauldrons which took place in and/or out of the large scale “Hokuroku basin.” Let us call it the “Otaki (resurgent) cauldron” associated with the Fukazawa, Ezuri, and Shinsawa Kuroko deposits and Takarakura epithermal ore veins, etc.

The ring distribution of volcanics, slumping structures, and normal faults indicate the existence of a cauldron. The shape of magma chamber is a key factor whether the cauldron or dome is formed on the crustal surface by underlying intrusion. If the horizontal projection of the magma body is circular, radial and concentric fractures are formed over the intrusion (Koide, 1978). If the magma body is nearly spherical, the excess magma pressure over lithostatic pressure forms a domal uplift and radial fractures in the roof rock (Fig. 7a). And, if the magma is circular in horizontal sections but extends deep in a stock-
like shape, concentric fractures are formed predominantly over radial fractures in the inside of a funnel-shaped zone above the top of the intrusion (Fig. 7b). The extension due to wedging of an underlying stock-like intrusion forms vertical ring tension fractures and cauldron subsidence along funnel-shaped ring normal faults in the center of domal uplift (Koide, 1978). After the opening of the ring fractures, the roof of the magma reservoir rises up and extends out along the ring fractures. Consequently, the horizontal section of the upper part of the magma seems greater in size than that of the main lower magma reservoir.

Ground waters and hydrothermal solutions possibly flow along the fractures which were formed around the magma body and can precipitate the mineral deposits.

There occurred many dacitic eruptions and intrusions of the pre-Kuroko stage, Yukisawa formation to form the submarine cauldron collapse (Fig. 8b, 8c). The Fukazawa, Ezuri, and Shinsawa Kuroko deposits were formed at the age of the development of the Yukisawa ring volcanism with the concentric fractures (Fig. 8d). Some part of the Kuroko deposits were formed at the time of lower Kagoya formation. The ring fracture system appears to have had little shifted to the northwest at the beginning of the time of the Shigenai formation to form the Otaki cauldron (Fig. 8e, 8f). The lateral shift of ring structure probably related to the new dacitic magma chamber penetrated.
Fig. 8 Development model of the Otaki resurgent cauldron (See next page for further information)
on the side of old dacitic magma chamber, which had been solidified during the interval between basaltic activities directly after the time of Kuroko deposition and muddy sediments deposited in the earlier post-Kuroko Kagoya formation. On the later post-Kuroko Shigenai formation, the central doming and ring dacite intrusion took place along the ring fractures (Fig. 8g). High Bouguer anomaly in this area (INOUE et al., 1973) support the existence of the central resurgent uplift (Fig. 5). Most epithermal ore veins are assumed to have been formed after this time. The central Otaki quartz diorite intruded around this stage (Fig. 8h).

The Otaki quartz diorite is a volcano-plutonic complex which belong to the magnetite-series (ISHIHARA, 1977) rock type. It contains abundant magnetite. If the hydrothermal systems have remained at the cooling time of the Otaki quartz diorite, they could form a porphyry copper type deposit.

The last sediments in this area are alternation of mudstone and pumiceous tuff which is very porous and contains some pisolites at some special portions. Andesitic intrusions (AND1) are the last igenous activity accompanying with the post-Kuroko vein deposits. Consequently, the environment of the post-Kuroko epithermal veins may have become shallower submarine condition with terrestrial spots which could easily be eroded. Kuroko deposits were formed under probably deeper submarine environment but the post-Kuroko veins were formed under the shallow submarine conditions or under the terrestrial condition.

Either epithermal ore veins or Kuroko deposits are thought to have been formed along the ring dacites or nearby the central uplift under which many fractures had developed. The further study of hydrothermal flow systems and water-rock interactions based on some chemical hydrodynamic experiments and computer simulations is necessary to prove the reliability of the author's cauldron model for hydrothermal mineralization.

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北鹿地域における環状構造・再生カルデラと鉱床群との関係

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要旨：海底で再生カルデラが生じたならば、環状に分布する岩脈群、正断層系が構造変化と海底地帯に堆積構造がみられるが、その痕跡としてみられる。秋田県大館東方地域では、後期鉱期の石英安山岩群と流熱水鉱床群が、中央の大湧石英緑岩体を環状に取り囲む現象が存在する。深沢鉱床などの黒鉱鉱床群も、やや東南にずれるものの、ほぼ環状分布に沿って、いくつか地下に存在する。鉱床群は環状分布の傾向に集中したのが、いくつかの層準で発見される海底地帯堆積構造は上下運動の痕跡と考えられ、ポーリング資料による地下構造からは、中央の大湧石英緑岩体付近の隆起と、周辺の環状石英安山岩群の内側に隣接構造が示唆される。このことから、8 km 程度の直径をもつこの環状鉱床は、中新世の海底にできた再生カルデラの痕跡と考えられ、鉱床生成もカルデラの形成に関連して説明することが可能である。すなわち Smith & Bailey (1968) 議の Koide & Bhattacharji (1975) 議で解析し直せば、尖頭的岩漑逆の上昇で海底付近に10 km 前後の直径をもつ火山性海底構造 (cauldron) が発生し、環状の断裂系が発達する。この断裂系に沿って鉱床が上昇し、海底下では黒鉱をつくり、続いて、環状分布内に中心隆起が生じ、環状石英安山岩が貫入し噴出し、その後海底が浅くなるか絶滅する。この時に鉱床が環状断裂系に沿って上昇し、後期鉱期の流熱水鉱床をつくったと説明できる。北鹿地域には、このような環状構造（再生カルデラ）がいくつか存在し、鉱床群は主要なカルデラに関係して生成したと推測される。