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Where are the large hydrothermal sulphide deposits in the oceans?

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Where are the large hydrothermal sulphide deposits in the oceans?

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Large sulphide deposits have been identified on slow and fast spreading ridges and back-arc basins. Their formation is controlled by a combination of several conditions, each of which alone is often only compatible with the formation of small and unstable deposits. The geological control of deposits has to be considered both at the regional and local scales. The convective system is dependent on the morphology of the heat source (magma chamber) and the magma supply. Major sites are controlled by regional topographic highs that are the locus of the highest magma and heat supply along the ridge. On slow spreading ridges the flow of hydrothermal fluids can also be controlled by major regional rift valley faults. The discharge within a field is controlled by the local near surface permeability related to faulting or permeability of rocks. Recent discoveries considerably enlarge the potential locations of hydrothermal activity. On slow spreading ridges we have now to consider the base and top of the rift valley walls and the non-transform offsets, in addition to the relatively well documented control by volcanic topographic highs. Known sites also demonstrate that slow spreading ridges are more favourable for the formation of extensive mineralization. On fast spreading ridges, deposits are numerous and very small because the upflow zone is relatively narrow and subject to perturbation by frequent tectonic and volcanic activity. However, near fast spreading ridges, first order sulphide deposits can be formed on off-axial seamounts. Geological and physical conditions are key parameters controlling the morphology and potential size of deposits. Among these parameters, boiling, mixing within the crust, or precipitation under an impermeable cap rock, can enhance the formation of extensive subsurface mineralization within the oceanic crust. However, the knowledge of these deposits requires further investigation in the vertical dimension.

1. Introduction

Since the discovery of the first black smoker, more than 100 hydrothermal fields have been found in the oceans. About 15 of these deposits are large enough to be considered as an ore deposit if they were located on land. Their size and grade are similar to those of fossil sulphide deposits now mined on land. The 146 known sulphide sites occur in four different tectonic settings (figure 1). The first sulphide mineralization on the seafloor was discovered in 1978 (Cyamex *et al.* 1979; Francheteau *et al.* 1979; Spiess *et al.* 1980) at 21° N on the East Pacific Rise and the Galapagos ridge (Corliss *et al.* 1979). These discoveries were the proof that hydrothermal activity was a major process associated with the formation of young oceanic crust. Numerous cruises have now confirmed that hydrothermal processes are responsible for the formation of large sulphide deposits (Rona 1988; Rona & Scott 1993; Scott 1987). Exploration conducted during the past 15 years has shown a wide variety of hydrothermal activities and deposits in the oceans. This variability is first due to the various geodynamic settings and nature of source rocks. Hydrothermal deposits are now known on fast spreading ridges (Embley *et al.* 1988; Francheteau *et al.* 1979; Fouquet *et al.* 1988), super fast spreading ridges (Backer *et al.* 1985; Renard *et al.* 1985; Fouquet *et al.* 1994), slow spreading ridges (Rona *et al.* 1986*a*; Thompson *et al.* 1988; Honnorez *et al.* 1990; Langmuir *et al.* 1996), sediment covered ridges (Peter & Scott, 1988; Goodfellow & Franklin, 1993; Koski *et al.* 1988), young and mature back-arc basins (Fouquet *et al.* 1991; Halbach *et al.* 1989, Fouquet *et al.* 1993), island arcs (Urabe *et al.* 1987; Herzig *et al.* 1994) and fracture zones (Bonatti *et al.* 1976).

The median size for significant volcanogenic massive sulphides in Canada is 1.3×10^6 tonnes and for every 'significant deposit' there are probably 100 or more small deposits (Scott 1985). Several modern seafloor deposits have size and grades comparable to these ancient deposits. This paper presents the variability of geological controls on the location of hydrothermal fields, with a specific emphasis on major sulphide deposits. Large hydrothermal deposits are listed in table 1. They are located in three main volcanic settings: slow and fast spreading ridges and back-arc basins. To better understand the different mechanisms controlling their formation an overview of the knowledge of the location of hydrothermal fields in the ocean is presented. Figure 2 shows that the majority (42%) of hydrothermal fields are located on fast spreading ridges. However most of these sites are not compatible with the formation of large sulphide deposits. The compositions of deposits and the special case of the Red Sea are not discussed in this short paper.

2. Geological control on the location of major sulphide deposits in the oceans

Considering our knowledge of the location of major hydrothermal fields the geological control of hydrothermal activity has to be considered both at the regional and local scales (figure 3). The flow of hydrothermal fluids is controlled by major structural and volcanic elements (neovolcanic ridges, rift valley faults, ...) but the discharge within a field is controlled by the local near surface permeability.

(*a*) *Slow spreading*

On slow spreading ridges a typical morphology is a 60 km long, 20 km wide and 1 km deep segment with fractures zones at both ends (figure 3*a*). The recent volcanic activity is concentrated on a narrow neovolcanic ridge generally located at the centre of the segment. The morphology of the neovolcanic ridge typically has a topographic high at its centre, indicating a higher magmatic budget in this area. On slow spreading ridges the volcanic ridge is very often an alignment of localized volcanic centres rather than a continuous ridge as seen on a typical fast spreading ridge. Volcanic ridges are punctuated by hundreds of discrete axial and off-axis volcanoes (Smith & Cann 1990). Less frequent tectonic events may promote long lived and more stable structures for hydrothermal upflow. Two types of *regional* controls are identified for major deposits: the topographic high (figure 3*a*), and the base (figure 3*b*) and top (figure 3*c*) of the rift valley walls. Major fields, such as TAG, controlled by graben walls faults, are also located at the latitute of the topographic high indicating a preferential location near the hot domain of the segment where the magmatic budget is

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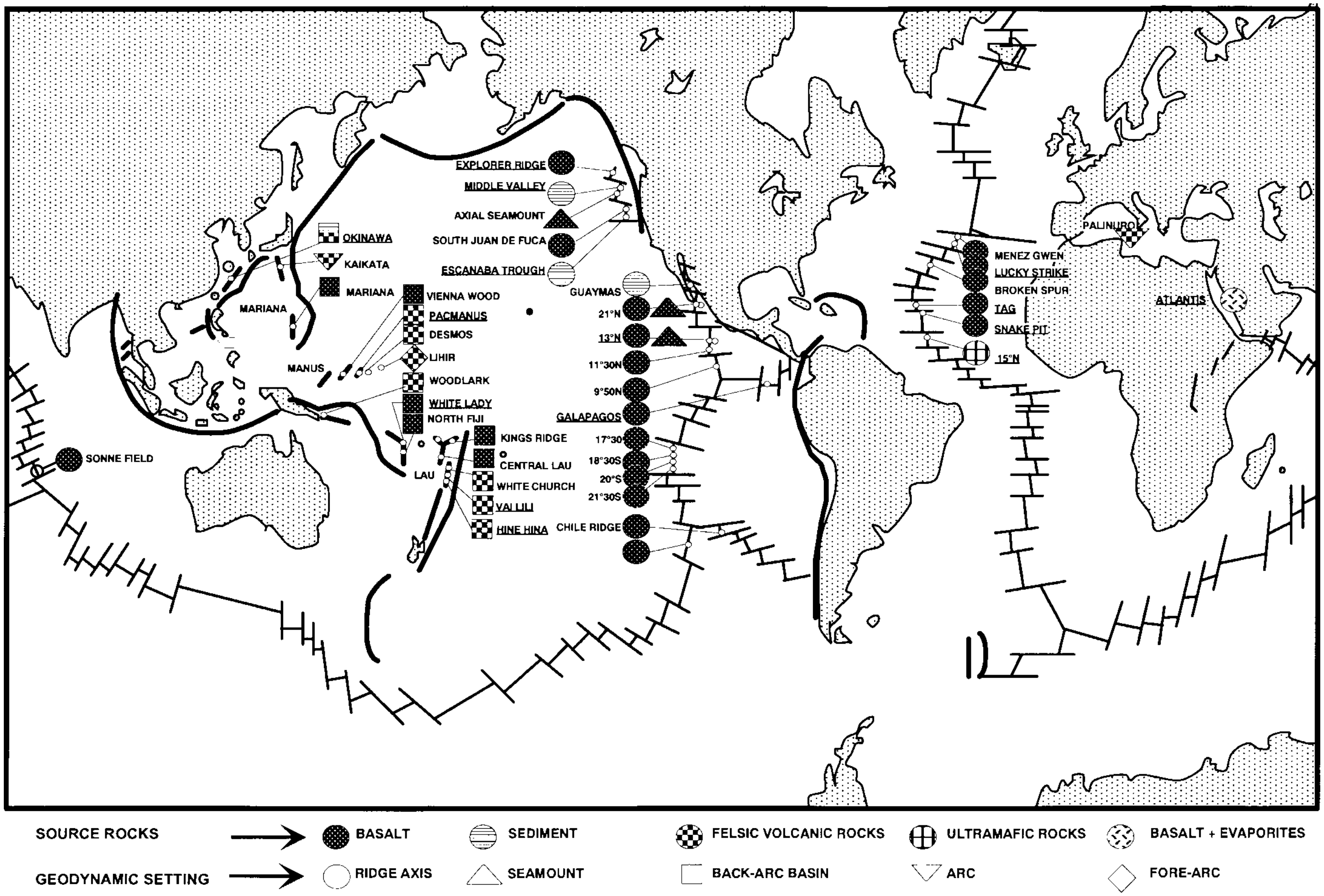

Figure 1. Location of hydrothermal sulphide deposits in the ocean, with indication of geodynamic setting and source rocks. Names underlined correspond to large deposits.

Table 1. *Principal characteristics of major sulphide deposits in the oceans*

site	geological setting	geological control	depth	cm yr^{-1}	source rock	type/size
Lucky Strike	slow spreading	topographic high + N–S faults + caldera	1650 m	2.2	enriched MORB	1 km × 1 km
TAG	slow spreading	valley wall + crossing faults + volc. centre	3650 m	2.6	MORB	250 × 45 m high + 2 mounds
Snake Pit	slow spreading	topographic high + volc. centre + graben	3465 m	2.6	MORB	3 mounds, 250 m × 55 m
14° 45′ N	slow spreading	valley wall + axial high + tranverse faults	3000 m	2.6	harzburgites	300 m × 125 m × 80 m
13° N off-axis	fast spreading	Seamount + pit crater + lava flows lid	2650 m	12	MORB	200 m × 70 m high, 800 × 200 m
Explorer ridge	intermediate spreading	neovolcanic ridge + crossing faults	1800 m	6	enriched MORB	200 × 25 high, + other mounds
Galapagos	intermediate spreading	faults + double rift + central rift faults	2850 m	6	MORB	3 mounds, 1000 × 150 × 35 m
Vai Lili	immature back-arc	topographic high, volcanic ridge	1710 m	6	basalt–andesite–dacite	400 × 100 m
Pere Lachaise	mature back-arc	triple junction + volcanic high	1950 m	7	MORB	1 km × 1 km
Pacmanus	immature back-arc	topographic high + pull-apart ridge	1675 m	?	Basalt-Dacite-Rhyolite	mounds discontinuous 3 km
Jade	immature back-arc	pull apart	1610 m	7.3	basalt–rhyolite/sediments	mounds and chimneys
Middle Valley	sedimented ridge	control by faults + sill + sediment lid	2500 m	6	basalt–sediment	75 × 35 × 95 m high
NESCA	sedimented ridge	volcanic centre + sediment lid	3300 m	2.2	sediment–basalt	several mounds (100 m long)
Atlantis 2	immature ocean	axial basin + Brines as a lid	2000 m	2	sediments	100 MT

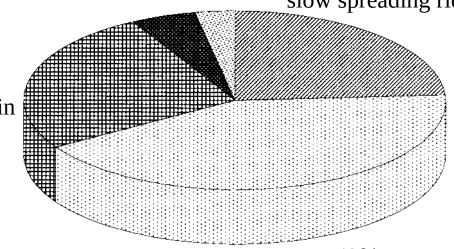

Figure 2. Relative abundance of identified hydrothermal fields in major geodynamic settings.

high. Typical locations at the topographic high include the Snake Pit (Fouquet *et al.* 1993*b*), Lucky Strike and Menez Gwen fields (Langmuir *et al.* 1996; Fouquet *et al.* 1996). The best example of a location at the base of the graben wall is the TAG field (Rona *et al.* 1993). Recent investigations at 14° 45′ N have demonstrated that the top of graben wall is also a potential site for high temperature venting (Krasnov *et al.* 1995). Recent investigations demonstrate that the Azores triple junctiun domain is hydrothermally more active than the rest of the ridge. At a *local scale* the control is an axial summit lenticular graben at Snake Pit (figure 3*e*) or a caldera (figure 3*f*) for Lucky Strike and possibly a discrete volcanic centre for TAG. Thus the local volcanic controls tends to be the opposite of the regional controls: for a regional volcanic control, the local control is tectonic and for a regional tectonic control the local control tends to be volcanic. Recent cruises in the Azores domain gave significant information on a possible third type of setting for hydrothermal activity on slow spreading ridges. Side scan sonar and plume particles indicate that non-transform offsets play a role in focusing hydrothermal flow (German *et al.* 1995) (figure 3*d*). Further submersible investigations are necessary in this environment, to determine if it is compatible with the formation of large deposits. The last type of setting is represented by stockwork like mineralization occurring within fracture zones (Bonatti *et al.* 1976).

(*b*) *Fast spreading*

On fast spreading ridges the regional control tends to be the topographic high between two major fracture zones (figure 3*l*) where the hydrothermal activity is more developed. This model was proposed by Francheteau & Ballard (1983) and demonstrated by Bougault *et al.* (1993) for the 13° N area on the EPR. However each segment between the major fractures has to be considered as independent for volcanic, tectonic and hydrothermal activity. At a local scale the style and location of activity depends on which stage the segment is at (figure 3$h--j$). During the volcanic stage, vents are controlled by axial summit caldera and lava lakes while at the tectonic stage vents tend to be controlled by graben faults (figure 3*j*). In most cases the instability of these two-dimensional convective systems does not favour the formation of large sulphide deposits at the axis. However, off-axis seamounts (figure 3*k*) are more stable systems compatible with long lived three-dimensional convective cells that are more efficient for the formation of large sulphide deposits (Fouquet *et al.* 1996).

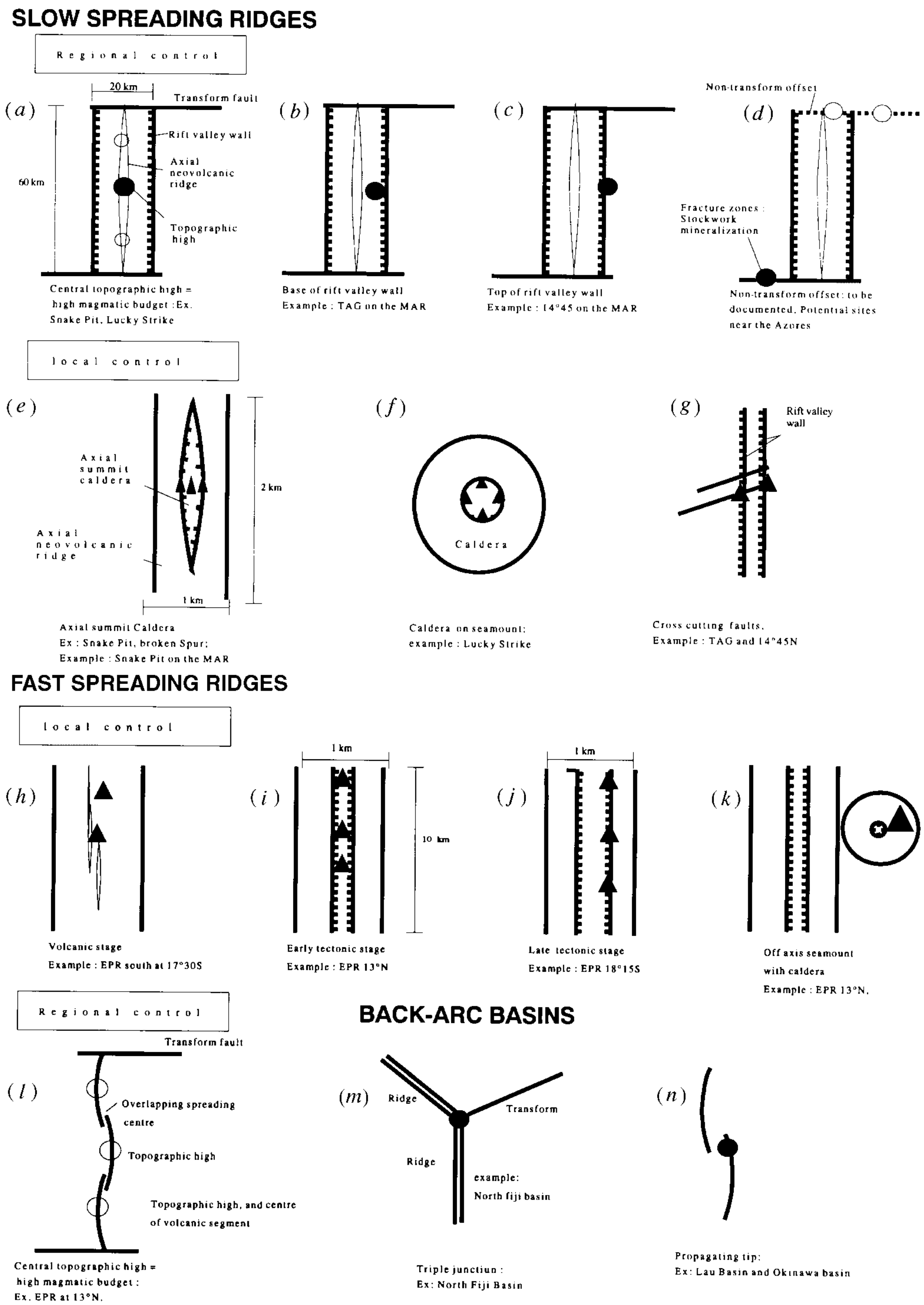

Figure 3. Geological controls of hydrothermal fields on spreading ridges.

(c) *Back-arc*

In back-arc environments hydrothermal processes are similar to that on mid-ocean ridges. However due to their instability and/or degree of maturity, some specific con-

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trols have to be considered. Typical locations on topographic highs are documented at several sites: North Fiji basin (Bendel *et al.* 1993), Lau Basin (Fouquet *et al.* 1993a), and Manus basin (Binns & Scott 1993). Seamounts, for example the Franklin seamount in the Woodlark intracontinental rifting (Binns *et al.* 1993*b*) are also good targets for hydrothermal deposits. The northern North Fiji basin is the best example of a large deposit controlled by a triple junction system where cross cutting faults play a major role in focusing the vents (figure 3*m*) (Bendel *et al.* 1993). In the Lau basin the most active and largest known sulphide deposit is close to an overlapping system along the spreading ridge (figure 3*n*). The Kuroko-type Okinawa deposit is controlled by a collapse system interpreted as a pull apart depression in the back-arc system (Halbach *et al.* 1993).

3. Geological, physical and chemical factors controlling morphology and size of deposits

Investigations on fossil deposits have shown that several factors can effect the morphology and size of the deposits (Large 1992). The same factors have to be considered in the modern ocean. In addition to the geological control of hydrothermal discharge, the formation of large sulphide deposits requires an efficient mechanism for precipitating and trapping the sulphide minerals from the fluid. In a typical black smoker chimney, 97% of the total amount of metals is dispersed in the ambient sea water due to mixing and thus rapid dilution of the fluid in the open ocean (Converse *et al.* 1984). Thus the formation of a large sulphide deposit needs to involve specific conditions resulting in a lowering of this percentage.

(*a*) *Mixing*

Restricted mixing within the mound or mixing of cold seawater with the ascending hydrothermal fluid will result in rapid precipitation of metallic sulphides and calcium and barium sulphates (sulphate being derived from ambient seawater) to produce the black smoker plume. Restricted mixing conditions within the chimneys are also necessary for the concentration of some elements such as gold (Herzig *et al.* 1993). At the scale of the mound, the presence of impermeable cap rocks are key factors to prevent rapid mixing and dilution of the fluid in ambient seawater. These cap rocks also play the role of a geochemical barrier. Hydrothermal solutions are conductively cooled and precipitate sulphides before their emission on the seafloor. Examples of this type are described at Lucky Strike and Lau Basin. Mixing of seawater and ascending hydrothermal fluid within the crust appears to be a process that can potentially form large deposits. This can happen in highly permeable rocks such as faulted grabens (figure 4I*b*) or porous volcaniclastic rocks (figure 4I*c*). However, further studies are necessary to better document the vertical extent of these types of deposits.

(*b*) *Permeability*

The type of permeability existing on the seafloor plays a major role on focusing the hydrothermal discharge which in turn is important to produce large deposits. In impermeable volcanic sequences, such as massive lava flows, significant fluid flow can only be achieved along major faults (figure 4I*a*). A common situation is at axial ridges where water is focused along cracks. This situation has a high potential for production of large mound shaped deposits on slow spreading ridges where convective

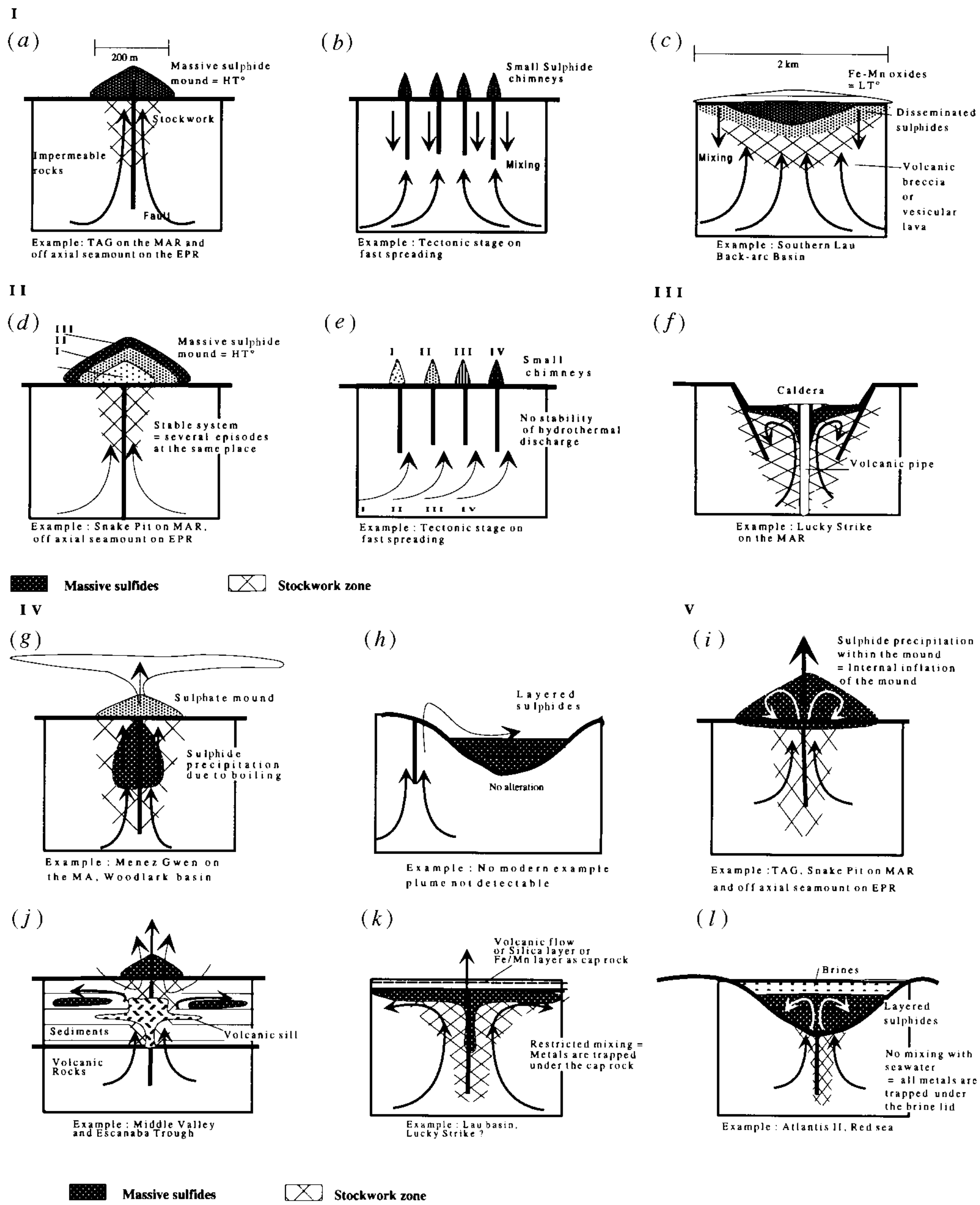

Figure 4. Factors controlling size and morphology of submarine hydrothermal sulphide deposits. (*a*), focused discharge; (*b*), diffuse discharge in tectonised lava; (*c*), diffuse discharge in permeable rocks; (*d*), stable system; (*e*), unstable system; (*f*), caldera; (*g*), venting of vapour phase = low salinity fluid; *h*, venting of brine = high salinity fluids; (*i*), trap is the mount itself; (*j*), trap is sediment cover; (*k*), trap is impermeable rock; (*l*), trap is a brine pool. I, permeability; II, stability of venting system; III, geometry of system; IV, water depth/phase separation; V, geological trap.

cells are stable. The permeability at the upper part of the convective system can increase for two reasons: (1) faulting and brecciation of lava and (2) permeability of volcanic rocks. At the end of the tectonic stage on fast spreading ridges, the crust is highly fissured (figure 4I*b*) and highly permeable. This configuration gives numerous pathways both for hot ascending hydrothermal fluid and cold descending seawater. The mixing front is located within the crust and at the surface both hot fluids and diffuse low temperature discharge are observed. Deposits are numerous and very small because the upflow zone is relatively narrow and subject to perturbation by frequent tectonic and volcanic activity. This situation is well documented on the East Pacific Rise at 13° N and on the southern EPR. On slow spreading the system is less permeable and hydrothermal discharge better focused.

In permeable volcanic sequences (figure 4I*c*), such as volcaniclastic material or highly vesicular volcanic rocks, hydrothermal flow is less focused. This situation is common in felsic volcanic environments where volcanic rocks are highly vesicular and brecciated. Few faults occur at the surface of the ridge and hydrothermal fluids are mixing with cold seawater within the permeable and porous volcanic rocks. The result is the formation of a low temperature Fe/Mn or Si crust at the seafloor. This crust can act as a lid on the system and allow the formation of massive sulphide by replacement of the pervasively altered volcanic rocks within the oceanic crust (Fouquet *et al.* 1993*a*). The morphology of the deposit is not a mound but occurs both as massive sulphide and disseminated mineralization within the crust.

(*c*) *Stability of hydrothermal system*

The depth and size of heat source and the stability of structure have a profound effect on the longevity of a vent area and therefore on the size of a deposit. The construction of a large mound implies the circulation of a large amount of hydrothermal fluid at the same location. On fast spreading ridges it has been observed that within a period of a few years the hydrothermal activity moves along the axis (figure 4II*e*). This is not favourable for the generation of large sulphide deposits. The formation of first order sulphide mounds requires that the convective cells be in the same place for several successive hydrothermal episodes (figure 4II*d*). For example at TAG several hydrothermal episodes have been documented at the same place for a period of a more than 26 000 years during which at least five hydrothermal episodes are documented (Lalou *et al.* 1993). This is also the case on the Snake Pit and probably the Lucky Strike sites. Thus we see that more stable convective systems at slow spreading are more favourable to the formation of large deposits than are the highly unstable fast spreading hydrothermal systems. However, it was recently demonstrated that a similar stable configuration can happen on off-axial seamount close to the ridge on fast spreading ridges (Fouquet *et al.* 1996). A particular situation is the border of a caldera (figure 4III*f*). The particular morphology of the system produces extensive deposits, with a massive part having the shape of a lens with a relatively flat or concave surface contrasting with the typical conical shape of a mound. Many seamounts have a summit caldera, a structural feature common to the environment of formation of some ancient massive sulphide deposits (Ohmoto 1978). Calderas are areas of high heat flow and intense fracturing, two important requirements for the formation of large deposits.

(*d*) *Boiling: water depth*

A typical vent fluid at 350 °C at a water depth of 3000 m (figure 4IV*a*) is well below the boiling point for this pressure and will precipitate sulphide as a cooling product when the fluid reaches the seafloor. In shallow water boiling may occur. Boiling and separation of a steam phase leaves a residual liquid cooler, more saline and enriched in metals (due to partitioning of NaCl into the liquid phase) and depleted in H_2S (due to its partitioning into the vapour phase). This process may result in the formation of stockwork-dominated mineralization (figure 4IV*a*) as a network of veins within the crust, whereas at the surface only low temperature and metal depleted mineralization is formed. In deep-water environments metal deposition is concentrated at the seawater interface with limited stockwork development. After phase separation, the venting fluids may result in two types of smokers the first will be venting fluids of low salinity and high gas content. A typical example is seen at the shallow (800 m) Menez Gwen site on the MAR. The fluid has a low salinity, is enriched in gas and both fluid and mineral precipitates are depleted in metal content (Fouquet *et al.* 1996). The surface precipitates are dominated by barite and anhydrite. This means that metals are probably trapped deeper in the system. The discharge of the more dense fluid may occur as bottom-seeking fluids. For the moment there is no way to identify this type of discharge from conventional equipment used to detect the hydrothermal plumes, however several distal fossil deposits are considered to have been formed through this process (Scott 1985). On fast spreading ridges recent investigations showed that the fluids could have higher or lower salinity than seawater at 2600 m water depth. On tectonized ridges the highly saline fluids are enriched in metals, and may correspond to the venting of dense brines generated during an earlier phase separation along the segment. Conversely the low salinity fluids are related to recent lavas and thus to early phase separation enhanced during basaltic eruptions (Charlou *et al.* 1996). A similar example is also known in the Woodlark back-arc basin (Binns *et al.* 1993*a*) where extensive stockwork mineralization is inferred from the fluid composition.

(*e*) *Geological trap/cap rocks*

Different types of traps may enhance the accumulation of metals and therefore the efficiency of the system. The first trap is the mound itself (figure 4V*i*). Old systems are sealed and enhance the focused discharge of deep fluids through discrete vents. As the mound is growing, mixing does not occur only in the open ocean as is the case for a typical smoker, but some restricted mixing occurs within the mound and allows a higher amount of metal to be precipitated. In other words, the mound acts as a cap on the hydrothermal system. This process was recently well documented when drilling through the TAG mound (Humphris *et al.* 1995).

Probably a more efficient system is the sediment cover on a ridge (figure 4V*j*). It has been demonstrated for the Guaymas Basin (Bowers *et al.* 1985) that compared to a typical black smoker fluid resulting from the interaction of seawater with basalt, the metal contents are highly depleted in fluids from sedimented ridges. One possible explanation is that a significant amount of metal was lost during interaction of the end-member hydrothermal fluid with the sediment during the ascent of the fluid. This again allows metal precipitation in environments where mixing and thus rapid dilution by seawater is restricted during cooling of the fluid. The morphology of these deposits can be a mound at the surface but also sill like replacement levels within the sediments. However, the knowledge of the associated deposit requires further investigation in the vertical dimension. ODP drilling on a sulphide mound at Middle Valley showed that sulphide bodies in these environments are particularly thick (at least 90 m) (Mottl *et al.* 1994).

Another potential trap is an impermeable layer acting as a physical cap and chemical barrier on the hydrothermal system. This layer can be a silica, carbonate or sulphate layer, or a series of lava flows. Few examples are known in the modern ocean. At Lucky Strike on the MAR, a layer of SiO_2 clearly acts as a barrier to the ascending fluid and may enhance the formation of extensive subsurface sulphide precipitate (Fouquet *et al.* 1996). The occurrence of an impermeable cap rock (silica) on highly permeable rocks (volcanic and tectonic breccia) is a favourable configuration to form large deposits within the crust. A similar situation was seen in the Lau back-arc basin where massive sulphide deposits are actively forming under a Fe/Mn crust, which acts as a cap to the highly permeable volcaniclastic breccia on the ridge (Fouquet *et al.* 1993*a*). Again here, further investiagtions are needed to document processes occurring along the vertical section of the hydrothermal system. In all these cases the morphology of the deposits will not be a mound but a lenticular body within the crust. In addition these deposits have a high potential to be preserved because they are protected from rapid oxidation by direct contact with seawater.

4. Conclusions and new perspectives for hydrothermal exploration

After 15 years of exploration, various hydrothermal systems are now well known in the ocean. The formation of a large deposit is controlled by the combination of several conditions, each of which alone is often only compatible with the formation of small and unstable hydrothermal systems.

Recent discoveries considerably enlarge the potential locations of hydrothermal activity. On slow spreading ridges we have now to consider the base and top of graben wall and the non-transform offsets in addition to the relatively well documented control of the volcanic topographic high. On fast spreading ridges, off-axial seamounts are potential sites that have to be explored to determine their preferential control for the formation of large deposits. Back-arc basins have more complex tectonic histories that may enhance the combination of the several factors necessary for the formation of large deposits. They are likely to represent the closest equivalent to major massive sulphide deposits on land. According to these results future strategy to explore hydrothermal systems on mid-oceanic ridges needs to be revised.

In addition to the typical formation of a mound shaped deposit, there is now clear evidence that major sulphides deposits can be formed within the crust as stockwork mineralization related to boiling or precipitation of sulphides due to restricted mixing under a geological lid. A great deal of work is still to be done to document these deposits because drilling operations are necessary to describe or even to discover them.

Finally, a number of deposits cannot be identified using the conventional equipment used to detect hydrothermal fields. Most active fields are identified through their buoyant plume using vertical or dynamic hydrocasts. These techniques will not be efficient at detecting venting of dense brines that cannot rise to form a plume. These brines will accumulate in depressions with a minimum of mixing, preserving most of the metallogenic potential of the fluid.

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Discussion

A. Schultz (*Earth Sciences Department, Cambridge University, UK*). Dave Butterfield has made a compelling case for phase separation being ubiquitous. I've observed diffuse effluent at Juan de Fuca Ridge traced by release of fluorescent dye during a slow dive programme I had in 1991. The broad low temperature diffuse flow appeared to achieve neutral buoyancy at a height in the water column of only *ca.* 1 m. Could there not be an even more extreme case in systems where both phase separation has occurred at depth (forcing anomalous chlorinity) which, as we've observed at TAG, is mixed with passively advected seawater inside the mound. Could this lead to non-bouyant 'crypto'-plumes trapped within the mound with no external surface signature – yet associated with internal mineralization?

Y. Fouquet. In some cases boiling clearly occurs at depth. Our recent investigations on super-fast spreading ridges have demonstrated that, just after an eruptive event on a volcanic dominated ridge, the hydrothermal fluid has low chlorinity, high gas content and low metal concentrations. On tectonic dominated segments the venting fluids have a high chlorinity and a high metal content. The best explanation is that, when phase separation occurs at depth, the light vapour phase migrates rapidly towards the surface and the dense brine is trapped deeper in the system. Then we can imagine several scenarios where a typical end-member fluid is mixed with variable amounts of brines, and/or vapour phase and/or seawater. The best scenario to produce a large deposit will be venting of a very dense brine that accumulates in a depression without any plume formation (see figure 4*h*) and with a minimum of

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mixing with seawater. The problem is that for the moment, because of the absence of a plume, there is no way to identify this type of vent. On a mound like TAG such a brine will probably dilute rapidly due to the advested seawater inside the mound.

R. Herrington (*Department of Mineralogy, The Natural History Museum, London, UK*). Has Dr Fouquet extrapolated the key elements seen to be important to the location of large massive sulphide deposits on the modern seafloor to the study of fossil massive sulphide deposits? For example, shouldn't features such as the texture of the massive sulphides be diagnostic for differentiating the different modes of mound formation which you propose in modern settings and if so are they seen in fossil deposits?

Y. Fouquet. Several of the ideas and observations on modern sulphide deposits are relatively new. Particularly the importance of subsurface formation of sulphides has been underestimated during submersible operations. Thus to really extrapolate our observations for fossil deposits we need more investigations of the vertical zonation of the sulphide deposits. For the moment, this can only be achieved through the international ODP program. In the fossil record there are several examples of sulphide deposits formed under a silica cap. The absence of oxidation under this cap may indicate that, as it is on the modern seafloor, an important part of these deposits was formed within the crust. At TAG on the Mid-Atlantic Ridge we also know that part of the mound is formed by replacement of basalt. Careful comparisons between modern and fossil deposits have still to be done. When preserved, the primary textures will help to identify the type of processes involved in the mound formation. This will only be possible in fossil environments with low metamorphic and tectonic modifications during emplacement on land.

R. W. Nesbitt (*Southampton Oceanography Centre, University of Southampton, UK*). Dr Fouquet's discussion drew attention to the possibility that some of the TAG mound sulphides represent replacement of basalt. Is it possible that the replacement begins within the so-called stockwork zone which as it develops, progressively overwhelms the basalt? One can imagine that as the process continues and the hydrothermal system matures, the stockwork will move downwards leaving behind zones of massive sulphide. As it does so, it also creates further sulphide-rich zones deeper within the basalt pile. Does he think this process is a possibility and if so, would he care to speculate on the relative proportion of the sulphide mound which was created in this way?

Y. Fouquet. At the TAG mound this is a major process that contributes to the formation of the mineralization. Thus the mound is built up through three major processes: accumulations of chimneys at the surface; internal inflation due to sulphides growth within the mound. These sulphides form by mixing and occur preferentially in veins and impregnation in the porous sulphides formed at the surface; replacement of the basalt. The different stages of basalt replacement are observed at TAG. The end-member assemblage of this process is a pyrite-silica breccia assemblage that constitutes the most important part of the stockwork. As at TAG the massive sulphide part is less than 20 m thick, we can speculate that as much as two-thirds of the mound may be formed by internal processes and not as a consequence of chimney accumulations.