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Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise

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Massive ore-grade zinc, copper and iron sulphide deposits have been found at the axis of the East Pacific Rise. Although their presence on the deep ocean-floor had been predicted there was no supporting observational evidence. The East Pacific Rise deposits represent a modern analogue of Cyprus-type sulphide ores associated with ophiolitic rocks on land. They contain at least 29% zinc metal and 6% metallic copper. Their discovery will provide a new focus for deep-sea exploration, leading to new assessments of the concentration of metals in the upper layers of the oceanic crust. —

THE area of the deposits of ore-grade zinc, copper and iron sulphide was explored and sampled in February–March 1978 by the manned diving saucer CYANA during the expedition CYAMEX[1]. The expedition, the only submersible diving programme that has so far been conducted on the East Pacific Rise (EPR), is part of the French–American–Mexican project RITA (Rivera–Tamayo), a 3-yr study devoted to detailed geological and geophysical investigations of the EPR crest. The ore deposits were sampled in water depths of close to 2,620 m at two neighbouring sites near 20° 54′ N 109° 03′ W, (refs 2–5) about 90 km north of the Rivera transform fault and 240 km south of the Tamayo transform fault (Fig. 1). Three dives of Cyana (CY 78–06, 08 and 12) crossed the two sampling sites, and we collected samples during two of these (CY 78–08 and 12). However, during all dives in the EPR axial zone, signs of hydrothermal activity were seen, including colonies of dead giant clams, fields of pillow lavas with pronounced colour-staining at the base of pillows, and coloured deposits on exposed scarp surfaces of normal faults and open fissures[1]. Coral-like growths, possibly of native sulphur, occur in other locations, including a sedimented fault-scarp about 1.0 km to the west of where the sulphide ores were sampled.

Sampling sites

The two sites where the sulphides were sampled lie on the lightly sedimented flanks of steep-sided structural depressions, about 20–30 m deep, 20–30 m wide, and about 600–700 m west of the axis of the 'extrusion zone' where the youngest lavas occur. Whereas the extrusion zone is marked by a 50 m-high sediment-free discontinuous ridge with no fissures or faults, the structural

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zone within which the sulphide deposits are located is a 1.5 km wide tectonically active band of fissured and/or faulted terrain, the fault pattern being typically of the small horst and graben type and with all the active structures running parallel to the local strike of the EPR.

The massive sulphides were sampled from various parts of tall (up to 10 m-high), extremely irregular columnar edifices about 5 m in diameter (Figs 2 and 3). At one site, explored in relative details during dive CY 78–08 (Fig. 2), the vertical edifices are 4–5 m apart and are aligned along a direction of 025° over a distance of at least 50 m, in gullies cutting through the 045°-trending, westwards-facing scarp of a structural depression (graben). The second site, explored during dive CY 78–12, is about 200–300 m away and lies on the eastwards-facing flank of a possibly older graben. Here, there is more sediment cover, there are yellow-coloured coral-like growths and the edifices seem to be more indurated. The true spatial relationship of the two sampled sites is not established because of navigational difficulties during dive CY 78–12.

The along-strike extent of the sulphide mineralisation is not known. However, during dive CY 78–08 the graben was followed for about 100 m to the SSW (200°) where it became a 2–3 m wide open fissure with truncated pillows entirely stained by ochre and red-brown deposits exposed on the scarp. The eastern lip of the fissure has small (about 0.5 m high), sponge-like porous edifices and coral-like, bright yellow growths on sediment between pillows. Further south the fissure narrows and is bare of any hydrothermal deposits.

In general, the vertical edifices are built on a pillow lava terrain covered with a light dusting of sediment, the colour of which suggests some contribution of weathering products from the deterioration of the columnar edifices themselves. The edifices are variegated, the dominant colours being ochre, red, yellow, brown, white and black. They are porous and their entire mass is composed of a labyrinth of small channels or tubes separated by thin walls. Their internal structure can be compared to that of a sponge or a mass of clinker or brains. The framework of the edifices is made up of both amorphous, white translucent silica (which has been seen bare in one case) and the sulphides. The presence of open vents on top of the edifices demonstrates that they are constructional features built directly on the ocean crust. For this reason, we described them as hornitos when first observed. The tubes, conduits and channels pervading the mass of the edifices presumably represent the passages through which hot, metal-laden solutions circulated on their exit from the sea floor.

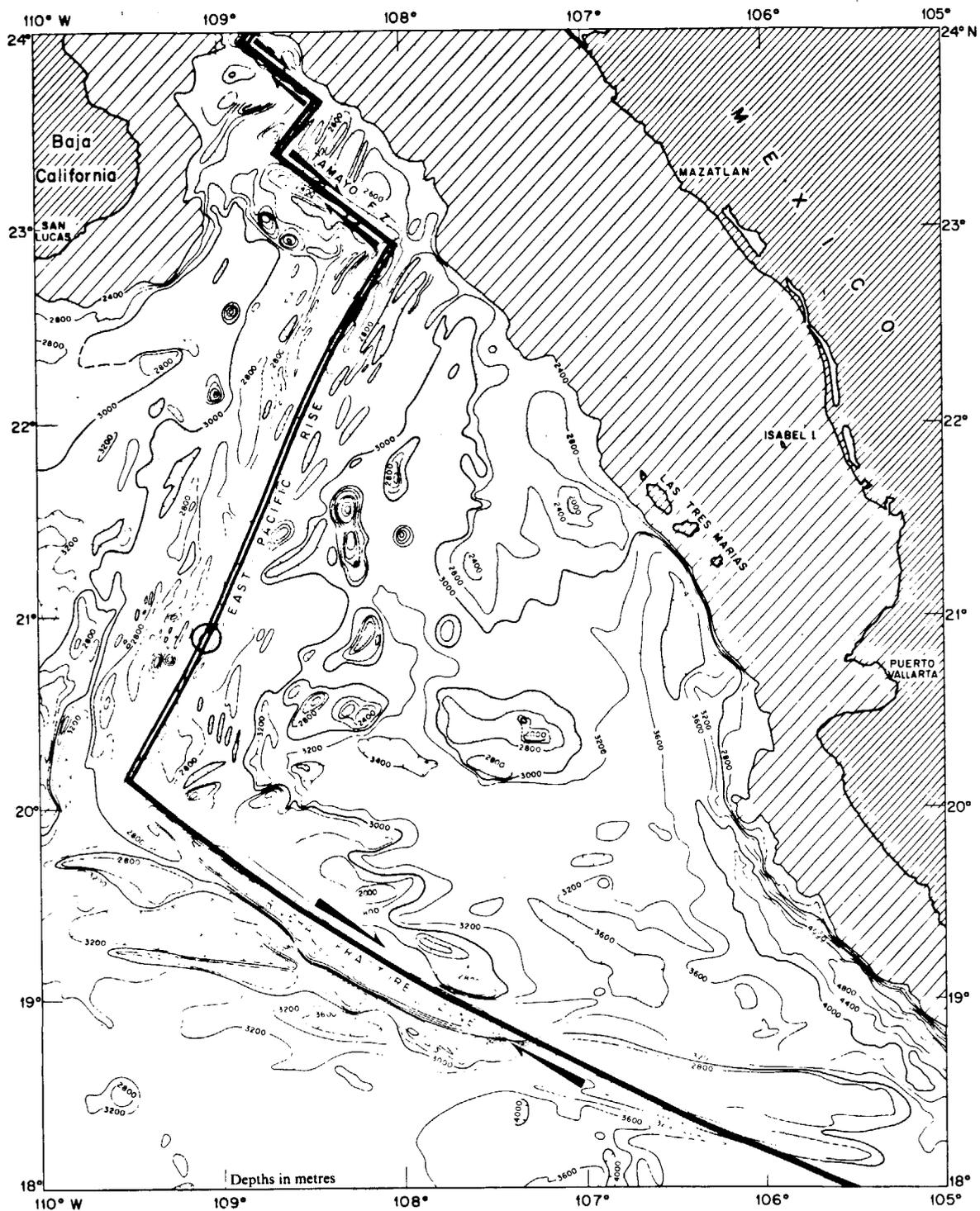Three other modes of mineralisation occur besides the spec-

Fig. 1 Setting of the axial zone of the East Pacific Rise where the sulphide ore deposits were explored and sampled (circle).

tacular vertical edifices: (1) flattish incrustations coating the moderately steep slopes with a rugose, heterogeneous surface texture made up of the same material as the tall edifices; (2) bright yellow or orange, 10–20 cm wide conelets built on sediment and with small holes at their tops and which lie around the large edifices; (3) yellow and red-brown travertine-like flows draping the near-vertical scarps of the graben that contains the row of vertical edifices. No unequivocal bottom-water temperature anomaly was observed during the exploration of any of the mineralised structures, suggesting completed or quiescent hydrothermal activity.

The material collected from each of the two sampling sites was separated on board ship according to colour and shape, giving a total of 14 samples (three from the site sampled during dive 8 and 11 from that sampled during dive 12). Some of the 14 samples thus designated comprise several subsamples or collections of fragments. A total of 215 subsamples and 11 boxes of small fragments were separated in the laboratory. The samples are very heterogeneous and complex, and no attempt is made at this stage to give a full description of them. We describe here only the gross mineralogy and give an indication of the chemistry of a few important subsamples.

Mineralogy and chemistry

The material consists of friable and porous compounds that are easily fragmented; thus some subsamples are as large as 7 cm in

diameter but many are smaller, and some consist of debris with diameters of one to a few mms, or are essentially powder. The subsamples are variegated: yellow to ochre-coloured, grey and blue metallic hues, and grey, bronze red and white reflections. The ochre-coloured material ranges from pale yellowish orange (10 YR 8/6) and moderate yellowish brown (10 YR 5/4) to moderate brown (5 YR 4/4) and from blackish red (5 Y 2/2) to moderate red (5 R 4/6). Most subsamples show well developed cylindrical tubes that display a concentric zonation of medium grey (N 5) layers on the outside to dark gray (N 3) and white (N 4) layers inside. Other tubes are composed of the lighter-coloured moderately brown material (5 YR 4/4). The inner walls of some of the tubes are lined with shiny, silvery deposits that are in part microcrystalline, whereas others are covered only by reddish deposits. Some tubes are lined with black deposits inside and coated with yellow and ochre-coloured deposits outside. Other tubes are filled or partially filled by black material. The tubes are variable in size (0.1–1.5 cm in diameter and up to 8 cm in length) and are irregularly scattered throughout the subsamples. Some tubes are closely spaced in a parallel fashion.

Five pieces from four samples were selected for macroscopic examination and preliminary mineralogical and chemical analysis. Four of the pieces (Cyp 78-12-38A-2, 38A-1-a, 40A-a and 40B) are relatively dense and consist mainly of sulphides. The fifth (Cyp 78-08-14A-1) is oxidised and less dense than the others. Subsample Cyp 78-12-40 B is elliptical in shape; the convex side is coated with dark, heavy sulphide aggregates and there are patches of greenish-yellow dust with a strong odour of sulphur. The concave surface of the specimen is coated by moderate yellowish brown and brownish ochre material. Small empty tubes (0.1–1 cm in diameter) are also seen. Specimen Cyp 78-12-40A-a is a nearly black material with circular tubes, one of which has its internal wall coated by a brass-yellow lamella. Concentric zonation of dark (outside) and white (inside) lamellae is exhibited by another adjacent tube. Specimen Cyp 78-12-38A-2 is dark grey with remnants of tubes and patches of yellowish-green, green and purple brown material similar to the other dark sulphide aggregates. Specimen Cyp 78-12-38A-1-a is a massive aggregate of black sulphide-rich material which is extremely friable and porous and gives off a strong odour of sulphur. It contains specks of yellowish-green material which

could represent a sulphur oxide compound. Subsample Cyp 78-08-14A-1 is a moderate brown to blackish red to ochre-coloured powdery material with abundant relicts of tubes, some of which are open and continuous across the specimen, while others are filled by a yellowish brown material. Sulphide material coats some of the walls of the empty tubes.

The mineralogy of the material was determined by X-ray diffraction after microscopic examination in reflected and transmitted light (Table 1). The ochre-coloured material consists mainly of amorphous iron-oxide. The oxides are reddish and yellow and are found in the interstices of the sulphide grains, resulting primarily from secondary alteration of the sulphides.

The sulphide phases consist mainly of sphalerite and pyrite with minor chalcopyrite and marcasite. The sulphides are represented by agglomerates of intimately associated, well-crystallised phases and amorphous material. The most common form encountered in the samples is an octahedron. Tetrahedra characteristic of sphalerite, cubes of pyrite, bipyramids, sphenoids characteristic of chalcopyrite, and tabular crystals with polysynthetic twins (probably of sphalerite) are also observed. Globular and reniform associations, probably consisting of chalcopyrite and pyrite, with anisotropic clay-size material are commonly associated with the well-crystallised sulphides.

The chemistry of the five specimens was determined qualitatively by X-ray fluorescence (XRF) spectrometry (dispersive) and quantitatively by atomic absorption spectrometry (Table 1). The XRF analyses show the presence of abundant zinc, iron, copper and sulphur and of lesser quantities of several other elements including cobalt, lead, silver and cadmium. The material used for atomic absorption analyses (100 mg to 1 g) should be reasonably representative of the subsamples which weigh from 19 to 91 g. The analyses show two principal modes: one zinc-rich (23–28.7%) and the other iron-rich (19.9–42.7%). Three specimens are copper-rich (2.2–6%) and we note the absence of manganese even as a minor element.

The subsamples can be divided into two major types according to their macroscopic features, mineralogy and chemistry: (1) the dark-coloured and porous, zinc, iron and copper sulphides in the form of sphalerite + marcasite, pyrite and chalcopyrite, with a skeleton made up of a white unidentified material; and (2) the fragile, pulverulent ochre-coloured material made up of amorphous iron oxides. The widespread occurrence of pure sulphur

Table 1 Mineralogy and chemistry of hydrothermal samples from 21° N on the East Pacific Rise (major and minor element content determined by X-ray fluorescence and atomic absorption spectrometry)

Subsample or specimen	Approx. size (cm)	Weight (g)	Microscopy Minerals	Microscopy Morphological features	X-ray diffraction Minerals	X-ray diffraction Peaks (Å) d(A)	Metal content (wt%) Fe	Metal content (wt%) Cu	Metal content (wt%) Zn	Other identified elements through XRF
CYP 78 12-40 B	6.5×4×4	90.7	Sphalerite Pyrite	Tabular, polysynthetic twins, octahedron Cubes with striation	Sphalerite Pyrite Chalcopyrite	3.12; 1.91 2.70; 2.42; 1.63 3.05	9	2.9	23	Co*·Pb*·Ag* Cd*·Mn*·Cl* S†·Ca*·K*
CYP 78 12-40 A-a	4×4×1	64.7	Sphalerite Amorphous silica	Octahedron, collomorph, banded Flaky	Sphalerite Pyrite Chalcopyrite (?)	3.13; 1.91 2.71; 2.42; 1.63 3.06 (?)	6.3	0.2	28.7	Co*·Pb*·Ag* Cd*·Mn*·Cl* K*·Si†·S†
CYP 78 12-38 A-2	4×4×2	26.5	Pyrite or chalcopyrite or sphalerite	Globular and collomorph, tetrahedron	Pyrite Chalcopyrite	3.13; 2.71; 1.63 3.06	29.6‡	6‡	non analysed	Co*·Cd*·Pb* Mn*·Zn*·Ca* K*·Cl*·S†
CYP 78 12-38 A-1-a	4×2×2	74.3	Pyrite Pyrite or . chalcopyrite or sphalerite	Cubes in lamellae, octahedron with striations Globular and collomorph	Pyrite Marcasite Chalcopyrite (?)	2.71; 2.42; 1.63 3.44; 2.71; 1.76 (3.04)?	14.9	2.2	0.0	Mn*·Cd*·Co* Pb*·Ag*·Zn* K*·S†
CYP 78 08-14 A-1	6×5×1.5	19	Iron oxides	Globular aggregates	Amorphous	Broad	42.7§	0.0	0.6	Mn*·Pb*·Cu* Ca†·Cd*·K* S†

*Few tens to few thousands p.p.m. †Few % to few tens of %. ‡ Analysed by XRF. § Red part of subsample CYP 78-08-14A-1.
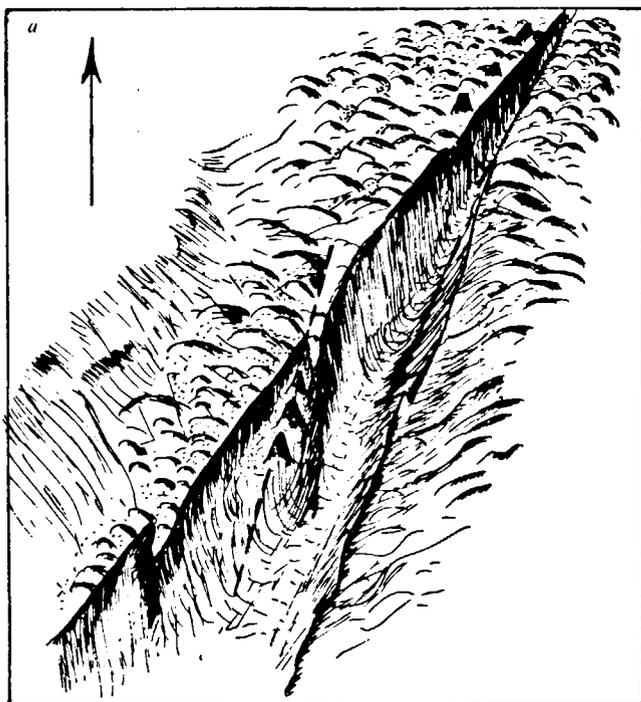
Fig. 2 *a*, Overall sketch of the 225° trending structural depression with a small gully or re-entrant trending 205° that crosses the east wall of the graben (dive CY 78-08). The width of the graben is about 20–30 m and narrows towards the SSW. The arrow points towards the south. *b*, Artist's view from CYANA's porthole of the site of sulphide ore edifices on the eastern flank of a structural depression (dive CY 78-08). The view is towards the south. The hornito-like edifices are aligned along 205 in a gully cutting across the graben. The spacing between 'hornitoes' is about 5 m. The small conelets associated with the vertical edifices are shown as well as the flows of hydrothermal material on the vertical scarp in the cul-de-sac of the small gully. All the sulphide material was sampled from the porous edifices.

on many of the subsamples suggests that the small yellow conelets and bright yellow crystal-like growths around them, which are associated with the larger variegated edifices on the sea floor, might represent massive concentrations of native sulphur.

The occurrence of sulphide mineralisations on the sea floor in an active tectonic region directly associated with an accreting plate margin can best be explained by a model in which the deposits formed within the discharge zone of a hydrothermal circulation system involving seawater as the convecting fluid[6,12]. A similar explanation has been put forward for the genesis of ophiolitic sulphide ore deposits on land, which share many common characteristics with the EPR deposits[6,9-17]. A typical example of the ophiolitic sulphide ores is found in Cyprus[6,10,12,13-15,17-20].

The Cyprus deposits occupy basin-like depressions in basalts and occur as irregular, elongate lenticles or lens-shaped bodies of massive sulphide ores (pyrite + chalcopyrite ± sphalerite ± marcasite with minor galena, pyrrhotite, gold and silver). Like the EPR deposits, which are also restricted to structural lows, they accumulated on the sea floor before the first sediments were deposited and in some deposits the ore is overlain by pillow lavas and sediments. An interval of 10^5 years has been tentatively proposed for the formation of the Cyprus ores[12]. The EPR deposits are adjacent to the main axial extrusion zone but there is direct evidence from the dives that lava can also be emplaced within the horst and graben tectonic zone so that burial of the deposits by off-axis volcanism is possible. We estimate the age of the EPR deposits to be $< 1-2 \times 10^4$ years using as a guide the fact that they occur on crust whose age is theoretically $1-2 \times 10^4$ years, based on spreading rate.

The Cyprus deposits can show alteration near the top to a geothitic material or to pyrite-bearing chemical sediments (ochres) enriched in silica and hydrated iron-oxides. The ochreous components of the EPR deposits are probably gossans and represent products of submarine weathering of the sulphide ores. The Cyprus deposits display prominent metal zoning with zinc-rich bodies lying deep in the Lower Pillow Lavas and larger copper-rich bodies at shallower levels in, or at the top of, the Upper Pillow Lavas. We have no evidence yet of whether or not there is metal zoning within the metre-scale sulphide cones of the East Pacific Rise. There are indications of some zoning at the scale of the samples. The sulphides on Cyprus exhibit primary breccia textures in the upper part and are massive in the lower part. Ore textures similar to the sponge-like texture of the EPR deposits have not been described in Cyprus or other Cyprus-type sites but the Cyprus ores are said to be very porous. The fragile tubular and heterogeneous texture of the EPR sulphides may not be preserved in the geological record or possibly they represent the equivalent of the upper breccias in Cyprus ores. Finally, the Cyprus ore deposits are separated by a mean distance of about 2.5 km in a direction perpendicular to the strike of the sheeted dikes and thus to the strike of the fossil spreading centre. The hydrothermal sulphur/sulphide sites of the EPR are separated by about 1 km in a direction transverse to the EPR axis.

Conclusions

Despite the differences in detail and in scale between the East Pacific Rise deposits and the Cyprus ores, there are enough general similarities in the type and style of metal concentration

to regard the EPR deposits as a modern analogue of the zinc-rich cupriferous massive sulphide deposits associated with ophiolite complexes. The EPR ore deposits, which have their primary features still preserved and which have been emplaced in a well defined geological setting directly associated with plate accretion, should shed a new light on the characteristics of, and genetic models for ophiolitic sulphide ore deposits such as found in Cyprus[6,10,12,13,15,17,20], Newfoundland[16], California[10], Turkey[10]. and Italy[9]. The EPR deposits further demonstrate that modern ocean floor sulphide deposits are not restricted to the initial stages of ocean rifting, as suggested by the Red Sea deposits.
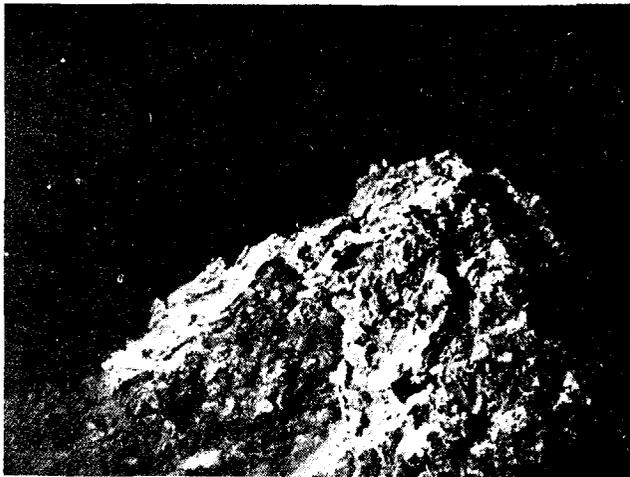
Fig. 3 Photograph of a variegated hornito-like edifice taken during dive CY 78-06. The diameter of the edifice is ~2 m. A second edifice can be seen in the background.

The metal-rich brines and muds that are found in the axial region of the Red Sea[21], or beneath the Salton Sea Trough[22] (a northwards extension of the Gulf of California) show iron-rich layers overlying a sulphide horizon with sphalerite and less abundant chalcopyrite, pyrite and marcasite. In contrast with the sulphide-rich, Mn-deficient EPR deposits, the other metalliferous deposits encountered in Mid-Ocean Ridge settings are essentially Fe–Mn concretions, Fe–Si rich clay material, and occasional pure MnO_2 deposits[23-26].

Mid-Ocean Ridge sulphides and ferromanganese deposits attributed to a hydrothermal origin are all chemical precipitates which form at the basalt–seawater interface when hot seawater solution, laden with Fe, Mn and other metals stripped at 'high temperature' (see refs 8, 10, 12) from the ocean crust, debouches onto the ocean floor. Sulphides, such as the EPR deposits, can be preserved either if the bottom waters are anoxic or if the sulphide deposits become rapidly buried under sediments or lavas. The ochres, such as those of the East Pacific Rise, result from the oxidation of the iron sulphide. The Fe–Mn deposits (umbers) encountered in the FAMOUS area, in the Galapagos and in the Gulf of Aden may be the product of a weaker flow of the convecting fluid although many other factors (such as temperature, redox conditions, and fugacity) may be critical. Sulphides in such settings would be deposited subsurface. Indeed, this is suggested in the FAMOUS area by the presence of pyrite in the deposits near the vents[24]. It is not clear whether the flow rate of ocean floor convective systems depends primarily on the spreading rate but it seems from the contrast between the RITA and Galapagos areas and the FAMOUS area that hydrothermal activity is more prevalent in higher spreading-rate environments.

It will be a test of ingenuity to assess the surface distribution of metal-rich deposits on the Mid-Ocean Ridge, let alone their distribution at depth. Furthermore, there is the problem that unusual circumstances might be required for their preservation. However, the discovery in the RITA area shows that metal deposition is not restricted to young oceans and that the axial zones of medium-fast (and perhaps fast) ridges are not only factories of oceanic crust and lithosphere but also plants for the concentration of heavy metals through leaching of the oceanic crust in zones of intense hydrothermal activity and deposition on the basaltic floor. Indeed, the EPR deposits throw a fresh light on the whole question of the concentration of metal deposits of the oceanic crust.

In the future one might envision that submarine metalliferous ore deposits are distributed in quasi-continuous, linear strips several thousand kilometres in length along the axis of the fast-spreading East Pacific Rise and south-east branch of the Mid-Indian Ocean Ridge. Certainly we will have to re-examine our estimates of the mineral resources which lie within reach on top of the bare crust of the Mid-Ocean Ridge. Slow ridges seem so far to yield only Fe and Mn-rich deposits in fracture-zone terrain; thus, the sites of priority interest for further sulphide ore exploration are the fast as well as super-fast ridges.

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