OLD MASSIVE SULPHIDE DEPOSITS: LESSONS FROM THE MAR SOUTH OF THE AZORES AND FROM DRILLED SITES

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Summary

Venting of "black smoke" is not a very efficient process to produce large mineral deposits, as part of the metals is lost into the water column and oxidation destroys sulphides exposed on the sea floor. ODP drilling (TAG, Juan de Fuca) has shown that sub-surface sulphide precipitation is more efficient. Iberian Pyrite Belt data showed the same years ago. At Neves-Corvo there is widespread replacement of silicate rocks by sulphides. At Aljustrel there are millions of tonnes of ores similar to the TAG sulphide-after-anhydrite pseudo-breccias.

The MAR South of the Azores contains hydrothermal fields in both neovolcanic (Lucky Strike and Menez Gwen) and ultramafic-dominated situations (Rainbow and Saldanha). Lucky Strike and Menez Gwen contain breccias of volcanic and sometimes hydrothermal fragments cemented by mostly hydrothermal precipitates, named slabs. This low permeability cover may favour sub-surface precipitation of MS ores. Rainbow and Saldanha are interesting because (1) ultramafic-associated VHMS deposits seem to be very rare, with significant deposits apparently restricted to the Precambrian; (2) Rainbow, with one of the main hydrothermal plumes known, may be a good example of dispersion; (3) at Saldanha there is a sea water methane anomaly and only weak venting through sediment. Sub-sediment sulphide precipitation may be dominant with little loss to the water column. The presence of a cap rock will enhance sulphide precipitation (1) increasing the residence time of the hydrothermal fluid thus greatly reducing dispersion; (2) preventing sulphide oxidation. In productive hydrothermal fields most of the ore-forming activity may take place under the sea floor.

Introduction

Recent advances in the exploration of submarine active hydrothermal fields have clarified massive sulphide formation. Here we report key observations and findings in the Mid Atlantic Ridge south of the Azores (especially the TAG field and the MOMAR area) of importance to massive sulphide metallogeny.

A general observation, probably applicable to all hydrothermal fields, is that oxidation of sulphides in contact with cold, unmodified sea water rapidly destroys chimneys and other surface precipitates, leaving a very friable outer layer of iron oxides which progresses to the interior of the edifices. Inactive chimneys exposed on the sea floor become rapidly devoid of any sulphides. This contrasts sharply with most of the important VHMS deposits of the geological record, where primary/diagenetic oxides are often rare. There is growing consensus on the replacement mode of emplacement of many ancient VHMS deposits, usually under some sort of cover rock capable of containing metal-bearing hydrothermal fluids long enough so that a large part of their metal content precipitates at the site of ore formation, instead of being lost as "black smoke". Two very different situations (in the Lucky Strike and Saldanha MAR hydrothermal sites, Langmuir et al., 1993; Barriga et al., 1998) may be good examples of this. Recent ODP drilling at TAG and Juan de Fuca provided key evidence in favour of such processes (Humphris et al., 1995).

The recent discovery of the Rainbow hydrothermal field (Fouquet et al., 1998) hosted in serpentinised ultramafic rocks and apparently devoid of associated magmatism raises interesting questions concerning the heat sources capable of fuelling large hydrothermal fields. Also, ancient counterparts to Rainbow do not abound, which deserves some thought as well.

The MOMAR Area of the Mid-Atlantic Ridge

There are four hydrothermal sites known in the MAR south of the Azores, relatively close to each other (within 100 miles or so) and to the Azores archipelago (within 200 miles or so). These are, from NE to SW, the Menez-Gwen (depth 800 metres) and Lucky Strike (1700m) sites in the segments with the same names, and the Saldanha (2200m) and Rainbow (2400m) sites in the South FAMOUS and AMAR segments, respectively.

In the MOMAR area (name of the InterRidge project "long-term multidisciplinary Monitoring the Mid-Atlantic Ridge near the Azores"), the ocean crust has a southward gradient in: (1) depth (from 800 m to 2800 m), (2) chemical properties of rocks, (3) nature of volcanism and (4) certain characteristics of the segmentation of the ridge axis. All of these characteristics are directly or indirectly controlled by the Azores hot spot.

Lucky Strike

Lucky Strike is one of the largest hydrothermal fields known in ocean floors. At the centre of the field there is a lava lake, the first discovered in a slow spreading ridge (Fouquet et al., 1995). Around the lava lake there are three volcanic cones which produced variably fragmented volcanic debris, coarse to fine grained, poorly to very well sorted, including spectacular hyaloclastites up to several metres thick. The fragmental volcanic products are commonly cemented by mostly hydrothermal precipitates, including silica, sulphides and barite, generating the so-called "slabs". Near large chimneys slabs include abundant fragments of chimneys. There is diffuse venting through slabs (up to about 100°C).

Thousands of chimneys and other edifices surround the lava lake (a few are on the lava lake itself). Many of these are mostly inactive, or mildly active only. Lucky Strike was far more active in the past than it is today. The larger active edifices exhibit small zones of high temperature discharge (up to 324°C). Elsewhere in the chimneys discharge is mostly diffuse, as leakage of transparent fluid, through the mussel-covered outer walls of the chimneys.

The chimneys depict clear evidence of oxidation provoked by sea water. In the more active chimneys oxidation is restricted to an outer layer, few millimetres thick, of oxides (mainly of iron). Once fluid flow ceases, oxidation progresses inwards. Primary sulphides are replaced by secondary sulphides and subsequently by oxides. Chimneys become rapidly friable, fall and break into progressively less recognizable fragments. Nearly half of the area of the Lucky Strike field is covered with chimney debris, deeply oxidised. Most of the remaining of Lucky Strike is composed of exposed "slabs".

The hydrothermal nature of the cement of slabs indicates that a large part of hydrothermal discharge at Lucky Strike is, or was, diffuse through the slabs. The formation of interstitial precipitates decreases the permeability of slabs. In many places, these seem to have become impervious or nearly so, greatly throttling hydrothermal discharge. Hydrothermal fluid may thus be forced to circulate horizontally, under the impervious blanket formed by the slab. These conditions are ideal for highly efficient sub-surface precipitation of sulphides.

Iberian Pyrite Belt Metallogeny

The Iberian Pyrite Belt (IPB, Lower Carboniferous, 350Ma) is the largest VHMS province in the world, in ore tonnage and contained Cu, Pb, Zn and Au (see for example Carvalho et al., 1999). Barriga and Fyfe (1988) have proposed a model of sub-sea floor ore genesis under a blanket of chemical sediments for the giant Feitais-Estação orebody of Aljustrel, Portugal (total sulphides at Aljustrel: 250Mt). The model is based on (1) presence of a cap rock with clear signs of having been formed and reworked by mineralising fluids; (2) complete lack of oxidation of the sulphide ores; (3) lack of sedimentary dilution. Recently Carvalho et al. (1999) extended the model to more general application in the IPB. The cap rock is mostly composed of jaspers, cherts and Fe-Mn sediments, with many similarities (considering that the lithologies and tectonic settings are different) to the Lucky Strike slabs (Costa et al., 1997). The lack of efficiency of "black smokers" in the generation of orebodies suggests that the deposits that do form are largely the result of sub-surface precipitation of the sulphides, either through hydrothermal clogging of the original black smokers and spire complexes (see Goodfellow and Franklin, 1993), or under a blanket of sediments. Recently Humphris et al. (1995) have reported on the results of drilling the TAG mound, concluding that most sulphide precipitation occurs within the mound itself, by internal inflation, and by cementing and replacing previously existing material, both hydrothermal and basaltic. Some of the textures (Fig. 1A) are strikingly similar to the extremely abundant (millions of tonnes) granular ore in the Aljustrel mine (Fig. 1B-1C), sometimes taken as "resedimented" (in conflict with numerous lines of evidence). The TAG findings provide undisputable evidence for the generation of in situ, non-transported, pseudo-breccias with rounded elements.

Recent studies (Relvas et al., 1997; in prep.) on the outstanding Neves-Corvo deposits (total sulphides: 300Mt) demonstrate that a large proportion of the sulphide ores precipitated under the surface as replacement of volcanic rock, both felsic lavas and tuffitic material (Fig. 1D-1E). As in Aljustrel, the sulphides are capped by chemical sediments that predate ore formation, and were partly replaced by the ores (Mirão et al., 1997).

In the IPB (as in many other VHMS provinces), ore samples resembling chimney fragments are unknown, despite extensive searches. Magnetite or other oxides are rare within massive sulphides. Inclusions of wall-rock in the massive ores can often be taken as remnants of replacement phenomena, or as drop stones in an internal inflation model (Barriga and Fyfe, 1988, 1991). Collectively, these data are interpreted as meaning that a large part (or the totality) of sulphide ore precipitation took place under the surface, protected from the corrosive effects of the open oceanic environment. Sulphide chimneys may have existed on the sea floor at the time of sub-surface ore formation, but may have been dissolved away once hydrothermal venting ceased, leaving only the hanging wall alteration present above the deposits. The latter is characterised by laterally discontinuous oxide-sulphide-carbonate assemblages in intimate association.

Rainbow and Saldanha

Following up on the results of segment scale geology and plume detection studies, (German et al., 1996, Bougault et al., 1998) diving operations were conducted during the Flores cruise (1997, Mast-3 AMORES Project, European Union) to find the Rainbow field and to study various aspects of hydrothermal processes on the MAR between 36°N and 37°N (Fouquet et al., 1998).

Rainbow chimneys and massive sulphides are enriched in Cu, Zn, Co and Ni compared to other sites in basaltic environments. The Rainbow hydrothermal site is hosted by serpentinites, which compose the Rainbow crest. There is a sulphide stockwork in serpentinites. Basalts are restricted to a thin veneer to the E of the Rainbow site, covering the serpentinites. These consist mostly of coarse- and fine-grained, porphyritic and non-porphyritic serpentinites with well-developed mesh textures. The main components of the Rainbow serpentinites are serpentine group minerals (antigorite/lizardite + fibrous chrysotile in late fractures), magnetite (± chromite) and aragonite in late veins. Bastite phenocrysts are present in some specimens. The lack (or scarcity) of brucite suggests that most serpentinisation took place at temperatures between 350-500°C.

The presence of a thin basaltic cover, without intervening abundant gabbros (or sheeted dykes), suggests that magmatic productivity became very low, or ceased, in this part of the ridge segment. In particular, magma chambers may be minor or absent. Thus the Rainbow hydrothermal site may result from hydrothermal circulation through peridotites/serpentinites, possibly driven by heat extracted directly from these rocks, not only from their cooling, but also from the exothermic serpentinisation process. These data have interesting consequences on the evolution of the oceanic crust (Barriga, 1999).

The Saldanha site (Barriga et al., 1998) is an area on the summit of a nearly 700-metre elevation, located on the southern tip of the FAMOUS segment in a second order discontinuity cutting the MAR south of the Azores. It was selected for detailed investigation through combination of new high-resolution multibeam bathymetry, sidescan sonar, dive data, and strong CH_4 hydrothermal anomalies (Bougault et al., 1998). These indicated discharge associated with serpentinisation of an ultrabasic diapir in the area. Mount Saldanha was identified as the likely candidate. During the Flores cruise, CTD / Rosette / Minirosette determinations confirmed the large production of methane associated with the site. Nephel and transmissometer anomalies, although present, are distinctly smaller than for example at Rainbow (German et al., 1996). During the Saldanha cruise a detailed diving survey of Mount Saldanha enabled discovery of a summital area of discharge of diluted, warm fluid. The venting orifices, through sedimentary ooze, are lined with hydrothermal precipitates and bacterial mats, but no protruding structures were found (Fig. 1F). The site is hosted in a melange of folded lithified sediment, relatively fresh to deeply altered basalt, variably deformed ultramafic rocks and some gabbroic rock, in large part covered by sedimentary ooze. The ensemble is interpreted as resulting from active serpentinite protrusion. Sediment clogging may explain the dominantly diffuse discharge of methane with only minor visible venting. It is considered likely that sulphide precipitation is taking place within the top of the rock pile, under a blanket of sediment.

Ancient ultramafic-hosted sea-floor mineralizations

There are scarce references in the literature to ancient equivalents to mineralizations like Rainbow (and possibly Saldanha). However, two cases deserve mention. Thus Hutchinson et al. (1980) have noted that the Ni-Cu sulphide deposits associated with ultramafic lavas (komatiites) often contain pyrite and a chert matrix. These characteristics are hardly explainable by magmatic immiscibility in an ultramafic environment, which led those authors to advocate the possibility of a sea-floor origin for mineralizations such as those at Langmuir, Canada and Kambalda, Australia (see also Lusk, 1976). Another interesting example, closer to Rainbow, is Outokumpu, Finland, where the serpentinite-

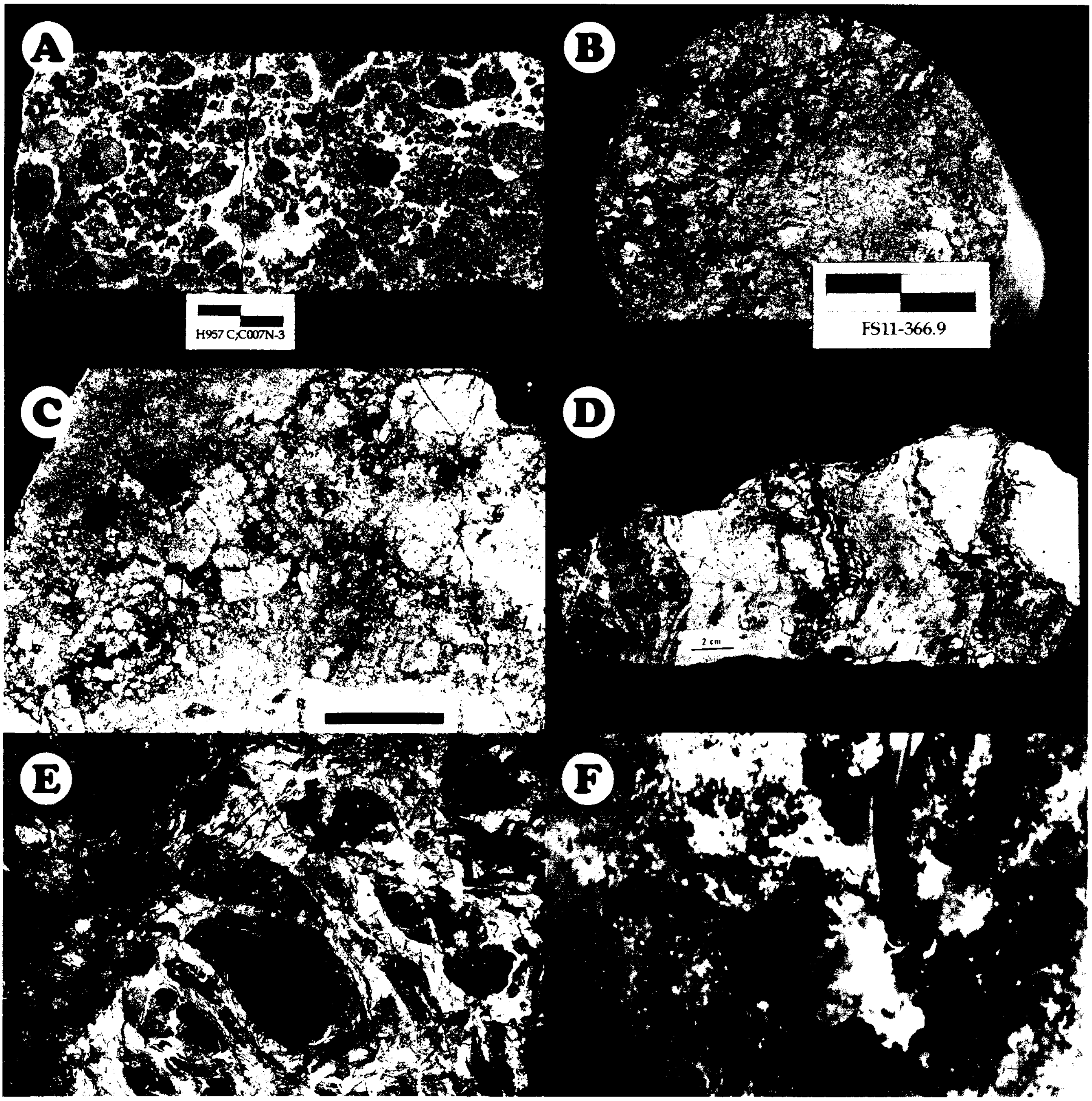

Figure 1.

A. Pyrite-anhydrite pseudo-breccia from the TAG mound (ODP Leg 158, 1994). The pyrite crystals (largely rounded) grew in the anhydrite matrix, by internal inflation.

B. Granular ore from the Feitais deposit, Aljustrel, Portugal. Rounded to sub-rounded sulphide grains (mostly pyrite) in a matrix of chalcopyrite/pyrite/chlorite/quartz.

C. Granular ore from the Feitais deposit, Aljustrel, Portugal. Note rounded pseudo-clasts (partly broken by subsequent deformation). Scale bar 1 cm.

D. Massive copper ore from the lower levels of the Corvo deposit, Portugal. White is rhyolite. On the right there is a large rhyolite fragment with relatively minor internal replacement; on the centre a similar rhyolite relic is far more attacked by sulphides; on the left extremity the process is nearly complete, rhyolite remnants are small and altered.

E. Mine exposure, tuffite (dark) being replaced by high grade massive copper ore (Corvo deposit, Portugal).

F. Detail of fluid sampling at an orifice with active hydrothermal discharge at the Saldanha hydrothermal site, FAMOUS segment, MAR (transparent fluid, not visible in single video frame). The orifice is lined with hydrothermal oxides, sulphides, carbonates and small bacterial mats.

hosted ores (Cu-Zn-Co; Ni-Cu-Zn) have been attributed to a sea floor origin, following volcanism and intrusion of the ultramafics ≅2Ga ago (see Loukola-Ruskeeniemi & Sorjonen-Ward, 1997).

Other examples may be found, once terrain studies are conducted admitting the possibility of serpentinites forming and outcropping on the sea floor. However, it is puzzling that deposits such as Rainbow, morphologically identical to those hosted in basalts, have escaped discovery in the main, well preserved ophiolites of Mesozoic or Tertiary age. We envisage several possible explanations for this: (1), Rainbow type deposits are rare; (2), Rainbow-like deposits are rarely preserved on the sea floor; (3) sea-floor serpentinites, abundant in slow-spreading ridges, may be rarely obducted and be poorly represented as ophiolites.

These results may open a new field of research both along slow spreading ridges and in ophiolite and similar terrains, with importance in delineating new exploration strategies for deposits rich in Ni, Co and Au.

Conclusions

There is much interest in comparing the modern and old sea floor metallogenetic situations. To mineral exploration on land we extract a wealth of information on the hydrothermal site landscapes, which help to explain many previously poorly understood field relationships at various scales.

To the exploration of the oceans we add the conclusion that major mineral deposits may exist, forming under blankets of sediments or other cover rocks. In the model of sub-surface ore formation, back smoker activity represents leakage from the system. Abundant metal-bearing fluid escaping through chimneys suggests less efficient ore accumulation below the surface and conversely, truly efficient systems may have a less obvious external expression. These may or may not relate to spire complexes at the surface. In many cases the only surface expression of major ore formation at depth may conceivably be relatively subtle diffuse discharge of warm fluids. New sea floor exploration tools and strategies are needed.

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