*Canadian Mineralogist*
Vol. 26, pp. 431-465 (1988)

# HYDROTHERMAL MINERALIZATION AT OCEANIC RIDGES

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## ABSTRACT

A compilation of over 100 mineral occurences at oceanic ridges and rifts comprising the global seafloor spreading center system has been made in terms of host-rock lithology (volcanic- or sediment-hosted) and of stage (early, advanced) and rate (slow-, intermediate- to fast-spreading) of opening of an ocean basin. At this early phase of exploration when less than 1 percent of the ~55,000 km global length of spreading centers has been systematically explored, examples of almost all major varieties of volcanic- and sediment-hosted hydrothermal deposits associated with basaltic rocks in the geologic record have been found at present spreading centers. Review of this global data base indicates that a range of hydrothermal mineral-deposit sizes from small to large ($\geq 1 \times 10^6$ tonnes) occurs at all seafloor spreading rates. Based on available data, however, larger deposits (but fewer per unit length of spreading axis) form at slow- rather than at intermediate- to fast-spreading centers. Larger deposits are more common in sediment-hosted than in volcanic-hosted settings regardless of spreading rate. A spectrum of hydrothermal deposit varieties (stratiform, stockwork and disseminated sulfides; various forms of sulfate, carbonate, silicate, oxide and hydroxide deposits) occurs in almost all of the tectonic settings. High-intensity, ore-forming, subseafloor, hydrothermal convection systems that conserve heat and mass, and concentrate hydrothermal precipitates, are extremely localized by anomalous physical and chemical conditions relative to nearly ubiquitous low-intensity hydrothermal activity at, and flanking, seafloor spreading axes at all spreading rates. Two distinct shapes of volcanic-hosted hydrothermal deposits at seafloor spreading centers and in the geologic record may be explained by differences in fluid dynamic behavior controlled by temperature–salinity properties of solutions. Massive sulfide deposits that are mound-shaped in profile are constructed by hydrothermal solutions that discharge as buoyant plumes; examples are the TAG massive sulfide mound forming on the Mid-Atlantic Ridge, and the Archean Noranda-area deposits. Massive sulfide deposits that are saucer- or bowl-shaped in profile are formed by ponded solutions denser than surrounding seawater; examples are the Atlantis II Deep deposits of the Red Sea, and the Cretaceous Troodos deposits of Cyprus. Review of an existing data set on 508 massive sulfide deposits in the geologic record indicates that fewer volcanic- and sediment-hosted massive sulfide deposits are associated with basaltic rocks than with rhyolitic rocks (<26% *versus* 56%, respectively). This observation suggests that seafloor spreading centers have been significant as tectonic settings for massive sulfide formation through geologic time, although subsidiary to continental rifts and volcanic island arcs.

*Keywords:* hydrothermal, mineral deposits, seafloor spreading centers, oceanic ridges, massive sulfides.

## SOMMAIRE

Plus de 100 exemples de minéralisation le long d'une crête ou d'un rift océanique faisant partie du réseau global d'axes de séparation de la croûte océanique ont été étudiés selon les points de vue suivants: lithologie de l'encaissant (volcanique ou sédimentaire), stade de minéralisation (précoce ou avancé), et taux de formation d'un bassin océanique (séparation des plaques, lente, intermédiaire ou rapide). L'exploration systématique de ces systèmes, bien que très préliminaire, étant donné qu'elle a porté sur moins de 1% des quelques 55,000 km de longueur des axes de séparation du globe, révèle toutefois des exemples de presque toutes les variétés connues de gisements hydrothermaux dans un encaissant volcanique ou sédimentaire associés à des basaltes. À la lumière des données à l'échelle du globe, la dimension des gisements peut varier de petite à importante ($\geq 1 \times 10^6$ tonnes), quel que soit le taux de séparation. Toutefois, la probabilité de formation des gisements importants est accrue si le taux de séparation est lent, quoique ceux-ci seront plus espacés le long de l'axe que lors d'un taux de séparation intermédiaire ou rapide. Quel que soit le taux de séparation des plaques, les gros gisements sont plus communs dans un encaissant sédimentaire que dans un milieu uniquement volcanique. On trouve une grande variété de gisements hydrothermaux (stratiforme, en «stockwork», sulfures disséminés; plusieurs types de dépôts de sulfates, carbonates, silicates, oxydes et hydroxydes) dans tous les milieux tectoniques. Quel que soit le taux de séparation, les systèmes à convection hydrothermale sub-crustale vigoureuse qui conservent à la fois chaleur et masse, et qui concentrent les précipités hydrothermaux, sont extrêmement circonscrits à cause des conditions physiques et chimiques anomales, en comparaison de l'activité hydrothermale de faible intensité, très répandue le long de tout axe, ainsi que sur les flancs d'une crête. Deux formes de gisement dans un encaissant volcanique, aussi bien le long d'un axe de séparation que sur terre, dans des roches plus anciennes, pourraient résulter des différences en comportement dynamique des fluides, régies par leurs propriétés (température, salinité). Les gisements de sulfures massifs à profil en forme de monticule, par exemple ceux du champ de TAG sur la crête médio-atlantique et du camp minier de Noranda (Québec), d'âge archéen, résultent d'une décharge hydrothermale en forme de panache de faible densité. Les gisements en forme de soucoupe ou de bol, par exemple ceux de l'abysse de Atlantis II dans la mer Rouge et ceux de Troodos (Chypre), d'âge crétacé, résultent d'une accumulation locale de saumures plus denses que l'eau de mer ambiante. Les données recueillies sur 508 gisements anciens montrent davantage de gisements de sulfures massifs dans un encaissant volcanique ou sédimentaire associés à des roches rhyolitiques (56%) que basaltiques (<26%). Quoique les milieux de séparation des plaques océaniques aient été importants comme centres de minéralisation au cours des temps, ils l'ont été à un degré moindre que les milieux de rifts continentaux et les arcs insulaires.

(Traduit par la Rédaction)

## INTRODUCTION

Hydrothermal mineralization at seafloor spreading centers is one of the most actively researched subjects in the Earth sciences. The seafloor sites of mineralization are natural laboratories to study ore-forming processes with implications for geochemical mass balances and cycles, thermal budgets, and adaptation of vent organisms. Certain of the seafloor deposits are resources for the future. Investigations at sea are synergetic with studies of deposits in the geologic record that were formed under similar conditions on the seafloor and subsequently were uplifted onto land. Several reviews have been published on recent mineralization at seafloor spreading centers (*e.g.*, Cronan 1980, Bonatti 1981, Rona 1984, Morrison & Thompson 1986, Bäcker & Lange 1987, Gross & McLeod 1987), and its relation to ancient deposits (*e.g.* Franklin *et al.* 1981, Mitchell & Garson 1981, Sawkins 1984, Scott 1985, 1987). This paper addresses aspects of the distribution of hydrothermal mineralization at seafloor spreading centers in terms of deposit varieties, observations on related hydrothermal processes, and evidence for the occurence of these deposit varieties and processes in ancient "analogs".

*Mots-clés:* activité hydrothermale, gisement, axes de séparation des plaques océaniques, crêtes océaniques, sulfures massifs.

## DISTRIBUTION OF HYDROTHERMAL MINERALIZATION AT SEAFLOOR SPREADING CENTERS

### *State of knowledge*

Since the initial discovery of hydrothermal mineralization at a seafloor spreading center in the Red Sea in the mid-1960s (Miller *et al.* 1966, Hunt *et al.* 1967, Degens & Ross 1969), the major varieties of mafic volcanic- and sediment-hosted hydrothermal mineral deposits known in the geologic record have been found at seafloor spreading centers. Known occurences of hydrothermal mineralization at seafloor spreading centers are compiled in Table 1, organized in terms of host-rock lithology (volcanic- and sediment-hosted), rate of seafloor spreading (slow-spreading half-rate ≤2 cm/y; intermediate- to fast-spreading half-rate >2 cm/y), and stage of opening of an ocean basin (early and advanced). All of the combinations of these parameters have been found except sediment-hosted hydrothermal deposits at a slow-spreading center at an early stage of opening (Table 1).

The occurrences of hydrothermal mineralization at seafloor spreading centers (divergent plate bound-

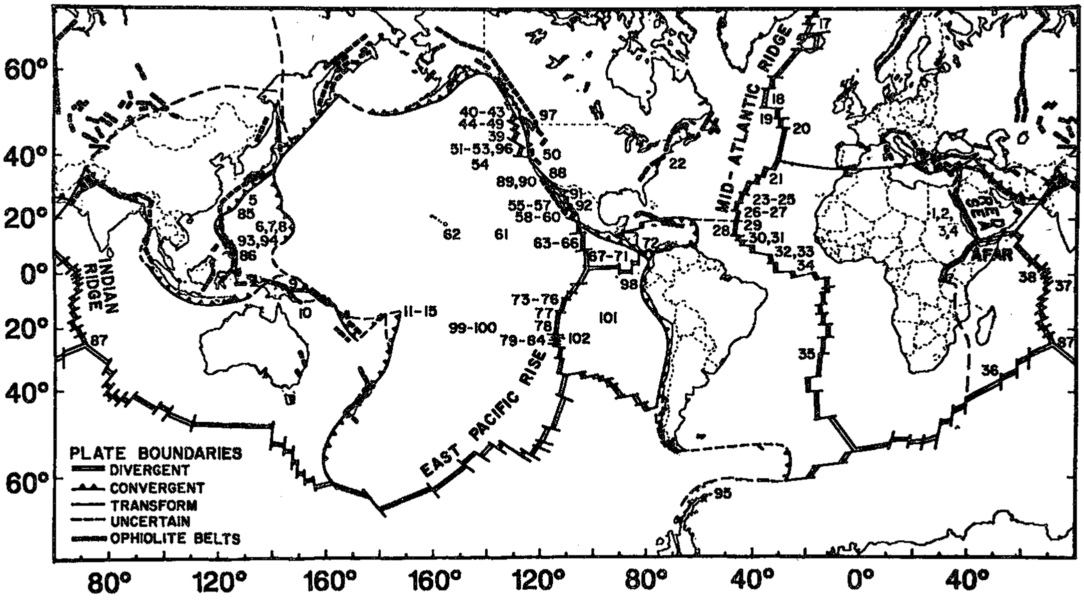

FIG. 1. World map showing lithospheric plate boundaries and locations of hydrothermal mineral occurrences at seafloor spreading centers (divergent plate boundaries). Numbers refer to locations in Tables 1 and 2. Ophiolite belts are also shown (Coleman 1972).

aries) listed in Table 1 are shown on a plate tectonic map of the world (Fig. 1). The distribution of mineralization is an artifact of incomplete knowledge at this early phase of exploration. Less than one percent of seafloor spreading centers has been systematically investigated, and thus the actual distribution of deposits along spreading centers is unknown. Recognition of such deposits is biased in favor of those that form prominent topographic features exposed on the seafloor, such as massive sulfide mounds at zones of focused high-temperature hydrothermal discharge. Relict stratiform deposits lacking appreciable relief, and all forms of deposits beneath the seafloor tend to remain unresolved by present exploration methods (Rona 1983).

The structural setting of a hydrothermal deposit at a spreading center is given with reference to structural elements common to all spreading centers (Table 1). These elements comprise (Fig. 2): i) an axial zone of volcanic extrusion of the order of 1 km wide, and marginal zones of active extension each about 10 km wide perpendicular to the spreading axis; and ii) linear spreading segments of the order of 10 km long which are offset by transform-fault sections of fracture zones, deviations from axial linearity (DEVALS), and overlapping spreading centers at distances up to tens of km parallel to the spreading axis (Rona 1984, Macdonald *et al.* 1987).

Knowledge of the size, shape and composition of hydrothermal mineral deposits at seafloor spreading centers (Tables 1, 2) is limited by inadequate measurement and sampling techniques. The only seafloor hydrothermal deposits that have been assessed in a manner approaching the rigor of mineral prospects on land are the stratiform metalliferous sediments (including massive sulfides) of the Atlantis II Deep of the Red Sea (Mustafa *et al.* 1984; Fig. 1, Table 1, location 1). Information on other mineral deposits at seafloor spreading centers is incomplete in two dimensions, and almost unknown in the third. Pattern drilling and excavation methods, both in unconsolidated and consolidated materials at oceanic depths, require further development. The compositions presented (Table 2) are based on surficial samples recovered by dredging and coring from surface ships, by manipulator arms from submersibles and, in several cases, by shallow drilling (locations 27, 56, 57, 72). The compositions of mid-ocean ridge basalt, and average Pacific and Atlantic pelagic clay are given at the end of Table 2 for comparison with the enriched elemental concentrations in the mineral deposits.

### *Size of deposits*

Most of the hydrothermal mineral occurences are so small that they may be characterized as mineralized showings (Table 1; Fig. 1). Exceptions are: i) an actively accumulating, volcanic-hosted, stratiform metalliferous sediment deposit with a dry bulk salt-free weight of at least 94 × $10^6$ tonnes, hosted in a basin about 10 km in diameter in basaltic rocks of the Atlantis II Deep at the slow-spreading axis of the central Red Sea (Table 1, location 1; Mustafa *et al.* 1984); ii) an elliptical mound, up to 250 m wide and 50 m high, composed primarily of massive sulfides with an estimated weight of 5 × $10^6$ tonnes, actively accumulating at a fault zone in basaltic rocks at the base of the east wall of the rift valley in the TAG Hydrothermal Field near latitude 26°N at the Mid-Atlantic Ridge crest (location 23; Rona 1985a,b, Rona *et al.* 1986, Thompson *et al.* 1988); iii) an active zone of massive sulfide accumulation about 200 m wide and 40 m high (the Snake Pit Hydrothermal Field), on a basaltic ridge along the slow-spreading axis of the Mid-Atlantic Ridge near latitude 23°N (location 27; ODP Leg 106 Scientific Party 1986, Thompson *et al.* 1988); iv) active and inactive massive sulfide deposits forming mounds up to 200 m in diameter and 10 m thick with an aggregate weight of $\geq 1.5 \times 10^6$ tonnes, associated with fault zones in the wall of the rift valley of the southern 9-km-long segment of the intermediate-spreading Explorer Ridge (location 42; Scott *et al.* 1984, 1985, Tunnicliffe *et al.* 1986); v) massive sulfides hosted in terrigenous sediment forming seven active mounds up to 400 m in diameter and 60 m high, each estimated to contain at least 1 × $10^6$ tonnes of massive sulfide in Middle Valley of the Endeavor segment of the intermediate-spreading northern Juan de Fuca Ridge (location 97; Davis *et al.* 1987); vi) massive sulfides in discrete outcrops around faulted margins of axial basaltic domes and possibly extending into terrigenous sedimentary strata of the Escanaba Trough on the slow-spreading southern Gorda Ridge (location 96; Morton *et al.* 1987); vii) inactive massive sulfide chimneys and mounds coalesced into a fragmented body up to 1 km long at a marginal fault zone in basaltic rocks of the rift valley of the intermediate-spreading Galapagos Spreading Center near longitude 86°W (location 71; Malahoff 1982 a,b); and viii) a massive sulfide body about 800 m long and 200 m wide occupying part of the flank and summit of a basaltic volcano located 6 km east of the fast-spreading axis of the East Pacific Rise (EPR) near 13°N (location 64; Hékinian *et al.* 1983).

### *Sediment-hosted deposits*

More than 99% of the ~55,000 km global length of the axial zone of seafloor spreading centers is sediment-starved (devoid of sediment cover), and the balance is sediment-filled. The degree of sediment fill is related to proximity to sediment sources. For example, for the 970 km length of the axial zone of the Gorda – Juan de Fuca – Explorer Ridge System

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| I. <u>VOLCANIC-HOSTED DEPOSITS</u> | | | | | | |
| | **EARLY STAGE OF OPENING OF AN OCEAN BASIN** | | | | | |
| | **SLOW-SPREADING (HALF RATE $\leq$ 2 CM/Y)** | | | | | |
| 1 | RED SEA ATLANTIS II DEEP NEAR 21°24'N, 38°03'E; OTHER DEEPS WITH SMALLER HYDROTHERMAL DEPOSITS INCLUDE DISCOVERY, CHAIN, SUAKIN, SUDAN, ERBA, SHAGARA, ALBATROSS, VALDIVIA, THETIS, NEREUS, VEMA, KEBRIT, GYPSUM, OCEANOGRAPHER AND CHARCOT (FOOTNOTE REFS.). | $\sim$2,000 | 1.0 | ELONGATE BASINS ALONG LINEAR SEGMENTS OF THE AXIAL ZONE OF VOLCANIC EXTRUSION NEAR INTERSECTIONS WITH TRANSFORM FAULTS. | METALLIFEROUS SED. WITH SULFIDE, SULFATE, OXYHYDROXIDE AND CARBONATE FACIES. BULK DRY SALT-FREE WT. OF THE UPPER 10 M OF THE ATLANTIS II DEPOSIT IS ESTIMATED AT 94 X $10^6$ TONNES (ACTIVE). | Fe-MONT (SMEC), GOETH, HEM, LEPIDOCROCITE, BAR, SULFIDES (SP, MARC, CP, PY), Mn-RICH SIDERITE, ANHY, MANG (BIRN), TOD. |
| 2 | RED SEA, ZABARGAD FRACTURE ZONE NEAR 23°22'N, 36°07'W (BONATTI ET AL. 1985). | $\sim$2,000 | 1.0 | LINEATED BASALTIC TOPOGRAPHIC HIGHS ALONG FRACTURE ZONE AWAY FROM THE AXIAL ZONE OF VOLCANIC EXTRUSION. | MASSIVE SULFIDES AND METALLIFEROUS SED. (RELICT). | PY, HEM, MAG/SID, SOLID SOLUTIONS. |
| 3 | AFAR RIFT, DANAKIL DEPRESSION (BONATTI ET AL. 1972, TABLES 2, 3). | 0 | 1.0 | AXIAL ZONE OF VOLCANIC EXTRUSION OF INCIPIENT OCEANIC SPREADING CENTER. | A) Fe-RICH ENCRUSTATION (RELICT). | GOETH, NONT (SMEC). |
| | | 0 | 1.0 | | B) Mn-RICH ENCRUSTATION (RELICT). | PYROLUSITE, BIRN, TOD, STRONT, BAR, RHOD, OPAL, GYP. |
| 4 | GULF OF ADEN AT 12°34'N, 47°39'E (LAUGHTON ET AL. 1971; CANN ET AL. 1977). | 2,500 | 1.0 | NORTHERN EDGE OF E-W TRENDING LINEAR SEGMENT OF RIFT VALLEY. | A) Mn-RICH ENCRUSTATION (RELICT). | BIRN, TOD. |
| | | | | | B) Fe-RICH ENCRUSTATION (RELICT). | SMEC. |
| 5 | OKINAWA TROUGH AT 27°34.4'N, 127°08.6'E, THE BACK-ARC BASIN OF THE RYUKYU ARC (UYEDA 1987; KIMURA ET AL. 1988). | 1,540 | ---- | SUMMIT CRATER OF A VOLCANIC SEAMOUNT 200 M HIGH IN THE AXIAL ZONE OF VOLCANIC EXTRUSION OF A SPREADING AXIS IN A BACK-ARC BASIN. | A) YELLOW MATERIAL AT TOP OF MOUND 5-6 M HIGH AND 15-25 M WIDE (ACTIVE). | AMORPH SILICA, Fe HYDROXIDE. |
| | | | | | B) DARK-COLORED MATERIAL AT BASE OF SAME MOUND. | Mn ENCRUSTATION. |
| 6 | MARIANA TROUGH AND WEST MARIANA RIDGE, VARIOUS LOCATIONS FROM 12°-28°N (LONSDALE & HAWKINS 1985; HEIN ET AL. 1987, TABLES 3, 11). | 50-3,900 | 3.0 | BACK-ARC BASIN, SEAMOUNTS, VOLCANIC ISLAND MARGINS. | Fe-Mn ENCRUSTATIONS, HYDROGENEOUS AND HYDROTHERMAL (ACTIVE AND RELICT). | $\delta$-$MnO_2$, BIRN, TOD. |
| 7 | MARIANA TROUGH WEST OF PAGAN ISLAND NEAR 18°13'N, 144°41'E (HORIBE ET AL. 1986; CRAIG ET AL. 1987; KASTNER ET AL. 1987; LONSDALE & HAWKINS 1987). | 3,600-3,700 | 3.0 | FISSURE SYSTEMS AND COLLAPSE STRUCTURES NEAR SUMMITS OF ELONGATE VOLCANOES 200-1,000 M HIGH ALIGNED ALONG THE SPREADING AXIS IN THE AXIAL ZONE OF VOLCANIC EXTRUSION OF A BACK-ARC BASIN. | MASSIVE SULFIDES AT TWO VENT AREAS (ACTIVE). | SP, GAL, CP, BAR, CHIMNEY MATRIX, SILICA AS OPAL-A, Fe AND Mn OXYHYDROXIDES. |
| 8 | MARIANA TROUGH, DSDP SITE 456 AT 17°56.7'N, 145°10.8'E (NATLAND & HEKINIAN 1982). | 3,586 | 1.4-2.2 | LOCAL BATHYMETRIC HIGH ON THE EAST SIDE OF A BACK-ARC BASIN $\sim$20 KM FROM SPREADING AXIS IN CRUST 1.6-2.5 X $10^6$ Y OLD. | DISSEM SULFIDES AT 134-169 M BELOW SEAFLOOR AS VESICLE FILLINGS AND GRAIN-BOUNDARY ZONES IN ALTERED BASALT (RELICT). | EUHEDRAL PY, CP, DIGENITE, Fe HYDROXIDE, CALCITE, WAIRAKITE, CHLORITE, OPAL. |
| I. <u>VOLCANIC-HOSTED DEPOSITS (CONTINUED)</u> | | | | | | |
| | **EARLY STAGE OF OPENING OF AN OCEAN BASIN** | | | | | |
| | **INTERMEDIATE- TO FAST-SPREADING (HALF RATE > 2 CM/Y)** | | | | | |
| 9 | MANOS BASIN AT 3°09.7'S, 150°16.8'E (BOTH ET AL. 1986). | 2,500 | > 5 | CREST OF AXIAL VOLCANO IN RIFT VALLEY OF LINEAR SEGMENT OF SPREADING AXIS IN A BACK-ARC BASIN. | MASSIVE SULFIDE CHIMNEYS (RELICT). | NO INFORMATION. |
| 10 | WESTERN WOODLARK BASIN, NEAR 9°55'S, 151°50'E (BINNS ET AL. 1986; MCCONACHY ET AL. 1986). | ------ | $\geq$ 5 | FLANK OF AXIAL VOLCANO IN RIFT VALLEY OF LINEAR SEGMENT OF SPREADING AXIS IN ANDESITIC VOLCANIC ROCKS OF A BACK-ARC BASIN. | STRATIFORM LAYERED Fe-Mn-$SiO_2$ OXIDE MATERIAL (ACTIVE). | NO INFORMATION. |
| 11 | LAU BASIN AT 16°55'S, 176°50'W (BERTINE & KEENE 1975). | 1,664-1,990 | ---- | TOPOGRAPHIC HIGH OF BASALT IN A FRACTURE ZONE OFFSETTING AN ACTIVE SPREADING AXIS IN A BACK-ARC BASIN. | HYALOCLASTITES (RELICT). | OPAL-CEMENTED HYALOCLASTITES CONTAINING FRAGMENTS OF GLASS, PALAGONITE, PLAG, AUGITE, AND AUTHIGENIC MONT, PHILLIPSITE AND BAR CRYSTALS. |
| 12 | LAU BASIN NEAR 18°30'S, 177°00'W (CRONAN ET AL. 1986). | 2,444-2,724 | ---- | BACK-ARC BASIN. | METALLIFEROUS SEDIMENTS ACTIVE). | Mn, Fe, Cu, Zn, AND As IN NON-DETRITAL FRACTION OF BROWNISH FORAMINIFERAL OOZE CONTAINING VARIABLE AMOUNTS OF VOLCANICLASTIC MATERIAL. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 13 | VALU FA RIDGE IN SOUTHERN LAU BASIN NEAR 22°15'S, 176°37'W. | 1,600–1,800 | —— | A 2 KM WIDE BY 60 KM LONG RIDGE OF FRESH VESICULAR BASALTS AT SPREADING AXIS OF A BACK-ARC BASIN. | A) YELLOW NONT. | Fe SILICATE WITH EXTREMELY LOW CONTENT OF TRACE METALS. |
| | | | | | B) Mn OXIDE ENCRUSTATION | BIRN. |
| | | | | | C) DISSEM SULFIDES IN BASALT. | PY, CP, OPAL-CT. |
| 14 | NORTH FIJI BASIN NEAR 16°10'S, 177°25'E (STACKELBERG 1985). | 2,000–3,000 | 3.5 | A NARROW TROUGH-LIKE VALLEY CONTAINING FRESH BASALT. | DISSEM SULFIDES IN BASALT. | NO INFORMATION. |
| 15 | NORTH FIJI BASIN NEAR 16°40'S, 173°30'E (AUZENDE ET AL. 1988). | 2,000–3,000 | 3.5 | A RIDGE-RIDGE-TRENCH TRIPLE JUNCTION. | WATER COLUMN ANOMALIES OF Mn AND METHANE (ACTIVE). | NO INFORMATION. |
| I. | VOLCANIC-HOSTED DEPOSITS (CONTINUED) | | | | | |
| | **ADVANCED STAGE OF OPENING OF AN OCEAN BASIN** | | | | | |
| | **SLOW-SPREADING (HALF RATE $\leq$ 2 CM/Y)** | | | | | |
| 16 | ALPHA RIDGE IN ARCTIC OCEAN AT 85°49.8'N, 109°09.2'W (VAN WAGONER & ROBINSON 1985; JACKSON ET AL. 1986; STOFFYN-EGLI 1987). | 1,365 | —— | SOUTHERN SIDE OF THE NORTHERN CREST OF AN ASEISMIC RIDGE RELATED TO A FORMER SPREADING AXIS. | BIOSILICEOUS SED OF CRETACEOUS (LATE MAASTRICHTIAN) AGE ENRICHED IN Mn AND Fe AND ALTERED BASALT WITH Mn AND Fe ENCRUSTATION (RELICT). | Mn OXIDE, GOETH. |
| 17 | KOLBEINSEY RIDGE ABOUT 100 KM NORTH OF ICELAND NEAR 67°05.5'N, 18°42'W (STEFANSSON 1983) | 100 | 1.1–1.5 | SUBMARINE VOLCANO AT SEAWARD EXTENSION OF NEOVOLCANIC RIFT ZONE. | HYDROTHERMAL DISCHARGE DETECTED AND SAMPLED (ACTIVE); NO INFORMATION ON DEPOSITS. | NO INFORMATION. |
| 18 | NORTH ATLANTIC OCEAN BASIN BETWEEN LAT 20°N–60°N (HOROWITZ & CRONAN 1976, TABLE 1; DSDP SITES 9A, 10, 112, 114, 117A, 118, 136, 137, 138, 141). | 4,700–5,400 | 1.1–1.5 | BASAL SEDIMENT ($10^6$ M.Y. AGO TO RECENT) DIRECTLY OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 IN BASINS ON EASTERN AND WESTERN FLANKS OF OCEANIC RIDGE. | SEDIMENT (RELICT). | GOETH, Fe-RICH MONT (SMEC), Mn HYDROXY-OXIDES. |
| 19 | AZORES-ICELAND RIDGE CREST, 43–47°N, 27–30°W (GROUSSET & DONARD 1984). | 2,000–2,600 | 1.1–1.5 | RIFT VALLEY AND FLANKS OF MID-OCEANIC RIDGE. | SEDIMENT (RELICT). | NO INFORMATION. |
| 20 | MAR CREST NEAR LAT. 45°N (CRONAN 1972). | 2,000–2,600 | 1.1–1.5 | RIFT VALLEY FLOOR AND WALLS AND RIFT MOUNTAINS ALONG LINEAR SECTIONS OF SPREADING CENTER. | SEDIMENT (RELICT). | AMORPH Fe OXIDES. |
| 21 | FAMOUS AREA OF MAR CREST AT 36°57'N, 33°04'W (ARCYANA 1975; HOFFERT ET AL. 1978, TABLE 2). | 2,700 | 1.1 | SHORT-OFFSET (~22 KM) TRANSFORM FAULT SECTION OF A FRACTURE ZONE. | A) BROWNISH RED, YELLOW, AND GREEN CLAY-RICH ENCRUSTATION (RELICT). | SMEC OF NONT COMPOSITION, HYDROMICA, MINOR TOD, BIRN, MANG. |
| | | 2,700 | 1.1 | | B) BLACK Fe-Mn RICH CONCRETION (RELICT). | TOD, RANCIEITE, AMORPH HYDRATED Fe OXIDE. |
| 22 | WESTERN CENTRAL NORTH ATLANTIC OCEAN BASIN AT 34°54'N, 69°10'W (DSDP SITE 105; HOLLISTER ET AL. 1972). | 5,251 | 1.1–1.5 | OXFORDIAN-KIMMERIDGIAN RED, CLAYEY LIMESTONE OVERLYING BASALT UNDERLYING LOWER CONTINENTAL RISE HILLS. | VEINLET (RELICT). | NATIVE COPPER CRYSTALS BORDERED BY PALAGONITE. |
| 23 | TAG HYDROTHERMAL FIELD AT MAR CREST NEAR 26°08'N, 44°49'W (SCOTT ET AL. 1974, TABLES 1B, 2; RONA 1980B; RONA ET AL. 1984; THOMPSON ET AL. 1985; LALOU ET AL. 1986; RONA ET AL. 1986, TABLES 1, 2; THOMPSON ET AL. 1988, TABLES 1–5; HANNINGTON ET AL. 1988, TABLE 1). | 2,000–3,500 | 1.3 | FAULT ZONES BETWEEN FAULT BLOCKS 4.5 TO 6.5 KM EAST OF SPREADING AXIS ON EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF SPREADING AXIS. | A) MASSIVE Fe SULFIDE; YELLOW TO GREY LAYERED XLLINE CHIMNEY FRAGMENTS. | PYR, MARC, SP, ARAGONITE. |
| | | | | | B) ENCRUSTATION AND INTERLAYERED BLACK XLLINE LAYERED PRECIPITATES (INTERMITTENTLY ACTIVE). | BIRN, TOD. |
| | | | | | C) INTERLAYERED GREEN EARTHY PRECIPITATES (INTERMITTENTLY ACTIVE). | NONT. |
| | | | | | D) INTERLAYERED RED EARTHY PRECIPITATES (INTERMITTENTLY ACTIVE). | AMORPH Fe HYDROXIDES. |
| | | 3,620–3,670 | 1.3 | MOUND UP TO 250 M WIDE AND 50 M HIGH AT FAULT ZONE IN MARGINAL ZONE OF ACTIVE EXTENSION 1.5 KM EAST OF SPREADING AXIS AT JUNCTURE BETWEEN FLOOR AND EAST WALL OF RIFT VALLEY. THE MOUND CONSISTS MAINLY OF MASSIVE SULFIDES WITH AN ESTIMATED BULK DRY SALT-FREE WT. OF 5 X $10^6$ TONNES. | E) MASSIVE Cu-Fe SULFIDE: DENSE YELLOW MATERIAL FROM INNER PORTION OF CHIMNEY WALL (ACTIVE). | PY, MARC, CP, SP DIGENITE, ATACAMITE. |
| | | | | | F) MASSIVE Zn-Fe SULFIDE: SPONGY-TEXTURED, FRIABLE INTERGROWTH OF YELLOW PY AND BLACK SP (ACTIVE). | SP, PY, ARAGONITE. |
| | | | | | G) SULFATE, GREY, COARSE GRANULAR. | ANHYDRITE. |
| | | | | | H) CHLORIDE, DARK GREEN CRYSTALS ON Fe OXIDE. | ATACAMITE, PARATACAMITE, GOETH. |
| | | | | | I) CARBONATE, WHITE, BOTRYOIDAL LINING IN CHIMNEY CAVITY AND AS WHITE VEINS IN SULFIDE. | ARAGONITE, CALCITE. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 23 | TAG HYDROTHERMAL FIELD (CONT.) | | | | J) SILICA, GREY PEBBLES AND REDDISH WHITE FRAGMENTS. | AMORPH. QTZ, HEM. |
| 24 | MAR CREST AT 25°48.5'N, 44°59.0'W (RONA ET AL. 1982, 1984; RONA 1984, TABLE 2, LOCATION 7). | 2,725–3,295 | 1.2 | FAULT ZONE BETWEEN FAULT BLOCKS OF EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF SPREADING AXIS. | DISSEM AND VEIN SULFIDES AND QTZ VEINS IN GREENSTONE (RELICT). | PY, CHLORITE, QTZ. |
| 25 | MAR CREST AT 24°21'N, 46°12'W (RONA ET AL. 1980; RONA & GRAY 1980; RONA 1984, TABLE 2, LOCATION 8). | 3,200 | 1.2 | FAULT ZONE BETWEEN FAULT BLOCKS OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF SPREADING AXIS. | EUHEDRAL QTZ DEPOSITED AT ~300°C IN VUG LININGS AND MASSIVE QTZ IN VEINS IN GREENSTONE WITH DISSEM AND VEIN SULFIDES (RELICT). | QTZ, CHLORITE, PY, CP. |
| 26 | MAR CREST NEAR 23°35'N, 45°00'W AT E. INTERSECTION WITH KANE FRACTURE ZONE (GALLINATTI 1984; DELANEY ET AL. 1987; KELLEY & DELANEY 1987). | 3,200–3,500 | 1.3–1.4 | FAULT SCARPS BETWEEN FAULT BLOCKS OF WEST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION NEAR INTERSECTION WITH LONG-OFFSET (~170 KM) TRANSFORM SECTION OF KANE FRACTURE ZONE. | QTZ-RICH GREENSTONE BRECCIAS WITH DISSEM SULFIDES; FLUID INCLUSIONS INDICATE QTZ PRECIPITATION BETWEEN 200°–290°C (RELICT); ALTERED GABBRO AND BASALT. | QTZ, PY, CP, CHLORITE, AMPHIBOLE, SMEC. |
| 27 | SNAKE PIT HYDROTHERMAL FIELD AT MAR NEAR 23°22.1'N, 44°57.0'W SAMPLED BY OCEAN DRILLING PROGRAM (ODP) HOLES 649 A–J (ODP LEG 106 SCI. PARTY 1986; HONNOREZ ET AL. 1986) AND BY SUBMERSIBLE (KARSON ET AL. 1987; THOMPSON ET AL. 1988). | —— | 1.3 | LINEAR TOPOGRAPHIC HIGH OF BASALT ALONG PRESENT SPREADING AXIS AT CENTER OF RIFT VALLEY. | MASSIVE SULFIDE, DENSE BRASSY; MASSIVE SULFIDES, FRIABLE, BLACK. | DENSE, BRASSY MASSIVE SULFIDES: PY, Zn-RICH ISOCUBANITE, Zn-RICH CP, PO, MARC. FRIABLE, BLACK MASSIVE SULFIDES: Zn-RICH ISOCUBANITE, SP, PO. ALSO BN, COV, CHLORITE, TALC. |
| 28 | WEST FLANK OF MAR AT LAT 23°N (THOMPSON ET AL. 1975). | ~4,000 | 1.4 | BLOCK-FAULTED TOPOGRAPHIC HIGH IN ABYSSAL HILLS 60 KM WEST OF RIFT VALLEY. | ENCRUSTATION (RELICT). | TOD. |
| 29 | MAR CREST AT 22°30.2'N, 45°00.3'W (RONA ET AL. 1982; RONA 1984, TABLE 2, LOCATION 11). | 2,535–2,820 | 1.4 | FAULT ZONE BETWEEN FAULT BLOCKS OF EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF SPREADING AXIS. | DISSEM SULFIDES AND QTZ VEINS IN GREENSTONE (ACTIVE). | PY, QTZ, CHLORITE (PENNINITE). |
| 30 | MAR CREST AT 16°47.7'N, 46°22.8'W (RONA ET AL. 1982; RONA 1984, TABLE 2, LOCATION 12; EBERHART ET AL. 1988). | 3,200–3,300 | 1.4–2.0 | FAULT ZONE BETWEEN FAULT BLOCKS OF EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION. | ENCRUSTATION UP TO 2.5 CM THICK (RELICT). | Mn OXIDE. |
| 31 | MAR CREST NEAR 14°56'N, 44°54'W (RONA ET AL. 1987; EBERHART ET AL. 1988). | 3,000–3,500 | 1.4 | FAULT ZONES BETWEEN FAULT BLOCKS OF EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ASSOCIATED WITH SERPENTINE DIAPIRISM NEAR EASTERN NON-TRANSFORM INTERSECTION OF LINEAR SEGMENT OF SPREADING AXIS WITH 15°20'N FRACTURE ZONE. | HYDROTHERMAL PRECIPITATES (ACTIVE). | NO INFORMATION. |
| 32 | MAR CREST AT 12°48.0'N, 44°47.3'W (RONA ET AL. 1982; RONA 1984, TABLE 2, LOCATION 13). | 2,205–2,440 | 1.4–2.0 | FAULT ZONE BETWEEN FAULT BLOCKS OF EAST WALL OF RIFT VALLEY IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF SPREADING AXIS. | DISSEM AND VEIN SULFIDES IN GREENSTONE (RELICT). | PY, CHLORITE. |
| 33 | EQUATORIAL MAR AT LAT. 11°N (BONATTI ET AL. 1976A; KIRST 1976). | 2,700–3,100 | 2.0 | LONG-OFFSET (300 KM) TRANSFORM FAULT SEGMENT OF VEMA FRACTURE ZONE. | DISSEM AND VEIN SULFIDES (STOCKWORK-TYPE) IN METABASALT (CHLORITIC) (RELICT). | CP, PY, PO, CHLORITE. |
| 34 | EQUATORIAL MAR AT LAT 0° (BONATTI ET AL. 1976A, B, TABLE 1; KIRST 1976). | 2,700–3,100 | 2.0 | LONG-OFFSET (980 KM) TRANSFORM FAULT SEGMENT OF ROMANCHE FRACTURE FRACTURE ZONE. | SULFIDE CONCRETIONS; DISSEM AND VEIN SULFIDES (STOCKWORK-TYPE) IN METABASALT (CHLORITIC) (RELICT). | CP, PYR, PO, GOETH, CHLORITE. |
| 35 | MAR CREST AND FLANKS IN SOUTH ATLANTIC OCEAN BASIN BETWEEN LAT 28°S AND 31°S (BOSTROM ET AL. 1972, TABLE 4; DSDP HOLES 14, 15, 16, 19, 20, 21, 22; PETERSEN 1984, DSDP HOLES 519A, 522B, 524). | 2,110–4,675 | 2.0 | BASAL SEDIMENT (LATE CRETACEOUS TO PLEISTOCENE AGE) OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 ON WEST FLANK OF MAR; BASALT ON EAST FLANK OF MAR | SEDIMENT; DISSEM SULFIDES IN BASALT (RELICT). | SID IN SEDIMENT; PO, ILMENITE, CHROMIUM SPINEL, TITAN, MAG IN BASALT. |
| 36 | NORTH FLANK OF SOUTHWEST INDIAN RIDGE AT DSDP SITE 251 AT 36°30.3'S, 49°29.1'E (KEMPE ET AL. 1974). | 3,489 | —— | ABYSSAL HILLS ON FLANK OF AN OCEANIC RIDGE. | BASAL RECRYSTALLIZED CALCIUM CARBONATE-RICH SED OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 (RELICT). | METASOMATIC ANDRADITIC HYDROGROSSULAR GARNET. |
| 37 | CARLSBERG RIDGE AT 5°24'S, 68°35'E IN NW INDIAN OCEAN (DMITRIEV ET AL. 1970; ROZANOVA & BATURIN 1971; BATURIN & ROZANOVA 1976; RONA ET AL. 1981). | 3,500 | 2.0 | BLOCK-FAULTED TOPOGRAPHIC HIGH IN MARGINAL ZONE OF ACTIVE EXTENSION AT INTERSECTION OF WEST WALL OF RIFT VALLEY WITH LONG OFFSET (~185 KM) TRANSFORM FAULT SEGMENT OF VITYAZ FRACTURE ZONE. | A) DISSEM GRAINS AND VEINS (STOCKWORKS) IN HYDROTHERMALLY ALTERED "AMPHIBOLITE" (RELICT).<br>B) DISSEM GRAINS AND VEINS (STOCKWORKS) IN "METASOMATIC" GRANULITE (RELICT). | PY, CP, ILMENITE, HEM, Fe HYDROXIDES, MALACHITE, COV.<br>ILMENITE, PO, PENT, Fe HYDROXIDES, LEUCOXENE, MAG. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 38 | ABYSSAL HILLS ON SW FLANK OF CARLSBERG RIDGE AT DSDP SITE 236 AT 1°40.6'S, 57°35.9'E (CRONAN ET AL. 1974). | 4,487 | ---- | ABYSSAL HILLS ON FLANK OF AN OCEANIC RIDGE. | BASAL SEDIMENT OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 (RELICT). | Fe-RICH (< 28 PERCENT) PHASES; MINERALOGY NOT SPECIFIED. |
| 39 | GORDA RIDGE AT 41°31'N, 127°27'W (CLAGUE ET AL. 1984, TABLE 6; CLAGUE & HOLMES 1985). | 3,350 | 1.2 | FAULT ZONE AT BASE OF WEST WALL OF RIFT VALLEY IN ZONE ON TRANSVERSE STRUCTURAL DISCONTINUITY BETWEEN SOUTHERN AND CENTRAL SECTIONS OF GORDA RIDGE. | A) STRATIFORM, LAYERED IRON SILICATES WITH HOLES PRODUCED BY WORM TUBES (RELICT).<br>B) STRATIFORM, LAYERED Mn OXIDE PRECIPITATES INTERLAYERED WITH NONT (RELICT). | NONT INTERLAYERED WITH ALTERED DETRITAL SED (ILLITE, SMEC, CHLORITE, QTZ, PLAG).<br>BIRN, TOD. |
| | I. VOLCANIC-HOSTED DEPOSITS (CONTINUED) | | | | | |
| | **ADVANCED STAGE OF OPENING OF AN OCEAN BASIN** | | | | | |
| | **INTERMEDIATE- TO FAST-SPREADING (HALF RATE > 2 CM/Y)** | | | | | |
| 40 | DELLWOOD SEAMOUNTS AND DELWOOD KNOLLS NEAR 50°46'N, 130°53'W (PIPER ET AL. 1975; RIDDIHOUGH ET AL. 1980; BLAISE ET AL. 1984; GROSS 1987). | NO DATA? | ? | THREE AND TWO BASALTIC VOLCANIC PEAKS, RESPECTIVELY, ORIENTED NW-SE ON THE FLANKS OF ACTIVE SPREADING AXES. | Fe AND Zn-RICH SEMI-CONSOLIDATED SED AND ALTERED BASALT WITH Mn-RICH ENCRUSTATIONS. | NO INFORMATION. |
| 41 | NORTHERN SEGMENT OF EXPLORER RIDGE (SE EXPLORER DEEP) NEAR 50°05'N, 129°45'W (GRILL ET AL. 1981). | 3,000-3,200 | 2.1 | MEDIAN RIDGE FLANKED BY SEDIMENTARY BASINS IN AXIAL ZONE OF VOLCANIC EXTRUSION ALONG LINEAR SEGMENT OF RIFT VALLEY. | A) ENCRUSTATION (RELICT).<br>B) ENCRUSTATION (RELICT). | NONT (SMEC).<br>BIRN, TOD. |
| 42 | SOUTHERN SEGMENT OF EXPLORER RIDGE, MAGIC MOUNTAIN SITE, NEAR 49°45'N, 130°18'W (SCOTT ET AL. 1984, 1985; SCOTT 1987; CHASE ET AL. 1985A, 1986; TUNNICLIFFE ET AL. 1986). | 1,800 | 3.0 | FAULT SCARPS IN MARGINAL ZONES OF ACTIVE EXTENSION ALONG 9 KM LONG LINEAR SEGMENT OF TWO PARALLEL VALLEYS AND INTERVENING RIDGE INTERSECTED BY ORTHOGONAL FRACTURE SYSTEM. | MASSIVE SULFIDES IN ∼60 HYDROTHERMAL VENTS, CHIMNEYS, AND INDIVIDUAL MOUNDS UP TO 20 M IN DIAM. WHICH COALESCE TO FORM STRATIFORM MOUNDS UP TO 200 M IN DIAM. X 25 M HIGH (E.G., PARIZEAU DEPOSIT; ACTIVE). | CP, MAR, SP, WURTZITE, BAR, PY, AMORPH SILICA. |
| 43 | ABYSSAL HILLS AT WESTERN FLANK OF EXPLORER RIDGE AT 49°40.5'N, 131°56.2'W (BORNHOLD ET AL. 1981). | 3,260 | 3.0 | PARTLY SED COVERED ABYSSAL HILLS 100 KM WEST OF SPREADING AXIS. | BASAL UNIT 10 CM THICK OF METALLIFEROUS LUTITE CONTAINING ABUNDANT Fe AND Mn OXIDE FRAGMENTS AND OLIVINE BASALT CLASTS OVERLYING BASALT RECOVERED IN 1.6-M LONG SEDIMENT CORE (RELICT). | Mn-OXIDE AND Fe-OXIDE MINERALS. |
| 44 | ENDEAVOR SEGMENT OF THE JUAN DE FUCA RIDGE CREST AT 47°56.7'N, 129°05.8'W (MORGAN & SELK, 1984; HAMMOND ET AL. 1984; KARSTEN ET AL. 1984; MERGE GROUP 1984; TIVEY & DELANEY 1985, 1986). | 2,090-2,120 | 3.0 | FAULT SCARPS IN MARGINAL ZONES OF ACTIVE EXTENSION AT BASE OF WEST WALL ALONG LINEAR SEGMENTS OF THE RIFT VALLEY ABOUT 20 KM LONG. | MASSIVE SULFIDES (ACTIVE). | PY, PO, CP, SP, WURTZITE, MARC, BAR, AMORPH SILICA, CHALCEDONY. |
| 45 | SPLIT SEAMOUNT NEAR COBB OFFSET OF JUAN DE FUCA RIDGE NEAR 47°35'N, 128°58'W (MURNAME & CLAGUE 1983; CRANE ET AL. 1985). | ------ | ---- | A 450 M-HIGH FAULTED VOLCANO IN AXIAL ZONE OF VOLCANIC EXTRUSION ALONG OVERLAPPING SPREADING CENTER (COBB-OFFSET). | Fe-RICH NONT CRUST DREDGED AT COBB-OFFSET (ACTIVE). | NONT, TOD, BIRN. |
| 46 | "ET" AREA, AXIAL VALLEY OF JUAN DE FUCA RIDGE NEAR 46°50'N, 128°25'W (CRANE ET AL. 1985). | ------ | ---- | A 20 KM-LONG, 200 M-HIGH DOMED AREA INCISED BY NARROW RIFT ALONG SPREADING AXIS IN AXIAL ZONE OF VOLCANIC EXTRUSION. | MOUNDS AND COALESCED CHIMNEYS PHOTOGRAPHED, ASSOCIATED WITH WATER TEMPERATURE ANOMALIES (ACTIVE). | NO INFORMATION. |
| 47 | BROWN BEAR SEAMOUNT ADJACENT TO AXIAL SEAMOUNT AT CENTRAL JUAN DE FUCA RIDGE NEAR 46°02'N, 130°33'W (SAMSON 1985). | ------ | ---- | VOLCANIC SEAMOUNT. | BASALT COATED WITH POLYMETALLIC GOSSAN (RELICT). | NO INFORMATION. |
| 48 | AXIAL SEAMOUNT AT CREST OF CENTRAL JUAN DE FUCA RIDGE NEAR 45°59'N, 130°04'W AT INTERSECTION WITH COBB-EIKELBERG SEAMOUNT CHAIN (MALAHOFF ET AL. 1984; CHASE ET AL. 1985B; HANNINGTON ET AL. 1986). | 1,500 | 3.0 | FISSURED CALDERA (10 X 5 KM) OF SEAMOUNT APPARENTLY INTERSECTED BY SPREADING AXIS AND AT INTERSECTION WITH SEAMOUNT CHAIN. | MASSIVE SULFIDES, SULFATES, SILICATES AND OXIDES IN VENT FIELDS AT NE AND SW SECTIONS OF CALDERA. COMPOSITION GIVEN IS OF SULFIDE CHIMNEY (ACTIVE). | SP, WURTZITE, MARC, BAR, AMORPH SILICA, MINOR CP, GAL, TET. |
| 49 | SOUTHERN JUAN DE FUCA RIDGE CREST NEAR 44°39'N, 130°22'W NORTH OF INTERSECTION WITH BLANCO FRACTURE ZONE (DELANEY ET AL. 1981; JONES ET AL. 1981; NORMARK & CLAGUE 1983; NORMARK ET AL. 1982, 1983; KOSKI ET AL. 1984, 1985A,B; BISCHOFF ET AL. 1983; U.S. GEOLOGICAL SURVEY, JUAN DE FUCA STUDY GROUP 1986; BRETT ET AL. 1987). | 2,200 | 3.0 | AT LEAST 7 ACTIVE VENT ZONES IN NARROW GRABEN (30-50 M WIDE BY 10-30 M DEEP) IN TOPOGRAPHIC HIGH ALONG AXIAL ZONE OF VOLCANIC EXTRUSION NEAR INTERSECTION WITH LONG-OFFSET (∼350 KM) TRANSFORM FAULT OF BLANCO FRACTURE ZONE. | A) ANGULAR SLABS OF DARK GREY Zn-RICH SULFIDE (TYPE A; ACTIVE).<br>B) SPONGY-TEXTURED GREY Fe-POOR SULFIDE (TYPE B; ACTIVE). | PY, CP, SP, WURTZITE, MINOR GAL, MAG, GOETH, HEM, MARC, ISOCUBANITE, ANHY LIZARDITE, STARKEYITE, ANASTASE.<br>PRIMARILY Fe-POOR COLLOFORM AND OPALINE SILICA. |
| 50 | NORTH WALL OF THE GORDA DEPRESSION IN THE BLANCO TRANSFORM FAULT NEAR 43°13'N, 127°06'W (HART ET AL. 1986, TABLE 4). | 2,300-4,100 | 3.0 | WALL OF TRANSFORM FAULT EXPOSING ALTERED BASALTS, GREENSCHIST GABBROS, AND GREENSCHIST BRECCIAS. | DISSEM AND VEIN SULFIDES IN GREENSCHIST GABBROS AND GREENSCHIST BRECCIAS. | PENT, PO, PY DISSEM IN GREENSCHIST GABBROS; CP, SP, PY, BN, GAL IN CHLORITE VEINS AND DISSEM IN ALTERED BASALT AS FRAGMENTS IN GREENSCHIST BRECCIA. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 51 | GORDA RIDGE CREST NEAR 42°59'N, 126°34'W (RONA ET AL. 1985; BAKER ET AL. 1987B; NELSEN ET AL 1987). | 3,300 | 2.8 | INTERSECTING NE-SW AND N-S FAULT ZONES BETWEEN VOLCANIC RIDGE ALONG SPREADING AXIS AND EAST WALL OF RIFT VALLEY. | NO INFORMATION (ACTIVE). | ANHY AND ATACAMITE IN WATER COLUMN. |
| 52 | GORDA RIDGE CREST NEAR 42°45'N, 126°42'W (RONA & CLAGUE 1986; NELSEN ET AL. 1987; HOWARD & FISK 1986, 1988). | 2,700-3,100 | 2.8 | INTERSECTING NE-SW AND N-S FAULT ZONES BOUNDING SOUTHERN END OF ANOMALOUS RIDGE (1 X 0.5 KM WIDE BY 50 M HIGH) AT MID-DEPTH (2,700 M) ON EAST WALL OF RIFT VALLEY AND AT JUNCTURE BETWEEN THE BASE OF THE EAST WALL AND THE FLOOR OF THE RIFT VALLEY (3,100 M). | METALLIFEROUS SEDS, ALTERED BASALTS AND POSSIBLE MASSIVE SULFIDES (ACTIVE). | BOEHMITE COATING BASALT TALUS AT BASE OF EAST WALL. ANOMALOUSLY HIGH COPPER CONTENT IN LAYERS IN METALLIFEROUS SEDS; ANHY AND ATACAMITE PARTICLES IN WATER COLUMN. |
| 53 | GORDA RIDGE SITES ALONG AXIS BETWEEN 42°42'N, 126°45'W AND 42°48'N, 126°42'W AND OFF-AXIS NEAR 42°45'N, 126°42'W (HOWARD & FISK 1986). | 2,600-3,520 | 2.8 | FLOOR AND EAST WALL OF RIFT VALLEY. | THIN FILMS OF HYDROTHERMAL PRECIPITATES ON BASALT SURFACES. | Fe AND Mn OXIDES AND HYDROXIDES, NONT, BOEHMITE, TALC, PY, SP. |
| 54 | CENTRAL NORTH PACIFIC OCEAN BASIN BETWEEN LATITUDES 32°N AND 41°N (DYMOND ET AL. 1973, TABLES 2, 6; DSDP SITES 37, 38, 39). | 3,010-5,137 | ---- | BASAL SED (32-60 M.Y.) OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2. | SEDIMENT (RELICT). | GOETH, Fe-RICH MONT (SMEC), Mn HYDROXYOXIDES. |
| 55 | BOLEO COPPER DISTRICT, CENTRAL BAJA, CALIF. NEAR 27°20'N, 112°20'W (WILSON 1955). | 0 | 3.0 | COASTAL BELT OF FAULTED ANDESITIC VOLCANICS ~60 KM WEST OF SPREADING AXIS IN GUAYMAS BASIN OF THE GULF OF CALIFORNIA. | MASSIVE, DISSEM AND STOCKWORK SULFIDES AND Mn ENCRUSTATIONS IN LAYERS UP TO 5 M THICK HOSTED IN PLIOCENE INTERBEDDED TUFF AND TUFFACEOUS CONGLOMERATE OF ANDESITIC COMPOSITION BETWEEN 50 AND 250 M THICK. | CHALCOCITE, CP, BN, COV, NATIVE COPPER, PY, GAL, COPPER OXIDES, CARBONATES, SILICATES, OXYCHLORIDES, CRYPTOMELANE, PYROLUSITE, GYPS, CALCITE, CHALCEDONY, JASPER. |
| 56 | DSDP HOLE 471 THROUGH THE DISTAL PORTION OF A DEEP SEA FAN WEST OF THE FOOT OF THE CONTINENTAL SLOPE OFF BAJA, CALIF. AT 23°28.9'N, 112°29.8'W (LEINEN 1981; DEVINE & LEINEN 1981). | 3,100 | 3.0 | BASAL METALLIFEROUS SED OF MIDDLE MIOCENE AGE (14.5-15 MA) OVERLYING AND INTERCALATED WITH ALTERED DIABASE SILLS CONSIDERED TO HAVE FORMED AT A FORMER AXIS OF THE EPR. | A) MASSIVE SULFIDE IN LAYER ~35 CM THICK.<br>B) METALLIFEROUS SED IN LAYER ~5 CM THICK, INTERCALATED WITH ALTERED DIABASE SILLS WITHIN 80 M-THICK SECTION PENETRATED. BASAL METALLIFEROUS SED SIMILAR TO THAT DESCRIBED FROM HOLE 471 WAS RECOVERED FROM HOLES 469, 470 AND 472 ALSO LOCATED W. OF BAJA, CALIF. | PY, CP AND SP IN CHERT AND CALCITE GANGUE.<br>NO INFORMATION. |
| 57 | DSDP HOLE 482C IN SED-FILLED VALLEY 12 KM E. OF THE AXIS OF THE EPR AND 15 KM S. OF TAMAYO FRACTURE ZONE AT 22°47.3'N, 107°59.6'W (SHIPBOARD SCIENTIFIC PARTY 1983). | 2,998 | 3.0 | SED-FILLED VALLEY IN ABYSSAL HILLS ON EAST FLANK OF A SPREADING AXIS IN CRUST ABOUT 0.5 X $10^6$ Y OLD. | VEIN 2-3 CM WIDE AND ~40 CM LONG IN BASALT PARTLY FILLED WITH SULFIDES, CARBONATES AND ZEOLITES; VESICLES IN A PRONOUNCED ALTERATION HALO ARE LINED WITH SMEC AND PARTLY FILLED WITH PY AND CARBONATE. | SMEC, PY, CALCITE. |
| 58 | EPR CREST AT LAT. 21°N (CYAMEX 1979; RISE 1980; HEKINIAN ET AL. 1980; HAYMAN & KASTNER 1981; BISCHOFF ET AL. 1983). | 2.620 | 3.0 | BLOCK-FAULTED AND FISSURED MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF A SEAFLOOR SPREADING AXIS. | A) MASSIVE SULFIDE MOUNDS SURMOUNTED BY CHIMNEYS 3 TO 10 M HIGH (ACTIVE).<br>B) EXTERIOR ALTERATION ZONE ON MASSIVE SULFIDE MOUNDS AND CHIMNEYS (RELICT). | PY, CP, MARC, SP, WURTZITE, CUBANITE, DIGENITE, NATIVE SILVER.<br>GOETH, LIMONITE, NONT (GOSSANS PRODUCED BY OXIDATION OF SULFIDES. |
| 59 | "GREEN" SUBMARINE VOLCANO AT 20°48.2'N, 109°17'W, 11 KM W. OF EPR AXIS (LONSDALE ET AL. 1982; ALT ET AL. 1987). | ~2,000 | 3.0 | CALDERA AND PIT CRATERS ON VOLCANIC SEAMOUNT. | Fe OXIDE SEDIMENT AND ENCRUSTATIONS, MASSIVE SULFIDES, SULFATES AND CHLORIDES (INACTIVE). | PY, CP, BAR, ATACAMITE, QTZ, OPAL, CHALCEDONY, MINOR GAL, SP. |
| 60 | "RED SUBMARINE VOLCANO AT 20°48.2'N, 109°22.7'W, 18 KM W. OF EPR AXIS (LONSDALE ET AL. 1982; ALT ET AL. 1987). | ~2,000 | 3.0 | CALDERA OF VOLCANIC SEAMOUNT. | Fe OXIDE SEDS, CHIMNEYS AND Fe-Mn ENCRUSTATIONS (ACTIVE). | AMORPH Fe-OXYHYDROXIDE, Fe-SILICATE (NONT) Fe-RICH TALC AND SULFIDE GRAINS IN NONT. |
| 61 | NORTHEAST PACIFIC NODULE AREA (BISCHOFF & ROSENBAUER 1977, TABLE 2) NEAR 15°12.2'N, 126°58.8'W. | 4,295 | ---- | ABYSSAL HILLS BETWEEN CLARION AND CLIPPERTON FRACTURE ZONES; METALLIFEROUS SEDIMENT MAY BE RELICT. | SEDIMENT (RELICT). | GLOBULES AV. 100 µm DIAM. COMPOSED OF OPAQUE REDDISH-YELLOW AGGREGATES AND DETRITAL MINERALS OF LOW R.I.; MINOR AMOUNTS OF RADIOLARIAN DEBRIS, VOLCANIC GLASS MICRONODULES. |
| 62 | CLARION FRACTURE ZONE NEAR HAWAIIAN RIDGE AT 14°N, 153°W (BEIERSDORF ET AL. 1982) | 5,600-5,840 | ---- | TROUGH 2 KM WIDE BY 7 KM LONG IN FRACTURE ZONE. | ENCRUSTATION (ACTIVE). | Fe-Mn OXIDE CRUSTS CONTAINING SILICEOUS MATERIAL ASSOC. WITH ANOMALOUSLY WARM NEAR-BOTTOM WATER. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 63 | EPR BETWEEN LAT 10°N AND 15°N (CRONAN 1973, TABLE 1; DSDP SITES 159, 160, 161, 162, 163). | 4,500–4,940 | 4.5 | BASAL SEDIMENT (EARLY COMPANIAN TO LATE OLIGOCENE) OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 ON WEST FLANK OF OCEANIC RIDGE. | SEDIMENT (RELICT). | GOETH, Fe-RICH MONT (SMEC), Mn HYDROXY-OXIDE. |
| 64 | EPR NEAR 11°N AND 12°50'N (BALLARD & FRANCHETEAU 1980; HEKINIAN ET AL. 1983; MERLIVAT ET AL. 1987; HEKINIAN & FOUQUET 1985, TABLE 9). | 2,630 | 4.5 | AXIAL GRABEN 200–600 M WIDE IN AXIAL ZONE OF VOLCANIC EXTRUSION AND FLANK OF VOLCANIC SEAMOUNT 6 KM EAST OF SPREADING AXIS AT 12°42'N, 103°52'W. | SED ENCRUSTATION, AND MASSIVE SULFIDE MOUNDS SURMOUNTED BY CHIMNEYS (24 ACTIVE, 60 RELICT) DISTRIBUTED ALONG 20 KM-LONG LINEAR SEGMENT OF SPREADING AXIS AND OTHER MASSIVE SULFIDE DEPOSITS IN AREA (800 X 200 M) ON SUMMIT AND FLANK OF OFF-AXIS VOLCANIC SEAMOUNT.<br>A) Cu-RICH CHIMNEY.<br>B) Zn-RICH CHIMNEY.<br>C) Fe AND Cu-RICH MASSIVE SULFIDE. | Mn OXIDE, WURTZITE, PY, MARC, CP WITH A HIGH CONTENT OF COBALT IN CERTAIN SAMPLES, Fe HYDROXIDE. |
| 65 | EPR CREST NEAR LAT 10°N (BATIZA ET AL. 1977). | 1,720–1,827 | 4.5 | CALDERA OF VOLCANIC SEAMOUNT 15 KM FROM THE RIDGE AXIS. | ENCRUSTATION (RELICT). | "ORANGE BROWN SPONGY AND EARTHY MATERIAL," PROBABLY GOETH. |
| 66 | EPR CREST AT 8°48'N, 103°54'W (LONSDALE ET AL. 1980). | 1,875 | 4.5 | CALDERA OF VOLCANIC SEAMOUNT 30 KM FROM THE RIDGE AXIS. | NODULES (RELICT). | BIRN. |
| 67 | HESS DEEP AT INTERSECTION OF GALAPAGOS SPREADING CENTER AND EPR NEAR 2°15'N, 101°30'W (MURDMAA & ROZANOVA 1976; ROZANOVA 1976; BURNETT & PIPER 1977; SCHMITZ ET AL. 1982). | 5,100–5,440 | — | SEMI-ENCLOSED BASINS AT GALAPAGOS TRIPLE JUNCTION. | LITHIFIED SED AND Fe-Mn ENCRUSTATIONS (RELICT). | TALC, SMEC, PO, TROILITE, Fe-Mn MINERALS. |
| 68 | GALAPAGOS SPREADING CENTER AT 2°30'N, 95°10'W (MOORE & VOGT 1976, TABLE 1). | 2,600 | 3.0 | BLOCK-FAULTED TOPOGRAPHIC HIGH IN MARGINAL ZONE OF ACTIVE EXTENSION. | ENCRUSTATION (RELICT). | BIRN, TOD. |
| 69 | GALAPAGOS SPREADING CENTER NEAR 86°W (WILLIAMS ET AL. 1974; WEISS ET AL. 1977; LUPTON ET AL. 1977; KLINKHAMMER ET AL. 1977; JENKINS ET AL. 1978; EDMOND ET AL. 1979A, B; CORLISS ET AL. 1979; CRANE & BALLARD 1980). | 2,450–2,500 | 3.0 | AXIAL ZONE OF VOLCANIC EXTRUSION ALONG LINEAR SEGMENT OF A SEAFLOOR SPREADING AXIS. | A) ENCRUSTATION (ACTIVE). | Mn OXIDES (MINERALOGY NOT SPECIFIED). |
| | | | | | B) SEDIMENT (ACTIVE). | |
| 70 | GALAPAGOS SPREADING CENTER AT 85°23'W (MALAHOFF ET AL. 1980, 1983). | 2,500–2,600 | 3.0 | INTERSECTION OF AXIAL ZONE OF A SEAFLOOR SPREADING AXIS WITH TRANSFORM FAULT SECTION OF A FRACTURE ZONE. | ENCRUSTATION (RELICT). | Mn OXIDE; MINERALOGY NOT SPECIFIED. |
| 71 | GALAPAGOS SPREADING CENTER NEAR 0°45'N, 85°50'W (MALAHOFF 1982A,B) AND AT 0°45.3'N, 85°49.5'W (SKIRROW & COLEMAN 1982; BACKER & LANGE 1987, TABLE 1; MARCHIG ET AL. 1987; EMBLEY ET AL. 1988; HERZIG ET AL., IN PRESS). | 2,600–2,850 | 3.0 | RELICT MASSIVE SULFIDE BODY AT NORMAL FAULTS IN MARGINAL ZONE OF ACTIVE EXTENSION ALONG LINEAR SEGMENT OF AN ANOMALOUS DOUBLE RIFT VALLEY (NORTHERN AND SOUTHERN RIFT VALLEYS). STOCKWORKS EXPOSED IN HORST BLOCK OF ALTERED BASALT BETWEEN NORTHERN AND SOUTHERN RIFT VALLEYS. ACTIVE SULFIDE CHIMNEYS SURROUNDED BY MOUNDS IN AXIAL ZONE OF VOLCANIC EXTRUSION. | A) MASSIVE SULFIDE BODY APPARENTLY UP TO 1000 X 150 M BY 35 M HIGH FORMED OF COALESCED MOUNDS (PRELIM. EST. WT. $\sim 10 \times 10^6$ TONNES) IN SOUTHERN RIFT VALLEY. INDIVIDUAL MASSIVE SULFIDE MOUNDS IN NORTHERN RIFT VALLEY. STOCKWORKS OF SILICA, CLAYS AND SULFIDES IN ALTERED BASALTS (RELICT). | PY, CP SP. |
| | | | | | B) METALLIFEROUS SEDS. (< 63 µm FRACTION) IN HYDROTHERMAL MOUNDS FORMING AROUND CHIMNEYS (ACTIVE). | OPAL-A AND CT, SMEC, MIXED-LAYER MINERALS, GOETH, MINOR PY AND CP, QTZ, FELD, CALCITE. |
| | | | | | C) METALLIFEROUS SEDS. (< 63 µm FRACTION) SITUATED 5 TO 100 M FROM VENT OUTSIDE MOUNT (ACTIVE). | GOET, MIXED-LAYER MINERALS, SMEC, OPAL-CT, QTZ, BAR, FELD, KAOLINITE, ANALCIME, JAROSITE. |
| | | | | | D) SILICA CHIMNEYS (INACTIVE). | OPAL-A. |
| 72 | SOUTH FLANK OF COSTA RICA RIFT AT 1°13.6'N, 83°43.8'W (DSDP HOLE 504B: SCIENTIFIC PARTY 1980; ANDERSON ET AL. 1982; ALT ET AL. 1986A, B). | 3,460 | 3.25 | ABYSSAL HILLS ON FLANK OF OCEANIC RIDGE IN $6 \times 10^6$ Y OLD OCEANIC CRUST. | DISSEM SULFIDES (MAINLY PY) IN ALTERED BASALT CORED BETWEEN 275 AND 1075 M WITHIN OCEANIC CRUSTAL LAYER 2; STOCKWORK SULFIDES (ABUNDANT PY, CP, SP) CORED BETWEEN 635 AND 655 M WITHIN OCEANIC CRUSTAL LAYER 2 (RELICT). | PY (CRYSTALS UP TO 1 CM), CP, SP, CHLORITE, LAUMONTITE, QTZ, TALC. |
| 73 | WILKES FRACTURE ZONE-EPR INTERSECTION NEAR LAT 9°S (VARNAVAS 1988). | 2,800–3,500 | 7.5 | SED OVERLYING BASALT IN A FRACTURE ZONE ACROSS INTERSECTION WITH A SPREADING AXIS. | METALLIFEROUS COMPONENT IN CALCAREOUS SEDIMENTS (ACTIVE). | Mn-OXIDES, Fe-OXIDES, HYDROXIDES (TOPS OF CORES). |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 74 | EPR AT 10°38'S. 109°36'W. Fe-RICH FRACTION (BONATTI & JOENSUU 1966. TABLE 1. FRACTION A; VEEH & BOSTROM 1971. TABLE 1). | 1.790-2.130 | 7.5 | VOLCANIC SEAMOUNT NEAR RIDGE AXIS. | A) ENCRUSTATION (RELICT). | GOETH. |
| | | | | | B) ENCRUSTATION (RELICT). | Mn OXIDE (ASSUMED TO TO BE BIRN AND TOD.). |
| 75 | EPR BETWEEN LAT 9°S-13°S (BOSTROM ET AL. 1976. TABLE 5; DSDP HOLES 319. 320. 321). | 4.300-4.830 | 7.5 | BASAL SEDIMENT (LATE OLIGOCENE TO QUATERNARY) OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 ON EAST FLANK OF OCEANIC RIDGE. | SEDIMENT (RELICT). | GOETH. Fe-RICH MONT (SMEC). Mn HYDROXYOXIDES. |
| 76 | EPR CREST BETWEEN LAT 12°S-14°S (BOSTROM & PETERSON 1969. TABLE 3: VEEH & BOSTROM 1971. TABLE 1). | 2.990-4.210 | 8.0 | OCEANIC RIDGE CREST. | SEDIMENT (RELICT). | GOETH. Fe-RICH MONT (SMEC). Mn HYDROXYOXIDES. |
| 77 | EPR CREST IN VICINITY OF 15°S (LUPTON & CRAIG 1981). | 3.100 | 8.0 | AXIAL ZONE OF VOLCANIC EXTRUSION. | DEPOSITS INFERRED FROM $^3$He AND $CH_4$ ANOMALIES IN SEAWATER (ACTIVE). | NO INFORMATION. |
| 78 | EPR AXIS BETWEEN 17°54'S AND 18°36'S (BACKER ET AL. 1985). | 2.600-2.650 | 9.0 | INTERSECTION OF GRABENS WITH TOPOGRAPHIC HIGH CENTERED AT 18°30'S IN AXIAL ZONE OF VOLCANIC EXTRUSION. | A) SULFIDES AS CHIMNEYS AND AS MATERIAL IN FISSURES. VOIDS AND DISSEM IN ALTERED BASALTS (ACTIVE). | PY. ISOCUBANITE. CP. ZINC SULFIDES. |
| | | | | | B) METALLIFEROUS SEDS (ACTIVE). | NO INFORMATION. |
| 79 | EPR CREST AT 20°S (CRAIG 1981: BALLARD ET AL. 1981: HUDSON ET AL. 1981: FRANCHETEAU & BALLARD 1983). | ~3.000 | 9.5 | TOPOGRAPHIC HIGH ALONG LINEAR SEGMENT OF AXIAL ZONE OF VOLCANIC EXTRUSION. | MASSIVE SULFIDE MOUNDS SURMOUNTED BY CHIMNEYS INFERRED FROM DEEP-SEA PHOTOS OF BIOTA INDICATIVE OF ACTIVE HYDROTHERMAL VENTS AND GEOCHEMICAL ANOMALIES IN WATER COLUMN (TOTAL DISSOLVABLE Mn; $^3$He; $CH_4$) (ACTIVE). | NO INFORMATION. |
| 80 | EPR AXIS BETWEEN 20°30'S AND 21°45'S (BACKER ET AL. 1985). | 2,775-2,950 | 9.0 | INTERSECTION OF AXIAL GRABENS WITH TOPOGRAPHIC HIGH CENTERED AT 21°30'S. IN AXIAL ZONE OF VOLCANIC EXTRUSION. | SULFIDES AS CHIMNEYS AND AS MATERIAL IN BASALT BRECCIAS AND PYRITE DISSEMIN IN BASALT (ACTIVE). | PY. MARC. CP. ISOCUBANITE. COV. SP. WURTZITE. |
| 81 | EPR AXIS BETWEEN 21°24.0'S. 114°17.1'W AND 21°30.2'S. 114°18.0'W (MARCHIG & GRUNDLACH 1987). | 2.800 | 9.0 | GRABENS ALONG SPREADING AXIS WITHIN AXIAL ZONE OF VOLCANIC EXTRUSION. | AT LEAST 16 VENT ZONES IN 10 KM DISTANCE ALONG SPREADING AXIS (ACTIVE). | NO INFORMATION. |
| 82 | EPR CREST BETWEEN 10°S AND 25°S (HEATH & DYMOND 1977). | ~3.000 | 8.0-9.0 | OCEANIC RIDGE CREST. | SEDIMENT (RELICT). | AMORPH TO POORLY XLLINE Fe-Mn HYDROXIDE. GOETH. $\delta$-$MnO_2$. Fe-RICH SMEC. |
| 83 | EPR AXIS AT 23°32.0'S. 115°34.0'W (MARCHIG & GRUNDLACH 1987). | 2.600-2.650 | 9.0 | TOPOGRAPHIC HIGH ALONG RIDGE WITHIN AXIAL ZONE OF VOLCANIC EXTRUSION NEAR JUNCTURE BETWEEN SPREADING AXIS AND TRANSFORM FAULT. | AT LEAST 6 VENT ZONES IN 2 KM DISTANCE ALONG SPREADING AXIS (ACTIVE). | NO INFORMATION. |
| 84 | EPR AXIS AT 26°12.3'S. 112°36.8'W (MARCHIG & GRUNDLACH 1987). | ~2.550 | 9.0 | JUNCTURE BETWEEN A RIDGE AND A GRABEN WITHIN AXIAL ZONE OF VOLCANIC EXTRUSION. | INCIPIENT MASSIVE SULFIDE CHIMNEYS (ACTIVE). | PY. CP. SP. |
| 85 | WEST PHILIPPINE BASIN AT DSDP SITE 291 (BONATTI ET AL. 1979). | 5.217 | ---- | BACK-ARC BASIN ON FLANK OF INACTIVE SPREADING CENTER. | BASAL SED OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 (RELICT). | SMEC. GOETH. CLINOPTILITE. QTZ. FELD. |
| 86 | WEST PHILIPPINE BASIN AT DSDP SITE 294/295 (BONATTI ET AL. 1979). | 5.784 | ---- | BACK-ARC BASIN ON FLANK ON INACTIVE SPREADING CENTER. | BASAL SED OVERLYING BASALT OF OCEANIC CRUSTAL LAYER 2 (RELICT). | HEM. QTZ. FELD. GOETH. SMEC. |
| 87 | SE INDIAN RIDGE BETWEEN LAT 16° AND 40°S (BOSTROM ET AL. 1969. TABLE 2). | 2.620-4.990 | 2.4-3 | OCEANIC RIDGE CREST. | SEDIMENT (RELICT). | NO INFORMATION. |
| II. | SEDIMENT-HOSTED DEPOSITS | | | | | |
| | **EARLY STAGE OF OPENING OF AN OCEAN BASIN** | | | | | |
| | **SLOW-SPREADING (HALF RATE $\leq$ 2 CM/Y)** | | | | | |
| | NO KNOWN LOCATIONS. | | | | | |
| | **INTERMEDIATE- TO FAST-SPREADING (HALF RATE > 2 CM/Y)** | | | | | |
| 88 | SALTON SEA OF IMPERIAL VALLEY. BAJA. CALIF. NEAR 33°30'N. 116°W (SKINNER ET AL. 1967: ELDERS 1979). | 0 | ---- | AXIAL TROUGH ALONG STRIKE OF GULF OF CALIF. SEAFLOOR SPREADING AXIS. | SULFIDES DISSEM IN WELL SCALE AND RESERVOIR ROCKS (ACTIVE). | WELL SCALE: BN. DIGENITE. CP. CHALCOCITE. STROMEYERITE. NATIVE SILVER.<br>RESERVOIR ROCKS: SP. PY. PO. CP. GAL. |
| 89 | CALIF. BORDERLAND AT 32°14'N. 117°44'W (LONSDALE 1979). | 1.800 | ---- | SCARP OF THE SAN CLEMENTE STRIKE-SLIP FAULT ZONE. | SEDIMENT (RELICT). | BAR. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 90 | NORTHERN BAJA, CALIF. AT 31°45'N, 116°45'W (VIDAL ET AL. 1978, 1981). | 3,000 | --- | ALONG AGUA BLANCA FAULT ZONE. | ENCRUSTATION (ACTIVE). | PY, GYPS. |
| 91 | GUAYMAS BASIN IN GULF OF CALIF. AT 27°18'N, 111°32'W (BISCHOFF & HENYEY 1974; SCIENTIFIC PARTY 1979; LONSDALE ET AL. 1980; LONSDALE 1980; KASTNER & GIESKES, 1981; SIMONEIT & LONSDALE 1982; LONSDALE & BECKER 1985; HANNINGTON ET AL. 1986). | 2,000 | 3.0 | VARIOUS SETTINGS INCLUDING AXIAL ZONE OF VOLCANIC EXTRUSION, FAULT SCARPS IN MARGINAL ZONE OF ACTIVE EXTENSION, AND IN SOUTHERN TROUGH NEAR INTERSECTION WITH AGUA BLANCA FAULT ZONE. | OVER 120 ENCRUSTATION (SINTER) AND MASSIVE SULFIDE MOUNDS SURMOUNTED BY CHIMNEYS UP TO 30 M HIGH (ACTIVE). | Fe-RICH TALC, SMEC, BAR, ANHY, CP, PO, ISOCUBANITE, MARC, SP, GAL, AMORPH SILICA, CALCITE, CLAYS, (Mg SMEC) AND HYDROCARBONS. |
| 92 | CARMEN, FARALLON, PESCADERO BASINS OF GULF OF CALIF. 24°-27°N, 190°-111°W (HEIN & YEH 1979). | ~2,000 | 3.0 | AXIAL ZONE OF VOLCANIC EXTRUSION ALONG LINEAR SEGMENTS OF A SPREADING AXIS. | SEDIMENT (RELICT). | SMEC, CHLORITE, AMORPH SILICA, OOLITIC QTZ, HEM ROCKS. |
| 93 | MARIANA TROUGH, MOUNDS HYDROTHERMAL AREA NEAR 18°05'N, 144°10'E (HEGARTY ET AL. 1980; LEINEN & ANDERSON 1981; HOBART ET AL. 1983; LEINEN ET AL. 1987). | 3,800 | 3.0 | ZONE OF NORMAL FAULTING OBLIQUE TO RIDGE-PARALLEL ABYSSAL HILLS ABOUT 50 KM WEST OF SPREADING AXIS IN BACK-ARC BASIN IN OLD OCEANIC CRUST. | CONICAL TO HUMMOCKY SED MOUNDS 1-2 M HIGH COMPOSED OF Mn OXIDE ENCRUSTATIONS AND FERRUGINOUS SED WITH SMEC VEINS IN PELAGIC BROWN CLAY (ACTIVE). | Mn-Fe OXIDES AND HYDROXIDES, SMEC. |
| 94 | MARIANA TROUGH AND WEST MARIANA RIDGE, VARIOUS LOCATIONS FROM 12°-28°N (HEIN ET AL. 1987, TABLES 3, 11). | 50-<br>3,900 | 3.0 | BACK-ARC BASIN, SEAMOUNTS, VOLCANIC ISLAND MARGINS. | Fe-Mn ENCRUSTATIONS, HYDROGENEOUS AND HYDROTHERMAL (ACTIVE AND RELICT). | δ-MnO$_2$, BIRN, TOD. |
| 95 | BRANSFIELD STRAIT BASIN AT THE ANTARCTIC PENINSULA NEAR 63°S, 60°W (SUESS 1987; BRAULT & SIMONEIT 1987; SCHLOSSER ET AL. 1987). | 2,000 | --- | PARTLY SED-FILLED ACTIVE BACK-ARC BASIN WITH PROTRUDING VOLCANIC RIDGES. | GREEN-BLACK BIOGENIC OOZE GRADING INTO HYDROTHERMALLY ALTERED RED AND GREY SEDS (ACTIVE). | MARINE ORGANIC MATTER ALTERED TO BITUMEN; NO INFORMATION ON MINERALS. |
| II. | <u>SEDIMENT-HOSTED DEPOSITS (CONTINUED)</u><br>**ADVANCED STAGE OF OPENING OF AN OCEAN BASIN**<br>**SLOW-SPREADING (HALF RATE $\leq$ 2 CM/Y)** | | | | | |
| 96 | ESCANABA TROUGH OF SOUTHERN GORDA RIDGE NEAR 40°45'N, 127°30'W (SESCA) AND 41°00'N, 127°30'W (NESCA) (CLAGUE ET AL. 1984; CLAGUE & HOLMES 1987; MORTON ET AL. 1986; HOLMES ET AL. 1987; ZIERENBERG ET AL. 1986; KOSKI & KVENVOLDEN 1986; KOSKI & ZIERENBERG 1987; MORTON ET AL. 1987). | 3,200-<br>3,300 | 1.1 | VOLCANIC CENTERS 3-6 KM IN DIAMETER WHICH INTRUDE SEDIMENT-FILL (< 500 M THICK) OF RIFT VALLEY ALONG SPREADING AXIS. | MASSIVE SULFIDE AND SULFATE (ACTIVE). | A) COMPOSITIONALLY HOMOGENEOUS PO RICH AGGREGATES WITH MINOR Cu-Fe SULFIDE AND SP.<br>B) POLYMETALLIC SULFIDES WITH INNER WALL ASSEMBLAGE OF SP, Cu-Fe SULFIDE, PO, ASP, LÖLLINGITE, Bi; OUTER WALL ASSEMBLAGE OF SP, GAL, TET, STIBNITE, ACANTHITE.<br>C) BAR CRUSTS ON SULFIDES.<br>D) SULFIDE-BEARING SED CONTAINS < 5.6 PERCENT NON-BIODEGRADED THERMOGENIC HYDROCARBON. |
| II. | <u>SEDIMENT-HOSTED DEPOSITS (CONTINUED)</u><br>**ADVANCED STAGED OF OPENING OF AN OCEAN BASIN**<br>**INTERMEDIATE- TO FAST SPREADING (HALF RATE > 2 CM/Y)** | | | | | |
| 97 | MIDDLE VALLEY, ENDEAVOR SEGMENT, NORTHERN JUAN DE FUCA RIDGE NEAR 48°27'N, 128°37'W (VILLINGER & DAVIS 1986; FRANKLIN 1987; DAVIS ET AL. 1987, TABLES 1, 2). | 2,400-<br>2,500 | 3.0 | A FAILED PROPAGATING RIFT FORMING AN ELONGATE TROUGH PARALLEL TO BUT ABOUT 25 KM EAST OF THE ACTIVE SPREADING AXIS; TROUGH IS FILLED WITH TURBIDITES AND HEMIPELAGIC SED UP TO 1.7 KM THICK WITH ANOMALOUSLY HIGH HEAT FLOW. | MASSIVE SULFIDES HOSTED IN SEDIMENT FORMING ~7 MOUNDS UP TO 400 M WIDE AND 60 M HIGH EACH CONTAINING AT LEAST AN ESTIMATED 1 X 10$^6$ TONNES OF MASSIVE SULFIDE. | PO, PY, MARC, SP, CP, ISOCUBANITE, PO, BAR, GAL, TALC, AMORPH SILICA. |
| 98 | MOUNDS HYDROTHERMAL FIELD NEAR 0°38'N, 86°07'W, 18 TO 32 KM SOUTH OF AXIS OF GALAPAGOS SPREADING CENTER (CORLISS ET AL. 1976, 1977; WILLIAMS ET AL. 1979; NATLAND ET AL. 1979; HOFFERT ET AL., 1980; HONNOREZ ET AL., 1981). | 2,700 | 3.0 | BLOCK-FAULTED TOPOGRAPHY OF ABYSSAL HILLS. | A) Fe-Si-RICH GREEN LAYERED ENCRUSTATION AND SEDIMENT IN MOUNDS UP TO 10 M HIGH (ACTIVE). | Fe-Si-TYPE OF SMEC (NONT). |
| | | | | | B) Fe-Mn RICH CONCRETIONS IN GREEN SEDIMENT (ACTIVE). | Fe-Mn OXIDE; MINERALS NOT SPECIFIED. |
| 99 | OCEAN BASIN ON WEST FLANK OF EPR BETWEEN LAT 15°N AND 15°S (LEINEN & STAKES 1979, APPENDIX, TABLE 1; DSDP SITES 42, 69-75, 77-82, 159-163). | 3,000-<br>5,000 | 4.5-<br>9.0 | BASIN ON FLANK OF OCEANIC RIDGE. | SEDIMENT (RELICT). | Fe-RICH SMEC, BAR PHILLIPSITE, δ-MnO$_2$, AMORPH TO POORLY XLLINE Fe-Mn HYDROXIDE. |

TABLE 1. HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (FIG. 1) (CONTINUED).

| LOCATION NUMBER (FIG. 1) | LOCATION[1] | WATER DEPTH (M) | SEAFLOOR SPREADING HALF-RATE (CM/Y) | STRUCTURE | TYPE OF DEPOSIT | MINERALOGY[2] |
|---|---|---|---|---|---|---|
| 100 | DSDP HOLES 597 (18°48.4'S. 129°46.2'W) AND 598 (19°00.3'S. 124°40.6'W) ON THE WEST FLANK OF THE EPR (LEININ ET AL. 1986: LYLE 1986: LYLE ET AL. 1987). | 4.166 AND 3.699 | | SED COVERED ABYSSAL HILLS ABOUT 1000 KM WEST OF SPREADING AXIS. | EPISODIC INCREASES OF Mn ACCUMULATION RATE UP TO A FACTOR OF 20 IN PELAGIC MARINE SED AT ABOUT 25. 18. 14 AND 9 X $10^6$ Y AGO. | COCCOLITH CALCITE. CLAY. GOETH. Mn ADSORBED ON COLLOIDAL Fe-RICH OXYHYDROXIDE PARTICLES. |
| 101 | BAUER DEEP ON EAST FLANK OF EPR BETWEEN LAT 10°S-15°S (SAYLES & BISCHOFF 1973. TABLE 3: SCIENTIFIC PARTY 1974: LYLE ET AL. 1977: HEATH & DYMOND 1977). | ~4.300 | ---- | BASIN ON FLANK OF OCEANIC RIDGE. | A) SEDIMENT (RELICT).<br>B) SEDIMENT (RELICT). | SMEC. GOETH. TOD.<br>Fe-RICH SMEC. BAR. PHILLIPSITE. δ-$MnO_2$. GOETH. |
| 102 | OCEAN BASIN ON EAST FLANK OF EPR BETWEEN LAT 15°S AND 25°S (HEATH & DYMOND 1977). | 3.000-5.000 | 8.0-9.0 | BASIN ON FLANK OF OCEANIC RIDGE. | SEDIMENT (RELICT). | Al AND Fe-RICH SMEC. BAR. PHILLIPSITE. δ-$MnO_2$. |
| -- | WORLD OCEAN BASIN (CLARKE 1924: TUREKIAN & WEDEPOHL 1961). | 1.000-9.000 | 1-10 | OCEANIC RIDGES AND FLANKING BASINS. | MID-OCEAN RIDGE BASALT (MORB). | CALCITE. PLAG. CPX. OLIVINE. ORTHOPYROXENE. |
| -- | PACIFIC OCEAN BASIN (WEDEPOHL 1960: TUREKIAN & IMBRIE 1966). | 1.000-11.000 | 1-10 | OCEANIC RIDGES AND FLANKING BASINS. | AVERAGE PACIFIC PELAGIC CLAY. | CLAY MINERALOGY. |
| --- | ATLANTIC OCEAN BASIN (TUREKIAN & IMBRIE 1966: BISCAYE 1965). | 1.000-9.000 | --- | OCEANIC RIDGES AND FLANKING BASINS. | AVERAGE ATLANTIC PELAGIC CLAY. | CLAY MINERALOGY. |

[1] LOCATION ABBREVIATIONS: MAR = MID-ATLANTIC RIDGE: EPR = EAST PACIFIC RISE: ODP = OCEAN DRILLING PROGRAM: DSDP = DEEP SEA DRILLING PROGRAM.

[2] MINERALOGY ABBREVIATIONS: AMORPH = AMORPHOUS: ANHY = ANHYDRITE: ASP = ARSENOPYRITE: BAR = BARITE: BI = NATIVE BISMUTH: BIRN = BIRNESITE: BN = BORNITE: CP = CHALCOPYRITE: CPX = CLINOPYROXENE: COV = COVELLITE: DISSEM = DISSEMINATED: FELD = FELDSPAR: GAL = GALENA: GOETH = GOETHITE: GYPS = GYPSUM: HEM = HEMATITE: MAG = MAGNETITE: MANG = MANGANITE: MARC = MARCASITE: MONT = MONTMORILLONITE: NONT = NONTRONITE: PENT = PENTLANDITE: PLAG = PLAGIOCLASE: PY = PYRITE: PO = PYRRHOTITE: QTZ = QUARTZ: RHOD = RHODOCROSITE: SID = SIDERITE: SMEC = SMECTITE: SP = SPHALERITE: TET = TETRAHEDRITE: TOD = TODOROKITE: XLLINE = CRYSTALLINE.

**REFERENCES FOR LOCATION NUMBER 1:** (DEGENS & ROSS 1969: BISCHOFF & MANHEIM 1969: HENDRICKS ET AL. 1969. TABLES 6. 8: STEPHENS & WITTKOPP 1969: BACKER & SCHOELL 1972: GARSON & KRS 1976: BIGNELL ET AL. 1976: BLISSENBACH & NAWAB 1982: GUENNOC & THISSE 1982: MUSTAFA ET AL. 1984. TABLE 3: NAWAB 1983: BACKER 1983: PAUTOT ET AL. 1984: BUTUZOVA 1984: DURGA PRASADA RAO ET AL. 1984: ISHUTIN 1982: PFEUFER 1983: SARKAR 1985: SKRIPCHENKO 1983. 1984: SVALNOV ET AL. 1984. 1985: THISSE ET AL. 1983: VALETTE 1983: ZHABINA & SOKOLOV 1982: ZIERENBERG & SHANKS 1982. 1983. 1986: ZIERENBERG 1985: OUDIN 1987).

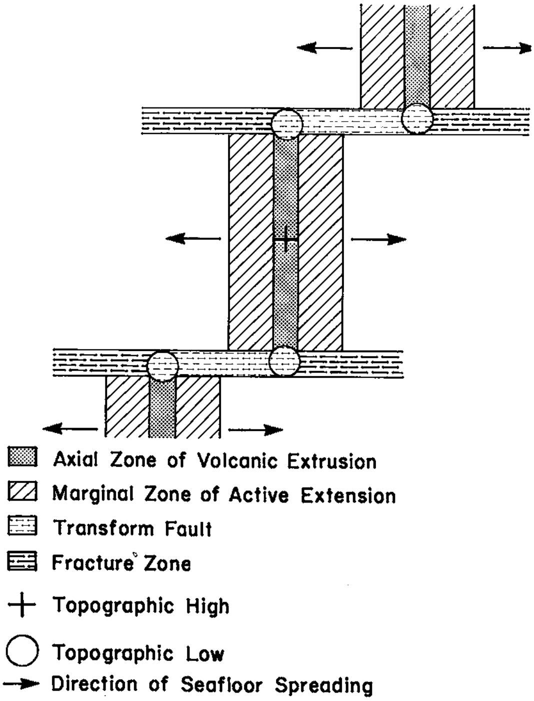

FIG. 2. Schematic plan view of first-order structural features common to all seafloor spreading centers (not to scale; Rona 1984). The linear segments of the spreading axis between offsets at transform faults and other deviations from axial linearity (DEVALS) are typically of the order of 10 km long at slow-spreading centers and may be longer at intermediate- to fast-spreading centers.

situated within 500 km of major river systems discharging along the northwestern North American coast, about 150 km is sediment-filled (Escanaba Trough: location 96; Middle Valley: location 97; Dellwood Knolls: location 40). Another important site of sediment-hosted mineralization is the Guaymas Basin of the Gulf of California (location 91), where terrigenous sediments contain more calcium carbonate and organic matter from biological productivity in surface waters than sediments of the Escanaba Trough and Middle Valley. Other oceanic ridges that are situated farther from land have a considerably smaller proportion of sediment fill, although turbidity currents can transport terrigenous sediment hundreds of kilometers, as in the case of sediment fill in fracture zones of the equatorial region of the Mid-Atlantic Ridge (MAR).

Sediment-hosted deposits may also result from i) off-axis hydrothermal activity on the flanks of spreading axes, as in the Mounds Hydrothermal Field 30 km south of the Galapagos Spreading Center (location 98; Fehn 1986); ii) diagenetic remobilization of hydrothermal and hydrogenous components in sedimentary basins distal to spreading axes, a process that contributes to the formation of manganese nodules (Cronan 1980, Fleet 1983); and iii) transport of hydrothermal components from axial sources to distal sedimentary basins in gravitational mass movements (cohesive masses or incohesive density flows), or as particles by oceanic currents as hypothesized for metalliferous sediment of the Bauer Deep several hundred km east of the EPR axis (location 101; Lonsdale 1976, Heath & Dymond 1977).

TABLE 2. CHEMISTRY OF HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (TABLE 1; FIG. 1).

| LOCATION TABLE 1; FIG. 1 | [1]COMPOSITION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WEIGHT PERCENT (RANGE) | | | | | | | | | | CONTENT PPM (RANGE) | | | | | |
| | Cu | Fe | Mn | Fe/Mn | Pb | Zn | Ba | S | $SiO_2$ | $Al_2O_3$ | Ag | As | Au | Cd | Co | Ni |
| 1 | 0.2–0.8 (AVG. 0.43) | 21–30 (AVG. 28) | 0.03–13.4 (AVG. 4) | 1–1000 | 0.003–0.1 | 0.9–6.0 (AVG. 1.7) | 0.03–2.0 | 2.1–5.5 | 2.3–15.3 | 0.05–3.0 | 5–250 (AVG. 180) | 4–600 (AVG. 345) | 0.5 | 2–600 (AVG. 295) | 12–198 (AVG. 140) | 9–90 (AVG. 46) |
| 3A | 0.001–0.01 | 22–29 | 0.15–0.30 | 70–200 | — | — | 0.013–0.014 | — | 4.0–20.8 | 3.7–5.8 | — | — | — | — | 17–22 | < 5–22 |
| 3B | < 0.005–0.003 | 0.03–1.64 | 31–54 | 0.0005–0.0529 | — | — | 0.01–6.2 | — | < 0.2–4.1 | 0–1.2 | — | — | — | — | < 5–17 | < 5–20 |
| 4A | 0.0008–0.0110 | 0.8–6.4 | 34.2–42.5 | 0.0118–0.187 | — | 0.0018–0.0780 | — | — | 2.0–5.4 | 0.1–1.1 | — | — | — | — | 2–75 | — |
| 4B | — | 19.1–24.2 | < 0.1 | > 191 | — | ≤ 0.0002 | — | — | 21.8–22.1 | 0.1–0.3 | — | — | — | — | 1–12 | — |
| 5A | < 0.001 | C. 30 | < 0.2 | > 150 | — | < 0.001 | — | — | — | — | — | 300 | — | — | < 10 | < 10 |
| 5B | < 0.001 | < 1.0 | — | — | — | 0.02 | — | — | — | — | — | 50 | — | — | < 10 | < 10 |
| 6 | 0.002–0.1 (AVG. 0.03) | 0.1–21.1 (AVG. 9.84) | 4.4–48.0 (AVG. 20.1) | 0.002–4.8 | < 0.001–0.2 (AVG. 0.05) | 0.002–0.09 (AVG. 0.03) | 0.02–1.0 (AVG. 0.13) | — | 0.2–20.8 (Si; AVG. 9.6) | 0.1–7.9 (Al; AVG. 3.3) | — | < 2–430 | — | < 0.2–27 (AVG. 5.7) | < 5–3,300 (AVG. 696) | 30–2,400 (AVG. 726) |
| 16 | — | 1.1–4.1 | 0.01–0.08 | 14–410 | — | — | — | — | — | — | — | — | — | — | — | — |
| 18 | 0.003–0.02 | 2.3–10.5 | 0.03–0.7 | 3.2–350 | — | 0.006–0.03 | — | — | — | 4.7–16.1 | — | — | — | — | — | 20–370 |
| 19 | — | — | — | — | — | — | — | — | — | — | — | < 123 | — | 161–1,560 | — | — |
| 20 | — | 3.0–14.3 | 0.17–0.9 | 3.3–82 | — | — | — | — | — | 2.7–8.0 | — | — | — | — | — | — |
| 21A | 0.005–0.01 | 20.8–40.6 | 4.0–11.5 | 2–10 | — | 0.001–0.008 | 0.006–0.01 | — | 4.7–44.2 | 0.2–5.9 | — | — | — | — | 2–27 | 28–225 |
| 21B | 0.005–0.03 | 13.7–38.6 | 1.1–37.2 | 0.4–35 | — | 0.001–0.01 | 0.004–0.06 | — | 8.7–16.6 | 0.2–1.7 | — | — | — | — | 2–91 | 2–570 |
| 23A | 0.09–2.74 | 16.9–36.2 | < 0.01 | > 1,690 | 0.05–0.11 | 1.09–4.45 | — | 29.2–52.1 | 0.45–3.66 | < 0.01 | 21–150 | 50–121 | 1.6–4.0 | 50–90 | 2–3 | < 100 |
| 23B | 0.001–0.01 | 0.01–0.11 | 38–52 | 0.0002–0.003 | — | < 0.01 | — | — | 0.06 | 0.03 | — | — | — | — | 14–25 | 50–790 |
| 23C | < 0.01 | 32.4 | 0.7 | 46.3 | — | < 0.01 | — | — | 12.2 | 0.05 | — | — | — | — | < 100 | < 100 |
| 23D | < 0.01 | 41.5 | 2.4 | 17.3 | — | — | — | — | 5.9 | 0.05 | — | — | — | — | < 100 | < 100 |
| 23E | 25.0–42.6 | 19.0–28.5 | < 0.01 0.04 | > 1,900 | < 0.01– | 0.04–6.25 | ≤ 0.01 | 16.5–35.8 | 0.27–1.22 | < 0.01 | < 5–265 | 28–64 | 0.8–16.4 | 10–40 | 3–32 | < 100 |
| 23F | 0.02–0.17 | 16.3–3.05 | < 0.005 | > 3,260 | 0.04–1.3 | 6.28–21.6 | 0.03 | 19.9–47.8 | 0.10–10.16 | 0.05 | 10–225 | 49–272 | 3.0–3.6 | 200–490 | 3 | < 100 |
| 23G | 0.77 | 0.7 | < 0.01 | > 70 | < 0.01 | 0.01 | — | 22.2 | 0.09 | < 0.01 | 30 | — | — | — | < 100 | < 100 |
| 23H | 43.8–68.3 | 1.8–24.4 | < 0.01 | < 180 | < 0.01 | 0.06–0.10 | < 0.001 | 0.04–1.17 | 0.06–0:43 | < 0.01 | < 5 | — | — | — | < 100 | < 100 |
| 23I | 0.1–0.29 | 3.8–4.9 | < 0.01–0.15 | < 33 | 0.01–0.02 | 0.47–6.65 | 0.001–0.07 | 0.20–2.40 | 0.97–7.58 | < 0.01 | 40–95 | — | — | — | < 100 | < 100 |
| 23J | 0.08–0.10 | 1.0–3.6 | < 0.01 | < 100 | < 0.01–0.03 | 0.06–1.55 | < 0.001–0.002 | 0.58–1.90 | 38.4–41.0 | < 0.01 | 150–160 | — | — | — | < 100 | < 100 |
| 28 | > 0.1 | LOW | HIGH | 0.0007 | — | — | — | — | — | — | — | — | — | — | — | — |
| 33 | 5–50 | 32–41 | < 0.01 | > 3,200 | — | — | — | — | 1.8–5.2 | — | — | — | — | — | — | — |
| 34 | 0.004–0.06 | 41–73 | 0.07–0.25 | 164–1,042 | — | 0.008–0.02 | — | — | 12–38 | 1.6–7.6 | — | — | — | — | 27–75 | 90–270 |
| 35 | — | 1.1–16 | 0.02–7.3 | 0.2–800 | — | — | — | — | — | 1.6–12.1 | — | — | — | — | — | — |
| 38 | — | ≤ 28 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 39A | 0.002–0.008 | 15.3–28.8 | 0.14–0.16 | — | — | 0.005–0.019 | — | — | — | — | — | — | — | — | — | 30–70 |
| 39B | 0.005–0.025 | 0.9–7.6 | 22.0–44.8 | — | — | 0.011–0.019 | — | — | — | — | — | — | — | — | — | 65–975 |
| 40 | 0.0006–0.002 | 28.5–31.6 | 1.7–2.1 | 13–18 | — | 0.05 | 0.03 | 18.4 | 1.9 | — | — | — | — | — | 5–10 | 54–62 |

TABLE 2. CHEMISTRY OF HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (TABLE 1; FIG. 1) (CONTINUED).

[1]COMPOSITION

| LOCATION TABLE 1; FIG. 1 | WEIGHT PERCENT (RANGE) | | | | | | | | | | CONTENT PPM (RANGE) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cu | Fe | Mn | Fe/Mn | Pb | Zn | Ba | S | $SiO_2$ | $Al_2O_3$ | Ag | As | Au | Cd | Co | Ni |
| 41A | < 0.0001–0.007 | 7.2–39.5 ($Fe_2O_3$) | 0.1–1.9 | —— | < 0.0001–0.0008 | 0.003–0.013 | < 0.01–0.10 | —— | 27.4–52.8 | 1.1–13.1 | —— | —— | —— | —— | 2–14 | 2–94 |
| 41B | < 0.0001–0.004 | 2.8–24.7 ($Fe_2O_3$) | 8.8–57.2 | —— | < 0.0001–0.0004 | 0.0009–0.005 | 0.07–0.19 | —— | 1.4–25.3 | < 0.1–2.9 | —— | —— | —— | —— | < 1–9 | < 1–86 |
| 42 | 1.0–29.3 (AVG. 8.1) | 4.1–20.1 (AVG. 10.8) | —— | —— | 0.1–0.7 (AVG. 0.1) | 0–34.3 (AVG. 9.0) | 7.9 | 5.2–43.3 (AVG. 26.8) | 1.3–31.2 (AVG. 19.2) | —— | 0–640 (AVG. (112) | —— | 0.07–1.5 (AVG. 0.8) | —— | —— | —— |
| 43 | 0.14 | 12.2 | 3.0 | 4.0 | 0.03 | 0.03 | —— | —— | —— | —— | —— | —— | —— | —— | 490 | 450 |
| 44 | 0.65–3.05 | —— | —— | —— | 0.01–0.15 | 0.43–13.2 | —— | —— | —— | —— | 17.5 | —— | 0.02 | 130 | 120 | —— |
| 45 | 0.002–0.005 | 21.5–37.8 | 0.04–11.0 | 2–945 | —— | 0.014–0.019 | 0.013–0.044 | —— | 32–52.4 | 0.3–6.7 | —— | —— | —— | —— | 1–10 | 60–130 |
| 48 | 0.07–0.78 (AVG. 0.43) | 2.81–8.53 (AVG. 5.82) | —— | —— | 0.10–0.63 (AVG. 0.35) | 3.15–39.2 (AVG. 22.7) | 0.05–34.2 (AVG. 8.70) | 11.3–27.5 (AVG. 18.6) | 15.5–39.4 (AVG. 28.5 | —— | 62.4–280 (AVG. 186) | 420–720 (AVG. 579) | 2.9–6.7 (AVG. 4.9) | 13–1.200 (AVG. 493) | —— | —— |
| 49A | < 0.0003–0.32 | 8.0–50.5 | —— | —— | 0.25 | 0.6–54.0 | —— | —— | —— | —— | < 3–290 | 323 | 0.13 | 8–490 | —— | —— |
| 49B | 0.07 (AVG. 0.22) | 1.8 | —— | —— | 0.06 (AVG. 0.25) | 59.2 (AVG. 54) | —— | —— | —— | —— | 230 (AVG. 260) | —— | —— | 1.060 (AVG. 775) | —— | —— |
| 54 | 0.08–0.15 | 21.1–27.8 | 5.7–7.6 | 3–5 | —— | 0.05–0.06 | 0.15–1.5 | —— | 4.3–8.9 | 1.5–3.4 | —— | —— | —— | —— | 55–110 | 570–800 |
| 56A | 0.4–34.1 | 7.6–45.6 | 0.01–0.06 | 127–4.560 | —— | 0.1–60.6 | —— | 33.8–53.0 | —— | —— | —— | —— | —— | —— | 0 | 0–100 |
| 56B | 0.0003–0.018 | 9.0–15.0 | 0.35–0.62 | 15–43 | —— | 0.0043–0.0098 | 0.006–0.114 | —— | 19.5–31.3 (Si) | 3.7–8.0 (Al) | —— | —— | —— | —— | 17–52 | 113–269 |
| 58 | 0.6–0.8 0.8 (AVG. 0.8) | 2.0–48.5 (AVG. 19.2) | —— | —— | 0.05–0.32 (AVG. 0.3) | 32–41 (AVG. 32.3 | 0.2 | —— | 7.8 | —— | 156 | 489 | 0.17 | 560 | 3–100 | 3 |
| 61 | 0.29 | 23.3 | 12.3 | 2.0 | —— | —— | —— | —— | 54.9 | 0 | —— | —— | —— | —— | —— | —— |
| 62 | 0.32 | 11.0 | 8.0 | 1.4 | —— | 0.05 | —— | —— | 32.0 | —— | —— | —— | —— | —— | 1,000 | 3,600 |
| 63 | 0.02–0.18 | 2.1–30.6 | 0.4–9.6 | 0.2–77 | —— | 0.003–0.05 | —— | —— | —— | —— | —— | —— | —— | —— | —— | 62–1,660 |
| 64A | 2.6–31.6 | 15.0–30.6 | —— | —— | 0.0002–0.003 | 0.04–0.25 | —— | 31.3–33.4 | —— | —— | 0–6 | 0–45 | —— | 4–12 | 160–500 | 10–40 |
| 64B | 0.3–2.9 | 14.8–26.5 | —— | —— | 0.09–0.24 | 14.0–41.7 | —— | 34.2–36.4 | —— | —— | 79–186 | 184–1,253 | —— | 557–815 | 30–50 | 50–90 |
| 64C | 0.8–7.9 | 41.3–44.9 | —— | 0.01–0.02 | —— | 0.03–0.07 | —— | 45.4–47.7 | —— | —— | 5–13 | 43–101 | —— | 3–5 | 500–3.000 | 20–30 |
| 66 | 0.0009–0.09 | 0.3–16.7 | 25.2–43.6 | 0.007–0.663 | —— | 0.10–0.14 | —— | —— | —— | —— | —— | —— | —— | —— | 0–4.100 | 0–5.700 |
| 67 | 0.38 | —— | —— | —— | —— | 0.02 | —— | —— | —— | —— | —— | —— | —— | —— | —— | —— |
| 68 | 0.0009–0.02 | LOW | 47–58 | 0.0002–0.0230 | —— | 0.009–0.486 | —— | —— | —— | —— | —— | —— | —— | —— | 15–86 | 58–500 |
| 71A | 0.3–2.7 (AVG. 4.1) | < 43 (AVG. 38) | 0.03–1.0 (AVG. .032) | 43–1 1,433 | —— | 0.1–1.8 1.8 (AVG. 1.4) | —— | —— | —— | —— | —— | —— | —— | —— | 460 | 5 |
| 71B | 0.32–1.45 (AVG. 0.94 | 29.0–48.5 (AVG. 39.4) | 0.1–0.6 (AVG. 0.2) | 48–485 | 0.01–0.13 | 0.08–0.69 (AVG. 0.31) | 0.23–0.76 (AVG. 0.38) | —— | 23.3–39.9 (AVG. 30.7) | 1.8–3.7 (AVG. 2.9) | —— | 107–307 (AVG. 152) | —— | —— | —— | 30–70 (AVG. 46) |
| 71C | 0.02–0.05 (AVG. 0.03) | 8.4–15.1 (AVG. 11.1) | 1.3–2.3 2.3 (AVG. 2.0) | 3.7–11.6 | 0.004–0.005 (AVG. .0045) | 0.02–0.10 (AVG. 0.04) | 0.90–0.96 (AVG. 93) | —— | 47.9–54.6 (AVG. 51.3) | 6.7–9.1 (AVG. 8.2) | —— | 2–10 (AVG. 5) | —— | —— | —— | 198–270 (AVG. 245) |
| 71D | —— | 0.2–9.6 | < 0.1–3.4 | 0.06–96 | —— | —— | —— | < 0.50 | 73.2–96.3 | < 0.20 | —— | —— | —— | —— | —— | —— |
| 73 | 0.002–0.006 | 2.6–15.4 | 0.1–6.7 | 0.4–154 | 0.001–0.002 | 0.001–0.003 | 0.7–2.1 | —— | 15.3–34.5 | 0.4–2.9 | —— | —— | —— | —— | 5–176 | 58–533 |
| 74 | 0.006–0.012 | 29–33 | 0.6–2.4 | 12–55 | —— | —— | 0.010–0.015 | —— | 12–18 | < 1.1 | —— | —— | —— | —— | 32–120 | 90–460 |
| 75 | 0.027–0.170 | 4.7–23.3 | 0.2–9.5 | 0.5–117 | —— | 0.022–0.105 | 0.17–1.40 | —— | —— | 1.3–8.4 | —— | —— | —— | —— | 18–290 | 270–805 |

TABLE 2. CHEMISTRY OF HYDROTHERMAL MINERAL OCCURRENCES AT SEAFLOOR SPREADING CENTERS (TABLE 1: FIG. 1) (CONTINUED).

| | [1]COMPOSITION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WEIGHT PERCENT (RANGE) | | | | | | | | | | CONTENT PPM (RANGE) | | | | | |
| LOCATION TABLE 1: FIG. 1 | Cu | Fe | Mn | Fe/Mn | Pb | Zn | Ba | S | $SiO_2$ | $Al_2O_3$ | Ag | As | Au | Cd | Co | Ni |
| 76 | 0.051–0.180 | 5.7–22.6 | 0.6–8.8 | 0.64–38 | — | 0.019–0.053 | — | — | 9–38 | 1.5–16 | — | — | — | — | 75–280 | 250–1,200 |
| 78A | 5.5 | 16.3 | — | — | — | 41.3 | — | 32.5 | 2.0 | — | — | — | — | — | — | — |
| 78B | 0.03–0.17 | 5.9–21.4 | 0.5–9.1 | 0.6–43 | — | 0.015–0.051 | — | — | 3.5–25.0 | 0.2–4.6 | — | — | — | — | — | — |
| 80 | 0.2–20 (AVG. 6.8) | 35.8 | 0.006 | 6,000 | 0.05 | 0.2–35 (AVG. 9.1) | — | 45.5 | 1.2 | — | — | — | — | — | 1,400 | 62 |
| 82 | 0.140–0.170 | 26.3–33.5 | 9.1–11.7 | 2.2–3.7 | — | 0.056–0.067 | 0.32–0.83 | — | 5.2–8.0 | 2.1–1.4 | — | — | — | — | — | 517–953 |
| 85 | 0.006–0.037 | 1.0–14.0 | 0.2–2.0 | 0.5–70 | — | 0.009–0.030 | < 0.01–0.14 | — | 13–80 | 2.2–22.0 | — | — | — | — | 12–63 | 15–310 |
| 86 | 0.019–0.120 | 5.0–44.0 | 0.6–9.24 | 0.5–73 | — | 0.011–0.052 | 0.018–0.305 | — | 5–58 | 3.8–20.0 | — | — | — | — | 32–100 | 45–850 |
| 87 | — | 0.03–7.0 | 0.1–2.0 | 0.02–70 | — | — | — | — | — | 0.2–7.4 | — | — | — | — | — | — |
| 88 | 0.05–35 | 3.8–17.5 | 0.5–29.2 | 0.13–35 | — | 0.05–6.0 | 0–1.45 | — | 16.3–15.1 | 1.0–14.3 | — | — | — | — | 200–8,600 | 0–1,300 |
| 91 | < 0.01–0.44 (AVG. 0.2) | 0.30–12.8 (AVG. 5.9) | — | — | < 0.01–2.31 (AVG. 0.4) | < 0.01–3.78 (AVG. 1.0) | < 0.01–43.8 (AVG. 14.9) | 0.94–12.6 | 2.72–81.0 (AVG. 28.4) | — | 0.5–205 (AVG. 69) | 24–110 | 0.093–0.270 (AVG. 0.2) | 1–41 | — | — |
| 94 | 0.002–0.01 (AVG. 0.03) | 0.1–21.1 (AVG. 9.84) | 4.4–48.0 (AVG. 20.1) | 0.002–4.8 | < 0.001–0.2 (AVG. 0.05) | 0.002–0.09 (AVG. 0.03) | 0.02–1.0 1.0 (AVG. 13) | — | 0.2–20.8 (Si; AVG. 9.6) | 0.1–7.9 (Al; AVG. 3.3) | — | < 2–430 (AVG. 132) | — | < 0.2–27 (AVG. 5.7) | < 5–3,000 (AVG. 5.7) | 30–2,400 (AVG. 726) |
| 96B | — | — | — | — | ≤ 7.6 | ≤ 43 | — | — | — | — | ≤ 700 | ≤ 27,000 | — | — | — | — |
| 96C | — | — | — | — | ≤ 4.0 | ≤ 17 | — | — | — | — | ≤ 390 | — | ≤ 2 | — | — | — |
| 97 | 0.27–0.58 (AVG. 0.42) | 29.1–47.1 (AVG. 361) | 0.07–0.20 (AVG. 0.12) | 145–673 | 0.02–0.1 (AVG. 0.06) | 2.4–5.0 (AVG. 3.56) | 0.13–3.10 (AVG. 1.48) | 25.9–42.8 (AVG. 37.7) | 3.90–20.6 (AVG. 11.2) | 0–3.53 (AVG. 0.87) | 1.1–7.5 (AVG. 4.6) | 134–410 (AVG. 232) | 0.118–0.153 (AVG. 0.14) | 32–66 (AVG. 47) | 17–24 (AVG. 19) | 5–48 (AVG. 20) |
| 98A | 0.0014 | 21.6 | 0.1 | 216 | — | 0.004 | — | — | 50.8 | 0.1 | — | — | — | — | 22 | 16 |
| 98B | 0.004 | 7.3 | 33.0 | 0.2197 | — | 0.013 | — | — | 0.7 | 0.2 | — | — | — | — | 16 | 81 |
| 99 | 0.002–0.149 | 0.01–17.4 | 0.02–4.4 | 0.002–87.0 | — | 0.001–0.172 | — | — | 0.7–43.1 | 0.07–9.8 | — | — | — | — | — | 0–945 |
| 100 | — | 2.0–18.2 | 0.30–4.48 | 0.4–61 | — | — | 0.06–0.29 | 0.03–0.12 | 0.5–13.1 (Si) | 0.1–4.3 (Al) | — | — | — | — | — | — |
| 101A | 0.071–0.120 | 9–18 | 2–7 | 1–9 | — | 0.011–0.068 | 0.8–2.8 | — | 18–28 | 1–4 | — | — | — | — | 90–330 | 410–1,700 |
| 101B | 0.091–0.144 | 9.8–18.0 | 3.7–7.2 | 1.4–4.9 | — | 0.038–0.044 | 1.42–2.32 | — | 4.5–21.1 | 2.6–4.1 | — | — | — | — | — | 777–1,408 |
| 102 | 0.070–0.126 | 9.2–17.5 | 2.5–5.5 | 3.2–3.7 | — | 0.027–0.063 | 1.34–2.25 | — | 8.1–22.8 | 5.3–7.8 | — | — | — | — | — | 823–1,538 |
| WOB[2] | 0.009 | 8.6 | 0.15 | 57 | 0.0006 | 0.011 | 0.033 | 0.030 | 49.2 (Si) | 13.55 (Al) | 0.11 | 2.0 | 0.004 | 0.22 | 48 | 130 |
| POB[3] | 0.04 | 5.1 | 0.9 | 5.6 | 110 | 0.02 | — | — | — | 8.3 (Al) | — | — | — | — | 110 | 300 |
| AOB[4] | 0.01 | 5.0 | 0.4 | 12.5 | 52 | — | — | — | — | 9.0 (Al) | — | — | — | — | 39 | 79 |

[1] COMPOSITIONAL ANALYSES ARE NOT STANDARDIZED WITH REFERENCE TO SAMPLING AND ANALYTICAL PROCEDURES. SEDIMENT ANALYSES ARE ON A $CaCO_3$-FREE BASIS.

[2] WORLD OCEAN BASIN AVERAGE BASALT (CLARKE 1924; TUREKIAN & WEDEPOHL 1961).

[3] PACIFIC OCEAN BASIN AVERAGE PELAGIC CLAY (WEDEPOHL 1960; TUREKIAN & IMBRIE 1966).

[4] ATLANTIC OCEAN BASIN AVERAGE PELAGIC CLAY (TUREKIAN & IMBRIE 1966; BISCAYE 1965).

### *Type of deposit and tectonic setting*

Both volcanic- and sediment-hosted deposits may occur in the tectonic settings of early and advanced stages of opening of an ocean basin (Table 1). The entire spectrum of hydrothermal mineral phases and deposit morphologies is present in each tectonic setting, excluding the slow-spreading sediment-hosted case. This includes stratiform, stockwork and disseminated sulfides as the high-temperature end members, and stratiform layered sulfates, silicates, carbonates, oxides, and hydroxides as the low-temperature end members (Table 1). Use of the term "massive" refers to mineralization of at least 60% sulfide and carries no textural connotation (Sangster & Scott 1976).

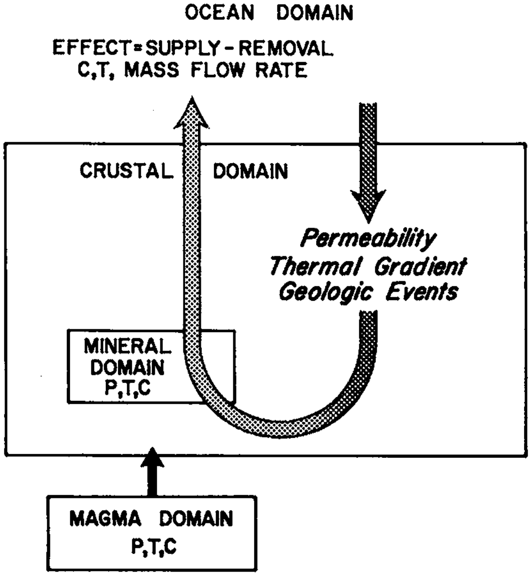

FIG. 3. Diagrammatic representation of the components of a subseafloor hydrothermal convection system involving the downwelling of cold, dense, alkaline seawater through permeable oceanic crust, heating by flow in proximity to magmatic heat sources, upwelling of hot, thermally expanded seawater and reaction with minerals under ambient pressure (*P*), temperature (*T*) and composition (*C*) fields to evolve acid, metal-rich hydrothermal solutions that interact with volcanic rocks along flow paths and discharge into the ocean.

## HYDROTHERMAL MINERALIZATION PROCESSES AT SEAFLOOR SPREADING CENTERS

### *Intensity of hydrothermal activity*

At and adjacent to seafloor spreading centers, subseafloor hydrothermal convection systems which circulate seawater through permeable volcanic rocks and sediments display a spectrum in terms of intensity, size, and depth of circulation (Fig. 3). Low-intensity hydrothermal activity that is nearly ubiquitous is distinct from the high-intensity activity that is extremely localized and plays a major role in ore-forming systems (Rona 1984). Low-intensity hydrothermal activity is characterized by discharge temperatures ≤200°C, low- to intermediate-temperature gradients, relatively slow flow rates, generally high water/rock mass ratios, and the production of zeolite metamorphic facies. High-intensity hydrothermal activity is characterized by discharge temperatures between 200 and ~400°C, high thermal gradients, relatively fast flow rates, generally lower water/rock mass ratios, and the production of greenschist metamorphic facies.

Both the low- and high-intensity components of hydrothermal activity contribute to estimates of global heat transfer (4.0–6.4 × $10^{19}$ cal/y) and mass flow of seawater (1.3–9 × $10^{17}$ g/y) attributed to hydrothermal convection at seafloor spreading centers (Table 3; Wolery & Sleep 1976, Williams & Von Herzen 1974). These global values account for about 20% of the Earth's total heat loss and 0.4–2.5% of global river discharge (Table 3). Less cer-

TABLE 3. HEAT AND MASS TRANSFER ESTIMATES RELATED TO THE FORMATION OF A MASSIVE SULFIDE DEPOSIT.

| MODEL | MASS FLOW (g/y) | MASS SOURCE (km³) | HEAT FLUX (W) | HEAT SOURCE (km³) | TIME (y) | DEPOSIT SIZE (tonne) |
|---|---|---|---|---|---|---|
| World river flux (Garrels & Mackenzie 1971) | 360 x $10^{17}$ | — | — | — | — | — |
| Earth heat flux (Williams & Von Herzen 1974) | — | — | 4.3 x $10^{13}$ | — | — | — |
| Hydrothermal flux at oceanic ridges (Williams & Von Herzen 1974; Wolery & Sleep 1976; Sleep & Wolery 1978; Jenkins et al. 1978; Sclater et al., 1981) | 1.3–9 x $10^{17}$ | — | 0.4–1.0 x $10^{13}$ | — | — | — |
| Hydrothermal flux: black smoker field, EPR 21°N (Converse et al. 1984, Table 3) | 2.9–6.4 x $10^{12}$<br>(226–351°C) | — | 1.4–3.1 x $10^{8}$ | — | — | — |
| Hydrothermal flux: individual black smokers, EPR 21°N (Converse et al. 1984, Table 3) | 1.6–4.5 x $10^{10}$<br>(226–351°C) | — | 0.5–2.3 x $10^{6}$ | — | — | — |
| Heat and mass transfer through permeable medium for a Cyprus deposit (Spooner & Fyfe 1973; Spooner 1977; Parmentier & Spooner 1978) | $10^{11}$ (300°C; 100 ppm Fe) | 0.2<br>(basalt) | 4.6 x $10^{6}$ | 3.5 | $10^{5}$ | 5 x $10^{6}$ |
| Mass transfer at Matagami (MacGeehan 1978) | — | 1.0<br>(basalt) | — | — | — | 1 x $10^{6}$ |
| Heat and mass transfer through fractures for Kuroko or Noranda deposits (Cathles 1981, 1983) | .5–5 x $10^{14}$<br>(> 300°C; Cu+Zn+Pb, 100 ppm) | ≤ 78<br>(mafic or felsic intrusions) | — | 78<br>(mafic or felsic intrusions) | $10^{2}$–$10^{3}$ | 4.7 x $10^{6}$ |
| Heat transfer through fractures (Lowell & Rona 1985) | 4 x $10^{12}$<br>(≳ 350°C; 100 ppm Fe) | Volume unspecified<br>(volcanic rocks or sediments) | 2.2 x $10^{7}$ | 2<br>(magma chamber with replenishment) | 40 x $10^{3}$ | 3 x $10^{6}$ |
| Heat transfer through fractures (Cann et al. 1985/86) | 0.4 x $10^{13}$<br>(350°C; 115 ppm Fe) | Volume unspecified<br>(basalt) | 2.3 x $10^{8}$ | 30<br>(magma chamber) | 4 x $10^{3}$ | 3 x $10^{6}$ |

tain are the relative contributions of high-intensity hydrothermal activity associated with the axial zone and low-intensity off-axis hydrothermal activity. Computation of chemical fluxes attributes the major portion of convective heat flux to high-intensity activity in the axial zone (Edmond *et al.* 1979a). Thermal modelling suggests that the axial zone accounts for only 10 to 20% of the convective heat flux, requiring extensive low-intensity circulation off-axis (Morton & Sleep 1985). Low-intensity hydrothermal activity extends to 400–700 km (corresponding to crustal ages of 40–70 × $10^6$ y) from the axis of the slow-spreading MAR and Carlsberg Ridge, and 100–500 km (4–15 × $10^6$ y) from the axis of the intermediate- to fast-spreading Juan de Fuca Ridge and EPR (Anderson 1972, Anderson *et al.* 1977, Morton & Sleep 1985). Active volcanic centers may occur more than 100 km from a spreading center, as observed at the subaerial Gregory Rift in East Africa (Bosworth 1987), which could generate localized off-axis high-intensity hydrothermal activity. However, it is the high-intensity activity at or near spreading axes in concert with other physical and chemical factors that focus the flow and concentrate the precipitates which play the predominant role in ore-forming subseafloor hydrothermal convection systems (Franklin *et al.* 1981, Rona 1984, Scott 1987).

### *Ore-forming hydrothermal systems*

Heat and mass transfer in individual high-intensity ore-forming systems may be considered with reference to convective heat flux (0.5–2.3 × $10^6$ W) and mass flow rates (1.6–4.5 × $10^{10}$ g/y) measured in individual black smokers at the 21°N EPR hydrothermal field (Table 3; Converse *et al.* 1984). These heat-flux values are similar to a range of values (0.9–4.6 × $10^6$ W) calculated from measurements above a small cluster of black-smoker vents near 11°N, EPR (Little *et al.* 1987). Formation of a typical Cyprus massive sulfide deposit (3–5 × $10^6$ tonnes) would require a convective heat flux and mass flow equivalent to 2 to 9 black smokers for a period of $10^5$ y (Table 3) using values from Spooner & Fyfe (1973) and Spooner (1977). A massive sulfide deposit of this size would require the heat flux and mass flow equivalent to 1–5 × $10^2$ black smokers for 4 × $10^3$ y, or 10–40 black smokers for 4 × $10^4$ y based on models of Cann *et al.* (1985/86) and Lowell & Rona (1985), respectively.

Modelling of heat extraction from permeable rocks of the oceanic crust by a hydrothermal convection cell indicates that a magmatic source is required to supply the heat in a hydrothermal system that generates massive sulfide deposits of $\geq 3 \times 10^6$ tonnes (Lowell & Rona 1985). The size of the magma chamber required to supply the heat for such a deposit varies, depending in different models on whether the latent heat of crystallization is extracted from a single batch of magma (30–78 $km^3$; Table 3), or from a replenishing magma chamber (2 $km^3$). Assuming that the metals in a massive sulfide deposit are leached from volcanic rocks, the volume of rock required as a metal source (0.2–5 $km^3$; Table 3) for a typical deposit of 5 × $10^6$ tonnes is considerably less than the volume of magma required to supply the heat to drive the convection for that deposit, as pointed out by Cathles (1983). With reference to water/rock mass ratios, a simplified "rule of thumb" presented by Elder (1977) and evaluated by Cathles (1981) states that the total mass of hydrothermally circulated fluid is approximately equal to the mass of the heat source.

### *Hydrothermal sources*

Early studies of hydrothermal effluents at oceanic ridges considered that high-temperature reactions between seawater and homogeneous basaltic rocks should produce a uniform solution chemistry at different sites (Edmond *et al.* 1979a,b). Subsequent investigations revealed significant differences in chemical and physical properties of hydrothermal sources at oceanic ridges (Edmond *et al.* 1987, Von Damm 1988). A spectrum of hydrothermal sources with different characteristics is emerging from investigations of oceanic ridges, as follows: i) seawater-rock chemical interactions may involve ultramafic (serpentinized peridotites of oceanic lower crust and upper mantle; Rona *et al.* 1987) as well as mafic (basalt, gabbro) rocks of oceanic lithosphere at a range of metamorphic grades (zeolite to amphibolite) to produce variations in solution chemistry (Hajash & Chandler 1981, Janecky & Seyfried 1986, Bowers *et al.* 1988); ii) solution properties exhibit large variations in the temperature field (≤400°C in the discharge zone and considerably higher in the heat-transfer zone) and pressure field of hydrothermal reactions, including phase separation (Bischoff & Rosenbauer 1985, 1986); iii) seafloor hydrothermal discharge exhibits a wide variation of behavior including diffuse discharge through permeable areas of the seafloor, discrete discharge by jet and plume flow from individual vents (Turner & Gustafson 1978), and cataclysmic venting of voluminous solutions in ~3 days equivalent to the annual heat and mass output of between 200 and 2,000 black smokers (Baker *et al.* 1987). The seafloor cataclysmic venting may be analogous to rapid release of gasses from fractured lava domes that may grow on subaerial volcanos caused by depressurization of a hydrothermal system or a magma body (Kieffer 1981, Eichelberger & Hayes 1981) as recently observed at Mount St. Helens (Newhall & Melson 1983, Gerlach & Casadevall 1986), with differences in venting fluids (liquid *versus* gas), shape of the area of inflation (elongate shape parallel to a spreading axis *versus*

Table 4. TIME SCALE OF EVENTS AND PROCESSES AT OCEANIC RIDGE CRESTS (MODIFIED FROM DELANEY ET AL. 1987).

| TIME SCALE | ACTIVITY |
|---|---|
| $10^6$–$10^7$ y | Plate reorganization (Rona & Richardson 1978) |
| $10^6$–$10^7$ y | Episodes of seafloor spreading (Schneider & Vogt 1968) |
| $10^5$ y | Magnetic polarity interval (Cox et al. 1964) |
| $10^{3-4}$ y | Eruption cycle: slow-spreading oceanic ridge (Hall & Robinson 1979) |
| $10^{2-3}$ y | Eruption cycle: fast-spreading oceanic ridge (Ballard et al. 1982; Lichtman & Eissen 1983; Macdonald 1983) |
| $10^3$–$10^6$ y | Duration of hydrothermal field (Scott et al. 1976; Macdonald et al. 1980; Converse et al. 1984; Rona et al. 1984) |
| $10^1$–$10^2$ y | Duration of individual hydrothermal vent (Macdonald et al. 1980; Bowers et al. 1985; Campbell et al. 1988) |
| $10^0$–$10^1$ y | Residence time of hydrothermal fluid in the oceanic crust from the onset of basalt alteration (Kadko et al. 1985/86) |
| $10^0$–$10^{-3}$ (1 y–8 h) | Duration of volcanic eruption (Sigurdsson & Sparks 1978; Holcomb 1980; Hauksson 1983) |
| $10^{-3}$–$10^{-6}$ (8 h–30 s) | Duration of earthquake swarms (Riedesal et al. 1982; Newhall et al. 1984) |
| $10^{-4}$ (50 min) | Transit time of hydrothermal upwelling (3 km at 1 m/s) (Converse et al. 1984) |
| $10^{-7}$–$10^{-8}$ (0.3–3 s) | Precipitation of sulfide particles by mixing of high-temperature hydrothermal effluent with ambient seawater and related chemical reactions. |

domed-shaped on land), and setting (axial zone of volcanic extrusion *versus* volcano). The effect of seafloor cataclysmic venting on mineralization is unknown.

### *Time scale of hydrothermal processes and geologic events*

On long time scales ($10^6$–$10^7$ y; Table 4) global reorganizations of plate motion involving changes in type and length of plate boundaries, and rate and direction of plate motion, are conducive to an increase in intensity of hydrothermal activity and a redistribution of hydrothermal discharge sites related to an increase in volcanic and tectonic activity. This association is evident from changes in the distribution of hydrothermal mineral deposits known on land, and an increase in the proportion of metalliferous components in the marine stratigraphic record during the global Eocene plate reorganization (Rona & Richardson 1978, Rona 1980, Owen & Rea 1985, Lyle *et al.* 1986; Tables 1, 2, location 100). The hydrothermal activity is energized by igneous intrusions and related volcanic eruptions, which occur in cycles of different periodicities at slow- ($10^3$–$10^4$ y; Table 4) and intermediate- to fast-spreading oceanic ridges ($10^2$–$10^3$ y), and is favored by tectonism which creates permeability by shear and rigid-plate deformation (Engeln *et al.* 1988). The duration of seafloor hydrothermal fields may range to $>10^6$ y, and is related to persistence of magma supply and favorable tectonic conditions at individual spreading segments. Processes involving mass flow, heat exchange, and chemical kinetics and equilibria during interaction between circulating solutions and oceanic crust are of much shorter duration (10 y to a few seconds).

The physical and chemical conditions which favor the existence of ore-forming hydrothermal systems (Fig. 3) include: i) a magmatic heat source and related thermal gradients sufficient to vigorously drive the convection (Table 3); ii) a distribution of porous medium and fracture permeability in the oceanic crust such that permeabilities are high enough in the downwelling zone to sustain fluid supply, low enough in the heat-exchange zone to maintain high fluid temperature ($<10^{-13}$ m$^2$), and sufficiently high and constrained in the upwelling zone to channel the flow and focus the discharge ($10^{-12}$ to $10^{-5}$ cm$^2$; 0.1 millidarcies to 1000 darcies) depending on the circulation models (*e.g.*, Ribando *et al.* 1976, Fehn & Cathles 1979, Lister 1983, Lowell & Rona 1985); iii) chemical gradients of Eh, pH, dissolved-metal and chlorinity–salinity concentrations, and other factors that act within different parts of the hydrothermal system to enhance fluid–mineral reactions, metal transport and precipitation; iv) pressure and temperature gradients that control the critical point for fluid-phase separation from a liquid to a cooler, more saline (due to partitioning of NaCl into the liquid) residual liquid phase depleted in $H_2S$ and an aqueous vapor phase (Delaney & Cosens 1982, Bischoff & Pitzer 1985); v) timing of cyclic plutonic and tectonic events to create sufficient magmatic heat and favorable permeability distribution. High-intensity ore-forming hydrothermal systems at specific sites are considered most likely to develop during the early tectonic stage when crustal extension exceeds volcanism, and during the late magmatic stage when volcanism exceeds extension (Fig. 4; Kappel & Ryan 1986, Bäcker & Lange 1987, Eberhart *et al.* 1988). Periodic repetition of geologic events that rejuvenate hydrothermal systems may superimpose the products of multiple ore-forming episodes at particular sites to produce large deposits. Supergene alteration of primary sulfides may result in secondary enrichments of certain metals, as first found for gold and copper in recent submarine sulfides in the massive sulfide mound at the TAG Hydrothermal Field in the rift valley of the Mid-Atlantic Ridge (Tables 1, 2, location 23; Figs. 1,5; Hannington *et al.* 1988).

### *Slow- and intermediate- to fast-spreading centers*

Similarities and differences in the plutonic and tectonic characteristics of slow- (spreading half-rate $\leq 2$ cm/y) and intermediate- to fast-spreading (half-rate $>2$ cm/y) oceanic ridges (Table 5) can be summarized as follows: i) axial zones of volcanic extrusion and marginal zones of active extension are structural features common to all spreading centers; however, vertical relief of marginal above-axial zones generally increases from 0 to 3 km to form a well-defined rift valley with decreasing spreading rate; an exception is the slow-spreading Reykjanes Ridge south of Iceland which lacks a rift valley (Talwani *et al.* 1971); ii) depth below sea level generally is greater for slow- than fast-spreading ridges as a consequence of the age–depth relation of oceanic crust (Sclater & Francheteau 1970); however, deviations from this relation exist at mantle plume-generated areas such as at Iceland and the Azores, and at other anomalous regions; iii) transform faults, overlapping spreading centers, and deviations from axial linearity (DEVALS) are structural features that may occur along all spreading axes; however, differences may exist in the types and spacing of structural discontinuities; iv) magma chambers are transient features common to all spreading segments but they exhibit systematic differences apparently related to spreading rate (*e.g.*, depth beneath seafloor to the top of a chamber may be inversely proportional to spreading rate, and length and width of the chamber may be directly proportional to spreading rate); v) the major-element chemistry of mid-ocean ridge basalts is similar at all spreading rates; however, differences which exist in the proportions of certain elements and minerals are possibly related to spreading rate through differences in fractionation regimes. Although the degree of chemical diversity of magmas apparently varies inversely with spreading rate, such diversity may be partly an artifact of sampling: for example, the compositional diversity at a closely sampled segment of the fast-spreading EPR is similar to that of the slow-spreading MAR (Langmuir *et al.* 1986); and vi) the periodicity of magmatic intrusive and related volcanic eruptive cycles appears directly proportional to spreading rate (Tables 4, 5).

Hydrothermal mineralization processes exhibit the following characteristics at slow- and intermediate- to fast-spreading centers (Table 5): i) high-temperature hydrothermal end-member solutions at all ridges exhibit similar temperatures (~350°C) and major-element compositions, but differences exist with reference to minor elements and certain isotopes (Edmond *et al.* 1986, Klinkhammer *et al.* 1986); ii) the convective heat flux (Rona & Speer 1987 and in prep.) and mass flux (Edmond *et al.* 1986) from individual vents and fields of vents seem to be similar; iii) the total convective heat and mass flux related to hydrothermal activity at a ridge segment is expected be directly proportional to the rate that heat is supplied by generation of lithosphere and, in turn, to spreading rate; however, insufficient information exists to compare the total hydrothermal heat and mass fluxes of slow- and of intermediate- to fast-spreading oceanic ridges; iv) the estimated hydrothermally convected heat per unit area of slow- (15.1 × $10^8$ cal/cm$^2$) and intermediate- to fast-spreading (11.5 × $10^8$ cal/cm$^2$) oceanic ridges is similar (Wolery & Sleep 1976); however, the temperature dependency of chemical reactions in ore-forming processes is related to local highs rather than regional averages of convective heat flux; v) preliminary surveys suggest that sites of high-temperature hydrothermal activity exist at spacings of the order of 10 km at both slow- and intermediate- to fast-spreading oceanic ridges (Hékinian *et al.* 1983, Rona 1984, Klinkhammer *et al.* 1985); known distributions at slow-spreading centers are the presence of 17 active hydrothermal systems with an average spacing of 15 km along the neovolcanic rift zone of Iceland (Palmason 1967, Palmason & Saemundsson 1974),

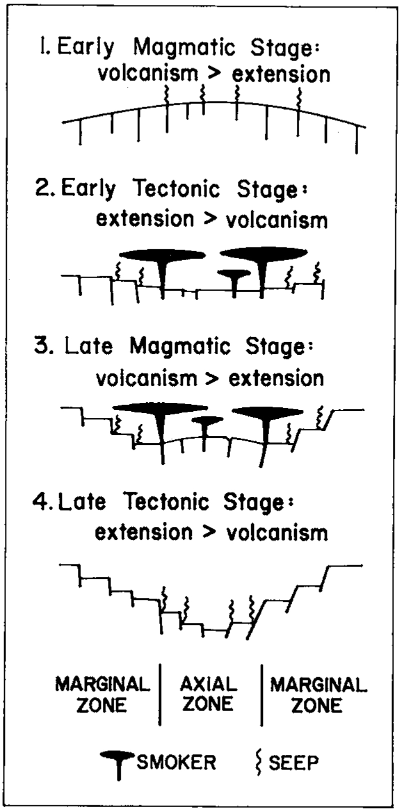

FIG. 4. Diagrammatic cross-sections perpendicular to a spreading axis showing relations between developmental stages of a seafloor spreading center and hydrothermal activity. Geologic conditions conducive to high-intensity hydrothermal activity are inferred to occur at an early tectonic stage when the rate of extension exceeds magma supply, which creates a favorable distribution of permeability and heat. Favorable conditions also prevail at a late-magmatic stage when magma supply exceeds extension. Discrete (smokers) and diffuse (seeps) components of hydrothermal discharge are shown.

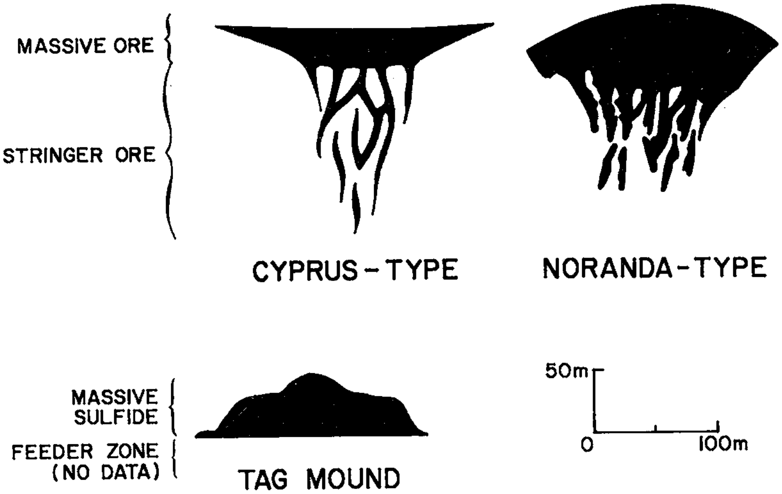

FIG. 5. Cross-sections showing the shapes of undeformed Cyprus-type and Noranda-type (Sangster & Scott 1976) massive sulfide deposits and the massive sulfide mound at the TAG Hydrothermal Field in the rift valley of the MAR (Table 1, location 23; Rona *et al.* 1986).

TABLE 5. COMPARISON OF SLOW- AND FAST-SPREADING OCEANIC RIDGES.

| PARAMETER | SIMILARITY | DIFFERENCE | REFERENCE |
|---|---|---|---|
| Structure | Structural elements parallel and perpendicular to axis | Relief 1/∝ spreading rate | Menard 1967; Rona 1984 |
| Depth (pressure) | ——— | Slow > fast | Menard & Smith 1966; Sclater & Francheteau 1970 |
| Magma Chamber | | | |
| Depth | ——— | 1/∝ spreading rate | Sleep 1975 |
| Width | ——— | ∝ spreading rate | Sleep 1975 |
| Length | ——— | ∝ spreading rate | Detrick et al. 1987 |
| Duration | ——— | ∝ spreading rate | |
| Basalt composition | MORB; major element chemistry | Certain minerals and elements (An/An+Ab; FeO/MgO; $TiO_2$; etc.); chemical variation 1/∝ spreading rate (?); degree of fractionation 1/∝ spreading rate(?) | Hekinian 1982; Klein & Langmuir 1987 |
| Crystallization | ——— | Formation of cumulates and of plagioclase phenocrysts 1/∝ spreading rate | Flower 1981 |
| Eruption Cycle | ——— | Periodicity ∝ spreading rate | Macdonald 1983; Rona 1984 |
| Solution Chemistry | Major elements (Fe, Mn, Cl, Si, $SiO_2$ $SO_4$); pH | REE; certain isotopes (B, etc.) | Edmond et al. 1986; Klinkhammer et al. 1986 |
| Chemical Flux | | | |
| Individual vent | No reliable comparisons | ——— | |
| Individual field | No reliable comparisons | ——— | |
| Spreading segment | No reliable comparisons | ——— | |
| Oceanic ridge | No reliable comparisons | ——— | |
| Solution Temperature | < 400°C | ——— | Edmond et al. 1986 |
| Mass Flow Rate | | | |
| Individual black smoker | 5–14 x $10^2$ g/s | ——— | Converse et al. 1984; Rona et al. 1986 |
| Hydrothermal field | No reliable comparisons | | |
| Convective Heat Flux | | | |
| Individual black smoker | 0.5–250 x $10^6$ W | ——— | Macdonald et al. 1980; Converse et al. 1984; Rona et al. 1986; Rona & Speer 1987; Little et al. 1987 |
| Field of black smokers | 0.1–3.1 x $10^8$ W | ——— | |
| Integrated flux of organized and diffuse flow at hydrothermal field | No reliable comparisons | | |
| Oceanic ridge | 11.5–15.1 x $10^8$ cal/cm² | ——— | Wolery & Sleep 1976 |
| Distribution of Fields | ——— | ∝ spreading rate (?) | Rona 1984, 1987 |
| Size of Fields | ——— | 1/∝ spreading rate (?) | Rona 1984, 1987 |
| Mineral Deposits | | | |
| Varieties | Forms and mineral phases | ——— | Rona et al. 1986 |
| Number | ——— | ∝ spreading rate (?) | Rona 1984, 1987 |
| Size | ——— | 1/∝ spreading rate | |
| Vent Biota | Chemosynthesis | Taxa; assemblages; habit | Rona et al. 1986; Grassle et al. 1986 |

∝ = Directly proportional to
1/∝ = Inversely proportional to

and at least 14 active systems with an average spacing of 64 km along the 900 km axial zone of the northern Red Sea (Bäcker & Schoell 1972); however, fewer hydrothermal deposits seem to occur per unit length of slow- than intermediate- to fast-spreading centers based on available data (Rona *et al.* 1982 a,b, Rona 1985b, 1987); vi) the size of individual hydrothermal fields and of mineral deposits is largely independent of spreading rate and dependent on extremely localized physical and chemical conditions that can occur at any spreading rate; however, larger hydrothermal fields and deposits seem to form at slow-spreading centers (Rona 1984, 1985b, 1987); conditions that favor the formation of larger deposits at slow-spreading centers include up to a factor of 10 longer residence time of a parcel of oceanic crust near heat sources beneath the rift valley to superimpose the products of multiple ore-forming cycles energized by multiple magmatic intrusive cycles; vii) a spectrum of hydrothermal mineral-deposit varieties (stratiform, stockwork, and disseminated sulfides; various forms of sulfates, carbonates, silicates, oxides, and hydroxides) occurs at all spreading rates.

It is increasingly evident that spreading rate is only indirectly related to physical and chemical characteristics and behavior of the oceanic lithosphere. The formation of a well-defined rift valley may be controlled by the relative rates of magma supply *versus* crustal extension (Deffayes 1970), which may be partly independent of spreading rate. Observed relations among oceanic ridge depth, basalt chemistry, and oceanic crustal thickness may result from temperature variations in the mantle which control its degree of partial melting as it ascends beneath spreading ridges (Klein & Langmuir 1987); this process is largely independent of spreading rate. Isotopic and trace-element data for oceanic crust indicate the existence of distinct geochemical provinces in the Atlantic, Pacific and Indian oceans (Dupre & Allegre 1983, Hart 1984, Hamelin & Allegre 1985, White *et al.* 1987, Ito *et al.* 1987, Dosso *et al.* 1988) that are apparently unrelated to spreading rate. Since hydrothermal activity and associated mineral deposits are directly related to thermal and structural conditions at spreading centers which, in turn, are only indirectly related to spreading rate, relations between hydrothermal activity and spreading rate are not clear-cut (Table 5).

## RELATIONS OF RECENT MINERAL DEPOSITS AT SEAFLOOR SPREADING CENTERS TO ANCIENT "ANALOGS"

### *Shape of deposits and fluid dynamics*

An analogy has frequently been made in the literature between volcanic-hosted massive sulfide deposits at modern spreading centers and Cyprus-type massive sulfides. The mineralogy, texture (Oudin & Constantinou 1984) and width/height ratios of both types of deposits are comparable. However, two overall differences exist. In addition to the likelihood that the Cyprus ophiolite may have formed in a volcanic island arc rather than in an oceanic ridge setting (Miyashiro 1973, Robinson *et al.* 1983, Moores *et al.* 1984), a distinct difference in shape exists between Cyprus deposits and those at spreading centers. A characteristic shape of the massive ore portion of Cyprus deposits is concave-up at the bottom and nearly planar at the top (Fig. 5; Searle 1972, Constantinou & Govett 1972, Constantinou 1973). In contrast, most massive sulfide deposits at seafloor spreading centers are mound-shaped with a convex-up top, like the well-developed mound at the TAG Hydrothermal Field on the MAR (Fig. 5; Table 1, location 23). An exception is the Atlantis II Deep metalliferous sediment deposit which is concave-up at the bottom and nearly planar at the top, but has a width/thickness ratio (~1000) much greater than the Cyprus deposits (~10).

Modern hydrothermal solutions venting from sites of massive sulfide deposition at oceanic ridges in the Pacific and Atlantic oceans generally are less dense than the surrounding seawater, and rise as buoyant plumes to a neutrally-buoyant equilibrium level typically about 300 m above the high-temperature vents (Lupton *et al.* 1985, Baker & Massoth 1987, Rona & Speer 1987); the equilibrium level is related to the thermal output and the buoyancy flux of the venting hydrothermal solutions (Morton *et al.* 1956). In the Atlantis II Deep, hydrothermal solutions venting from basaltic basement are denser than surrounding seawater, and have salinities up to ten times those of normal seawater (Table 6) as a result of dissolution of evaporite beds containing halite. The increased densities more than compensate for thermal expansion, and the venting solutions become density-stratified within the basin.

In the Pacific and Atlantic oceans, salinities of high-temperature hydrothermal solutions are generally close to that of surrounding seawater (35–40‰). However, fluid inclusions in quartz veins in gabbro sampled from the Mathematician Ridge, a failed spreading center near the EPR, reveal early-stage solutions of extremely high salinity (370–625‰) and temperature (409 to >635°C) and later stage solutions of lower salinity (20–70‰) and temperature (150–350°C) (Table 6; Stakes & Vanko 1986, Vanko 1988). Fluid inclusions in quartz veins on the wall of the rift valley of the MAR (Table 1, location 26) exhibit an increase in salinity with depth in the crustal section. Values are up to 3 times that of present seawater in basalt altered to greenstone, and up to 13 times in underlying gabbro (Table 6; Delaney *et al.* 1987, Kelley & Delaney 1987).

Systematic studies of the Troodos ophiolite of Cyprus also reveal an increase in the salinity of fluid inclusions in quartz veins with depth in the volcanic

TABLE 6. SALINITY OF FLUIDS IN RECENT AND ANCIENT SEAFLOOR HYDROTHERMAL SYSTEMS.

| SITE | SALINITY (NaCl EQUIVALENT WT‰) | FLUID TEMP. (°C) | REFERENCE |
|---|---|---|---|
| Open ocean surface seawater | 32–38 | Ambient | Riley & Chester 1971 |
| EPR vents at 10°57'N | 21 | 347 | Kim et al. 1984 |
| Endeavor Ridge vents | 28 | 380 | McDuff et al. 1984 |
| EPR vents at 21°N | 35 | 350 | Von Damm et al. 1985a,b |
| Explorer Ridge vents | 38 | 291 | Tunnicliffe et al. 1986 |
| Guaymas basin vents | 42 | 315 | Von Damm et al. 1985a,b |
| EPR vents at 11°15'N | 46 | --- | Kim et al. 1984 |
| EPR vents at 12°50'N | 49 | 381 | Michard et al. 1984;<br>Kim et al. 1984 |
| Southern Juan de Fuca Ridge vents | 70 | ---- | Von Damm & Bischoff 1987 |
| Atlantis II Deep, Red Sea | | | |
| Brine pool | 40–321 | 44–56 | Brewer et al. 1969 |
| Metalliferous sed. (fluid inclusions) | 150–320 | 250–420 | Oudin et al. 1984 |
| Mathematician Ridge near 17°N, 111°W: quartz veins in metagabbro (fluid inclusions) | 1) 370–625$^1$<br>2) 470–620$^1$<br>3) 20–70$^3$ | 550–>635<br>409–545<br>150–350 | Stakes & Vanko 1986;<br>Vanko 1988 |
| MAR at 23°35'N, 45°00'W: quartz in greenstone breccia fragments, matrix and veins (fluid inclusions) | 1) 56–98$^1$<br>2) 47–78$^2$<br>3) 46–60$^3$ | 237–270<br>196–240<br><200 | Delaney et al. 1987 |
| MAR at 23°35'N, 45°00'W: quartz veins in metagabbro (fluid inclusions | 1) 380–476$^1$<br>2) 5–65$^2$<br>3) 7–71$^3$ | >700<br>360–430<br>230–330 | Kelley & Delaney 1987 |
| Troodos ophiolite, Cyprus (fluid inclusions) | | | |
| Limni 1 ore body | 27–40 | 301–309 | Spooner & Bray 1977 |
| Limni 2 ore body | 33–35 | 309–322 | Spooner & Bray 1977 |
| Alestos ore body | 27–35 | 314–351 | Spooner & Bray 1977 |
| Sheeted dyke complex | 37–71 | 340–440 | Richardson et al. 1987 |
| CY-4 drillhole in gabbro | 1) 57–80<br>2) 240–640 | 140–354<br>130–300 | Vibetti et al. 1985 and in press |
| Upper Plutonic Complex | 370–480 | 330–430 | Cowan & Cann 1988 |
| Kuroko deposits, Japan (fluid inclusions) | 35–70 | 200–300 | Pisutha-Arnond & Ohmoto 1983 |
| Mattagami Lake deposit, Canada (fluid inclusions) | 350–380 | 250–300 | Costa et al. 1984 |

$^1$early stage; $^2$intermediate stage; $^3$late stage.

and plutonic section. In the massive and stringer ore hosted in pillow lavas, salinities are close to that of present seawater (Table 5; Spooner & Bray 1977); values up to twice that of present seawater occur in diabase sheeted dykes hydrothermally altered to epidosite beneath the massive orebodies (Table 5; Richardson *et al.* 1987). Plagiogranites of the Upper Plutonic Complex (Cowan & Cann 1988), and altered gabbros at least 15 km from the nearest massive sulfide deposit, in the hydrothermal recharge zone of the Troodos convection system (Vibetti *et al.* 1985 and in press), record salinities up to 18 times the present seawater values.

The range of salinity/temperature relations measured in modern and ancient mineralizing hydrothermal systems indicates that values may evolve both in space and time (Table 6). Higher salinities and temperatures are encountered deeper in the oceanic crust. Multiple populations of salinity/temperature relations are present in fluids in the same rocks, and generally represent a progressive decrease in salinity and temperature with time. Several processes could increase the salinity of circulating hydrothermal solutions above that of surrounding seawater, which may be difficult to differentiate: i) dissolution of, or fluid injection from, evaporites which may be present early in the opening of an ocean basin, as in the case of the Red Sea deeps; ii) formation of hydrous mineral assemblages, in oceanic crust, under greenschist to lower amphibolite facies may increase the salinity of residual seawater by a factor of two (Cathles 1983, Kelley & Delaney 1987); iii) membrane separation by serpentinization reactions (Macdonald & Fyfe 1985); iv) reduction of salinity by transient retention of chloride and certain cations along the flow path of the hydrothermal fluid during initial alteration, followed by increase of salinity through retrograde alteration or dissolution of phases rich in these components (Rucklidge & Patterson 1977, Ito & Anderson 1983, Vanko 1986, Seyfried *et al.* 1986, Delaney *et al.* 1987); v) mixing of a seawater-derived vent fluid with saline magmatic fluid (Sawkins & Kowalik 1981, Bryndzia *et al.* 1983, Michard *et al.* 1984); and vi) two-phase separation of a seawater-derived aqueous fluid that would concentrate salts in the denser phase (Delaney & Cosens 1982, Bischoff & Rosenbauer 1984, Hedenquist 1984, Kelley & Delaney 1987).

A fluid-dynamics model for the formation of massive sulfide deposits by density stratification of hot saline fluid venting into a submarine depression from below is shown in Figure 6 (Sato 1972, McDougall 1984a). The model requires that the venting hydrothermal solution is initially more saline (denser) than the surrounding seawater until the fluid interface in the depression rises past the level of a sill. Once fluid has ponded in the depression, further hydrothermal solutions which discharge require salinities only slightly greater than that of surrounding seawater to maintain the pond. This results from the larger rate of molecular diffusion of heat (buoyancy) relative to that of salt across the double-diffusive interface that forms at the level of the sill (Turner & Gustafson 1978). For example, a salinity only 7‰ (0.1 *M* NaCl) higher than surrounding seawater at 35‰ (0.5 *M* NaCl), suffices to maintain the pond for a hydrothermal solution venting at 300°C (the hydrothermal solution would have to be 3.5 *M* NaCl to be as dense as seawater at 300°C). The double-diffusive buoyancy flux acts to increase the density of the ponded fluid and maintain the pond. Infilling in excess of the capacity of the pond will result in flow of the ponded fluid over the sill and downslope until it collects in a lower topographic depression or is dispersed (Fig. 6; McDougall 1984b).

These considerations support the inference that the

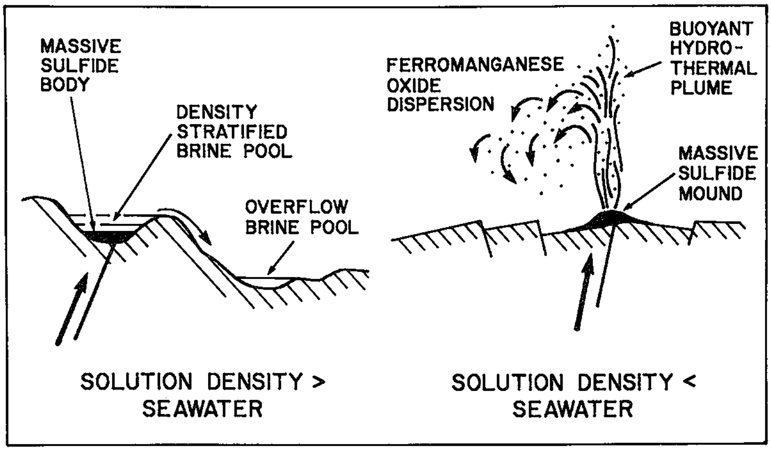

FIG. 6. Sketch showing how a ponded hydrothermal solution denser than surrounding seawater forms a hydrothermal deposit with a bowl-shaped profile, whereas a hydrothermal solution less dense than surrounding seawater buoyantly rises to form a mound-shaped deposit (modified from Zierenberg & Shanks 1988).

striking difference in shape of volcanic-hosted, mound-shaped massive sulfide deposits at modern seafloor spreading centers and bowl-shaped Cyprus massive sulfide deposits is related to differences in the fluid dynamics of their accumulation (Fig. 5). The mound shape of modern massive sulfide deposits, such as the TAG mound (Table 1, location 23), results from construction by buoyantly venting hydrothermal solutions with some component of precipitation within and beneath the mound (Campbell *et al.* 1984, Hékinian & Fouquet 1985). The bowl-shaped profile of Cyprus deposits is inferred to be the product of accumulation from ponded hydrothermal solutions that were initially more saline than surrounding seawater, but may have evolved to salinities close to that of surrounding seawater while remaining ponded. This model would be consistent with the salinities close to present seawater measured in fluid inclusions in the massive and stringer portions of certain Cyprus deposits (Table 6; Spooner & Bray 1977). Although the Altlantis II Deep deposit of the Red Sea is forming from dense, ponded brines, it lacks many of the characteristics of the Cyprus massive orebodies, indicating it is not a modern analog of these deposits.

### *Perspective: size, type and frequency of ancient massive sulfide deposits*

How does the emerging knowledge of hydrothermal mineralization at seafloor spreading centers relate to hydrothermal mineral deposits in the geologic record? A perspective may be gained from the compilation of grade, tonnage, mineralogy, ore type, host rock, and geologic age for all those massive sulfide deposits associated with volcanic rocks (either volcanic-hosted or sediment-hosted) for which such information is available (508 deposits; Mosier *et al.* 1983). The data set is influenced by the area of terrestrial exposure of bedrock type and age, the incompleteness of the geologic record, accessibility to exploration, and practical factors in development of the various deposits.

The frequency of occurence of the massive sulfides represented in the compilation (Fig. 7; Mosier *et al.* 1983) ranges between 0.07 and 1.4 deposits per $10^6$ y, with a bias to the Phanerozoic era (0.2–1.4 deposits per $10^6$ y) relative to the Proterozoic and Archean eras (0.06–0.07 deposits per $10^6$ y) for reasons stated. An increase in frequency of massive sulfide deposits seems to be associated with intervals of global plate reorganization (*e.g.*, Eocene epoch and Ordovician period in Fig. 7), when increased seafloor volcanism and tectonism create heat sources and permeability favorable for high-intensity hydrothermal activity (see Table 4, and also the section on Time scale of hydrothermal processes and geologic events).

Basalt-hosted massive sulfide deposits that may have formed at spreading centers constitute 17% of the deposits in the compilation (Fig. 8; Mosier *et al.* 1983) and range in size up to 30 × $10^6$ tonnes (Madenkoy deposit, Cretaceous of Turkey). Sediment-hosted massive sulfide deposits associated with volcanic rocks of various compositions constitute only 9% of the deposits, and range in size up to 125 × $10^6$ tonnes (San Guillermo-Sierra, Carboniferous of Spain).

The most numerous (56%) and largest massive sulfide deposits known, up to 231 × $10^6$ tonnes (Rio Tinto, Carboniferous of Spain), are hosted in rhyolites. Rhyolites may be assigned to either a subduction-related basalt–andesite–dacite–rhyolite

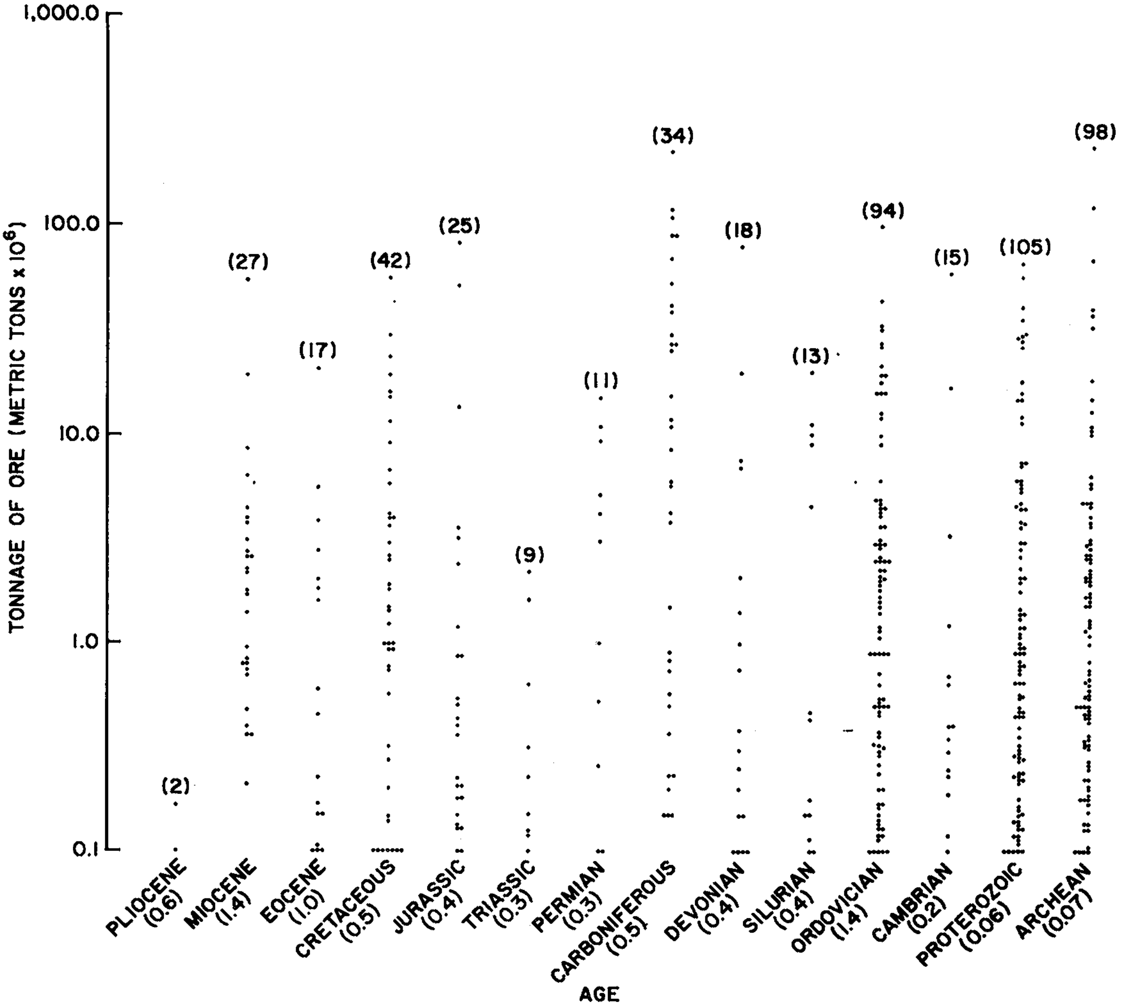

FIG. 7. Plot of size of 508 known massive sulfide ore deposits on land *versus* geologic age, based on a data compilation by Mosier *et al.* (1983). The number in parentheses above each column of points is the number of deposits plotted. The number in parentheses beneath each geologic age is the number of deposits per $10^6$ y for that time interval (time scale of Harland *et al.* 1982).

volcanic suite, or to an extension-related bimodal basalt–rhyolite suite representative of island-arc or continental rift-related tectonic settings (Martin & Piwinskii 1972, Sillitoe 1982). Hydrothermal ore-forming processes in island-arc and continental rift settings are similar to those described at seafloor spreading centers and produce analogous deposits (Cronan 1976, Skinner 1983, Cronan *et al.* 1984, Moorby *et al.* 1984, Usui *et al.* 1986, McConachy *et al.* 1986, Binns *et al.* 1986, Urabe *et al.* 1987). Laboratory experiments reacting seawater with basalt, rhyolite and andesite, which are the volcanic rock types in these diverse settings, produce similar ore-forming solutions at temperatures between 200 and 500°C, water/rock mass ratios between 5 and 50, and 1 kbar pressure (Hajash & Chandler 1981). Global plate reorganizations favor the development of continental rifts as tectonic settings for volcanic- and sediment-hosted massive sulfide deposits with rhyolitic associations (Rona 1980), either as failed rifts (aulacogens; Burke 1977) or more fully propagated rifts (Hey 1977) which may develop into interarc or back-arc basins.

## SUMMARY AND CONCLUSIONS

A synthesis of the occurrence of hydrothermal mineralization at seafloor spreading centers, observations of related hydrothermal processes, and information from ancient "analogs" supports the following conclusions:

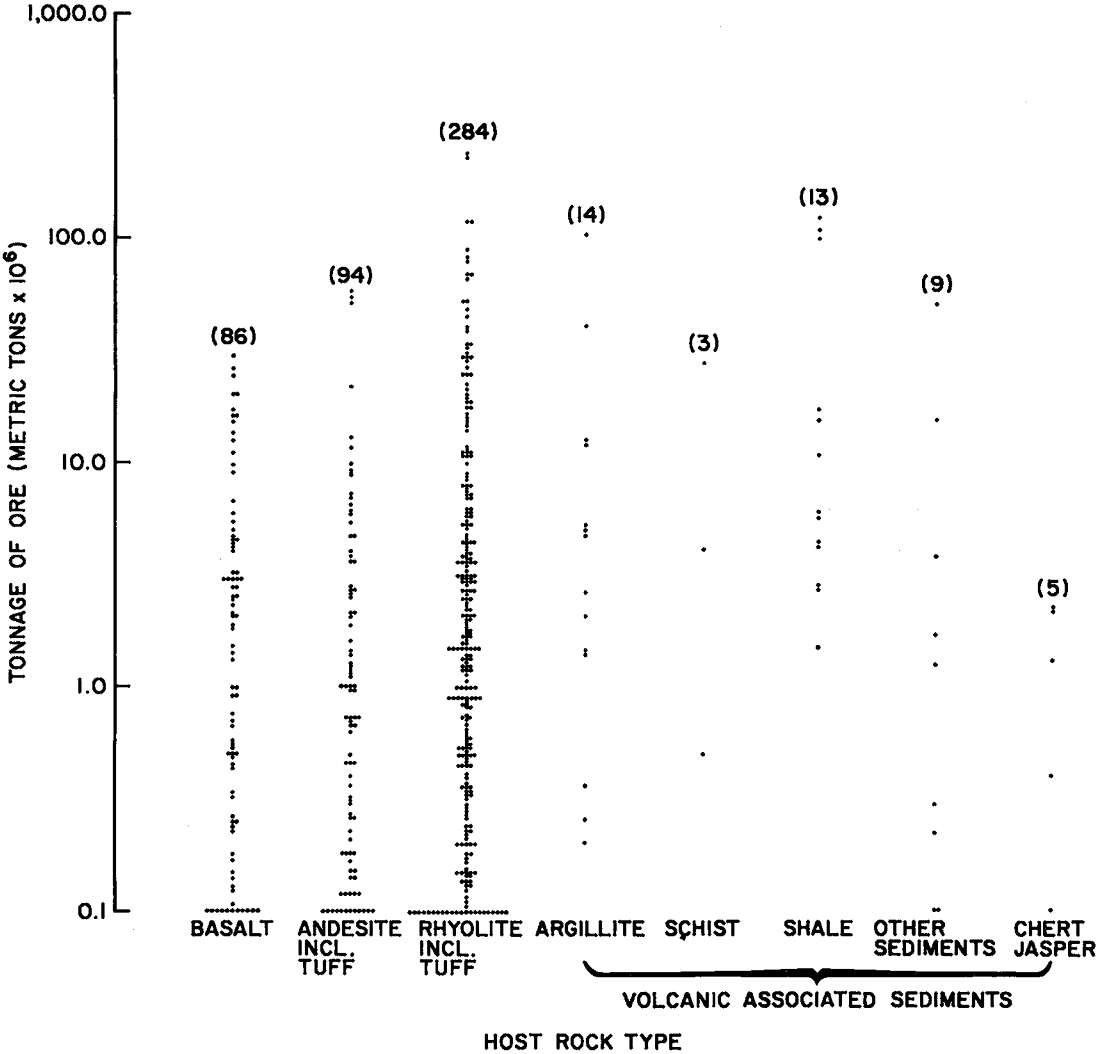

FIG. 8. Plot of size of 508 known massive sulfide ore deposits on land *versus* type of volcanic host rock immediately underlying each deposit, based on a data compilation by Mosier *et al.* (1983) and Lowell & Rona (1985). The number in parentheses above each column of points is the number of deposits plotted.

(1) A compilation of 102 mineral occurrences at the global seafloor spreading-center system reveals that almost all major varieties of volcanic- and sediment-hosted hydrothermal deposits associated with basaltic rocks in the geologic record have been found at oceanic ridges and rifts (Fig. 1; Tables 1, 2).

(2) Mineralization at seafloor spreading centers is directly related to thermal, structural, and chemical properties of oceanic lithosphere which are controlled by processes that are only indirectly related to rates of seafloor spreading; therefore, relations between ore-forming hydrothermal systems and seafloor spreading rates are not clear-cut, but certain trends are present.

(3) Different varieties of hydrothermal mineral deposits occur independently of seafloor spreading rate. A nearly complete spectrum of hydrothermal mineral-deposit varieties (stratiform, stockwork, and disseminated sulfides; stratiform, layered sulfates, carbonates, silicates, oxides, and hydroxides) occurs in each of the tectonic settings related to stage (early, advanced) and rate (slow-, intermediate- to fast-spreading) of opening of an ocean basin about a spreading axis (Tables 1, 2). Such a spectrum of deposits is also present in volcanic island-arc and continental rift settings wherever the requirements for ore-forming subseafloor hydrothermal convection systems are met (volcanogenic heat source, permeable rock, seawater, and physical and chemical conditions that conserve heat and mass and con-

centrate and preserve precipitates).

(4) Size of hydrothermal mineral deposits is largely independent of spreading rate. A range of hydrothermal mineral deposit sizes from small to large ($\geq 1 \times 10^6$ tonnes) occurs at all spreading rates (Table 1, locations 23, 27, 42, 64, 71, 96, 97); based on available data, however, larger deposits seem to form at slow- rather than at fast-spreading centers; the concept that deposit size is directly proportional to spreading rate, which has influenced disproportionate exploration efforts on the fastest spreading portions of the global oceanic ridge system, is no longer tenable.

(5) Sediment-filled segments constitute <1% of the length of the global seafloor spreading-center system, but may host a disproportionate number of large hydrothermal deposits because of the efficiency of sediments in conserving hydrothermal precipitates regardless of spreading rate. At least two potentially large sediment-hosted deposits (locations 96, 97) are present along the 970-km length of the Gorda - Juan de Fuca Ridge system.

(6) Preliminary surveys suggest that sites of high-temperature hydrothermal activity exist at spacings of the order of 10 km, both at slow- and intermediate- to fast-spreading centers; based on available data, however, fewer hydrothermal deposits seem to occur per unit length of slow- than intermediate- to fast-spreading centers (Table 5).

(7) Heat and mass fluxes of high-temperature black-smoker-type venting require magmatic heat sources with volumes about one order of magnitude larger than those of source rocks for the mass flux of metals, and involve time periods between $10^3$ and $10^5$ y to form large deposits (Table 3).

(8) A spectrum of hydrothermal sources exists, with a range of physical and chemical properties related to rock type in seawater–rock interaction (mafic or ultramafic), pressure and temperature fields within subseafloor hydrothermal convection systems (phase separation), and discharge behavior in venting zones (diffuse, discrete, cataclysmic) with implications for mineralization.

(9) Hydrothermal activity is a cyclical phenomenon, with low- and high-temperature stages controlled by magmatic (volcanism > crustal extension) and tectonic (extension > volcanism) events (Fig. 4); high-intensity ore-forming hydrothermal activity is favored by a combination of magmatic and tectonic activity to provide heat sources and permeability; large deposits are accumulated by the superposition of the products of multiple high-intensity hydrothermal cycles.

(10) The shape of seafloor hydrothermal deposits is related to fluid dynamics through temperature/salinity relations that determine the density of the effluent relative to surrounding seawater (Table 6). Mound-shaped deposits are formed by less dense (more buoyant) effluents, whereas saucer- to bowl-shaped deposits are formed by ponding of denser effluents (Figs. 5, 6); a relatively small contrast in solution densities can control ponding *versus* buoyant behavior. The mound shape of many massive sulfide deposits on oceanic ridges (*e.g.*, Table 1, locations 23, 42) is produced by precipitation from buoyant solutions; the saucer shape of the Atlantis II Deep metalliferous-sediment deposit and the bowl shape of Cyprus massive sulfide deposits are inferred to be produced by ponding of hypersaline solutions, although these deposits differ in other characteristics; no modern seafloor analog of the Cyprus deposits is known. The processes that control salinity in hydrothermal effluents are sufficiently diverse that different processes acting in different tectonic settings may converge to produce deposits with similar shapes. For example, hypersalinity acquired from dissolution of evaporites controls ponding of precipitates in the Atlantis II Deep of the Red Sea, whereas phase separation due to boiling may control ponding of precipitates in the caldera of a seamount or a seafloor depression.

(11) The growing knowledge of plate tectonics and of hydrothermal mineralization processes at seafloor spreading centers suggests that increases in the frequency of occurence of massive sulfide deposits through geologic time (Fig. 7), and changes in their geographic distribution, are closely related to episodes of global plate reorganization ($10^6$–$10^7$ y; Table 4) through associated changes in intensity and distribution of volcanic and tectonic activity.

(12) Review of lithologic associations of 508 massive sulfide deposits in the geologic record indicates that basalt- and sediment-hosted massive sulfides inferred to have formed at seafloor spreading centers constitute a smaller percentage (<26% of 508 deposits; Fig. 8) than such deposits hosted in rhyolitic rocks inferred to have formed in volcanic island arc- and continental rift-related tectonic settings (56% of 508 deposits); these observations suggest that seafloor spreading centers have been significant as tectonic settings for massive sulfide formation and preservation through geologic time, although subsidiary to island arcs and continental rifts.

## ACKNOWLEDGEMENTS

I thank J.S. Fox and the Mineral Exploration Institute (IREM–MERI) for the opportunity to participate in the 1987 conference at McGill University: "Recent Hydrothermal Mineralization at Seafloor Spreading Centres: Tectonic, Petrologic and Geochemical Constraints." I acknowledge helpful comments from T.J. Barrett and two anonymous reviewers. G. Derr provided capable word processing. I thank the NOAA VENTS Program for funding support and the opportunity to investigate seafloor hydrothermal systems.

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*Received March 10, 1988; revised manuscript accepted June 26, 1988.*