IV. HYDRODYNAMIC CONSIDERATIONS

IV-A. Introduction

Hydrodynamic models of the cooling of new oceanic crust through convective interaction with seawater, in conjunction with certain of the observations summarized in the previous sections, give insight into the ore deposits potential of the seafloor spreading process for the formation of massive sulfide ore deposits, factors that favor large massive sulfide deposits, and features that may have exploration significance. In this section we will show that heat flow data from one ridge spreading at ~6 cm/yr precludes the presence of shallow magma chambers further than a few kilometers from the ridge axis. If this is generally true, it means that the crustal portion of an oceanic plate (perhaps down to the moho) cools very rapidly right at the ridge axis. The heat from such cooling would be sufficient to continuously sustain black smoker activity at the ridge axis and vent enough sulfide smoke to cover each square centimeter of newly created oceanic plate with ~ 277 g of Cu- and Zn rich pyrite deposits, if all the constituents of smoke precipitated. From the observed accumulation of sulfide material at ridges we estimate the efficiency of sulfide precipitation and its variation with time. The efficiency of sulfide precipitation in land-based massive sulfide camps is similar to the estimates obtained for the efficiency of sulfide deposition on the seafloor during their most active stages of hydrothermal venting and surface sulfide deposition.

The hydrothermal system envisioned is compatible with permeability measurements made to date on the ocean crust, geochemical estimates of the time required to form the ocean ridge massive sulfide deposit at 21°N, and the residence time of seawater in the hydrothermal convection system at 21°N.

Larger deposits will be produced if sulfide deposition is less spatially uniform at a ridge, if heat sources travel with the plate as it spreads, or if the efficiency of sulfide precipitation is greater. The efficiency of deposition appears to increase with the duration of hydrothermal venting at any one site.

Areas of the oceanic plate are identified where larger massive sulfide lenses are most likely to be found. The principles developed are general and could also be applied to deposition in inland areas or continents (see Cathles, submitted), although we have not done this in this report.

IV-B. General Heat Balance Constraints

It has been appreciated for some time that the heat flow within several hundreds of kilometers of ocean ridges falls far short of the heat flow expected of the basis of conductive cooling models of the oceanic plate (Wolery and Sleep, 1976; Sleep and Wolery, 1978). Two views have been expressed as to how this extra heat is carried out of the plate by hydrothermal convection of seawater. In the first view, the heat is dissipated rather gradually over an area extending hundreds of kilometers on either side of the ridge, although more heat is carried out near the ridge axis than further away (Sleep and Wolery, 1978), and discharge must be concentrated in fractures if the constraints imposed by heat flow measurements are to be accomodated (Fehn and Cathles, 1979). In the second view, the heat in the crustal portions of the oceanic plate above the moho is dissipated very near the ridge axis by intense hydrothermal circulation (Lister, 1982; Cathles, submitted).

The first view has been generally considered more probable in part because it appears to be supported by some seismic studies of the oceanic plate (although not by others which show a very restricted magma chamber, Ried, 1981) and by interpretations of petrologic data from ophiolite suites exposed on land. Ocean bottom seismic surveys and analogy to the form of magma chambers deduced from study of the gabbro section of ophiolite suites (Hopson et al., 1981; RISE, 1981) suggest magma chambers at ridges spreading at intermediate or faster rates (> 6 cm/yr total opening rate) persist to ~15 km from the ridge axis and have an inverted pyrimid form. Fractionation in such a magma chamber would allow formation of a thick sequence of layered cumulate gabbros in the lower two thirds of oceanic layer 3, and also allow steady state segregation of the plagiogranites that commonly cap the cumulate layer in ophiolites. We believe new ocean heat flow data make it very unlikely this model is correct.

Heat flow measurements can be made only in sediments and this generally precludes measurements very close to an ocean ridge. However, the Galapagos Rift lies in the equatorial zone of very high pelagic sedimentation, and there is sufficient sediment cover at this location to allow heat flow measurements to be made within 2 km of the ridge axis. Green et al. (1981) reported over 400 heat flow measurements in a 25 x 30 km area near the Galapagos spreading center at 86°W. The survey shows the heat flow near the ridge axis is astonishingly low and, in fact, increases with superimposed variations away from the ridge to rejoin values expected for the conductive cooling of the plate at distances of about 22 km from the ridge. (see Figure IV-I).

The low heat flow values and their pattern indicates that a shallow magma chamber of the inverted pyramid type envisioned by petrologists studying ophiolite sequences cannot exist at the Galapagos Spreading Center; convection must remove nearly all the heat contained in the upper 5 km of oceanic plate within a few kilometers of the ridge. If a magma chamber existed at ~ 2 km depth out to ~ 15 km from the ridge, the average heat flow out to 15 km from the ridge would be ~ 32 HFU*. The average heat flow is ~ 7.1 HFU and, in fact, decreases to near zero very near the ridge. Convection might redistribute the 32 HFU required by the presence of a shallow magma chamber, but the lows would be compensated by much higher highs, and such highs are not observed. At face value the heat flow survey suggests that the oceanic crust is cooled below equilibrium values very near the ridge axis and reheats in the ~ 630,000 years it takes to move 22 km from the ridge axis. Indeed, Fehn et al. (1982) come close to concluding this in their preferred model of the heat flow pattern. They show the observed heat flow pattern is consistent with a convection model in which essentially all the heat is removed within 1 km of the ridge axis for the upper 2 km of the oceanic crust near the ridge, and within 2 km of the ridge axis for the lower 2 km crust (see Fig. IV-2), but for some reason they do not emphasize what appear to us to be the important ramifications of this conclusion. <u>The important point for ore deposits is that nearly the entire heat content of the oceanic crust is clearly removed by hydrothermal circulation within a few kilometers of the Galapagos Spreading Center, and the hydrothermal circulation responsible for this removal will almost certainly all vent at or very close to the ridge axis (see Figure IV-2). This conclusion forms the basis for the analysis that follows.</u>

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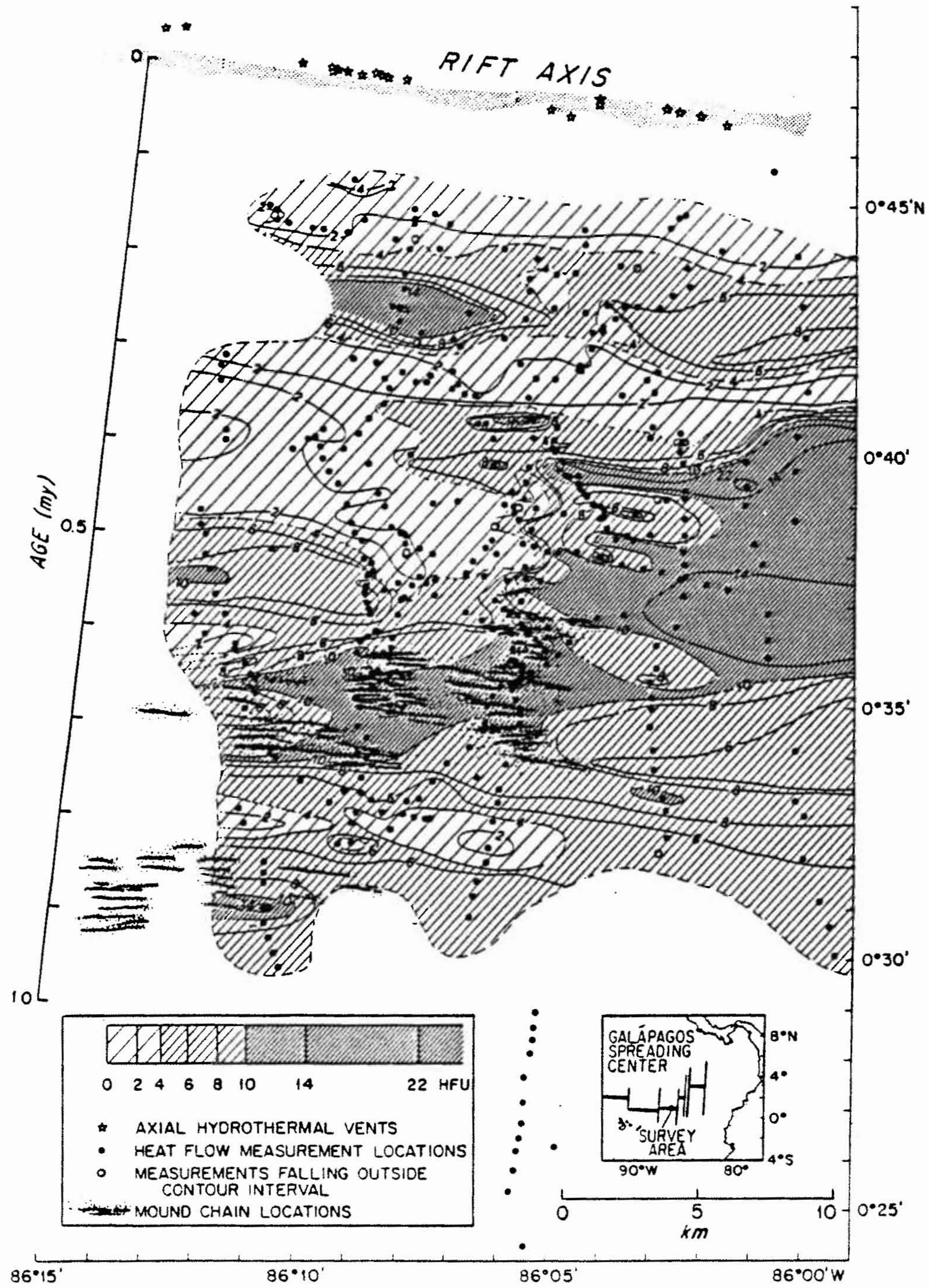
* 32 HFU = $K \Delta T = (5 \times 10^{-3}$ cal/cm^2-sec-^{0}c) x (1300°C) ÷ (2 x 10^5 cm) x 10^{-6} HFU/Cal/Cm^2 - sec

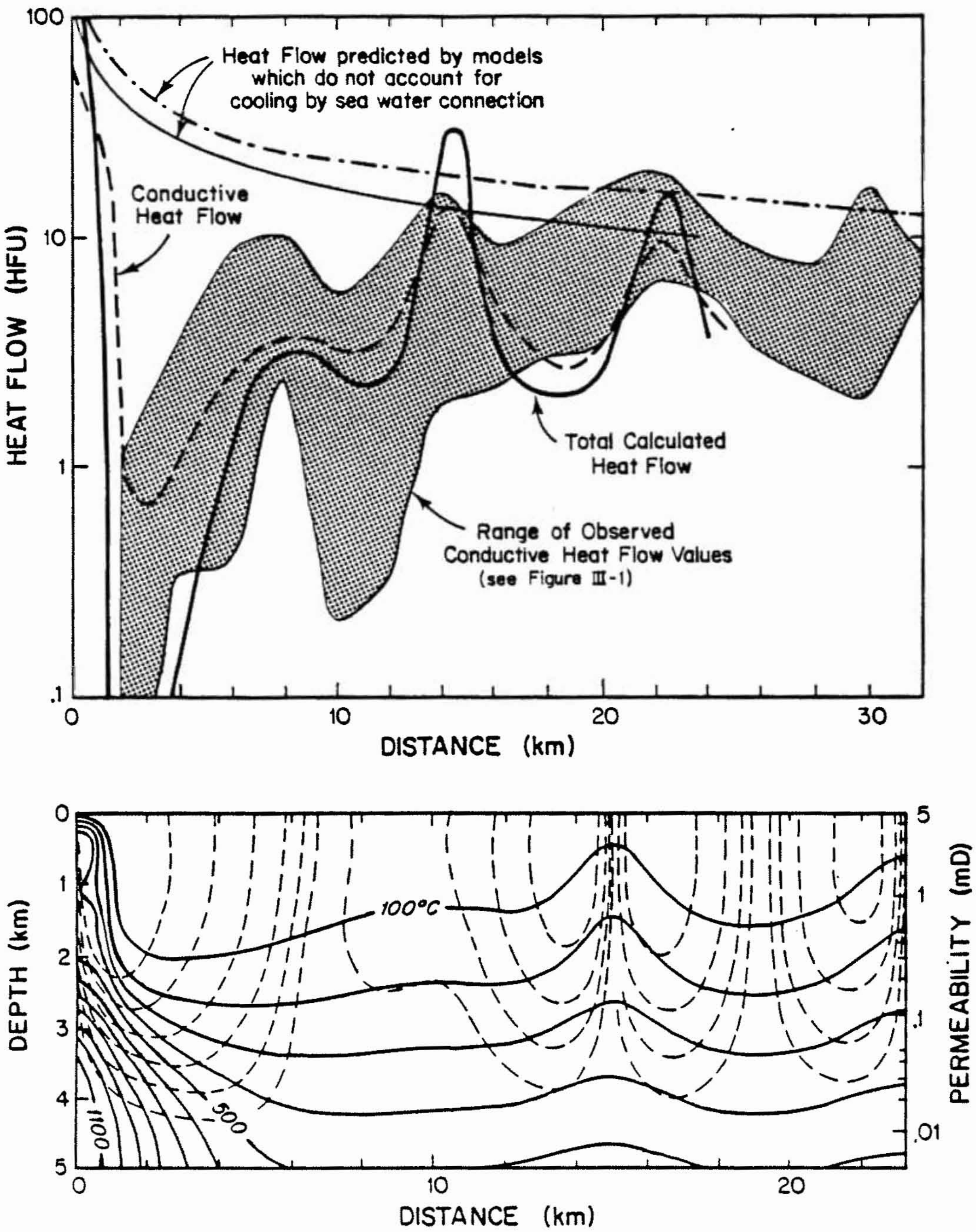


Heat flow near the Galapagos Spreading Center (Green et al., 1981).

FIGURE IV-1

IV-2. Top: Heat flow away from Galapagos spreading center. Stippled region. Stippled band shows generalization of heat flow away from Galapagos spreading center shown in plan in Figure IV-1. Also shown are heat flows predicted by conductive and convective plate cooling models. The heat flow is much less than predicted by conductive cooling models, but well matched by models that take into account convection of seawater through the oceanic plate. The sinuous solid curve is the total heat flow of the calculated model below; the sinuous dashed curve is the heat flow that would be measured by a conductive heat flow probe.

Bottom: Convective cooling model showing isotherms in the oceanic plate (solid curves) and the pattern of convective circulation of seawater (dashed lines). Both Figures are from Fehn et al. (1982).



100
10
1
.1
HEAT FLOW (HFU)
Heat Flow predicted by models which do not account for cooling by sea water connection
Conductive Heat Flow
Total Calculated Heat Flow
Range of Observed Conductive Heat Flow Values (see Figure III-1)
0
10
20
30
DISTANCE (km)
DEPTH (km)
0
1
2
3
4
5
100°C
500
1100
PERMEABILITY (mD)
5
1
.1
.01
0
10
20
DISTANCE (km)

FIGURE IV-2

Let us assume for the moment that hydrothermal activity is completely uniform temporally and spatially along the ridge axis. This is not quite the case, but if it were, and if the solutions vented at 350°C and precipitated all their contained metals (1.8 m mole/1 Fe and 4.0 m mole/1 H_2S, or the constituents for 215 ppm FeS_2 at 21°N), the oceanic crust could provide enough heat to uniformly precipitate about 277 g/cm^2 of pyrite over the entire surface of the oceanic plate.* The significance of this calculation is that it places an upper limit on the magnitude of ocean ridge mineralization. For example, if an area one kilometer square contributes to the formation of a localized sulfide lense, the maximum size of the lens is 2.77 x 10^6 tonnes.

The above estimate of surface mineralization is a realistically generous upper limit. The heat available from the oceanic plate is probably something less than 1000 cal/cm^3; the efficiency of precipitation of minerals from venting hydrothermal solutions is certainly less than 100 percent. There is reason to believe that, moreover, solutions will commonly vent with exit temperatures around 350°C. Therefore, the metal concentrations observed at 21°N may be typical of solutions venting on other ocean ridges. Chemical rock alteration reactions appear to preclude significant flow of water through rock at temperatures greater than about 350° (Cathles, submitted). The irregularities and debris that prop fractures open at lower temperatures are

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* We assume 1000 cal/cm^3 are available from the cooling of the oceanic crust. This represents about 648 cal/cm^3 for cooling 1200°, plus about 356 cal/cm^3 heat of crystalization and alteration (Oldenberg, 1975). The oceanic crust is about 5 km thick, so 5 x 10^8 calories are available to each cm^2 of new ocean plate from a prism running from the surface to the moho. Water at 350°C has an enthalpy of 388 cal/g so this amount of heat could cause 1.3 x 10^6 grams of 350°C fluid to vent the surface. If that fluid carried 215 ppm FeS_2, and precipitated this metal load upon contact with seawater, 277 g of pyrite would be precipitated per cm^2 of oceanic plate. The water rock ratio during cooling of the oceanic plate is ~ 0.87 [= (1.3 x 10^6) ÷ (5 x 10^5 cm) (3.0 g/cm^3)]

dissolved at temperatures greater than 350°; the fractures collapse, the fracture walls fit tightly, and the permeability is drastically reduced. Calculations (Cathles, submitted) show it is not possible to regulate venting temperature by appealing to the pressure and temperature dependence of fluid properties like viscosity and density as suggested by Bischoff (1980) and Chen (1981).

Finally, the constraints on mineralization imposed by heat balance considerations are considerably more severe than those imposed by the availability of the metals. For example, the solutions venting at 21°N contain 2 ppm Cu, so the 1.3 x 10^6 grams of hydrothermal solution vented by the cooling crust (see previous footnote) could deposit 2.6 g Cu per cm^2 of ocean floor. Basic rocks typically contain about 60 ppm Cu (Solomon, 1976), so the oceanic crust contains about 90 g Cu/cm^2 surface area, and hydrothermal solutions remove, at most, only about 3 percent of the copper contained in the crust. The estimate made in the previous paragraph thus appears to be a generous but realistic upper bound on the intensity of surface mineralization we can expect from processes occurring near mid-ocean ridges.

There are further questions we must answer: (1) How much spatial concentration occurs in the sulfide deposition process at mid-ocean ridges Sulfide mineralization is not uniform, but occurs in localized pods surrounded by barren plate. What is the ratio of the plate area covered by sulfide mineralization to the barren area. (2) What is the efficiency of deposition of metals from hydrothermal plumes. Temporal variation in hydrothermal activity is not of first order importance. New plate is created either steadily or in bursts, and sulfides are deposited on top of this new plate. Unless the efficiency of sulfide deposition depends on the manner in which the plate is formed (which is possible, but which we consider, at this point, to be a second order question), new plate supplies the heat and makes its own surface mineralization. The rate of spreading (fast, slow, pulses), within limits, should make no difference to the intensity of surface mineralization since the plate conveyor carries deposited minerals away at a rate precisely proportional to the rate of introduction of heat by the seafloor spreading process.

IV-C. Modeling Massive Sulfide Deposition

IV-C-1. East Pacific Rise at 21°N

IV-C-1a. Density and Precipitation Efficiency

The best studied site where sulfide deposition has taken and is taking place is the East Pacific Rise at 21°N (Figures I-25, -26, -27). The 21°N site itself is a roughly 7 kilometer segment of ridge that shows evidence of very recent or current hydrothermal activity (i.e., the presense of clams and other biota, the venting of warm (8°C) and hot (350°C) solutions, accumulations of sulfides, etc.). The active segment lies between two major fracture zones, the Rivera and the Tamaya, that lie ~ 330 km apart and significantly offset the East Pacific Rise. The Rise section between the fracture zones, although apparently smooth on most maps, is in fact offset by 4 to 6 minor transforms spaced about 50 km apart, and within the one of these ridge segments that has been studied, the ridge is divided into 7 to 10 km long en-echelon spreading segments. It is along one of these 7-10 km long segments that present hydrothermal activity is occurring and massive sulfide lenses have been discovered and studied.

The hot (350°C) vents are on the southeastern part of the 7 km active ridge segment. The southeastern part of the active segment is also about 70 m higher in elevation, has a larger ratio of sheet to pillow lava flows, and is less fractured (Ballard et al., 1981). The 7 km segment of the ridge that contains the black smokers and warm vents with biologic activity actually consists of about 10 major vent or biologic clusters that appear to be spaced at a quite regular interval of 680 ± 190 m (1σ) apart, as measured from the data in Figure I-25. Eight of these major (and one minor) vents or biologic clusters contain sulfide mineralization. Ballard (unpublished data) has obtained nearly complete photographic coverage of two of these deposits, at the NGS (Figures I-26, -28) and OBS (Figure I-27) vent fields, and partial coverage of three more using the ANGUS camera sled. We have estimated the size of the deposits from this data in Table IV-1. The estimated range for six deposits is 840-6100 tonnes and the mean is 2200 tonnes. All the deposits except that at the OBS field occur within 50 m of a single eruptive fissure near the edge of a 120-600 m wide pillow ridge, which is the most recently formed pillow ridge in the inner rift valley. The youngest part of the inner rift (Zone 1; Figure I-25) is 0.6 to 1.2 km wide and consists of at least three volcanic cycles (sheet flows-pillow basalts). The younger cycles are most easily distinguished and the youngest cycle of all has the narrowest pillow ridge, which suggests either that this ridge will grow further, or that there are more older flows than have been so far identified.

The 21°N hydrothermal vents are probably in the process of turning off. First of all, the rate of thermal discharge is low. Despite comments to the contrary in the literature (MacDonald _et al._, 1980), the heat required to drive the observed geothermal system could be supplied by the average 6 cm/yr

TABLE IV-1

ESTIMATES OF THE TONNAGE OF SULFIDE DEPOSITS
ON THE EAST PACIFIC RISE AT 21°N

Vent Field	Photographic (ANGUS) Coverage	Modelled as:	Volume m^3	Tonnes* ($=10^6$gm)
OBS	2 passes (Fig. I-27)	elliptical cone, 29 x 35 m^2, 45° sloping sides	2050	6150
NGS	3 passes (Figs. I-26,28)	2 pods: 1) 8 x 22 m^2 2) 7 x 7 m^2 2 m thick	352 +98 450	1056 +294 1350
SW	none**	15x15x1.3 m^3	293	880
A	1 pass: showed semi-circle with vent at center of presumed circle	disc, r = 9 m 2 m thick	763	2290
B	1 pass: 25 x 10 m^2 observed	>(25x10)m^2, 2 m thick	>500	>1500
C	1 pass: 20 x 7 m^2 observed	>(20x7)m^2, 2 m thick	>280	>840
			Average of 6:	2170

*assuming a bulk density of 3 gm/cm^3

**based on visual estimates and photographic coverage from ALVIN spreading rate. Converse et al. (1982 as revised by personal communication) estimate the thermal output of the NGS and OBS vents to be 2.7×10^7 cal/sec. This thermal output could be supplied by 6 cm/yr spreading on a ridge segment 2.7 km long.* Since the vents near these two most active vents are relatively dormant, extraction of heat from this length of ridge is not unreasonable. Furthermore, when the ALVIN returned in November of 1981 and revisited the site of the black smoker renowned for being pictured on the cover of National Geographic Magazine, the smoker was dormant. When the submarine set down, the depressions in the mound caused by the submersible became sites of numerous small black smokers. The demise of black smoker activity at the NGS site, the obvious lack of a large buoyant head behind the remnant thermal reservoir, and the ~8 inactive vents north of the active NGS and OBS sites, suggest the hydrothermal activity at 21°N is turning off.

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*At a spreading rate of 6 cm/yr, ~ 10^7 cal/sec are available per kilometer of ridge ($9.5 \times 10^6 = 6$ cm/yr $\times 5 \times 10^5$ cm $\times 10^5$ cm $\times$ 1000 cal/cm^3 3.15×10^7 sec/yr). The conclusion that black smoker heat can be steadily supplied by the heat introduced by spreading differs from the conclusion reached in the literature (see MacDonald et al., 1980). The new conclusion is based on Converse et al. updated estimates of heat flux. MacDonald et al's estimate is about an order of magnitude too large because they assumed a vent diameter of 30 cm for the black smoker whose discharge they calculated. We have carefully examined photographs of the site and conclude the diameter of the vent can be no more than 10 cm, a diameter much more in accord with the diameters of other vents at 21°N. Converse measured the two vents at NGS and one vent at OBS and then multiplied the one vent at OBS by 9 to estimate the total venting of the nine vents at OBS. If we correct MacDonald et al's estimate for the 10 cm rather than 30 cm diameter, the heat flow from the vent would be 6.7×10^6 cal/sec. If, in April, 1979, 11 vents were active similar to the one MacDonald et al. measured, the total heat flow for OBS and NGS would have been 7.3×10^7 cal/sec or about 2.7 times greater than Converse estimated 2 1/2 years later in November, 1981.

Observations at 21°N provide some basis for estimation the surface density of mineralization. The question is how far apart might lines of massive sulfide lenses be at 21°N. The string of sulfide deposits is associated with a pillow ridge less than 120-600 m wide that forms part of a sheet flow-pillow ridge pair (Figure I-25). There is no reason to suppose the most recent pillow ridge is special, so presumably the other pillow ridges in zone 1 also contain massive sulfide lenses spaced roughly the same distance apart along the ridge and having roughly the same size. Also it is reasonable to suppose that each pillow ridge spreads out from its source area and so overlaps somewhat other pillow ridges and sheet flows of previous cycles. Thus, the lines of sulfide deposits will be less than 120-600 m apart. We have measured the area of the youngest pillow-sheet flow pair shown in orange and red in Figure I-25 to be 1.8 km^2 for the 7-km segment containing the eight sulfide deposits. Assuming that about half of this area is new crust and half covers older flows, we arrive at an area of 110,000 m^2 per deposit. Thus, each 2200 tonne sulfide lens is associated with a plate area of about 680 m along the axis and 160 m perpendicular to it (=110,000 m^2), and the average surface density of sulfide mineralization is about 2 g/cm^2*. Also, since 277 g/cm^2 sulfide could be deposited if the oceanic crust convectively cooled at the ridge axis and 100 percent of the sulfide dissolved in the hydrothermal solutions precipitated, the observed surface density of 2 g/cm^2 suggests the overall efficiency of sulfide deposition is about 0.8 percent.

Other evidence suggests the present efficiency of sulfide deposition at 21°N may be greater than this overall efficiency. Converse et al. (1982 as

*Note we consider each line of sulfide deposits to move to one side or the other of the ridge axis; i.e., that the sulfide line will not be split. Subsequent ridge activity will form a new line of deposits ~160 m away.

revised by personal communication) have recently estimated the thermal output of the OBS vent cluster at 21°N (2.4 x 10^7 cal/sec). If this heat vents into or through the near surface at 350°C as measured and indicated by geochemical extrapolations, the rate of venting is 1.9 x 10^{12} g/yr, and the rate of pyrite deposition at 100 percent efficiency would be 410 tonnes per year. Such a rate of deposition could produce a 2200 tonne sulfide lens in 5 yrs. The age of the sulfide chimneys in the mounds have been measured at ~ 50 yrs, (Chung et al., 1981) so the efficiency of sulfide deposition from the hydrothermal fluid is about 10 percent.

It is, of course, possible that the density of massive sulfide mineralization at 21°N is greater than the 2 g/cm^2 estimated above. There is some indication of this in the observation that the most recent pillow ridge is smaller than the older ridges in the area and thus may grow further. It is possible that there may be several sulfide lenses stacked vertically on top of one another in any one pillowed ridge. There is also some uncertainty in the measured age of the chimneys. They might be 100 years old rather than 50. If three sulfide lenses were stacked in pillowed ridges 160 m apart, and the age of the deposits were 100 years, estimates of sulfide precipitation efficiency from surface mineralization density would be closer to estimates from the rate of venting and the radiometric age of the deposits (2.4 percent vs. 5 percent). Given the uncertainties involved, the two methods of calculating the efficiency of sulfide precipitation are in agreement. Both indicate low efficiency.

We are inclined, however, to believe that the surface precipitation efficiency is not constant with time and increases the longer a vent area is active. The largest deposits found in Cyprus suggest this is the case, as well shall discuss later. Comparison of vents in several stages of development also suggest this conclusion. Initially, the solutions vent through small, short chimneys, mainly as black smoke. Little of this smoke settles in the vent area. Later, when the chimneys are larger, it appears that tube worms control the chimney growth and regulate the temperature of discharge to their liking. At this stage, venting is in the form of "white smoke" that contains mainly anhydrite. Nearly 100 percent of the metal sulfides precipitate in or beneath the chimney.

Thus it is also possible that the 2 g/cm^2 surface sulfide density observed at 21°N is reasonably accurate and reflects the average precipitation efficiency. The precipitation efficiency is greater at hydrothermal systems that have been active long enough to have developed mature biologic communities. The surface mineralization density at 21°N may be small because the intrusive pulses at 21°N are small and the duration of each episode of hydrothermal activity is therefore relatively short.

We might comment at this point that we do not envision sulfide material precipitated beneath the surface to greatly alter the above reasoning or conclusions. In massive sulfide camps over half the ore is generally contained in massive lenses and less than half is in disseminated ore feeder pipes beneath the massive lenses. Thus inclusion of the disseminated ore could change the estimates we have made of the surface density of mineralization by at most a factor of two and this is not significant in light of the other uncertainties involved.

IV-C-1b. Subsurface Hydrology

The duration of hydrothermal activity is related to the size of the intrusive that provides the heat to sustain the system, the permeability of the host formations, and the temperature dependent permeability of the intrusive. Consideration of the geology and hydrodynamics at 21°N in somewhat greater detail provides further tests of the above concepts of sulfide deposition.

Anderson and Zoback (1982) recently measured the permeability of 6.2 million year old oceanic crust off the Costa Rica rift. They found the permeability of the upper 200 m of the hole to be ~ 40 millidarcies and the permeability of the lower 3-15 m to be ~ 2-4 millidarcies. Cathles (submitted) has calculated the convective cooling history of a 1 km wide dike intruded between 5 and 2.25 km depth beneath the floor of a 2500 m deep ocean. The permeability of the host rock was 5 millidarcies. The permeability of the intrusive was sharply reduced from 5 millidarcies at temperatures above 300°C, so that the hydrothermal solutions vented at ~ 300°C. The intrusive in this calculation took 5000 years to cool from 700° to less than 200°C everywhere. The average Darcy rate of fluid circulation along the 300°C edge-isotherm of the intrusive was about 75 g/cm^2-yr. If the fractures that allow fluid flow are close enough together that weakly reactive chemical species can reach roughly the same concentrations in the rock between fractures as in the fractures themselves (this will be the case in the calculated example for fractures less than about 10 m apart), the velocity of a chemical front along the sides of the intrusive will be about 38 m/yr (assuming a 2 percent connected rock porosity), and a chemical front will traverse the side of the intrusive and vent into the sea in about 133 years.

Since a 150 meter wide basalt intrusive pulse is 15 percent of the size of the intrusive in the above calculation, but intrudes at roughly twice the temperature, the 150 m wide intrusive will take about 1500 years to cool. If the permeability of the host is increased from 5 to 25 millidarcies, the intrusive will take about 300 years to cool and the velocity of the fluid at the sides of the intrusive will be such that the 5 km distance from base (where the fluid first interacts with hot rock) to top (where it vents into the sea) is traversed in ~ 26 years.

At 3 percent deposition efficiency, a 2200 tonne deposit requires the heat from a 30 m wide, 700 m long intrusive "dike" extending to 5 km depth. Such a dike would cool in about 60 years if the host rock permeability was 25 millidarcies. Hydrothermal fluid would pass from the base of the intrusive to the surface in about 26 years with a host of this permeability.

Chung et al. (1981) have radiometrically dated the sulfide chimneys at 21°N and concluded that each sulfide lense took about 50 years to form. This is close to the 60-300 years we estimate is required to cool a 30-150 m dike at 25 millidarcies permeability. The fluid transit time of 26 years is also within the range estimated by Turekian et al. (1981) of 15 to 60 years based on the Ra isotope content of clams. The Ra is produced from fluid/rock interaction when the fluid first comes into contact with the hot intrusive. A 25 millidarcy permeability is reasonable in light of Anderson and Zoback's measurements on much older and possibly much less permeable crust.

The evolution we envision for hydrothermal activity over an actively spreading ridge segment is shown in Figure IV-3. First, a sheet lava flow covers a segment of the ridge axis and blocks discharge. This sheet flow is subsequently broken by a major extensional fissure penetrating ~350 m into the crust. Discharge of the hydrothermal fluids ponded beneath the sheet flow is initially uniform but induces convection of seawater in the fissure that penetrates about 350 m into the crust (see Figure III-3a). Because of the seawater convection (or perhaps permeability irregularities in the fissure) the spacing of major initial discharge points along the fissure is about 700 m. Mixing of seawater with the hot hydrothermal fluids precipitates anhydrite, sulfur, and silica, and freezes in the initial discharge pattern. With continued discharge, some of the vents may clog and become less active or even inactive. Periodically, vent plugging or earthquakes may cause vent location to shift. At a later time a new sheet flow erruption might cover the vent field, a new fissure penetrate the lava flow, and the whole process described above be repeated. We thus can offer some basis for the ~ 700 m spacing of sulfide lenses at 21°N. Furthermore, since weaker vents tend to plug off as minerals precipitate and contribute their fluids to stronger vents (e.g., Sleep and Wolery, 1978) larger intrusives should tend to produce fewer but larger massive sulfide lenses.

Finally, if a portion of the oceanic crust is anomalously hot, thermal expansion will cause that segment of the ridge to be elevated. The coefficient of thermal expansion of the crust is between 3 and 4.5 x 10^{-5} (Parsons and Sclater, 1977; Crough, 1975). If the crust undergoing a spreading pluse is 600° to 1000°C hotter than the surrounding crust, the thermal elevation of the spreading segment will be 90 to 225 m. Topographic bumps between fracture zones are of precisely this magnitude.

IV-3 Conceptualization of venting through a near surface fracture. Initially, (top) venting is uniform and near surface seawater convection establishes a pattern of outflow with vents spaced 700 m apart. Subsurface mixing of cool seawater and hot solutions venting from depth causes mineral precipitation which seals off some vents and freezes in the 700 m spacing (3b). For further discussion of this kind of convective instability see Cathles (1982, p 937).

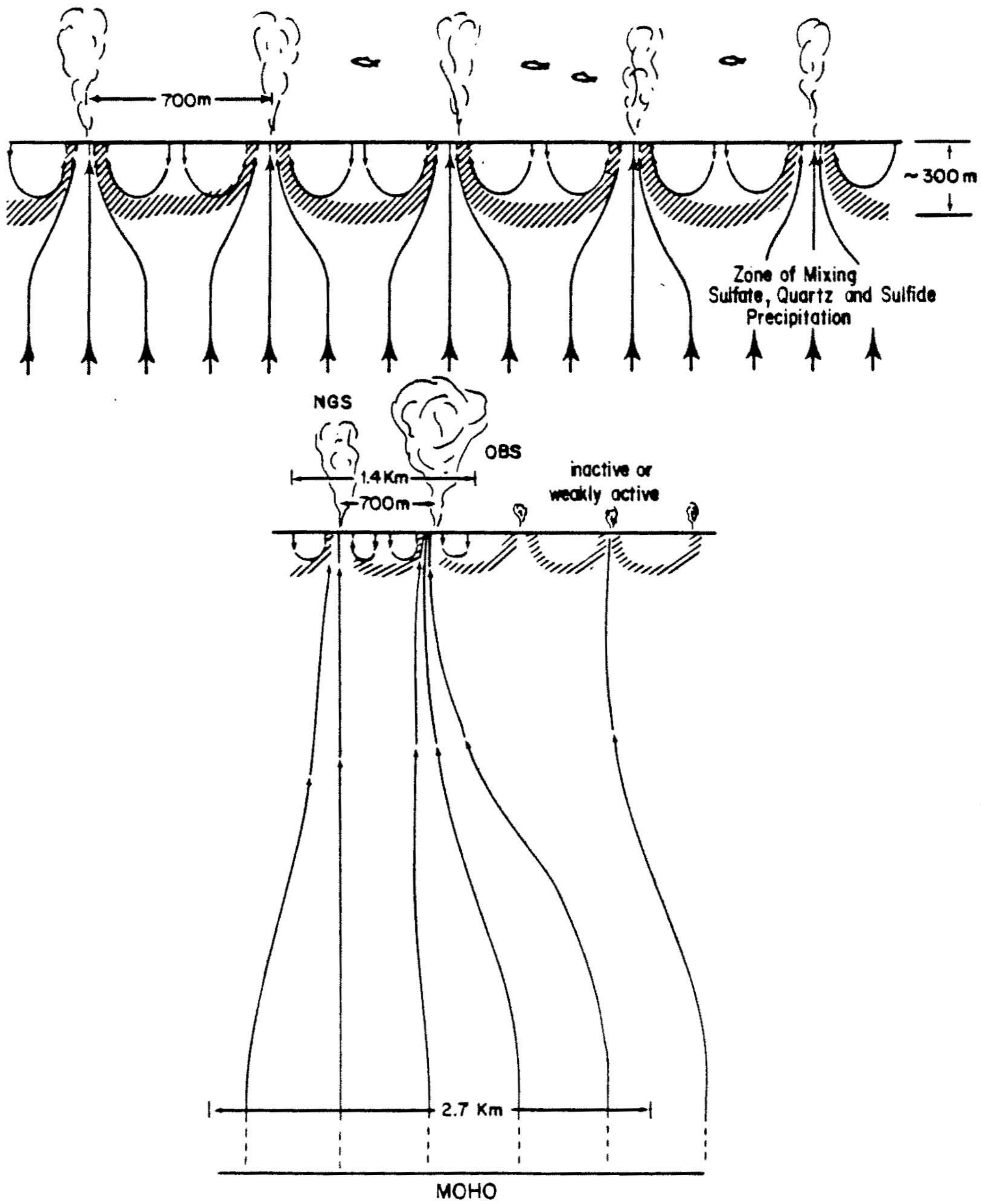
700m
~300 m
Zone of Mixing
Sulfate, Quartz and Sulfide
Precipitation
NGS
OBS
1.4 Km
700m
inactive or
weakly active
2.7 Km
MOHO

FIGURE IV-3

In conclusion, the geologic/hydrodynamic model sketched above, although admittedly not completely constrained, is hydrodynamically reasonable, enjoys a fair degree of internal consistency, can account for a diversity of data, and thus offers a reasonable basis upon which to interpret data from other areas and to speculate about where larger massive sulfide lenses may be found on the seafloor. For example, the precipitation efficiency can be estimated at 0.8 percent from the observed density of surface mineralization at 21°N and at 10 percent from the present rate of deposition occurring there. We do not know whether multiple sulfide lenses exist beneath those at the present surface that could account for the difference in these estimates. We suspect, however, that the efficiency of sulfide deposition increases with the duration of hydrothermal venting, and that the precipitation efficiency from the mature vents at 21°N is greater than the overall average precipitation efficiency. The sulfide deposits at 21°N could have been formed by a 150 m wide intrusive pulse or by a 30 m wide pulse (in which case each pillowed ridge would be formed by three such pulses). The rate and duration of hydrothermal circulation inferred from radiometric measurements are compatible with either size intrusive pulse given the range of measured ocean plate permeability. Heat flow measurements near the Galapagos Ridge indicate rapid cooling of the oceanic plate to 5 km depth very near the ridge, and this kind of cooling can account for the topographic variations observed between transform faults along the ocean ridge.

IV-C-2. Areas Other Than 21°N:

Other ridge segments studied to date appear to be fundamentally similar to 21°N. Hydrothermal activity and massive sulfide lenses have been found on seven locations* along ridges spreading at 6 cm/yr or faster. In each case, the hydrothermal activity appears to be associated with a restricted ridge segment straddling a topographic bump of 70 to 250 m height. The length of the hydrothermally active zone seems to bear some relation to spreading rate. There are 8 km of active smokers and 20 km of active and inactive vents along the 10 cm/yr spreading ridge at 13°N on the East Pacific Rise, for example, but only ~ 7 km at 21°N which is spreading at 6 cm/yr. Sulfide deposition is apparently denser at 13°N than at 21°N (Section I-B-1). The separation of minor transforms that do not significantly offset the ridge, but lie between transform faults that do, is a remarkably uniform 50 km in the Atlantic and in much of the Pacific, but can be larger or smaller (i.e., is more erratic) in the fastest spreading ridges.

No hydrothermal activity or sulfide deposits have yet been found in the Atlantic (2 cm/yr spreading rate), but the Cyprus massive sulfide deposits, which range in size from 0.1 to 15 million tonnes (Bear, 1963) may have formed at a slow spreading ridge in a marginal basin setting. Geomorphological evidence and magnetic and petrologic studies on drill core from the Mid-Atlantic Ridge suggests that extrusive volcanic activity at the FAMOUS

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* Biologic activity and sulfide depositss indicating venting of warm or hot water has been observed on the Juan de Fuca Ridge (6 cm/yr total spreading rate, and the Galapagos Ridge near 86°W (7 cm/yr), and at the following locations along the East Pacific Rise: The Guaymas Basin (5-6 cm/yr), 21°N (6 cm/yr), 13°N (10 cm/yr), 11 N (10 cm/yr) and 20°S (18 cm/yr). Venting of hydrothermal solutions hotter than 300°C has been observed at Guaymas, 21°N, 11°N, and 20°S.

study area occurred in brief ~100 yr pluses followed by 4900 years of quiescence (Ballard and van Andel, 1977; Hall and Robinson, 1979).

^3He surveys of the Gulf of California have detected anomalies only over the southern spreading segment of the Guaymas Basin (Lupton, 1979). This suggests hydrothermal venting is presently occurring only in one of the nine 20-50 km long spreading segments in the Gulf.

In summary, spreading could be more "sticky" at slow spreading ridges or close to transform faults that significantly offset the ridge axis and expose the ridge end to cool oceanic plate, and could occur in larger, less frequent bursts at these locations. The periodicity of volcanism is basically similar at slow and fast spreading systems. Slow spreading systems have much more rugged topography than fast spreading ridges, as do fast spreading ridges near major transform offets, however, and these differences could affect the nature of sulfide deposition.

If the overall deposition efficiency in a ridge segment is about 3 percent, as estimated in section A, the surface mineralization density is 8 g/cm^2 or 0.08 million tonnes per km^2, and is similar to the average surface mineralization density found in land based massive sulfide camps that have been explored and exploited. Table IV-2 shows the total ore tonnage of several massive sulfide districts and the area of the districts, as reported by Sangster (1980). Table IV-2 shows that the average surface mineralization density of all the districts considered by Sangster is 0.12 $\pm$ .06 million tonnes per km^2. Sangster comments that the total metal contents of the districts (Cu + Zn) are remarkably similar, and that the areas of the districts are also similar (~ 32 km diameter equivalent circle). Sangster offered no explanation for these regularities and gives them as simply an

Table IV-2

TOTAL ORE TONNAGE IN SEVERAL VOLCANOGENIC MASSIVE SULFIDE CAMPS, THE AREA OF THE CAMPS (OR ORE DISTRICTS), BOTH FROM SANGSTER (1980), AND THE SURFACE DENSITY OF SULFIDE MINERALIZATION IN THE CAMPS

District	Millions of tons of Ore Contained	Area of District (km^2)	Surface Density of Mineralization (10^6 tonnes/km^2)
Hokuroku District, Japan	90	720	0.125
Bathurst No. 1, Canada	180	880	0.205
Bathurst No. 2, Canada	98	1150	0.085
Flin Flon, Canada	65	560	0.116
Snow Lake, Canada	19	840	0.023
Noranda, Canada	204	1550	0.132
Matagami, Canada	34	230	0.148
			0.12±.06

empirical observation that might be useful in evaluating the resource potential of unexplored districts. Cathles et al. (submitted) have argued that all volcanogenic massive sulfide deposits are genetically related to rifts, just as are oceanic massive sulfide deposits. Sometimes the rifts are intra-oceanic (Cyprus-type deposits), sometimes the rifts occur in island arcs (usually along the andesitic volcanic chain which is a convenient line of weakness along which the rift is localized; Kuroko-type massive sulfide deposits and probably Archean greenstone massive sulfide deposits occur in island arc rifts), and sometimes the rift is in a continent (sediment hosted massive sulfide deposits). The similarity in average surface density of sulfide mineralization in land based volcanogenic massive sulfide districts and the ocean floor at 21°N suggests: (1) the heat available in the crust newly formed in a rift (spreading ridge axis) fundamentally limits the amount of sulfide that will be precipitated on the surface, and (2) that the mineralization of all mineralized rifts will be about 0.1 million tonnes per square kilometer. The area of most massive sulfide camps is equivalent to a circle about 32 km in diameter which is about the same dimension as the 50 km separation of the minor transform faults that divided ridges in the Atlantic and Pacific (see above).

IV-D. Conditions Favorable to the Formation of Larger Massive Sulfide Deposits in the Ocean

There are basically two ways the size of deposits on the ocean floor can be increased: (1) The mineralization from a greater area of oceanic plate can be deposited in one location, or (2) the efficiency of precipitation of metals from venting hydrothermal solutions can be increased. Table IV-3 estimates

TABLE IV-3

FACTORS THAT CAN INCREASE THE SIZE OF OCEAN FLOOR MASSIVE SULFIDE DEPOSITS

	Increase of Sulfide Lenses size above 2200 tonne deposits at 21°N	Rationale	Cyprus	Kuroko	Sediment Hosted
I. <u>Spatial Concentration</u>					
A. Collection from 2.5 km strip perpendicular to long axis of magma chamber	~ 50x	A 2.5 km wide magma chamber at <2 km depth could vent hydrothermal fluids through a single major fracture	X	X	X
B. Increase in deposit separation along the long axis of the magma chamber	~ 7x	spacing of deposits at Cyprus is ~ 5.2 km rather than the 700 m spacing at 21°N	X	X	X
C. Magma chamber which moves with plate	10 to 100x	seamounts near ocean ridges are typically ~ 4 km^3 in in volume and could produce a 25,000 tonne sulfide deposit at 4 percent deposition efficiency if all fluids vented at a single site			
II. <u>Efficiency of Precipitation</u>					
A. Prolonged or rapid venting or venting in a restricted basin	~ 10x	Prolonged venting leads to greater precipatation efficiency due to development of mature biologic communities that regulate the temperature of discharge (white smokers) and lead to enhanced sulfide precipitation. Rapid venting would allow hydrothermal fluids to control the oxidation state of the bottom ocean waters. Increased smoke particle agglomeration and settling might result. Venting in a restricted basin would favor settling of smoke particles.	X	X	

TABLE IV-3 (cont.)

	Increase of Sulfide Lenses size above 2200 tonne deposits at 21°N	Rationale	Cyprus	Kuroko	Sediment Hosted
B. High salinity	125x	High salinity will allow vented solutions to pond in depression on the ocean floor, cool slowly, and precipitate ~ 100 percent of their metal content which would be higher than that in solutions of lower salinity			X
II. Depth of Hydrothermal Circulation					
A. Continent or Island Arc	11x	Crust under a continent or island arc is ~ 35 km rather than 5 km thick. Thus, a magma chamber ~33 km rather than 3 km in depth extent can be thermally tapped by hydrothermal solutions		X	X
		Total tonnage enhancement	1.2×10^3	1.3×10^4	1.6×10^5 or
		Total size of deposit	2.6 mt	28. mt	361 mt

the magnitude of increase in deposit size that might be achieved in these two ways, and comments briefly on the reasoning behind each estimate.

First of all, in terms of spatial concentration, its seems reasonable that a 2.5 km wide intrusive dike whose top lies 2 km below the seafloor could vent out one very permeable fracture near its apex most or all of the hydrothermal fluids it would cause to convect in cooling. If the magma chamber were widerthan this, venting out a single apical fracture would be unlikely for simple geometrical reasons. The upward-venting solutions at the sides of the intrusive would find it hard to turn inward into the central fracture. Thus, the 30-150 m intrusive pluse we considered for each small deposit at 21°N could be increased to 2.5 km, but magma chambers bigger than this would probably contribute to more than one deposit.

Secondly, deposit size can be increased if the spacing between sites of deposition along the ridge axis is increased. Massive sulfide deposits at Cyprus, which recent petrologic data indicate were formed in a marginal basin, are spaced approximately 5.2 km apart (Spooner, 1977), so it seems reasonable that deposits could be spaced seven times further apart than the 700 m observed at 21°N. Thus, fluid from seven times more new plate could contribute to a single ore deposit, and the deposits could consequently be seven times bigger.

The size of a deposit can also be increased if the magma chamber responsible for forming the deposit moves with the ocean plate, especially if the magma chamber is replentished as it moves away from the ridge. Seamounts represent such magma chambers. If the size of the magma chamber is roughly the same as the size of the accreted volcanic ediface that forms the seamount, the 1 to 10 km^3 seamount edifaces found along the East Pacific Rise could produce 23,000 to 230,000 tonne massive sulfide deposits.* On this basis, a seamount could produce deposits 10 to 100 times the size of the small 2200 tonne deposits at 21°N.

Increasing the efficiency of precipitation is also a very good way to increase the size of a deposit. If circulating seawater encounters evaporites and becomes very saline, it may be denser than seawater when it discharges, even if it is very hot (~350°C). In this case, the discharged solutions will pond in depressions on the seafloor, cool slowly, and deposit nearly 100 percent of their metal content, which would be higher than in a solution of seawater salinity (Section III-D-2). Under such circumstances the average efficiency of precipitation will be increased 125 fold over the 21°N, 150 m dike efficiency of 0.8 percent. Also, saline solutions from several vents may collect in the same bottom depressions. It may be largely due to the increased efficiency of deposition that sediment hosted massive sulfide deposits such as are forming in the Red Sea today (Degens and Ross, 1969) tend to be an order of magnitude larger than volcanogenic massive sulfide deposits.

As commented before, efficiency of precipitation appears to increase as mature biologic communities develop in longer-lived vents. Also, because weaker vents tend to close off more rapidly than large ones under the agency of mineral precipitation, a mature vent system along a ridge segment will tend to have fewer, more widely spread and rapidly discharging vents. It is possible that solutions venting voluminously enough to dominate the oxidation

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* 1 km^3 rock has a mass of 3×10^9 tonnes and could circulate 87 percent of this mass of hydrothermal solution ~ 350°C (see footnote p. IV-5). If the venting solutions deposit 4 percent of the 215 ppm FeS_2 they carry, a single 23,000 tonne deposit could be formed for each km^3 of magma, if the hydrothermal solutions vented at one location.

state of bottom waters might enjoy increased efficiency of deposition. Smoke particles would not be oxidized and dissolved by oxidiating seawater. More agglomeration of smoke particles might occur if venting were more vigorous. For both reasons, smoke might have a greater tendency to settle around the vents. Also, venting in a restricted basin should favor the settling of sulfide smoke particles. Pyrrhotite crystals have been found in the sediment at Guaymas (Lonsdale et al., in press). For all these reasons, more vigorous, prolonged venting or venting into a restricted basin might increase the average efficiency of sulfide precipitation observed at 21°N of 0.8 percent by a factor of 10.

Finally, if hydrothermal solutions can have access to a magma chamber over a greater depth extent, more hydrothermal solution can be circulated and larger ore deposits formed. In the oceanic setting, the base of hydrothermal circulation is the Moho. Below the Moho, the rock composition changes from gabbroic to ultramafic. The ultramafics contain olivine, which hydrothermally alters to very plastic and therefore impermeable serpentine. The Moho is thus a permeability barrier. The crust is much thicker in an island arc or continental setting, typically 35 km rather than 5 km. Thus, it is possible magma chambers in continental or island arc settings could be thermally tapped to form an ore deposit over a 33 rather than 3 km depth extent and the deposits formed could be 11 times larger.

The above estimates can be tested by applying them to Cyprus, Kuroko and sediment hosted deposits. Table IV-3 shows the factors believed to apply to these types of deposit. The Cyprus deposits are typically a few hundred thousand to a few million tons of ore, the Kuroko-type, a few millions to tens of millions of tons, and the sediment hosted a few tens to hundreds of millions of tonnes. Table IV-3 shows that application of the factors we have just discussed would lead to estimates in the right range and predict the relative size of the deposits.

We have some trouble, however, accounting for the largest Cyprus deposits. Bear (1963) reports the Skouriotissa deposit contains 6 million tonnes of ore and the Mavrovouni deposit 15 million tonnes. The crust at Cyprus is thicker than average oceanic crust, being 6-8 km (Allen, 1975, p. 115) rather than ~ 5 km. Assuming an 8 km thick crust, a deposit spacing near the largest deposits of 7 rather than 5 km, and an intrusive width of 4 rather than 2.5 km, we obtain a deposit size of only 9.3 million tonnes. The only reasonable way to obtain a 15 million tonne deposit is to increase the efficiency of deposition to 6.5 percent. If we take the "base case" 5 km thick crust, deposit spacing of 5 km, and intrusive width of 2.5 km, an efficiency of deposition of 23 percent would be required. If the deposition efficiency were 100 percent, the base case could produce a 65 million tonne deposit.

The 25 million tonne massive sulfide deposit reported by NOAA workers at the Galapagos spreading center is on the large end of the range we would consider reasonable in terms of the above discussion and reasoning. A 25 million tonne deposit would require a 39 percent deposition efficiency and a large (2.5 km wide) intrusive that circulates hydrothermal solution from a 5 km length of the ridge axis through a single vent. These are optimistic conditions, but the 15 million tonne deposit at Cyprus indicates they are not impossible.

Some features of the Galapagos spreading center near the NOAA deposit do suggest a larger magma chamber may have been present at the time the Galapagos deposit was formed and may be again present now. The Galapagos deposit lies off the present axis in Zone 2 volcanics. Zone 2 contains much more extensive sheet flow volcanics than the 21°N site. Such sheet flows could form a cap that might focus hydrothermal discharge out a restricted set of vents. Extrusive volcanism is also extensive in Zone 1 at Galapagos. A larger magma chamber should tend to produce more voluminous extrusive volcanies. Thus, the greater volumes of extrusive flows at Galapagos suggest the magma chambers there, both at the time of formation of the deposit and at present, were for some reason larger than at 21°N. Also, there is significant, very recent, off axis volcanism (2 km from the ridge axis) at Galapagos at 86°W. This, again suggests a wider magma chamber, perhaps a chamber as wide as 2 km. The length of the spreading zone is longer at Galapagos (>30 km) than at 21°N (7 km). Galapagos lies near the Galapagos hot spot and therefore, at a higher elevation than 21°N (2450 vs 2600 m water depth). Due to the proximity of a hotspot, the heat input to the Galapagos site is greater than at 21°N and for this reason the oceanic crust may be thicker (more heat for partial melting of the mantle) and the depth extent of magma chambers greater.

In light of the above discussion, it seems clear that to find larger sulfide deposits, we must seek areas where there are larger axial magma chambers. The best guide we can offer at present is to search where extrusive activity is greatest, on the basis that greater extrusive activity will reflect a larger subcrustal magma chamber. Empirically, such areas appear to be associated with major hot spots along the ridge. These hot spots are obvious from their elevation. Iceland is the most extreme example. We offer no explanation as to why axial magma chambers at ridges near hot spots should tend to be bigger. Empirically, it is our present guess that they are.

Seamounts may also deserve some attention in the exploration for ocean massive sulfide deposits. Most of the ocean's seamounts are < 7.4 km^3 in volume, but the aggregate volume of such seamounts is small compared to the lava volume represented by less numerous but larger seamounts (Batiza, manuscript). Some (perhaps most) seamounts appear to grow slowly compared to the rate of intrusion of magma in a spreading pulse at a ridge axis. For example, Batiza (ms) estimates that the average growth rate of Pleistocene volcanoes is 100 km^3/my. The accretion rate of a 5 km segment of a ridge spreading at 6 cm/yr is ~ 1500 km^3/my, assuming accretion is steady, and much greater if accretion is episodic. Vigorous hydrothermal activity should be associated with the greater rates of introduction of magma (and therefore heat) into the crust at mid-ocean ridges. However, Batiza (ms) notes that some seamounts appear to have formed much faster, perhaps as rapidly as $10^4 km^3$/my (Wadge, 1980). Seamounts that accrete fast could thus be competative with mid-ocean ridges in terms of the rate of magmatic heat input into the crust. Such seamounts might be favorable places to seek massive sulfide mineralization despite the fact massive sulfides might be rapidly covered by lava flows from the growing seamount.

It is interesting to note that many (but perhaps not all) seamounts are associated with mantle hot spots. Therefore, mantle hot spots are worth paying attention to for two reasons: (1) massive sulfide deposits found to date seem to be bigger near hot spots (Galapagos), and (2) seamounts associated with hot spots may provide suitable sources of heat for massive sulfide deposits that ride with the moving plate and hence, enjoy some advantages in venting hydrothermal solutions at one plate location.

It is possible intrusive pulses may be less frequent near transform faults. The permeability may be higher there due to greater fracturing of the rock mass. Cooling of less frequent but larger intrusive pulses may be more rapid due to the greater permeability. The more rapid cooling could help account for the topographic depression near the transform faults. Stated another way, less rapid cooling and more frequent intrusive pulses away from transform faults may account for the tendency of the topographic bumps and their associated hydrothermal activity to be located on ridge segments between transform offsets. Larger massive sulfide deposits might be found associated with these less frequent but larger intrusive pulses and greater permeabilities near major transform offsets of the ridge axis for the reason discussed above and detailed in Table IV-3. Favorable factors and locations where larger than average massive lenses might be found are summarized in Table IV-4.

The apparent size of the Galapagos massive sulfide lense and its association with a major hotspot along the ridge suggest major topographic maxima (hotspots) along the ocean ridge are the most likely sites of deposition of large massive sulfide lenses in the open ocean setting.

TABLE IV-4

FEATURES OF THE OCEAN PLATE THAT FAVOR LARGER MASSIVE SULFIDE ACCUMULATIONS AND THE LOCATIONS WHERE THESE FEATURES MAY BE FOUND

Favorable Features	Rationale	Location
Ridge capped by extensive (2 km wide) sheet lava flows fractured in only a few locations	more focused venting	central portions of fast spreading ridges
Large magma chamber	stable venting more likely because only one spreading pluse (less tectonic disturbance), prolonged venting plugs vent competitors, and mature biota increase depositional efficiency	Locations with extensive volcanic extrusives marginal basins newly jumped or propagated ridges seamounts
Magma chamber which moves with plate	more stable discharge location because heat source moves with plate	seamounts
Deep and very permeable fractures	increased rate of discharge of very permeable fractures may lead to increased efficiency of deposition; permeable and deep fractures promote localized venting	slow spreading ridges transform faults
Rifting thicker than normal crust	larger depth extent of magma chamber is thermally tapped	newly rifted continental plateau marginal basin