Geology and Mineralization of the Shimokawa Mine:
An Allochthonous Ridge-type Massive Sulfide Ore Deposit

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Abstract: The Shimokawa volcanogenic massive sulfide ore deposits were formed 126 Ma by submarine exhalative activity on the mid-oceanic spreading axis between the Kula-Izanagi and the Farallon plates. A hydrothermal system resulted from the convective circulation of seawater near the spreading axis, as evidenced by the sheeted-dike complex, was responsible for the sub-sea-floor metamorphism and subsequent ore deposition. During mineral deposition, massive sulfide ores were separated by a double diffusive phenomenon from quartz-chlorite and sulfide laminated ores. Ore formation appears to have occurred during a quiescent stage of volcanism; the ore deposits were possibly covered by later siliceous exhalites and/or lavas and then these covers were removed during a subsequent tectonic phase. As trench approached, the oceanic crust containing the ore deposits was overlain by distal and proximal turbidites; these turbidites originated from the Eurasian continental margin volcanic belt in Sikhote-Allin, prior to the Cenozoic opening of the Sea of Japan. These Hidaka Supergroup epiclastic sediments, underlain by oceanic crust and the massive sulfide deposits, suffered oblique slip subduction that caused scaling-off a part of the oceanic crust, particularly the sheeted-dike complex. This part of accretionary prism is known as the Shimokawa tectono-stratigraphic unit, and contains a chaotic mixture of deformed epiclastic sediments and melange units of oceanic crust, in which semi-continuous massive ore deposits occur more or less parallel to the general tectonic trend; eventually the opening of the Sea of Japan caused this belt to be displaced from the continental margin to their present position in the Hidaka zone of Hokkaido.

Other volcanogenic massive sulfide deposits in the Cretaceous Shimanto accretion complex, such as Makimine in eastern Kyushu and Asakawa in eastern Shikoku, appear to have similar allochthonous origin.

Introduction

The Shimokawa tectono-stratigraphic unit is located in the north-south trending axial zone of central Hokkaido (Figs. 1 and 2). This zone, known as Hidaka terrane is composed of thick slates, greywacke turbidites, volcanic fyliesches, and various amount of fault-bound-ed melange units. The Shimokawa unit trends NNW-SSE for 20 km and averages 3.5 km in width; it consists of the ophiolitic melange core flanked by strongly sheared slate. Within the melange terrane, greenrock blocks, ranging in size from tens of centimeters to hundreds of meters, are embedded in argillaceous and sandy matrix.

Sako and Osanai (1955) first described this peculiar mass in their Shimokawa quadrangle map, and refered it as a “Diabase-slate Complex”, because the relations between diabase and slate are so complicated that they could not distinguish these rock units individually on their map. Their description for this complex is particularly interesting as it is very similar to that of an ophiolitic melange. However, until recently we did not have the term melange in our vocabulary and no one was aware of true geological meaning of the complex concerned. Besides, an epigenetic replacement theory for this type of massive ore deposit (Bateman, 1950) was popular among earlier investigators (Ushizawa, 1952; Sako and Osanai, 1955; Shirai, 1955; Nakamoto, 1956); therefore, no one doubted that the Shimokawa deposit formed epigenetically by replacing the sheared zone between the eastern margin of the “Diabase-slate Complex” and the Hidaka slates.

In the late 1950s, the occurrence of pillow lavas in the diabases was recognized for the
first time by the mine geologist, H. Takahashi; the diabases, originally taken as a steeply intruded dike swarm into slates, were interpreted to be sills and submarine lava flows related to initial magmatism within the Hidaka eugeosyncline. Significance of this fact was not fully understood until Miyake (1961) suggested a syngenetic origin of the ore deposit. He showed clear evidence of post-ore basaltic activity as well as colloform textures indicating open space ore deposition.

Although the major features of the ores were explained by a syngenetic origin, some important problems still remained to be solved, i.e. the origin of the “Diabase-slate Complex”, wall rock alteration of diabases and the origin of the ore forming solution. Some workers have attempted to explain the wall rock alteration as epigenetic (Ikeda et al., 1972; Suzuki and Kubota, 1980); however this was explained by sub-sea-floor metamorphism near the mid-oceanic spreading axis (Miyake et al., 1981).

Bamba et al. (1970) noted that the Shimokawa diabases are tholeiite, while Kosaka (1975) designated them as classical eugeosynclinal basalts despite his recognition of their similarity to MORB. The Shimokawa diabases have typical MORB characteristics (Miyake, 1980), based on Miyashiro’s (1975) classification scheme. Recently, from the chondrite normalized REE patterns, Honda et al. (1986) suggested a probable provenance of them from an oceanic ridge. The corollary of this awareness is that the Shimokawa diabases, together with their ores, are fragments of oceanic crust which failed to subduct, i.e., they migrated far from a spreading axis before being incorporated into the Hidaka accretionary wedge to form a melange (Miyake, 1980).

Opponents to this allochthonous origin argued for the overturn of the overall Shimokawa “stratigraphic” sequence (Mariko et al., 1982; Mariko, 1984), based on local reverse graded bedding and upside-down pillow structures. However, their hypothesis seems to be inconsistent with the geological setting of the Shimokawa area, as will be discussed later.

Although the Shimokawa melange theory has been accepted by structural geologists (Kimura, 1985), it is becoming more controversial among mining geologists in Japan after the closure of the mine. This paper attempts to sort through this confusion, and reinterprets the genesis of the Shimokawa ore deposit in the light of modern theories concerning this type of mineralization.

**Tectonic Setting**

Before discussing the genesis of the Shimokawa ore deposits, it is necessary to explain the regional geological background in which the deposits occur, since several hypotheses for the subdivision of structural units of Hokkaido have been proposed in terms of plate tectonics (e.g., Miyashiro, 1977; Hori-koshi, 1972; Okada, 1979, 1983; Kimura et al., 1983; Kimura, 1985; Cadet and Charvet, 1983); these hypotheses have led to various interpretations concerning the provenance of ophiolites as products of volcanic arc, marginal sea, or mid-oceanic ridge volcanism. The recent, rapid accumulation of geological information concerning the central Hokkaido, together with the Sihkote-Alin belt and Sakhalin basin provides an improved paleogeography of the Cretaceous in this region of the northwest Pacific rim (Natal’in and Parfenov, 1983; Kimura et al., 1983; Kimura, 1985).

In Sihkote-Alin and Sakhalin, three tectonic units are recognized from the continent towards the sea; (1) Eastern Sihkote-Alin volcano-plutonic belt, (2) Western Sakhalin forearc basin, and (3) Eastern Sakhalin folded accretional system (3, 4, 5 in Fig. 1, respectively). Such a zonation is similar to that of modern convergent plate margins. Before the Cenozoic opening of the marginal Sea of Japan, each zone extended southward to Hokkaido, so that the north-south trending Rebun-Kabato zone in western central Hokkaido corresponds to the Eastern Sihkote-Alin volcano-plutonic belt, and the Ishikari-Teshio zone east of the Rebun-Kabato zone is the extension of the Western Sakhalin forearc basin. The southern extension of the Eastern Sakhalin folded accretional system in Hokkaido widens to about 100 km, and is sub-
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Fig. 2 Cretaceous tectonic division of Hokkaido. Shimokawa-Tomuraushi line divided into three zones from west to east; Kamuikotan zone, Sorachi zone and Hidaka zone (Fig. 2). The abundance of ophiolite contained in each zone decreases from west to east. The Hidaka zone is underlain by the Cretaceous Hidaka Supergroup, consisting of an accretionary complex characterized by repetition of argillaceous sediments containing exotic blocks of limestone, chert and greenstone and sandy flysch type sediments. In the Shimokawa area these greenstones are noticeably concentrated to form a mappable unit, referred to as the “Shimokawa diabase-slate complex”, and is interpreted here to be a melange (Fig. 3). The Shimokawa ore deposits occur along the northeastern margin of the Shimokawa melange terrane.

Fig. 3 Simplified geological map of the Shimokawa-Asahi area, showing the location of the Shimokawa Melange. 1: Cenozoic volcanics and sediments, 2: Sandstone and slate, Hidaka supergroup, 3: Shimokawa melange terrane, containing exotic greenstone blocks, 4: Olistolith of limestone, chert and greenrock complex, 5: Granite, 6: Diorite, 7: Gabbro, 8: Shimokawa melange terrane, 9: Fault, 10: Town site. Abbreviation: NK: Nakanosawa Creek, TW: Towari Peak, NS: Nisama village.

Geological Setting of Shimokawa Ore Deposits

The tectone-stratigraphic unit of the Hidaka Supergroup, in which the Shimokawa ore deposits occur, are designated informally as the Shimokawa Group, which is divided into lower Shimokawa Formation and upper Iwaonai Flysch (Kimura, 1985). The Shimokawa Formation is highly deformed, thick black argillites often intercalated by thin sandstone layers with or without graded bedding (Fig. 4) and is characterized by abundant basic igneous inclusions of various sizes together with fragmental inclusions of pelagic
Fig. 4 Overturned turbidite bed with perfect Bouma sequence, striking N55°W, dipping 78°N. Near Yamadori bridge, Nakanosawa Creek.

sediment to form a malange terrane. I use melange as a purely descriptive, nongenetic term for the mappable body of rocks with mesoscopic shear structure which contains competent rock inclusions embedded in a sheared fine-grained matrix. The Shimokawa Formation (=Shimokawa melange terrane) is exposed along the Ochiaizawa Creek and the Nakanosawa Creek (tributarries of the Panke River) and along the Teshio River near the Iwaonai Dam site to the south. The melange terrane extends NNW for about 20 km and is 3 to 4 km in width (Fig. 5).

The Shimokawa Formation is likely to be bounded by fault to the east, adjoining the tightly folded, thinly interbedded sandstone and slate of the Iwaonai Flysch with an eastward fold vergence (Kimura, 1985). The western edge of the Formation cannot be clearly located by the presence of later intrusives and or by alluvium, and is tentatively delineated by the line of the Towari River. The gross configuration of the melange terrane is described that a broad core (maximum width ≈2 km) of the Main zone characterized by the abundance of the greenrock inclusions (>50%) in the sheared sedimentary matrix is sheathed by the sediment-predominated highly sheared zone which is tentatively divided into the Eastern and the Western sheared zones. The Main zone will be described somewhat in detail in the next section. The Eastern sheared zone comprises eastward
decreasing sporadic greenrock blocks in argillaceous matrix with scaly cleavage. Southward along the Iwaonai River the coherent Iwaonai Flysch has been less sheared, containing little.
greenstone blocks (see Fig. 4 of Kimura, 1985). The Western sheared zone is similar to the Eastern zone as observed at the entrance of the Towari exploration tunnel (Fig. 5), though it is devoid of greenrock inclusions.

Mesoscopic deformations began during argillites had been still ductile and fractures in the disrupted competent rocks were injected by argillite tongues (Fig. 6). Pull-apart structure is ubiquitous. Phacoidal or lense-form deformation in a thin sandstone layer is commonly observed, and anastomosing cleavages develop in slate enclosing blocks of the fragmented competent rock (Fig. 7). At the Iwaonai section in the melange terrane interbedded sandstones and argillites are characterized by lack of large-scale fold and by chaotic dismemberment of bedding (Fig. 8; see also Fig. 6 of Kimura, 1985), while argillites of the Eastern and the Western sheared zone show characteristic scaly cleavages, from which derived the name shear zone. These mesoscopic structural features display a close similarity with other well-documented occurrences of the melange terrane from the subduction-accretion complex (e.g., More and Karig, 1980; Byrne, 1984).

The lithologic composition of the accretion complex commonly represents that of the trench floor sequence consisting of terrigenous trench-fill turbidites, overlying trench outer-wall hemipelagic and pelagic sediments, which is turn overlie basic volcanics of the oceanic basement (Moore et al., 1982). By analogy the constituent of the Shimokawa melange terrane may be grouped as follows interbedded sandstones and argillites as the trench-fill turbidite; hemipelagic argillites and pelagic sediments (chert, cherty tuff and limestone) as the trench outer-wall sediments and pillowy basalts, diabases gabbros and serpentinites as the basaltic oceanic crust basement.

Fold vergence of the Iwaonai Flysch is eastward, indicating a west-dipping subduction. The shear stress that deformed the Shimokawa Complex is interpreted as having been produced by an eastward movement of the overlying accreting segments over the melange. The presence of the abundant tec-
Fig. 9  Block diagram showing the occurrence of sheeted-dike (1), off-acial dikelet (2), pillow lava inter-dike screen (3) and slate (4) in the Towari exploration tunnel (E) and parallel ventilation tunnel (V) at the site 900–935 m from the entrance. The dikelet first intruded into the sheeted-dike (left-hand on the roof of the ventilation tunnel, V), then between the sheeted-dike and pillow lava screen (on the south wall of the explosioon tunnel, E) and finally into the pillow lava inter-dike screen (on the north wall of the exploration tunnel, E).

thin and that an oblique subduction and/or fracture zone related sea-floor morphology may have facilitated the accretion of pieces of oceanic crust to the inner trench slope (KIMURA, 1985).

Lithology of Melange Inclusions in the Main Zone

The north trending ridge of the Main zone of the melange is covered by a thick forest, restricting observations to the following sites (Fig. 5): (1) Shimokawa mine, where underground mine workings are localized near the northeastern margin of the Main zone, (2) Nakanosawa Creek, where the crosscutting stream provides outcrops on its floor and bank, (3) the Towari exploration tunnel, started from a site 1500 m NW from Towari Peak; the tunnel (azimuth 51°E, gradient −9°28′) constructed by the Metal Mining Agency of Japan is 1500 m in length and cuts obliquely across the melange terrane from the Western sheared zone, through the Main zone, to the Eastern sheared zone; geological sketch maps made by the Agency (M.M.A.J., 1975, 1976, 1977) provide valuable data concerning the melange, and (4) the south shore of Iwaonai Lake, where the melange terrane is exposed continuously along the shore line about 3 km long.

The early interpretation that the Shimokawa diabase-slate Complex was originally a sedimentary sequence accompanied by the coeval basaltic volcanism constrained us to regard the diabases as thick massive lava flows and/or sills. Given that the pseudostratigraphic sequence in the vicinity of a spreading axis is pillow lavas, sheeted dikes, gabbros and peridotites, it is highly unlikely that all the Shimokawa diabases are flows and sills. In this context we present an evidence that will constrain us to recognize the diabases as intrusive dikes but not flows nor sills.

In the Towari Tunnel (910–930 m from the entrance; Fig. 9), a narrow pillow lava is clearly intruded by a thin, fine-grained basalt dikelet about 3.5 m wide that also tongues into the wall of the diabase. In all probability, the occurrence of the dikelet that ascended from the depth of the magma chamber should
Table 1  Size distribution of greenstone blocks in sedimentary matrix at the Towari exploration tunnel and Shimokawa mine

<table>
<thead>
<tr>
<th>Class boundary</th>
<th>4.9m</th>
<th>5-9.9m</th>
<th>10-31m</th>
<th>30-59.9m</th>
<th>60-99.9m</th>
<th>100m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T W R.T.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blocks</td>
<td>10</td>
<td>8</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Average size in m.</td>
<td>3.2m</td>
<td>7.8m</td>
<td>22.5m</td>
<td>-</td>
<td>-</td>
<td>142m</td>
</tr>
<tr>
<td><strong>S M K.M.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blocks</td>
<td>15</td>
<td>11</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Average size in m.</td>
<td>3.0m</td>
<td>6.8m</td>
<td>18m</td>
<td>40m</td>
<td>78m</td>
<td>-</td>
</tr>
</tbody>
</table>

Any diagrammatic representation of the Shimokawa melange should indicate the fact that about 60% of the greenstones from "Shimokawa" and about 40% of the greenstones from "Towari" consist of numerous, discontinuous blocks less than 30m across difficult to represent on small scale maps.

TWR.T.: Towari exploration tunnel, about 1400m in length.
SMK.M.: Shimokawa mine underground, L8. N2., westward crosscut and diamond drilling, about 1100m in length.

have been upright at the time of emplacement. As the contact between the diabase and the pillow lava is subparallel to the wall of the dikelet, the original mode of occurrence of the contact must have been also nearly vertical. This implies that the, “diabase” concerned is a sheeted dike and the “pillow” lava is an inter-dike screen of the pillow lava. Similar occurrence of probable off-axial dikelet can be seen elsewhere in the Tunnel and Shimokawa mine under-ground (e.g., those described in BAMBA, 1977).

The chilled selvage of the sheeted dike is seldom observed within a massive diabase body, e.g. one at 1320 m in the Towari tunnel (M.M.A.J., 1977), probably because each succeeding dike nearly splits the preceding, yet hot dike into two, resulting in the formation of nearly marginless dike or half dike (KIDO and CANN, 1974). Chilled selvages of about 10 m interval noted by BAMBA (1977) therefore provide an exceptional occurrence. In contrast the edge of the diabase blocks often shows a chilled margin indicating the fragmentation proceeded along the chilled selvage. SUZUKI and KUBOTA (1980) also stated that “the coarse and medium grained diabase obviously cuts across the pillow lava in Nisama (Iwaonai) area”. The observation is consistent with the view that the Shimokawa diabase and some of the basalts represent the sheeted dike unit and the inter-dike screen, respectively. Abundance of diabase over basalt was the reason why the whole complex was once designated as a diabase.

The characteristics of a melange such as the abundance ratio of igneous rock inclusions to sedimentary matrix, the size distribution of the igneous inclusions, etc. vary from place to place. The ratio of igneous to slaty rock ranges from 59:41 at the Shimokawa mine (L8, N2)*1, through 61:39 at the Towari tunnel, to 90:10 on the shore of the Iwonai Lake

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*1 Mine coordinate grids are placed at 30 m intervals taking the Ochiaizawa main shaft as the origin (Fig. 5). Levels also having 30 m intervals are numbered upward and downward, taking the adit (275 m a.s.l.) as 0 level. Thus (L8, N2) represents 240 m below the adit and 60 m north from the shaft.
The size distribution of the igneous inclusions at both underground occurrences shows a surprising abundance of the inclusions less than 30 m across (Table 1 and Fig. 10 and 11). The footwall unit of the ophiolite complex is characterized by an absence of the sedimentary layers, as seen in Cyprus (e.g., CONSTANTINOU and GOVETT, 1973) and in Newfoundland (UPADHYAY and STRONG, 1973). Hence such an extreme mixing of sedimentary materials within the footwall unit and a disruption into small blocks indicate tectonic disturbance in a convergent plate margin where scales off the accreting oceanic crust must have been intermingled with the deformed trench fill sediments.

Meager but ubiquitous occurrence of the pelagic sediments such as chert, micritic limestone as inclusions suggests an environment of sediment-starved spreading ridge above CCD (carbonate compensation depth). Also the vigorous submarine hydrothermal activity responsible for the formation of any remarkable ore deposit appears to be restricted to the topographic high along the ridge bounded on both sides by transform faults, underlain by a shallow magma reservoir (BALLARD and FRANCHETEAU, 1982). These constraints would exclude any other environment than a spreading axial oceanic ridge for the origin of the Shimokawa diabases as well as the Shimokawa ore deposits.

Ore Deposits

Mining of the Shimokawa deposits began in 1942 and closed in 1983; during this period about six million tons of crude ore with 2.5% copper were produced. As mentioned, the
Shimokawa deposits are localized between the Main zone and the Eastern sheared zone of the Shimokawa Formation, therefore in most cases diabases and slaty rocks form footwalls and hanging walls, respectively. Toward the north (N10, Adit level), the Eastern sheared zone bends sharply to the west, resulting in the disappearance of the Main zone together with its ores. Ore zone extends for 2800 m along a northerly strike, and dips 30 to 70° eastward; its depth is 800 m at the northern part. The average thickness is 7 m with a maximum 25 m in the Main orebody, where the highest grade of copper was found. Individual orebodies are displaced by post ore faulting or isolated, originally and are called (north to south) the Northern orebody; the New orebody; the Main orebody; the Hanging Wall orebody and its lower extension; the 17th orebody; the Southern orebody and the Nakanosawa orebody (Fig. 12). Except for the last two, each orebody has a northward plunging ore
shoot of low angle and may represent a segment of an originally flat lying layer displaced by a series of faults. The morphology of the orebodies is highly variable, showing lobe-, pod-, bounding-, narrow leaf-, and lens-shaped unit bodies deformed by small step faults (Figs. 12 and 13).

These features as well as the absence of definite stratigraphic sequence, and the dominance of structural boundaries all indicate a gradual deformation of a competent ore layer in the ductile argillite of under-thrusting accretion complex. Their provenance appears to be the same as that of greenrocks transported from a mid-oceanic ridge to a trench to form the melange.

The Shimokawa deposits consist of massive ore and "banded ore" (Fig. 14); the former is subdivided into high grade compact ore and low grade plain iron sulfide ore and the latter comprises sulfide chlorite-quartz laminated ore and disseminated ore. The "banded ore" predominates in the Northern orebody and the New orebody with subordinate amount of massive ore. In the Main ore-body, the hanging wall orebody and the 17th orebody, the predominant compact ore is underlain by plain iron sulfide ore which gradually changes laterally into "banded ore". The Southern orebody and Nakanosawa orebody consist mainly of "banded ore" (for distribution of the ores see Fig. 12).

The ore mineralogy, although variable, is dominated by pyrite ± marcasite (≈70%), pyrrhotite (15%), chalcopyrite (15%), with minor sphalerite (5%), magnetite, cubanite, cobalt mackinawite, cobalt pentlandite and electrum.

As already mentioned, the Shimokawa deposits overall appear to overlie basaltic lavas as typical volcanogenic massive sulfide ore deposits. However, this relationship of the ore body being in direct contact with greenrocks is observed for only half of the cases; in others, slaty rocks separate the two (TAKATORI, 1983). Since environment of the ocean spreading axis may generally be characterized by a topographic high and absence of epiclastic sediments, the presence of slaty rocks between ores and lavas is indicative of a tectonic contact. Even in the case where a direct contact between orebodies and greenrocks is observable, their smooth curvilinear contacts seem to have no original features that indicate the sulfide ores were deposited on rugged or pillowy surfaces of lava flows. Moreover, an absence of stringer ore in altered basalts beneath the massive ores may support a tectonic contact for the ores with the footwall greenrocks, even though some massive sulfide deposits are known to be devoid of distinct stockwork zone and are explained by their distal nature of the deposition (e.g., at Skouriotissa, Troodos, CONSTANTINOU and GOVETT, 1973).

Furthermore, unlike other similar deposits (e.g., Troodos; Semail, Oman; Bett Cove, Newfoundland), unique feature of the Shimokawa deposits is the absence of hanging wall pillow lavas. The hydrothermal activity responsible for this type of mineralization is thought to have occurred during quiescent periods of volcanism, with the deposited ores subsequently covered by exhalites (e.g., the Ochre Group, Troodos) and/or pillow lavas; otherwise, it may be unlikely that the ores persist intact in the oxidizing sea water. Therefore, the original Shimokawa deposits would have been covered by lavas and/or siliceous exhalites which were subsequently removed by later tectonism. Observations that support this hypothesis include; (1) the occurrence of off-axial thin basaltic dikes intruding into the orebodies (e.g. the Hanging Wall
orebody, L4, S23, see Fig. 13) and (2) the occurrence of basaltic rocks overlying orebodies (e.g. the Kaigen-Hi orebody, a part of the Hanging Wall orebody, L4, S15, see Fig. 13 and the Nakanosawa orebody), though it is not certain if the contact between orebody and hanging wall basaltic rock is primary or tectonic. In this connection SUZUKI and KUBOTA'S (1980) following description is interesting—“In the underground exposure near the hanging wall side of the ore deposit there are several pillow lavas, from 20 to 100 m thick and 300 m in maximum.” They may represent a portion of the pillow lavas that originally covered the orebodies.

Ore Genesis

The Shimokawa deposits exhibit a rough zonation of the ores either from footwall to hanging wall or laterally; the zonation pattern is from basal or marginal plain iron sulfide ore, through massive cupferous ore, to “banded ore” (and vice versa), then partially overlain by disseminated ore in a quartz-sericite matrix. Recently, models have been developed to explain the zoning in volcanogenic massive sulfide deposits (SOLOMON, 1976; SOLOMON and WALSH, 1979; LARGE, 1977); on the basis of these models the temporal and spatial zonation and the textural features of the ores of the Shimokawa deposits (MIYAKE, 1965) seem to be reasonably interpreted.

Pyrite-dominated plain iron sulfide ores (Cu 0.3–0.8%, S 35–40%) vary from being massive to a somewhat loose aggregate of colloformic iron sulfide. They may contain sphalerite as erratic, narrow bands or small clots, but are devoid of pyrrhotite. These plain iron sulfide ores represent rapidly grown sulfide mounds on the sea floor deposited from hydrothermal plumes quenched by mixing with sea water; this period may be termed the initial stage. During the subsequent culminating stage, these unstable, coalescing and permeable iron sulfide mounds suffered percolation of hydrothermal solutions; this resulted in a heating of the system, allowing the replacement of precursory pyrites (see BAMBA, 1985, Fig. 1) and precipitation of the higher temperature mineral assemblage—chalcopyrite, pyrrhotite, idiomorphic cubic pyrite (annealed gel pyrite?), sphalerite and cubanite—that constitutes the Main orebody and Hanging Wall orebody.

The Northern orebody is a northward lateral extension of the Main orebody and Hanging Wall orebody and partially overlaps with them; it consists of “banded ore”, the origin of which has been debated. Epigenetists (SUZUKI and KUBOTA, 1980) contended that the banded ore resulted from chloritized slate partially replaced by thin sulfide seams along the original slaty cleavage. In contrast, MIYAKE (1961) suggested it had a volcaniclastic origin; however, he was unable to present a more convincing process to form the laminated structure of the ore than that of the epigenetists. The contemporaneity of “banded ores” and massive ores is conceivable from their laterally equivalent position and the similarity of their sulfide mineralogy; this may be a constraint on the formation process of the “banded ores”. It is probable that the massive ores represent a proximal deposit near or within hydrothermal vents area, and that banded ores have formed somewhat distant from the vents. In this context double diffusive phenomenon, recently outlined by TURNER and GUSTAFSON (1978), is attractive, in that it makes it possible to separate discharges of variable composition from pulsating sources depending on their specific gravities, i.e. separation of heavier sulfide-dominated fluids from lighter silicate-dominated fluids. The higher specific gravity fluid will deposit its content near the vent, forming the proximal massive sulfide deposit, while the lighter fluid flows some distance away from the source to form a distal deposit; fluidized particles may then be sorted by their densities to form individual lamina of chlorite-quartz and sulfide, i.e. “banded ores”.

Based on the characteristics of the Shimokawa deposits (virtually no lead, only minor zinc and association with igneous rocks of ophiolitic affinity), it appears to belong to the HUTCHINSON'S (1973) third group of volcanogenic massive sulfide deposit (cupfer-
ous pyrite); this group invariably exhibits a well developed stringer ore zone within the footwall of the basaltic rocks (Hutchinson and Searle, 1971; Large, 1977; Plimer, 1978). Despite extensive underground exploration and development done in footwall green-rocks, such footwall mineralization has never been encountered in the Shimokawa mine; the observation is strongly suggestive of an exotic origin for the ore deposits.

**Sub-Sea-floor Metamorphism**

Shimokawa basaltic rocks have suffered greenschist facies metamorphism. Thus, people initially referred to them as spilites and diabases (in the old European usage). Subsequently, extensive surface mapping and exploration to the south showed that these altered rocks appear to be dominant in the northeastern part of the Main zone, i.e. the footwall side of the ore deposits. This alteration was believed by epigenetists (Ikeda et al., 1972; Suzuki and Kubota, 1980) to be the wall rock alteration caused by mineralizing hydrothermal solution; this was the basis for their epigenetic theory, though they could not specify the origin of the hydrothermal solution. Miyake et al., (1981) suggested that sub-sea-floor metamorphism was responsible for the alteration. Since the original metamorphosed oceanic crust was disrupted in forming the melange, the metamorphic zoning is no longer preserved, with the present pattern bearing no direct spatial relationship to the ore deposits. Diabasic rocks of sheeted-dike complexes are commonly metamorphosed to greenschist facies by sub-sea-floor hydrothermal circulation near the axis of spreading (e.g. Stakes et al., 1984). Since the major part of the Shimokawa diabases is interpreted to be a sheeted-dike complex, their greenschist facies alteration is not surprising. Unique features of sub-sea-floor metamorphism—i.e. retention of variable amount of the original unaltered igneous minerals and a broad range of mineralogy, from actinolite±epidote, chlorite and intermediate plagioclase to albite an chlorite—which are also observed in the Shimokawa diabases can be explained by variable, low and high, water/rock ratios (e.g., Mottl, 1983).

The rare but characteristic occurrence of brown hornblende, representative of the amphibolite facies, is believed to have been formed as veinlets in an upflow zone of the hydrothermal system. Provided that the ores deposited at the top of the pillow lava complex, they were not originally in contact with the sheeted-dike complex lying beneath the pillow lavas. Therefore, direct contact of ores with the diabases of greenschist facies must be due to tectonic movement; alternatively, mineralization may have occurred within or near the sheeted-dike complex, as at Bett Cove, Newfoundland (Upadhyay and Strong, 1973).

**Discussion**

It is an enigma how such allochthonous ore layers have been emplaced as the Shimokawa deposits into their present position with rather little disturbance of their continuity. Oblique subduction of the Izanagi-Kula plate may partly be responsible for the peculiar occurrence of the Shimokawa melange, in which the Shimokawa ore deposits were plastered along its eastern margin of the Main zone. Oblique subduction results in lateral faulting parallel to the continental margin in the area near the trench (Kimura, 1985). During the fault movement competent blocks such as part of the sheeted-dike accompanied by layered ore deposits may have been oriented sub-parallel to the tectonic trend within the incompetent argillaceous sediments. In this connection a brief look at the Shimanto accretion terrane in eastern Kyushu may be most pertinent, because there occur the Makimine ore deposits in similar geological settings with the Shimokawa deposits area.

The Makimine volcanogenic massive sulfide deposits had produced about 4.5 Mt of ores with a grade of about 2.2% Cu until the mine closed in 1966 (Tatsumi, 1953; Borchert, 1957). The lower Cretaceous Makimine Formation hosts the deposits and represents the lowest horizon of the Morotsuka Group of the Lower Shimanto Supergroup. The Makimine
Formation is known as one of the most typical subduction melange zones in the Shimanto accretionary complex (Mackenzie et al., 1987), in which abundant inclusions of greenstone block of various sizes together with massive sulfide orebodies occur in the argillaceous rock. The precise mode of emplacement of greenrocks and sulfide orebodies is still a matter of debate (Sakai and Kanmera, 1981), but there is little doubt that the greenrocks covered by pelagic chert (Sano et al., 1979) as well as massive sulfide orebodies were formed at a submarine spreading center in the terrigenous detritus starved environment, and that then moved into the convergent margin to be scraped off and intermingled with trench-fill sediments. Two parallel ore zones, the Eastern and Western, were delineated on the eastern and western limb near the crest of the gently (<30°) plunging Makimine-Yanasaki anticline. Elongated ore zones with the same sense of pitch as the plunge axis of the anticline extend up to 3300 m (Eastern zone) and consist of clustered, semi-continuous orebodies, most likely disrupted from originally a layered body. Unit orebodies are less than a meter to 3 meters thick and some tens meters long, and exhibit the morphology characteristic to tension tectonics such as boudin, pinch and swell, and podiform, indicating a deformation of competent layers surrounded by ductile argillites. These tectono-stratigraphic features of the Makimine ore deposits are consistent with those of the Makimine Formation which is taken by Mackenzie et al. (1987) as gradually underthrusting sediments with fragments of oceanic crust beneath the prism to accrete eventually at depth (greenschist facies) to the base of the Shimanto complex.

At the Shimokawa area the greenrocks and orebodies are found only in the argillites dominated Shimokawa Formation, and not in the Iwaonai Flysch. This relation is also observed in the Makimine area where greenrocks and orebodies occur as melange units in the Makimine Formation composed of shale and sandstone, and not in the overlying Yato Formation of massive sandstone. These observations indicate that the thrusting chip in an accretion complex preferentially propagated along weaker shaly horizons, and that scalloping-off of the melange units took place in early accretional stage where mud was still ductile, in which sulfide orebodies would behave as one of the most competent units. The contrast in relative competency would be maintained throughout the successive burial and deformation stages. This is the reason why orebodies suffer least disturbance among various melange units. Even before the discovery of the sediments-hosted massive sulfide deposits in the Guaymas Basin, Gulf of California (Lonsdale and Becker, 1985; Koski et al., 1985), some Japanese workers (e.g., Mariko, 1984) have suggested that the tectonic setting of the Shimokawa deposits is an ancient analogue of the Guaymas Basin where dolerite sheets in Recent mud and hydrothermal activities are found (Kastner, 1982). However, both Hidaka and Shimanto belts composed of fault-bounded melange units, broken formations and flysch sequences, are typical accretion complexes on the Cretaceous convergent margin and are thought to represent the oceanic trench, slope and slope basin domains as recognized in the modern convergent margin (Aoki et al., 1982; Taira et al., 1982). The problem is how can we make a spreading center at trench settings like the Hidaka and Shimanto belts. Plate boundary volcanism in the Guaymas Basin differs from the mid-oceanic ridge volcanism because seafloor eruption is inhibited by rapid deposition of low density sediment; in contrast the presence of pillow lavas in both Hidaka and Shimanto belts is notable. It should also be noted that the greenrocks and surrounding sediments in the Shimokawa area are not coeval and the former is always older than the latter. Miyashita and Katsushima (1986) reported that the radiolarian ages of the central Hidaka zone are Santonian to Campanian (Late Cretaceous), whereas 126 Ma (Early Cretaceous) fission track age of the Shimokawa diabases was reported by Miyake et al., (1981); it may be one of the best pieces of evidence for the melange hypothesis of the
Shimokawa Formation. An absence of high-temperature hydrothermal alteration in sediments from the Shimokawa deposits, except for the one of post-ore stage, also suggests the ore-forming environment different from the Guaymas Basin.

The Tomuraushi greenstone complex at Shintoku town, about 80 km south of the Shimokawa area, was recently studied in detail by Miyashita and Katsushima (1986). According to their results, the complex occurs along a marked north-south trending fault and shows exactly the same occurrence and petrological characteristics as that of the Shimokawa area. A small showing of sub-economic mineralization may be taken as an evidence of southern extension of the Shimokawa area. Though the area between Shimokawa and Tomuraushi is obscured by Cenozoic volcanic covers, there appears to exist a significant tectonic line (informally designated as the Shimokawa-Tomuraushi line) which may indicate an extensive subduction melange in the Hidaka accretionary terrane (Fig. 2).

When the hypothesis of the Shimokawa melange was suggested (Miyake, 1980), Kanehira (1981) recognized its significance for other occurrences of volcanogenic cupferiferous massive sulfide deposits in Japan. The massive sulfide deposits in the Shimanto accretionary complex such as Makimine in Kyushu and the Asakawa in Shikoku (Nakamoto, 1961) may be typically allochthonous in a tectono-stratigraphic unit containing greenstones.

Conclusion

The conclusions of this paper may be briefly stated.

1. The Shimokawa massive sulfide mineralization is related to submarine volcanism and exhalative activity, and the deposits of which precipitated on the seafloor. The primary texture is still preserved despite extensive structural movement and displacement of the orebody.

2. Diabases associated with the orebody are interpreted as dikes which have a multiple intrusion history (sheeted-dikes). These diabase dikes were subsequently metamorphosed to green schist facies by circulating seawater that related to the hydrothermal mineralization, but an original spatial relationship between metamorphosed rocks and ore deposits is not preserved because of the post-ore tectonic disturbance. Therefore, most of the contact between diabase and orebody is considered tectonic.

3. The orebody was intermingled with trench-fill sediments to form a melange during subduction. This resulted in an abundance of exotic blocks juxtaposed with the orebody, and caused some of the foot-and hanging-wall volcanics to be scraped off from the orebody.

4. The Makimine volcanogenic massive sulfide ore deposits, occurring in the melange terranes of the Cretaceous Shimanto belt of southwestern Japan, may have a similar allochthonous origin.

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下川鉱山の地質と鉱床：異地性海嶺型塊状硫化物鉱床

三宅輝海

要旨：下川火山成塊状硫化物鉱床は126 Maにクラ・イザナギおよびファラロン両プレート間の中央海嶺部に生成した。拡大軸における、循環海水に起因する熟水系が海底変成作用およびそれに続く鉱化作用をもたらした。鉱床が沈殿している間にdouble diffusive 現象により塊状鉱および極状鉱が形成された。鉱床は恐らく地質のexhalite ないし熔岩により覆われたが、引続きテクトニックな運動により割裂取られたものと思われる。日本海が開く前であったので鉱床を含む海洋地殻は海底に近づくにつれ、シホテアリンの火山帯から供給されたタバダイライトにより覆われた。日高黒層群の堆積物および海洋地殻は斜め沈み込みに伴い、シートダイクの部分等がはじ取られた。この付加体プリズムの一部が下川テクトノストラティグラフィック・ユニットとして知られ、複雑に変形した堆積物やメランジェ帯によって特徴づけられる。下川鉱床はこのテクトニックな方向にはほぼ平行に、連続して胚胎している。新生代の日本海の拡大に伴い、この下川複合岩体は現在の北海道日高帯に移動した。九州の横峰、浅川両鉱床も同様な異地性起源と考えられる。