Ore Geology Reviews 76 (2016) 108–121

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

# Metallogenic information extraction and quantitative prediction process of seafloor massive sulfide resources in the Southwest Indian Ocean

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ARTICLE INFO

*Article history:*
Received 24 August 2015
Received in revised form 16 January 2016
Accepted 22 January 2016
Available online 23 January 2016

*Keywords:*
Quantitative prediction
Metallogenic information extraction
Weights-of-evidence
Seafloor massive sulfides
Southwest Indian Ridge

ABSTRACT

Seafloor massive sulfide (SMS) deposits have significant development potential. In 2011, the China Ocean Mineral Resources Research and Development Association (COMRA) and International Seabed Authority (ISA) signed a contract to explore a 10 000 km$^2$ region of the seafloor along the Southwest Indian Ridge (SWIR) containing hydrothermal sulfides. As regulated by the contract, China will have to relinquish 50% and 75% of the contract area within 8 and 10 years, respectively. However, exploration for seafloor hydrothermal sulfide deposits in China remains in the initial stage. Based on quantitative prediction theory and the status of exploration for SMS, we assemble factors related to the deposits in terms of topography, geology, geophysics, and several other related aspects along the SWIR and extract the most favorable information to establish a prospecting prediction model for SMS. By employing the weights-of-evidence method, we obtain a weighting for each prediction factor and thereby obtain a posterior probability map for the SWIR. The prediction result suggests that the central region of the SWIR has the highest posterior probability, i.e., it is the most prospective for the formation of hydrothermal vents and related SMS. Known hydrothermal areas such as Mt. Jourdanne, area A and 10°E–16°E are all located in the regions with high posterior probability values. The Chinese contract area (47°–51°E) has the highest posterior probability value and thus can be selected as a reserved region for additional exploration. By narrowing the exploration area and improving exploration accuracy, the predictions made will provide a focus for further exploration of seafloor hydrothermal sulfide resources.



## 1. Introduction

The Southwest Indian Ridge (SWIR), which is representative of super-slow-spreading mid-ocean ridges, is characterized by an oblique spreading direction and non-transform discontinuities (NTDs). In 1997, scientists on the "Fuji" voyage found six hydrothermal anomalies in the eastern region of the SWIR. In 1998, the Mt. Jourdanne hydrothermal field was the first seafloor massive sulfide (SMS) deposit to be discovered on the SWIR (German et al., 1998; Fujimoto et al., 1999). Since then, the SWIR has become one of the hotspots of hydrothermal sulfide resource investigations because of its unique characteristics in the global mid-ocean ridge system. In 2007, Segments I and II of China's Voyage 19 identified the first region of hydrothermal activity in the Southwest Indian Ocean and obtained sulfides, basalt, and biological samples that confirmed the inference that there are areas of hydrothermal activity along super-slow spreading ridges. Since then, China has investigated eight segments during four voyages in the SWIR to identify hydrothermal activities and as a direct result has discovered eight new hydrothermal areas. China submitted an application to explore a 10 000 km$^2$ region of the Southwest Indian Ridge containing polymetallic sulfides, which was subsequently approved by the International Seabed Authority at their 17th meeting on July 19, 2011. As regulated by the contract, only 25% of the contract area will be retained in 2021 (Tao et al., 2004; Tao, 2011; Tao et al., 2014). However, the survey for SMS deposits is still in the general exploration stage both at home and abroad, and the exploration process in China has just started. The question of how to explore the seafloor hydrothermal sulfides both rapidly and precisely has become a top priority.

Compared with the achievements of surveys that have assessed sulfide resources on land, the amount of research of seafloor sulfide resources is extremely low because of the limitations of natural geographical conditions and technical methods. Because some traditional geological surveying methods are not applicable for submarine resources, performing metallogenic prediction work to assess prospective targets prior to a survey is currently important (Ren et al., 2015). This paper uses the weights-of-evidence method to carry out comprehensive metallogenic prognosis research of seafloor sulfides in the Southwest Indian Ridge using multivariate information. With guidance from the metallogenic law, metallogenic prediction theory (Zhao et al., 2006)

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http://dx.doi.org/10.1016/j.oregeorev.2016.01.008
0169-1368/

and comprehensive mineral information evaluation theory (Wang et al., 2000), we have collected extensive datasets of geological, geophysical and other related information and assess these data to determine prospective targets that possess substantial ore potential. The results will provide a basis for the exploration of SMS in the SWIR.

## 2. Geological background of the SWIR

The Southwest Indian Ridge, which spans a distance of approximately $8 \times 10^3$ km, is located fully within the southern hemisphere (Fig. 1). It intersects the Mid-Atlantic Ridge (MAR) and the Americas-Antarctica Ocean Ridges (AAR) at the Bouvet triple junction (BTJ) (55°S, 00°40′W), and it intersects the Central Indian Ridge (CIR) and the Southeast Indian Ridge (SEIR) at the Rodriguez triple junction (RTJ) (25°30′S, 70°E). The oceanic crustal thickness adjacent to the SWIR is between 3.0 and 6.0 km, the spreading rate changes slowly along the axis (8.4–16 mm/yr), and the expansion direction varies from N18°E to N0°E. The SWIR separated the African and Antarctic plates before 100 Ma, and it is currently a major plate boundary within the global ocean (Muller et al., 1999; Bach et al., 2002; Dick et al., 2003; Zhang et al., 2012).

Non-magmatic and magmatic spreading ridges alternate along the length of the SWIR. The tectonic environment of the axial rift valley is diverse, with large variability of terrain; the deepest water depth is as much as 5000 m. The SWIR is cut by a series of N–S transform faults, and mantle material—serpentinized peridotite—is exposed near these faults. Gabbro and basalt can also be collected in some segments of the large-scale faults. The hot spots Bouvet, Marion, Crozet, Reunion, Kerguelen, and Conrad (inactive) are located in the Southwest Indian Ocean (Fujimoto et al., 1999; Tao, 2011). According to existing geological and geophysical data, dynamic volcanism and tectonic activity in some segments of the SWIR make it possible for hydrothermal systems to have heat and fluid flow channels, which provide favorable conditions for hydrothermal activity and the formation of massive sulfide deposits. So far, hydrothermal activity and its products have been found in the Mt. Jourdanne, A area, and 10°E–16°E hydrothermal area on the SWIR (Munch et al., 2001; Bach et al., 2002).

## 3. Conceptual and data-driven models of hydrothermal sulfide deposits

### *3.1. Ore-controlling factors and conceptual model*

SMS deposits, through the combined effect of internal and external forces, are formed by water-rock hydrothermal processes in the oceanic crust, which are closely related to tectonic activity, volcanic activity, regional geological changes and cycles of local physical and chemical events. Hydrothermal circulation between the crust and surface is the fundamental process that controls the transfer of energy and material from the lithosphere to the hydrosphere. The distribution and formation of hydrothermal circulation patterns are primarily controlled by the thermal regime and the permeability structure, both of which are strongly influenced by magmatic and tectonic processes (Nath, 2007). Almost all seafloor hydrothermal activity occurs at the plate margins, where a strong spatial and temporal correlation exists between magmatism, seismicity, and high-temperature venting. The majority of known vents are located along midocean ridges (65%), with the remainder in back-arc basins (22%), along volcanic arcs (12%), and on intraplate volcanoes (1%: Baker and German, 2004; Hannington et al., 2004).

For SMS in the modern seafloor, a number of factors such as faults, deep magmatic activity, sediment cover, spreading rate, depth, and basement properties play controlling roles in mineralization. Fault systems can increase the permeability of the material affected by hydrothermal circulation, and thus can contribute greatly to massive water–rock interaction and subsequent mineralization. Magmatic activity provides a heat source that can lead to convective circulation of fluids in the oceanic crust. Sediment cover protects sulfides from oxidation and destruction. A conceptual model of hydrothermal sulfide deposits (Table 1) has been established based on the topography, geology, geophysics, geochemistry and several other related aspects. The model can highlight the main ore-controlling factors and anomalies associated with SMS deposits and provide the key information for prospecting to improve the credibility of prognoses.

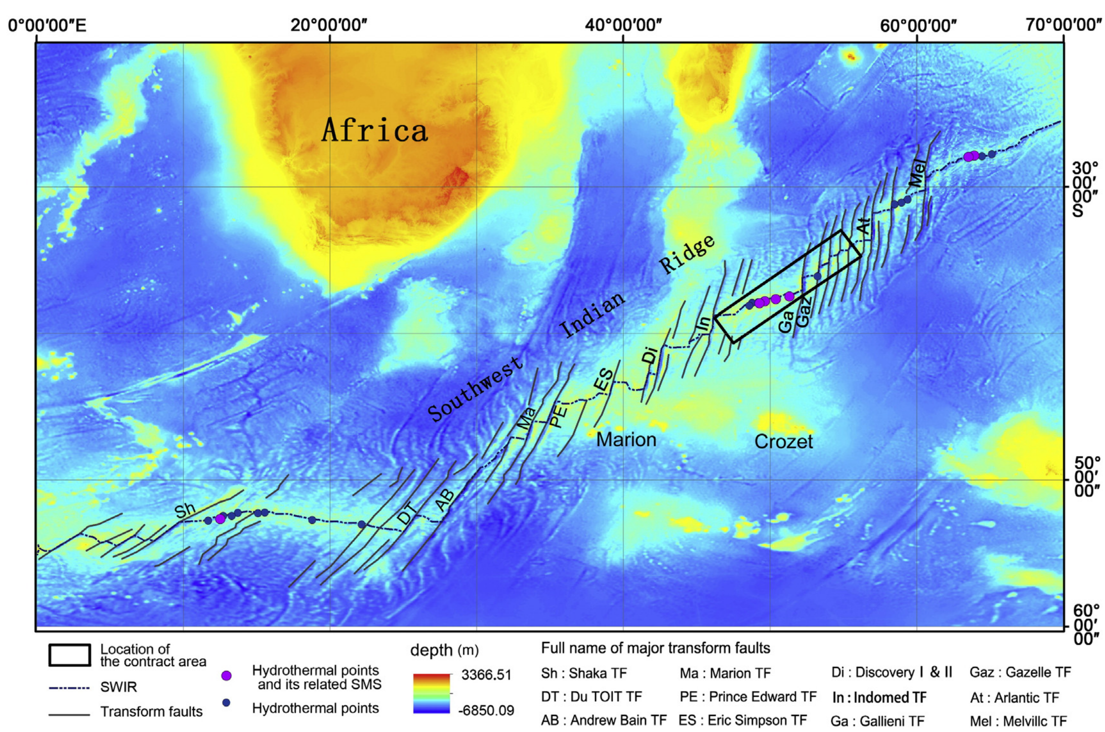


**Fig. 1.** Geology sketch of the Southwest Indian Ridge.