

## **Seminar on Sea-Floor Hydrothermal Systems**

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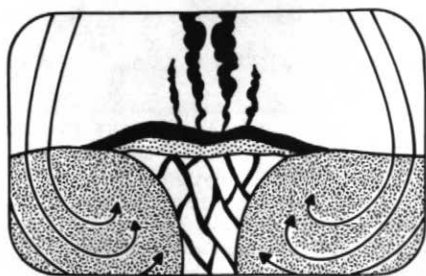
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## Seminar on Sea-Floor Hydrothermal Systems

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**Editor's Note:** *This article properly belongs with the Conference Reports. Because I am persuaded that this is a topic of great interest to economic geologists, and very topical, I have agreed to publish it in a format that allows comments from some participants to be included as a second part of the report.*

### Introduction

On the evening of January 12th, 1981, at Queen's Park in Toronto, the Ontario Geological Survey and the Toronto Geological Discussion Group held a jointly sponsored seminar entitled: "How can modern sea-floor hydrothermal systems help us understand ancient ore deposits?". It was organized by the Discussion Group, principally by Roly Ridler (Newmont Exploration of Canada), Sandy Colvine (OGS), and Ray Goldie (Greenshields), and the space was provided courtesy of the OGS. The seminar was attended by over 100 geologists from industry, the OGS, and various universities.

The seminar began with presentations by Professor John Edmond, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, and by Professor John Corliss, Department of Oceanography, Oregon State University. Both of these speakers have been personally involved in the discovery and examination of modern hydrothermal systems in the Pacific Ocean.

Following a movie and videotape presentation on the active sea-floor systems, a panel discussion was held with short

presentations by Tony Andrews (OGS), Julian Boldy (Gulf Minerals Canada), Jim Crocket (McMaster University), Dick Hutchinson and Rob Kerrich (University of Western Ontario), John Lydon (Geological Survey of Canada), Roly Ridler (Newmont Exploration of Canada), and Steve Scott (University of Toronto). The panel was chaired by Ed Spooner (University of Toronto).

Substantial discussion followed, from the floor and between the speakers and panelists, on the importance of the modern discoveries on the sea-floor and their relevance to volcanogenic base-metal, massive-sulphide deposits, particularly those in the Canadian Shield.

Because of the considerable interest in these discoveries, the organizers made a tape-recording of the session, from which the following report was prepared. It was subsequently suggested by Dick Hutchinson that the speakers and panelists be allowed the opportunity to express in writing their presentations with minor clarifications and amplification. These written discussions are given towards the end of this conference report, from those who responded to the invitation to submit them.

As can be seen from the report and the appended written discussions, these discoveries are the subject of considerable disagreement, both as to some aspects of the modern systems, and particularly their relevance to possible ancient analogues. This disagreement, however, continues to generate new ideas, foster important new lines of research, and, we hope, may eventually lead to the discovery of new ore deposits.

### Modern Sea-Floor Hydrothermal Systems

The origin of massive-sulphide, base-metal deposits in volcanic rocks has been the subject of considerable debate for as long as the subject of economic geology has existed. However, for almost two decades many geologists have accepted the idea that these deposits were formed on the sea-floor from hydrothermal solutions which had passed through the underlying volcanic rocks in fluid-convective systems. The origin of these deposits became summarized by the use of the term "volcanogenic". Later, Ridler suggested the term "exhalite" to describe the deposits and the associated chemical sediments produced by this process.

In the presentation, Edmond pointed out that, whereas previous oceanographic exploration had found considerable evidence of exhalative systems, particularly in widespread iron and manganese encrustations, it is only in the last few years that direct visual evidence has been obtained of actual hydrothermal discharge vents along various spreading centres of the Pacific Ocean. He went on to describe how these modern vents have now been directly observed discharging hydrothermal solutions on to the sea-floor to form columns of base-metal sulphides (Figure 1). These are therefore probably the first mineral deposits that have actually been observed in direct formation by a relatively unambiguous process. However, it is most interesting that they were discovered not as a result of a direct search for mineral deposits, but in the scientific investigation of a number of features of ocean floor geology. These investigations were prompted



Figure 1 A "black smoker", 21° N. Photo by J. Edmond.

by oceanographic evidence for the existence of hydrothermal fluid-convective systems, in particular:

1) Calculations which suggested that only half of the total heat emplaced during the formation of new crust at mid-ocean ridges is lost by conduction. Seawater convection through this crust is an appealing mechanism for removal of the remainder of this heat.

2) A plume shaped  $^3\text{He}$  anomaly exists over the East Pacific Rise. Hydrothermal transport is probably the only efficient way of stripping this helium from crustal rocks.

3) Samples previously dredged from the sea-floor, in cores from the various deep sea drilling projects, and from ophiolite complexes thought to represent preserved slices of ancient oceanic crust had all shown mineralogical alteration suggestive of contact with hydrothermal solutions.

4) The occurrence of metalliferous sedimentary layers, along the ridge axes and in cores from the sedimentary cover of the abyssal plains, interpreted from seismic profiles, and found in the exploration for deep sea manganese nodules, implied production from an original hydrothermal source.

5) Some form of fluid interchange with the oceanic crust would provide an explanation of the source of certain elements which are present in the oceans in amounts in excess of what would be expected from continental run-off.

The exploration described by Edmond, including very impressive "home movies", was undertaken from the deep-sea submersible "Alvin", belonging to the Woods Hole Oceanographic Institution. The latest precision navigation techniques, using satellites and transponders combined with high resolution topographic control from acoustic reflection systems, were used to explore the various sites of specific interest.

Three areas of the Pacific Ocean have been the subject of the most intense exploration to date: on both the Galapagos and East Pacific Rises, hydrothermal discharges and exhalative precipitates have been discovered on sea-floor basalts in association with a most prolific and spectacular group of life-forms. A related, but significantly different system, has been found in the Guayamas Basin of the Gulf of California where hydrothermal discharges are precipitating various minerals at the distal end of the Colorado River fan.

The site on the Galapagos Rise was the first to be found, and though considerable numbers of warm vents were located, none were actually found to be actually depositing sulphides. However, they were

sufficiently active to support a thriving array of biota.

It was the subsequent discovery of the now famous site at  $21^\circ\text{N}$  on the East Pacific Rise that has for the first time permitted economic geologists to observe actual massive-sulphides and related exhalites in the process of deposition. Here the sea-floor is 2.5 km deep along the axis of the Rise, in a steep walled, fault-bounded trench with great variability in the volcanic surface: lava lakes, collapse pits, lava tubes, pahoehoe and pillowed basalts. The original discovery at this site by the French-American-Mexican CYAMEX expedition (Francheteau *et al.*, 1979) was of dead vents: columns of porous and massive sulphide, present on the walls of the axial ridge trench associated with the fault zones. During the subsequent dives of the "Alvin", active vents were observed for the first time, discharging hydrothermal fluid and depositing sulphides.

These active hydrothermal discharge vents were found over a 7.5 km section of the axial trench, with a regular spacing of  $215 \pm 20$  metres. They tend to be around the edges of lava lakes, which are over 100 metres wide and about 20 metres deep. Seismometry has indicated that there is a magma chamber 1.5 km below the present ridge axis, and that the limit of brittle fracturing, and hence presumably seawater convection, is about 1000 metres below the surface.

Near the base of the zone of brittle fracture, seawater expands as it is heated to between  $600$  and  $800^\circ\text{C}$ . Expansion of this hydrothermal solution is responsible for the propagation of fractures into the overlying rock, and for its replacement at depth by colder, denser seawater by recharge through the basalt column. Hence a fluid-convection recharge-discharge system is established between seawater and the hot sea-floor basalts along the active ridge axis.

The hydrothermal fluid rising towards the sea-floor partially mixes with some fresh seawater so that at discharge it has a temperature of  $350^\circ\text{C}$ , a density of 0.6, a pH of 4.5, an enrichment in  $\text{H}_2\text{S}$  in excess of total dissolved metals, and enrichment relative to seawater in Mn, Si, Ba, Li, Rb, Ca, and K, but depletion in Mg and sulphate. It is also enriched in Fe, Cu and Zn, and possibly in Au and Ag, though there is as yet little analytical data available on the precious metals. At  $21^\circ\text{N}$  these fluids reach directly to the sea-floor where they mix turbulently with far larger volumes of ambient cold, alkaline seawater drawn in towards the vents. The clear hydrothermal fluid chills rapidly by mixing with seawater, precipitates metal sulphides and turns black. The vents

have therefore been referred to as "black smokers". Part of the precipitation takes place immediately at the discharge site and a column of porous iron-copper and zinc-sulphide sinter along with anhydrite, sepiolite, and minor silica is formed as a chimney to the hydrothermal fluid. Because the columns are porous, seawater is drawn in through their walls to mix within the columns, and hence, by cooling, precipitate some minerals within. This presents a very steep temperature gradient which is reflected in the mineralogy of the chimney: the inside is rich in chalcopyrite; the outside is rich in wurtzite. The final result has the form of a porous tree-stump or closely spaced clusters of tree-stumps. The largest group discovered to date is on the eastern end of the Galapagos Rise where a "forest" sits upon a mound 600 m long and 80 m high.

The energy output of individual vents at  $21^\circ\text{N}$  is of the order of one megawatt. Precipitation of the metal sulphides is rapid, but inefficient. Most of the dissolved species are lost to seawater without precipitation, including virtually all of the soluble alkali metal ions. Some of the precipitate, carried upwards by the jetting stream of fluid, subsequently falls back as a rain of sulphide grains which is rapidly oxidized to form metalliferous ochres and umbers.

At the  $21^\circ\text{N}$  site the fluids reach the sea-floor directly. Those rising along the Galapagos Rise, however, appear to have mixed with fresh seawater at some depth within the basaltic column. This mixing may be taking place within a permeable breccia which also may be a site of sulphide precipitation. The discharging fluids on reaching the sea-floor are only a 5% convective solution and have a discharge temperature of only  $21^\circ\text{C}$ .

In many respects, such as shape, mineralogical facies and geological setting modern sulphide chimneys are very different from most ancient massive-sulphide deposits. It was suggested that ancient deposits were formed from similar chimneys by subsequent alteration and diagenetic processes. Chimneys may have accumulated into large mounds, perhaps within sea-floor depressions such as lava lakes. During the continuing passage of active hydrothermal fluids through the accumulated chimneys, the more soluble species, such as zinc, were redissolved from the sulphide accumulation and reprecipitated at the top along with silica, clays and iron and manganese oxides. Burial and compression of this reworked accumulation would then produce a massive deposit with a basal copper and an upper zinc zone, typical of many massive-sulphide deposits. Sul-

phide breccias seen in such deposits may reflect fragments derived from the original chimneys, and the stringer copper (with minor zinc) sulphide zones, typical of the footwalls of massive-sulphides, would have been deposited in fractures in the original discharge vent and between basalt pillows.

In addition to the Galapagos and 21°N sites, Edmond summarized the yet more recent discovery of a stratiform sulphide-barite body in the Colorado River fan of the Guayamas basin. The suggestion was made that this deposit is due to hydrothermal fluid generation in the East Pacific Rise beneath the sediments, and from the intrusion of rising basalt into the wet sediments. Analogies were drawn between this modern sea-floor situation and that responsible for the Besshi or Kieslager type of ores, which have similar geological settings and mineralogical compositions. The sediments in the Guayamas basin include substantial amounts of matured organic debris to the extent that the expelling, heated pore fluid has attained the grade of diesel fuel!

At both the Galapagos and 21°N sites the hydrothermal systems support a fascinating biota of bacteria, algae, "Pompeii worms" (polychaetes), giant tube worms (pogonophera), small fish, giant clams, and both Galatheid and Brachyuran crabs. The life-support system may be entirely chemogenic in its origins, in distinct contrast to most modern systems which are photogenic. H<sub>2</sub>S metabolizing bacteria are the main food source for the fish, clams, polychaetes and crabs. The "tube worms", although gutless, have a symbiotic relationship with the H<sub>2</sub>S metabolizing bacteria which reside in their body cavities. If, as suggested, these systems are chemogenic then they are entirely powered by the heat from the interior of the Earth, rather than from the Sun.

Following up on this idea, Corliss devoted most of his presentation to the organic chemical processes which may be taking place within the hydrothermal vents. His basic theme was that life originated in similar Precambrian hydrothermal oceanic systems, and was not, as commonly supposed, the result of lightning discharges or extra-planetary sources. The series of reactions necessary for the generation of complex organic molecules that are the basis of life are probably difficult to perform by lightning or other sudden energy pulses within a primordial homogeneous oceanic "organic soup". Instead, a steady stream of molecules is required, in a high energy environment which provides rapid changes from one set of chemical and physical conditions to another within an essen-

tially steady-state system. The suggestion was made that such an environment existed, and still exists within hydrothermal discharge vents.

At deeper levels of the vent, at the interface between the fluid and the host rock, H<sub>2</sub>S, CH<sub>4</sub>, NH<sub>3</sub>, H<sub>2</sub>, CO, and HCN were formed. As these rose within the fluid path they merged to produce simple amino acids. At higher levels, as the system cooled from 600° towards 350° C, the amino acids condensed via the formation of peptide bonds to form nucleotides. Various clay minerals, saponite, etc., acted as necessary catalysts and as sites for the joining of the simple molecules into more complex ones. The condensation process was also substantially facilitated by hydrogen cyanide, a very important component in life-forming processes. Further condensation near or at the surface led to the precipitation of protocells.

#### Comparison of Modern and Ancient Systems

The panel discussion started with a presentation by Andrews of a comparison of modern sea-floor geology as revealed by the various deep-sea drilling programs and as seen in ophiolite complexes. Modern oceanic crust is composed of a sedimentary layer overlying a sequence of largely monotonous pillow basalt, minor massive basalt flows and a few intrusions. Because of rapid cooling and continual tectonic activity, the basalt layer is highly fractured. The resulting pervasive, fine scale faulting makes stratigraphic correlation almost impossible, even between closely-spaced drill holes. Furthermore, the considerable permeability of the basalts is strongly anisotropic, both vertically and laterally. Shortly after emplacement, the top kilometre or more of crust undergoes extensive alteration at surprisingly low temperatures. Typical products are palagonite, celadonite, saponite, carbonates, goethite, hematite, phillipsite and pyrite. High temperature alteration occurs only in localized regions of intense hydrothermal activity and is focussed along zones of high permeability such as deep faults and fracture systems. This focussed, convective hydrothermal circulation is strongly controlled by structure and has a periodicity of about 6 km. Most of the lateral movement of water takes place at depths of 3 to 5 km.

In contrast, ophiolites show a progressive trend to more intense hydrothermal alteration with age. Andrews correlated this with a reduction in the intensity of fluid-convective systems, consistent with a slowing down of oceanic spreading rates as the Earth gradually cools down.

Hence, the modern sulphide systems observed in the Pacific are far smaller, and are associated with alteration less pervasive and intense than that seen in the older geological record of ophiolites and Precambrian greenstone belts. On this basis he predicted that no large deposits comparable to ancient ones will be found on modern ridges.

In almost total disagreement with Andrews, Edmond suggested that the observed differences are due to local circumstances rather than any temporal or crustal evolutionary process. The activity and spacing of hydrothermal systems is a function of spreading rates, which are highly variable across the Earth even at present. Faster spreading ridges, such as the East Pacific, derive their heat from the mantle at a higher rate and hence will support more activity, for example, in comparison with the slower spreading Atlantic ridge.

Scott emphasized the similarities in the tectonic setting of these modern vents and that of known volcanogenic massive-sulphide deposits. Both are related to major zones of regional extension characterized by linear grabens. As on the East Pacific Rise, the volcanic and hydrothermal centres associated with volcanogenic deposits are within the divergent sections of volcanic belts, rather than in the intervening transform fault zones. A particularly striking example of this was demonstrated from the Green Tuff belt of Japan which hosts the type volcanogenic Kuroko deposits of the Hokuroko district. Similar tensional-extensional features were demonstrated for various older volcanogenic districts in the Canadian Shield and Appalachians.

Due to the current high level of interest in the origin of gold deposits in the greenstone belts, Kerrich addressed his presentation to an evaluation of the possibility that certain of these gold deposits are analogues of modern sea-floor hydrothermal or exhalative systems, but different, in many fundamental ways, from the black smokers. In particular, he discussed the isotopic and geochemical evidence that the cherts closely associated with many gold deposits were deposited from an Archean ocean with a mean temperature of about 70° C. He pointed out the importance of the sepiolite and talc being precipitated in the modern vents, and the similar association of talc with many volcanogenic, massive-sulphide deposits. The sepiolite removes Mg from the oceans and hence frees CO<sub>2</sub>, otherwise tied up in dolomite, into the atmosphere. As a result of this reaction, a higher rate of sea-floor hydrothermal activity in the Archean would imply a higher flux of CO<sub>2</sub> into the atmosphere,

resulting in a greenhouse effect. Various people commented on the problems inherent in Kerrich's suggestion of a warmer ocean and an atmospheric greenhouse effect. It was suggested that under such conditions the weathering regime would have been extremely different from that of the present, but that evidence for such a regime is entirely lacking in the observable Archean clastic sediments.

In subsequent heated discussions Kerrich suggested that seismic pumping may be an alternative to thermal convective systems for forcing pore-fluids through permeable rocks, especially at the margins of calderas.

In discussing Archean volcanogenic massive-sulphide deposits, Boldy presented a most appropriate figure of a "whale of a tale" (Boldy, in press), summarizing the various features of their setting. This figure generated some very lively discussion on one of the more striking differences between known deposits and the modern sea-floor black smokers: namely, that the former are associated with rhyolite accumulations, whereas the modern situation is, as far as we know, exclusively basaltic. The modern systems appear closest in setting to the cuprous pyrite deposits of ophiolite complexes as in Cyprus, but even then, there are major differences. For example, these deposits are very low in zinc compared to their modern analogues. Scott suggested that the process which gives rise to the volcanogenic massive-sulphide deposits does not necessarily require a felsic volcanic component, and that the role of the rhyolites in greenstone belts has never been clearly understood.

Following up on Corliss' discussion on the biological aspects of modern sea-floor hydrothermal systems, Ridler provided a well illustrated description of many of the organic features found in volcanogenic deposits and other exhalites. Most, if not all, Archean fossils have been found in exhalites, including some spectacular stromatolites from the Steep Rock Iron Mine of Ontario (Fig. 2). Furthermore, organic matter, now mostly as graphite, is frequently found around volcanogenic deposits, and often along the same stratigraphic horizon which hosts the deposit. It is possible that this organic-base-metal association is a reflection of biological concentrations similar to those observed around the modern vents, and further supports Corliss' ideas on the environment for the origin of life.

In addition Ridler showed evidence from the Archean for many of the features observed in the modern systems, for example spectacular examples of sul-

phides within the spaces between pillow-lavas.

Hutchinson proposed that many other types of ore deposits, in addition to base-metal, massive-sulphides, and gold, are formed by exhalative processes on the sea-floor. He suggested that the particular metals associated with each deposit are primarily a function of the local rock types through which the hydrothermal fluid-convective system circulated. Examples were given of possibly exhalative deposits of Sn, W, Ni, Cr, and Au, all of which have generally been considered up till now as having been formed by other processes. A heated discussion again ensued with some participants strongly supporting the generalized exhalative model, and others preferring the traditional alternatives. Hutchinson presented slides of the Jan shoot, at Kambalda mine, Australia, where Ni-Fe sulphides are delicately laminated with black carbonaceous cherts and show soft-sediment deformation (Fig. 3). In disagreement, Naldrett, (University of Toronto) pointed out that there was no gradation between Cu-Ni and Cu-Zn types of massive-sulphide deposits as would be expected if all these deposits were formed by a single process. A similar disagreement followed on the concept of tin exhalites, again prompted by the presentation of spectacular examples of supposedly sedimentary tin-exhalites from the Luina Mine, northwest Tasmania by Ridler (Fig. 4).

Further discussion continued on the various possible sources for sulphur in

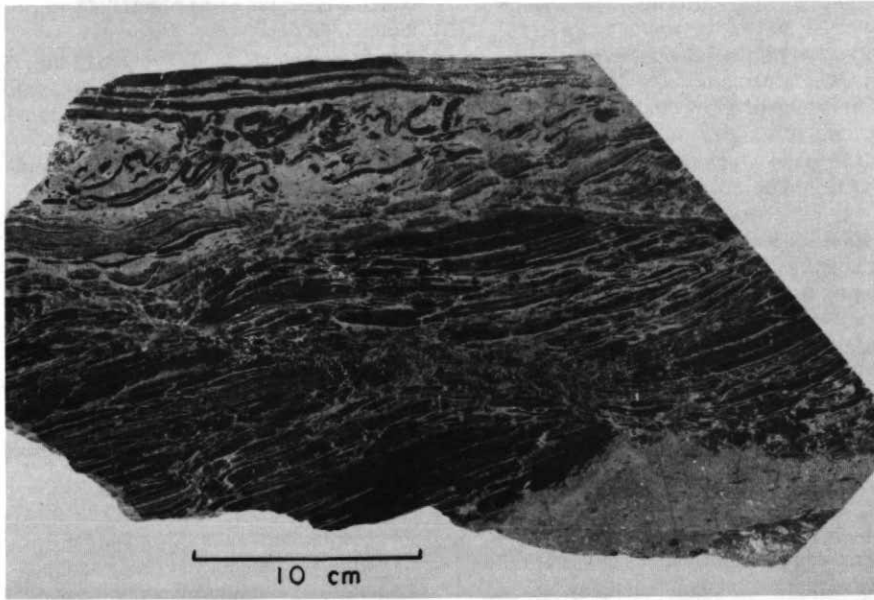
the sea-floor deposits. Spooner suggested that the sulphur came from reduced seawater sulphate, whereas Lydon suggested that the metal ratios and sulphur isotopes indicated that the sulphur came from the underlying rocks. He showed on a (Cu/Cu+Zn) vs.  $\delta^{34}\text{S}$  plot that Cu-Zn deposits, which are underlain by a rock succession composed dominantly of basic volcanic rocks, occupy a field quite distinct from that of Cu-Zn-Pb deposits, which are underlain by a rock succession composed dominantly of felsic volcanic rocks and/or sediments. Because of the pressure of time, Lydon was unable to present his paper. It is therefore given in full in the attached discussions.

Finally, there was a comparison of the morphology of modern vents with massive-sulphides as seen in Canadian Archean examples and within the largely undeformed Tertiary deposits in Japan. Tetsuro Urabe, then at the University of Toronto, and now in Tokyo, described pipe-like features similar to the chimneys of the black smokers, but bigger. A note in the discussions from Scott describes some remarkably similar pipes.

The meeting closed with the participants being much impressed by the modern systems and the comparisons and contrasts that were described from the older ore deposits. They were equally impressed by the value of the discussion and the open disagreement between various of the panelists and the participants on the importance of so many of the textural features and the geochemical data.



**Figure 2** Giant Archean stromatolite bands in dolomite from footwall of the Steep Rock Iron Range, northwest Ontario. Photo by R. Ridler.



**Figure 3** Massive nickel sulphide ore showing syn-depositional deformation, Jan Shoot,

Kambalda, Western Australia. Photo by R. Hutchinson.



**Figure 4** Banded stanniferous pyrrhotite exhalite ore from Luina Mine, northwest Tasmania. Photo by R. Ridler.

In conclusion, everybody was pleased to hear of the continuing research effort being undertaken in the hydrothermal vent areas of the Pacific Ocean, as well as new lines of research that are being suggested to improve our understanding of the older deposits. In particular, the French Ministry of Industry is funding a program, due to start this November, of 50 dives at 21°N and later the Guayamas basin. MIT, Scripps and NOAA also remain active.

### Contributed Discussions

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For many geoscientists, especially those of us directly involved in the study of ore genesis, the recent discoveries of metal-sulfide bearing, submarine hot springs, located along modern mid-oceanic ridge systems, are truly opportune.

In response to this, our first impulse is to test established concepts of ore genesis by comparing the modern, presently active systems, with the ancient ones. Particularly relevant in this respect are volcanogenic massive-sulphide ores characteristic of ophiolite complexes (e.g., Cyprus) and those which occur in Archean greenstone environments. Engaging in this exercise, it is not difficult to find analogies between the modern and ancient systems and on this basis to deduce new and exciting models concerning the process of ore genesis. However, as modern hot springs are only a surface manifestation of a much larger, more complex system active in the crust below, the process must be viewed within the broader context of what we know about modern oceanic crust at depth. Within the last decade, the truly spectacular success of the ocean crust drilling programs, DSDP (Deep Sea Drilling Project) and IPOD (International Phase of Oceanic Drilling), has yielded prolific information concerning the dynamic environment of modern oceanic crust which reveals that there are very important differences between the modern and ancient ore-forming systems characteristic of spreading ridges.

Perhaps the most dramatic difference involves geothermal gradients, as reflected by the pattern of mineralogical alteration. Ancient oceanic crust, now preserved as ophiolites, characteristically exhibits a pervasive metamorphic effect, indicating very high geothermal gradients, commonly on the order of 300° C/km or more. Such patterns have

been documented in many ophiolitic complexes including those in Chile, Luzon, Taiwan, Greece, Italy, Newfoundland and Cyprus. The latter two are fairly well known and their metamorphic relationships together with those representative of modern oceanic crust are compared on Figure 5. Note that zeolite and greenschist grade metamorphism occur at the very top of the ophiolite complexes and rapidly increase to amphibolite grade with depth. The occurrence of highly oxidized phases such as hematite and  $Fe^{3+}$ -bearing epidote in the uppermost zeolite and greenschist assemblages, attests to the introduction of fresh, oxygenated seawater, along very steep geothermal gradients. The pervasive metamorphic effect characteristic of ophiolites, indicates that the *bulk volume* of these crustal segments experienced rock-fluid interaction at very high temperatures ( $300^{\circ}$  to  $600^{\circ}$  C). Under these conditions it is not hard to envisage a pervasive leaching of metals from rock to fluid and an environment conducive to the generation of massive sulphide ores. There is much evidence to suggest that the Archean volcanogenic environments were also characterized by high heat flow and steep geothermal gradients. Indeed, the metamorphic relationships observed are often very similar to the crustal section represented on the left of Figure 5.

In contrast to the ancient systems, geothermal gradients measured in modern oceanic crusts are surprisingly low (often  $< 20^{\circ}$  C/km), a condition which appears to have been maintained at least through Cenozoic time and possibly

longer. Such low geothermal gradients are reflected in the type of alteration observed (Fig. 5). Deep drilling of the modern ocean crust revealed the predominance of a low-temperature, sub-metamorphic alteration effect (basalt diagenesis) which extends to depths of at least 1 km or more into the basalt (layer 2). The successive transitions through zeolite, greenschist and amphibolite grade presumably occur at much greater depth. Despite the occurrence of very hot fluid ( $\sim 360^{\circ}$  C) emanating from the newly discovered, submarine hot springs, deep drilling directly into these areas reveals predominantly low geothermal gradients and low temperature alteration effects. In contrast to the ancient systems, therefore, it appears that the bulk volume of modern oceanic crust experiences comparatively low temperatures. Rock-fluid interaction under metamorphic, hydrothermal conditions must be highly restricted to a) very deep levels, and b) deeply penetrating faults and fracture systems sporadically located along the axis of the spreading ridge.

The crustal sections illustrated in Figure 5 are broadly representative of Paleozoic, Mesozoic and Cenozoic to modern oceanic crust, in terms of the metamorphic relationships. The pattern of alteration reflects decreasing geothermal gradients as the rocks become younger, which may be interpreted as an evolution of mid-oceanic ridge systems through geological time. In this respect, the ancient systems (Late Precambrian through Paleozoic time) must have involved vigorous spreading in small

ocean basins, linked to small scale, turbulent mantle convection. Through time, these systems gradually evolved to the present day, relatively subdued spreading systems, characteristic of large ocean basins and tied in with large scale, less turbulent mantle convection. The general trend with time is towards decreasing energy, one result of which would be decreasing geothermal gradients in the upper oceanic crust. In detail, parameters such as crustal structure, spreading mechanism, magma configuration (Fig. 6) and others, would have all played their part.

The features characteristic of ancient, stratabound, sulphide orebodies all bespeak the massive, high energy systems which must have been operating within the crust of the time. These include the extent and intensity of hydrothermal alteration associated with the orebodies; the nature of metamorphism in the surrounding country rocks, which suggest fluid input at temperatures of  $300^{\circ}$ - $500^{\circ}$  C (that is, under dominantly greenschist conditions); and the scale of the orebodies themselves. The low energy systems established in modern oceanic crust indicate that present day mid-oceanic ridge environments are, in general, not conducive to the generation of such massive-sulphide ores. It is therefore not surprising that sulphide deposits associated with the presently active hot springs occur on a very small scale.

Modern ocean basins are characterized by widely dispersed metal-enriched sediments, which in the Pacific blanket more than two-thirds of the deep ocean floor. Recent studies indicate that these metals are most likely indigenous to the underlying crust and have reached their present location through a combination of low

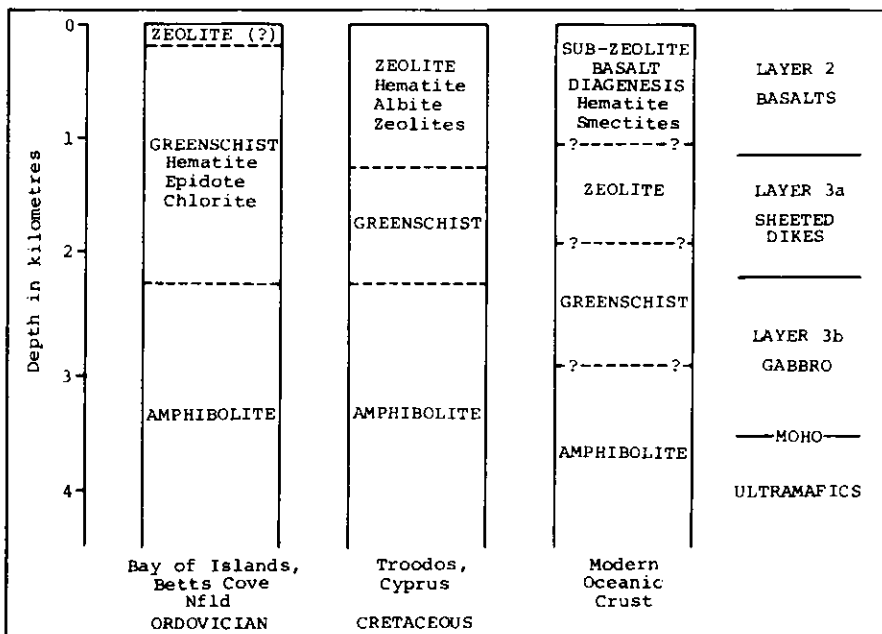


Figure 5 Cross-sections through oceanic crust of different ages.

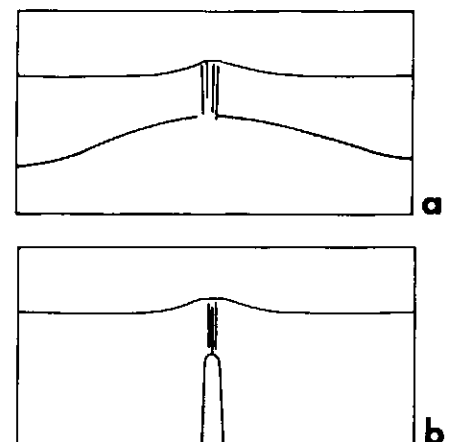


Figure 6 Possible configuration of sub-surface magma chambers in ancient (a) and modern (b) spreading ridge environments. In contrast to (b), the bulk volume of crust in (a) would experience high geothermal gradients.

temperature leaching, discharge from small scale hot springs and widespread dispersal by bottom currents. While the broad mechanism of metal cycling has remained unchanged (that is, leaching, discharge and precipitation), the drastic differences in metal distribution and form in ancient versus modern environments is perhaps not hard to rationalize, on the basis of such parameters as decreasing geothermal gradients, evolving seawater chemistry, and the dynamics of ore-fluid-seawater mixing in large versus small discharging systems.

It is thus apparent that examination of modern and ancient sulphide deposits should not be conducted on the level of simple comparison. Rather, comparison should be holistic and must be viewed in the light of an evolving system and a metallogeny changing with time.

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The "black smokers" described by Corliss and Edmond occur in mid-oceanic environments, analogous to ophiolitic terrains. It is true that the importance of felsic volcanites in the generation and localization of ore deposits in such terrains is uncertain. However, Noranda-type deposits and Kuroko-type deposits did *not* form in mid-oceanic environments. Furthermore, Noranda-type and Kuroko-type deposits *do* have a genetic link with felsic volcanism. By denying this, Scott (see below) is splitting hairs. True rhyolites may indeed be absent in some cases; however, felsic volcanites of some sort or another are generally present (Boldy, in press).

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The comparison of ancient massive-sulphide deposits with these modern sea-floor analogues, where the generative processes can be directly observed, is unquestionably of prime importance in understanding the older deposits. Without in any way intending to deny or minimize the significance of this comparison however, some reservations over the role of modern active systems - such as those at 21° N - in forming massive, base-metal, sulphide deposits may merit consideration.

Firstly, on a purely comparative basis it appears that examples of porous, massive, pyritic sulphide, like the "chimneys" deposited at the "black smoker fumarolic vents", are exceedingly rare in massive, base-metal sulphide orebodies. These ores are commonly dense, fine-grained (except where metamorphosed) and well banded to massive and structureless. Examples of cavernous or porous pyritic sulphides are indeed rare, although certain of the orebodies in Cyprus may be examples (Hutchinson, 1965, p. 976). It is interesting that one of the few places where pyritic sulphide of this particular textural variety is known is in the cupreous pyrite variety of these ores - formed, as at 21° N, at a mid-ocean rift ridge system in ophiolitic rocks of the oceanic crust. The lack of such a texture in many other deposits, however, suggests either that these "chimneys" are not readily preserved - which seems very likely considering their morphology at 21° N - or that this particular type of sulphide deposition does not commonly lead to large accumulations of massive-sulphide ore.

Secondly, and in similar sense, it seems possible, considering the nature of the hydrothermal activity at 21° N, that this particular system is too dynamic, that much of the sulphide is being widely dispersed rather than concentrated, and that active systems of this kind do not generate significant metallic sulphide accumulations. In contrast one might consider the Red Sea geothermal system with its much more quiescent flow, feeding density stratified brine pools in marked topographic depressions on the sea-floor. Here it seems that there may be a much greater chance of metallic sulphide accumulation through chemical precipitation from the warm metalliferous brines. It is interesting that metalliferous sediment up to ten metres thick and containing up to 7% zinc and 1% copper has been cored on the floor of these brine pools.

There is no question that sea-floor movement of dense, saline metalliferous brine has contributed to formation of some transported "fragmental" sulphide orebodies of the polymetallic type such as those at Buchans (Swanson *et al.*, 1981). These brines clearly moved down topographic paleoslopes on ancient sea-floors. Buchans seems much more akin to the Red Sea analogue than to the "black smokers" at 21° North.

Finally, it may be useful to consider the potential applicability of systems such as this to deposit types *other* than massive base-metal sulphides. There is little doubt that Algoman type (volcanogenic) iron formations are of similar, sea-floor,

chemical precipitate origin and that they form in association with submarine volcanism. If sub-seafloor hydrothermal circulation transports Fe, Zn, Pb, Cu, Au, Ag, etc., to the sea-floor to form massive base-metal sulphide deposits, then surely the very presence of gold in these ores is compelling evidence that exhalative processes have also contributed to certain gold deposits. Tin too, is a common - perhaps almost ubiquitous - minor element in the massive-sulphide deposits. In some massive-sulphides tin is the most valuable element, as in the massive pyrrhotite - cassiterite ores of western Tasmania (Fig. 4). The same argument as applied to gold merits careful consideration; tin has clearly been mobilized by, transported in, and deposited from such sea-floor exhalative systems in massive-sulphide orebodies and perhaps in certain other tin orebodies hitherto attributed to different genetic processes.

The argument may logically be extended to still other metals and rocks. For example, in the case of submarine komatiitic Archean lavas, it is pertinent to ask what metals might have been released to circulating sea-floor hydrothermal fluids during the extrusion, burial and diagenesis of rocks of this composition. The answer is clearly Ni, Cr, Pt, etc. On simple logical grounds, one should consider the possible role and applicability of exhalative processes in the formation of certain nickel and chrome ores, particularly those of Kambalda-type and of podiform type respectively. There is considerable field evidence to support this possibility as shown in Figure 3. The common association of these ores with iron formations and various cherty talc - carbonate - chlorite rocks, all of which may be in part chemical sedimentary strata, is also strongly suggestive of such an origin.

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Archean lode gold deposits, although typically extremely enriched in a suite of rare elements (Au, As, Sb, W, B, Se, Te, Bi), are generally depleted in, or have low concentrations of the abundant and mobile base-metals (Cu, Pb, Zn); separation of rare elements from base-metals is also observed in sedimentary gold deposits. Massive base-metal sulphide deposits, on the other hand, are enriched in both noble and base metals, by factors of 200 to 2000. These relations are illus-



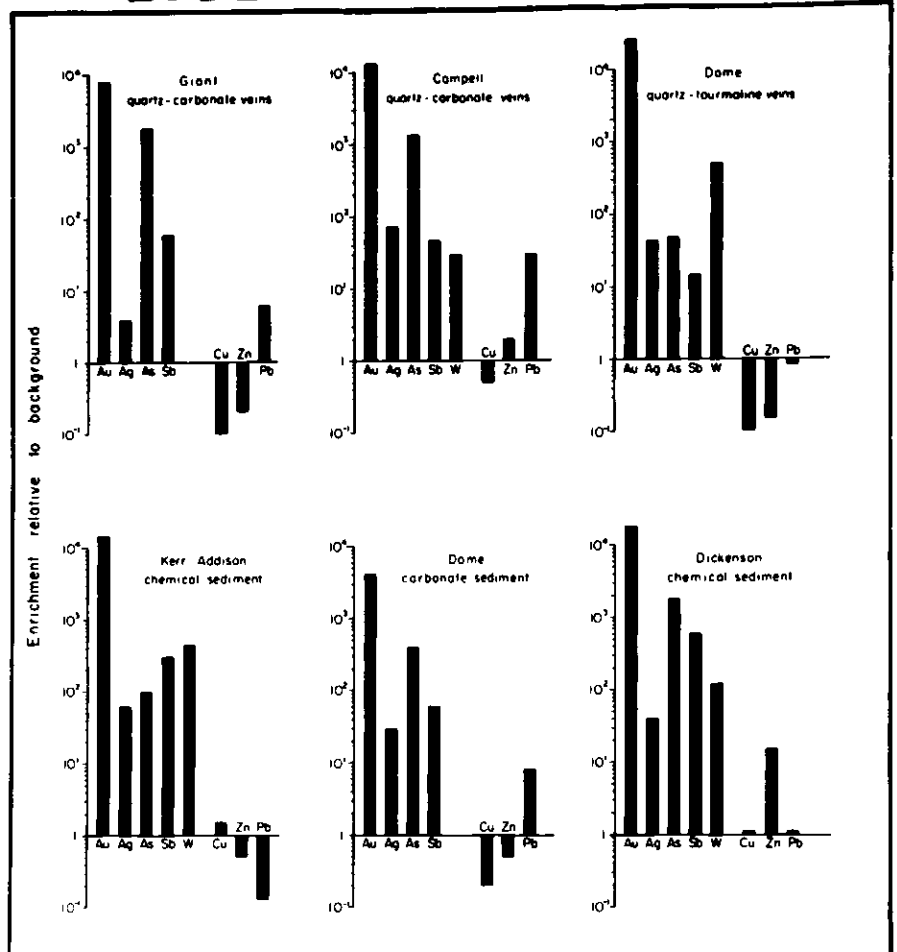
trated in Figure 7. In spite of important exceptions, these patterns hold true in general.

One approach to explaining the disparity in metal distribution between Archean lode gold and base-metal sulphide deposits is to consider properties of the hydrothermal systems involved in the two deposit types. Evidence from oxygen isotopes suggests that gold bearing vein deposits were precipitated, at temperatures of 320° to 480° C, from hydrothermal reservoirs having the isotopic character of metamorphic fluids ( $\delta^{18}O = 8$  to 11 ‰). Patterns of hydro-fracturing indicate that the precipitating fluids were discharged under conditions of elevated hydraulic pressure. The hydrothermal reservoirs were characterized by low redox, low salinity (< 30 ‰), low pH, high CO<sub>2</sub> contents and K/Na ratios of about one. The latter two properties can account both for the ubiquitous carbonate-potassium (Na loss) alteration observed in vein deposits (via hydrolysis of Fe-Mg-Ca silicates in wall rocks, with CO<sub>2</sub> fixation to form Fe-Mg-Ca carbonates), and hydrolysis of albite, accompanied by fixation of K, to form muscovite.

The  $\delta^{18}O$  of cherts in gold-bearing sediments is within the range of values recorded for Archean marine cherts (18 to 22 ‰ at about 2.8 Ga). This implies that auriferous hydrothermal fluids ejected onto the ocean floor were efficiently mixed with the seawater around them. Volcanic flows and volcanoclastic rocks enveloping auriferous sediments are usually, like vein deposits, enriched in K. Locally, however (e.g., Kerr Addison flow ore and the East Malartic Mine) the alteration is oxidative and sodic. In the latter cases, marine water presumably had become entrained in the metamorphic discharge. In summary: auriferous sediments may have originated where metamorphic fluids debouched onto the sea-floor and equilibrated with marine water, whereas the vein deposits formed during fluid ascent along fracture systems.

Base-metal sulphide deposits were precipitated from hydrothermal reservoirs having the isotopic signature of ocean water ( $\delta^{18}O \approx 0$  ‰). Fluids underwent convection at approximately hydrostatic pressure, with high water to rock ratios in the source region, and were ejected at temperatures of 240° to 320° C. The fluids were of approximately seawater salinity and possessed low CO<sub>2</sub>. Their passage through footwall rocks enriched the latter in Fe, Mg, Si and S. Carbonate is not abundant, and liquid inclusions imply that there was more sodium than potassium in the hydrothermal discharge.

## LODE GOLD DEPOSITS



## BASE METAL DEPOSITS

**Figure 7** Enrichment of selected elements in Archean lode gold and base metal deposits. The upper three figures are for vein-type ore-bodies, whereas the second row of figures represent gold-bearing chemical sediments.

Solid bars represent enrichments relative to background abundance in unaltered basalts, open bars signify enrichments calculated relative to abundances in primary felsic igneous rocks.

The  $\delta^{18}\text{O}$  of quartz isolated from strata-bound ore is in the range of 10 to 12 ‰. Perhaps the discharged fluids formed gravitationally stable brine pools, and did not attain equilibrium with seawater.

Fractionation of base metals out of auriferous systems can be accounted for by fluid generation during metamorphic dehydration at 350° to 480°C in systems with low water to rock ratios. The limited availability of water and of halogens (typically about 600 ppm chlorine), constrains the solution and complexing of base-metals. The solute concentration of rare elements, however, would not be limited by solubility. By contrast, in base-metal systems, which are the product of thermally driven seawater convection, the ratio of fluid to rock is very high, and total seawater halogens (19,000 ppm) exceed dissolved metals. As a result, there is no constraint on the uptake of either base-metals or rare elements into solution.

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There is no doubt that a thorough understanding of submarine hydrothermal systems is fundamental to the sound scientific prediction of the nature and distribution of those metalliferous deposits, notably the "volcanogenic" and "shale-hosted" types of massive-sulphides that appear to have formed at or near the discharge sites of submarine hydrothermal systems. Currently popular is the idea that "volcanogenic" massive-sulphide (VMS) deposits have formed from a convective, or at least circulatory, type of submarine hydrothermal system. Following the recent exciting discovery of the "black smoker" vents on the East Pacific Rise (EPR) at 21°N it is tempting to conclude that these vents and their sulphide deposits are indeed modern analogues to ancient ore-forming systems. However, it should be borne in mind that our present data on stratiform massive-sulphides do not preclude genetic interpretations different from those that have received the most recent attention.

There is no conclusive evidence that hydrothermal systems responsible for the formation of VMS deposits were of the convective type. Currently quoted "evidence" supporting a convective system consists of: 1) analogy with modern sub-aerial hydrothermal systems that have been explored for their geothermal

resource potential (e.g., Wairakei) and, therefore, are by definition of the circulatory type; and 2) geophysical and geochemical evidence from the modern oceanic lithosphere, which indicates that there is a continuous, and almost ubiquitous, circulation of seawater to depths of up to 5 km in the oceanic crust, this hydrothermal activity being most pronounced near ridge axes.

Attractive as this analogy may be, unfortunately many characteristics of stratiform massive-sulphide deposits are difficult to explain in terms of a convective hydrothermal cell. One of these is the phenomenon of the "favourable horizon", a specific stratigraphic interval to which sulphide deposits are restricted and which represents only a very small proportion of the total interval occupied by volcanic activity. Examples are the Kuroko deposits of Japan and those of the Bathurst area, N.B. By analogy with the modern situation, one would expect hydrothermal convection cells to operate throughout the duration of the geothermal anomaly manifest by the volcanic activity, and hence expect VMS deposits to occur throughout every submarine volcanic pile. Explorationists know that this is not the case. Another factor difficult to explain in terms of a convective model is that computer simulation (Cathles, 1977, 1978) suggests that, to sustain the flow of a hydrothermal convection cell at the temperature and with the quantity of fluid required for the formation of even a modest sized VMS deposit (Solomon, 1976), several cubic km of a cooling magma are required. The existence of the genetically similar "shale-hosted" deposits indicates that the presence of large volumes of molten rock is not a prerequisite for the formation of stratiform massive-sulphide deposits. A model akin to "seismic pumping" (Sibson *et al.*, 1975), in which the hydrothermal solutions of pressured reservoirs, heated by normal conductive heat loss, are suddenly, quickly and almost completely released by the onset of deep-seated dislocation tectonics, is much more in accord with the known facts.

Equally entrenched in the popular model for VMS deposits is the opinion that the ore-forming solutions are dominantly seawater. The main evidence for this point of view is based on the oxygen, hydrogen, strontium and sulphur isotopic ratios of rocks, minerals and fluid inclusions associated with VMS deposits, particularly the Kuroko and Cyprus deposits. Notwithstanding the uncertainties inherent in the diagnosis of processes from stable isotope evidence, circulating seawater or other solutions have most likely affected rocks of the stringer zone both

before and after, as well as during, the passage of the ore-forming fluids. This suggestion is favoured by the fact that rocks with similar isotopic signatures are found not only locally within mineralized stringer zones but also regionally within unmineralized rocks, e.g., the Cyprus situation. As an illustration, one may interpret those "barren" solutions, which have altered the hanging-wall rocks (and, presumably at the same time, also the footwall rocks) of some VMS deposits, to represent a secondary cell involving seawater which utilizes the upper part of the same plumbing system previously used by the ore fluids. This would be analogous to the way the ore-forming fluids themselves followed the same pathways as, say, feeder dykes to lava flows (e.g. the Millenbach Mine, Norandà). Therefore, it may be dangerous to assume that the solutions which have imparted the most widespread alteration or dominant isotopic signature to the rocks and minerals near an ore deposit, are one and the same as the ore-forming fluids themselves.

Convective hydrothermal systems characteristically sustain a more or less continuous flow over an extended time period. This appears to be the case for the black smoker situation based on: 1) the ecosystem unique to hydrothermal discharge areas (Edmond), whose mature establishment at the site indicates that the vents have been operating for at least tens and probably hundreds of years; 2) from the few observations made to date, flow rates appear to be more or less constant; 3) sulphide accumulation rates of about 3 tonnes/year/vent (see below) suggest a sulphide mound 10 m high and 5 m in diameter has required about 200 years to form.

The chemistry of the black smoker discharge solutions are also indicative of a dynamic circulatory hydrothermal system. The chemistry of natural hydrothermal solutions is determined by water-mineral interaction in the subsurface, resulting in many of the components, particularly the major cations, being buffered to specific values. Thus for the discharging black smoker solutions, as Edmond noted, the iron concentration is apparently controlled by saturation with respect to pyrrhotite and the calcium concentration is likewise controlled by epidote solubility. Figure 8 is a pH vs. temperature projection of a  $\text{H}_2\text{O}-\text{Na}_2\text{O}-\text{MgO}-\text{SiO}_2-\text{Al}_2\text{O}_3-\text{HCl}$  system showing only the equilibrium curves of various alteration assemblages during seawater-basalt interaction. The pH of about 4.5 reported by Edmond indicates that a smectite-dominated assemblage is controlling the chemistry of the black smoker

solutions, a situation which demands an influx of magnesium into the system to maintain the balance. This in turn means that the hydrothermal systems responsible for the "black smokers" (as distinct from VMS deposits) are of the circulatory type.

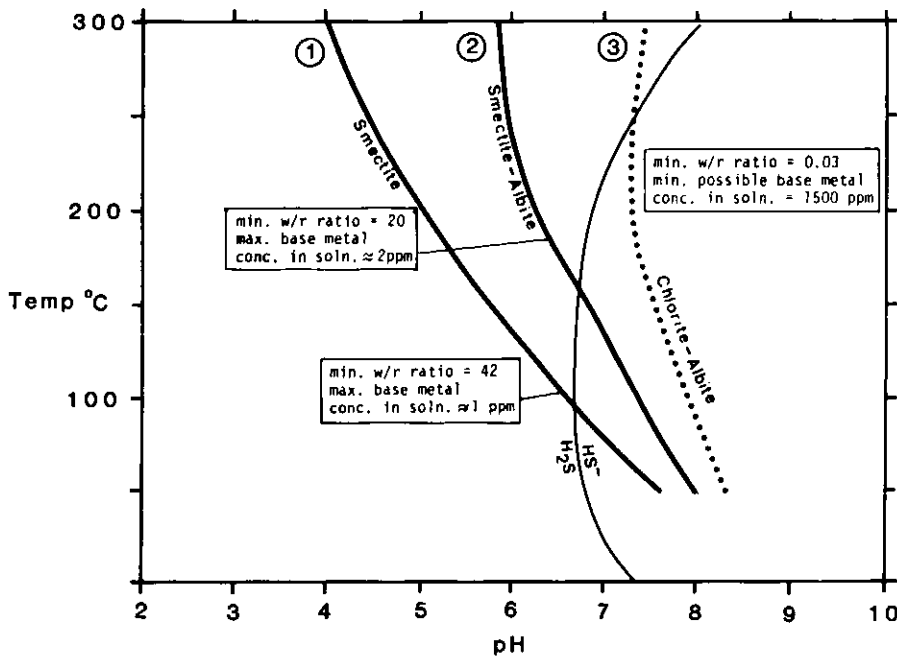
The reason why the metal contents of the black smoker solutions are higher than predicted in Figure 8 is probably because the present discharge represents the initial stage (i.e., within the first few hundred years) of hydrothermal circulation, so that the bulk water to rock ratio of the system is still relatively low (remembering that in a circulatory hydrothermal system bulk water to rock ratios generally increase with time). The pertinent data on the black smoker solutions are not yet published, but the data from the geothermally similar Galapagos Ridge extrapolated to 350° C (Edmond *et al.*, 1979) suggests a present bulk water to rock ratio of about 3, based on Li, K, Rb and Ba contents. Using the same calculations as in Figure 8, this water to rock ratio would permit a maximum Cu+Pb+Zn content of about 15 ppm,

which is approximately the concentration reported by Edmond. As the bulk water to rock ratio of the 21° N system increases with time, the concentration of base-metals will decrease. The fate of the sulphide chimneys and mounds appears to be one of complete oxidation (Hekian *et al.*, 1980).

The base-metal compositions of VMS deposits are illustrated in Figure 9. This diagram differs from the usual Cu-Zn-Pb ternary plot of ore compositions, in that I have weighted individual deposits according to their content of base-metal. This is desirable because some of the smaller deposits in particular may represent only a portion of the original sulphide mound, and what is important from the chemical point of view is information on the composition of the total cumulate precipitate from a single hydrothermal system. Figure 9 shows that there is a strong bimodality in the ore-element compositions of VMS deposits. This restriction of the metal ratios of the ore deposits to specific ranges and metal associations despite the great variation of metal proportions possible in

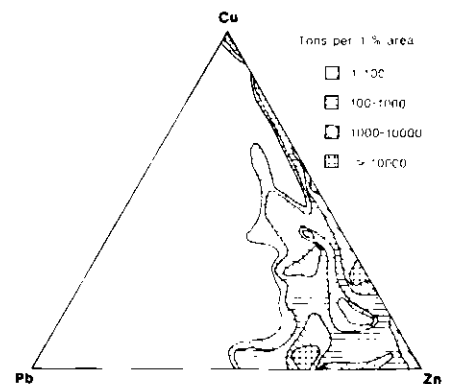
potential source rocks, suggests that in ore-forming hydrothermal solutions the proportions of the major ore elements are buffered to narrow ranges, in the same way as the major cation chemistry of all hydrothermal systems is buffered by the rock-forming minerals of the reservoir rocks. Lydon and Hodgson (in prep.) suggest that those ore deposits with Zn/Zn+Pb ratios of 0.6 to 0.8 (Zn-Pb-Cu type) were formed from acid solutions, in which the metals were transported mainly as chloride complexes, whereas those ore deposits with Zn/Zn+Pb ratios of greater than 0.9 (Cu-Zn type) were formed from alkaline solutions in which metals were transported mainly as bisulphide complexes. In turn, these two chemical groups, including the pH of the hydrothermal solutions (e.g., Figure 8) can be related to the dominant lithologies of the underlying rock column (which hosts the hydrothermal reservoirs): the Cu-Zn type occurs in areas in which the stratigraphic column beneath the mineralized stratigraphic interval is composed dominantly of mafic volcanic rock or their derivatives (e.g., Abitibi Belt, Norwegian Caledonides), whereas similarly situated lithologies for the Zn-Pb-Cu type are dominantly felsic volcanics and/or sediments (e.g., Bathurst, New Brunswick, Green Tuff Belt, Japan). In addition to major ore element associations and proportions, other chemical characteristics separate the two groups: barite (and gypsum) are confined to the Zn-Pb-Cu type; Au grades and Au/Ag ratios are higher in the Cu-Zn type; and the sulphur isotope patterns of the two groups are distinctly different, as mentioned in the meeting.

The reported chemistry and sulphide mineralogy of the precipitates of the "black smoker" vents suggest them to be of the Cu-Zn type, and at first glance



**Figure 8** Equilibrium curves for some hydrous alteration mineral assemblages in the system  $H_2O-Na_2O-MgO-SiO_2-Al_2O_3-HCl$ . Curves for (1) Smectite - (sol. ?) and (2) Smectite-albite from experimental runs of more than 14 days duration for basalt-seawater interaction reported by Bischoff and Dickson (1975), Hajash (1975), Mottl and Holland (1978), Seyfried and Bischoff (1977, 1979). Curve for (3) chlorite-albite (at quartz saturation) calculated. Curve (1) represents a steady state exchange or equilibrium between smectite and evolved seawater in a closed system or possibly equilibrium between smectite and, say, another clay; Curve (2) represents the lower pH limit of albite stability

in evolved seawater; Curve (3) represents chlorite/albite coexistence for the magnesium concentrations of Curve (2). Water to rock ratios calculated assuming total alteration of original basalt to the assemblages indicated (plus actinolite-epidote-quartz for Curve (3)). Composition of starting basalt and smectite is that reported by Seyfried and Bischoff (1977). Composition of chlorite, actinolite, and epidote is average of natural basalt alteration minerals reported by Humphries and Thomson (1978). Metal concentrations calculated assuming about 50 ppm of original metal content of basalt is leached into solution.



**Figure 9** Bulk compositions of VMS deposits of Abitibi Belt, Bathurst, N.B., Norwegian Caledonides and Green Tuff Belt, Japan as reported in the literature (referring to individual mines), contoured to show tons of contained Cu+Zn+Pb per 1% area of plot.

would appear to make them comparable to ancient VMS deposits that are situated on oceanic crust. However, the precipitates not only contain appreciable amounts of barite and gypsum but also have low Au/Ag ratios (RISE Project Group, 1980; Hekinian *et al.*, 1980), all features which are typical of products of acid solutions, but distinctly anomalous for Cu-Zn types of deposit. The compositional differences between "black smoker" precipitates and VMS deposits suggest that the present 21°N hydrothermal system is not analogous to ancient ore-forming systems.

Information on the concentration of Pb in the solutions and precipitates is desirable for further comparison. Although Pb is not often included in chemical analyses of modern oceanic basalt, the data available suggest a range of 1 to 5 ppm. This is low when compared to Zn (about 80 ppm) but still sufficient to form significant concentrations in oceanic metalliferous sediments (e.g., Bostrom and Peterson 1966). This consideration is relevant to ore-forming systems because, if the concentrations of ore elements in solution are determined by saturation limits, there is no direct relationship between the proportions of the major ore elements in solution and the proportions of those elements in the source rocks.

Physical differences between the modern sulphide chimneys or mounds and VMS deposits are obvious. The mass of ore minerals in each mound (10 m high and 5 m in diameter) does not exceed 500 tons, whereas the average mass of a VMS deposit is about 7 million tons (Boldy, 1977; Sangster 1980). In internal structure the mounds typically exhibit a concentric zonation of minerals around small interconnected channels or tubes (Francheteau *et al.*, 1979, RISE Project Group 1980), compared to the massive, banded and breccia textures of VMS deposits. The ore-forming process on the EPR is highly inefficient, with probably over 99% of the metal load becoming dispersed in the seawater. At 1% efficiency and presently estimated flow rates (10 m/sec from an orifice 15 cm in diameter), a single ore chimney would take over 2 million years to form a 7 million ton deposit, which is a much greater span of time than geological considerations indicate for individual VMS deposits (probably less than 3000 years). Even if ten chimneys coalesced, the time disparity still remains.

The spatial association of polymict agglomerates ("mill rock" of Sangster, 1972), the fracture pattern of some alteration pipes, and even the presence of stringer sulphide ore itself, suggest that boiling and phreatic explosions were

commonplace during formation of VMS deposits. Boiling may greatly increase the efficiency of sulphide precipitation and hence may be an essential prerequisite for some cases of ore formation. Again, this contrasts with the situation of the EPR. By comparison, the expulsion of saline fluids accompanying the Matsu-shiro earthquake swarm of 1966-1967, a hydrothermal discharge considered to be of the seismic pumping type proceeded at a flow rate (Sibson *et al.*, 1975) about 1000 times greater than the flow rate cited above for a "black smoker" vent. A discharge system operating at 1000 times the capacity and 100 times the precipitation efficiency of a black smoker vent, is probably more comparable to those vents responsible for VMS deposits.

In conclusion, there is no doubt that the discovery of the "black smoker" vents is an exciting and significant event for ore deposits geology. Further documentation of this hydrothermal system, particularly in the subsurface, will provide much needed facts for the purpose of genetic modelling. Until this system is understood and the differences between the sulphide precipitates on the EPR at 21°N and VMS deposits are explained, caution should be exercised in selecting exploration criteria based either on a "black smoker" empirical model or theoretical models based on convective hydrothermal systems.

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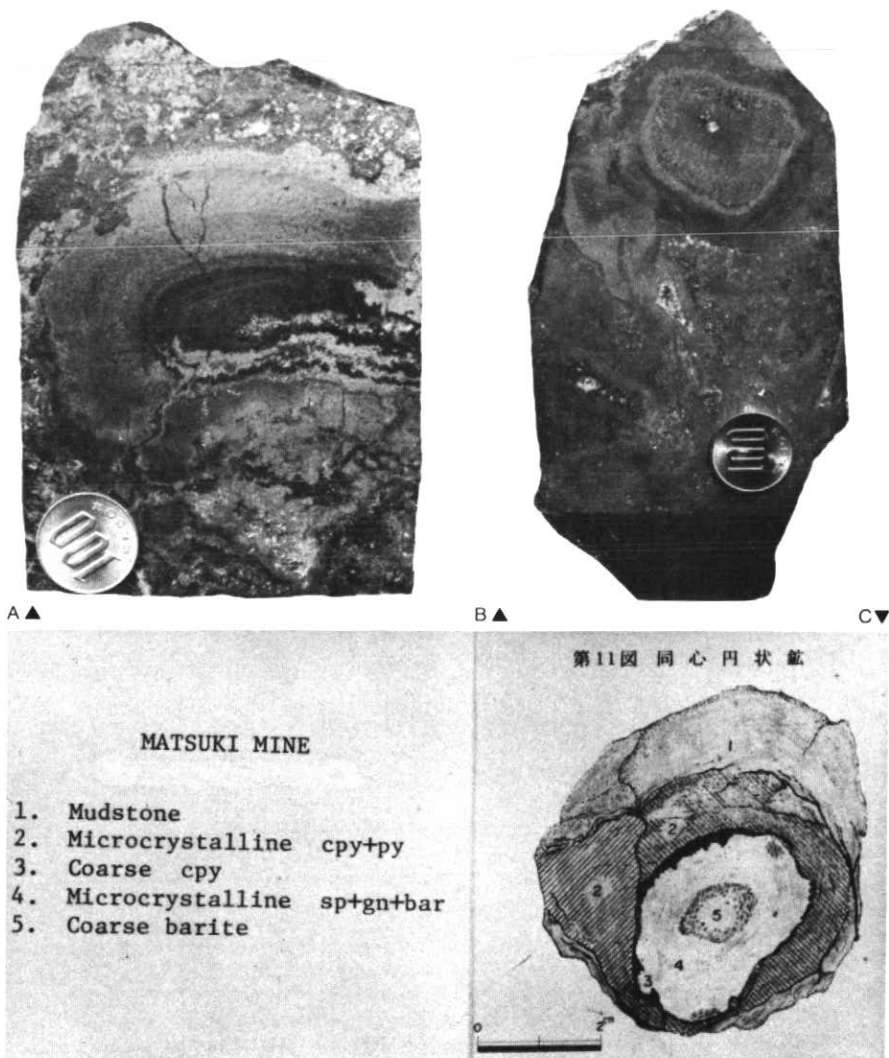
Cylindrical masses of delicately textured sulphides, several centimeters long and with diameters of usually 1 to 5 cm, but up to 10 cm, have been described from the massive ore and overlying mudstones at the Matsumine (Narita *et al.*, 1977) and nearby Matsuki mines (Kuroda *et al.*, 1976) of the Hokuroku district, Japan. These oddly textured sulphides have been known for some time and are called "tora-no-me" in Japanese, or "tiger's-eye" structure. Typically they are in sharp contact with the surrounding ore or mudstone and are compositionally zoned. The outer portion is fine-grained pyrite and chalcopyrite, followed inwards by dendritic or coarse, bladed chalcopyrite, fine-grained sphalerite + galena + barite and/or a small core of barite (Figure 10). The origin of tora-no-me is unknown but a reasonable hypothesis is that they are small scale versions of the sulphide "chimneys" described, for example, by Ballard and Grassle (1979) and RISE pro-

ject group (1980) from 21°N at the East Pacific Rise. A major difference, though, is that the chimneys from 21°N have copper sulphides on their interior surfaces and zinc sulphides (but no galena) concentrated in the outer zones (Hekinian *et al.*, 1980; Styrts *et al.*, 1981); just the opposite to the tora-no-me. Also, anhydrite rather than barite is the common sulphate mineral in the 21°N samples. I am anxious to learn if anyone has seen such structures in Canadian massive-sulphide deposits.

I re-emphasize that the presence of rhyolitic rocks is not necessary for the process by which Noranda-type or Kuroko-type deposits are formed. For example, the Corbet deposit in the Noranda district is hosted entirely by basalt (locally termed "andesite").

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**Figure 10** Cross sections of delicately-textured, zoned, cylindrical masses of sulphides from Kuroko deposits, Hokuroku district, Japan. (A) Matsumine; (B) Matsuki mine; (C) Matsuki mine (modified slightly from Figure 11 of Kur-

oda et al., 1976). See text for description of mineral zoning. The 100 yen coin used for a scale in A and B is 22 mm in diameter. The bar scale in C is 2 cm. Photos A and B by S. Scott.

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