Hydrothermal discharge zones beneath massive sulfide deposits mapped in the Oman ophiolite

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ABSTRACT

The area in the Oman ophiolite containing the volcanic-hosted Bayda and Aarja massive sulfide deposits exposes a cross section of ocean crust and reveals to an unprecedented extent the fossil zones of hydrothermal upwelling that fed these sea-floor deposits. The fossil discharge zones are elongate areas of alteration and mineralization characterized by numerous small (metres to tens of metres in length), linear, discontinuous gossans. The gossans result from oxidation of hydrothermal pyrite replacing primary igneous phases and filling voids and fractures in the altered host rocks. The two deposits have separate discharge zones that appear to be sub-sea-floor extensions of their stockworks. The Bayda zone extends through the volcanic section into the upper sheeted dike complex and is interpreted as having formed on the ridge crest above an axial magma chamber; the Aarja zone terminates against a plagiogranite pluton that intrudes the lower volcanic section and is thought to have formed after Bayda in an off-axis environment. Structural, stratigraphic, and compositional characteristics of the Bayda and Aarja massive sulfide bodies are consistent with this interpretation. The geometry of the discharge zones suggests that in both cases upflow occurred in broad zones (at least 400–600 m wide) that were elongated along strike (i.e., parallel to the spreading axis).

INTRODUCTION

Studies of hydrothermal vents on and near oceanic spreading centers have shown that the temperatures, compositions, flow rates, and precipitates of active sea-floor vents vary significantly from vent to vent and from site to site (e.g., von Damm et al., 1985; Michard et al., 1984; von Damm and Bischoff, 1987; Rona et al., 1986; Haymon and Kastner, 1981; Tivey and Delaney, 1986; Koski et al., 1984; Malahoff et al., 1983; Alt et al., 1987). This variation is evidently due to nonuniform sub-sea-floor processes at spreading centers that affect the properties of hydrothermal fluids, but these sub-sea-floor processes cannot be observed easily and are not well understood from a chemical or physical perspective.

Ophiolites, fragments of sea floor formed at spreading centers and later thrust onto land, are convenient places to observe that which is hidden at modern spreading centers; i.e., the record of crustal alteration and mineralization left by hydrothermal fluids that once passed through the sea floor. In the volcanic section of the Samail ophiolite in northern Oman (Fig. 1), we have mapped alteration/mineralization zones that we believe are fossil zones of hydrothermal upwelling (or discharge) beneath two massive sulfide deposits analogous to those found on modern spreading centers and on ridge-flank seamounts in the eastern Pacific (Haymon et al., 1984; Ixer et al., 1984). The two deposits, Bayda and Aarja, are close together, but geologic mapping (Fig. 2) and satellite imagery (Fig. 3) show that each is underlain by a separate discharge zone. In this paper we describe the field characteristics of the deposits and their respective discharge zones, and we propose that the Bayda and Aarja deposits formed at different times during distinct ridge-crest and off-axis hydrothermal episodes.

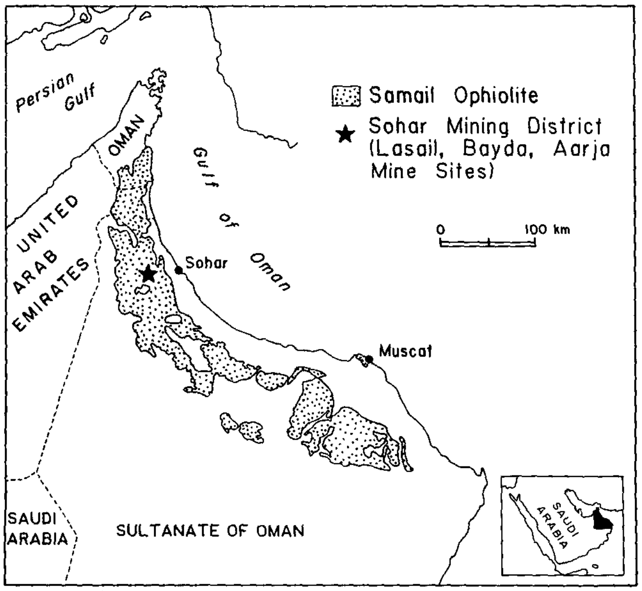


Figure 1. Site of Bayda and Aarja massive sulfide deposits (star) within Samail ophiolite (stippled area) in northern Oman. Modified after Coleman et al. (1979).

DESCRIPTION OF THE BAYDA AND AARJA DEPOSITS

The Samail ophiolite in the Sultanate of Oman (Fig. 1) exposes a complete section of Tethyan ocean crust (Reinhardt, 1969; Glennie et al., 1974; Smewing, 1980; Hopson et al., 1981) that includes numerous sulfide deposits and metalliferous sediments formed by Cretaceous sea-floor hydrothermal activity (Bailey and Coleman, 1975; Coleman et al., 1979; Fleet and Robertson, 1980). The Bayda and Aarja deposits are volcanic-hosted Fe-Cu-Zn massive sulfide deposits containing, respectively, 0.5–0.75 and 2.5–3 Mt of 2 wt% copper ore. The two deposits are located north of Wadi Jizzi in an area of northern Oman designated "The Alley" (e.g., Smewing et al., 1977; Coleman et al., 1979; Alabaster and Pearce, 1985), and they are separated by only 1.6 km (Fig. 2).

Bayda Deposit

The Bayda deposit consists of two bodies of massive sulfide (north and south Bayda; Fig. 2). We observed underground that these bodies are bounded by steep normal faults with opposing dips, a structural configuration suggesting that the deposit accumulated within a sea-floor graben. The bounding faults on the east side strike N10°W, subparallel to the average strike of the sheeted dikes in the ophiolite (Lippard, 1980), and thus subparallel to the Samail spreading center.

A composite cross section through the Bayda deposit constructed from our underground maps and drill-core logs is shown in Figure 4. The volcanics along the bounding faults are altered to a distinctive red assemblage of hematite-quartz-chlorite-albite. These faults were evidently conduits for the hydrothermal fluids from which the Bayda deposit precipitated. The Bayda deposit consists of a breccia unit overlain by a massive sulfide unit, which is composed mainly of pyrite, sphalerite, chalcopyrite, and quartz. The breccia unit contains clasts of altered volcanics, including some hematized fragments similar to the bounding fault rocks, as well as clasts of massive sulfide. The breccia clasts are cemented within a quartz-sulfide matrix. We interpret this breccia as a talus pile on the graben floor that was altered and mineralized by hydrothermal fluids discharging through the pile. Stockwork (quartz-sulfide veins cutting altered volcanics) occurs on the eastern (upthrown) side of the bounding faults and is particularly well developed and exposed at north Bayda.

The presence of massive sulfide clasts and fragments of fault rocks in the quartz-cemented breccia is evidence for fault movement during hydrothermal deposition, and suggests that the Bayda graben was within the active plate boundary zone when the deposit formed. By analogy with the East Pacific Rise, this places the formation of Bayda within about 10 km of the Samail ridge axis (Macdonald, 1982; Bicknell et al., 1987). A ridge-crest setting is consistent with the scarcity of pelagic sediments in the Bayda host volcanics, as well as with the overall size of the Bayda deposit, its Zn-rich composition, and the textural features of Bayda sulfide samples. Fossilized hydrothermal worm tubes preserved in massive sulfide sampled underground at Bayda are virtually identical to fossilized worm tubes recovered from active vent sites on the crests of the southern Juan de Fuca Ridge and the East Pacific Rise at lat 21°N (Haymon et al., 1984).

Aarja Deposit

The Aarja deposit has not been mined; hence, our interpretations are based on what can be seen in surface exposures and drill cores. Drill cores at Aarja contain massive sulfide, altered and mineralized volcanic breccia, and volcanic stockwork. Because the drill cores are cut by numerous shears, the structural and stratigraphic relations between these rock types are difficult to reconstruct. Construction of a detailed cross section for Aarja like that shown for Bayda in Figure 3 will be possible when future mining exposes these relations. Drill cores show that the deposit is a roughly cigar-shaped body plunging ~30° to the south. At the north end of the deposit, a conspicuous gossan containing layered, cherty metalliferous sediments crops out at the surface.

The Aarja-Bayda area has an overall dip to the south-southeast; however, the thin-bedded sedimentary rocks in the Aarja gossan strike N40°W and dip steeply to the southwest, suggesting that the Aarja deposit occurs on the west limb of a north-northwest–south-southeast–trending anticline. Other metalliferous sediment units in the volcanic rocks near Aarja are also folded about north-northwest–south-southeast axes. Compressional deformation at Aarja may be related to strike-slip motion along northwest-southeast faults in the area (Fig. 2).

The mineral content, bulk composition, sulfur isotope composition, and basalt alteration assemblages of the Aarja deposit are distinct from Bayda (this study; Ixer et al., 1984, 1986; Table 1). Aarja massive sulfide samples contain less zinc and more arsenic than Bayda samples (Table 1). Minor bravoite and traces of tennantite and galena found at Aarja are not seen at Bayda (Ixer et al., 1984). Aarja massive sulfide samples exhibit a markedly lower range of $\delta^{34}S$

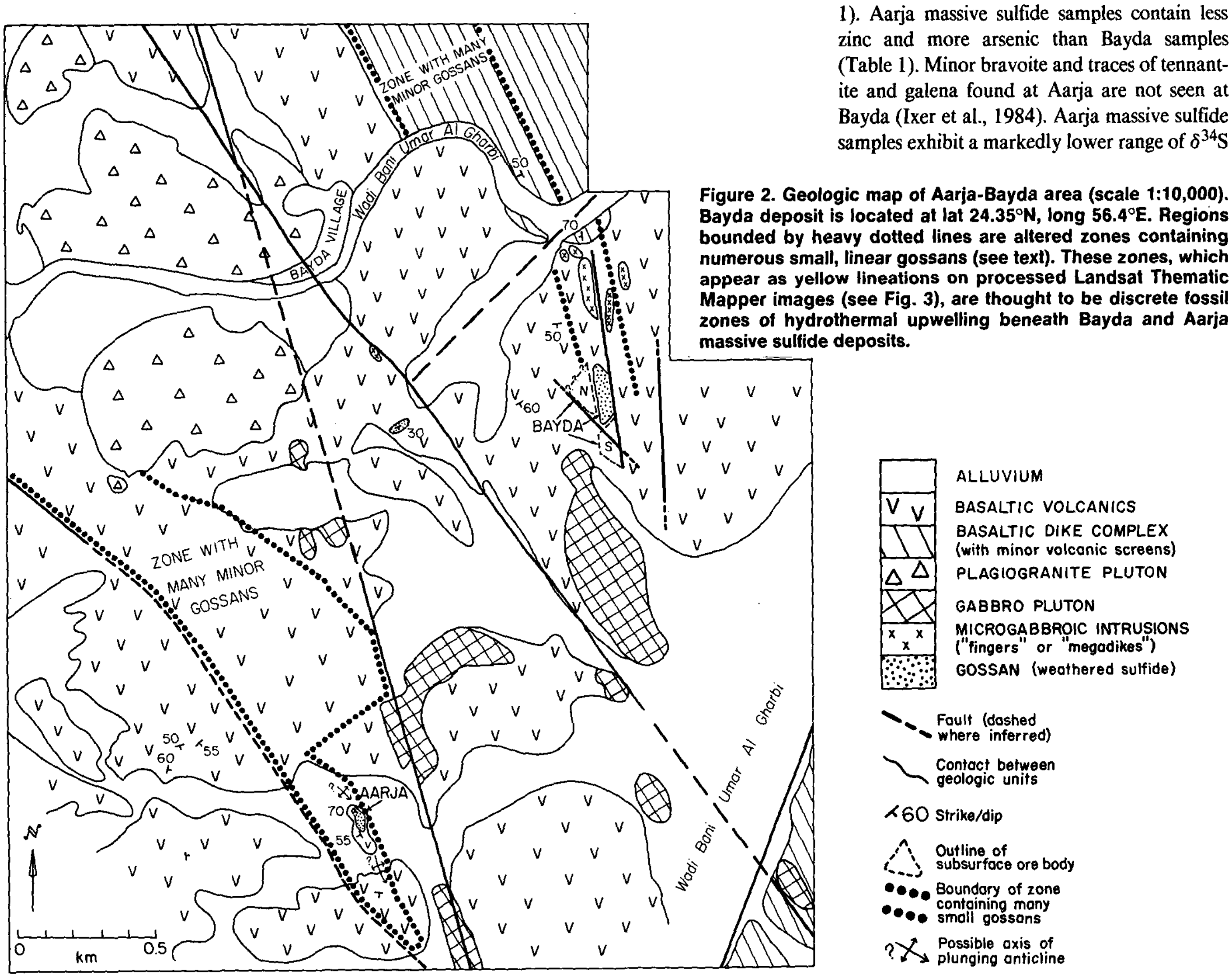


Figure 2. Geologic map of Aarja-Bayda area (scale 1:10,000). Bayda deposit is located at lat 24.35°N, long 56.4°E. Regions bounded by heavy dotted lines are altered zones containing numerous small, linear gossans (see text). These zones, which appear as yellow lineations on processed Landsat Thematic Mapper images (see Fig. 3), are thought to be discrete fossil zones of hydrothermal upwelling beneath Bayda and Aarja massive sulfide deposits.

values (averaging +2.6 $^{0}/_{00}$ at Aarja compared to +7.2 $^{0}/_{00}$ at Bayda), and show a rare-earth-element pattern that is distinctly different from the pattern found at Bayda (Haymon and Koski, 1988). Volcanics in the Aarja area show a well-developed zeolite facies alteration assemblage and contain celadonitic clay minerals, in contrast to the greenschist facies assemblages seen in the lavas hosting the Bayda deposit.

STRUCTURE AND STRATIGRAPHY OF THE AARJA-BAYDA AREA

The Samail ophiolite is an extremely well preserved ophiolite; however, considerable structural complexity has been imposed on it by faulting and folding during and after obduction. Geologic maps of the Samail ophiolite at 1:100,000 scale show that structure is particularly complicated in the northern part of the ophiolite (Lippard, 1980). This complexity is revealed in detail by Landsat Thematic Mapper images of the area (Abrams et al., 1988; Fig. 3 here), which show that the ophiolite north of Wadi Jizzi has broken up into many tectonic blocks. Some rotation of the individual blocks is indicated by variations in the strikes of the sheeted dikes between different blocks.

Although in general the ophiolite dips to the east, our 1:10,000 scale geologic map of the Aarja-Bayda area (Fig. 2) shows that the tectonic block containing this area is dipping to the south-southeast. Thin sediment units in the volcanics as well as massive volcanic flows have a consistent south-southeast dip similar to the plunge of the Aarja deposit. Thus, a traverse northward across the Aarja-Bayda area penetrates progressively deeper into the volcanic section and into the upper part of the sheeted dike complex. The transition from volcanic flows into sheeted dikes containing volcanic screens is well exposed along Wadi Bani Umar al Gharbi, north of Bayda.

Figure 3. Landsat Thematic Mapper image showing Aarja and Bayda hydrothermal discharge zones in Samail ophiolite of Oman. In this false-color composite, infrared channels 4, 5, and 7 are displayed in blue, green, and red, respectively. Colors represent different spectral reflectance characteristics of surface materials, and hence correspond to variability in surface rock and soil chemical compositions. In this arid region of little vegetation, image is essentially surface outcrop map of geologic units in area 8 km × 6.9 km within northern Samail ophiolite. Central part of image includes area mapped in Figure 2. Hydrothermally altered rocks appear in yellow or orange-yellow due to presence of ferric iron. Two separate alteration zones (linear yellow features) are interpreted as fossil zones of hydrothermal upwelling through sea floor beneath Bayda and Aarja massive sulfide deposits.

Increasing stratigraphic depth northward across the Aarja-Bayda area is accompanied by a progressive increase in the metamorphic grade of alteration in the volcanic rocks, from zeolite facies at Aarja to greenschist facies at Bayda. This change in the grade of alteration with depth in oceanic crust is consistent with alteration trends previously described in drill core from young ocean crust (e.g., Alt et al., 1986) and in several ophiolites, including Samail (Evarts and Schiffman, 1983; Alabaster and Pearce, 1985; Spooner and Fyfe, 1973).

From our map, we conclude that the Bayda deposit occurs stratigraphically less than 500 m above the transition from volcanics into sheeted dikes and appears to be entirely within the lower lavas erupted at the Samail spreading axis. The Aarja deposit is stratigraphically higher, and thus younger, than the Bayda deposit and lies directly above a late plagiogranite pluton that intrudes through the upper part of the sheeted dike complex into the lower volcanic section immediately west of the Bayda deposit.

BAYDA AND AARJA DISCHARGE ZONES

Underlying the Bayda and Aarja deposits are separate, mappable zones of hydrothermal alteration and mineralization that extend downsection through the volcanics. These are areas containing may small (metres to tens of metres in length), discontinuous linear gossans resulting from oxidation of secondary pyrite replacing primary igneous phases and occurring with Fe-oxide minerals, quartz, and epidote in interpillow spaces, vesicles, fractures, and veinlets in altered volcanic rocks. On processed Landsat Thematic Mapper (TM) images, the Bayda and Aarja zones appear as discrete, bright yellow lineations (due to their high ferric iron content; Fig. 3). We interpret these features as separate discharge zones formed by hydrothermal fluids upwelling through the ocean crust and venting onto the sea floor at the sites of the Bayda and Aarja massive sulfide deposits.

The Aarja discharge zone terminates at the margins of the plagiogranite pluton located in the northwest part of the area. The contact between the pluton and the volcanics is a relatively sharp intrusive contact, and the gossanous zones within the volcanics stop at the contact without penetrating the pluton. We infer from these observations that the hydrothermal discharge zone developed in the volcanics above the ascending plagiogranite pluton and was intruded subsequently by the rising magma. In contrast, the

Bayda discharge zone extends down into the sheeted dike complex beneath the Bayda deposit. Within the dike complex beneath Bayda, the linear gossanous zones are manifested as quartz + Fe-oxide + sulfide + epidote veins along dike margins, and as altered, mineralized dike margins and pillow screens between dikes. Additional mapping north of the area in Figure 2 (planned for early 1990) will determine how far the discharge zone can be followed northwest along strike. Landsat TM images suggest continued exposure in the sheeted dikes for another 2 km along strike, ending in the gravels of the wadi bounding the northwest side of the tectonic block containing Bayda (Fig. 3).

The stratigraphically deeper parts of these discharge zones crop out for 400–600 m normal to the strike of the paleo-ridge axis (i.e., normal to the strike of the sheeted dikes), and do not appear to be following fault planes (the zones are too wide) or shear zones (there is no evidence for shear or ridge-perpendicular structures within these zones). The discharge zones appear to be extensions down into the sea floor of the stockworks associated with the massive sulfide deposits.

The stockworks in contact with the massive sulfide are dense networks of quartz-sulfide veins, up to 2 cm in diameter, cutting basalts that are partially to completely altered to assemblages dominated by quartz + chlorite + pyrite. Farther downsection, the veins in the discharge zones are narrower, wall-rock alteration is less intense (relict igneous texture is largely preserved), and mineralization and alteration are more sparse and discontinuous on the macroscopic scale. This change in the character of the discharge zones downsection probably results from their current geometric orientations relative to the land surface. The surface outcrops present oblique cross sections through the discharge zones. The central cores of the discharge zones are exposed at the stratigraphic level of the sulfide deposits, but deeper in the volcanic section (toward the northwest in Fig. 2), the land surface intersects the peripheral parts of the upflow zones at a distance of several hundred metres from the original central axes of upwelling.

The Aarja discharge zone crops out for about 1500 m subparallel to the strike of the paleo–spreading ridge, and 400–600 m across strike, suggesting that its length parallel to the strike of the paleo–spreading axis was at least twice its width normal to the ridge axis. Bayda also crops out for a significant distance subparallel to the ridge axis relative to its ridge-normal width. Both discharge zones are apparently elongated parallel to the paleo–spreading center.

Both the Bayda and Aarja discharge zones exhibit much narrower outcrop widths normal to the paleo–ridge axis at the upper (stratigraphically higher) ends of the zones. At Bayda this can be attributed to channeling of upwelling hydrothermal fluids along the bounding faults of the Bayda graben as the fluids emerged from the sheeted dike complex into the volcanic section. The structural configuration of the Aarja deposit is not observed, but the narrowing of the Aarja discharge zone upsection may also indicate that fluid rose through the crust in a broad zone until its path of ascent intersected a fault that focused flow directly to the sea floor. Alternatively, the outcrop pattern of the Aarja discharge zone may result from compressional deformation related to block rotation and strike-slip motion along the northwest-southeast faults in the area. If the Aarja deposit lies within a north-northwest–south-southeast–trending anticline that plunges south-southeast parallel to the dip of the section, widening of the surface outcrop area of the discharge zone toward the north-northwest would result.

The Aarja discharge zone appears to extend into volcanic rocks overlying the Aarja massive sulfide deposit. This alteration and the occurrences of metalliferous sediment layers in the overlying volcanics suggest that hydrothermal activity at Aarja was continued or renewed after the deposit was capped by volcanic flows.

BAYDA AND AARJA: DISTINCT RIDGE-CREST AND OFF-AXIS HYDROTHERMAL SYSTEMS?

Three salient field characteristics suggest that Bayda and Aarja were not cogenetic deposits: (1) Aarja appears to be stratigraphically above Bayda; (2) each deposit is underlain by a distinctly separate discharge zone, the Bayda zone striking N10°–20°W and the Aarja zone striking N30°W; and (3) the Bayda zone extends downward directly into the upper part of the sheeted-dike complex, whereas the Aarja zone extends to the margin of a high-level plagiogranite pluton intruding through the dike-volcanic transition zone into the base of the volcanic section (Fig. 2). We propose that the Bayda deposit formed on the crest of the Samail spreading center from fluids circulating above the main axial magma chamber (Fig. 5). We argue that the Aarja deposit formed after deposition of Bayda, somewhat off-axis above a high-level cupola, or above a discrete off-axis magma chamber (as suggested by Alabaster and Pearce, 1985). The structural, compositional, and alteration characteristics of the two deposits (Fig. 3, Table 1; Ixer

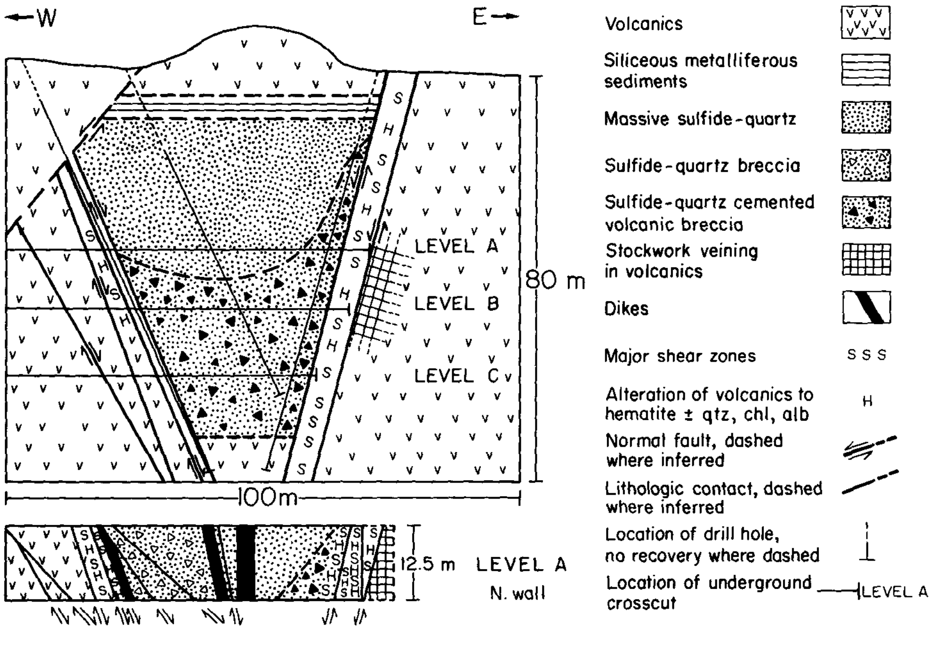


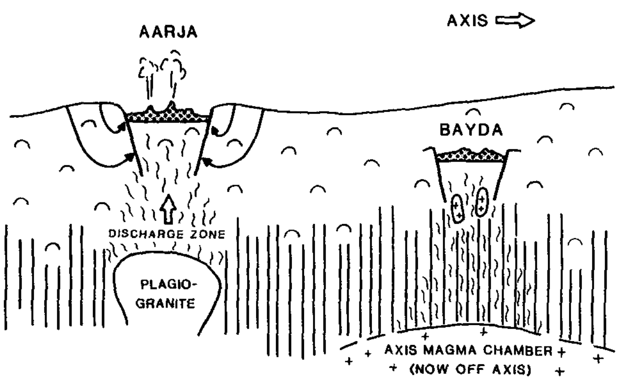
Figure 4. Composite cross section of Bayda deposit compiled from underground maps and drill-core data. Cross section is projected onto vertical east-west plane passing through south Bayda ore body; more extensive exposures of stockwork than shown here are found east of north Bayda ore body. For simplicity, many faults and basaltic dikes cutting through deposit are deleted from cross section and are displayed on detailed blow-up of north wall of Level A crosscut (below cross section).

TABLE 1. METALLIC AND SULFUR ISOTOPE COMPOSITION RANGES FOR REPRESENTATIVE MASSIVE SULFIDE SAMPLES FROM THE BAYDA AND AARJA DEPOSITS

	Bayda	Aarja
Major Metals (wt. %)		
Fe*	13.3 to 36.4	4.5 to 44.6
Cu†	0.5 to 25.4	0.01 to 11.5
Zn*†	0.1 to 65.9	0.01 to 12.8
Trace Metals (ppm)		
As*	<1 to 104	2 to 910
Ba*	<35 to 133	<20 to 1100
Cd†	10 to 896	7 to 214
Co*†	38 to 1510	34 to 2583
Pb†	105 to 338	104 to 601
Mn†	42 to 1087	77 to 408
$\delta^{34}S$ (‰)	6.2 to 8.0	1.9 to 3.3

* Analyzed by neutron activation analysis.
† Analyzed by atomic absorption spectroscopy.

Figure 5. Schematic cross section normal to Samail spreading center illustrating stratigraphic relation between Aarja and Bayda deposits and proposed formation of Aarja deposit above off-axis magma chamber. Bayda deposit is thought to have formed on Samail ridge crest above axial magma chamber. Ridge-parallel component of hydrothermal circulation is not shown.



et al., 1984, 1986; R. Haymon and R. Koski, unpublished data) are consistent with their formation in these two distinct sea-floor settings.

GEOMETRY OF HYDROTHERMAL UPFLOW ZONES

The Aarja-Bayda area affords an exceptional view of the geometry of sub-sea-floor zones of hydrothermal upwelling. We note that at depth both discharge zones are several hundred metres wide normal to the strike of the paleo-ridge axis, and narrow considerably at higher stratigraphic levels. These observations suggest that submarine hydrothermal fluids may be thermally channeled toward the sea floor above zones of intrusion, thus forming broad plumes of ascending hydrothermal solutions that may be tapped in the upper crust and focused onto the sea floor by faults intersecting the rising plumes.

We also note that the discharge zones and deposits are linear features that are elongated along strike. We suggest that the sizes and shapes of hydrothermal plumes ascending through the crust are influenced both by the sizes and shapes of the heat anomalies (i.e., magmatic intrusions) responsible for the plumes and by the permeability structure of the crust. The stress regime at spreading centers produces crustal faulting and cracking subparallel to the spreading axis. The tendency of magma and fluid to follow these cracks may impose elongate shapes on intrusions and a preferred ridge-parallel component of fluid circulation, which together result in linear discharge zones.

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