Structural Control of the Kuroko Deposits of the Hokuroku District, Japan*

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Abstract: Clusters of Kuroko deposits of Miocene age in the Hokuroku district of northern Honshu lie along one of a conjugate set of lines with NNW and NE strike and most of the larger deposits lie at or close to the intersections of these lines. A wide variety of structural features of northern Honshu have NNW and NE strikes crosscutting the predominant N-S structural trends of Miocene and younger age and are thought to be of basement (pre-Tertiary) origin. It is proposed that fractures in the basement of the Hokuroku district and particularly their intersections were responsible for the distribution of the Kuroko deposits. Presumably, such sites facilitated the diapiric rise of dacite domes and provided a suitable plumbing system for metal-bearing hydrothermal fluids. Several intersections of the NNW and NE lines do not have known Kuroko deposits and may be good exploration targets.

Introduction

The Kuroko deposits of Japan are regarded world-wide as the “type” volcanogenic Cu–Pb–Zn–Ag massive sulfides against which all others are compared. Decades of geological research as revealed to the English-speaking world in two notable compilations, Volcanism and Ore Genesis (TATSUMI, 1970) and Geology of Kuroko Deposits (ISHIHARA, 1974), and in recent reviews (e.g. HASHIMOTO, 1977; HORIKOSHI, 1969; LAMBERT and SATO, 1974; SATO, 1977; URABE and SATO, 1978) have provided a good understanding of the geology, petrology and mineralogy of these deposits. Comparative studies, such as SPENCE (1975) and those summarized in SANGSTER and SCOTT (1976), have shown that there are significant similarities between the young (middle Miocene, 13 m.y.) Japanese Kuroko deposits and much older deposits elsewhere (e.g. Noranda, Quebec, Canada; Archean age). Consequently, an understanding of the factors controlling the genesis and localization of the Kuroko ores is important for interpreting the origins of other volcanogenic massive sulfides and might be an aid in their exploration. The formation of the Kuroko deposits by hydrothermal emanations onto the sea floor accompanying explosive felsic volcanism and dacite domes, their regional distribution near the eastern margin of the Green Tuff volcanic belt of the Japanese island arc and their short time interval of deposition are reasonably well known. However, less certain is the control, if any, on the distribution of deposits within a particular ore district.

The most important and extensively studied Kuroko deposits in Japan are those of the Hokuroku district of northern Honshu (Fig. 1). The currently popular explanation for their distribution is that they were formed around the margins of a sedimentary basin (SATO et al., 1974) and exploration over past decades based on this hypothesis has been successful in locating new deposits (K. HASHIMOTO, personal communication, 1977). However, recent discoveries by Dowa Mining Company of the Fukazawa deposit in the center of the basin and of the Etsuri deposit well removed from the margin have demonstrated that this working hypothesis is not correct and has opened large areas of the Hokuroku basin to more intensive exploration. In this paper I...
propose as an alternative hypothesis that the Kuroko deposits of the Hokuroku basin occur at the intersections of a conjugate set of well-defined linears and that these linears are a manifestation of NNW and NE fracture patterns in the underlying basement rocks.

**Distribution of Deposits In the Hokuroku Basin**

It has long been recognized that several ore clusters within the Hokuroku basin occur along linear trends or "troughs". For example, as early as 1944 Kinoshita demonstrated that the then-known deposits of the Hanaoka mine are located along NE or NW trending lines and the largest deposit, Doyashi, is at the intersection of the two lines. Iwao et al. (1954) found that the orientation of a siliceous ore body and the distribution of altered zones and of pebble dykes cutting through the altered zones in the southern part of the Motoyama deposit at Kosaka are aligned in a NE direction. More recently, Hashimoto et al. (1962) considered from Bouguer anomalies and diamond drilling that the distribution of deposits in the Kosaka mine area was controlled by a NNW striking and ENE dipping structure which they assumed was related to structures in the basement rocks.

Figure 2 shows the present-day clusters of Kuroko ores in the Ōdate area (Hanaoka, Matsuki and Shakanai mines), in Kosaka mine and in Hanawa mine, all drawn at the same scale. At Ōdate there is an obvious and well-known NNW trend of deposits (line B-B) and a weaker NE trend (line 1-1). The largest ore mass, shared by the Matsumine and Shakanai mines, is at the intersection of the two lines. In the Kosaka area, the line D-D drawn parallel to B-B is nearly coincident with the line of best fit (dashed) through the trend of the Motoyama, Uchinotai and Uwamuki ore bodies. In the Hanawa mine, line 4-4 is the best fit through the southern group of ore pods and is parallel to 1-1. The dashed line through the Hanawa cluster shows a poor though possible fit which includes the northern ore body. It seems unlikely that the parallelism of line B-B with D-D and 1-1 with 4-4 in such widely separated areas (Fig. 1) is coincidental.
and suggests, as stated by NISHIWAKI et al. (1975), that there is a significant regional structural control in the distribution of individual ore bodies within each cluster.

Figure 3 demonstrates that an even more remarkable relationship exists for the distribution of ore bodies on the scale of the entire Hokuroku district. All of the known ore occurrences lie along or within 500 meters of one of a set of lines lettered A to E and striking N29°W and a set numbered 1 to 4 and striking N52°E. Furthermore, most of the ore occurrences are at or very close to intersections of these lines. The worst fits are Ōmaki which lies 600 meters south of intersection A3 and the main ore body of Fukazawa which lies 1000 meters south of C3. Removal of some deposits from their original sites of deposition on the flanks of rhyolite domes by slumping (HORIKOSHI and SATO, 1970) may have caused some scatter around the trend lines but the distances involved are commonly less than 100 meters. Hereafter the lines in Figure 3 are referred to as the NNW trend and the NE trend, respectively. They are the same as the solid labelled lines in Figure 2.

The construction of Figures 1 and 3 requires comment. The location and shapes of most of the ore deposits were obtained from the 1:50,000 scale maps accompanying the geological reports for Odate, Ikariigaseki, Hanawa and Towada. Etsuri and Aosabayama were located from information kindly provided by Mr. K. HASHIMOTO, Research Geologist for Dowa Mining Company. (Etsuri is a newly discovered ore body. Aosabayama is a small occurrence of high-grade Kuroko ore which gave an intersection of approximately 3 meters in one drill hole and ~10 cm in another but drilling on 200 meter centers failed to extend the ore.) This information was transferred to a single 1:50,000 scale map which was made by joining the four topographic sheets for the area. There is a consistent accumulative distortion in scale of about 250 meters per sheet between the older ore deposits maps and the newer topographic maps. Error in transferring information from one sheet to the other was minimized by relating the location of the ore bodies to surveyed points where available or to prominent topographic and cultural features. All of the subsequent analysis of the distribution of ore occurrences and trend lines was carried out on this 1:50,000 scale composite map. The NNW set of lines was constructed by first establishing a best fit line (D) through the ore clusters at Furutobe and Ainai mines (two mines exploiting neighboring ore bodies), Kosaka mine and Hanawa mine. The remaining lettered lines were drawn parallel to D so as to intersect a maximum number of ore bodies although lines A and C intersect only one ore cluster each. The NE trend was established by extending line 1 for Matsuki and Matsumine-Shakanai (Fig. 2) through Furutobe-Ainai and Ginzan and drawing the other lines parallel as for the NNW set. For the purposes of this paper, Figures 1 and 3 were drafted by transferring the ore occurrences and trend lines from the 1:50,000 scale map to a single 1:200,000 scale topographic map which probably has produced some distortion.

It is clear from Figure 3 that the only strong colinearity of widely spaced ore clusters is line D of the NNW set and line 1 of the NE set and is the reason why they were chosen as the base lines for drawing the remaining members of each set. It could be argued that the remarkable geometric array of deposits in Figure 3 is
fortuitous and that other sets of lines might be drawn. For example, a good fit can be obtained for Doyashiki, Matsumine-Shakanai, Fukazawa and Hanawa and another for Ômaki, Fukazawa, Kosaka and Aosabayama but neither of these trends has more than a single ore cluster on any line drawn parallel to them. Furthermore, such trends are not consistent with the elongation of ore clusters in Figure 2. The significance of the NNW and NE trends as drawn in Figure 3 is strengthened by the predictability of ore occurrences at or near the intersections of the lines. At the time that I was originally establishing the trend lines in Figure 3 (June 1977) I did not know about Ôtsuri or Aosabayama. Their locations could have been correctly predicted at intersections B2 and E2. However, of greater significance is the relationship of the NNW and NE trends to known geological features of the Hokuroku district and of northern Honshu.

**Geological Features Consistent With the NNW and NE Trends**

Although the geology of northern Honshu and the immediate Hokuroku district is complex, there are a large number of features with NNW and NE strikes as described below to which the trend lines in Figure 3 may be related. Here, I will point out only the obvious structures and will leave a more detailed analysis for a later paper. Throughout this discussion, it is important to bear in mind that the geology of northern Honshu is dominated by Tertiary and younger structures which have the north-south strike of the Backbone Range and Dewa Hills. This can be clearly seen in Figure 4 by the alignment of the majority of the faults and of the Quaternary volcanoes and in the Hokuroku basin by some of the faults (e.g. Ôshigenai fault, Fig. 3). In other words, the alignment of the Kuroko deposits is cross-cut by the majority of Miocene
Fig. 4 Structural geology of northern Honshu, redrawn and simplified from Fig. 1 of Kitamura (1976).

The ERTS lineament was superimposed on Kitamura’s map from a photographic mosaic. The Hokuroku district can be located with reference to Towada Lake.

and younger structures both outside and within the Hokuroku basin.

**Towada Lake**

Towada is a Quaternary Krakatoa-type caldera (Oide, 1968) in the northeast of the Hokuroku district (Fig. 1). Although renewed activity has altered its shape by adding two peninsulas to its southern margin, the original rectilinear outline of the steep-walled caldera is preserved. The western and eastern walls of the caldera are, respectively, subparallel and parallel to the NNW trend lines of the ore bodies in Figure 3 and, ignoring the peninsulas, the southern wall is parallel to the NE trend. According to Oide (1968), such rectilinear shapes are common for Krakatoa-type calderas and are a consequence of intersecting deep-seated linear fractures. In the case of Towada, Oide declares (p. 120–121) “...The NEE (sic) direction corresponds to the direction of the deep fissure structures predominant in this district... and the NNW direction may represent the predominant structural trend in the Tertiary formations of this district or the structure of the pre-Tertiary basement complex...” Oide (1968) and Kuno (1956) both place a fault with NNW strike cutting the north rim of the Towada caldera (Fig. 3). Although the geological map of Aomori Prefecture does not show such a fault, there is a steep NNW trending scarp for which a fault is a likely explanation. An extrapolation of this fault across Towada Lake passes through the Quaternary volcanoes of Mikado-ishi (below the water level) and Ogura-yama on the eastern peninsula.

**Hanawa Fault**

The Hanawa fault (Inoue and Ueda, 1965) is part of a large system of faults which generally have a N–S strike parallel to the Backbone Range (Fig. 4) and which traverse northern Honshu from Hitachi to Aomori (N. Kitamura, personal communication, 1977). The fault can be easily seen on ERTS (Earth Resources Technology Satellite) photographs extending northward from the Quaternary volcanic field NE of Tazawa Lake. A peculiar feature of the Hanawa fault is its deflection in strike to the NNW as it enters the Hokuroku district (Figs. 3 and 4) followed by a change back to a northerly strike at the northern edge of the Hokuroku basin.

**Quaternary Volcanoes**

As already mentioned, most of the Quaternary volcanoes are aligned in a N–S direction parallel to the Backbone Range. However, as seen in Figure 4, Nishi-dake, Nanashigure-yama and Arakida-yama, are aligned in a NE direction across the Backbone Range and parallel to the Kurile trend of the island arc.

**ERTS Lineament**

A pronounced lineament with a NE strike is clearly visible on ERTS photographs extending from a prominent flat-faced peak in the northern part of the Kitakami Mountain-land south of Hachinohe on the Pacific Ocean
side of Honshu to the coastal plain south of Akita on the Japan Sea side (Fig. 4). It is parallel to and passes a few kilometers to the north of the NE trending Quaternary volcanoes mentioned above and is lost under the Quaternary volcanic pile northeast of Tazawa Lake. This major NE trending structure is probably a fault which, to my knowledge, has not been previously mapped.

The Japanese Remote Sensing Research Group (1976, 1977) has defined a large number of ERTS/LANDSAT lineaments in northern Honshu, many of which have NE strikes and including portions of the ERTS lineament shown in Figure 4. Of particular interest is a strong lineament traversing Honshu parallel to that shown in Figure 4 but about 110 km to the south and passing just north of Tôno in the central Kitakami Mountainland to north of Murakami on the Japan Sea side (not shown in Fig. 4). The Remote Sensing Research Group (1977) has also examined a number of geological features on the ground which they have attempted to relate to ERTS/LANDSAT observations. NNE and NE trending features are found throughout the region. Interestingly, their Figure 9 shows that the vast majority of Miocene veins south of Akita in Akita and Yamagata Prefectures have northeasterly strikes. Although these deposits are more than 50 km south of the Hokuroku district, their orientations are reflecting a predominant structural control which is also apparent in the NE strikes of some of the vein deposits in the Hokuroku district (e.g. Namariyama, Osarizawa and Furokura).

**Hot Springs**

Figure 5 shows the distribution of thermal springs in northern Honshu classified into those having relatively low (<42°C) and relatively high (>42°C) temperatures. Taken as a whole, the springs do not show any particular trends in their distribution. However, when only the hotter springs are considered three trends emerge. One, as expected, follows the Backbone Range (X-X' in Fig. 5); another distinct trend is aligned in a NNW direction passing through the Hokuroku district (Y-Y') and there is possibly a third weak NE trend north of Towada Lake (Z-Z'). Recognition of these trends only in the distribution of the hotter thermal springs is probably a consequence of zones of high heat flow following only the strong deep-seated structures.

**Kitakami Mountainland**

The Kitakami mountainland is the largest mass of pre-Tertiary (Mesozoic and Paleozoic) "basement" rocks in northern Honshu (Fig. 4) and reveals the probable source of the NNW and NE trends of the Hokuroku basin.

As shown in Figure 4, most of the faults in the mountainland strike NW to NNW at a distinct angle to the Backbone trends but parallel to some of the features described above. Note particularly the Iwaizumi fault for which there is geological evidence of post Oligocene movement (N. Kitamura, personal communication, 1977). The outcrop of the
Kitakami mountainland ends abruptly near Hachinohe along a NE line parallel to the prominent ERTS lineament. The approximate shape of the basement surface north of the mountainland has been ascertained by Kitamura et al. (1975) who mapped structure contours on the top of a Miocene andesite immediately overlying the basement rocks (Fig. 6). The contours define a steeply dipping plane with a NE strike for several km north of the basement outcrop. The Iwaizumi fault can be traced in the subsurface by the structure contours and is seen to swing gradually to a more northerly strike between Towada and Noheji. Furthermore, there is a NE striking fault near Kamikita and Shichinohe (Fig. 6) which is known to have had early Pliocene movement (N. Kitamura, personal communication, 1977).

Small fault-bounded outliers of pre-Tertiary basement rocks are found NE of the Hokuroku basin in Aomori Prefecture (Figs. 3 and 4). Faults adjacent to the outliers have NNW strikes. Interestingly, the NNW faults bounding the larger of the two outliers are on strike from line C through the Fukazawa deposit in Figure 3.

**Model of Structural Control**

It is well-known by Japanese geologists that NNW basement trends are visible in the overlying younger rocks of northern Honshu and it is clear from the above that these trends which cross-cut the common Miocene structures are particularly well revealed in and around the Hokuroku district. It is more difficult to demonstrate that the NE trends are of basement origin but it seems reasonable that they are at least as old as Miocene and may be older. Although uplift of the Backbone Range (stage III of Kitamura, 1963) postdated the Nishikurosawa formation which hosts the ores (top of stage II), the predominantly northerly trend of Miocene structures was already well established at the time that the ores were deposited (as can be seen, for example, in the distribution of the Green Tuff) and the upward propagation of the deep-seated basement fractures cut across these middle Miocene trends.

The coincidence of the NNW and NE linears through the Kuroko ore clusters of the Hokuroku district with major NNW and NE structures of northern Honshu is remarkable and leads naturally to the proposition that deep-seated fractures of basement origin have controlled the distribution of the ore deposits. There are no major faults along lines A to E and 1 to 4 in Figure 3, so it is unlikely that the basement fractures fully penetrated the Green Tuff here although, as described above, they obviously have penetrated through the Green Tuff elsewhere. The occurrence of the larger ore bodies at the intersections of the linears may be a consequence of (1) the ease of upward movement of dacite domes in areas of intersecting fractures in the basement and
(2) the development of highly permeable zones in which suitable hydrothermal plumbing systems were established for the formation of ores. Most likely, tectonic jostling in the Hokuroku district during the middle Miocene caused renewed movements on the deep-seated NNW and NE structures.

The idea that major structural features or linears have controlled the distribution of ores is by no means new. Kutina and his co-workers (Kutina, 1968, 1969, 1971, 1972; Kutina and Fabbri, 1972; Kutina et al., 1968) have expounded on the principle although their work is more regional in scope and is not without its critics (Gilluly, 1976). Sakakibara (1958) pointed out that hydrothermal ore deposits of northeastern Japan trend en echelon in a NW direction and that this direction is parallel to tectonic lineaments in basement rocks and to the distribution of blocks of Green Tuff that were uplifted during the late Miocene. Another example is the Noranda district of Canada where Sangster (1972; see also Sangster and Scott, 1976, p. 174–175) has proposed that the distribution of the massive sulfide deposits is controlled by well-defined linears. This is a particularly significant observation because of the similarity of the Noranda and Kuroko deposits and suggests that such structural controls may be widespread for volcanogenic massive sulfide ores.

**Conclusions**

The coincidence of the distribution of Kuroko deposits along NNW and NE trending linears in the Hokuroku basin (Fig. 3) with a variety of geological features which cross-cut the main N–S structural trend of northern Honshu has suggested a model whereby the ore deposits were formed where deep-seated fractures intersected to produce favourable sites for the development of dacite domes and mineral deposition on the sea floor. The implications of this model for mineral exploration are obvious. Intersections of the two sets of linears in Figure 3 where no Kuroko deposits are known such as at C1, C2, B3 and perhaps A1, A2, C4 and E3 are potentially favorable sites. However, location of such a target does not necessarily mean that an economic deposit will have formed as witnessed by the small uneconomic Aosabayama occurrence near E2. Obviously, all of the geological, geophysical and geochemical indicators that are usually sought in the search for Kuroko deposits must be fulfilled before a drilling program can be justified. However, the intersections in Figure 3 may be an aid in narrowing the area of search.

It is not known whether the linears in Figure 3 can be extrapolated outside of the present limits of Kuroko mineralization at the margins of the middle Miocene basin. If the basin is truly sedimentary, extrapolation to close-by areas outside of the basin where the Nishikurosawa formation occurs in the subsurface may be possible. On the other hand, if the basin is a caldera as proposed by Hodgson and Lydon (1977) and by Ohmoto (1978), then the development of the NNW and NE fracture pattern is likely to be a local phenomenon related to the caldera structure as is the case for Towada Lake.

I have not attempted to place my model into the plate tectonic framework of the Japanese island arc although some of the relationships have been presaged by Inoue (1969), Ishihara et al. (1974) and Nishiwaki et al. (1975). Inoue has subdivided what he calls the “Kuroko Belt” of northeastern Japan into zones which he has related to distinguishable segments of basement rocks cutting diagonally NNW across the Kuroko Belt. Ishihara et al. (1974) and Nishiwaki et al. (1975) have carried this concept further by recognizing that clusters of sulfur deposits lie at the intersections of the eastern volcanic front of the Green Tuff with deep seismic zones located by Carr et al. (1973). These seismic zones are thought to have the form of transverse faults which divide the island arc into segments although they have not been recognized in the surface geology of Japan. The strike of the zones is the same as the present direction of movement of the Pacific plate. However, prior to the Miocene, plate movement was in a NNW direction (Jackson...
et al., 1972; Morgan, 1972) suggesting that the older deep-seated NNW fracture system may be a manifestation of fossil seismic zones. **Acknowledgments:** The ideas for this paper evolved over four months in 1977 during which time I was a Visiting Professor to the Institute of Mineralogy, Petrology and Economic Geology of Tohoku University, Sendai, Japan. My visit was sponsored by Professor Asahiko Sugaki, Chairman of the Institute, and was financed by grants from the Japan Society for the Promotion of Science and the National Research Council of Canada. A great number of Japanese friends spent considerable time teaching me and showing me the geology and mineral deposits of Japan and of the Hokuroku district in particular. Koji Hashimoto, now Research Geologist for Dowa Mining Company; Professor Nobu Kitamura, Chairman of the Institute of Geology and Paleontology of Tohoku University; Professor A. Sugaki; and Y. Oguma and K. Kato of Shakanai Mines Company were fountains of information. Professors Sugaki, K. Aoki, I. Sunagawa and K. Yamaoka and their students of Tohoku University; Dr. J. Sato of the Faculty of Engineering, Hokkaido University; and Dr. H. Ueno of the Faculty of Engineering, Yamaguchi University brought to my attention pertinent maps and geological reports and patiently translated key sections. The management and geological and engineering staffs of the operating mining companies in the Hokuroku district were gracious and informative hosts during my three weeks of visits to their mines. These include Dowa Mining Company (Ainai, Fukazawa, Kosaka and Hanaoka-Matsumine mines), Mitsubishi Metal Corporation (Furutobe and Matsuki mines), Nippon Mining Company (Namariyama-Ginzan mine) and Shakanai Mines Company (Shakanai mine). One of my visits was during a field trip of geologists from the Texasgulf Company organized by Dr. Morland Smith. K. Hashimoto, N. Kitamura, S. Ishihara and T. Sato critically examined an earlier version of the manuscript. To all of the above I express my thanks and appreciation. They are, of course, in no way responsible for any errors or omission which may appear in this paper.

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**References**


北鹿地域の黒鉱鉱床の構造規制

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要旨：北鹿地域に密集する黒鉱鉱床は北北西と北東系の共役断層群に規制され、大規模鉱床は両者の交点やその近くに分布する。本州北部全体についても、顕著な南一北系を切る種々の性格の北北西系と北東系の構造があ る。これらは先第三紀の基盤の性格に起因すると思われ る。北鹿地域の基盤に由来する上記２方向、とくにその
交差部は黒鉱鉱床の分布を規制する主要因である。恐ら
くその交差部がデイサイトドームマグマのダイアピール
上昇と鉱液の垂直循環機構の発達をうながした。交差部
に鉱床が知られていない所では新鉱床が発見される可能
性がある。