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Kuroko-Type Massive Sulfide Deposits of Japan: Products of an Aborted Island-Arc Rift

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Abstract

The Green Tuff belt of Japan and its Kuroko-type exhalative volcanogenic massive sulfide deposits exhibit many unusual features which are best explained if the Green Tuff belt and the deposits formed as the result of an aborted attempt to rift the volcanic chain and open a new marginal sea. This failed rift hypothesis can account for the distribution of mining districts in the Green Tuff belt, the observed extensive and substantial premineralization subsidence and postmineralization uplift in the belt, its volcanic evolution, and other features. The premineralization subsidence results from the same mechanism proposed for the formation of rift valleys at mid-ocean ridges—a dynamic loss of fluid pressure in asthenospheric material that must well up as the lithosphere extends. The Green Tuff belt of Japan is strikingly similar in geology, tectonics, and mineral deposits to Archean greenstone belts, suggesting that Archean belts may be failed rifts. Ore deposits formed in failed rifts have a high probability of permanent incorporation into stable cratons because the deposits are underlain and surrounded by sialic crust and are near sea level. Areas of crustal extension are ideal sites for the kind of very vigorous hydrothermal circulation required to form massive sulfide deposits because they combine unusually high rates of heat input into the crust with a tensional, fracture-dilating stress environment. It is suggested that all exhalative massive sulfide deposits may form in rift settings. Differences between traditional deposit classes reflect mainly the different geologic settings of the rifts. Exploration implications of the failed rift hypothesis are detailed.

Introduction

THE Kuroko massive sulfide deposits of Japan exhibit several well-known and almost universally agreed upon characteristics that appear curious, particularly perhaps to one becoming acquainted with them for the first time. Many of these characteristics are concisely summarized by Sato (1974) (see also Uyeda and Nishiwaki, 1980, p. 332–333; Ohmoto, 1983) and may be briefly stated: the Kuroko-type massive sulfide deposits of Japan are restricted to the so-called Green Tuff belt, a thick accumulation of hydrothermally altered submarine volcanic tuffs and flows about 100 km wide and >1,500 km long (see Fig. 1). The distribution of Kuroko deposits within the Green Tuff belt is not uniform (Fig. 1); economic mineralization is concentrated in several mining districts which appear, in many cases, to have been topographic depressions at the time of mineralization. The most important Kuroko mining district, for example, has traditionally been referred to as the Hokuroku basin. Guber and Merrill (1983) show turbidites accumulated in the Hokuroko district chiefly from a submarine source area to the southwest but also from the northeast and northwest.

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The Kuroko mineralization event may have begun about 15.6 million years and ended as recently as 11 million years ago. Most mineralization occurred 12 ± 2 m.y. ago (Ohmoto, 1983). This agrees with the traditional view that mineralization occurred within a few million years of 13 m.y. ago throughout the Green Tuff belt and all Kuroko mining districts (Sato, 1974). Ueno (1975) has shown that the Kuroko deposits of the Hokuroku and Aizu mining districts formed in the same reverse magnetic polarity interval and thus were created within <200,000 years of one another. Mineralization in the San'in district of southwestern Honshu may have occurred slightly but distinguishably earlier than in northern Honshu (Watanabe and Soeda, 1981). Some of the deposits in the Hokuroku district consist of several stacked lenses (see discussion in Cathles, 1983; Ohmoto, 1983), so all deposits were clearly not formed at exactly the same time. A general time horizon for mineralization appears well established.

Prior to the time of ore formation (from ~28 to 14 m.y. ago) large quantities of andesite (mainly tuff) erupted in northern Honshu. At the time of mineralization, however, the volcanism was dominantly bimodal in character (basalt and dacite), reduced in volume, and quiescently erupted (Sato, 1974, 1976; Horikoshi, 1975, 1976; Kitamura, 1979; Ohmoto, 1983).

Just prior to mineralization the Green Tuff belt rap-

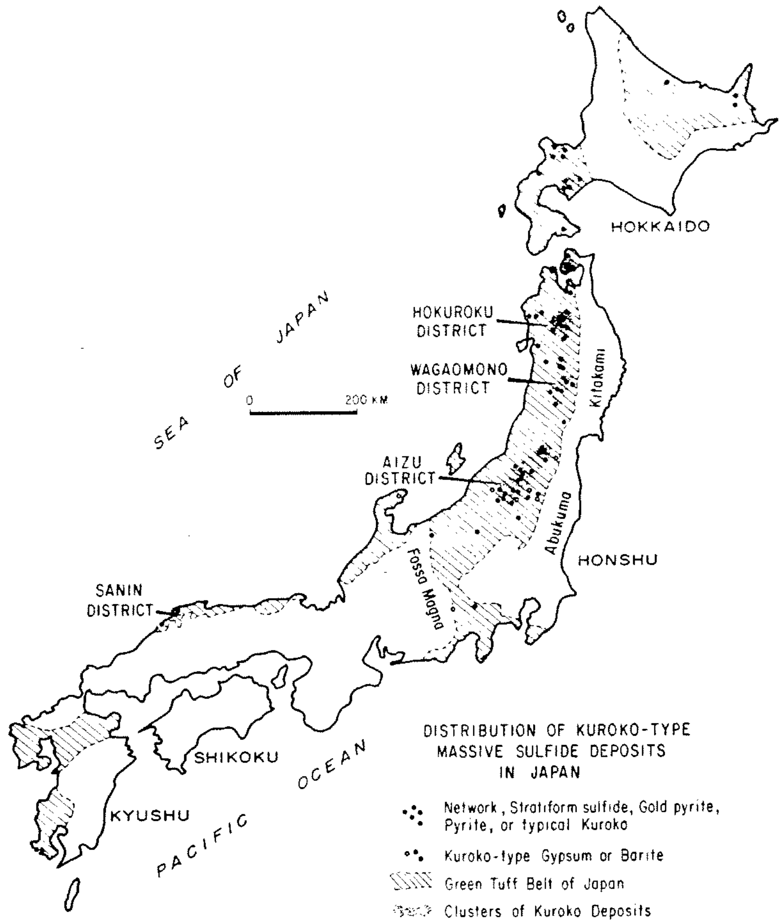
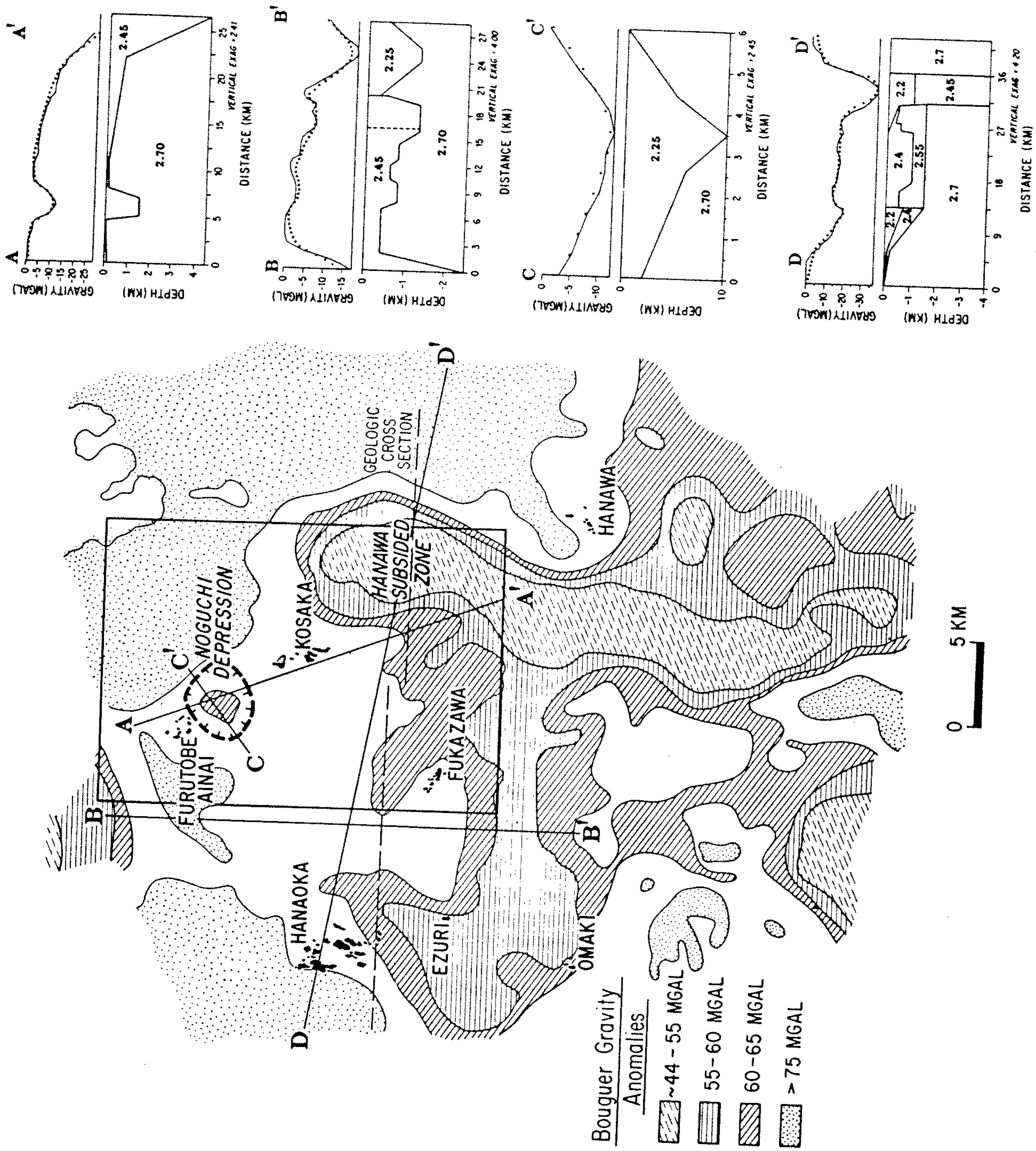


FIG. 1. The distribution of the Green Tuff belt of Japan and the Kuroko-type massive sulfide deposits within it. Major mining districts are labeled and ore deposit clusters outlined. Simplified slightly from Sato (1974, fig. 2).

idly subsided from subaerial conditions to substantial depths below sea level (>2,000 m from fluid inclusion evidence, Pisutha-Arnond and Ohmoto, 1983; ~3,500 m from foram evidence, Guber and Merrill, 1983). The subsidence was accomplished in the Hokuroku district in perhaps as short a time as a few million years and therefore occurred at a rate of ~1,000 m/m.y. (Sato et al., 1974). The thickness of pyroclastic sediments and lavas indicates a subsidence rate of 400 m/m.y. for the early Miocene Green Tuff belt, and 600 m/m.y. for the middle Miocene (Kitamura, 1978, p. 72). Although some areas subsided more than others, the subsidence was of a broad, general nature ultimately involving the entire Green Tuff belt (Kitamura, cited in Tanaka and Nozawa 1977, p. 377; Kitamura and Onuki, 1973; Minato et al., 1965). Present-day gravity data suggest differential displacement of crustal blocks of at least several kilometers magnitude in the Hokuroku area (Fig. 2). After mineralization the Green Tuff belt uplifted, returning to subaerial conditions by 5 m.y. ago (Ohmoto, 1983; Sato, 1976).

Hanging-wall isotopic and chemical alteration indicates that hydrothermal activity persisted for at least a million years after mineralization (Iijima, 1974; Green et al., 1983). Calderas are common along the Japanese volcanic arc today; the abundance of explosive Miocene tuffs suggests that they were common prior to and perhaps also at the time of Kuroko mineralization. Basement fractures or lineaments appear to have influenced the distribution of ore (Fujii, 1974; Scott, 1978, 1980; Utada et al., 1981). Calderas may also have influenced or facilitated the development of economic mineral deposits (Hodgson and Lydon, 1977; Ohmoto, 1978; Ohmoto and Takahashi, 1983).

This set of features or associations is unique and at first perplexing. Why should an area that strongly subsides reverse itself and uplift? Why should mineral deposits form during a restricted interval of time in


Bouguer Gravity Anomalies
~44 - 55 MGAL
55 - 60 MGAL
60 - 65 MGAL
> 75 MGAL
0
5 KM
HANAOKA
EZURI
OMAKI
FURUTOBE
AINAI
FUKAZAWA
KOSAKA
NOGUCHI DEPRESSION
HANAWA SUBSIDED ZONE
HANAWA
GEOLOGIC CROSS SECTION
A
A'
B
B'
C
C'
D
D'
GRAVITY (MGAL)
DEPTH (KM)
DISTANCE (KM)
2.45
2.70
2.25
2.2
2.4
2.55
2.7

a volcanic belt which has been active for a much longer period? Why is the distribution of deposits within the Green Tuff belt not more uniform and why do the mining districts tend to occur in topographic lows? Any model must answer at least these questions. This paper argues that the best answers are provided if the Kuroko massive sulfide deposits formed as the result of an aborted attempt to rift the volcanic arc of Japan so as to form a new back-arc marginal basin.

There recently has been a trend away from interpreting strata-bound massive sulfide deposits as products of a calc-alkaline subduction zone environment (e.g., Mitchell and Garson, 1976) and toward interpreting them as products of a tholeiitic or bimodal rift environment. Munha (1979), for example, concluded from mineralogic observations, high geothermal gradient, bimodal volcanism, and trace elements that the Spanish pyrite belt, which contains the famous Rio Tinto exhalative stratiform massive sulfide deposits, was a continental rift. MacGeehan and MacLean (1980a and b) have concluded on the basis of geochemical studies that the Archean Noranda-type massive sulfide ores in Quebec are associated with bimodal basalt thyolite volcanism and were formed on the sea floor. The previous assumption of calc-alkaline association resulted from not taking into proper account the effects of greenschist-grade seawater hydrothermal alteration. Scheibner and Markham (1976, p. 58) conclude: "From evidence available from the Paleozoic complexes of eastern Australia [which include such massive sulfide deposits as Captains Flat, Woodlawn, Rosebery, and Mt. Lyell], it is suggested that Kuroko-type strata-bound sulfide deposits are associated with volcanic rifts, and this conclusion is probably valid for the deposits in Japan and elsewhere." By volcanic rift these authors mean "a basic tectonic unit characterized by the orogenic volcanism, transitional regressive tectonic realm (extended continental crust) and upwelled asthenosphere, [which] forms in a setting of lithospheric tension in orogenic areas. It represents a combination of two basic tectonic units: an inter-arc basin and a volcanic arc or arch" (p. 57–58). Hutchinson (1973, 1980) notes the association of all types of base metal massive sulfide deposits with subsidence and places Kuroko-type deposits in a rifted back-arc or a young island-arc setting.

Uyeda and Nishiwaki (1980) have called attention to the fact that exhalative massive sulfide deposits such as the Kuroko deposits in Japan appear to form in Mariana-type arcs in a tensional stress environment, whereas porphyry copper deposits are formed in Chilean-type arcs that are by definition subject to compressional stress (Uyeda, 1979, 1981; Uyeda and Nishiwaki, 1980; Nishiwaki and Uyeda, 1980). Uyeda and Nishiwaki's suggestion goes a long way toward explaining the old observation that porphyry copper and massive sulfide deposits both occur in island arcs but seldom together. Porphyry copper deposits are concentrated in the compressional Chilean arcs of the eastern Pacific, whereas massive sulfide deposits are concentrated in the tensional arcs which commonly have marginal basins in the western Pacific. Uyeda and Nishiwaki (1980) point out that, compared to Chilean-type compressional arcs, Mariana-type (tensional) arcs have deeper trenches, steeper Benioff-Wadati seismic zones, fissure eruptions from numerous monogenetic cones rather than repeated eruptions from single vents, and bimodal (basalt-rhyolite) rather than andesitic volcanism.

We agree with the trend toward viewing strata-bound volcanogenic massive sulfide deposits as products of a tensional rift environment and would in this paper extend this view by: (1) relating massive sulfide mineralization more directly to basaltic volcanism, (2) calling attention to the consequences of a termination of rift extension and the implications of rift geometry for the distribution of mining districts in the rift, and (3) by pointing out that complicated ad hoc plate tectonic models are not required to account for the features of the Green Tuff belt and its mineralization.

The aborted or failed rifts we discuss have much in common with aulacogens. An aulacogen is the third arm of a continental rift which failed because it lost out in competition with the other two limbs to form an ocean (Burke, 1976, 1977; Burke and Dewey, 1973; Burke et al., 1977). Our discussion differs from and extends previous discussions of aulacogens in focusing (1) on the very early stages of arc (rather than con-

FIG. 2. Bouguer gravity map of the Hokuroku district simplified from the Akita Prefecture Survey Bulletin (Inoue et al., 1973). Cross sections A to D were modeled using geology, drill logs, and rock densities measured by Inoue et al. (1973) to constrain the models as much as possible. Numbers give strata densities. Dots = calculated gravity values; lines = observed gravity. The steep horst and graben gravity anomalies that dominate the Hokuroku district require 2- to 4-km displacements on near-surface normal faults with the downthrown blocks filled with light tuffaceous material.

Some circular gravity anomalies such as the Noguchi ("rat hole") depression are related to Neogene features that are probably collapse calderas. No older circular gravity anomalies are apparent. The area studied structurally in detail by Guber and Green (1983) is outlined by a box. Gravity models were calculated using the techniques of Talwani et al. (1959).

tinental) rifting, (2) on the geometry of the axis of magma injection in the rift, and (3) on the consequences of the termination of rifting (uplift). Aulacogens may exhibit uplift after failure (Milanovsky, 1981), but compared to the intensively studied Miocene Green Tuff belt, it is not as easy to demonstrate convincingly this uplift or its magnitude. The mechanism of aulacogen rift failure is probably different from that of arc rift failure in that global plate motions are more directly involved.

Hodgson and Lydon (1977) and Ohmoto (1978) have suggested that Kuroko mineralization in Japan may be related directly or indirectly to resurgent calderas. The main evidence cited for caldera collapse is premineralization subsidence (Ohmoto, 1978) and the fact the deposits occur in depressions (Ohmoto et al., 1983). Caldera collapse could account for some of the observed premineralization subsidence, but for reasons best discussed later we find it more convincing to relate both the Kuroko deposits and any coordination in caldera activity to the rifting event.

The first part of this paper outlines the broad features of the failed rift hypothesis as it applies to Japan. The second part discusses other areas where failed rifts may have left their geologic imprint and the broader implications of the failed rift hypothesis to ore genesis, deposit classification, and exploration.

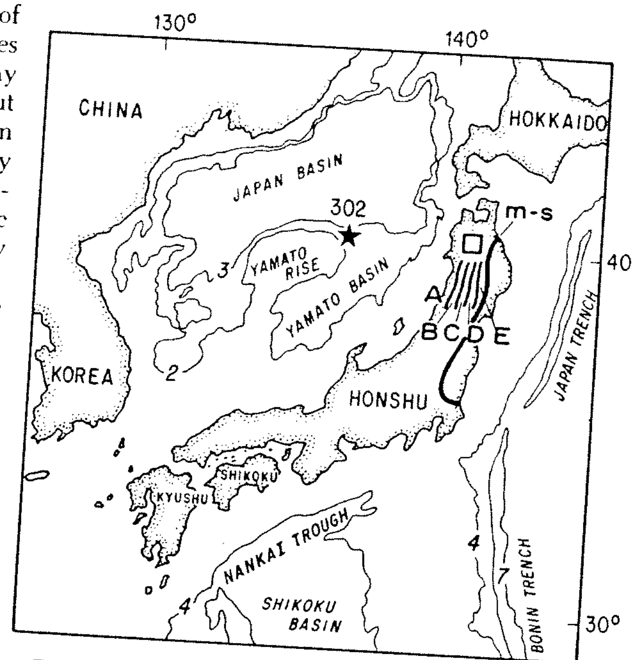


FIG. 3. Index map showing features referred to in the text. Bathymetric contours are in thousands of meters. Lines in northern Honshu demarcate Kitamura and Onuki's (1973) tectonostratigraphic divisions of the Green Tuff belt. A = Japan Sea coast, B = Dewa Hills, C = Intermontane basin, D = Backbone Range, and E = the Kitakami River area; m-s = the Morioka-Shirakawa tectonic line from Tsumboi (1956). The box encloses the Hokuroku basin and outlines the area covered in Figure 2. Also shown is Deep Sea Drill Hole 302 (star) drilled on the flank of the Yamato Rise. Modified from Chase et al. (1971).

Failed Rifts and Miocene Japan

The geologic context of the Green Tuff belt

The geology of northern Honshu is divided into two parts by the Morioka-Shirakawa line (see Fig. 3), which was initially defined by Tsuboi et al. (1956) on the basis of a steep Bouguer gravity gradient. It separates the Kitakami and Abukuma massifs from the Green Tuff belt to the west, which has a 70-mGal lower gravity (Kitamura and Onuki, 1973). The gravity indicates a near-surface fault across which 0.4 g/cc denser strata are upthrown 6 to 7 km and lie nearer the surface under the Kitakami and Abukuma massifs than under the Green Tuff belt. The Kitakami and Abukuma massifs are composed of folded and faulted pre-Tertiary formations that have been invaded by several huge Mesozoic intrusives. Except for substantial (~3 km) subsidence in the Pacific shelf area of these massifs owing to subcrustal erosion associated with subduction in the Japan trench (Von Huene et al., 1980) or subcrustal thermal cooling associated with subduction (Langseth et al., in press), the massifs have been stable since late Early Cretaceous time (Tanaka and Nozawa, 1977, p. 13).

This contrasts strikingly with the Green Tuff region which was formed in early to middle Miocene time as the result of major vertical tectonics and volcanism. Since about 1960 the Green Tuff region has been recognized as a series of about five grabens and horsts that parallel the island arc of northern Honshu but crosscut and show no relation to pre-Miocene geologic features (Kitamura and Onuki, 1973). From east to west these grabens and horsts are: the Kitakami River (graben), the Backbone Range (horst), the Intermontane basin (graben), the Dewa Hills (horst), and the Japan Sea coast (graben) (Fig. 3). The Backbone Range (also called the Ou Mountains) and the Dewa Hills are present topographic highs that contain Quaternary volcanoes. The axis of subsidence began in the early Miocene in the Backbone Range, widened, and then migrated west. As it migrated west, the eastern areas uplifted (Kitamura, 1978, 1979; Kitamura and Onuki, 1973; Matsuda and Kitamura, 1974; Fujii, 1974). Gravity anomalies in the Hokuroku district indicate ~4 km of horst and graben displacements and testify today to the vertical movements of the Miocene (Fig. 2). It is important to appreciate that the subsidence in the Green Tuff region (including the Fossa Magna area and the San'in area on the northern coast of southwestern Honshu) was extensive in nature and took place in all localities shown in Figure 1 at about the same time—the beginning of the early Miocene (Kitamura, 1978). By far the greatest volume of volcanics erupted at the beginning of the Green Tuff event, and there was a tendency for the volcanism to become more siliceous and bimodal with time (Kitamura, 1979; Konda, 1974; Sato, 1974, 1976; Horikoshi, 1975, 1976). The ±3,500-m subsidence in the Hokuroku area is of much greater magnitude than previously suspected. The vesiculated basalts found in the Hokuroku district were previously thought to indicate that the sea depth was shallow at the time of Kuroko mineralization, but Dudás (1983) has shown that ore vesiculation can reflect water content and need not indicate shallow water depth. Paleontologic and fluid inclusion evidence compellingly indicates the greater water depths.

To the west and north of the Green Tuff belt lies the Japan Sea. Seismic profiles show that thick (30 km) continental crust underlies northern Honshu but that only oceanic crust is present in the Japan Sea (Research Group for Exploration Seismology, 1973, 1977; Yoshii, 1979). The northeastern half of the Japan Sea consists of two basins (three if the Tsushima basin southwest of the Yamato Rise is counted) separated by the shallow, 1,000-m deep Yamato Rise which may be a continental or island-arc fragment (see Fig. 3). Closest to Asia is the Japan Sea basin. It is 3,000 to 3,500 m deep and contains 2 km of sediments. On the Japan side of the Yamato Rise is the 2,500-m-deep Yamato basin which has thinner sediments (Kobayashi and Isekazaki, 1976). The Pn velocity under the Japanese arc is anomalously low, which can be interpreted to indicate that the subcrustal lithosphere is anomalously hot, i.e., the lithosphere is no thicker than the crust itself (Uyeda, 1979).

Leg 31 of the Deep Sea Drilling Project drilled four holes into the Japan basin, Yamato basin, and Yamato Rise in an attempt to determine when the Japan Sea opened. Unfortunately, gas shows or slumping precluded any of the holes from penetrating deeper than 532 m and none reached basement. The Yamato Rise flank hole (site 302, Fig. 3) penetrated the oldest sediment—late Miocene (~9.5 m.y. old). Using sedimentation rates determined in the upper 532 m of core to extrapolate to basement, those responsible for drilling hole 302 concluded that the base of the section at that site could be no older than early Miocene (~22.5 m.y. ago; The Shipboard Scientific Party, 1975, p. 447). A 25 to 30 m.y. age for the Japan Sea is suggested by its depth (corrected for sediment load), according to an empirical reduced depth vs. age relationship developed by Watanabe et al., (1977, fig. 21).

Magnetic lineations in the Shikoku basin have been interpreted to indicate opening at 27 to 13 m.y. ago with a pulse of rapid opening between 26 and 22.5 m.y. ago (Watts and Weissel, 1975) or between 20 and 15 m.y. ago (Tomoda et al., 1975). The oldest sediments from deep-sea drilling cores are more consistent with the latter interpretation (Klein et al., 1980), but the sediments may overlie volcanic sills, not basement, and thus not reflect the correct basement age.

The Green Tuff belt as a failed or aborted island-arc rift

It is in the above context that we must seek to understand the development and vertical tectonics of the Miocene Green Tuff belt. We propose that the Green Tuff belt is a back-arc phenomenon and is related to back-arc rifting in a fashion similar to that sketched in Figure 4. Prior to 30 million years ago Japan was presumably attached to Asia. Subduction under Japan may have been occurring for some time, as suggested by Ohmoto (1983), but the rate of subduction must have increased 42 m.y. ago when the motion of the Pacific plate changed from north to west-northwest, as evidenced by the bend in the Emperor-Hawaiian seamount chain (Clague and Dalrymple, 1973). Since that time, Pacific plate motion appears to have been remarkably steady (McDougal and Duncan, 1980). Since there is little evidence of andesitic volcanism prior to ~30 m.y. ago, extrusive volcanic activity between 40 and 30 m.y. ago must have been minor (e.g., Horikoshi, 1976). This may suggest that subduction under Japan was initiated 42 m.y. ago and volcanism took some time to become established. About 30 m.y. ago back-arc rifting began and Japan started to separate from Asia.

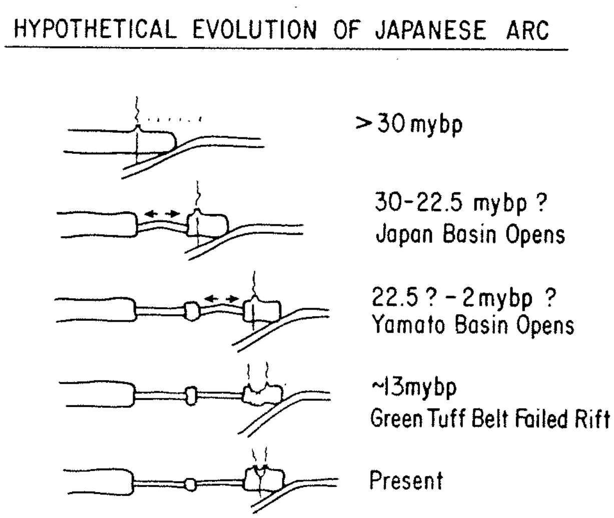


FIG. 4. Hypothetical evolution of the Japanese island arc. Before 30 m.y. ago, Japan was attached to Asia and subduction was of the Andean type. Subsequently there were two successful riftings of the Japanese island arc. The first opened the Sea of Japan and the second, the Yamato basin (see Fig. 3). We associate the formation of Kuroko massive sulfide deposits in the Green Tuff belt with a rifting event that occurred ~13 m.y. ago that tried unsuccessfully to open a third marginal basin. We call this aborted attempt a failed rift.

The opening of the Japan Sea between 30 and ~22.5 m.y. ago allows time for the crust of the marginal basin to cool and reach its present observed depth and heat flow (Watanabe et al., 1977, fig. 21). The Shikoku basin may have also opened mainly at this time. The Yamato Rise is older than 9.5 m.y. and perhaps younger than ~22.5 m.y. Thus the Yamato basin probably opened between 22.5 and ~2 m.y. ago. The termination date is suggested by timing of stress realignments in the Japanese arc (Nakamura and Uyeda, 1980). The fact that the Yamato basin is shallower than the Japan Sea basin and has a thinner sediment cover indicates that it is younger than the Japan Sea. Rifting associated with the opening of both the Japan Sea and the Yamato basin was successful in the sense that marginal seas were successfully produced.

Rifting activity in the Green Tuff belt began at the same time that the Japan Sea opened. As discussed, activity centered in a depression which later evolved into a series of grabens and horsts parallel to the present volcanic arc, with the axis of subsidence migrating westward toward the coast of the Japan Sea with time. We suggest, as have others (e.g., Uyeda and Nishiwaki, 1980, p. 332), that this activity was associated with an attempt to rift the volcanic arc of Japan to form a marginal sea and in so doing to find a sustainable locus along which to open the Japan Sea and the Yamato basin. We would have the most rapid Green Tuff belt crustal extension occur at the time of Kuroko mineralization. The Green Tuff belt rifting aborted or failed; it did not successfully open a new marginal basin.

Many geologists in Japan would initiate crustal rifting in the Green Tuff belt before the opening of the Japan Sea and Yamato basin, although the main development of the Green Tuff belt dated from the early Miocene (Kitamura, 1979, and pers. commun.). Some (e.g., Uyeda and Miyashiro, 1974) have suggested that the Japan Sea opened considerably earlier than 30 m.y. ago. Ohmoto (1983) would start development 65 m.y. ago but would date subsidence below sea level only after 30 m.y. ago. The precise sequence of events, or that rifting may have occurred at several places at the same time, is not critical to our model of Kuroko genesis. What is critical is that the Kuroko mineralization occurred as the result of an aborted attempt to rift the Japanese volcanic arc along the present locus of the Green Tuff belt.

The failed rift and Kuroko mineralization

The failed rift hypothesis is supported mainly by the fact that it can explain the features associated with Kuroko mineralization outlined in the introduction of this paper in a particularly simple way.

The voluminous, explosive outpourings of andesitic volcanics 28 to ~20 m.y. ago (Horikoshi, 1975; Sugimura et al., 1963) can be related to the rifting of the Japanese volcanic chain and the breaching of existing andesitic magma chambers. The initial rifting of a volcanic arc is often accompanied by large outpourings of welded and nonwelded tuff (e.g., Karig, 1971; later discussion in this paper). As the magma reservoirs became depleted, volcanism as a whole became dominated by rift-related bimodal (basalt rhyolite or dacite) activity. Two sources of late Quaternary volcanism (calc-alkaline and rift-related basaltic) are indicated by the increasing mantle character of Nd/Sm and $^{87}Sr/^{86}Sr$ isotopic signatures as the Japan Sea is approached across northern Honshu (Nohda and Wasserburg, 1981). Nohda and Wasserburg were compelled by their data to relate some of the volcanism in northern Honshu to back-arc processes, although they were bothered by what they felt was the ad hoc character of this explanation. Dudás et al. (1983) point out that Miocene alkali basalts occur in the Hokuroku district and, further, that the trace elements in basalts and dacites are compatible with the hypothesis that these rocks originated through the interaction of a mantle melt and crustal material in an extensional, rift environment. Studies on the Oslo graben (Oftedahl, 1978) indicate that felsic volcanism and collapse calderas occur as mafic magmas differentiate.

Crustal extension caused heat to be carried into the crust by mafic and felsic magma intrusions. The tensional environment opened fractures and created high permeability. This combination is ideal for producing the unusually vigorous hydrothermal circulation needed for massive sulfide mineralization (Cathles, 1983). Marsh (1979, p. 168) has reviewed the appropriate literature and concluded: "The volume of magma erupted and intruded in island arcs may be typically about 5 km^3 per km of arc per million years; estimates vary between 1 and 10." A rift extending at just 1 cm/yr will introduce 50 km^3 of magma per kilometer of rift per million years to the upper 5 km of crust alone. The amount of heat will be in fact much greater than this because, unlike the case of the volcanic arc where magma mainly passes through the lithosphere and lower crust, a rift introduces magma to the lithosphere and crust at the rate of crustal extension. The assumption in the calculation that magma is introduced just to the upper 5 km of crust is conservative by about an order of magnitude. Even with this conservative assumption, the rate of introduction of heat per unit surface area in a rifting arc such as the Green Tuff belt is an order of magnitude greater than in the volcanic arc before rifting.

Geometric considerations require crustal extension (rifting) to have geographic continuity, i.e., to extend throughout the Green Tuff belt. The Kuroko deposits formed throughout the Green Tuff belt when the crustal extension was most rapid.

At mid-ocean ridges (Ballard and van Andel, 1977; van Andel and Ballard, 1979; Hall and Robinson, 1979) the crustal volcanism occurs in bursts or pulses. Such pulses could account for the multiple ore lenses observed in some parts of the Horkuoko basin (Cathles, 1983). The subsidence is related to the average rate of extension, not to individual pulses of crustal magma intrusion. The axial valleys at mid-ocean ridges maintain their topographic depression between pulses of surface magmatism.

The subsidence of the Green Tuff belt prior to mineralization is related to the onset of crustal extension. The rapid subsidence rates of 400 to 1,000 m/m.y. observed in the Green Tuff belt in fact indicate rifting (Fischer, 1975; Tiercelin and Faure, 1978).

The uplift that followed the termination of crustal extension in the Green Tuff belt is expected on the basis of one theory of how central rift valleys form at mid-ocean ridges (Sleep and Rosendahl, 1979). According to this theory mid-ocean rift valleys are formed because mantle material suffers a dynamic loss of fluid head as it wells up to replace the lithosphere laterally removed by sea-floor spreading. The situation is analogous to the wood blocks floating in water shown in Figure 5. If the blocks are stationary, the fluid level in a small crack between the blocks is the same as the water level outside. If the blocks are moving apart, fluid must well up between the blocks and it encounters viscous resistance in so doing. Consequently the fluid level between the blocks is depressed. This drop in fluid level is dynamic in the sense that if the motion of the blocks is halted, the fluid will return to its normal level, i.e., its level before the separation of the blocks was initiated. In the case of the earth, the water is analogous to the "fluid" asthenosphere upon which the lithosphere floats in isostatic equilibrium. According to Sleep and Rosendahl's theory the 1- to 1.5-km, ~30-km-wide downdrop observed in axial rifts of slowly spreading mid-ocean ridges reflects the dynamic depression of asthenospheric fluid levels between the separating lithospheric plates (wood blocks). Sleep and Rosendahl (1979) show that for reasonable asthenospheric viscosity, axial oceanic lithosphere thickness, and channel width, the observed axial depression of 1 to 1.5 km can be produced by observed spreading rates. Axial valleys occur only at slowly spreading ridges. Sleep and Rosendahl point out this is because at fast spreading rates the axial channel is wide enough for little resistance to be offered to mantle upflow.

The older, thicker lithosphere of a newly rifted island arc will provide greater resistance to upflow than new, thin oceanic lithosphere at an established mid-ocean ridge spreading center. The subsidence caused by

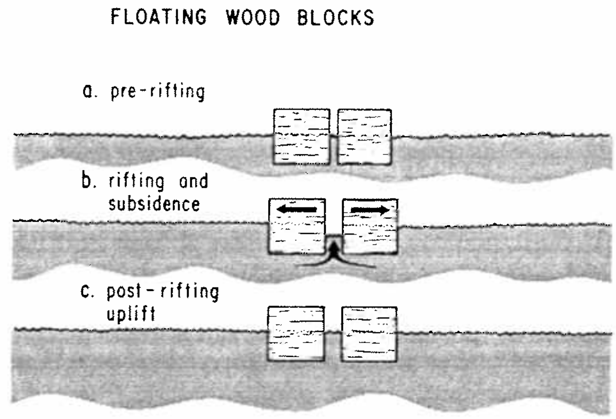


FIG. 5. The premineralization rift-related subsidence and postmineralization uplift observed in the Green Tuff belt can be understood by analogy to the water level between two wood blocks floating in water. If the blocks are stationary, the water level is the same between the blocks as outside (a). When the blocks are moved apart, water must flow up between the blocks. In doing so it encounters viscous resistance and loses fluid head. Thus, while the blocks move apart, the fluid level between the blocks is depressed relative to the normal level (b). If the motion of the blocks is stopped, fluid level between the blocks returns to normal. The water is analogous to the fluid asthenosphere upon which the lithosphere floats in isostatic equilibrium. Rifting should produce subsidence of the magnitude and character that occurred in the Green Tuff belt (see discussion in text). Cessation of rifting will result in an uplift to near prerifting elevations.

crustal extension in an island-arc setting can be expected to be greater than ~1 km in roughly the proportion that the arc lithosphere is thicker than the lithosphere at mid-ocean ridges; for this reason a 3.5-km subsidence is not at all unreasonable in the Japanese island-arc setting.

Two points are important for the case of the Green Tuff belt. First, the magnitude of premineralization subsidence is reasonable on the basis of the analogy to mid-ocean rifts. Subsidence to depths sufficient to prevent boiling is probably required if strata-bound massive sulfide deposits rather than vein deposits are to be formed (see Drummond, 1981; but also see Russell et al., 1981). Second, the postmineralization uplift observed in Japan is to be expected. Rifts that fail before the sialic crust is too substantially thinned enjoy a kind of automatic obduction mechanism that will return areas depressed far below sea level to near their original elevation. This allows massive sulfide mineral deposits formed in the process to be subaerially mined.

Mineral deposits will be incorporated into cratons at elevations that minimize exposure to erosion. As Scheibner and Markham (1976, p. 59) point out, the fact that volcanogenic massive sulfide deposits are incorporated into cratons at near sea-level elevations means that it is not surprising that so many of these deposits have been preserved from Archean times.

Rifts (mid-ocean or continental) exhibit another feature of relevance. Rifts typically consist of spreading segments offset by transform faults. Figure 6 depicts such segments of the East Pacific Rise in the Gulf of California. Each active spreading segment (identified by magnetic lineations in the Gulf) is a topographic depression or basin because of the dynamic loss of fluid head which characterizes the upwelling asthenosphere. The spreading segments are areas of high heat flow and geothermal activity (Williams et al., 1979). On land, the Salton Sea and Cerro Prieto geothermal fields, which are spreading segments overlain by enough sediments to make the surface subaerial (Elders et al., 1972), are currently being exploited for geothermal energy.

Spreading segments offset by transform faults can explain the distribution of mining districts in Japan. Figure 7 shows a reasonable pattern of spreading segments offset by transform faults drawn such that the spreading segments underlie the major Kuroko mining districts of the Green Tuff belt of Japan. Spreading segments were areas of particularly high heat flow, intense hydrothermal activity, and basins similar to the depressions in the Gulf of California shown in Figure 6.

Fujii (1974) has pointed out that the Kuroko ore deposits and associated dolerite and rhyolite intrusions within a mining district such as the Hokuroku show a relationship to an approximately rectilinear grid of basement faults that are the boundaries of uplifted and subsided blocks. The boundaries of these blocks are marked today by steep gravity gradients, some of which are shown and modeled in Figure 2 (see also Fujii, 1974, fig. 6 and table 3). Scott (1978, 1980) has pointed

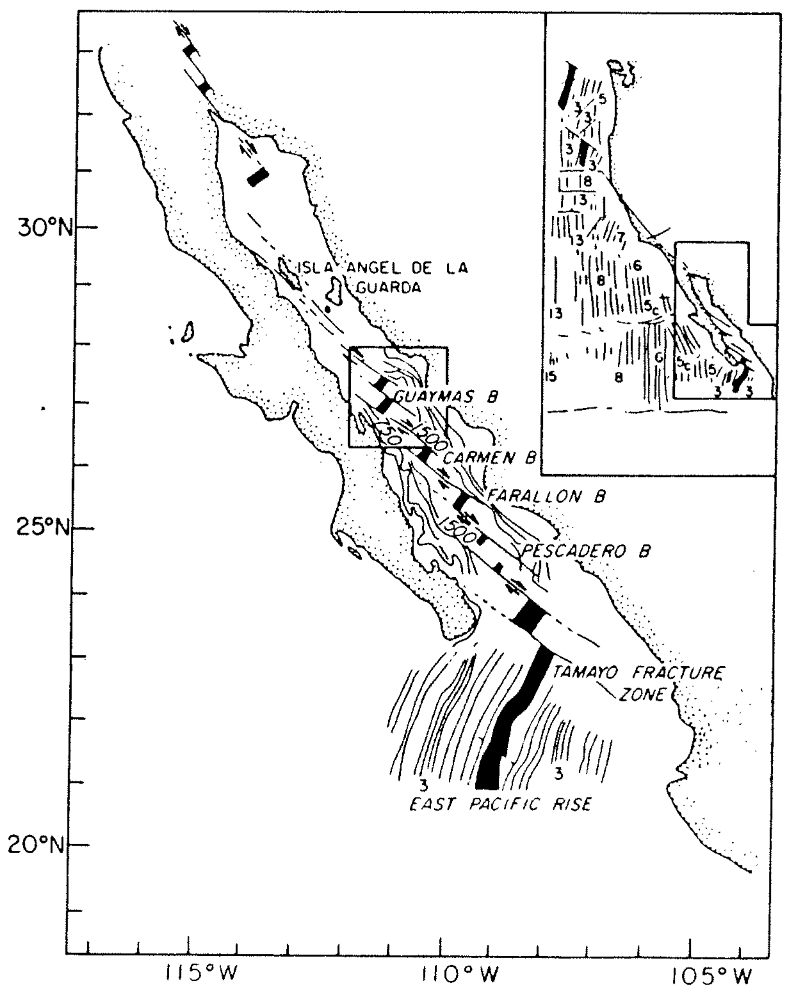


FIG. 6. The spreading segments of the East Pacific Rise in the Gulf of California are offset by transform faults. Each spreading segment (black) is a topographic depression or basin, as indicated by the names (B = basin). From Williams et al. (1979).

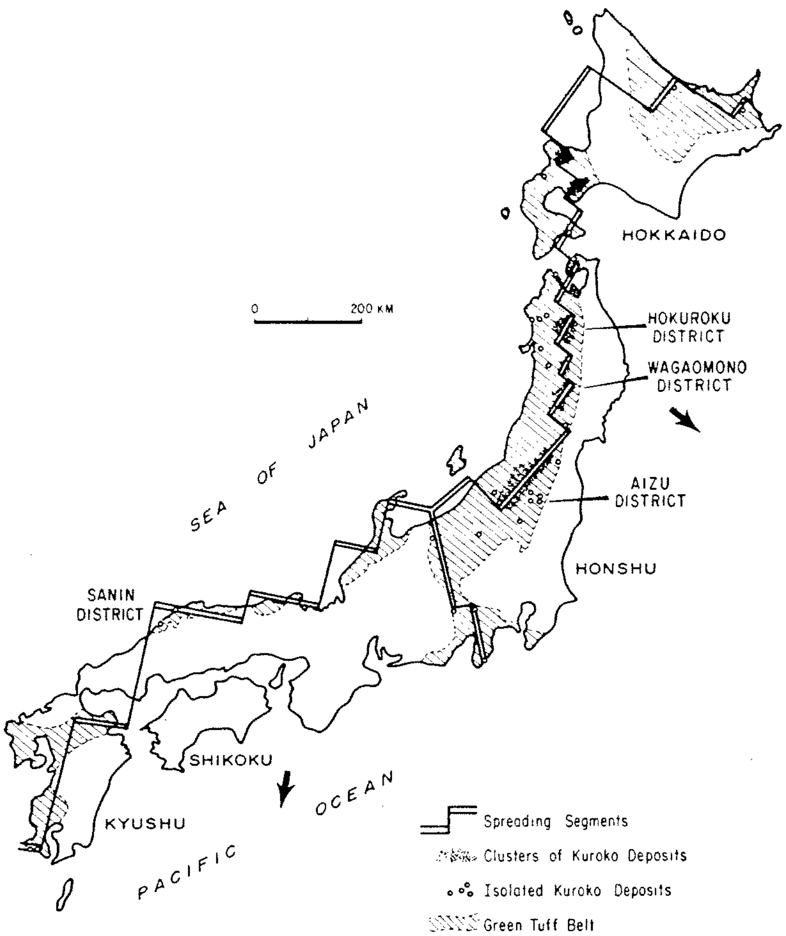


FIG. 7. Mining districts within the Green Tuff belt can be associated with a reasonable distribution of spreading centers offset by transform faults. The orientation of spreading segments in this illustration is chosen to be perpendicular to the presumed extension (heavy arrows). Divergence between the extension in northern Honshu, which follows the migrating Japan trench, and the extension in southern Honshu causes extension in the Fossa Magna area in central Honshu (see Fig. 1 also). The pattern of spreading segments and transforms is not the only pattern that can match the distribution of ore deposit clusters in northern Honshu. A pattern with spreading centers oriented northwest-southeast offset by northeast-southwest transform faults will do almost equally well; however, the pattern chosen accounts for the Green Tuff belt in southern Honshu and the Fossa Magna area in a more natural way.

out basement zones of weakness in the Hokuroku basin oriented northeast-southwest and north-northwest–south-southeast which appear to exert an influence on the distribution of sulfide lenses in a given deposit or deposit cluster, and on the distribution of ore deposit clusters. Sulfide lenses in a given deposit tend to lie along lines striking either northeast or north-northwest, a conclusion supported by Utada et al. (1981). Ore deposit clusters tend to be located at the intersection of lines passing through other clusters and oriented northeast or north-northwest. Basement faults and the sides of Quaternary calderas show the same northeast and north-northwest directions of basement weakness (Scott, 1978).

Control of sulfide lens location and geometry by zones of basement weakness is expected. Rifting and crustal extension will take advantage of and occur preferentially along weak zones. Dilated fractures will serve as high permeability conduits for hydrothermal fluid and felsic and mafic magmas. Offsets and lineaments along the banks of the Red Sea, for example, correlate with brine pool occurrences along the spreading axis of the sea (Garson and Krs, 1976). The observed association of Kuroko massive sulfide deposits and small dacite domes and basalt flows indicates simply that hydrothermal solutions and magmas utilized the same zones of crustal weakness. The dacite domes are too small to have played a significant role in the mineralization process (Cathles, 1978; Urabe and Sato, 1978; Ohmoto, 1978).

Irrespective of the role that calderas may have played in Kuroko mineralization, one need only recall the classic and well-studied calderas of the Oslo rift (Oftedahl, 1978), the calderas of the Rio Grande rift (Lipman et al., 1976), and Owens Valley, California (Sheridan, 1978), to appreciate that calderas are common and expected inhabitants in the tensional environment of a rift.

Finally, hydrothermal activity persists for millions of years after the main mineralizing event, as required by hanging-wall alteration, because the entire lithosphere has been heated by crustal extension and magma invasion.

The failed or aborted rift hypothesis thus can account in a particularly simple way for all the features of Kuroko mineralization in Japan, including the evolution of volcanism from early explosive andesitic outpourings to later basalt (bimodal) and finally to felsic volcanism (± calderas); the timing of mineralization, premineralization subsidence, and postmineralization uplift; the uneven distribution of ore districts in the Green Tuff belt; the fact that ore districts are often described as basins; the localization of ore clusters along lines of basement weakness; the association with dacite domes, basalt flows, and caldera structures; and the persistence of weaker hydrothermal activity long after the mineralizing event.

The mechanism of rifting

Marginal basins (successful island-arc rifts) are common in the western Pacific. Marginal basins typically form through a rifting of the volcanic chain associated with a subduction zone (Karig, 1970, 1971, 1972, 1974). The plate is hot along the volcanic axis and therefore weak, and this is a likely place for rifting (Karig, 1974; Molnar and Atwater, 1978). Sea-floor spreading opens the marginal basin, but the spreading in the basin is not usually restricted to a single axis as it is in ocean basins, so interpretable magnetic lineations are not usually produced (Karig, 1974).

Opening of marginal basins is promoted by the natural tendency of a trench to migrate seaward. Elsasser (1971) pointed out that migration of trenches seaward (toward the subducting plate) is a natural consequence of the fact that the lithosphere is denser than the underlying mantle. In addition to sliding, the oceanic plate tends also to sink vertically into the mantle. Geometrically, this requires oceanward trench migration. Elsasser's mechanism is particularly important because it is a direct physical consequence of the heavier weight of the lithosphere as compared to that of the underlying mantle.

The tendency to create new sea floor in front of the migrating trench by a sea-floor-spreading process is inhibited by the circulation produced by the subducting plate in the asthenosphere (see Sleep and Toksöz, 1971, but note that we interpret different consequences to their calculated convection). This circulation is such as to sweep the overlying plate (i.e., the island arc) against the trench and cause both to migrate seaward together. Such joint migration is possible only for a fairly small plate, however. When spreading in the marginal sea makes the arc plate too large, the resistance to dragging the arc plate along with the trench increases and the volcanic arc tends to break and opens a new marginal sea. Thus island arcs in the Pacific commonly have several marginal seas of increasing age behind them, separated by small arc remnants (Karig, 1972, 1974). The point at which an arc plate becomes too large to keep up with a migrating trench depends on the viscosity of the asthenosphere under the plate (which may vary between arcs), the rate of migration of the trench (which may depend on the age of the subducting oceanic plate; Molnar and Atwater, 1978), and other factors, and thus is difficult to predict. Nakamura and Uyeda (1980) point out that dikes, faults, and volcano types indicate that some inactive marginal basins are under tensional stress and that the stress on the marginal basin side of the volcanic arc of Japan was tensional in the Miocene but is generally compressional today.

Of course, the formation of marginal basins can be prevented if the motion of the overriding continental plate toward the trench is greater than the oceanward migration of the trench (Chase, 1978). Marginal basins form in the western Pacific where Asia is stationary or retreating with respect to the mantle, and trenches can easily migrate away from it (Chase, 1978; Uyeda and Kanamori, 1979). No marginal basins form along the western margins of the American plates because both North and South America are moving west over the mantle. The exception is in Central America adjacent to the Caribbean plate. The Caribbean plate is moving eastward (relative to the North and South American plates), following the eastward migration of the Antilles trench. The Central American arc is rifted in an incipient marginal basin fashion in Guatemala and Nicaragua. The volcanic arc there runs through shallow seas (Lake Managua, Lake Nicaragua, see King, 1969) that are analogous to the deeper seas we envision to have formed in the Miocene rifting of the Japanese arc.

The reasons a rift should fail once it is initiated are much less clear. Seemingly sustainable rifts do fail, however, with the ultimately successful rifts forming nearby but in a distinctly different location. Good examples are the failed Triassic rifts of the east coast of the United States adjacent to the Atlantic Ocean (Sheridan, 1974). Evidently the Atlantic tried unsuccessfully to open at least once—twice in the Grand Banks area—before finding a sustainable locus of opening. Spreading in the Red Sea has occurred in two discrete episodes, one from the late Miocene to early Pliocene, and one from 3 m.y. ago to the present (Garson and Krs, 1976).

Comparison to other hypotheses

Other authors have generally related the processes which led to Kuroko mineralization more directly to ocean plate subduction and the series of events that produced Kuroko mineralization to changes in the rate of subduction. Fujii (1974), for example, suggests that the uplifted and subsided fault blocks of the Green Tuff belt were caused by flexure of the island arc produced by frictional resistance to subduction at the Japan trench. Slowing of subduction in the late Miocene to the present relaxed the flexural tensional stresses and caused compression and uplift (the Dewa disturbance). Horikoshi (1976) has related Kuroko mineralization and arc tholeiitic volcanism and, following Miyashiro (1972), suggested that tholeiitic volcanism occurred when subduction rates exceeded 8 cm/yr. In another paper Horikoshi (1975) relates Kuroko mineralization to the change from a tensional to the compressional stress environment of the Dewa disturbance. Compression squeezed out brines accumulated by hydrothermal activity in the tensional state and produced the mineralization.

Some (e.g., Ramsden, 1982) have related the spacing of massive sulfide deposits in greenstone belts and hydrothermal systems in back-arc settings (e.g., Hodder, 1983) to the natural spacing of volcanic centers along island arcs (Marsh and Carmichael, 1974). Hodgson and Lydon (1977) and Ohmoto (1978) relate the subsidence and uplift cycle associated with Kuroko mineralization to a cycle of caldera collapse and resurgence. Both articles ascribe the time horizon association of deposits in a district to caldera activity, although Hodgson and Lydon put caldera phenomena in the context of a broader volcanotectonic cycle that involves initial graben formation and mafic volcanism and later felsic volcanism and possibly collapse calderas.

Changes in the motion of Asia would certainly affect the back-arc phenomena we have discussed, although they are not required to initiate marginal basin spreading or to cause a new marginal sea to open in front of an old one. Changes in landward plate motion could be important in the termination of marginal basin spreading altogether, or other processes could be involved.

It seems unlikely that the vertical tectonics of the Green tuff belt is directly related to fore-arc (subduction) processes for the following reasons: (1) The motion of the Pacific plate appears to have been quite steady over the last 27 million years (McDougal and Duncan, 1980); there have been no changes in subduction rate of the kind appealed to by K. Fujii or E. Horikoshi. (2) The Green Tuff belt lies at or behind the Miocene volcanic arc in a back-arc position. The Kitakami and Abukuma crustal blocks that lay directly adjacent to the Miocene trench were not involved in the vertical tectonics of the Green Tuff event. If subduction-related arc flexure is responsible for the horst and graben activity, it is hard to see how these areas could have avoided being involved. (3) The 3,500-m magnitude of subsidence and uplift seems excessive for a simple flexural phenomenon. (4) The large amount of heat evidenced by the hydrothermal alteration of the Green Tuff belt, the Kuroko mineralization, and the persistence of hydrothermal activity for millions of years after Kuroko mineralization are more consistent with the substantial crustal extension and intrusion expected in a back-arc process than with the relatively minor near-surface extension underlain by compression expected in a fore-arc flexural process. In flexure, roughly the upper half of the island-arc lithosphere would be in tension, and the lower half, below a neutral fiber, would be in compression. The zone of compression would inhibit magma intrusion.

The main difficulty with relating the spacing of ore districts to the spacing of volcanic centers in a normal island arc is that the volcanic centers in an island arc are always edifices of great positive relief. They are in no sense basins (like the Hokuroku) into which turbidites would accumulate. They are topographic highs that should shed turbidites from their flanks.

There are several problems with the suggestion that calderas could entirely account for Kuroko mineralization in the Green Tuff belt. Calderas could produce local basinlike subsidence and could uplift with resurgence. Large volumes of ashfall and pyroclastics would have to erupt to produce the 3.5-km subsidence of the Hokuroku district in this fashion, however. For example, the 16- × 30-km Long Valley caldera in California subsided 2 to 3 km following the eruption of 800 km^3 of Bishop Tuff and pyroclastic flows. Resurgence brought 3 to 4 km of uplift (Williams and McBirney, 1979, p. 213ff). We see no evidence of tuff or pyroclastic flows of this volume associated with the Hokuroku district.

Even assuming that the Hokuroku district was a large middle Miocene collapse caldera, or several smaller calderas, the caldera(s) would be unlikely to have a connection to the sea unless the whole region was much lower than present, and this would require another (noncaldera) explanation. Modified seawater is almost certainly the hydrothermal fluid responsible for Kuroko mineralization (Ohmoto and Rye, 1974; Ohmoto et al., 1983). The Quaternary Towada caldera that lies close to the Hokuroku mining district, for example, is a fresh-water lake with substantial walls and is protected from the sea by >170 km of land surface in all directions. The deepest part of the lake bottom lies 80 m above sea level; the lake level is 400 m above sea level (information from Towanda Science Museum exhibits).

Caldera collapse could explain the time horizon association of massive sulfide deposits in a single mining district; however, without some other factor being involved, it is not clear why calderas associated with all the mining districts throughout the Green Tuff belt of Japan should develop and collapse at the same time. The general time horizon constraint applies to all mining districts in Japan, not just to one district, which could be related to the activity in a single caldera complex (see Introduction). Thus if the deposits are related to calderas, we still require some mechanism to coordinate the activity of the separate calderas.

For these reasons it is unlikely that caldera collapse and resurgence is the entire story or even the most fundamental part of it. Subsidence, uplift, and the time horizon of mineralization in the Green Tuff belt are best related to a failed rift episode. No appeal to changes in subduction rate or dip (Ohmoto, 1983) are required. The premineralization subsidence noted by Hutchinson (1973, 1980) as characteristic of massive sulfide base metal deposits in general may indicate rifting, not caldera collapse. Note that Guber and Green (1983) are careful to refer to volcanic centers rather than calderas in their paper. The pyroclastic andesite → basaltic (bimodal) → felsic (caldera) → pyroclastic andesite cycle noted by Hodgson and Lydon (1977) and others is naturally accounted for by a rifting event or series of events.

Discussion

Examples of arcs now rifting and other failed rifts

In addition to arcs that have rifted in the past, leaving remnant arcs between successively older marginal basins, and arcs that have recently rifted to form marginal seas that are still active, insight can be gained by examining arcs which are today in the initial stages of rifting. Reviewed briefly by Karig (1971), these include the Taupo zone of the North Island of New Zealand, Sumatra, Java, and Central America.

The Taupo zone is a direct extension of the Havre trough, a marginal basin opening behind the west-dipping Kermadec trench. Ignimbrite eruptions preceded development of the few-million-year-old Taupo graben, and calderas are present in it today (Cole and Lewis, 1981). The area is famous for the pioneering development of geothermal power stations at Wairakei. Interestingly, the pattern of zones with surface heat flow exceeding 1,000 heat-flow units[1] is strikingly similar to the pattern of tetsusekiei distribution in the Hokuroku district (compare Elder, 1966, fig. 17, to Kalogeropoulos and Scott, 1983). Tetsusekiei probably formed as the result of weak, postmineralization venting of hydrothermal solutions in a fashion similar to the present weak discharge at Wairakei (Tsutsumi and Ohmoto, 1983).

In Sumatra (Westerveld, 1952; see also Fitch, 1972) and Central America (King, 1969), grabens now split the volcanic chain down the axis. This is particularly evident in Nicaragua, where the Nicaraguan depression includes the Gulf of Fonseca, Lake Managua, and Lake Nicaragua, and the volcanic chain passes through the middle of these lakes and seas (King, 1969; McBirney and Williams, 1965). Pflaker (1976, p. 1206), interpreting the devastating Guatemalan earthquake of 1976, concluded his study: "[in] the preferred model . . . the region of extension is bounded on the south by the Middle America Volcanic arc, rather than the trench. It requires incipient decoupling within the Caribbean plate along the volcanic chain, a possibility that is suggested by the discontinuous line of graben developed along and near the volcanoes. The process, if continued long enough, could result in the opening of a marginal sea along the volcanic chain; the Gulf of Fonesca may be the incipient stage in formation of such a sea." In both Sumatra (Westerveld, 1952) and Nicaragua (McBirney and Williams, 1965), ignimbrite outpourings preceded graben subsidence. Basaltic flows also occur in both areas.

At the southern end of Lake Nicaragua the present volcanic chain is offset to the southwest and continues into Costa Rica where it terminates along with subduction under Central America at the Costa Rica fracture zone (de Boer, 1979). Southern Costa Rica (south of the Central Valley) is presently uplifting at ~150 m/m.y. presumably owing to rebound from the cessation of subduction (de Boer, 1979, p. 254). In northern Costa Rica there are perhaps five parallel horsts and grabens similar to those in the Green Tuff belt in Japan. From northeast to southwest they are: the extension of the Nicaraguan depression, the present volcanic chain, the Tempisque depression which incorporates the Gulf of Nicoya, the Gulf of Dulce, and perhaps the Valle del General, a block that includes the Nicoya Peninsula and the Osa Peninsula, and a downdropped block farther off the coast (see de Boer, 1979; Weyl, 1980, p. 112). Basaltic volcanism as young as Paleocene-Eocene age occurs along border faults of the Tempesque depression (Weyl, 1980, p. 122; de Boer, 1979,

[1] 1 heat-flow unit = 10^{-6} cal/cm^2/sec. Normal heat flow is about 1.5 heat-flow units.

p. 235, 242). Basalt of unknown age occurs in the Valle del General (Weyl, 1980, p. 139). Numerous unconformities in the Nicoya complex, the southern border of the Tempesque depression, suggest uplift and subsidence cycles from Miocene to Pliocene (de Boer, 1979). Ignimbrite outpourings occurred in the late Tertiary and in Quaternary time. The Tempesque graben area may thus have undergone a series of failed rift episodes in the late Tertiary, and the current arc may be rifting now.

Volcanic ash horizons are observed at various intervals in deep-sea drilling core, and the ash layers appear to correlate over large areas. This has been taken as evidence of episodic volcanism that might suggest pulses of sea-floor spreading or the effects of glacial isostatic kneading (Kennett and Thunell, 1975; Donnelly, 1973). The explosive outpourings of tuff could reflect arc rifting and the inherent episodicity of that process, however, and thus do not require fluctuations in global processes. Ash layers off the coast of northwestern Honshu correlate well with land evidence of volcanic activity (Cadet and Fujioka, 1980). Ash layers in marine core could provide evidence for failed rift arc activity.

In Panama, and also in northern Colombia, Bandy (1970) has documented subsidence-uplift cycles of ~4,000-m magnitude in Paleogene and Miocene time using depth-sensitive benthic foraminifera. Almgren (1978) documented three to four similar but shallower (200 to 2,000 m) uplift subsidence cycles in the northern half of the Great Valley, California, from Paleogene to Miocene time. Thus subsidence-uplift cycles of comparable magnitude and time scale to those documented in the Green Tuff belt of Miocene Japan have been observed in other locations. The setting in all these cases was inland from a trench at the time of vertical activity, and the setting in other ways looks as if it could be accounted for by failed back-arc rifting.

Mafic rocks with oceanic characteristics are encountered in the well-exposed Rocas Verdes complex of southern Chile. The Rocas Verdes is a synclinal association of gabbros, sheet dikes, and pillow basalts with minor andesitic and siliceous lavas, clastic sediments, cherts, and ironstones separated and surrounded by diapiric gneiss domes and underlain by granitic crust (Tarney et al., 1976; Dalziel, 1981). It has been interpreted as a marginal basin that formed 140 m.y. ago by extension of continental crust. The present width of the Rocas Verdes zones varies along its >700-km length. In the southern Tierra del Fuego area the present width is ~50 km. Farther north the present width is much less. A compressional event in the mid-Cretaceous (100–90 m.y. ago) arrested development of the basin, allowed uplift to subaerial conditions from what were presumably submarine depths of 1 to 1.5 km, compressed the basin up to 50 percent, and may have caused some subduction of mafic rocks and almandine-amphibolite-grade metamorphism (Dalziel, 1981).

The events terminating rifting in the southern Tierra del Fuego area had a greater compressive component than that of the Green Tuff belt of Japan, perhaps owing to collision with an aseismic ridge or microcontinent (Dalziel, 1981). The presence of substantial continental crust beneath the mafic rocks of the Rocas Verdes indicates that compression was not required for uplift, however; the termination of extension would have been sufficient. The Rocas Verdes as described by Dalziel (1981) and Tarney et al. (1976) represents almost a perfect analogue for the Green Tuff belt of Japan. Tarney et al. (1976) point out that the Rocas Verdes is also an excellent analogue and, in fact, suggest that it is a present-day example of an Archean greenstone belt. The similarity of the Archean massive sulfide deposits found in the greenstone belts to the Kuroko massive sulfide deposits found in the Green Tuff belt of Japan is striking (Urabe et al., 1983; Sangster and Scott, 1976) and supports this suggestion.

The Rocas Verdes and Archean greenstone belts may be examples of failed rifts. Windley (1973, 1977) has suggested that greenstone belts are marginal basins. The similarity of names is itself interesting: Green Tuff belt, greenstone belts, Rocas Verdes (green rocks). The names reflect the pervasive hydrothermal greenschist-grade (chlorite) alteration in these areas that was produced by the great heat input during rifting. It is perhaps not coincidental that geothermal power stations such as Cerro Prieto, the Salton Sea, and Wairakei are located in present zones of crustal extension. It is our contention that Proterozoic exhalative massive sulfide deposits were also formed in belts of crustal extension. Because of the enhanced probability of preservation, most of these belts may have been failed rifts. In general, belts of massive sulfide deposits may indicate the location of failed rifts, and their presence suggests that this process was not uncommon in past geologic times. Failed rifts were perhaps particularly common in the Archean, when the earth's landmass consisted entirely of island-arc-sized fragments (Windley, 1977).

Implications for exploration

The processes of crustal extension and rifting that introduce magmatic heat especially rapidly into a tensional crustal environment strongly favor the genesis of hydrothermal massive sulfide ore deposits. Different types of massive sulfide deposits may form in different rift settings. If the rift is in an island arc, Kuroko-type exhalative massive sulfide deposits may result. If the island arc was rifted before the earth developed an oxygenating atmosphere, mineralogic differences such as the absence of sulfate minerals and pyrrhotite instead of pyrite would classify the deposit as of Archean or primitive rather than Kuroko type. If rifting occurred in a more mature marginal basin or at a mid-ocean ridge, the deposit would be classified as a cupreous pyrite or Cyprus type (Hutchinson, 1980). Rifting in a continental landmass will often produce extensive evaporite deposits (Kinsman, 1975a). If hydrothermal solutions encounter evaporites, the resulting hot brines will be denser than seawater and will spread out in brine pools on the sea floor as in the Red Sea today (Pottorf and Barnes, 1983). When continents are rifted, massive sulfide deposits of a large tonnage such as Sullivan, Broken Hill, and McArthur River may form. These deposits would be classified as sediment hosted (Hutchinson, 1980; Russell et al., 1981). The important point is that when one seeks massive sulfide deposits, one looks basically for zones of crustal extension or rifts, for hydrothermal circulation systems driven by the heat from the intrusion of mafic (or bimodal) magmas.

Plate tectonic considerations (the motion of the overriding plate) as well as the present distribution of island arcs with marginal basins suggest that at any geologic time there will be broad regions where island-arc rifting will be favored and broad regions where it will not be favored. At present the western Pacific and the eastern Pacific adjacent to the Caribbean are favorable areas for extensional (marginal basin) rifting and massive sulfide formation. Most of the North and South American coast is unfavorable. Consideration of the motion of overriding plates at the time of mineralization may allow attention to be focused on broadly favorable continental margins. Indications that a particular locality is favorable can be an indication that a much broader region has exploration potential.

Within a favorable area, gravity surveys (Fig. 2) or magnetic surveys (anomalies reflect mafic intrusives) may be useful in searching for rifts. Pervasive hydrothermal alteration should be considered as a favorable sign.

Once a rift belt has been identified, the time of principal crustal extension should be identified. This will be particularly important in an island-arc setting where volcanism may have been active for long periods of time. Evidence of explosive volcanism or vertical subsidence may be useful. There will generally be one period, or at most a few periods, of time when crustal extension is most rapid and during which the best massive sulfide deposits are formed. Within these periods of rapid crustal extension, pulses of near-surface intrusion may produce multiple or stacked ore lenses. Once the time of principal crustal extension has been identified, exploration effort should be focused on this time horizon throughout the rift belt.

The distribution of mining districts will probably not be uniform throughout the belt. Mining districts will be located at spreading centers and be offset from other districts by transform faults (Figs. 6 and 7). The spreading centers will be topographic depressions and will tend to be areas of turbidite accumulation. Mining districts, like zones of extension along a mid-ocean ridge, must for geometrical reasons be continuous in a piecewise manner. They may be segmented by transform faults, but the mining districts and spreading segments must be continuous if the fault displacements are removed. One good mining district in a rift belt suggests other districts also exist. The fact that spreading segments are usually perpendicular to the direction of crustal extension, and that transform faults are localized by zones of crustal weakness, may be used to guide the orientation of spreading segments and transforms. Dewey (1980) gives a nice discussion of how crustal extension in a marginal basin is related to the motion of the fore-arc plate, the motion of the overriding plate, and other less important variables.

Within a mining district massive ore lenses will be produced where hydrothermal solutions discharged into the sea. High permeability vents will tend to be localized on fractures or zones of basement weakness and be reactivated and dilated by extensional forces. From the failed rift perspective, one is justified in projecting lineaments from the surrounding areas into the mineral district (e.g., Scott, 1978, 1980). Lineaments in these areas reflect prerift zones of weakness that could focus discharge over a spreading segment. In fact, the usefulness of lineaments in Newfoundland, for example (Scott, 1980), could be used as evidence that the Dunnage zone (Schenk, 1978) is a failed rift or very small marginal sea and not a closed ocean. It would be unlikely that a large marginal sea would close so as to preserve the usefulness of lineament projects. Fracturing in an area of crustal extension tends to be rectilinear. The favorable 070 direction at Noranda and the tendency of deposit clusters to lie in a rectilinear grid within any mining district has theoretical foundation and additional exploration credence may be justified (Scott, 1980).

Summary and Conclusions

In this paper we argue that the unusual characteristics or associations of Kuroko mineralization in Japan are best explained if the deposits formed as the result of an aborted attempt to rift the Japanese volcanic arc and form a new marginal sea. The unusual features we see as particularly significant include: (1) restriction of mineralization to the ~100-km-wide, ~1,500-km-long Green Tuff belt (Fig. 3); (2) uneven mineralization intensity within the Green Tuff belt; (3) location of mining districts in basins; (4) simultaneous generation of Kuroko deposits in all mining districts throughout the Green Tuff belt between 15.6 and 11 m.y. ago near a volcanic arc that has been continuously active for the last ~28 m.y.; (5) a shift in volcanism from early voluminous and explosive andesitic outpourings to less voluminous, more quiescent bimodal (basalt-dacite) volcanism at the time of mineralization; (6) rapid and extensive premineralization subsidence followed by postmineralization uplift; (7) a pattern of ore-lens clusters and a distribution of clusters within the district that appears controlled by basement fractures, lineaments, or zones of weakness; (8) persistence of hydrothermal activity in mineralized areas for at least a few million years after mineralization; and (9) the presence of calderas after and perhaps at the time of mineralization. We suggest that the time of Kuroko mineralization is controlled by the time of the aborted rift attempt (Fig. 4). The premineralization subsidence is related to the onset of rifting; the postmineralization uplift to the cessation of rifting (Fig. 5). Mining districts are located over spreading segments of the rift and are offset from one another by transform segments (Fig. 7). Spreading segments will be areas of high heat flow and intense hydrothermal activity and will also be topographic depressions (Fig. 6). Explosive andesitic volcanism is related to the rifting of the calc-alkaline arc; later bimodal volcanism, to the intrusion of the rift by basaltic magmas from the asthenosphere. Ore deposits are associated with lines of basement weakness because these zones were pulled apart during rifting and provided high permeability channelways for convecting hydrothermal solutions (and magmas). Calderas are common in rift environments.

The failed rift hypothesis appears to account best for the features enumerated. Difficulties we see in other hypotheses are noted. The uplift after rifting observed in the Green Tuff belt of Japan offers strong support for the mid-ocean rift model proposed by Sleep and Rosendahl (1979).

A rationale for the sequential rifting of island arcs with some new features is presented. Island arcs tend to rift periodically along their volcanic axes, provided the overriding (landward) plate is not moving toward the trench at too great a rate. We offer no explanation why rifting an arc might fail but point out that failed or aborted rifts (unrelated to aulacogens) are not uncommon in the geologic record. The Green Tuff belt of Japan is strikingly similar in its tectonics and mineralization to many Archean greenstone belts.

Rifts are areas where the thermal input to the crust by magma intrusion is unusually high—at least an order of magnitude higher than in nonrifting volcanic arcs. Geothermal activity, pervasive metamorphism, and hydrothermal mineralization is therefore to be expected in rifts. We suggest that strata-bound, exhalative massive sulfide deposits should be thought of as fundamentally related to rifts. Deposits classified as different types reflect different rift settings: mid-ocean ridge or mature marginal basin (Cyprus type, 21°N), island arc (Kuroko), and continental (sediment hosted).

Explosive volcanism associated with episodic arc rifting may account for volcanic ash layers observed in deep-sea drill cores. Periodic failed (?) rifting may help explain episodes of ignimbrite eruption in Central America, Sumatra, New Zealand, and elsewhere.

Failed rifts return massive sulfide deposits that probably must be formed ⩾2,000 m below sea level (to prevent boiling and formation of a vein deposit) to near sea-level elevations in a sialic crustal environment. These conditions favor preservation and may, together with the island-arc character of Archean plate tectonics, account for the prevalence today of Archean massive sulfide deposits.

The failed rift hypothesis has exploration implications. If the present is a guide, global plate motions can be expected to make large portions of subduction-related volcanic arcs permissive for massive sulfide mineralization (motion of overriding plate not too fast toward trench) and broad portions nonpermissive. The rifting of an arc provides both time and space restrictions on massive sulfide mineralization. Space restrictions apply on a mining district scale (transform offsets of spreading segments) and within a mining district (fabric of basement weaknesses). It should be useful to keep firmly in mind that when exploring for massive sulfide deposits, one is exploring for rifts.

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