

Hydrothermal Sulphide Mineralization on Seafloor Spreading Centres

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The evidence for the existence of the first submarine hydrothermal mineral deposit along the seafloor spreading centre appeared as an anomaly on the hydrographic data¹ of the Swedish vessel *R/V Albatross* while transecting the Red Sea in 1948. The active submarine hydrothermal field on an ocean ridge was a chance discovery^{2,3} during the Trans Atlantic Geotraverse (TAG) Project in 1972. Inactive massive sulphide mounds were recorded⁴ for the first time in 1978 and the high temperature (350°C) black smoker vents were also observed⁵ at the same site at 21°N East Pacific Rise (EPR) in 1979. Almost at the same time *DSRV Alvin* reported 4 groups of low temperature vents discharging hydrothermal solutions at the Galapagos spreading centres⁶.

These ocean floor hydrothermal systems account for the formation of massive polymetallic sulphide mineral deposits (Fig. 1) formed by precipitation from hot aqueous solution that convects through seafloor spreading centres, driven by volcanogenic heat sources. In the framework of plate tectonics, seafloor spreading centres are divergent plate boundaries where oceanic lithosphere is being created above the Moho discontinuity. The spreading centre is formed either as a rift zone, such as the Red Sea and Galapagos or as mid oceanic ridge such as Mid-Atlantic Ridge, the East Pacific Rise, the Central India Ridge and the Carlsberg Ridge. Most of the sites of known hydrothermal mineral deposits are situated along the 65000 km length of oceanic ridges and rifts⁷ at water depths of 2500 to 3500 m (Fig. 2). Observations suggest that these sulphides are truly renewable ore formations deposited at a rate of about 8 cm.d⁻¹ sulphide chimney growth. These submarine deposits are not only of commercial value but they also provide a clear picture of the geochemical cycles of the world ocean system and

the generation of commercial size deposits on the land.

Genesis

Hydrothermal ore formation is controlled by processes at the spreading centres of the ocean. Each spreading segment is characterised by deep transform fault intersections caused by increase in cooling and resulting heat loss in the upwelling mantle material. This cooling results into a thermal gradient along the strike of the spreading system forming a single elevated topographic high. At this high the vertical thermal gradient between seawater and underlying magma chamber is the greatest, resulting in maximum hydrothermal activity in the region.

The metallic ore formation system involves circulation of seawater through the fractured volcanic rock of the oceanic crust. The heating of the seawater is carried out during passage through newly emplaced hot plutonic and volcanic rocks. Depending on the degree of mixing of the hot aqueous metal rich hydrothermal solution with normal seawater, chemical exchanges between

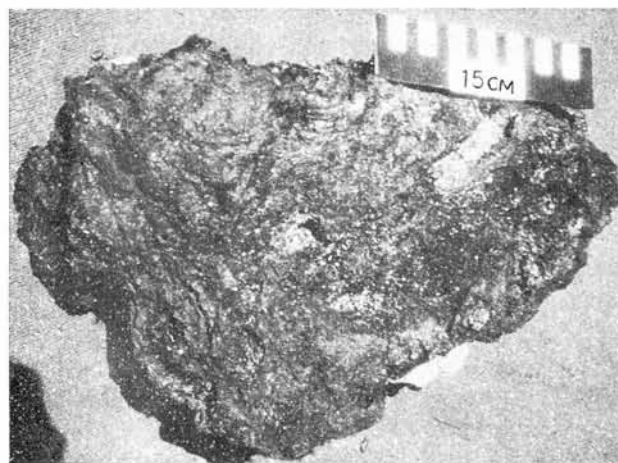


Fig. 1—Specimen of polymetallic sulphides from the East Pacific Rise (collected during GEOMETEP-4)

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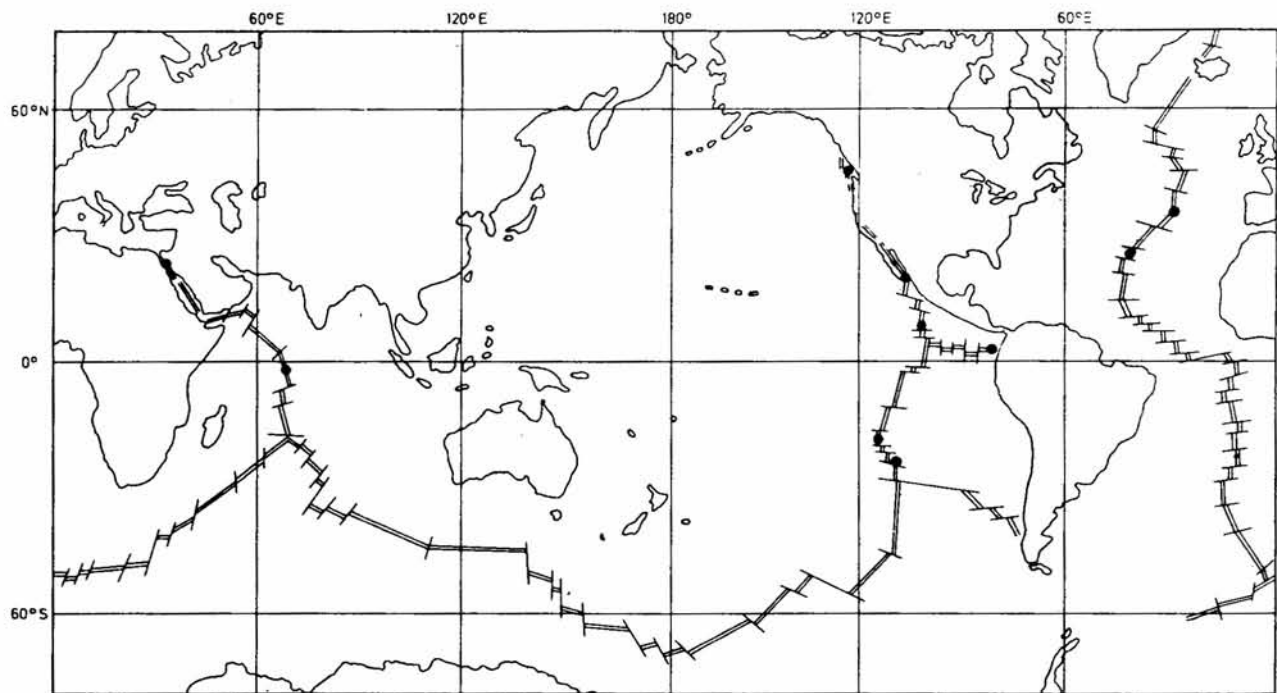


Fig. 2—Divergent zones and the mineralization (found up to 1988) associated with them. The ore discoveries are marked by black dots

seawater and oceanic crust (Fig. 3) result in the transfer of certain transition metals (Cu, Fe, Mn, Ni, Zn etc.) from crust to seawater and certain alkaline earth metals (Mg, K, B, Rb, Cs, etc.) from seawater to sulphides of Cu-Fe-crust⁸. Polymetallic sulphides of Cu, Fe, Zn precipitate from the unmixed hydrothermal solutions, which are at high temperatures (350°C) and under acidic and reducing condition when they come in contact with the cold seawater.

Classification and Geologic Setting

On the basis of the period of hydrothermal discharge formation and subsequent deposition 3 kinds of sulphide ore bodies can be recognised⁹ (Fig. 4).

(a) Hydrothermal pre-discharge deposits: These include those which are formed within the igneous crust before discharge of the solutions through the seafloor. They are exemplified by the stockwork type sulphides of the Mid-Atlantic Ridge.

(b) Hydrothermal syndischarge deposits: They are deposits formed at the site of hydrothermal discharge through the seafloor. These include the massive sulphides of the EPR.

(c) Hydrothermal discharge deposits: These are formed by precipitation on the seafloor of hydrothermally derived elements after some resid-

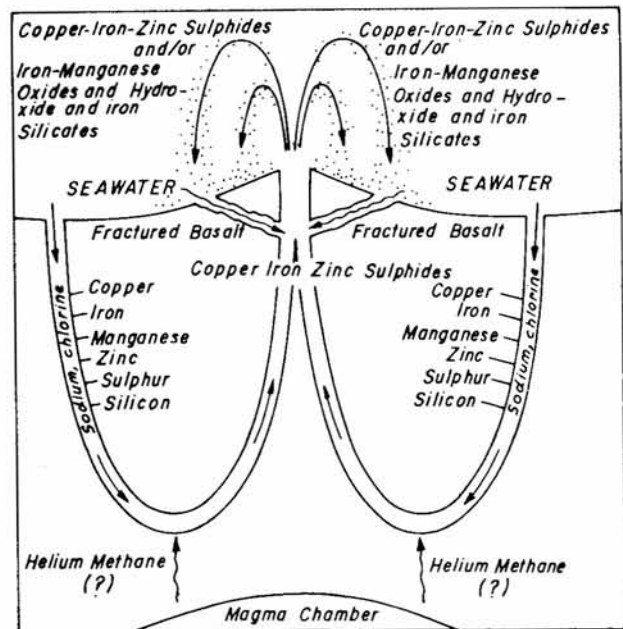


Fig. 3—Hypothetical diagram showing circulation and emplacement of metallic sulphides in the spreading ridge

ence time in bottom seawater, such as the Red Sea deposits.

Observations on the contemporary depositional sites suggest 2 principal tectonic settings that hold the sulphide bodies^{2,10,11}.

(a) Local tectonic subsetting with conditions conducive to hydrothermal mineralization at slow

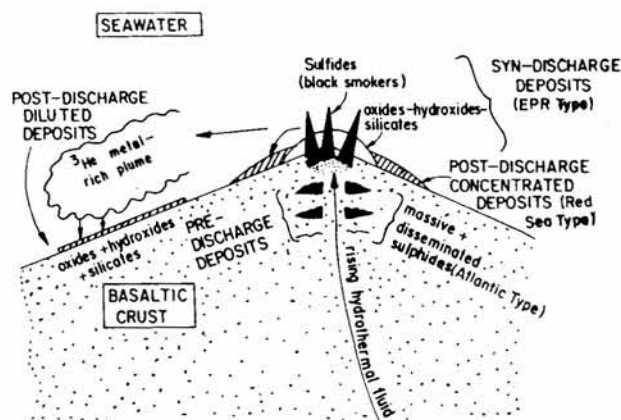


Fig. 4—Schematic representation of different types of metal deposits resulting from sub-seafloor hydrothermal circulation in the axial zone of accretion [After E Bonatti, in *Hydrothermal processes at the seafloor spreading centers* (Plenum Press, N.Y., 1983, 491. With kind permission from Plenum Publishing Corp., New York, USA)]

spreading centres (2 cm.y^{-1}) and are characterized by following types:

- (1) Basin along linear sections of axial zone of volcanic extrusion near transform faults at an early stage of opening, represented by large sulphide deposits of the Atlantic II Deep of the Red Sea.
- (2) The wall along linear sections of the rift valley in the marginal zone of active extension at an advanced stage of opening, represented by encrustations of manganese and iron oxides and hydroxides underlain by stock work sulphides at the Trans Atlantic Geotraverse field.
- (3) Transform faults, especially those with large ridge-ridge offset ($> 30 \text{ km}$) at an advanced stage of opening, represented by stock work sulphides exposed in the walls of equatorial fracture zones of the Atlantic and Indian oceans.
- (4) Axial zone of volcanic extrusion at an advanced stage of opening.
- (b) Local tectonic subsetting with conditions conducive to hydrothermal mineralization at intermediate to fast spreading centres (half rate $> 2 \text{ cm.y}^{-1}$) and are characterized by the following types:
 - (1) Basin along linear sections of the axial zone of volcanic extrusion at an early stage of opening, represented by massive sulphide deposits of the Guayamas Basin of the Gulf of California.
 - (2) Axial zone of volcanic extrusion at an advanced stage of opening, represented by individually small sulphide mounds surmounted by chimneys of the EPR at lat. 21°N .
 - (3) Marginal zone of active extension at an advanced stage of opening represented by a large,

massive sulphide deposit at a double rifted section of the Galapagos spreading centre.

(4) Transform faults especially those with large ridge-ridge offset ($> 50 \text{ km}$) represented by Mn-encrustation in a transform fault at the Galapagos spreading centre.

(5) Volcanic seamounts related to persistent hot spots at spreading centres, represented by oxide and sulphide deposits on the seamount off the axis of EPR.

(6) Portion of spreading centres with anomalous configuration such as multiple, bent or extended rifts, represented by massive sulphide deposits at a doubly rifted section of the Galapagos spreading centre suggesting the operation of a thermal structural feed back indicative of presence of hydrothermal mineralization.

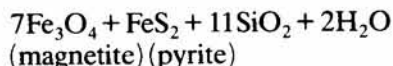
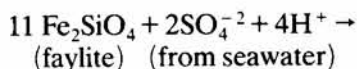
(7) Discrete spreading centres in back arc basins represented by hydrothermal deposits at sites in marginal seas of the West Pacific.

From the above it may seem that the seafloor spreading centres should be covered with hydrothermal mineral deposits. However, it is not so, as the concentration of these deposits is controlled by special structural and thermal conditions comprising anomalous high thermal gradient and high permeabilities to facilitate voluminous circulation, and a favourable system geometry conducive to high intensity hydrothermal activity¹².

Chemistry and Mineralogy

The expression of the hydrothermal activity of the seafloor is controlled by the extent and site of entrainment of ambient seawater by the ascending hot waters. At the region where this occurs subsurface sulphides are precipitated in mixing zones leading to mineralization. This process also serves to seal the conduits of upcoming primary solutions. This results in the formation of 'black smokers', rich in fine grained sulphide minerals of Fe and Cu together with sulphate, oxide and silicate phases. The material consists of friable and porous compounds with the edge of the chimney generally composed of anhydrite. Isotopic composition of minerals reveals that they precipitate at temperatures of about 300°C ¹³. On the other hand the 'white smokers', which form at lower temperature (around 270°C), seem to have lost their sulphide forming minerals to subsurface precipitation and in this case Mg silicates, barite and Zn-sulphides constitute the smoke¹⁴.

A number of redox reactions leading to increasingly reducing conditions are possible¹⁵ during the subbottom, hydrothermal circulation, such as:



From the above reaction it is evident that metal sulphides are formed during high temperature basalt seawater interaction under reducing conditions in presence of S. Hajash¹⁶ has produced chalcopyrite and pyrrhotite by similar reaction at 400°-500°C. According to Bischoff and Manheim¹⁷ the source of S is questionable. It could form from reduction of SO_4^{2-} ion in seawater or it could be derived by leaching of S from oceanic basalt. Moore and Schilling¹⁸ estimated that the ocean ridge basalt contains on an average about 800 ppm S. The third possible source could be from volatiles of direct mantle derivation, though no quantitative assessment of the latter source is available.

The quantitative chemical analysis¹⁴ of samples from Galapagos shows an average density of 4.1 g.cm⁻³ and a composition of 40% S, 38% Fe, 6.5% Cu, 7% Si, 1% Zn, 0.5% Mn, 0.3% Al, 360 ppm Se, 250 ppm Co, 270 ppm Mg, 181 ppm Mo, 215 ppm Pb, 45 ppm As and Ba and 40 ppm Cd, Cr, P, Hg, Ni, Sn, V, U and Th. Au is <0.05 ppm. The principal constituents in all these sulphides are 4 elements making up to 40, 20, 20, 20% in each of S, Fe, Cu and Zn. The Fe-Cu-Zn ratio is highly variable and is temperature dependent.

The mineralogy of the sea bottom sulphides from the EPR crust at 21°N, collected by the CYAMEX team⁴ (Table 1) reveals that the sulphide phase mainly consists of sphalerite and pyrite with minor chalcopyrite and marcasite. The

CYAMEX team believes that these could be akin to sulphide deposits found associated with the ophiolite complexes on land such as those in Cyprus, New Foundland, California, Turkey and Italy. The sulphides recovered recently by the GEOMETEP cruises at 18°S and 21°S on EPR are principally composed of pyrite, marcasite, chalcopyrite, chalcopyrrhotite, covellite, sphalerite and wurtzite. Nonsulphide gangue is almost negligible. They are akin to the sulphides from 21°N EPR¹⁹. However, some stockwork type mineralization is in the basalts as disseminated pyrite.

The sulphide minerals recovered generally show two distinct²⁰ types: (a) weakly friable dark grey ZnS and (b) subrounded, compact, spongy light grey ZnS. The former consists of porous aggregate of sphalerite and wurtzite with lesser amounts of pyrite, galena, chalcopyrite, cubanite, pyrrhotite, covellite and marcasite. The nonsulphide phases include the amorphous silica, barite, anhydrite and gypsum. The light grey sulphides of a higher porosity comprised brown sphalerite together with pyrite, amorphous silica and barite. Based on the studies of sulphides Rona²¹ has tabulated the major metal and mineral phases of the 3 basic types of massive sulphide occurrences derived from the upper mantle and oceanic crust (Table 2; Fig. 5).

The studies by Bonatti *et al.*²² on stockwork type sulphides from Mid-Atlantic Ridge of northern Atlantic show an almost similar mineralogy as those from the Pacific. The study reveals association of chalcopyrite (main phase) with pyrrhotite, pyrite, atacamite, Fe-hydroxide and cryptocrystalline limonite. In addition delafossite (FeCuO_2), mooihoekite ($\text{Cu}_9\text{Fe}_9\text{S}_{16}$) and haycockite ($\text{Cu}_4\text{Fe}_5\text{S}_8$) are also recorded.

Table 1—Mineralogy and Chemistry of Sea-Bottom Sulphides from 21°N EPR (Adopted from CYAMEX⁴)

Mineral	Morphological features	XRD minerals	Metal content (wt%)			Other elements identified by XRF
			Fe	Cu	Zn	
Sphalerite	Tabular, polysynthetic twins and octahedron	Sphalerite & pyrite	9.0	2.9	23.0	Co, Pb, Ag, Cd, Mn, Cl, Ca, S & K
Pyrite	Cubes with striation	Chalcopyrite				
Sphalerite	Octahedron, collomorph and banded	-do-	6.3	0.2	28.7	Co, Pb, Ag, Cd, Mn, Cl, K, Si & S
Amorphous silica	Flaky					
Pyrite or chalcopyrite	Globular and collomorph	Pyrite & chalcopyrite	29.6	6.0		Co, Cd, Pb, Mn, Zn, Ca, K, Cl & S
Pyrite	-do-	Pyrite chalcopyrite & marcasite	14.9	2.2	0	Mn, Cd, Co, Pb, Ag, Zn, K & S
Iron oxide	Globular aggregate	Amorphous	42.7	0	0.6	Mn, Pb, Cu, Ca, Cd, K & S

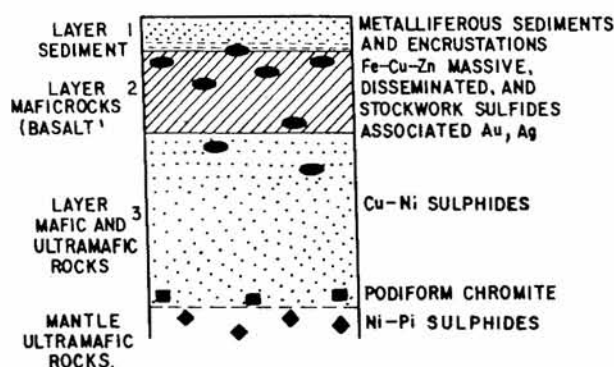


Fig. 5—Schematic section of oceanic crust and upper mantle showing potential distribution of metal deposits [After P. A. Rona, *Marine Mining*, 4 (No. 1) 1983, p. 13. With kind permission from Taylor & Francis, New York, USA]

Table 2—Major Metal and Mineral Phases in the Massive Sulphides of Oceanic Crust (Adopted from Rona²¹)

Type of deposit	Major metals	Mineralogy
Massive sulphide phase (EPR type)	Cu, Fe, & Zn	Pyrite, marcasite, sphalerite, wurtzite, pyrrhotite, chalcocopyrite, cubanite, digenite, covellite & native silver.
Stockwork and disseminated sulphides (Atlantic type)	Cu, Fe, Zn & Ti	Pyrite, chalcocopyrite, pyrrhotite, covellite & ilmenite.
Metalliferous sediments (Red Sea type)	Fe, Cu, Zn, Cd, Pb & Hg	Pyrite, chalcocopyrite & Sphalerite

Indicators of Hydrothermal Sulphide

The various criteria that have proven useful for recognition of hydrothermal sulphide deposits have been comprehensively discussed by Rona²³. The important indicators are geological, petrological, geophysical (acoustic, seismic, electrical and magnetic) and biological.

On the basis of the petrographic study, sediments of hydrothermal origin are recognised by distinctive mineralogical and compositional types in addition to their isotopic characters. Hydrothermal sediments contain high proportions of transition metals such as Fe, Mn, Cu and Zn, low Al and high Si/Al ratios and Fe/Mn ratios between 1 and 200. Base metal sulphides are associated with anomalous ²³⁴U/²³⁸U ratios. So isotopic compositions are at equilibrium with seawater and Pb isotopic compositions resemble those of oceanic ridge tholeiitic basalts. The rare earth element pattern is similar to seawater, and a high-

er U and lower Th content than in normal pelagic sediments characterize metalliferous sediments.

Certain geochemical processes can also reveal the presence of metalliferous deposits. Geochemically in the hydrothermal seawater interaction, low dilution favours direct discharge of hot, acid solutions enriched in metals as in the Galapagos spreading centre²⁴. An excess of rare He stable isotope, ³He, above oceanic background together with an excess of unstable ²²²Rn isotope, may indicate discharge areas of hydrothermal circulation. Methane and hydrogen concentrations in 21°N EPR fluids are greater by 10⁵ times than normal deep sea concentrations²⁵. Higher suspended particulate matter together with high silica saturation with respect to seawater background is a strong evidence of hydrothermal discharge. Moreover the sum of the Fe₂O₃ and MnO₂ components shows a distinct increase in the direction of the vent following the same pattern as the percent carbonate free matter²⁶.

Hydrothermal mineral deposits are influenced by crystal structure, permeability, rate of spreading and distribution of heat sources. Structurally they occur along block faulted topographic highs adjacent to rift valley, volcanic seamounts on oceanic ridges, fracture zone that transect spreading centres and basins along axial trough present during the rift stage in opening of ocean basin. The faults and associated fractures which enhance the permeability of the rocks facilitate hydrothermal circulation.

Mid oceanic hydrothermal sulphide environment is associated with characteristic patterns of convective and conductive heat flow. Highest value of heat flow occurs at discharge zones and the convective heat flow is manifested according to water circulation. Under restricted circulation the temperature of near bottom water may increase by 10°C. However, under conditions of open circulation the thermal anomaly is insignificant and intermittent conductive heat flow in sediments near the axis of spreading ridge shows a large variability²⁶⁻²⁹ between adjacent values (0 to 30 heat flow unit) and high average flux (2.5 HFU).

Geophysically, the presence of contrasting acoustic impediment between seawater and hydrothermal fluids will produce a reflecting interface for echosounder waves and this will reveal the presence of metallogeny. In a similar fashion a hydrothermal field is identified by shallow focus microearthquakes along the rift zones. Even earthquake which swarms along spreading centres in Atlantic and Indian Oceans are associated with

seafloor metallogeny. Self potentials involving a gradient of redox potential are often encountered with metalliferous sediments³⁰. A distinct low value of residual magnetic intensity by alteration of the magnetic minerals in the basalts along a high temperature discharge zone constitutes an important criteria in recognition of such sites³¹.

Biologically, evidences at Galapagos spreading ridge³² and at the EPR 20°S³³ reveal the presence of rich and diverse fauna of giant clams, mussels, crabs, sea anemones, limpets and chitons whose presence is related to proliferation of bacteria in H₂S rich solutions emanating from the vents. Si derived from hydrothermal discharge may also support varied population of silica bearing organisms like sponges in the vicinity of discharge as in TAG field. As a consequence of hot fluids passing through the organic rich muds, occurrence of hydrothermal petroleum is reported from the vents, as in the sea of Cortez. The materials condensing at the seafloor give the mineral deposits a petro-liferous odour³³.

Some Massive Polymetallic Sulphides

Pacific Ocean—Massive sulphides have been located within the rift axis of the Galapagos rift¹⁵ at 85°50' W and 0° 45' N lying at a depth of 2600 m. It appears to have been formed by extensive high temperature (350° to 400°C) hydrothermal activity. The deposits are in the form of coalesced inactive chimneys, surrounded by a blanket of sulphides amounting to several million tons¹⁵. The principal source of the sulphides is the oceanic crust. Seawater percolates through faults and cracks to depths where molten magma is encountered. The trapped water which attains a temperature of 400°C without boiling has a long residence time to form a solution incorporating the metallic elements and sulphides from the host rock. This charged, superheated water comes up through the fractures and comes in contact with the cold (2°C) seafloor water, whereby metallic sulphides crystallise to form pyrite, chalcopyrite and sphalerite. The crystallizing components are released in the form of smokers or chimneys which are of 2 types—the early formed 'white smokers' with zinc rich components and with temperature of formation 350°C and the higher temperature 'black smokers' in Fe and Cu.

Hydrothermal mineral deposits at an advanced stage of fast seafloor opening are those of the EPR at lat. 21°N in form of relict chimneys composed of sulphides⁴. Still larger deposits of massive polymetallic sulphides consisting of coalesced

mounds have been recently discovered on the EPR crust near lat. 31°N³⁴ and near 20°S³⁵.

The whole setup consists of hundreds of chimneys standing on top of mounds with combined dimensions of 30 m high and 30 m in diameter (Fig. 6). They are associated with rich faunistic assemblages in the form of giant clams and crabs which burrow in these hydrothermal muds to form tubular structures. Growth possibly of native S also occurs which makes the associated sediments look greenish. Hydrothermal solutions of temperatures up to 350°C are discharged from active chimneys which directly precipitate black clouds of metallic sulphides on the seafloor. Estimates³⁶ reveal the tenor of metals at 21°N EPR as about 14% Fe, 34% Zn, 0.23% Cu and 37.3% S in the inactive basal mounds while the active black smokers record 4% Fe, 1.7% Zn, 0.12% Cu and 4.3% S in the sulphide phases namely wurtzite, pyrite, marcasite and chalcopyrite. The percentage of CaO and MgO are higher for black smokers. The non sulphide phases are anhydride and barite. The associated minor elements are Ag, Au, As, Co, Cd, Te and Ge. The GEOMETEP 4 expedition³³ at 21°S reveals metal contents up to



Fig. 6—Underwater active smoker from East Pacific Rise at a water depth of 3800 m (Photo taken during GEOMETEP-4)

Fe 36 %, Cu 4.9%, Zn 8.6% and S 45% though variability exists (Table 3). These sulphides show typical biogenic relict structures, mainly of tube worms.

Atlantic Ocean—Mineralization at the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge at lat. 26°N is the only example of its kind on a slow spreading oceanic ridge. In the TAG area hydrothermal solutions discharge through faults in one wall of the rift valley³⁷. Low temperature discharge and mineralization are preferentially concentrated along high angle fault zone between depths of 2500 and 3500 m. These fault zones serve as a conduit for the upwelling limb of hydrothermal convection system that is recharged by downwelling at the adjacent transform fault zone.

Two distinct types of hydrothermal deposits are observed in the TAG field³⁸. The first type consists of stratiform deposits composed of interlayered, black, crystalline Mn oxide and greenish Fe silicate (nontronite) and earthy red Fe hydroxides. They are inferred to be the products of precipitation from low temperature hydrothermal solutions. The second type of mineralization appears as black or red patches of several metres consisting of thin (1 to 5 mm) layer of Mn oxide and/or Fe hydroxide on surface of foraminiferal ooze. These patchy surficial mineralizations are products of slow, diffuse seepage of low temperature hydrothermal solution through thin sediments. A representative transect along the TAG area³⁹ shows that an inner mound is flanked by outer mound, the former up to 55 m higher than the surrounding outer mound. A dredge at the inner mound reveals hydrothermal precipitates of sulphides (66%), sulphates, oxides, hydroxides, silicates and carbonates with no basalt. Greater part of the sulphide (93%) is spongy intergrowth of pyrite and black sphalerite. It is high in Fe (38 weight %) Zn (9%) and low in Cu (<1%). These are precipitated from moderate temperature solution discharging into open spaces. The rest of the sulphide occurs as dense curved plates which are several centimeters thick and show mineralization. The concave side is made of chalcopyrite and pyrite, while the convex side is composed of sphalerite. The Cu content is high (22-30 weight %) and low in Zn (1-3%). These sulphides are precipitates from chimneys that vented high temperature solution.

Cu-Fe sulphide mineralization in form of stockwork and disseminated deposits have been also reported from metabasalts occurring in the Vema and Romanche Fracture Zones of the Mid Atlan-

Table 3—Bulk Chemical Composition of Some Sulphides Ores Recovered during GEOMETEP-4, SO-40 (Determined on board, GEOMETEP-4, ref. 33) (values in wt%)

	Sample Nos			
	152-G(a)	152-G(b)	182-G(c)	200-G(e)
Fe	29.76	30.32	16.30	0.85
Cu	14.47	16.58	0.20	0.15
Zn	2.00	0.62	35.00	36.60
Mn	0.00	0.03	0.043	0.003
SiO ₂	1.13	0.44	4.00	69.20
Al	0.08	0.02	0.005	0.04
Ca	0.03	0.03	0.03	0.03

tic Ridge⁴⁰. These deposits which are a direct evidence of metal mobilization within the basaltic oceanic crust of spreading centres are principally made of chalcopyrite together with pyrite and pyrrhotite. These deposits are a ready explanation for the occurrence of massive sulphides associated with present day ophiolite complexes which are formed in the ancient spreading centres.

Indian Ocean—The occurrence of active ridge metalliferous sediments in the Indian Ocean was first reported by Boström and Fisher⁴¹. Subsequently, Mc Arthur and Elderfield⁴² studied samples from Mid-Indian ocean Ridge and Marie Cleste Fracture Zone, which offsets the ridge north of its triple junctions. Fe-Mn encrustations were collected from the valley wall and sulphides were detected in the vesicles of the basalts. The associated Si and Ca clays also showed a strong influence of hydrothermal activity.

Further examples of sulphide mineralization in the Indian Ocean are given by many authors⁴³⁻⁴⁵. While Cann⁴⁵ has reported hydrothermal Fe-Mn encrustations on the basaltic lava from near Gulf of Aden in the form of spongy, brown MnO coating over friable yellow to green smectite, Rozanova and Baturin⁴⁴ have reported stockwork type Cu-Fe sulphides in larger offset, ridge-ridge transform fault segments.

Plüger and Friedrich⁴⁶ and Rona⁴⁷ after a preliminary reconnaissance of Carlsberg Ridge between Owen Fracture Zone (lat. 9°50'N) and Vityaz Fracture Zone (lat. 5°17'S) and the Central Indian Ocean Ridge between 5°N and 20°S have observed possible hydrothermal activity. Around 1° 40'S-67° 46'E and 5° 21'S-68° 37'E in a structurally disturbed zone at the intersection of the west wall of the rift valley with the Vityaz Fracture Zone, mineralization in the form of disseminated grains and veins of Cu-Fe sulphides (chalcopyrite) occurs in a matrix of basalt hydrother-

mally altered to greenschist facies⁴⁷. Higher levels of He³ values in the Carlsberg Ridge zone of Indian Ocean correlate with a higher CH₄ content⁴⁸. These occurrences have recently been reviewed by Roonwal^{49,50}.

Red Sea—Sulphides in this area are an example of mineralization at an early stage of slow spreading centre of the ocean floor⁵¹, within a closed basin with restricted circulation. They occur in a number of deeps in the Red Sea where transform faults intersect the Median Valley⁵². When seawater comes in contact with the thick layers of rock salt, buried in the seafloor, it acquires high metal transporting capacity. The hot, metal rich hydrothermal solution when ascends to the top, comes in contact with the cooler water and under reducing conditions precipitates the sulphides in stratified form. Their deposition is controlled by transform faults.

The sulphides occur in two facies, viz. (a) mixed sulphides of Fe, Cu, and Zn and (b) pyrite. The former occurs as grey, fine grained, massive beds, principally made of sphalerite together with pyrite, chalcopyrite and marcasite.

Bignell⁵³ analysed the Atlantis II Deep sediments and gave a value of Zn, Co and Fe over 10, 2 and 15% respectively. The metal is supposed to have been derived by leaching from volcanic rock and transported by brine. The pyrite occurs within the Atlantis II Deep and contains a higher concentration of Fe up to 29% with Cu 1.3% and Zn 3.4% with minor amounts of Au and Ag⁵³.

Conclusion

At a time of growing scarcity of critical minerals, the discovery of hydrothermal metalliferous sulphide deposits associated with divergent plate boundaries along the ocean floor is of much significance. These deposits in the oceanic crust hold significance in context of mineral exploration. The long term significance is the actual recovery of metals from these formations which however involves development of new technology at high costs. Nevertheless, the sulphide deposits constitute an important source for future metal needs and the oceanic crust in which they occur constitute a large part of the ocean bottom. Their short term significance lies in the fact that the findings on large slices of oceanic crust can provide practical guidelines for their commercial exploitation in near future.

References

- 1 Bruneau L, Jerlov N G & Koezy F, *Swedish Deep Sea Expedition Report*, 3 (1953) 1.
- 2 Rona P A, *Sci American*, **229** (1973) 86.
- 3 Rona P A, *J Geol Soc London*, **137** (1980) 385.
- 4 Cyamex Scientific Team, *Nature Lond*, **277** (1979) 523.
- 5 Rise Project Group, *East Pacific Rise hot springs and geophysical experiments*, **207** (1980) 1421.
- 6 Corliss J B, Dymond J, Gordon L, Edmond J M, Von Herzen R P, Ballard K, Green K, Williams D, Bainbridge A, Crame K & Van Andeel T H, *Science, Wash*, **203** (1979) 1073.
- 7 Rona P A, *Mar Tech Soc J*, **16** (1982).
- 8 Edmond J M, Measures C, Magnum B, Grant B, Sclater F R, Collier R, Hudson A, Gordon L & Corliss J B, *Earth Planet Sci Letts*, **46** (1979) 1924.
- 9 Bonatti E, in *Hydrothermal processes at the sea floor spreading centers*, edited by P A Rona, K Boström, L Laubier & K Smith (Plenum Press, New York) 1983, 491.
- 10 Rona P A, *Trans Am Geophy Union*, **55** (1974) 293.
- 11 Rona P A, in *27th International Geological Congress, Moscow*, **3** (1984) 68.
- 12 Rona P A, *Mar Mining*, **4** (1983) 1.
- 13 Lonsdale P, *Oceanus*, **27** (1984) 21.
- 14 Edmond J M, *Mar Tech Soc J*, **16** (1982) 23.
- 15 Spooner E T & Fyfe W S, *Contrb Mineral Petrol*, **42** (1973) 287.
- 16 Hajash A, *Contrb Mineral Petrol*, **55** (1975) 245.
- 17 Bischoff J L & Manheim F T, in *Hot brines and recent heavy metal deposits of the Red Sea*, edited by E T Degens & D A Ross (Springer-Verlag, New York), 1969, 348.
- 18 Moore S G & Schilling J G, *Contrb Mineral Petrol*, **41** (1973) 105.
- 19 Bäcker H, Lange J & Marchig V, *Earth Planet Sci Lett*, **72** (1985) 9.
- 20 Koshi R A, Goodfellow R & Bouse R M, *US Geol Survey Report*, **82** (1982) 200.
- 21 Rona P A, *Mar Mining*, **4** (1983) 7.
- 22 Bonatti E, Guerstein-Honnorez B M, Honnorez J, *Eco Geol*, **71** (1976) 1515.
- 23 Rona P A, *Eco Geol*, **73** (1978) 135.
- 24 Edmond J M, Gordon L I, Corliss J B, *Trans Am Geophy Union*, **58** (1977) 1176.
- 25 Welhan J A & Craig H, in *Hydrothermal processes at seafloor spreading centers*, edited by P A Rona, K Boström, L Laubier & K Smith (Plenum Press New York) 1983, 391.
- 26 Erickson A J & Simmons G, *Hot brines and recent heavy metal deposits in the Red Sea* (Springer-Verlag New York) 1969, 114.
- 27 Langseth M G & Von Berzen R P in *The sea* edited by A E Maxwell (Wiley, New York) 1971, 299.
- 28 Girdler R W, *Royal Soc Phils Trans*, **267** (1970) 191.
- 29 Williams D L, Von Bergen R P, Sclater J G & Anderson R N, *Royal Astron Soc Geophy J*, **38** (1974) 587.
- 30 Sato M & Mooney H N, *J Geophy*, **26** (1960) 226.
- 31 Rona P A, *Volcanology Geothermal Res*, **3** (1978).
- 32 Corliss J B, Ballard R D, *Nat Geogr*, **152** (1977) 441.
- 33 GEOMETEP-4, *Preliminary Cruise Report 1985-1986* B G R Hannover, 1987.
- 34 Hekinian R, Fevrier M, Needham H D, Avedek F & Camban P, *EOS Trans Am Geophy Union*, **62** (1981) 913.
- 35 Ballard R D, Morton J & Francheteau J, *Trans Am Geophy Union*, **62** (1981) 912.

- 36 Bischoff J L, Rosenbauer R J, Aruscavage P , Baedeker P A & Crock J G, *Eco Geol*, **78** (1983) 1711.
- 37 Rona P A, *Trans Am Geophy Union*, **62** (1981) 45.
- 38 Rona P A, *Mar Mining*, **6** (1985) 117.
- 39 Rona P A, Klinkhammer G, Nelson T A, Trefry J H & Elderfield H, *Nature Lond*, **321** (1986) 33.
- 40 Bonatti E, Gueratein Honnorez B M & Honnorez J, *Eco Geol*, **71** (1976) 1515.
- 41 Boström K & Fisher D E, *Earth Planet Sci Lett*, **11** (1971) 95.
- 42 McArthur J M & Elderfield H, *Nature Lond*, **266** (1977) 437.
- 43 Dimitriev L, Barsukov V & Udintsev G, *Geokhimiya*, **8** (1970) 937.
- 44 Rozanova T V & Baturin G H, *Oceanology*, **11** (1971) 874.
- 45 Cann J R, Winker C K & Pritchard R G, *Mineral Mag*, **41** (1977) 193.
- 46 Plüger W L & Friedrich G, *Alma Mater T H Aachen*, **20** (1983) 109.
- 47 Rona P A, *Earth Sci Review*, **20** (1984) 1.
- 48 Plüger W L, in *Fahrtbericht SO-28 GEMINO-1*, RWTH Aachen (1985) 274.
- 49 Roonwal G S, in *Int Cong Indian Ocean Studies Perth (ICIOS II) Resources Envn & Eco Development*, 1984, 1.
- 50 Roonwal G S, *The Indian Ocean: exploitable mineral and petroleum resources* (Springer-Verlag, Berlin) 1986, 198.
- 51 Degens E T & Ross D A, (eds) *Hot brines and recent heavy metal deposits in the Red Sea* (Springer-Verlag, New York) 1969, 600.
- 52 Bignell R D, *Trans Inst Min Metall*, **B-84** (1975) 1.