

# High to Intermediate Sulfidation, Shallow Marine, Sulfide Mineralisation in the South-eastern Tyrrhenian Sea, Italy

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**Abstract:** Semi-massive to massive sulfides with abundant late native sulfur were drilled in a shallow-water hydrothermal system in an island arc volcanic setting at the Palinuro volcanic complex in the Tyrrhenian Sea, Italy. Overall, 12.7 m of sulfide mineralisation were drilled in a sediment-filled depression at a water depth of 630 - 650 m using the lander-type Rockdrill I drill rig of the British Geological Survey. Polymetallic (Zn, Pb, Sb, As, Ag) sulfides overlie massive pyrite. The massive sulfide mineralisation contains a number of atypical minerals, including enargite-famatinite, tennantite-tetrahedrite, stibnite, bismuthinite, and Pb-,Sb-, and Ag-sulfosalts, that do not commonly occur in mid-ocean ridge massive sulfides. Analogous to subaerial epithermal deposits, the occurrence of these minerals and the presence of abundant native sulfur suggest an intermediate to high sulfidation and/or high oxidation state of the hydrothermal fluids in contrast to the near-neutral and reducing fluids from which base metal-rich massive sulfides along mid-ocean ridges typically form. Oxidised conditions during sulfide deposition are likely related to the presence of magmatic volatiles in the mineralising fluids that were derived from a degassing magma chamber below the Palinuro volcanic complex.

**Keywords:** Seafloor sulfides, Tyrrhenian Sea, high-sulfidation hydrothermal systems, Palinuro

## 1 Introduction

Seafloor hydrothermal systems in island arcs have seen increased exploration efforts by the scientific community in the past years due to their resource potential. These hydrothermal systems are different to those commonly studied at mid-ocean ridges

(Hannington et al., 2005) because of magmatic contributions of gases and possibly metals to the convecting fluids and their shallow water depths (Stoffers et al., 2006; de Ronde et al., 2007). The southeastern Tyrrhenian Sea in the Mediterranean is host to several shallow-water (<700 m) sites (Palinuro, Panarea, Figure 1) of hydrothermal activity that are associated with island arc volcanism and may be a modern analogue for deposits that form the transition from deep marine base metal volcanic-rock-hosted massive sulfide deposits to subaerial magmatic-epithermal precious metal deposits. In August 2007, we deployed the British Geological Survey (BGS) Rockdrill from the German research vessel Meteor (cruise M73/2). The drill rig was lowered to the seafloor on a power-and-lift umbilical and takes up to 5 m of core using either a rotary diamond bit coring system for hard rock or a vibro-coring tool kit for sediments. Our drilling campaign has documented the nature of unique, island arc polymetallic massive sulfide mineralisation in three dimensions.

## 2 Tectonic Setting

The Tyrrhenian Sea is a semi-closed basin in the western Mediterranean that is bounded by the Italian mainland to the east, Sicily to the south, and Corsica and Sardinia to the west. The SE portion of the Tyrrhenian Sea comprises a small, oceanic back-arc basin, referred to as the Marsili abyssal plain, and the Aeolian island arc (Figure 1) that formed as a consequence of roll-back of the NW-dipping Ionian subduction zone and migration of arc volcanism from

the island of Sardinia towards the E-SE (Savelli, 2001). Volcanism in the Aeolian volcanic arc was initiated about 1 Ma ago and changed from tholeiitic through calc-alkaline to shoshonitic over time (Beccaluva et al., 1985; Savelli, 2001; Calanchi et al., 2002). Present-day Aeolian volcanism is likely related to post-collisional extensional processes in an arc collision zone rather than to subduction processes (de Astis et al., 2003).

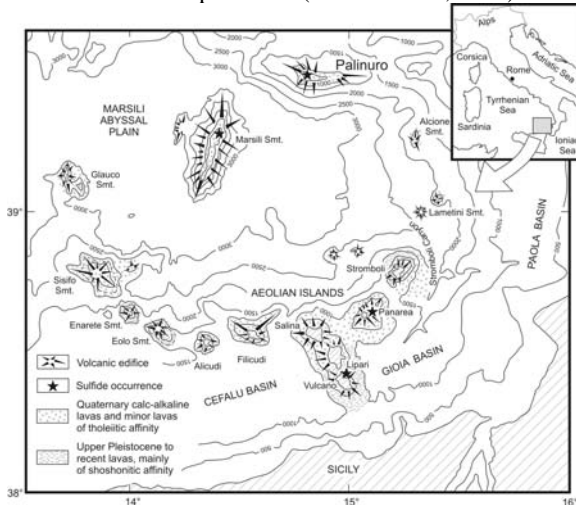


Figure 1 Location of the Palinuro volcanic complex in Aeolian arc of the Tyrrhenian Sea, Italy. Diagram from Beccaluva et al (1985).

### 3 Geology of the Palinuro Seamount

Palinuro is a complex, 50 km-long volcanic feature that consists of five coalesced volcanic edifices lying along an E-W trending fault system. Palinuro can be divided into two sectors, a western part (min. water depth of 570 m) and an eastern part (min. water depth of 70 m). The two sectors appear to be offset by an NE-SW trending fault system. High-alumina basalt, low-silica andesite, and high-K andesite, (all less than 0.35 Ma old), have been recovered from the Palinuro volcanic complex (Colantoni et al., 1981).

### 4 Mineralisation and Metal Content

Hydrothermal sulfides at the Palinuro volcanic complex were first described from two localities 5 km apart at a water depth of 400 to 600 m on the western sector by Minniti and Bonavia (1984) and Puchelt and Laschek, (1987). At that time the areal extent of the polymetallic mineralisation at Palinuro was poorly constrained and no information on the third dimension of the mineralisation was available. The mineralisation previously recovered contained, in addition to base metal sulfides, unusual minerals such as tennantite-tetrahedrite, farnatinitite, enargite, stibnite, native silver, and rare Bi-, Se-, Pb-, and Ag-sulfosalts (Dekov and Savelli, 2004).

During our research cruise, 11 holes were successfully drilled into a sediment-covered, basalt-hosted, sulfide/sulfate occurrence located in a small topographic depression (ca. 610 to 650 m water depth) on the summit of a volcanic edifice in the western

sector of the volcanic complex. Shallow drilling was conducted at a closely spaced grid covering 70 by 50 m in an area of active fluid venting as indicated by the discovery of small tubeworm clusters at the seafloor in 2006 and by TV-guided grab-sampling of warm (60°C) sediment in 2007. In total, 12.7 m of mineralised and brecciated rocks were recovered, with up to 4.9 m of continuous mineralised core in a single drill hole. Drilling proved the occurrence of semi-massive to massive sulfide mineralisation below a centimeter- to several meter-thick cover of unconsolidated sediments and a locally occurring polymictic breccia containing pumice clasts. Footwall volcanic rocks or sediments were not recovered during drilling; all drill holes ended in sulfide mineralisation and the vertical extent of the mineralised zone remains unknown.

From this drilling campaign, a vertical distribution of sulfide and sulfate mineral facies can be determined (Figure 2). The uppermost portion (<1 m depth) is an exhalite and/or low temperature altered sediments comprising banded amorphous silica, pyrite ± barite, Fe-Mn oxides and oxyhydroxides, and rare orpiment. The next facies (1-2.5 m depth) consists of barite breccias with minor amounts of clay, pyrite, marcasite, sphalerite, galena, tennantite-tetrahedrite, farnatinitite, chalcocopyrite, covellite, stibnite, and Pb-, Sb-, and Ag-sulfosalts. From 2.5 to 4 m depth the mineralisation comprises semi-massive pyrite, barite, and traces of clay. The deepest core recovered (>4 m depth) contains massive pyrite with minor barite. Late veins of pyrite, marcasite and native sulfur crosscut all other mineralisation styles.

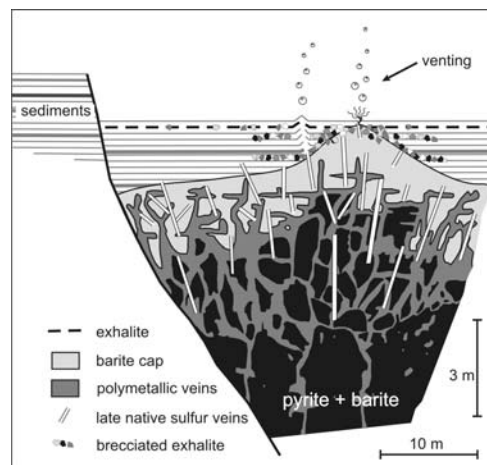


Figure 2. Schematic cross section of the Palinuro hydrothermal system. The system comprises an upper exhalite unit underlain by barite-cemented breccias and a polymetallic sulfide section. The lower part consists of massive pyrite with minor barite. Late pyrite/marcasite-native sulfur veins crosscut all mineralisation stages.

Geochemical analyses of the drill core (Table 1) indicate that the mineralisation at Palinuro is base- and precious-metals-rich, with one 4.74 m intersection containing 1.44 wt% Cu, 0.39 wt% Pb, 0.72 wt% Zn, 50 ppm Ag, and 0.2 ppm Au. Metal enrichment at the top of the mineralisation is evident in some cores with

polymetallic (Zn, Pb, Ag) sulfides overlying more massive pyrite. The polymetallic sulfides are enriched in trace metals that are more commonly associated with epithermal deposits forming in volcanically active areas on land (some drill core intervals contain up to 925 ppm Ag, 3.4 ppm Au, 1.5 wt % As, 1190 ppm Bi, 2032 ppm Hg, and 2.2 wt.% Sb).

## 5 Discussion and Conclusion

In comparison to ancient volcanic-hosted massive sulfide deposits that typically contain low amounts of Au and Ag (average Au content ~ 1-3 ppm; Hannington et al., 1999), modern seafloor systems with anomalous Au concentrations typically occur in boiling hydrothermal systems that are located in comparably shallow water (<1500 m; Hannington et al., 1999; 2005). Elevated concentrations of Au, As, Sb, and Hg have also been reported from some modern seafloor hydrothermal systems in island arc settings and young back-arc rifts (Hannington et al., 2005). In many respects, deposition of metals in the shallow water environment can be compared to the formation of epithermal deposits on land suggesting that there is a continuum from submarine base metal massive sulfides to subaerial epithermal gold deposits (Hannington et al., 1999).

The massive sulfide mineralisation at Palinuro contains a number of minerals that are not commonly encountered in base metal massive sulfide deposits, including enargite, famatinitite, and tennantite-tetrahedrite. Similar to epithermal deposits forming on land, the occurrence of these minerals and the abundance of native sulfur at Palinuro suggest an intermediate to high sulfidation and/or high oxidation state of the hydrothermal fluids rather than near-neutral and reduced, typical of those forming base metal-rich massive sulfide deposits (Hannington et al., 1999). In conclusion, the oxidised conditions during sulfide deposition at Palinuro are likely related to the presence of magmatic volatiles that were derived from a degassing magma chamber.

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Table 1. Weighted averages for selected massive sulfide/sulfate cores from the Palinuro volcanic complex

Hole	from (cm)	to (cm)	Intercept (cm)	N	Cu (%)	Zn (%)	Pb (%)	As (%)	Sb (%)	Au (ppm)	Ag (ppm)	Bi (ppm)	Hg (ppm)
M73/2 851RD	0	134	134	(5)	1.85	2.29	1.84	0.44	0.82	0.23	71	19	2032
M73/2 852RD	38	96	58	(1)	1.76	0.76	1.40	0.86	0.73	0.38	189	4	499
M73/2 853RD	0	34	34	(1)	5.58	1.67	4.01	1.14	2.23	1.62	925	8	1200
M73/2 857RD	2	47	45	(3)	3.75	6.83	5.35	0.46	0.96	0.73	353	1190	1284
M73/2 865RD	10	484	474	(14)	1.45	0.73	0.39	0.30	0.39	0.21	50	34	120
M73/2 931RD	0	45	45	(3)	0.67	6.50	2.68	0.41	0.22	0.32	61	11	317
M73/2 932RD	18	291	273	(6)	1.74	3.44	2.97	0.58	0.52	0.14	160	8	256

(N = number of subsamples analysed)