

Sea-floor hydrothermal mineralization from the Mt. Jourdanne, Southwest Indian Ridge

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shipboard scientific party⁸¹; INDOYO diving cruise (MODE-98 leg 3)^{*3}

Although hydrothermal activity is well documented from many fields on most mid-ocean ridges, no hydrothermally mineralized area was known from the ultraslow spreading Southwest Indian Ridge since October 1998 when *RV Yokosuka* with the submersible *Shinkai 6500* investigated in this area. This newly discovered massive sulfide field is located near 27°51S/63°56E in the 11th segment west of the Rodriguez Triple Junction.

Hydrothermal precipitates were found in a water depth of about 2,960 m close to the top of a neovolcanic ridge, informally referred to as Mount Jourdanne. Massive sulfides occur on the ocean floor as smaller mounds with an average size of about 5 m³. The surface is often weathered and shows therefore a typical reddish to brownish crust. Besides mound-like hydrothermal structures small tube-like chimneys were observed on the ocean floor. These chimney edifices rise for approximately 40 to 50 cm from the floor and are less than 10 cm in diameter. All of the hydrothermal features and structures were spatially related to an E-W trending graben or to smaller fissures and cracks.

Furthermore the summit of Mt. Jourdanne is characterized by pillow basalts, tubes and basaltic fragments as well as by basaltic sheet flows including folded, platy and scrambled textures. Extrusive rock assemblages are partly covered by a thin sediment layer.

Key words : Southwest Indian Ridge, hydrothermalism, massive sulfide chimneys

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1. Introduction

In the past, a number of diving programs on massive sulfide deposits on the modern seafloor were concentrated on the ridges in the Pacific and in the Atlantic Ocean. The investigations on marine sulfide deposits and/or high temperature venting fields were carried out along the major rift systems like the East Pacific Rise and the Mid-Atlantic Ridge (Francheteau et al., 1981; Alt, 1987; Rona et al., 1993). Subsequent exploration efforts on hydrothermalism and metal enrichments on the ocean floor were expanded to backarc basins like in the Woodlark, Lau and Fiji Basin (Binns et al., 1993, Fouquet et al., 1993).

In order to locate hydrothermal vent or mineral fields in the southern Indian Ocean first submersible investigations along the Southwest Indian Ridge were carried out in October 1998 during the INDOYO cruise with *R/V Yokosuka/submersible Shinkai 6500*. The dives were planned and performed based on the detailed TOBI images and on transmission anomalies obtained from the previous EDUL and FUJI cruises (Mevel et al., 1997, 1998; German et al., 1998).

In the Central Indian Ocean three different ridge systems meet at the Rodriguez Triple Junction at 25°30'S/70°06'E, the intermediate spreading Central and the Southeast Indian Ridges and the ultraslow spreading Southwest Indian Ridge. The Southwest Indian Ridge (SWIR), separating the African and Antarctic plates, diverges with a half rate of 0.7 to 0.8 cm/a in a N-S direction. Caused by the extremely slow spreading rate the SWIR is characterized by a very rough and deep axial valley morphology with water depths of more than 6000 m; the rift graben is cut by a series of more or less N-S running transform faults like the Gallieni, the Atlantis II and the Melville fracture zones.

According to Dick (1989) such major fracture zones at ultraslow spreading ridges are marked by valleys with a depth between 1 to 6 km and are between 15 to 40 km wide measured from the top of the valley walls. Mantle material like serpentinized peridotites is occasionally exposed in the vicinity of fracture zones. Gabbros as well as basaltic rocks were also sampled along larger fault zones.

An accumulation of small seamounts, only several of tens or hundreds of meters high, can be observed between the Atlantis II and the Melville fracture zone (Mendel and Sauter, 1997). Besides the seamounts and volcanic cones several neovolcanic ridges can be observed between the Melville fracture zone and the Rodriguez Triple Junction. Such neovolcanic structures can be up to 1000 m high and extend often for several tens of km; these areas are generally considered to be ideal for hydrothermal activity and the formation of massive sulfide fields, because they have both, volcanic and tectonic activity, which are of importance because of the heat source and of the pathways for fluid convection, respectively.

2. Geological setting

A well defined neovolcanic ridge, referred to as Mt. Jourdanne, is located in the 11th segment of the SWIR west of the Rodriguez Triple Junction (central coordinates 27°51'S/63°56'E). The approximately E-W running magmatic construction shows a hummocky topography and is propagating to the west into seemingly tectonized extrusives and a partly sedimented area.

The summit of Mt. Jourdanne is characterized by a series of extrusive units, principally alternating sheet flows, pillow and lobate flows comprise the main outcrop of the eastern part of the axial volcanic ridge (AVR). Sheet flow patterns predominate on the shallowly dipping flanks to the north, whereas pillow mounds and basaltic rock fragments are more dominant on the uppermost, shallower portion of the summit. Widely sedimented areas were also observed, but the sediment coverage is usually very small.

The top of Mt. Jourdanne is marked by an at least 10 m wide and approximately 5 m deep graben. This prominent E-W trending tectonic feature is accompanied by several smaller fissures and faults running both parallel and perpendicular to the graben. Those fissures are often a few tens of cm wide with a lateral extension of several meters. Therewith the scale of the tectonism varies from 10-20 m wide fault scarps to clusters of small (less than 20 cm) fractures.

Extinct hydrothermal activity was detected at the northern edge of the main graben at a water depth of about

2941 m. The newly discovered hydrothermal site at Mt. Jourdanne is the first known sulfide deposit along the ultraslow spreading SWIR.

Within an area of approximately 0.5 km² several hydrothermal sites were found. Hydrothermalism is strictly related to fault structures, either to the E-W trending graben or to smaller fissures running both parallel and perpendicular to the strike direction of the neovolcanic ridge (Fig. 1). Hydrothermal products occur as mound-like features with an average size of about 5 m³; the mounds are usually cracked and highly weathered at the surface. Larger chimney edifices are seldom observed in the vicinity of these mounds. However, extraordinary small tube-like chimneys were noticed in a slightly more sedimented area within the graben. Upstanding chimneys were rarely recognizable, most of them were broken and

laid on the ocean floor. Overall approximately six tube-like chimneys were found and two were sampled.

Although the sample material look quite fresh no indications for activity like shimmering water or chemical anomalies in the water column were detectable. Neither biological features nor any remnant clam shells were observed in the entire area of the summit of Mt. Jourdanne. This might indicate that hydrothermal activity has ceased possibly a few hundred years ago; the residence time for vent biota is maximal 300 years (Kennish et al. 1997).

3. Sampling and analytical methods

Ocean floor observations were carried out to identify the geological setting as well as structural features; the sampling was realized with the submersible *Shinkai 6500* during the INDOYO cruise.

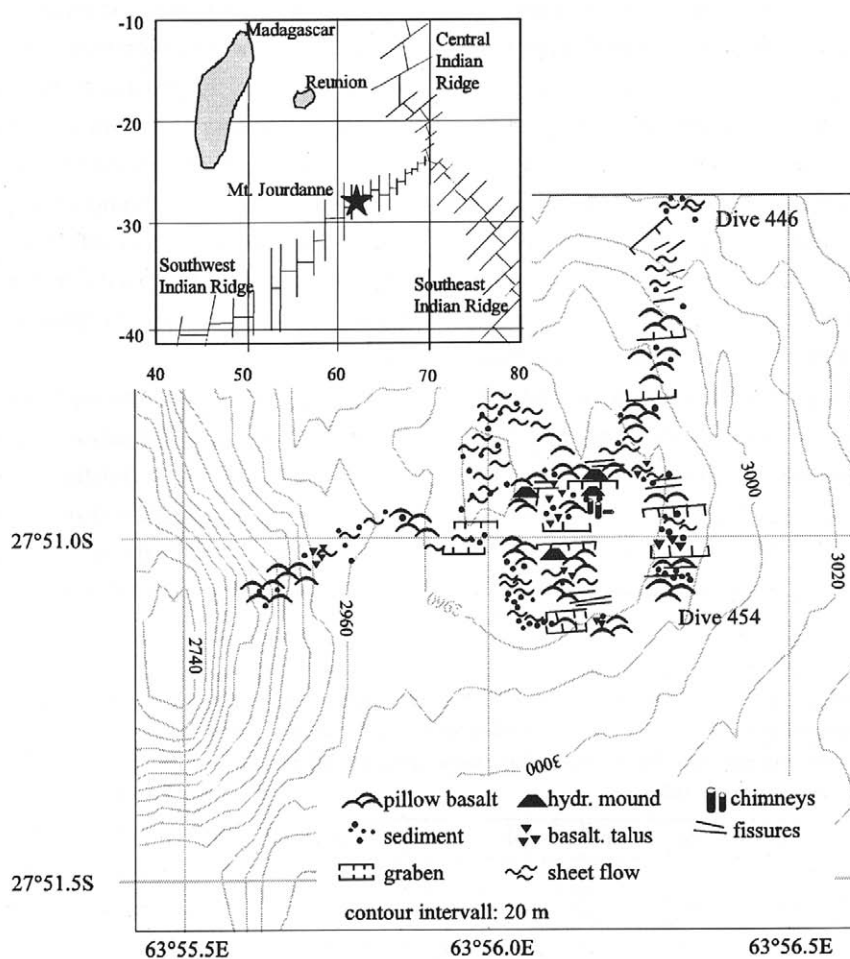


Fig. 1 Inset gives the general location of the study area. Bathymetric map shows a part of the summit of Mt. Jourdanne. Both diving traces as well as the main geological features were illustrated in the map.

Polished sections were prepared for petrographic examination. Major and minor element compositions of bulk ore material were determined by optical emission inductively coupled plasma (ICP-OES) and atomic absorption spectrometry (AAS), the detection limit varies between 5 ppm and 50 ppm, depending on the element quantified and the analytical method employed. Microchemical analyses of individual mineral aggregates, aligned along profiles traversing slabs of smoker fragments (Cu-Fe-S sulfide series) were carried out with an energy dispersive X-ray (EDX) device combined with a scanning electron microscope (SEM). The limit of detection is about 1 wt.% for EDX measurements.

4. Mineralogical and chemical composition of sulfide samples

Hydrothermal products consist of clastic gangue ores (almost completely sulfide impregnated basalts), chimney fragments and tube-like chimneys. In this paper we present the first results on the last two sample groups.

4.1 Macroscopic and microscopic description

First of all both sample groups are described macroscopically; microscopic studies will be demonstrated to distinguish specific mineral textures.

4.2 Sulfide fragments

The sulfide fragments were examined macroscopically for mineral abundances and mineral zonation. Most sulfide specimen show a well preserved layering from more iron-sulfide dominated portions to lead-, copper- and particularly zinc-sulfide-rich zones. Samples vary caused by the different mineralogical compositions between a brownish to a slightly yellowish or to a more grayish col-

oration, respectively. Samples are partly encrusted by a thin rusty-brownish jarosite layer. In addition to the ore minerals high amounts of silica were detected in sulfide samples (Table 1). Commonly amorphous silica fills open pore spaces, but in addition silica forms filaments and drop-like or globular structures on outer sample portions.

Samples #454 No 2a and b mainly consist of iron-sulfides, whereas pyrrhotite is widely replaced by pyrite and to a minor amount also by marcasite, only skeletal relicts of pyrrhotite are left. In marginal portions marcasite forms acicular crystals, but towards inner portions the size of individual crystals decreases so that marcasite intergrown with fine grained pyrite often forms chain- or band-like aggregates. Collomorphic pyrites were also observed in some places. In the inner part of samples remnants of sphalerite can be identified. Sphalerite often occurs together with chalcopyrite, whereas chalcopyrite replaces sphalerite either from the outside to the inside or contrariwise. Typical disease pattern were observed in sphalerite minerals in more marginal portions of the sample. Occasionally smaller relicts of sphalerite are replaced by covellite. Amorphous silica seals to a large extent open pore spaces especially in outer sample portions. Seldom small barite crystals can be identified in vugs, which are also subsequently filled by silica.

Sample #454 No 3 shows small vent orifices lined by a thin chalcopyrite and/or sphalerite rim. Sphalerite contains occasional small, mostly dust-like inclusions of galenite. Dust-like inclusions of chalcopyrite in sphalerite are seldom, whereas triangular inclusions of chalcopyrite are more often detectable. Collomorphic sphalerite,

Table 1 Preliminary results on the mineral content of sulfidic precipitates from Mt. Jourdanne as well as the relative mineral abundances: (++) very often, (+) often, (+-) less frequently; (-) seldom, (-) traces; (x) not observed. Abbreviations: pyrrhotite, po; marcasite, mc; pyrite, py; sphalerite, sph; galenite, ga; chalcopyrite, cp; cubanite, cb; covellite, cv; barite, ba; jarosite, ja; silica, si

	po	mc	py	sph	ga	cp	cb	cv	ba	ja	si
chimney fragments											
#454No2a, b	(-)	(+)	(++)	(+-)	(x)	(-)	(x)	(--)	(-)	(-)	(+-)
#454No3	(x)	(+-)	(+-)	(++)	(+-)	(-)	(-)	(x)	(-)	(-)	(+-)
#454No6	(x)	(+-)	(+-)	(++)	(+)	(+-)	(x)	(--)	(-)	(-)	(+-)
tube-like chimneys											
#454No7, 8	(x)	(+-)	(+-)	(++)	(-)	(+-)	(+)	(--)	(--)	(-)	(--)

which is probably of low temperature origin can be identified as well. Iron-sulfides are only subordinated in this sample, nevertheless framboidal as well as collomorphic pyrite can be identified in marginal sample portions. Former fluid pathways are often clocked by silica and contain occasionally platy barite crystals.

The upper portion of sample #454 No 6 is dominated by a massive sphalerite layer. The collomorphic sphalerite contains spot-like inclusions of chalcopyrite as well as frequently dust-like inclusions of galenite. In addition galenite forms also cubic crystals towards the interior. Pyrite as well as marcasite are seldom observed in this sample. Besides ore minerals the sample contains occasionally barite crystals, whereas open pore spaces are again sealed by amorphous silica.

4.3 Chimney tubes

The chimneys have a tube-like shape and are up to 30 cm high and approximately 10 cm wide in diameter. Chimneys have a narrow, non-filled feeder channel in their center, but they can contain small barite crystals. Barites can also be identified in vugs in outer portions of chimney walls, although the chimneys are particularly encrusted by a thin iron-manganese crust. Chimneys are characterized by a dark grayish to blackish coloration, which indicates the dominance of sphalerite. Copper minerals as well as some small pyrite cubes were also observed, whereas silica seems to be almost absent in sulfide tubes and might explain the fragility of the samples.

Samples #454 No 7, 8 are characterized by a feeder channel with a mineral zonation from the inner portion

Table 2 Preliminary results on the major, minor and trace element composition (bulk analyses) of hydrothermal precipitates Mt. Jourdanne. Element compositions of ore material were determined by ICP-OES and AAS.

	Cu wt.%	Fe	Zn	As	Pb	Sb ppm	Cd	Ni	Co	Ag	Au
chimney fragments											
#454No2 a	<0.1	20.6	<0.1	0.8	0.05	453	9	5	<1	77	4
#454No2 b	<0.1	18.8	0.5	0.6	0.02	420	8	12	3	80	-
#454No3	4.5	20.3	16.9	0.1	0.85	-	1104	10	8	363	0.7
#454No6	<0.1	11.1	16.7	>1.0	>3.0	425	400	5	9	997	>5
tube-like chimneys											
#454No7	3.8	16.0	31.5	<0.1	>1.0	908	1680	6	102	<1000	>5
#454No8	5.1	15.8	36.2	0.2	0.6	-	2418	2	195	430	3

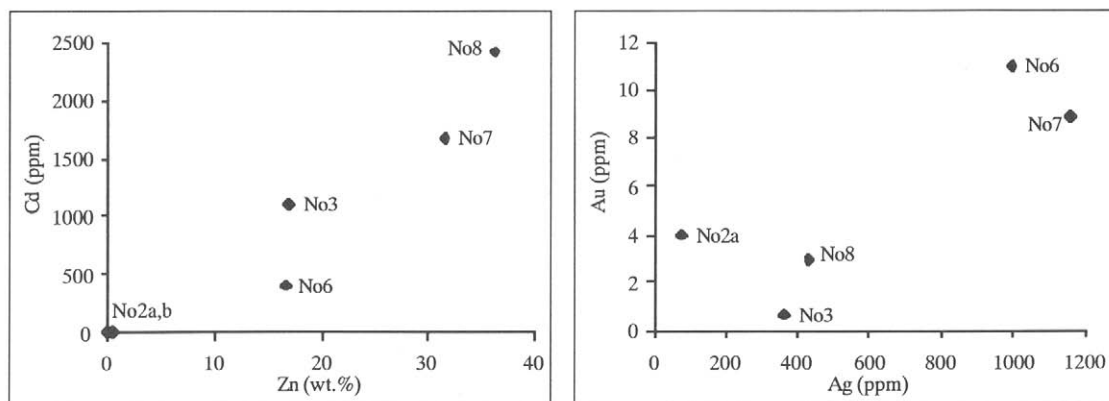


Fig. 2 Diagram showing the correlation between Cd and Zn as well as between Au and Ag for the different sulfide fragments and chimneys, respectively.

towards the outer chimney wall as follows: sphalerite is the dominant mineral phase particularly in inner chimney portions. Sphalerite often contains small, dust-like inclusions of chalcopyrite. Besides dust-like inclusions chalcopyrite forms larger crystals, whereas the core contains typical exsolution lamellas of cubanite. Galenite is seldom observed in inner portions of chimney samples, whereas iron-sulfides such as pyrite and marcasite can be identified in outer chimney portions (Table 1).

4.4 Chemical composition

To identify the characteristic trace element composition of the two different sample groups described here, chemical analyses were carried out.

Sulfide fragments are, in general, characterized by low copper, but high zinc concentrations. Caused by the high amount of sphalerite the samples contain also high Cd concentrations (Fig. 2). The samples hold also high As, Sb and Pb concentrations, which might indicate the mobilization of these elements under low temperature conditions during the late or even the waning stage of hydrothermal activity. Moreover the Zn content of the sulfide

samples seems to control the Ag and Au concentration, whereas the Ag content in zinc-poor samples amounts to 80 ppm, the Ag content in zinc-rich sulfides can be higher than 900 ppm. The positive relation between the Zn and the Au concentration is less obvious, but zinc-rich samples contain up to 5 ppm Au (Table 2).

Microchemical studies were carried out on individual Cu-Fe-minerals to examine their composition (Fig. 3). The analyses confirm the replacement of pyrrhotite by pyrite, which can be seen in data points plotting between the ideal pyrite and pyrrhotite composition, respectively.

As described above chalcopyrite grains are enriched in Fe and contain therefore exsolution lamellas of cubanite, which can be seen in the ternary diagram as well. Bornite and covellite were not detected so far.

5. Discussion and conclusions

Exploration and investigations on hydrothermal seafloor mineralizations have mainly been focused on spreading ridges in the Pacific and in the Atlantic, so far, because it was assumed that only fast to intermediate spreading ridges may generate such high temperature events.

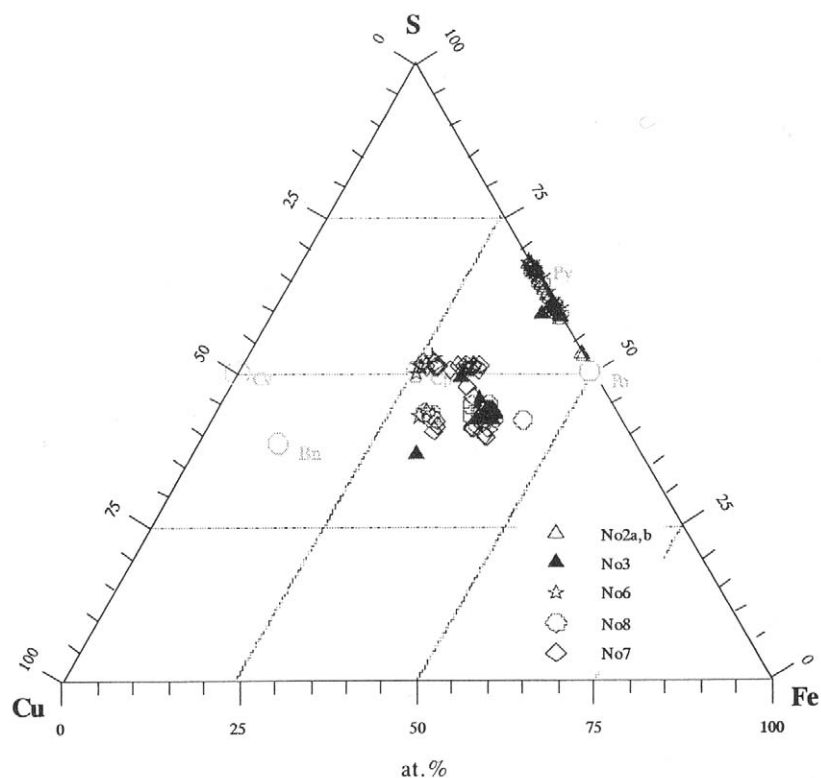


Fig. 3 Cu-Fe-S ternary diagram showing the composition of dominant mineral phases. Idealized mineral compositions shown are: pyrite (Py), covellite (Cv), bornite (Bn), chalcopyrite (Cp), pyrrhotite (Po). Compositions of selected minerals were determined by SEM-EDX.

Meanwhile it is quite well known that high temperature massive sulfide chimneys also develop even at slow spreading ridges (Rona et al. 1986).

Hydrothermal activity was not documented from the ultraslow spreading Southwest Indian Ridge till fall 1998 when *RV Yokosuka* investigated in this area (Fujimoto et al. 1999). It is known that the spreading rate influences the location and extent of sulfide deposits on mid-ocean ridges as well as the composition of the source rock. Therefore the discovery of massive sulfides from the Southwest Indian Ridge will now fill a major gap in the understanding of hydrothermal processes along ultraslow spreading ridges.

In the main the sulfide samples from Mt. Jourdanne are comparable to those from other mid-ocean ridge deposits, but nevertheless there are some substantial differences:

(1) as far as we know such extremely small and thin tube-like chimney samples were not described from any other location. The exceptional appearance of the sulfide structures might point to different transport velocity or fluid flow rates. Another important aspect might be a different range/distance of the pathway for the uprising hydrothermal fluid or the residence time of the fluid within the pathway for example.

(2) the occurrence of galenite in sulfide samples from a sediment-starved ridge is another interesting feature. Usually galenite can be determined in sulfide samples from a highly sedimented ridge like the Juan de Fuca ridge, or likewise in backarc basins, where we have usually a larger sediment coverage as well as a more alkaline source rock.

(3) sulfide samples from the Mt. Jourdanne contain relatively high noble metal concentrations, which seems to be related to the high amount of sphalerite.

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