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Massive sulfides of Mount Jourdanne along the super-slow spreading Southwest Indian Ridge and their genesis

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ABSTRACT

Modern massive sulfide deposits are known to occur in diverse tectonic settings and it is generally expected that hydrothermal deposits of similar geological settings shall have more or less similar mineralogical and geochemical signatures. However, the Mount Jourdanne sulfide deposits along the super-slow spreading Southwest Indian Ridge deviate from this common concept. These sulfide precipitates are Zn-rich (up to 35 wt.%) and are characterized by high concentrations of Pb (≤3.5 wt.%), As (≤1.1 wt.%), Ag (≤0.12 wt.%), Au (≤11 ppm), Sb (≤967 ppm), and Cd (≤0.2 wt.%) which are unusual for a modern sediment-free mid-oceanic ridge system. Therefore, we have reinvestigated the sulfide samples collected during the INDOYO cruise in 1998, in order to explain their unusual mineralogy and geochemical composition. The sulfide samples are polymetallic and are classified as: a) chimneys, b) mounds, and c) hydrothermal breccias. The chimneys are small tube-like symmetrical bodies (30–40 cm high; ~10 cm diameter) and consist mainly of sphalerite and less chalcopyrite, set in a matrix of late amorphous silica. The inner wall shows a late-stage colloform sphalerite containing co-precipitates of galena and/or Pb–As sulfosalts. In contrast, the mound samples are dominated either by Fe-sulfides (pyrite) or by a mixture of pyrite and chalcopyrite with less sphalerite, pyrrhotite, amorphous silica and barite. Both, the chimney and mound samples, are characterized by layering and mineral zonation. The hydrothermal breccias are highly altered and mineralogically heterogeneous. They consist of silicified basaltic material that are impregnated with sulfides and contain cm-sized chimney fragments within a matrix of low-temperature minerals such as sphalerite and pyrite. The latter fragments mainly consist of chalcopyrite with isocubanite lamellae. In addition, these breccias contain late-stage realgar, boulangerite, galena, Pb–As sulfosalts and barite that are mostly confined to vugs or fractures. At least five mineralogical associations are distinguished that indicate different thermal episodes ranging from black smoker mineralization conditions to cessation of the hydrothermal activity. Based on the mineralogical associations and established literature in this regard, it is inferred that the mineralization at Mt. Jourdanne occurred mainly in three temperature domains. Above 300 °C, the chalcopyrite (with isocubanite)–pyrrhotite association formed whereas the sphalerite dominated assemblage with much less chalcopyrite and pyrite formed around and below 300 °C. The late-stage mineralization (below 200 °C) contains colloform sphalerite, galena, Pb–As sulfosalts, realgar and barite. The unusual mineralogy and trace element chemistry for this modern VHMS deposit could be explained assuming hydrothermal leaching of some felsic differentiates underneath the basaltic cover and subsequent zone refining processes.

1. Introduction

In the last three decades, numerous research programs focused on submarine modern massive sulfide deposits at the mid-ocean ridge systems. Investigations of marine sulfide deposits and hydrothermal vent fields were carried out along most major rift systems like the East Pacific Rise and the Mid-Atlantic Ridge (Alt et al., 1987; Francheteau and Ballard, 1983; Rona et al., 1986), and the Central Indian Ridge (Herzig and Plüger, 1988), and were later extended to back-arc basins (Okinawa Trough, Halbach et al., 1989; Woodlark Basin, Binns et al., 1993; and Lau Basin, Fouquet et al., 1993a). Extremely slow-spreading ridges like the Southwest Indian Ridge and the Gakkel Ridge have also been investigated (Baker et al., 2004; Edmonds et al., 2003; Fujimoto et al., 1999; German et al., 1998). From these studies, various genetic models were developed. It has been demonstrated that the spreading rate influences

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the location, extent and morphological features of such sulfide- and oxide-dominated deposits (Fouquet et al., 1993b; Lalou et al., 1995; Rona et al., 1984, 1993). Compared to axial deposits on fast spreading ridges in the northeastern Pacific, hydrothermal activity is more durable on slow to intermediate spreading ridges. Caused by slow spreading rates, fissures and faults are expected to be preserved for a longer time period, so that hydrothermal fluid pathways can exist for several thousands of years which also explain the larger size of deposits at ridges with slow spreading rates (Lalou et al., 1995). The accumulation of massive sulfides, often exposed as hydrothermal mounds, is caused by recurring heat-flux and fluid-flow and several generations of mineral formation (Hannington et al., 1995a; Herzig and Hannington, 1995). In the Central Indian Ocean, the intermediate-spreading Central Indian Ridge (CIR), the Southeast Indian Ridge (SEIR), and the super-slow spreading Southwest Indian Ridge (SWIR) meet at the Rodriguez Triple Junction (RTJ: 25°30′S/70°06′E; Fig. 1). Investigations of hydrothermal activity along the southern CIR started with the GEMINO program in 1983 (Herzig and Plüger, 1988; Plüger et al., 1990). During these and following campaigns, hydrocast stations as well as ocean floor mapping and hard rock sampling were carried out in order to detect hydrothermal plumes and/or massive sulfide deposits (Gamo et al., 2001; Halbach et al., 1998; Jian et al., 2008; Kumagai et al., 2008). It was possible to locate three inactive mineralized areas together known as the MESO Mineral Zone in the 4th segment (counted from the RTJ) of the CIR (Halbach et al., 1998). Subsequently, two active hydrothermal vent sites were also discovered in the CIR; one in the 1st segment (the Kairei Field, Gamo et al., 2001) and another in the 3rd segment (the Edmond Field, Van Dover et al., 2001). In the SEIR, only hydrothermal plume activities have been reported (Banerjee and Ray, 2003; Scheirer et al., 1998; Wang et al., 2011). The SWIR separating the African and the Antarctic plates that diverges with a half rate of 0.7 to 0.8 cm/yr in a N–S direction was once considered to be devoid of hydrothermal activity due to its low thermal budget (Baker et al., 1996). The first indirect evidence for the presence of hydrothermal venting, from water-column anomalies overlying the eastern SWIR, was obtained in 1997 (German et al., 1998). To locate hydrothermal vents or sulfidic mineralizations along the super-slow spreading SWIR, first submersible investigations were carried out in 1998 during the INDOYO cruise with *RV Yokosuka*/*submersible Shinkai 6500*. Highly tectonized areas, which are deemed to be favorable for hydrothermal activity, were targeted during this cruise (Fujimoto et al., 1999). An extinct hydrothermal system was detected at the northern edge of a graben structure at a water depth of about 2940 m. This hydrothermal site at 27°51′S/63°56′E in the 11th segment of SWIR is known as the Mt. Jourdanne deposit (Münch et al., 2000). In addition, hydrothermal fields have also been reported from SWIR within 10°–16°E (Bach et al., 2002) and 50°–70°E (German, 2003). Surprisingly the first active hydrothermal vents from an ultraslow-spreading ridge were discovered from SWIR near 49°E in 2007 (Tao et al., 2007, 2012). The mineralogy and chemistry of the chimney samples from this newly discovered site have been studied to some extent (Tao et al., 2011; Ye et al., 2012). The Mt. Jourdanne massive sulfides were investigated by Münch et al. (2001) and age data indicated hydrothermal activity between 70,000 and 13,000 years ago. However, the mineralogical complexities of the samples were not addressed properly and no satisfactory explanation was provided as to why these massive sulfides are so different with respect to their mineralogy and chemistry when compared to sulfide samples from similar geological or tectonic settings. Therefore, the sulfide samples of Mt. Jourdanne that were housed in the Department for Economic and Environmental Geology of Freie Universität — Berlin were reinvestigated and here we present a detailed account of the mineralogy and chemistry of these sulfides and discuss the genesis of the deposit to explain the unusual mineralogical and geochemical features of these sulfides that are uncommon for a modern sediment-starved mid-oceanic ridge system.

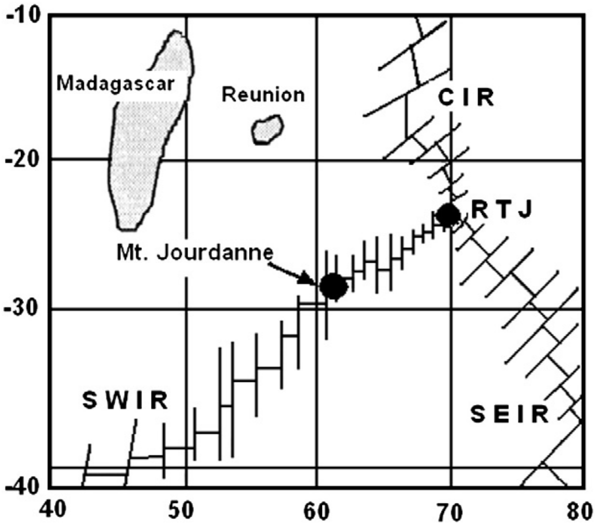

Fig. 1. Sketch map showing the three ridge systems in Indian Ocean: Central Indian Ridge (CIR), Southeast Indian Ridge (SEIR), Southwest Indian Ridge (SWIR) meeting at Rodriguez Triple Junction (RTJ) and the location of Mt. Jourdanne in SWIR.

2. Geological setting

Consistent with the extremely slow-spreading rate, the SWIR shows very rough and deep axial valley morphology with water depths sometimes greater than 5000 m (Mendel et al., 1997). The valley is cut by a series of almost N–S running transform faults like the Atlantis II and the Melville Fracture Zones. These fracture zones are the result of the lateral extension of the ridge, since the SWIR widened to more than 1000 km E–W for the last 44 Ma (Royer et al., 1988). Mantle material (serpentinised peridotite) is occasionally exposed within the fracture zones in addition to outcropping gabbros and basaltic rocks. A cluster of small seamounts (several tens or hundreds of meters high) occur between the Atlantis II and the Melville Fracture Zone (Mendel and Sauter, 1997). In addition to seamounts, several larger neovolcanic ridges occur between the Melville Fracture Zone and the RTJ. Such neovolcanic structures are few hundreds of meters high and have a lateral extent of tens of kilometers. Between the Melville Fracture Zone in the southwest and RTJ in the northeast occurs an axial volcanic ridge (AVR) near 27°51′S/63°56′E which is referred to as Mt. Jourdanne (located in the 11th segment of the SWIR). According to Mendel and Sauter (1997), segment 11 has an hourglass shape that extends more than 40 km, and is bounded to the east and west by non-transform discontinuities. The approximately W–E running volcanic structure has a lenticular shape and extends for several kilometers along the rift axis and is ~300 m high with the peak reaching a minimum water depth of about 2740 m (Fig. 2). Mt. Jourdanne shows a hummocky topography in the TOBI image and is propagating to the west into tectonized extrusives and a partly sedimented area (Mevel et al., 1998; Searle and Bralee, 2002). The summit of the mount is characterized by a series of extrusive units, principally alternating sheet flows, lobate flows, tubes and pillow basalts, which comprise the main outcrop of the northeastern part of the AVR. Sheet flow patterns predominate on the smoothly dipping flanks to the north, whereas pillow mounds and basaltic rock fragments are more dominant on the uppermost plateau of the summit. The rocks do not appear fresh, but rather slightly weathered or coated with a thin oxidic crust. Sheet flow units show a wide variety of surface features such as folded, draped, shredded and fragmented textures, indicating different lava viscosities. Lava surfaces are partly covered by a thin unconsolidated sediment layer. Although wider sedimented areas were observed, the sediment thickness is generally less than 10 cm. The sediment has a uniform pale cream color, except in hydrothermal influenced areas, where the sediment is whitish, reddish, brownish or blackish due to oxidized particles and sulfide fragments (Münch et al., 2001).