Tectonic Transport of Massive Sulfide Deposits in Submarine Volcanic and Sedimentary Host Rocks

WILLIAM F. JENKS

Abstract

Massive Cu–Zn–Fe sulfide deposits appear to be replacements or syngenetic sediments related to submarine volcanism. Undisturbed kuroko deposits or moderately deformed and metamorphosed orebodies like those of the Noranda district may be considered as models.

Massive sulfide deposits in high grade metavolcanic and metasedimentary rocks are postulated to have originated largely in a submarine volcanic environment near the edges of tectonically active troughs sinking and receiving clastic sediments. Adjacent rising segments eventually expose deep structures almost devoid of base metals. Massive sulfides and volcanics, together with enclosing sediments, are susceptible to transportation by slides and nappes. Thus ores and enclosing rocks may be moved several kilometers and effectively separated from former root structures such as alteration zones and hypabyssal intrusives. The Elizabeth massive sulfide deposits, Vermont thus appear to have moved westward from root zones near the Connecticut River prior to their metamorphism. Possibly some of the metamorphosed massive sulfide deposits of the Sanbagawa terrane, Shikoku, Japan have been transported southward from root zones near the Median Tectonic Line. After initial transposition by sliding, ores and host rocks may be subjected to deep burial, strong metamorphism and one or more episodes of folding.

Introduction

The present study concerns ores accumulated in a submarine environment in tectonically active regions. It deals with two general types of deposits: those massive sulfide bodies, commonly lenticular, formed at or very close to submarine volcanic centers, and those formed in protected marine areas as syngenetic, sedimentary, stratiform deposits. For tectonic purposes the distinction between ores clearly related to volcanic activity around specific vents and those which are more widely developed as sediments on some protected sea floor must be made. The former type is initially irregular in shape and surrounded by a diversity of rock and alteration products of different physical properties. Because of such diversity, extreme local structural complexity could eventually result during later deformation. The latter type is a sedimentary rock unit, blanket-like, with little or no accompanying alteration, and susceptible to the structural complications normally developed in stratified rocks of contrasting physical properties during a tectonic episode.

Although the environment of deposition and original geometry of slightly or moderately deformed ores can be determined with some certainty, stronger deformation and metamorphism make the restoration increasingly difficult. The only method that will establish proof of original spatial relations of a massive sulfide deposit in spite of a screen of advanced deformation and metamorphism is painstaking structural analysis, mostly in the field. The most careful geophysical and geochemical studies should not be expected to unravel the convolutions of high grade metamorphic rocks.

The purpose of this paper is to show that some mechanisms which have been widely accepted as active in strongly deformed geosynclines should be more seriously considered in establishing the origin and history of massive sulfide deposits than has been apparent to this time.

Massive Submarine Sulfide Deposits Essentially in Original Position

Kuroko Ores

The best known submarine massive sulfide ores which have undergone very little deformation are the Miocene kuroko deposits of northern Honshu, Japan (Matsukuma and Horikoshi, 1970). The black ores (and associated yellow and siliceous ores) are related to dacitic submarine domes and explosive vents in protected marine environments. Ore deposits, formed on or just under the Middle Miocene sea bottom, were preserved under a blanket of volcanic or clastic rocks before being unlifited to their present position. The region has been affected by post-ore faulting but little folding.

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The relationships of the various types of ore to the volcanic and sedimentary rocks and to the extensive alteration zones have been described (Kinoshita, 1931; Iwao et al., 1954; Hashimoto et al., 1962; Horikoshi, 1965, 1969; Horikoshi and Sato, 1970; Matsukuma and Horikoshi, 1970). Some orebodies are irregularly lenticular; others are cross-cutting and apparently of replacement origin, and still others, particularly in the upper parts, are blanket-like syn-genetic sediments (Kajiwara, 1970). Horikoshi

![Diagram of Plan and Vertical Section](fig1)

**Fig. 1.** Plan and vertical section, Uchinotai-nishi ore deposit, Kosaka, Japan. After Horikoshi (1965).
(1965, 1969) demonstrated the close genetic relationship of some of the ores at Kosaka to explosive eruption and breccia formation at one side of a low rhyolite dome on the sea floor (Fig. 1). In nearby but somewhat more disturbed areas, stockwork and vein deposits in a subvolcanic environment are genetically related to kuroko ores (Sekine et al., 1962).

Cyprus Ores

Another type of relatively undeformed submarine massive sulfide deposit is represented by the cupriferous pyrite ores of Cyprus (Hutchinson, 1965; Hutchinson and Searle, in press). The principal orebodies are at the top of a thick sequence of basaltic pillow lavas and below thin Cretaceous sedimentary rocks (Hutchinson, 1965, p. 289). Beneath some of the orebodies are breccia and alteration zones (Hutchinson and Searle, in press). The ores were apparently introduced by hydrothermal fluids derived from the lower parts of the Troodos ultramafic to mafic igneous complex. The igneous complex and the ores were not deformed during the Alpine orogeny, so that original relationships are preserved.

Precambrian Examples in Quebec

In many other districts massive sulfide orebodies related to volcanic activity have been subjected to appreciable and in some cases repeated post-ore deformation, yet their original geologic setting is still clear. Goodwin (1962, 1965) and Hutchinson (1965) demonstrated the close relationship of certain Canadian massive sulfide deposits to volcanism. Hutchinson (1965, p. 296-298) points out

"that the Canadian ores have undergone an additional and complex genetic history . . . related to the post-volcanic deformation, intrusion and regional metamorphism that has affected the Keewatin rocks and the primary sulfide bodies. Orogenic events have not altered the broad geologic features of regional and local setting, size, overall composition, and metal content. Minor features of attitude, local structure, texture and mineralogy, however, have been re-shaped and the degree to which this has occurred varies from district to district and from body to body within districts, depending on the regional and local metamorphic conditions, and on their type and intensity."

Thus the structure of the Noranda region of Quebec is complicated by faulting, broad folding, moderate metamorphism, and intrusives, yet the relationship of many individual orebodies to their original environment is clear. Massive sulfides tend to be concentrated at the contact between andesite above and rhyolite below, with a root zone of veinlets and alteration in the rhyolite (Roscoe, 1965, p. 281).

The Waite and the Amulet Sections of the Waite-Amulet Mines both show root zones (sub-volcanic alteration and orebearing pipes) stratigraphically below massive sulfide deposits (Gilmour, 1965). The Delbridge massive sulfide deposit (Fig. 2) is an example of an orebody and volcanic host which, as reconstructed in pre-folding condition (Boldy, 1968) resembles the kuroko deposits (Fig. 1). The ores and surrounding rocks have been steeply folded but have not been separated from their roots by extreme deformation. In the Normetal Mine sheared rhyolite agglomerate in which the ores occur dips 82° (Brown, 1948). The plan of the Normetal 2300 level (Brown, 1948) would be a reasonable vertical section of a blanket-like kuroko orebody. Although any folding which consistently produces steep dips indicates a certain amount of transportation of the ore zones involved, they have not moved far from their place of formation and their relation to host rock and original infrastructure is reasonably clear. These Quebec orebodies, as well as the kuroko deposits, may tentatively serve as relatively undistorted prototypes similar to those from which strongly deformed and metamorphosed orebodies were derived.

Some Pertinent Aspects of Geosynclinal Tectonics

Many massive sulfide deposits are associated with intensely deformed and metamorphosed volcanic and sedimentary sequences along major eugeosynclines, as in the Caledonides of Norway, the older terranes of Japan, and the Appalachians. Reconstruction of the original relationship between ore and host rock may be extremely difficult, or virtually impossible (cf. Kalliokoski, 1965). Metamorphism of ores has been reviewed by Vokes (1969) and will not be considered here.

The strong, repeated deformation in parts of the Appalachians has affected some sulfide deposits, causing them to be tectonically transported appreciable distances and thus apparently separated from their roots.

In recent decades studies of the northwestern side of the Appalachian geosyncline have demonstrated detachment and extensive horizontal displacement of large masses of sedimentary rocks. Decollement in the central and southern Valley and Ridge Province and the adjacent Appalachian Plateau produced major separations (Rodgers, 1953; King, 1959). Farther north, the slices making up the Taconic allochthon must have moved tens of kilometers westward late in Middle Ordovician time (Zen, 1967, 1968; Bird, 1969).

In general, the rocks on the west side of the folded and faulted Appalachians have little volcanic admixture except for an occasional bentonite bed, and no
massive copper-zinc-iron sulfide deposits. The rocks are generally little metamorphosed; their depth of burial has most likely never been more than three or four kilometers. Resultant structures, although locally extremely complicated as in the Taconic area, are not indicative of compressive stresses, but rather of vertical movements, which were relatively upward in the crustal segments from which the glide blocks escaped (Zen, 1967; Cady, 1968).

In contrast to shallow foreland disturbances, deformation in the eugeosynclines is in large part deep and commonly accompanied or overprinted by strong metamorphism. Early sliding events, only slightly later than the formation of the rock units involved, may produce transportation over much greater distances than would be anticipated from later deep folding and high angle faulting. With convincing and abundant evidence of great lateral sliding in the miogeosynclines, why should we not find far more such sliding along the contrasting upward and downward moving blocks of the eugeosyncline? We should, indeed, rather commonly encounter wildflysch with great exotic blocks like those of the argille scaglioise of the Appenines. Deeper, we may expect isoclinal recumbent folds, penetration by diapiric intrastratal injection of sedimentary masses, and strong metamorphism, all related and variable phenomena depending upon local conditions.

The eugeosynclines are principal zones of relative vertical movements. During an active tectonic stage there will be blocks rising and relatively hot adjacent to blocks sinking and relatively cool. In geologically old terranes, the roots of the former may now be exposed as domal or diapiric gneiss and segments of other high grade metamorphic rocks. These once deep rocks may now be close to blocks which sank syntectonically in compensation. Material in the sinking blocks is likely to be thicker, to represent a more complete stratigraphic section, and to exhibit a distinctive metamorphic series.

Marginal belts, tilted and faulted between rising and sinking blocks, are zones of instability along which turbidity currents and gravity slides originate. Material first deposited in these unstable zones may thus be quickly transported basinward, in large part as slides. The various manifestations of such transported masses in New England (early recumbent folds, intrastratal diapiric nappes, submarine slides, slide breccias, etc.) have been summarized by Cady (1969, p. 39-41). Another type of basinward movement ("down-to-basin faulting") was recently proposed by Moench (1970) for the Rangeley area, Maine.

Negative blocks, with accumulations of thick clastic sediments and volcanics and further thickening by gravity sliding and consequent duplication would
tend to be covered quickly and deeply by turbidites of mixed erosional and volcanigenic debris. Their contents are thus brought quickly into an environment where, because of rapid burial and locally low heat flow, pressure is high but temperature moderate. This is in contrast to adjacent rising blocks full of granitoid rocks with steep metamorphic gradients, particularly near syntectonic domes.

Widespread or local volcanism, commonly of basaltic to andesitic composition, appears to be in part related to deep faults separating segments of the tectonic region. Intertongued as some of these volcanic units are with relatively weak clastic sediments, they may also be affected by basinward sliding along with the sediments, and thus severed from their subvolcanic root zones.

### Location of Massive Sulfide Deposits in Eugeosynclines

In and near a rising block where temperatures may be high, magmas of intermediate to acid composition leak out toward the surface, accompanied by some of the fluids released by deep metamorphic processes. Metals, regardless of their source, move upward along with solvents, and may accumulate as sulfiderich veins or replacements not far below land surface.

On the other hand, massive base metal pyritic ore deposits associated with mafic to intermediate volcanic rocks and more felsic differentiates may be formed on or under the sea floor at the marginal zone between rising and sinking blocks. Their position and relationship to mafic, and occasionally ultramafic, sequences suggest that the metals may have originated deep in the crust or in the upper mantle.

Sedimentary ores, nourished by submarine springs, may be expected to accumulate in isolated subsiding and protected seaways in some cases near and between submarine volcanoes. Generally the sulfiderich sedimentary bodies would be thin and irregular, only occasionally sufficiently concentrated to make an orebody. Nevertheless, regardless of the tenor and thickness of such beds they can be important guides to more significant accumulations formed at about the same time and under similar conditions. Determination of the stratigraphic and structural relationships even of thin sulfidic beds is therefore essential in the search for new ore.

Unfortunately, in highly deformed and metamorphosed regions there is no assurance that originally sedimentary sulfide mineralization has remained as a stratigraphic unit and is therefore still mappable as such. It is interesting, however, that Magee (1968), writing about the Ducktown District, affirms that the ores are replacements of favorable zones. Yet his Figures 3 and 4 (1968, p. 216-219) are even more suggestive of an early, essentially syngenetic origin, giving the impression that, if the ore beds and their sub-economic correlatives had been used as stratigraphic markers, exploration in the district would have been facilitated. A pre-metamorphic origin for these ores is proposed by Salotti (1969) on mineralogical grounds.

Ores emplaced on or under the sea bottom at the boundary between positive and negative zones are in a position peculiarly susceptible to mass dislodge-ment and sliding on oversteepened submarine slopes. Stripping of a stratiform sulfide layer by turbidity currents or gravity sliding was first suggested by Suffel (1965, p. 306).

Judging by the close association of massive sulfide deposits with volcanic rocks in regions where there has been little or moderate later deformation, it may be anticipated that similar associations existed in regions now intensely deformed and metamorphosed. Such, indeed, seems to be the case. In New England, for example, the Elizabeth Mine, Orange County, Vermont and the Milan Mine, Coos County, New Hampshire may be cited. Both deposits are in close relationship to amphibolites of undoubted volcanic origin. The Milan Mine is in a sequence of hornblende schists, biotite schists, amphibolites, and quartz-mica schists, all of volcanic origin. The amphibolites are in part derived from pillow lavas.

Although ores like those of the Elizabeth and Milan Mines, related as they appear to be to submarine volcanism, might be expected to have a close spatial arrangement with underlying alteration zones, subvolcanic breccia pipes, or intrusive bodies, such relationships are not evident. In fact, one will find on examining the literature that one possible source,
subjacent igneous bodies, which could be responsible for generation of massive sulfide bodies in high grade metamorphic rocks, is notably absent. Among many examples of orebodies with no clear source zone cited in Kinkel's (1967) survey of Appalachian massive sulfide deposits are Ore Knob, North Carolina, Ducktown, Tennessee, the Gossan Lead in Virginia, the Elizabeth Mine in Vermont, and the Milan Mine in New Hampshire.

**Strongly Deformed Massive Sulfide Deposits in Metamorphic Rocks**

*Japanese Examples*

The Sanbagawa metamorphic terrane on the island of Shikoku, Japan, provides one of the best examples of the transposition of orebodies so far recorded. Kanehira (1959) described and figured two rod-like cupferiferous pyrite orebodies of the Chihara Mine, noting that the axial dimensions of the orebodies are about $2 \times 10 \times 500$ meters. The elongation is parallel to lineation in the enclosing schists and to the B-axis of folds. The Sanbagawa rocks in this area belong in the epidote amphibolite facies, green schists probably representing original mafic tuffs and flows. Quartz schist near the mine contains 5-10 percent muscovite and 10-20 percent piemontite (Kanehira, 1959, p. 312), and thus may represent siliceous and manganiferous sediments in a submarine volcanic region.

It is worthwhile recalling the kinds of features developed by transportation of stratified formations with contrasting physical properties. Whitten (1966, p. 201) describes how quartzite units "which were originally a hundred meters thick, but which were bounded by pelitic rocks may be wholly or partly attenuated on the limbs of major isoclinal folds, so that a significant thickness is preserved in the fold closures only. Regional transposition structures are de-
veloped, and in the process huge “rootless” fold closures of competent and cohesive rocks become isolated as tectonic “fish” within pelitic rocks.

Examples of mullion structure and rodding on various scales are also given by Whitten (1966, p. 312-321). The most common orientation of these tectonically shaped bodies is parallel to the axial (B) directions of folds. In western Norway the ratios of principal axes of quartzite pebbles in conglomerate reach 1:3:100 (Kvale, 1945, cited in Whitten, 1966). It seems safe to assume that the whole rock unit suffered distortion at least as great as that of the pebbles.

In similar manner, the orebodies of the Chihara Mine appear to have been molded to their present rod-like shape during one of several tectonic events which affected the area. In order to be so shaped they were transported an unknown but considerable distance from their original location, in one or more stages, and subjected to high grade metamorphism. The resultant B-tectonite fabric of both host rock and ores was demonstrated by Kanehira.

A few kilometers east of the Chihara Mine is the Besshi-Shirataki mining district, described in detail by Hide (1961), Doi (1961, 1962), and Takeda (1970). According to Hide and Doi, the structural history of the Besshi ore zone and the enclosing late Paleozoic metamorphic rocks involved an early isoclinal folding which was caused by westward movement of the area to the north. Rocks of higher metamorphic grade locally rest on lower grade rocks.

The main, early, now steeply plunging isoclinal fold which affected the Besshi ore deposit has its axial plane parallel to bedding. According to Hide the ratio of wavelength to amplitude produced at this time is 1:100. Ores and enclosing metamorphic rocks were then subjected to a later folding of considerably larger amplitude and wave-length, with a N 60° W trend. The ore bed was thus isoclinally folded, then refolded. Larger, and locally richer orebodies occur where two limbs of the ore layer are tightly pressed together. The ore bed was interpreted by Hide as “derived from a single stratum of ore deposited on the floor of the geosyncline, then folded isoclinally during tectogenesis and metamorphism” (1961, abstract, p. 1).

How much displacement or transport took place during the first isoclinal folding event cannot be determined. Considering the amplitude of the folds, however, we may assume that each segment of the folded orebody has moved at least one kilometer, and that the summation of major and minor movements at the time of first folding may have been of the order of five kilometers. It may be noted that the Besshi-type ores are not far south of the Median Tectonic Line, a major fault of large displacement separating distinctively different metamorphic terranes. To the north is the Ryoke metamorphic terrane, essentially barren of ores, with abundant synkinematic granites and associated metamorphic rocks (Miyashiro, 1961, p. 290). Nothing in the various published reports precludes the possibility that the ore-bearing horizon, in its early isoclinal folding, records a sliding event during the early history of the median line fault. A section by Takeda (1970) strongly suggests such an event in the vicinity of the Shirataki ore deposit. The sulfide-rich layer, along with associated sedimentary rocks, may have moved southward from the vicinity of the break, close to the igneous terrane of the Ryoke belt.

Another example of extensive displacement of massive sulfide ores as a result of folding is the Hitachi Mine, in the Abukuma metamorphic belt northeast of Tokyo. As in the Sanbagawa terrane, two periods of folding appear to have been involved. The distribution of the various Hitachi orebodies and the complexity of individual orebodies is demonstrated by Kitami and Tsutsui (1969). The orebodies are located on the crests and sheared limbs of complex refolded folds. Small bodies of igneous rock close to some of the orebodies are as strongly deformed as the ores. The orebodies, unlike those of the Sanbagawa terrane are close to a granodiorite stock intruding the Abukuma metamorphic rocks. For a long time it was thought that the ores were a replacement of susceptible zones in schists by hydrothermal solutions derived from the nearby granodiorite intrusive (Watanabe and Landwehr, 1924). Careful mapping of structural detail and attention to stratigraphic control has, however, led to the discovery of major new orebodies. Apparently the stock is later than the ores and left its mark of thermal metamorphism on both the schists and the ores.

The massive sulfide deposits of the Sanbagawa and Abukuma terranes are essentially concordant with formational boundaries. They appear to have been formed more or less syngenetically with enclosing rock units, whether in direct relation to volcanic activity or as sediments. In both regions there have been at least two periods of folding. During the earlier folding transposition with respect to originally subjacent zones appears to have been considerable. The two regions were later affected by a second strong folding, metamorphism, and, at Hitachi, igneous intrusion.

The Elizabeth Mine, Vermont

The massive copper and zinc bearing sulfide deposits of the Elizabeth Mine are about 12 kilometers west of the Connecticut River. They are associated
with metavolcanic and metasedimentary rocks of probable lower Devonian age. These beds were affected by two distinct episodes of folding, the earlier one isoclinal and recumbent. After studying the works of Doll (1943), Doll et al. (1961), Billings (1956), Thompson et al. (1968), and Cady (1969) and quadrangle reports on adjacent areas, it seems to the author that the first major folding event may be interpreted as a major intrastratal nappe with movement toward the west. The Elizabeth orebodies are adjacent to amphibolite beds. Ores and amphibolites follow the same pattern of tight folding (McKinstry and Mikkola, 1954; Howard, 1959). The orebodies have been somewhat remobilized during later tectonic and metamorphic events including a late arching over the Strafford dome. Evidence presented by Howard (1959) for the introduction of the ores by replacement after major folding and during a later metamorphism will serve equally well to substantiate the metamorphism of ore layers and hydrothermally altered zones produced essentially syngenetically.

The concept that the ores and associated rocks of the Elizabeth (South Strafford) district have been transposed some distance westward, perhaps from the vicinity of the present Connecticut River, is diagrammatically illustrated in Figure 3. The folds around the Elizabeth Mine and the Strafford Dome are interpreted as digitations on the nose of a nappe which moved from the East, as suggested in Figure 3A. The nappe or nappes, may have been completely severed from roots near or east of the complex structural zone along the river. Early positive movements farther to the east, antecedent to the Acadian domes, intrusives, folding, and metamorphism, combined with subsidence in eastern Vermont are believed to have provided the conditions necessary for nappe formation. Metavolcanics in the Elizabeth Mine may be approximate equivalents of amphibolitic metavolcanics in the lower part of the Littleton formation (Lower Devonian). An idealized reconstruction of the present structure from the Strafford Dome and Elizabeth Mine east to the vicinity of the Connecticut River is shown in Figure 3B.

General Illustration and Synthesis

Sliding of sedimentary and associated volcanic or or near-surface intrusive rocks into a subsiding trough is illustrated in Figure 4. Submarine volcanism occurs in a subsiding segment of a tectonically active geosyncline. Depending upon a number of factors, certain of the submarine volcanoes (Fig. 4A) may contain sulfide concentrations as syngenetic sediments or as replacements. Hydrothermal alteration is likely to be extensive, surrounding and underlying the massive orebodies, especially attacking tuffs and breccia zones. Hard, massive flows, dikes and sills making up the volcano are thus close to light, ductile masses rich in clay and sulfide minerals as well as to heavy and fairly strong masses of ore, all of irregular shape. Adjacent, protected sea-bottom areas (Fig. 4A) are potential loci of sulfide sedimentation (perhaps like that of the Red Sea). As uplift continues to the right and subsidence and renewed sedimentation go on to the left, a condition of instability is reached (Fig. 4B). Volcanic piles rest on and are covered by poorly consolidated sediments. The whole is a weak system susceptible to turbidity currents, detachment, and gravity sliding. As postulated earlier, both volcanic masses and intervening sediments may thus be transported appreciable distances in a more or less horizontal direction (Fig. 4C). The whole would come to rest in a subsiding basin, producing, in this example, a series of recumbent isoclinal folds with basal glide planes essentially parallel to axial planes of the folds and also to most bedding planes.

Isolated small submarine volcanoes and associated ores might be expected to react differently from sedimentary sequences because of the extremes of ductility presented by adjoining rock masses. Some strong units might become exotic blocks; others might actually shape folds, dragging and molding more ductile rocks around them.

The immediate result of gravity sliding is the basinward transport of the originally associated

Fig. 5. Idealized slip-folding of segments A, A', and B of Figure 4C. The original slide surfaces (heavy lines), subparallel to bedding and to one or two cleavages, may be only a few cm thick.
volcanoes and sediments for a distance which in some cases might be measurable in tens of kilometers. The newly positioned rock masses and associated orebodies will be covered by rapidly deposited sediments and new gravity slides, as suggested in Figure 4C. The subsiding zone is thus quickly and deeply buried. The lower materials will be subjected to high pressures and to a succession of adjustments in volume and water content.

Metamorphic grade will increase rapidly. Presumably distortion of individual segments will include both lateral compression as subsiding and rising blocks move past each other and slip phenomena as smaller segments undergo penetrative movements in depth.

Supposing that now rootless volcanic rocks, ores, and sedimentary rocks are thus trapped in a new environment of increasing disturbance and metamorphism, they may be expected to be subjected to a variety of deformational overprints. One such deformational style might well be similar folding. A single simple example, derived from idealized slip-folding of the part of Figure 4C including potential ore-areas A (and its severed continuation A') and B is shown in section in Figure 5. Although the transposition of once adjacent rock masses may be relatively small during such folding, the new relationships tend to obscure the earlier structure.

Techniques for tracing orebodies concentrated at fold hinge-lines where two sets of folds are present are discussed by Stauffer (1968). However, a prior necessity where a strong second folding is imposed on sequences some of which were inverted, duplicated, or cut out by gravity sliding is the field recognition and study of structural and stratigraphic irregularities developed during the period of sliding. Although it is suspected that the complexity of some massive sulfide deposits in metamorphic terranes is largely due to events such as those postulated here, proof must await much more, and more detailed, study. Difficult and time consuming as it is, such study is more amenable to satisfactory analysis and eventual proof than the vague theories of deep hydrothermal replacement so long in vogue. The analysis must be directed not only toward the meticulous collection and assessment of structural detail, but also to an eventual understanding of the geologic history of the region as a whole.

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DEPARTMENT OF GEOLOGY,
THE UNIVERSITY OF CINCINNATI,
CINCINNATI, OHIO 45221,
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