

Massive sulphide deposits and their possible significance to other ores in Southeast Asia

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Abstract: Broad and multi-faceted studies during the past 15 years have shown that all massive base metal sulphide deposits were formed on the sea floor by chemical precipitation from discharged metalliferous hydrothermal fluids. The fluids were generated within the sub-area floor rock column by reactions between connate, or convectively circulated sea water and the rocks themselves. Differing rock columns in various tectono-stratigraphic environments give rise to differing fluids and varieties of deposits. Nevertheless, because of their common genetic process, all massive sulphides share a set of common identifying primary geologic characteristics. Later metamorphism of various ranks, types and episodes inevitably reshapes, partially to completely, all these primary characteristics including fundamental geochemical relationships.

Many of the geological characteristics of the massive base metal sulphides are duplicated in certain barite, manganese, iron-tin, iron skarn and base metal deposits of the central and eastern belts in Peninsular Malaysia, and their extensions northward and southward into Thailand and Indonesia. Some of the characteristics may also be present in the podiform chromite deposits of the Phillipines. These similarities suggest that many of the genetic and metamorphic processes involved in massive sulphide formation may have also contributed to formation of these southeast Asian deposits. Thus, the geology of massive sulphides may be significant to, and might enhance our understanding of such enigmatic deposits as complex tin-iron and podiform chromite ores.

Some of the problems of these ores, whose genesis has been traditionally explained by concepts derived from other, less enigmatic tin and chromite ores, might be elucidated by an approach utilizing the concepts, principles and relationships established in studies of the massive sulphide deposits. Objective studies to determine the extent to which massive sulphide geology is applicable to these ores should be undertaken.

INTRODUCTION

If all tin deposits are related to distinctive granitic intrusions then exploration for tin can be directed entirely along granite contacts. But if the metallogenic evolution of tin fields is more complex than this, and if some tin deposits are of exhalative, sea floor origin, then exploration must use a very different approach. In the latter case, favourable stratigraphic successions and horizons must be identified and stratigraphic relationships must be emphasized in exploring them. Syndepositional structures such as fault intersections, which controlled the sites of exhalative activity within the favourable horizons on the sea floor, must be sought. And, rock alteration patterns around the exhalative discharge vents must be evaluated.

All these relationships have proven to be important, and are currently used in exploration for exhalative massive base metal sulphide deposits. They will also be important in exploring for any tin ores which are of exhalative origin.

The purpose of this paper is to briefly review the main geological characteristics of

massive base metal sulphide deposits, the genetic processes that form them, and their resulting geological characteristics. Further, it is to consider their possible significance to certain other ore deposits, particularly to primary tin-iron lodes that occur in virtually all of the world's great tin fields, including those of southeast Asia and possibly also to podiform chromite ores that occur throughout the southwestern Pacific.

MASSIVE BASE METAL SULPHIDE DEPOSITS

General

During the past 25 years, much has been learned about the geology of stratiform and stratabound massive base metal sulphide deposits. As recently as 1959, the origin of these ores was considered to be one of the most enigmatic problems facing ore deposits geologists (Gunning, 1959). This problem has been essentially solved by detailed descriptive studies of the ores in many areas throughout the world, by experimental and geochemical laboratory investigation and, most recently, by oceanographic research which has located sea floor sites where the ores are currently being formed. The lessons and principles learned during the course of these studies, the genetic processes identified for the massive sulphide deposits, and certain characteristics of the ores themselves are relevant, however, on a broader basis to geological and genetic problems in other types of deposits.

Genesis

Although the detailed genetic mechanisms are not fully understood, the broad processes by which the massive base metal sulphide ores form are well documented. Fundamentally, this is by sea floor discharge of metalliferous hydrothermal fluids (Figs. 1, 2), followed by precipitation of the ore and gangue material above and around the discharge vents due to cooling, pressure decrease and increased Eh and pH (Hutchinson, 1980a; Large, 1977; Oftedahl, 1958). This process is comparable to that observed in the black smokers at 21° N on the East Pacific Rise (Haymon and Kastner, 1981), and in the deep brine pools of the Atlantis II Deep in the Red Sea (Degens and Ross, 1969). The fluids themselves are derivatives of sea water (Bachinski, 1978) which was either connate in the subaqueously deposited rocks beneath the sea floor, or drawn in through these rocks by convectively induced recharge (Hutchinson *et al.*, 1980). As the sea waters circulate; either convectively in the sea floor rock column, or perhaps due to compaction, dehydration and lithification, they evolve, through water-rock reactions, into reduced, metalliferous hydrothermal fluids, their metals leached from the rocks during the reactions and transported to the sea floor as soluble metal chloride or other complexes.

As the fluid nears the sea floor, it mixes with cooler, more oxygenated, near-surface water to produce complex alkali and alkaline earth element alteration mineral assemblages in the rocks of the sea floor. It also deposits silica, base metal sulphides and iron sulphide or oxide minerals in all open spaces in these rocks so that fractures, joints, pillow interstices are infilled with silica, sulphide or magnetite. Where the fluid discharges onto the sea floor, the same minerals are precipitated by chemical sedimentation, in a definite sequence according to their Eh-pH-temperature stability

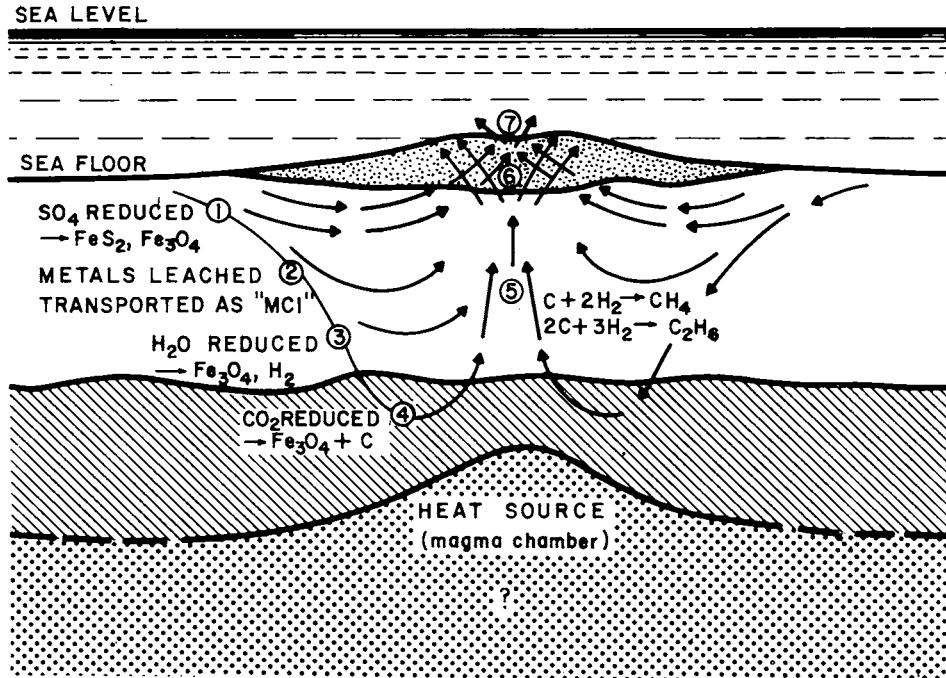


Fig. 1. Convective circulation of saline conate or marine waters (in a system buffered by Fe^{2+} — as ferrous silicate).

A. Downward (intake) circulation

- (1) 'Shallow level'—reduction of sulphate SO_4 + ferrous silicates → pyrite, magnetite.
- (2) Leaching of metals from ferrous and other silicate structures, transport as various metal chloride complexes.
- (3) 'Deeper level'—dissociation of water H_2O + ferrous silicates → magnetite + H_2 .
- (4) CO_2 + ferrous silicates → magnetite + C, production of strongly reduced, H_2 and C-rich, increasingly saline fluid.

B. Upward (outflow) circulation.

- (5) Carbon-hydrogen combinations; $C + 2H_2$ or $2C + 3H_2$ → light hydrocarbons, CH_4 or C_2H_6 . Production of strongly reduced CH_4 C_2H_6 rich, highly saline fluid.

C. Exhalative vent on sea floor.

- (6) 'Deeper level'—in vent system below water-sea floor interface; alterations, stringer sulphides.
- (7) 'Surface'—at sediment-water interface: massive sulphide precipitation.

relationships, to form bodies of mineralogically zoned, massive or nearly pure iron and base metal sulphide minerals. These bodies commonly exhibit complex breccia and soft sediment deformation textures, the products of reworking of already precipitated metalliferous sediment on the sea floor due to continued activity in the discharge vent.

As the reduced fluid becomes exhausted toward the top and margins of the flow system, higher oxygenation results from mixing with sea water. Here, iron may be precipitated chiefly as magnetite rather than as iron sulphide, forming either a massive body or banded silica-magnetite iron-formation. This commonly overlies and/or surrounds the more reduced, sulphide-rich core of the deposit.

Manganese too, is carried in the rising, reduced fluid but remains soluble under reducing conditions in the deeper and central parts of the flow system. However, it is oxidized to an insoluble manganese oxide toward the top and margins of the system where it is consequently precipitated to form manganese-rich, chemical sedimentary strata or manganiferous iron formation. Barium is also abundant in the rising reduced fluid and, like manganese, remains soluble under reducing conditions. It is precipitated however, as barite, again toward the top and margins of the flow system where oxidation is extensive.

Common Geological Characteristics

Due to their common origin as sea floor chemical precipitates from discharged hydrothermal fluids in the manner outlined above, all massive base metal sulphide deposits share a set of common identifying geological characteristics (Fig. 2; Table I). Although not all of these are present in every deposit, collectively, they serve to identify all members of this family of ores (Hutchinson, 1980a; 1973).

First, the distribution of the ores is stratigraphically controlled. Individual sulphide bodies may be stratiform and well bedded where deposition occurred from a single vent in a relatively quiescent sea bottom environment. Alternatively, where several vents were active in a more disturbed setting, several stratabound sulphide lenses may result, all located at a common stratigraphic position in the succession. Another common characteristic is a close spatial association at, or near, this stratigraphic position between the orebody and some other chemical sedimentary rock, often manganiferous iron-formation, chert, cherty tuff, cherty carbonate or barite. As a result, these distinctive strata are important as stratigraphic horizon markers for unravelling both structure and stratigraphy, and also as guides for exploration. They often contain sedimentary structures such as slump folds, geopetal indicators like graded bedding or bottom fluting and even fragments of sulphide ore (Fig. 2). These results from their initial deposition as soft chemical precipitates accompanied by some reworking and redeposition of earlier-deposited sulphides by turbidity or density currents on the sea floor. Yet another common characteristic is a zone of highly and variably altered and fractured rock that underlies the massive orebody in the stratigraphic footwall. This contains both sulphide stringers and disseminated sulphides. It may be rich enough, usually in copper, to be mined, and marks the location of the vent through which the generative fluids were discharged to the sea floor.

The orebodies themselves are lenticular to tabular bodies of nearly pure metallic sulphide minerals, invariably rich in iron sulphides pyrite, or pyrrhotite. Thus, as chemical sedimentary rocks, they may be considered simply as unique varieties of the sulphide facies of Algoma-type iron-formation (Gross, 1966). They also commonly contain some magnetite (Large, 1977), as well as varying amounts of the base metal sulphides, chalcopyrite, sphalerite and galena for which they are primarily mined. These bodies are prominently zoned, both laterally and vertically, with pyrite-sphalerite-galena-rich ore common toward their margins and stratigraphic tops, and pyrrhotite-chalcopyrite ore more abundant centrally and toward their stratigraphic bases. The contacts of the orebodies, both externally with their enclosing rocks, and

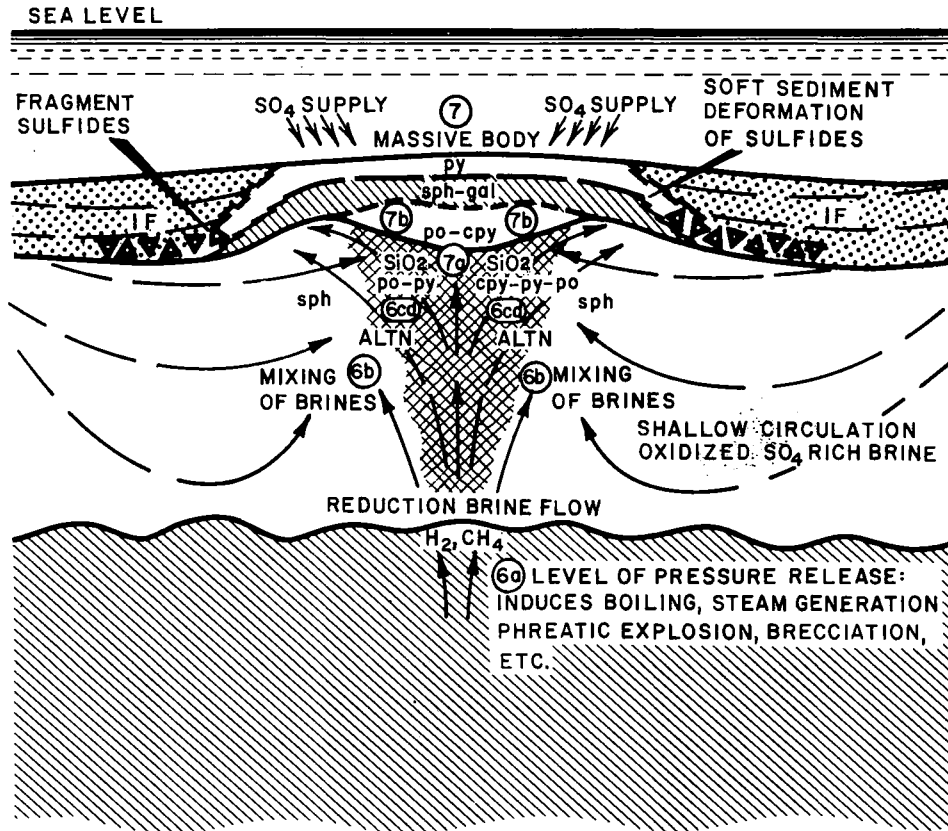


Fig. 2.

C. Exhalative vent on sea floor.

- (6) 'Deeper level'—in vent system below water-sea floor interface.
 - (a) Pressure release boiling; phreatic explosion, brecciation begin.
 - (b) Reaction, mixing of shallow-circulated, oxidized sulphate-rich brine with deep-circulated reduced brine.
 - (c) Precipitation of FeS, FeS₂, CuFeS₂, SiO₂ in fractures.
 - (d) Rock alteration by reaction between gas, liquid fractions, and shattered porous rocks. Production of zoned, but Cu-rich, stringer-disseminated ore (Keiko type) in altered rocks of vent system.
- (7) 'Surface'—at sediment-water interface: massive sulphide deposition.
 - (a) Exhalation of reduced brine onto sea floor.
 - (b) Mixing, reaction of exhalative reduced brine with sea water; precipitation of all metallic sulphides, silica, carbonate, magnetite, etc. as 'exhalative' chemical sediment under varying Eh-pH conditions. Massive banded orebody with prominent metal zoning (Okō, Kuroko), soft sediment deformed ore, fragmental ore, various 'facies' of iron formation, etc.

Table 1
MASSIVE BASE METAL SULFIDE FAMILY
COMMON IDENTIFYING CHARACTERISTICS

Stratigraphically-controlled distribution:

Stratabound in exhalative volcanogenic group
 Stratiform in exhalative sedimentary group

Massive lens:

Iron sulphide-rich (py \pm po)
 Base metal sulphides (cp, sph, gal)
 Important precious metals (Ag, Au)
 Massive to prominently bedded: good compositional layering
 sharp contacts; top, base, margins

Stratigraphically overlying:

Fe-rich chemical sedimentary rock (I.F.—4 facies,
 chert, tuff)

Stratigraphically underlying:

Stringer-disseminated sulphides, Cu-rich
 Altered footwall rock (vent or pipe sometimes
 recognizable)

Prominent metal-mineral zoning:

Vertical, within deposits
 Cu(Au) base \longrightarrow Zn, Pb(Ag) top
 po base \longrightarrow py top
 Lateral, between deposits
 Cu(Au) proximal \longrightarrow Zn, Pb(Ag) distal

Fragmental sulphides:

Mainly in exhalative volcanogenic group

Soft-sediment deformation structures:

Mainly in exhalative sedimentary group

Widely variable metamorphism \longrightarrow textural variability

internally between the zones of differing mineralogical composition, are remarkably sharp.

Metamorphism and its Importance

An unavoidable consequence of their sea floor origin is the widely variable degree and type of post-depositional metamorphism seen in these deposits (Vokes, 1969; Kalliokoski, 1965). They have inevitably been exposed to all of the same ranks, types, and episodes of metamorphism as have affected their host rocks.

The possibilities are multiple and the results as reflected in the ores are extremely complex (Table 2). An appreciation of the effects of this metamorphism on the ores is vital to proper understanding of their genesis. Broadly stated, metamorphism causes remobilization and redistribution of the soft sulphide minerals by plastic flow (Clark and Kelly, 1968; Buerger, 1928) causing them to penetrate fractures that develop simultaneously in more brittle, competent nearby minerals or rocks. The results are discordant, crosscutting relationships. For decades, these were considered positive proof of late, epigenetic origin for these orebodies (Suffel, 1935). This conclusion was incorrect for it is now known (Mookherjee and Suffel, 1968) that the ores were formed contemporaneously with their associated rocks on the sea floor, and the discordant relationships were due to later, superimposed metamorphism. In considering the relevance of massive sulphide geology to other types of deposits, it is important to remember the erroneous genetic conclusion that resulted from initial failure to understand the role and importance of metamorphism in reshaping the primary sea floor deposits.

Another important effect of metamorphism is the reshaping of geochemical relationships within these ores and their host rocks. It is difficult, and sometimes impossible, to distinguish between those geochemical relationships that were induced by later metamorphic, and those caused by primary genetic processes. This applies to major element ratios in the host rocks, to metallic element ratios in the ores themselves, to rare earth element ratios, and to stable isotope ratios (Hutchinson, 1982, 1983). It is particularly problematical where metamorphogenic fluids have been involved in partial to complete metamorphic re-equilibration of the ores with their host rocks. Sulphide geothermometers and geobarometers too, may have been reset under metamorphic environments. Fluid inclusion temperatures derived from any other than primary inclusions will reflect metamorphic conditions.

In short, an important principle arises from sulphide metamorphism, which is indeed relevant to all other types of deposits that may have formed initially on the sea floor. All field and geochemical relationships in such ores that have undergone even modest degrees of metamorphism may partially to wholly reflect superimposed metamorphic conditions rather than primary genetic ones. They may lead, consequently, to erroneous genetic conclusions. They must therefore be interpreted with utmost caution and in full awareness of the possible metamorphogenic possibilities.

Differences Among Massive Base Metal Sulphides

Notwithstanding their many genetic similarities, there are vast differences among

Table 2
METAMORPHISM OF MASSIVE BASE METAL
SULFIDE DEPOSITS

—begins when deposition ends

1. Diagenetic Metamorphism (diagenesis)
 - Compaction, burial, lithification, dehydration
 - incipient crystallization of primary amorphous or microcrystalline sediment, fine grained texture, colloform texture
2. Dynamic Metamorphism
 - Compression; tension
 - Plastic flow: banding, boudinage structure, augen texture, penetrative cross cutting veinlets in soft, incompetent sulfides
 - Cataclasis, fracture, brecciation in hard, brittle sulfides
3. Thermal Metamorphism
 - Recrystallization
 - Coarse grained texture, porphyroblastic texture
 - Mineral breakdown reactions: new minerals: resorbtion—reaction textures
4. Regional Metamorphism
 - Combines 2. and 3. — similar processes and effects
5. Retrograde Metamorphism
 - Relaxation of compression
 - Twining
 - Cooling
 - Unmixing or exsolution textures, overgrowth textures
6. Polyphase Metamorphism
 - Superimposition of two or more stages of any of 2. to 5.

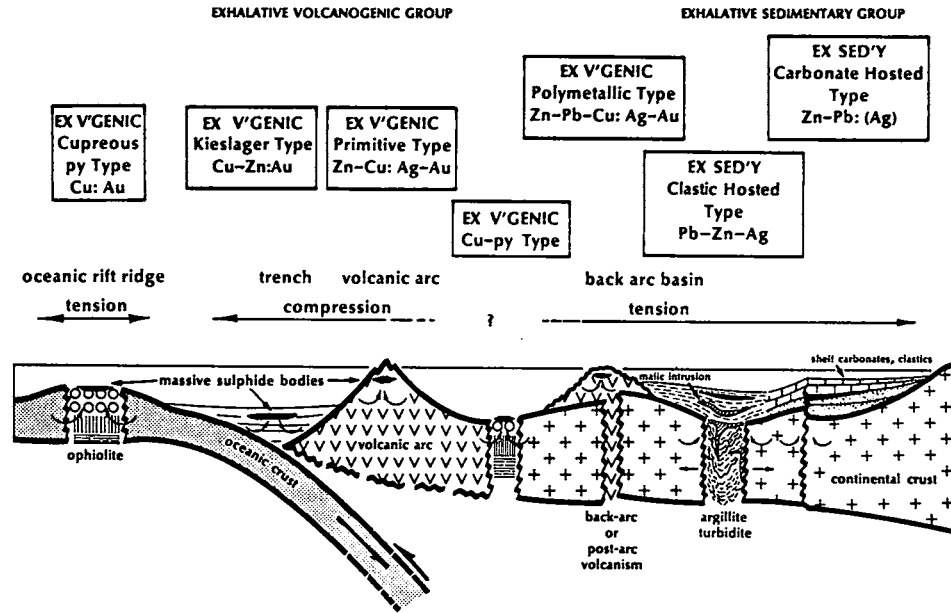


Fig. 3. Plate Tectonic Relationships: Depositional Environments of Various Massive Base Metal Sulphides.

various massive base metal sulphide deposits. These differences have been used as the basis for classification (Hutchinson, 1980a), so that this family of ores can be divided into two major groups, and each group into a number of differing varieties. The differences can also be used for assignment of the varieties to differing tectono-stratigraphic genetic environments (Fig. 3). These distinctions are based on the differing proportions and lithotypes or lithofacies of the volcanic and sedimentary host rocks; differing ratios of the three base metals, copper, zinc and lead and of the precious metals, gold and silver; and differing ages, both absolute on the broad geological time scale but also relative in sense of the sequence of generation of the differing varieties within an evolving orogenic belt.

Comparison of the similarities and differences among the various massive base metal sulphide deposits shows clearly that, although these deposits are formed by similar depositional sea floor exhalative hydrothermal processes, these processes were active throughout a complete range of geological environments, from ensimatic, in oceanic crust, on the one extreme to ensialic, in shallow cratonic basins, on the other (Fig. 3). Similarly, it is clear from the widely varying age of the ores, that these processes continued throughout the entire span of geologic time from early Archean until the present, and also throughout all evolutionary stages of the tectonic cycle, from initial oceanic rifting through continent-margin volcanic arc and post- or back-arc spreading, into intra-cratonic rifting and basinal filling.

Although temperatures may be highest, reaching 350° C in the ensimatic variety (Fig. 3, left) and may normally grade downward to lowest, perhaps 150° C in the intracratonic, basinal type (Fig. 3, right) it is interesting in the shallow-water, lime-rich continental shelf environment. In this case, bedded skarn rocks, with the distinctive assemblage of Fe-Mg-Ca-silicate minerals, might be generated. These would have no genetic affiliation whatsoever with granitic intrusions, although they might be considerably recrystallized and metamorphosed where they were subsequently invaded by granitic bodies.

Further consideration of the common genesis of the ores, through sea water reaction and leaching of the footwall rock column (Figs. 1 and 2), suggests that the differing rocks affected by this process over the wide range of differing tectono-stratigraphic environments is a major, albeit not the only, factor in governing the amounts and proportions of the metals extracted, transported and deposited by these fluids. Indeed, differing rock compositions, particularly content of ferrous iron (Fig. 1), in reaction with circulating fluids may play an important role in governing fluid Eh, pH and salinity, and therefore metal balance in the fluid.

In addition to wide variations in amounts of copper, lead, zinc, and of gold and silver, these ores exhibit an extremely diverse and interesting assemblage of minor minerals and elements. Two of these, chromium and tin, are an interesting geochemically distinctly incompatible pair. Chromite, a mineral of prominent ultramafic igneous rock affiliation is, admittedly, rare in most massive base metal sulphide ores, but is reported as "relatively common" in ensimatic, or cupreous pyrite type ores as in the Gull Pond, Tilt Cover and Little Bay deposits in Newfoundland (Bachinski, 1978 p. 69). In contrast, it is remarkable that cassiterite, a mineral of marked granitic igneous rock affiliation is a widespread and common mineral in differing varieties of massive base metal sulphide ores (Hamilton *et al.*, 1982; Walker *et al.*, 1975; Lea and Rancourt, 1958). Although usually present in minor amounts, it is sufficiently abundant to be recoverable at both the Kidd Creek and Sullivan Mines in Canada, and in some locations within these orebodies tin content ranges up to 2.0 percent.

The significance of these compositional and mineralogical differences has been overlooked. The chromite and cassiterite are integral minerals in the ores, and cannot be genetically separate, or different from the other, major metallic components. Presence of these minerals is simple but compelling evidence that the same generative hydrothermal fluids which deposited copper, zinc and lead also, in certain cases and under certain conditions, leached chromium and tin from the footwall rocks, transported them to the sea floor where they, too, were deposited in the ores. The suite of minor and trace elements found in the ores reflects the same broad spectrum of tectono-stratigraphic environments throughout which the ores form (Fig. 3). Thus, Co and Cr occur in the ensimatic types whereas Sn and W are present in ores of the cratonic-affiliated ensialic types. In any case, the significance is clear; crystallization of ultramafic melts is not the only means of chromite generation, and crystallization-differentiation of volatile-rich granitic melts is not the only process that gives rise to cassiterite-bearing ores.

RELEVANCE OF DEPOSITS IN SOUTHEAST ASIA

Many of the foregoing aspects of the geology of massive base metal sulphide deposits may be relevant to geological problems of other types of deposits, some of which are present in Southeast Asia. These include possible massive base metal sulphides as well as certain other deposits of the two metals last cited above, chromium and tin.

Massive Base Metal Sulphide Deposits

It is probable that the volcano-sedimentary rocks of the central and eastern belts in Malaysia, and their extensions to the north and south into Thailand and Indonesia contain exhalative iron sulphide- or iron oxide-rich ores. There are indications that some of these may also contain significant amounts of base and precious metals. Examples are the numerous iron-rich deposits of Pinyok in Thailand, Sokor, Bukit Besi, Bukit Bangkong and Tasek Cini in Malaysia and Kelapa Kampit and Selumar in Belitung, Indonesia. Indeed, many of these show some of the typical characteristics of the exhalative massive base metal sulphide family of ores that have been reviewed above.

For example, at Tasek Cini in Pahang, dark, probably ferruginous bedded barite underlies a hanging wall schist or gneiss, and is, in turn, underlain stratigraphically by bedded, manganese-rich iron oxides. The latter are now mainly hematite, but this probably consists of martitized magnetite. The dark ferruginous barite is cut by veins of coarsely crystalline, white barite, probably remobilized by a very local, lateral secretion process from the bedded barite. Footwall schist and gneiss underlie the manganese-iron rich unit. Although not in contact with any of the above rocks, so that its stratigraphic relationships to them are not known, massive sulphide mineralization is also present nearby, apparently somewhere deeper in the succession. This consists of nearly massive pyrite-pyrrhotite-chalcopyrite mineralization, and pyrite-silica mineralization which is banded and contains prominent, alternating layers of pyrite-rich and silica-rich material. Large blocks of the massive sulphide ore stockpiled at the site are cut by a network of chalcopyrite-bornite-rich veinlets.

At Ulu Sokor in Kelantan, two small lenses of massive, polymetallic sulphide containing lead, zinc, copper, silver and gold occur in limestone along the contacts between limestone and phyllite. A manganese-rich and limonitic gossan is associated with these sulphide bodies. Other occurrences of bedded barite and manganese-rich iron ore are known, and have been mined on a small scale throughout the central and eastern belts in Peninsular Malaysia.

At the Kelapa Kampit Mine in Belitung, Indonesia, a significant tonnage of bedded, stratiform zinc-lead-silver-rich mineralization is present, although not mined, in close association with the cassiterite-bearing Nam Salu bedding-plane lode (pers. comm., mine staff, 1981; F. Omer-Cooper, 1984). This mineralization has been described as thinly laminated, alternating sphalerite- and galena-rich bands that are interbedded with black shale and radiolarian chert. The body is stratigraphically continuous, can be used as a stratigraphic marker horizon and has been followed semicontinuously for nearly seven kilometres by geochemical sampling and a few

diamond drill holes (pers. comm., F. Omer-Cooper, 1984). Bedded barite is described as common at Kelapa Kampit in early reports of the former mining company. Also in Belitung polymetallic lead-zinc-copper mineralization is associated with the massive magnetite body at Selumar.

All these occurrences show many characteristics similar to those recognized in exhalative massive base metal sulphide deposits. These include the presence of bedded barite, manganese-rich strata, magnetite-rich iron-formation or massive magnetite, bodies of mineralogically zoned, polymetallic massive sulphide, containing Zn, Pb, Cu, Ag, Au, stratiform distribution of ore, sharp contacts between the various lithologic members etc. It is probable that these deposits are indeed, exhalative massive sulphides, deposited originally by hydrothermal activity on the sea-floor. The occurrences in Peninsular Malaysia are hosted in limestone and may represent a shallow-water, shelf-deposited carbonate-hosted, exhalative sedimentary type (Hutchinson, 1980). Whereas those in Belitung, where limestone is rare, are hosted predominantly in tuffaceous shale, radiolarian chert and siltstone. They may represent a deeper water-deposited, clastic-hosted, exhalative sedimentary type, perhaps formed in closer association with submarine volcanism, than those in Malaysia.

This activity must have occurred in Carbo-Permian time, as the host rocks to the sulphide occurrences are believed to be of this age. If, as seems probable, they are indeed sea floor exhalative deposits, then they clearly pre-date the regional granitic intrusions of Permo-Triassic age which invade the older sedimentary rocks.

The deposit at Bukit Besi is another interesting possible example of an exhalative, iron-rich massive sulphide-oxide-silicate body. It lies within, and its layering appears to be concordant with the bedding in a host limestone. During the 1950s, substantial tonnages of magnetite ore were removed. At present, the body is exposed on the uppermost benches toward the northwestern end of the old open cast. Here it consists essentially of massive to well layered, pyrite- and pyrrhotite-rich massive sulphide that also contains significant amounts of chalcopyrite. In the centre of the body however, flanked concordantly on both sides by heavy sulphide mineralization, are several feet of iron-rich skarn, apparently intercalated within and between the massive sulphides both above and below. These relationships suggest that some of these skarn beds may be of sea floor exhalative origin, formed through interaction between discharged high-temperature, Fe-Mg-rich exhalative fluid and lime mud. They may represent simply an Fe-Mg-Ca-silicate-bearing variant of the four well recognized facies of Algoman-type iron formation; sulphide, oxide, silicate and carbonate (Gross, 1966). There seems no reason, providing only that sufficiently high temperatures were attained on the sea floor for growth of these minerals, why the SiO_2 , Ca, Fe and Mg which were discharged to form these facies might not combine in this manner. If so, the genesis has little to do with intrusions of the younger Permo-Triassic granite, although the skarns and the flanking massive sulphides, may have been thermally recrystallized by the intrusions. Similar iron-rich skarn beds are also present in close association with iron orebodies at Pelepah Kanan in Johore. Here, they have however, been intruded by the later granite and are cut by a network of cassiterite-bearing veins.

Tin Deposits

Particularly significant in southeastern Asia is the question of the possible

relevance of the geology of massive sulphide ores to certain types of tin deposits. The widespread presence throughout Thailand, Malaysia and Indonesia, as well as elsewhere in the major tin fields of the world, of distinctive, coarse-grained, K-feldspar-porphyritic, volatile-rich, S-type granites with associated cassiterite-rich veins, stockworks, greisens and alluvial deposits (Stemprok, 1979; Hosking, 1967) has led to the perhaps overly broad and comprehensive generalization that all tin deposits of these regions are genetically related to these intrusions. Here, the evidence from massive sulphides—that tin is commonly transported and deposited in sea floor exhalative hydrothermal systems—offers a second genetic alternative for certain tin ores.

Many of the primary, complex tin-ore ores of southeastern Asia, like Bukit Besi and Pelepah Kanan in Malaysia (Hasbi *et al.*, 1981; Hosking, 1970), Kelapa Kampit and Selumar in Belitung, Indonesia (Sujitno *et al.*, 1981) and Pinyok in Thailand (Hosking, 1970) exhibit many geological characteristics of massive sulphide ores, including well bedded (Plates 1, 2) concordant, stratiform or stratabound character, sharp contacts, abundance of iron minerals including pyrite, pyrrhotite and magnetite, presence of bedded barite, and of minor base metal sulphide minerals. Moreover, some of them, like Kelapa Kampit, lack the close spatial association with the late Palaeozoic or Mesozoic tin granites that is so characteristic of the vein and greisen deposits. Also at Kelapa Kampit, the Sarsaparilla orebody, which is a discordant breccia zone consisting of large blocks of the quartzitic wall rock in a siliceous sulphide-cassiterite-rich matrix (Plate 3), occurs only along the stratigraphic footwall, but not the hanging wall, of the subperpendicular, stratiform, Yen Salu bedding-plane lode. It may represent a brecciated, altered and mineralized footwall feeder pipe or hydrothermal discharge vent beneath the latter.

Tin-ores of this type are also common, not only in Southeast Asia, but in most tin fields of the world. Thus, they are known in Cornwall, England (Dines 1956). The Dominique zone, near Yarmouth, is one of this type in the recently recognized tin district of southwestern Nova Scotia (Muise, pers. comm. 1982; Smith *et al.*, 1982). They occur also in Tasmania where their origin has been heatedly argued (Patterson, 1982; Patterson *et al.*, 1981; Hutchinson, 1982, 1981a, 1981b, 1980b, 1979; Newnham, 1981; Solomon, 1980). It is possible—and here, unlike the case for chromite discussed below, there is direct supporting evidence (Hutchinson, 1979)—that these deposits are not granite-related replacements, but pre-granite, sea floor exhalative bodies like the massive sulphides. They are therefore older than the granite affiliated ones that occur in the same area. If so, the complicating effects of metamorphic remobilization observed and established in studies of massive sulphide must be considered. The ores in this case cannot have escaped the metamorphic consequences of the later granitic intrusions, of re-equilibration reactions with the later, granite-derived fluids that formed the co-regional veins and greisens. Thus, it is not surprising that geochemical and stable isotopic studies of these ores fail to yield unequivocal results that might finally establish their origin (Patterson *et al.*, 1981; Patterson, 1982; Hutchinson, 1982).

Not all discordant, epigenetic vein deposits of tin are identical, and in fact at least two differing types may be identifiable. The first are high-sulphide, fracture- or shear-controlled veins or vein systems that trend to be extremely irregular in shape,

branching or ramifying, and discontinuous. They commonly exhibit strong chloritic alteration of the vein walls, which are commonly highly mineralized with sulphides and cassiterite. Although quartz is present, it is often low grade, and not so abundant as in the second type, and tourmaline is rare. Although granite may occur nearby, often a depth below, these veins may extend upward in the wall rocks for some distance from the granite contacts. The Sungei Lembing mine of Pahang Consolidated is a Malaysian example (Hosking, 1970) as is the Wheal Jane deposit in Cornwall (Rayment *et al.*, 1971). The second type are low-sulphide, high-quartz tourmaline veins, sheeted vein zones or vein stockworks. These appear to be of higher temperature origin, are commonly pegmatitic and contain rich pods of cassiterite. They are closer to granite contacts or even within greisenized granite, and have greisenized vein walls. They often exhibit more regular morphology than the former, particularly the sheeted vein zones, with persistent strikes and dips, apparently due to vein emplacement in joint or fracture systems. The Rahman Hydraulic or Tekka deposits in Malaysia, and the occurrence at Cligga Head in Cornwall (Moore and Jackson, 1977) are examples.

Although both are clearly epigenetic and granite-affiliated, their differences suggest somewhat differing genesis for these two types of veins. Perhaps the first were formed from sub-volcanic granites—possibly like those of the eastern belt in Malaysia, medium-grained, equigranular and somewhat older (pers. comm., C.S. Hutchinson, 1984). These perhaps rose to a relatively high level in the crust, and cooled rapidly, venting their hydrothermal, volatile-rich differentiates, which mixed with shallower meteoric formational waters, to the surface. Perhaps the second type of veins were derived from deeper-seated, possibly younger, typically K-feldspar-porphyritic granites like those of the western belt in Malaysia. These crystallized more slowly at greater depths. Their volatile-rich hydrothermal differentiates may have been employed nearby at higher temperatures than the former type, without appreciable mixing with cooler meteoric formational waters, in cooling-shrinkage fracture or joint systems around the granite contacts which were extensively greisenized by the impounded fluids.

The repeated occurrence together of what may be two genetically different types of tin deposits, one syn-sedimentary and of pre-granite age and the other epigenetic and of syn- or post-granite age, in most important tin fields however, is enigmatic. Perhaps the most plausible explanation is that of Plimer (1980) who suggested that these two might be genetically, but indirectly related to one another, through anatexis and partial melting. According to Plimer's suggestion, the earlier, pre-granite, sea floor exhalative ores, together with their host rocks, may be essential progenitors of the later, granite-affiliated type. Partial melting in deeply subsided and buried, or subducted successions containing tin-enriched strata and deposits of the earlier type may generate distinctive tin- and volatile-rich, S-type granitic melts. These may invade the very rocks from which they were derived and give rise, on crystallization, to the various types of later vein and greisen deposits.

Another problem is the specific tectono-stratigraphic environment in which the earlier tin-rich exhalative deposits are formed. The wide variability in the generative tectono-stratigraphic environments of various types of massive sulphide deposits has already been noted (Fig. 3), but under what conditions does tin become enriched to



Plate 1. Weathered surface exposure, Nam Salu Open Cut, Kelapa Kampit Mine, Belitung, Indonesia; thin regular stratification in stanniferous bedding plane lode; darkest band (right of centre) is magnetite, others are limonite-goethite after pyrite-pyrrhotite.



Plate 2. Weathered face, Nam Salu Open Cut, Kelapa Kampit Mine, Belitung, Indonesia; well bedded stanniferous lode, sulphides altered to iron oxides.



Plate 3. Underground face, "Sarsaparilla breccia" ore zone, -3 m level, Kelapa Kampit Mine, Belitung, Indonesia; large blocks of barren quartzitic wall rock (upper right, lower left), smaller blocks (lower right and throughout) in silica-sulphide matrix.

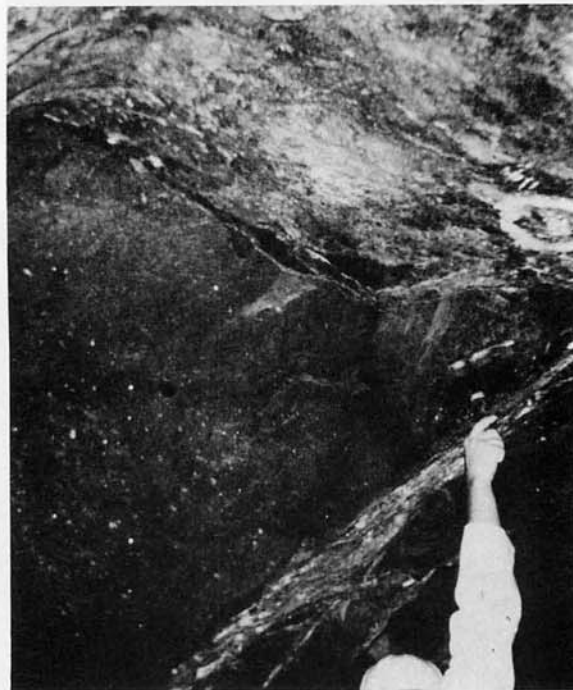


Plate 4. Underground face, 10th level, Railway Block Mine, Selukwe, Zimbabwe; lens of massive "SX Type" chromitite in serpentine, sharp contacts.



Plate 5. Broken slab, from Peak Mine, Selukwe Zimbabwe; thin, regular banding in "Priority Type" chromitite.



Plate 6. Underground face, level, Peak Mine, Selukwe, Zimbabwe; small pod of massive "Priority Type" chromitite in thinly banded chromite-talc-carbonate rock.

mineable levels from its normal trace or minor level of concentration in submarine exhalative systems? The answer is obscure. What seems evident from the descriptive geology of possible examples of these deposits around the world is that they occur in marine sedimentary sequences. These contain a mixture of shallow water-deposited, well worked, mature, epiclastic sedimentary rocks such as sandstone, siltstone and shale with less mature, deeper water-deposited types like argillite or greywacke together with thin, tuff beds, spilitized mafic, or even serpentinized ultramafic igneous rocks (Plimer, 1980; Williams *et al.*, 1975; Solomon, 1965). Inferentially, these were formed on, or within, an older, preexisting cratonic basement. This may have been initiated by rifting, followed either by closure of the rift, compression and subduction in a fore-arch trench (Hutchinson, 1979), or by subsidence in a back-arc basin (Badham, 1982). In any case, it appears that some involvement of older continental crust, in which tin may have been previously pre-enriched, is necessary to attain its later, higher concentrations in the exhalative systems. If so, it appears that not one, but at least two and perhaps three successive tectonic stages are involved in, and necessary for, the evolutionary metallogenesis of major tin fields.

Chrome Deposits

Chromite occurrences are widespread throughout many of the islands of the southwestern Pacific and are important producers in the Philippines and New Caledonia. Most of the world's chromite reserves are of magmatic origin; layers of chromitite, or nearly pure chromian spinel, within differentiated ultramafic-mafic igneous complexes (Willemsse, 1969; Jackson, 1969; Irvin and Smith, 1969; Bichan, 1968). Consequently, magmatic processes accompanying the crystallization and differentiation of mafic melts have been widely, in fact virtually exclusively advocated to explain the geology, particularly the morphology and mode of emplacement, of the somewhat different podiform, or sac-type chromite deposits (Thayer, 1969; Cotterill, 1969), and it is deposits of this type that are most important in southeast Asia. These do not occur as layers within differentiated igneous bodies, but as lenses or pods associated with highly serpentinized, but poorly differentiated igneous, and deep water-deposited sedimentary rocks.

Perhaps the evidence from massive sulphide ores, which shows that under certain conditions chrome can be hydrothermally transported and deposited, offers a possible genetic alternative for these deposits. Much circumstantial evidence can be found to support this alternative. Magnetite—like chromite a spinel, crystallizing at high temperatures, and forming nearly pure layers in the same differentiated mafic igneous rocks—is also abundantly deposited by sea floor chemical sedimentation to form the banded, Algoman-type iron-formations (Gross, 1966). Although some of the podiform chromitite bodies are massive lenses in serpentinite with sharp contacts against their enclosing rocks (Plate 4), others, like some of those at Selukwe, Zimbabwe, or in the J-361 pit at the Acoje Mine in the Philippines, are thinly laminated or banded; a fabric resembling the layering in iron-formations or massive sulphides (Plate 5). Some of them consist of small pods in alternating bands of chromite and talc-carbonate (Plate 6). Although the talc-carbonate rocks have generally been considered to represent alteration products of ultramafic igneous rocks, there is, again, the second alternative.

Recent studies of certain massive sulphide ores (Costa *et al.*, 1983) and at submarine hydrothermal vents (Lonsdale *et al.*, 1980) have shown that talc and carbonate are also products of sea floor chemical sedimentation from discharged hydrothermal fluids. Fluid inclusions, rich in NaCl, CO₂, CH₄, C₂H₄ and C₂H₆, and with filling temperatures of 337–357° C, have been identified in some chromite from the podiform lenses (Johan and LeBel, 1979; 1978), and anomalous amounts of chromium have been reported in hydrothermal discharge fluids of the Mid-Atlantic Ridge and Lake Kivu in East Africa (Scott *et al.*, 1980; Degens and Ross, 1976). Although this evidence is not proof of hydrothermal exhalative chromite ores, it is sufficient to raise this possibility, which merits direct investigation for substantiation or negation.

SUMMARY

Many geological characteristics similar to those known in massive base metal sulphide deposits are present in some barite, manganese, iron and base metal occurrences in the central and eastern belts of Malaysia, and their extensions north and south into Thailand and Indonesia. Some of the primary high-iron tin deposits and skarns in the same belts also exhibit these characteristics. This raises the possibility that, as for the massive sulphides, similar sea floor exhalative hydrothermal processes may have played some role in forming all these deposits. If so, it follows inevitably that post-depositional metamorphism must have variably affected, and reshaped all of their primary relationships and characteristics. In the Malaysian-Thai-Indonesian belts, this takes the form of late Palaeozoic-Mesozoic granitic intrusions and orogenesis which have deformed and recrystallized the older exhalative stratiform deposits. They also gave rise to stanniferous greisens, veins and vein systems, some of which are superimposed on the older stratiform deposits.

Complex tin-iron and podiform chromite ores of southeast Asia are two possible cases to which the genetic and metamorphic processes known in massive base metal sulphide deposits may be applicable. The origin of these has traditionally been explained by well established concepts based on studies of other, somewhat different types of granite-affiliated tin and magmatic chromite ores. These hypotheses however, do not provide an adequate explanation for some aspects of the geology, and genesis of these tin and chromite ores, which therefore remain enigmatic.

Perhaps a new approach, not based on the classic genetic theories established from the granite-affiliated tin and magmatic chromite deposits, might aid in resolving these enigmas, thereby provide improved understanding. Genetic processes in ore deposits are seldom uniquely applicable to all ores of a metal. On the contrary, differing processes in some cases generate similar products. In this context, thorough and extensive studies to evaluate the role of sea floor, exhalative hydrothermal activity, followed by metamorphism, in formation of complex tin-iron and podiform chromite ores would greatly enhance our knowledge and understanding of these deposits and their genesis.

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