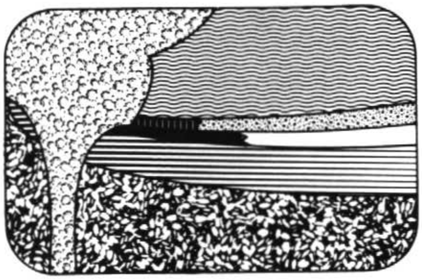

Ore Deposit Models — 4. Sedimentary-Type Stratiform Ore Deposits: Some Models And A New Classification

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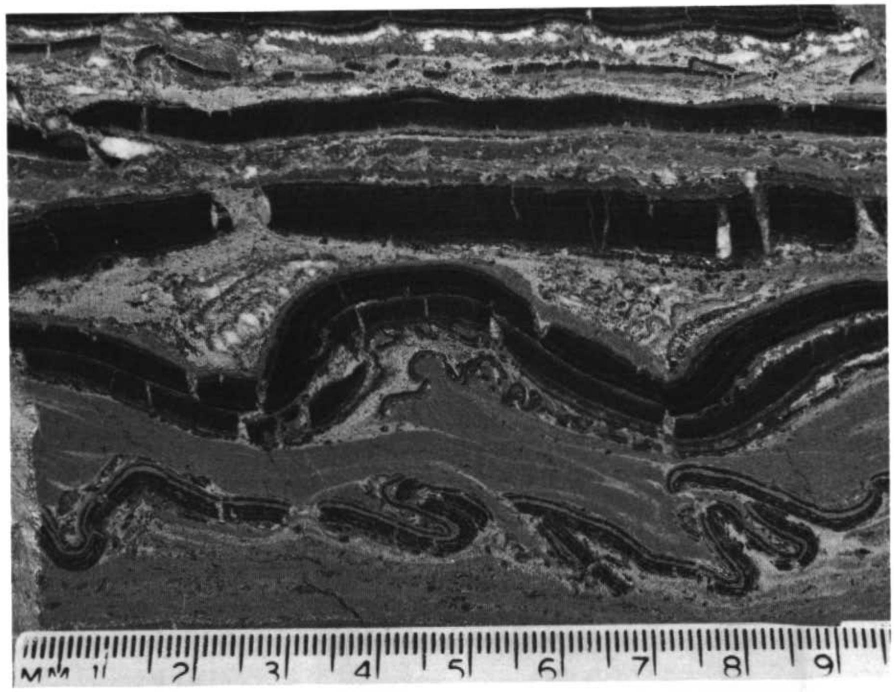

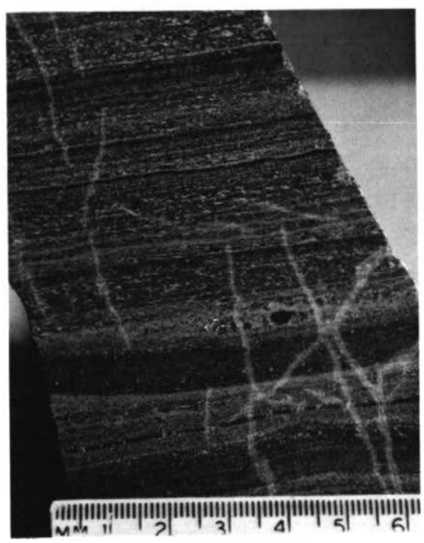

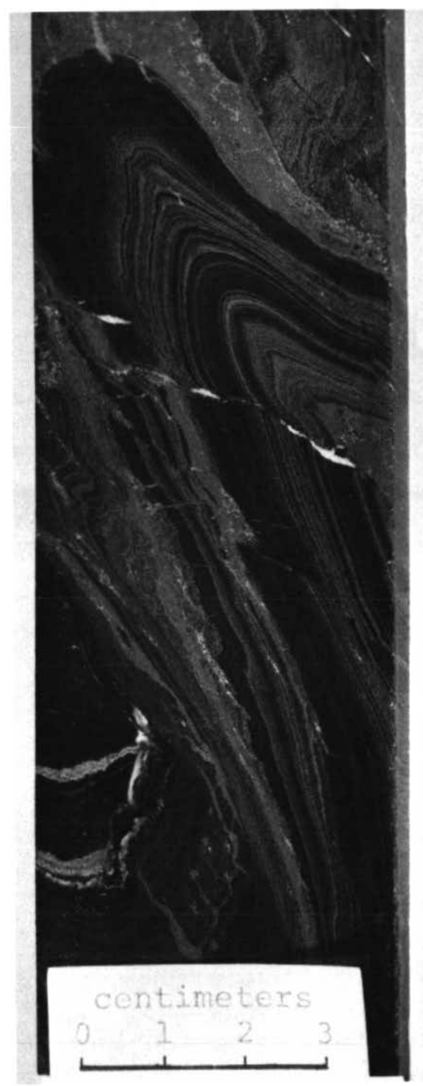

Figure 1 *Specimens of laminated ore from sedimentary-type stratiform ore deposits: a) laminated sulphide and chert, from Mt. Isa, Australia; b) laminated argillite with sulphides, from the Sullivan deposit, Canada; c) laminated sulphide and darker chert, from the Howards Pass deposits, Canada.*

Introduction

Many mineral deposits containing zinc, lead, copper, barium and/or precious metals are stratiform in that their general morphology is similar to sedimentary strata (Stanton, 1972, pp. 498-503). Some of these deposits occur in predominantly clastic sedimentary sequences where volcanic rocks are not demonstrably related to ore formation. These are herein referred to as sedimentary-type stratiform deposits. Major examples are McArthur River, Sullivan, Meggen, Mufulira and XY. Typically, these deposits consist of stratiform sulphide bodies that internally contain at least some bedded sulphides suggesting that deposition of the sulphides occurred before lithification. Furthermore many deposits, when specifically grouped, occur in one major sedimentary basin, although individual deposits may occur within separate, second-order or sub-basins. Examples of major basins or first-order basins are found in the Zambian Copperbelt where Mufulira, Muliashi and Chambishi sub-basins represent remaining roots of a very extensive basin in which Katanga sediments were deposited (Fleischer *et al.*, 1976). The Kupferschiefer deposits of central Europe are contained within the Permian Zechstein Basin, and all the Howards Pass deposits occur within the Selwyn Basin of the Northern Cordillera. As a group, the deposits are loosely associated with carbonaceous sedimentary rocks, but individually some occur within specific associated lithologies. The stratiform nature of the deposits and their clastic

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sedimentary rock association help separate these deposits from the strata-bound Mississippi Valley type deposits (Anderson, 1978) which are generally associated with carbonate rock sequences. The separation of the sedimentary-type deposits and distal volcanogenic stratiform deposits (Plimer, 1978; Large, 1979; Jambor, 1979) is gradational, since few sedimentary basins are totally lacking in a volcanic component (Conybeare, 1979).

The sedimentary-type stratiform deposits constitute substantial reserves of zinc, lead, copper and barium. For example, the McArthur River deposit in Australia contains 200,000,000 tonnes grading 10% Zn, 4% Pb and 45 g/tonne Ag (Murray, 1975). The areal extent of this class of deposits is exemplified by the Zambian Copperbelt where an area 7500 km^2 contains most of the deposits, or the Howards Pass area where potential mineral deposits occur over 130 km of regional strike length. Thicknesses of the deposits are highly variable ranging from 15 cm at Creta (Argall, 1975) to over 650 m at Mt. Isa (Mathias and Clark, 1975). Locations of deposits discussed in this paper are shown in Figure 2, and represent the major examples of the class of deposits termed sedimentary-type stratiform deposits.

This paper is a review of some of the models proposed for the formation of sedimentary-type stratiform mineral deposits; and proposes a three-fold classification based on the type of sedimentary basin of deposition for the associated sediments. This classification aids in rationalizing the location of these deposits and allows for comparison of deposits. The combination of this classification with the possible behaviour of ore forming fluids allows for an appreciation of the classes' diversity.

Most sedimentary-type stratiform ore deposits show evidence of similar processes operating during formation. Thus models proposed by many workers have several features in common. For the purpose of model construction the generation of an ore deposit involving a hydrous fluid is considered to have four critical aspects: 1) a source for the ore constituents, 2) solution of the ore constituents, at least in part, in a hydrous fluid, 3) migration of the fluids after acquiring their metal content, in directions controlled by pressure and/or chemical differentials, 4) formation of the ore deposits by selective precipitation of certain constituents in response to physical and/or chemical changes as the fluids migrate into new environments. Therefore, models must focus on source, solution of elements, migration and precipitation.

The present paper emphasizes the migration and deposition of metals. Four possibilities exist in the sedimentary environment: 1) metal and sulphur are both truly sedimentary, 2) metal is truly sedimentary while sulphur is imported and fixed in the sediment during diagenesis, 3) sulphur is truly sedimentary while metal is imported and fixed in the sediment during diagenesis, 4) metal and sulphur are both imported and fixed in the sediment during diagenesis. These four models of formation may operate either individually or in combination to produce any particular deposit.

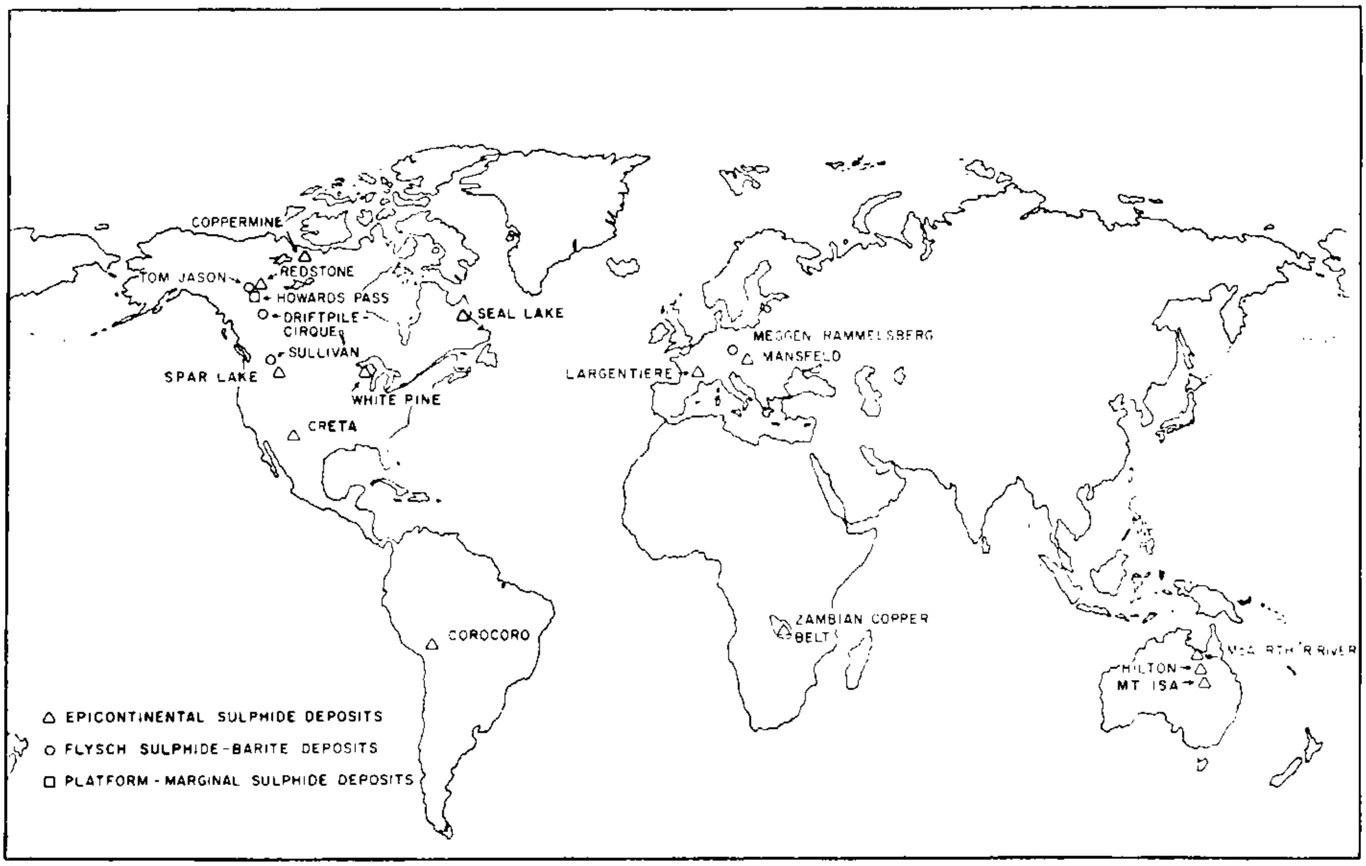


Figure 2 *World location map of sedimentary-type stratiform ore deposits. Symbols identify the types of deposit as proposed in this paper.*

Tectono-Sedimentary Framework Classification

For discussion and for mineral exploration purposes, sedimentary-type stratiform deposits may be divided into three sub-classes based on gross sedimentation related to major tectono-stratigraphic environments: 1) intracratonic basin sulphide deposits in shallow water shales, silt and sandstones associated with carbonates and evaporites, 2) flysch basin sulphide and barite deposits in turbidites and associated lithologies, 3) platform-marginal basin sulphide deposits in carbonaceous laminites associated with deep water mudrocks and cherts, outboard of cratons or platforms. Idealized stratigraphic sections associated with the three sub-classes are shown in Figure 3.

Intracratonic Basin Deposits

Intracratonic basins occur on a continental shelf or within a craton. Facies models (Walker, 1979) included in this type of basin are coarse alluvial, fluvial, deltas, barrier island, shallow marine and supratidal systems. Examples of ore deposits associated with intracratonic basins are those of the Kupferschiefer (intracratonic basin), those of the Zambian Copperbelt (marine marginal intracratonic basin), McArthur River (intracratonic trough) and Largentiere (alluvial fan complex).

Five general characteristics are common to deposits of the intracratonic subclass. 1) The deposits are associated with poorly sorted sandstones, siltstones, silty limestones and dolomites; locally, conglomerate may be associated with or underlie the deposits. Examples of this association are the Copper Harbor Conglomerate underlying the White Pine deposit, (Ensign *et al.*, 1968), the calcareous siltstones and silty limestones of the Copper Cap Formation in the Redstone deposits (Helmstaedt *et al.*, 1979), the footwall conglomerate and sandstone in the Zambian Copperbelt (Annels, 1979). 2) Typically many of the clastics in the associated sequence are coloured red by the presence of hematite. Cross-cutting red "Rote Faeule" associated with the Mansfeld deposit (Jung and Knitzschke, 1976), the Copper Harbor Conglomerate and Freda Sandstone near the White Pine deposit (Ensign *et al.*, 1968), and the W-fold shale underlying the McArthur River deposits (Williams, 1978) exemplify the red bed association. 3) Most of the deposits of this sub-class occur in, or very near, mudstones or shales that were reducing in nature. Examples are carbonaceous shales containing the Mansfeld deposit (Rentzsch, 1974), the carbonaceous dolomitic mudrocks containing the McArthur River deposits (Croxford and Jephcott, 1972), carbonaceous mudrock with pyrite containing the White Pine deposit (Brown, 1971), algal mat-related organic matter in some of the Zambian Copperbelt deposits (Renfro, 1974), and green, possibly methane reduced zones associated with the Belt-Purcell copper-silver deposits. 4) Gypsum is present or inferred to be associated with the deposits. Examples include, the Zambian Copperbelt (Annels, 1979), Kupferschiefer (Renfro, 1974) and West Texas-Oklahoma areas (Johnson, 1976). 5) Lateral chemical zoning may be evident in many of the deposits. Examples include the Mansfeld deposit where the zoning of copper, lead, zinc and pyrite occurs away from the "Rote Faeule" sediments (Deans, 1948), the Roan (Zambia Copperbelt) where a basinward zoning of chalcocite, bornite, chalcopyrite, pyrite is evident (Garlick, 1961), and McArthur River were copper occurs near the Emu Fault and the (Zn + Pb)/(Cu + Zn + Pb) ratio increases basinward (Williams, 1978) (Fig. 4).

There are many possible sources of base metals in these deposits. For example, in the Zambian Copperbelt and the Kupferschiefer it has been proposed that copper was released initially by weathering of basement rocks which in the case of the Copperbelt, contain porphyry copper-type mineralization (Wakefield, 1978). At White Pine, Coppermine River

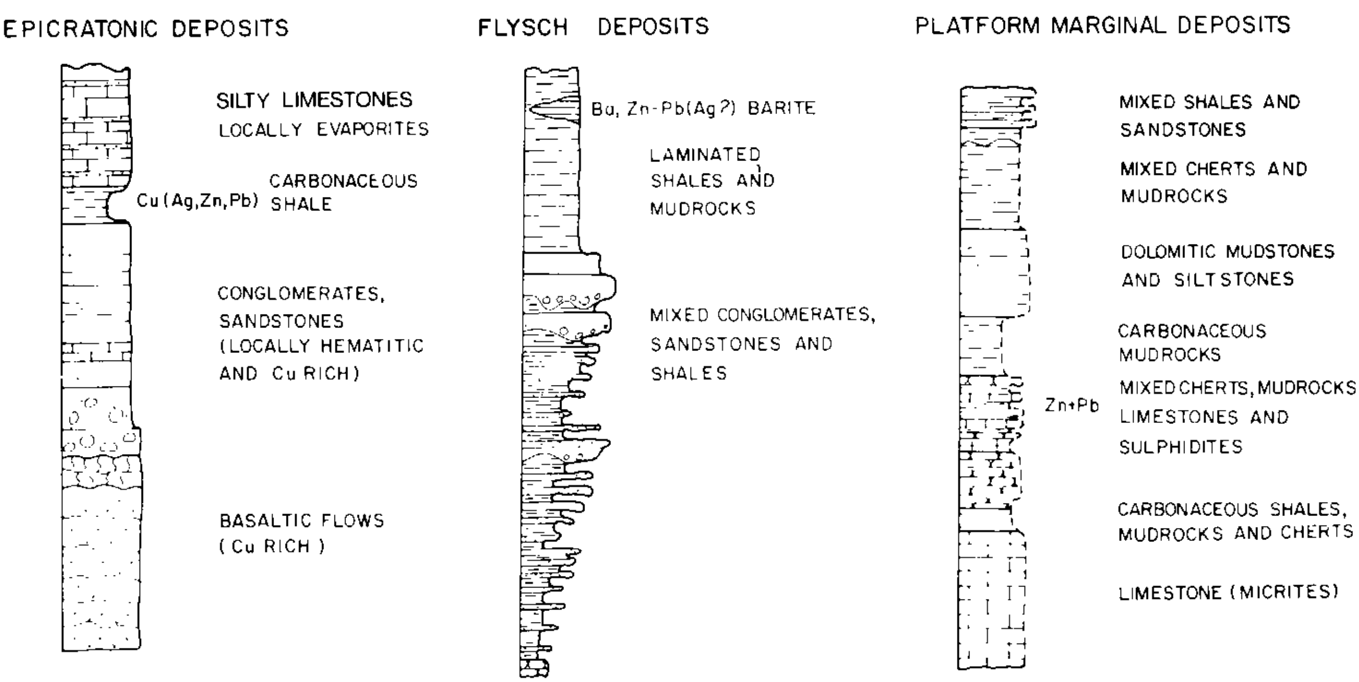


Figure 3 *Comparative generalized stratigraphic columns for the three sub-classes of sedimentary-type stratiform ore deposits. Columns are not to scale.*

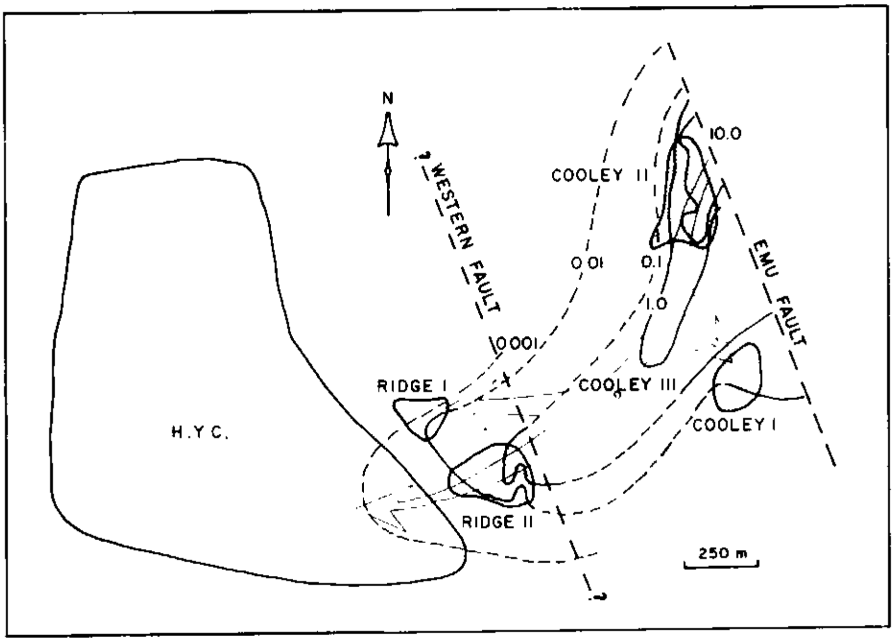


Figure 4 *Generalized plan of the sulphide deposits in the McArthur River area. Numbers refer to Cu/Zn+Pb ratios and suggest a zoning of elements related to the EMU fault. The arrows show the inferred direction of ore fluid migration. Shaded deposits are epigenetic; unshaded deposits are bedded. This suggests that fluids migrated within the carbonates to the east of the western fault and subsequently surfaced near that fault and flowed into the H.Y.C. sub-basin (modified from Williams, 1978).*

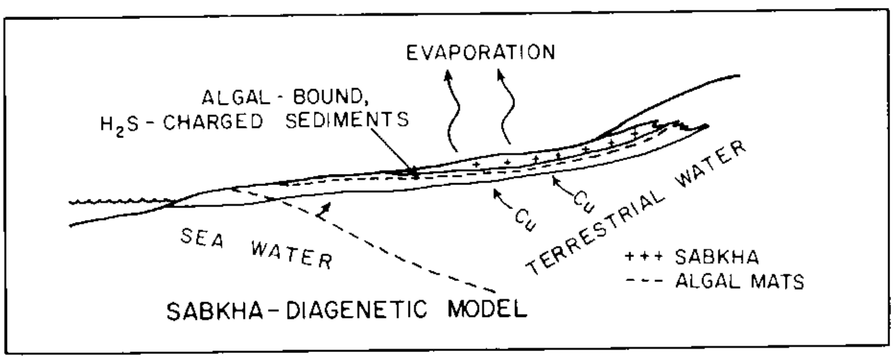


Figure 5 *Sabkha-diagenetic model for copper mineralization to explain the origin of the Zambian Copperbelt and other intracratonic (diagenetic) Cu deposits (Renfro, 1974).*

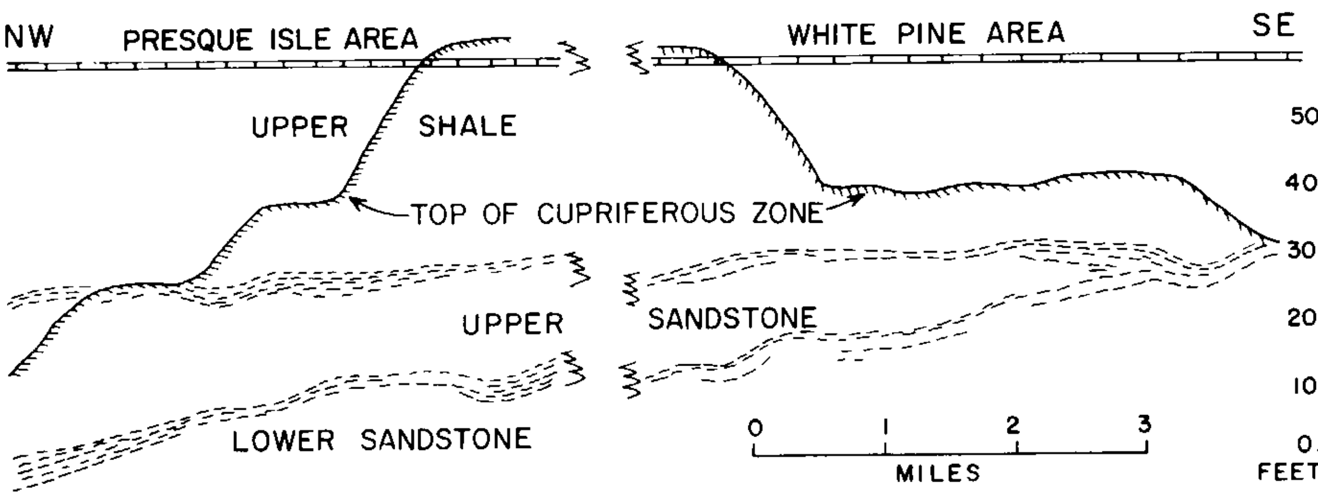
and Seal Lake, copper may have originated from underlying cupriferous basalts. For example, late Proterozoic mafic flows containing native copper in amygdaloidal and fragmental flow tops underlie the White Pine deposit (Brown, 1974).

The association of red beds and evaporites may be important in the transport of base metals. The formation of strong complexes between cuprous ion (Cu^+) and chloride ion is recorded in the chemical literature. If chloride solutions are responsible for dissolution and/or transport of copper, then deposits formed from these solutions should be associated with sources of chloride such as evaporites (Rose, 1976). In many cases the porous nature of the red beds may also provide the medium for brine migration.

The association of reductants with the intracratonic deposits indicates that sulphides were formed at the site of deposition and not transported in solution. Reduced sulphur in low temperature environments may be formed by bacterial sulphate reduction or, at higher temperature (> 80° C) by chemical reduction (Orr, 1977) possibly related to biogenic methane generation. Reduced sulphur may also be formed by the destruction of other sulphides such as pyrite (White and Wright, 1966).

Several genetic models have been proposed for intracratonic ore deposits. The sabkha model (Renfro, 1974) attributes the formation of evaporite-associated stratiform metalliferous deposits to diagenetic processes of costal sabkhas.

Figure 6 *Schematic cross-section showing the transgressive nature of the cupriferous zone at White Pine, Michigan (modified from Ensign et al., 1967).*



This model is applicable to stratigraphic sequences such as that shown in Figure 5. Coastal sabkhas form in a hot, arid climate with a large evaporation debit. Regression causes the evaporite-encrusted sabkhas to prograde basinward across the landward-thinning wedge of strongly reducing, organic rich intertidal-lagoonal sediment. The trailing edge of the sabkha is nourished by subsurface flow of metal-bearing, oxygenated, terrestial water. This dilute, metalliferous, solution must pass upward from its oxygenated source beds through the overlying, hydrogen sulphide-charged algal mats in order to reach the area of evaporative discharge. The hydrogen sulphide-laden algal mats act as a reduction membrane that causes the trace metals in the acending water to be precipitated as sulphide minerals (Fig. 5). In the White Pine district where copper-rich basalts underlie the deposits, migration of fluids up through the oxygenated red beds moved metals upward through the reductant shale (Fig. 6). Although both of the above models infer that the base metals are diagenetic, they differ in proposed depth of burial and temperature of formation.

Most workers who have studied the geology of the McArthur River deposit have concluded that it formed on the sea floor from metalliferous exhalations (e.g. Murray; 1975, Lambert, 1976; Croxford and Jepheott, 1972). This is based on the conformable nature of the ore, its sedimentary and early diagenetic structures and its association with tuffaceous sediments. An epigenetic origin has also been proposed for the deposits (Williams, 1978), but the relatively minor amounts of sulphides which must have formed after deposition (Lambert, 1976) support the sedimentary origin for the HYC deposit. A general model for McArthur River includes exhalation into the sub-basins from associated synsedimentary faults. Such exhalation may not necessarily be related to volcanism, but may simply be caused by abnormally high heat flow or late stage, deep compaction. In this context, the distinction between "formation waters" and "volcanic exhalation" maybe of great importance.

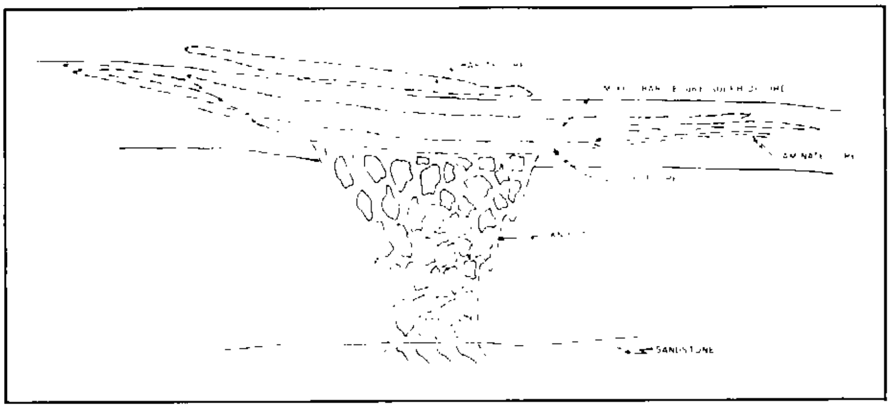


Figure 7 *Reconstructed cross-section of the Rammelsberg deposit showing the relationships between the underlying kniest, laminated sulphides and overlying barite (modified from Gunzert, 1969).*

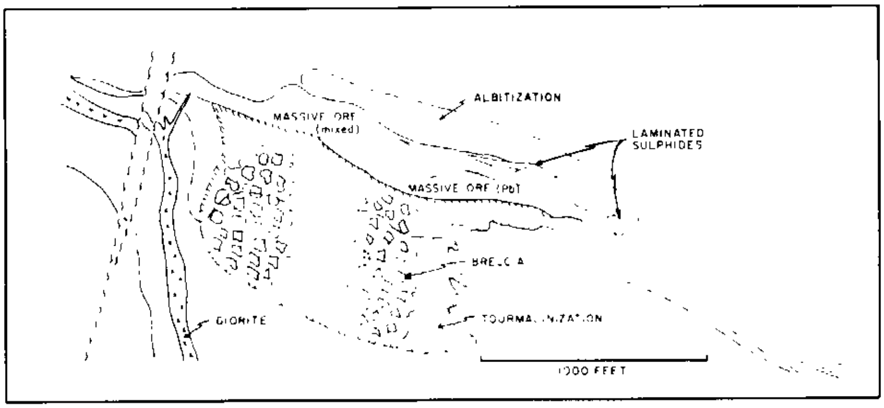


Figure 8 *Longitudinal section of the Sullivan deposit showing the marginal, laminated sulphides and the underlying tourmaline alteration and breccia (modified from Freeze, 1966).*

Flysch Basin Deposits

Flysch basin sulphide and related barite deposits occur in thick turbidite sequences. Typical rocks associated with these are deep water greywackes, siltstones, conglomerates and mudrocks (Walker, 1976).

Three general characteristics are common to the flysch basin deposits. 1) Barite is a major constituent with most Phanerozoic deposits and is present in some Proterozoic examples. Barite occurs with and above the sulphide ore at Rammelsberg (Gunzert, 1969), (Fig. 7). The Tom deposit is essentially a Pb-Zn-Ag-Ba deposit within intercalated carbonaceous mudrocks, sulphides and laminated barite. In contrast the Proterozoic example of this sub-class, the Sullivan, does contain minor barite, but not nearly in the proportions associated with the younger deposits. In the northern Cordillera, laminated barite deposits are abundant at approximately the same stratigraphic position as stratiform sulphide deposits, but separated laterally from them. The barite deposits consist of laminated lenticles of barite, some of which contain over 1,000,000 tonnes grading over 50% $BaSO_4$. The main differences between these barite deposits and the Pb-Zn-Ag rich deposits is simply the lack of sulphide in the former. 2) Many flysch basin deposits have a related alteration-feeder zone underlying or adjacent to them. The Rammelsberg deposit is underlain by kniest ore, a hard, partly brecciated, mineralized silicified rock (Gunzert, 1969) in which sulphides have filled veins and fractures (Fig. 7). The Sullivan ore body is underlain by breccia and extensive tourmalinization (Freeze, 1966) (Fig. 8). The Tom deposit is underlain by a siderite alteration zone (Carne, 1979) with minor veins of chalcopyrite and tetrahedrite (Fig. 9). 3) Many of the deposits are contained in sub-basins, related to synsedimentary grabens. The lenticular shape of the Rammelsberg and Sullivan deposits and the rapid thickening of the sulphide-barite horizon at the Tom and other similar barite deposits, suggest that the sub-basins may be fault bounded. However, reactivation of the faults may have obscured movement penecontemporaneous with sedimentation. The MacMillan Pass graben (Smith, 1978) contains at least two sulphide-barite deposits, the Tom and Jason (Fig. 10). Faults associated with the Sullivan deposit may also represent a much smaller graben.

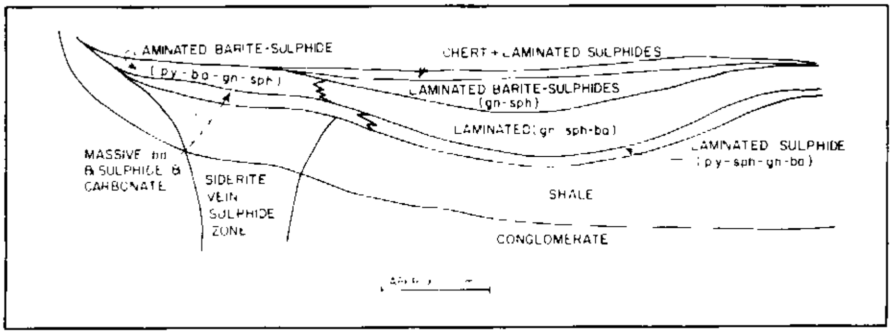


Figure 9 *Reconstructed cross-section of the Tom deposit. Note the sub-basin containing most of the laminated sulphides and the underlying feeder zone (modified after Carne, 1979).*

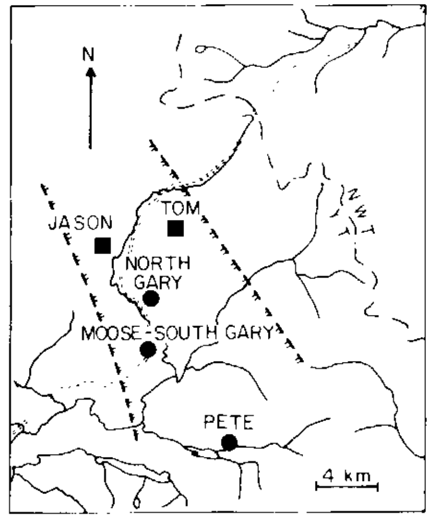


Figure 10 *Spatial relationships between Ba (circles), Ba-Zn-Pb-Ag (squares) deposits and the McMillan Pass Graben (modified from Smith, 1978).*

The possible sources of the base metals in these deposits are most likely the underlying sediments. For example, the Tom deposit and other regionally extensive barite deposits in the Earn Group of Devonian-Mississippian age, are associated with carbonaceous mudrocks having high barium, zinc and lead background values. Thus it is reasonable to consider that underlying sediments provided the metals for the deposits. Turbidite lithologies can potentially provide large amounts of connate fluids during compaction. The sediments are rapidly deposited and as a consequence, interstitial fluids are trapped within the sedimentary sequence. As the weight of the overlying sediments increases, internal overpressures may be generated. Sediments which show such overpressures are also undercompacted because the weight of the overlying sediments is in part supported by the interstitial fluid rather than by the contained grains (Chapman, 1972). Faults, common in flysch environments, cutting the overpressured sediments, bring about release of the pressure and removal of the fluids. The resulting collapse of the sediments would produce grabens and provide a brine source. Igneous activity such as the intrusion of sills or the extrusion of tuffs can produce similar features or compliment them, causing high heat flow and higher temperature ore fluids. Excessively rapid loading by deposition of conglomerates associated with submarine fan progradation could also initiate rapid fluid migration. Although highly simplifed, this model fits the general geology of these deposits.

The deposition of sulphide and barite in the flysch deposits reflects the proximity to the vents within the sub-basins. Sulphur isotope studies (Anger *et al.*, 1966) suggest that the cause of fractionation between metal sulphides and barite in a hydrothermal precipitate is largely a process of oxidation of the hydrothermal solutions (Lydon *et al.*, 1979). The ore solutions undergo progressive oxidation from the sulphide to the barite zones. At Rammelsberg the majority of the barite samples have a sulphur isotope composition similar to that of contemporaneous seawater. It is this mixing of oxygenated seawater with the ore solutions that is the major cause of the oxidation process. Thus there are two sources of sulphate: contemporaneous seawater and the oxidation of hydrothermal reduced sulphur species. High rates of discharge within the sub-basin provide optimum conditions for displacement of marine water from the vent area and tend to insulate the immediate vent area. At lower rates of discharge, or the opening of the sub-basin, seawater sulphate would be more important resulting in more sulphate deposition. If this is true then the regionally associated barite deposits differ from sulphide-rich barite deposits because of a lack of sulphide-rich or metal-rich discharge, low discharge rate, lack of a closed basin, or combinations of the above parameters.

An alternative theory that also fits the data is that of a low sulphur brine entering an isolated sub-basin. This model envisions the alternate isolation and opening of the sub-basin. In this case reducing brine would reduce seawater sulphate to form sulphide when the basin is isolated, but if the brine influx is diminished or the basin is open to seawater sulphate, barite becomes stable. If this model is accepted then the regionally extensive barite deposits differ from the sulphide-rich barite deposits because of low discharge rate or lack of sub-basin isolation.

Platform-Marginal Deposits

Platform-marginal sedimentary-type stratiform sulphide deposits occur in basins seaward of major platforms or shelves associated with cratons. These basins differ from the intracratonic basins in that a large portion of the basin is deep water. In contrast, local deeps within a generally shallow water environment are associated with intracratonic basins (e.g. the McArthur River area). Deposition rates within these deep water, starved basins are low compared to the flysch environment. Although the only deposits grouped into this sub-class are the XY, ANNIV and OP (i.e. Howards Pass) deposits of the Selwyn Basin, sufficient work has been completed to demonstrate that these deposits define a third sub-class (Morganti, 1979). Five characteristics are exhibited by all of the deposits. 1) The sulphide mineralogy is simple: predominantly sphalerite and galena. The XY, ANNIV and OP deposits, for example, show galena, sphalerite and pyrite to be the only sulphides, except for a few grains of chalcopyrite noted in the XY deposit. 2) The pyrite content is low compared to other stratiform sulphide deposits. For example, the XY deposit contains less than 5% pyrite, even where sphalerite and galena constitute 70% of the rock. Furthermore, the pyrite content within the Howards Pass Formation is almost constant throughout, and the main difference between the pyrite of the deposit and that of the rest of the stratigraphic section is textural, in that framboidal pyrite occurs in the deposit and nodular pyrite in the rest of the section. 3) The Ba content is low compared to other Paleozoic stratiform sulphide deposits, typically less than 2000 ppm; furthermore there are no barite deposits directly associated with the sulphide bodies. 4) There are no copper zones associated with these deposits such as those found at Mt. Isa or Meggen. Of the few hundred copper analyses completed on material from the Howards Pass deposits the highest copper value obtained was 150 ppm. 5) The deposits are associated with anomalously thick sedimentary sequences (i.e. sub-basins, Fig. 11), but lack evidence for rapidly formed graben structures similar to the flysch deposits.

Within the Selwyn Basin, platform-marginal deposits occur in graptolitic carbonaceous mudrocks, cherts and limestone of the Howards Pass Formation (Morganti, 1977). This unit contains slope, base of slope and basin floor facies which developed west of the MacKenzie Platform (Fig. 12). Within the base of slope (rise ?) facies, sub-basins occur as seafloor depressions (Fig. 13) in which cherts, mudrocks, limestones and sulphides were deposited. The laminated, sulphide rich beds occur in a rhythmic sequence limited to these sub-basins within the active member of the Howards Pass Formation. A general trend upsection of limestone-mudrock-chert (Fig. 14) also occurs as individual cycles within the major cycle. A sequence such as this could be the result of the increasing isolation of a sub-basin, accompanied by formation of limestone as a by-product of sulphate to sulphide reduction. A decrease in pH and resultant change in the relative stability of carbonate to amorphous silica, could have been brought about by the influx of low pH metalliferous brine into the high pH reducing sub-basins. The lack of associated feeder zones underlying the deposits of this sub-class, their low copper and silver contents, and the large lateral dimensions of the deposits all suggest that the source of the brine was not nearby, such as is evident in flysch deposits. In the case of the eastern Selwyn Basin, tuffs associated with basin-platform transition suggest that anomalous heat flow and possible brine exhalation may have occurred and provided a brine which subsequently migrated down slope.

Ore-Forming Fluids for Sedimentary-Type Stratiform Deposits

The fluids which transport the metals to their site of deposition constitute the second parameter to be considered here. These brines deposited their metals within the lithifying sediment or at the sediment-water interface.

Within the sediment, migration of ore-forming brine may be somewhat analogous to oil migration. Thus primary migration includes the release of metals from source beds and their transport within and through the capillaries. Metal

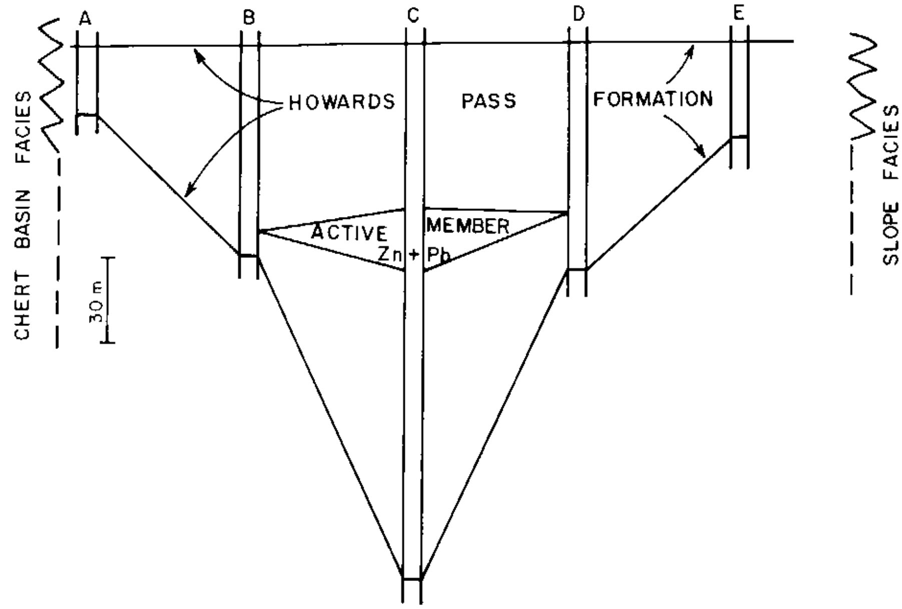


Figure 11 *Composite stratigraphic sections of the Howards Pass formation across the base of slope facies (see Figure 12). These sections show a general thickening of the formation and the presence of the Zn-Pb containing active member in the sub-basins. Distance between sections A and E is approximately 8 km.*

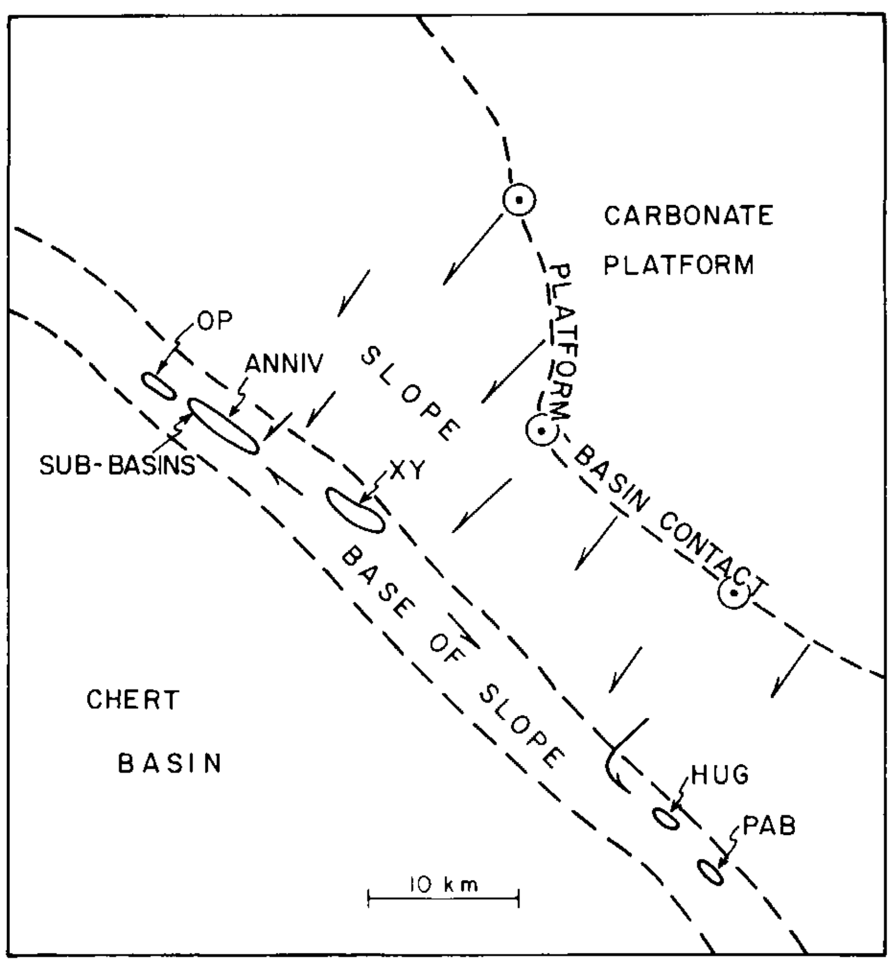


Figure 12 *General model for the formation of the platform-marginal deposits showing the geometry of the platform-slope-base of slope and chert basin facies. Arrows show surface movement of ore fluids which migrate up to the sediment-water interface, down the basin slope and are trapped in the sub-basins at the base of slope.*

complexes expelled from a source bed pass through the pores of more permeable rock units (Tissot and Welte, 1978). Migration of brines above the sediment-water interface is here also considered as secondary migration of brine. Secondary migration in the subsurface occurs through primary or secondary porosity. Examples of deposits which show associated subsurface deposition in secondary porosity are the Cu deposits in the Mt. Isa and McArthur River areas (Flinlow-Bates and Stumpfl, 1979; Williams, 1976) and the feeder zones underlying the flysch deposits such as the Tom and the Sullivan. Subsurface brines responsible for White Pine and Mufulira appear to have migrated through primary porosity (Brown, 1971; Annels, 1979).

Little is known about the nature of these brines, but recent studies on fluid inclusions (Roedder, 1976; 1979) and stability relationships from Mississippi Valley type deposits (Anderson, 1973, 1978), and recent subsurface brines (Carpenter *et al.*, 1974) suggest that the brines were dense (> 1.1 g/cm^3), moved slowly (few m/yr), were of a low temperature (100-160° C), high salinity (> 15wt.% NaCl equivalent), and had a low sulphur content.

Upon exhalation onto the sea-floor a brine may behave variably depending on its physical properties. Such low temperature brines occurring in seawater may be classified on the basis of physical behaviour (Sato, 1972). Subsequent model experiments (Turner and Gustafson, 1978) have supported this classification. The density of brines with various concentrations of NaCl at varying temperatures can be compared to seawater density (Fig. 15), resulting in three major brine types, two of which are considered here.

Type I brines are low temperature, relatively high salinity brines which, upon exhalation flow down slope due to a higher density than the surrounding seawater. Mixing with seawater during down-flowing will take place only to a very limited extent because the fresh ascending solution forms a stable bottom layer. Because of the high brine density the resultant deposits are strongly controlled by sea floor topography. Alteration feeder zones are poorly developed because of the low temperature of the brine, and they may be spatially removed from the stratiform mineralization because of the high density of the brine. Homogenization due to internal mixing may occur during transport, but density stratification is characteristic of Type I brines after sub-basin containment. As a result there is very little lateral metal zoning in the resultant deposits. Examples

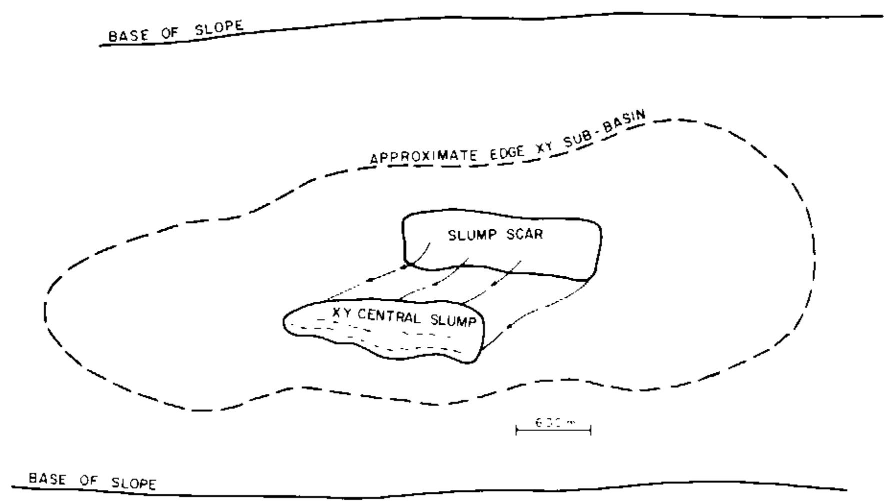


Figure 13 *Generalized plan view of reconstructed XY sub-basin, Howards Pass. The sub-basin axis of elongation parallels that of the base of slope. Slumping has produced a high grade "plumb" within the larger XY deposit. (Arrows indicate direction of movement of slumped sediment).*

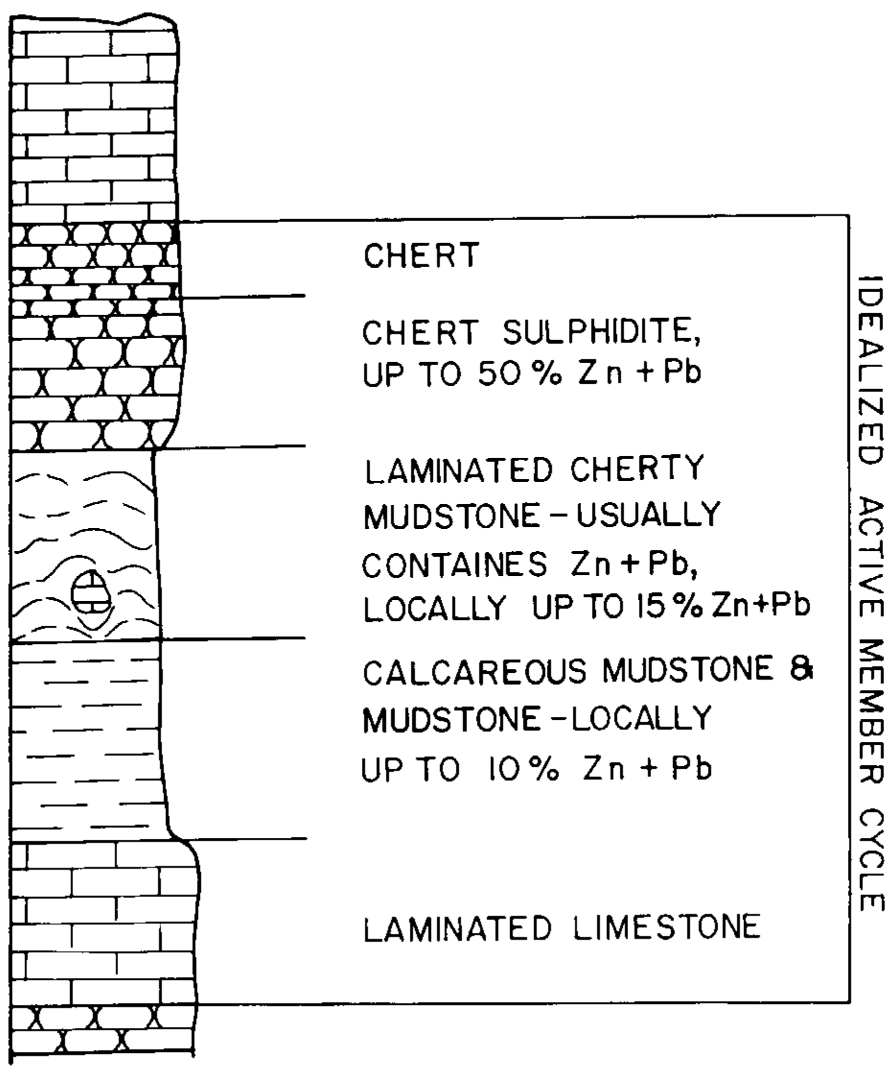


Figure 14 *Generalized stratigraphic section of an idealized active member showing a typical sequence of facies. Note that there is a decrease in carbonate and an increase in chert upward*

which display many of the characteristics of a deposit formed by a Type I brine are the Howards Pass deposits and McArthur River. The control of submarine topography, a lack of distinct mineral zoning and a large distance between proposed feeder zones and stratiform sulphides are characteristic of these deposits.

Type II brines are moderate to high temperature solutions of moderate salinity. Their relatively high temperatures produce increased leaching capacity in the aquifer, and an obvious, associated feeder zone. Type II brines are subdivided into two sub-types based on a reversal of density trend during their evolution. Brines of Type IIa are heavier than seawater. Only minor mixing with seawater takes place and therefore the geometry of the deposit is strongly influenced by seafloor topography. Alteration pipes or stockwork stringer mineralization should underlie the deposit because of the association with graben structures. Both the Sullivan and Tom deposits exhibit many of the characteristics expected in a deposit formed from such a brine. Related feeder zones are characteristic of these two examples.

Type IIb brines are slightly higher temperature and less saline than Type

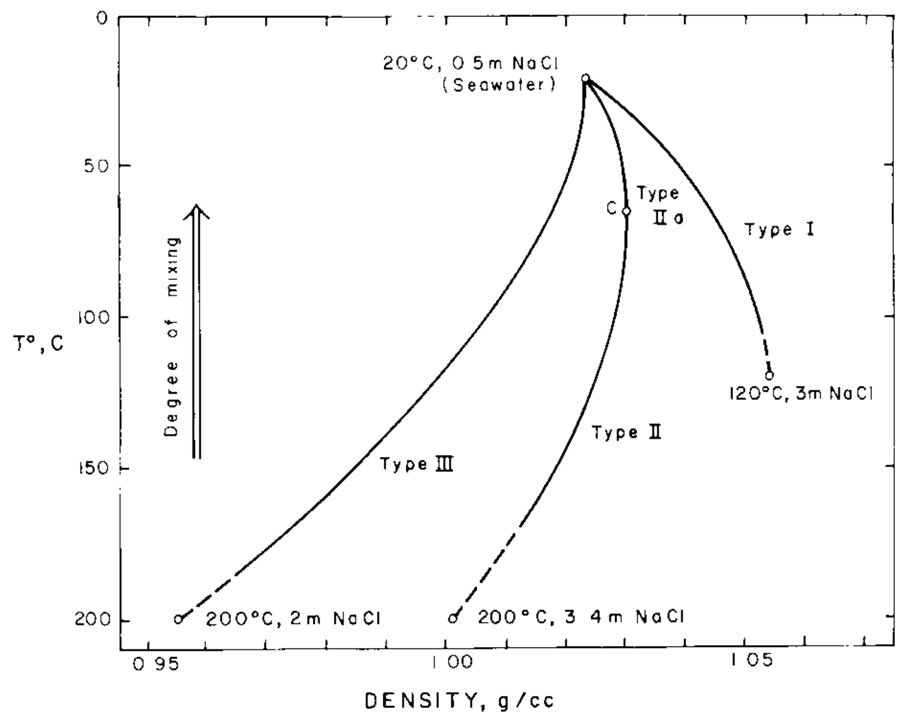


Figure 15 *The evolution of brines (NaCl solutions) as they mix with seawater, showing temperature and density. Note Type II changes at point C forming brine Type IIa, (after Sato, 1972).*

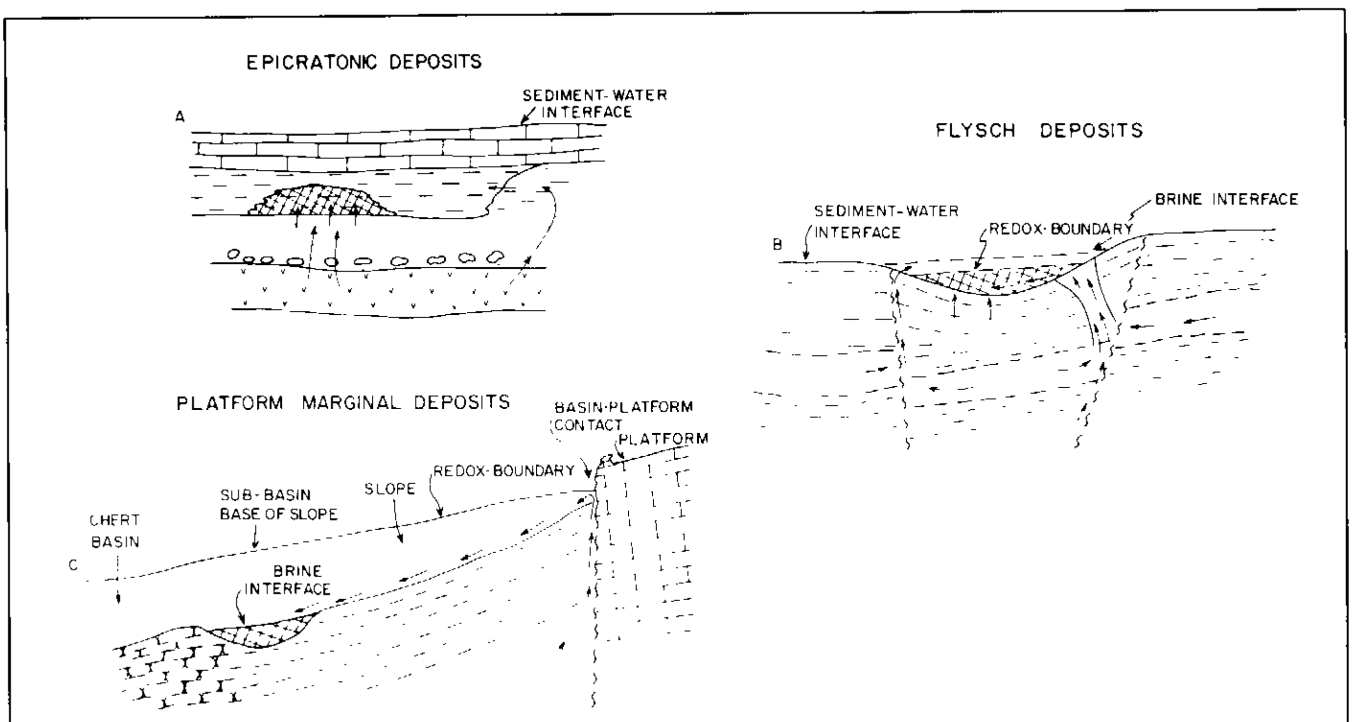


Figure 16 *Generalized models of formation for sedimentary-type stratiform sulphide deposits. Unlabeled arrows show direction of brine migration. Deposits formed in such a manner are synsedimentary and the models show what may be best termed the sedimentary-exhalative model of ore formation (Morganti, 1977).*

IIa. Upon exhalation into seawater these brines are less dense than seawater, but convective mixing above the vent (Turner and Gustafson, 1978) causes cooling, which in turn causes the brines to become more dense than seawater. Yet because of the initially less dense nature of the brine, seafloor topography does not exhibit as important a control on the distribution of stratiform mineralization as brine Types I and IIa. Because of the high temperature, copper may be deposited near the vent. Mixing of brine and seawater away from the vent would produce an intimate association of layered sulphide and barite, and furthermore, a strong zonation within the deposits. The Rammelsberg deposit is strongly zoned and underlain by a well developed feeder zone suggesting it is a deposit formed by a Type IIb brine.

Metallogenic Epochs and Provinces

Metallogenic provinces and epochs are of prime importance to economic geologists for conceptual regional exploration. Major metallogenic epochs for Intracratonic ore deposits are the Proterozoic and the Permian periods. The age of these deposits coincides with extensive deposition of red beds, which are in turn a function of tectonic and paleogeographic setting. Metallogenic provinces such as the Kupferschiefer and the Zambian Copperbelt occur in major intracratonic basins containing many deposits. In the case of flysch basin deposits the major metallogenic epoch is the Devonian-Mississippian with two major provinces evident. These are the Antler equivalents in the Cordillera (Boucot *et al.*, 1974) and the Variscan geosyncline in Europe (Krebs, 1976). Flysch sequences show a close association with major tectonic events. For example the Proterozoic Sullivan deposit shows an association with rifting (Stewart, 1972). The metallogenic epoch for the platform-marginal deposits is the Ordovician-Silurian and corresponds to a period of world wide black shale deposition (Berry and Wilde, 1978). Metallogenic provinces appear related to major starved basins, such as the Selwyn Basin, where sub-basins occurred down slope of exhalative sites.

Conclusions

Sedimentary-type stratiform ore deposits are those stratiform deposits occurring in clastic sequences with no strong volcanic association. Three different tectono-sedimentary environments have been considered: intracratonic, flysch and platform-marginal. Brines generated within these environments may precipitate sulphides during diagenesis or be exhaled onto the sea floor and precipitate sulphides and sulphates in sub-basins. Overprinting is common because of the evolutionary nature of the deposits before lithification of the surrounding sediments. Furthermore, subsequent post-lithification metamorphism and structural events make elucidation of the original textures of many deposits more difficult. More detailed stable isotope, fluid inclusion and organic geochemical studies are required if we are to have the required data for detailed unified models.

Acknowledgements

D.F. Sangster, V. Hollister and D.N. Hillhouse reviewed an early draft and made comments, some of which have been incorporated in the final draft.

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