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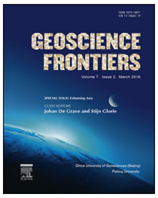

Research paper

Quantitative prediction process and evaluation method for seafloor polymetallic sulfide resources

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ABSTRACT

Seafloor polymetallic sulfide resources exhibit significant development potential. In 2011, China received the exploration rights for 10,000 km^2 of a polymetallic sulfides area in the Southwest Indian Ocean; China will be permitted to retain only 25% of the area in 2021. However, an exploration of seafloor hydrothermal sulfide deposits in China remains in the initial stage. According to the quantitative prediction theory and the exploration status of seafloor sulfides, this paper systematically proposes a quantitative prediction evaluation process of oceanic polymetallic sulfide resources and divides it into three stages: prediction in a large area, prediction in the prospecting region, and the verification and evaluation of targets. The first two stages of the prediction process have been employed in seafloor sulfides prospecting of the Chinese contract area. The results of stage one suggest that the Chinese contract area is located in the high posterior probability area, which indicates good prospecting potential area in the Indian Ocean. In stage two, the Chinese contract area of 48°–52°E has the highest posterior probability value, which can be selected as the reserved region for additional exploration. In stage three, the method of numerical simulation is employed to reproduce the ore-forming process of sulfides to verify the accuracy of the reserved targets obtained from the three-stage prediction. By narrowing the exploration area and gradually improving the exploration accuracy, the prediction will provide a basis for the exploration and exploitation of seafloor polymetallic sulfide resources.

1. Introduction

Polymetallic sulfides have attracted significant attention as a potential seabed mineral resource due to their high grade of precious metal elements, such as Cu, Zn, Pb, Au, and Ag. In 1979, scientists discovered high-temperature chimney and massive sulfide mounds at 21°N of the East Pacific Rise, which proved the close relationship between the formation of seafloor polymetallic sulfides and sea floor spreading caused by oceanic crust accretion (Francheteau et al., 1979; Spiess et al., 1980). Since the beginning of the 1980s, research on seafloor hydrothermal activities has gradually extended to global tectonic zones in oceans. Recent exploration activity has focused on polymetallic sulfides in a variety of tectonic settings on the modern seafloor, including mid-ocean ridges, arcs, and backarcs (Li, 2007; Wen and Xia, 2010). In addition to deep-sea manganese nodules and Co-rich crusts, polymetallic sulfides are another type of seabed mineral resource with substantial prospecting and development potential. The exploration and evaluation of seafloor sulfide resources has become a research hotspot at home and abroad.

Based on the quantitative prediction method of sulfides on land, and the special environment and physical conditions necessary for the formation of this deposit type in the ocean, this paper systematically establishes a three-stage quantitative prediction process for seafloor polymetallic sulfide resources. The results of each stage will provide an indispensable foundation for the subsequent stages of the exploration survey.

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2. Status of exploration for seafloor polymetallic sulfides

In 1978, the American scholar Rona announced the locations of 17 hydrothermal mineral occurrences on the world's seafloor (Rona, 1978); the number of occurrences increased to 139 in 1993 (Rona and Scott, 1993). In 2004, more than 400 locations had been discovered, of which nearly 280 locations had active hydrothermal vents (Baker and German, 2004). By 2010, more than 500 locations had been discovered due to the expansion of international investigation of polymetallic sulfides (Jing, 2012). Additional hydrothermal vents and mines have since been explored. Of the known hydrothermal ores, many of their indicated resources are designated in the million–ten million ton class (Rona, 1988; Herzig and Hanning, 1995; Wu, 2000). Seafloor polymetallic sulfides are abundant in Cu, Zn, Fe, Mn, Pb, Ba, Ag, Au, Co, Mo and rare metals, and can be exploited via simple decomposition processing (Deng, 2007) to attain great mining value.

Since the 1980s, several major industrial countries began to investigate and explore polymetallic sulfides in the oceans (Mao, 2002; Ding et al., 2009). In the early mid-1960s, Russia obtained polymetallic sulfide samples in the Pacific and explored the causes of the ocean hydrothermal circulation process. After submarine black chimney and massive sulfides were discovered in 1979, the United States, France, Germany, Britain, Japan, Canada and Australia successively investigated seafloor sulfides.

In contrast to foreign marine investigations, China has only gradually begun to study hydrothermal polymetallic sulfides since the early 1980s (Tao, 2011; Tao et al., 2014). In 2003, China independently conducted research on seafloor hydrothermal sulfides. Since 2005, the China Ocean Mineral Resources Research and Development Association has organized a series of voyages to perform sulfides surveys. In 2007, China discovered a hydrothermal activity region in the Southwest Indian Ocean; it was the first submarine hydrothermal activity region in the world to be discovered in an ultra-slow spreading ridge. By 2010, China had discovered eight hydrothermal regions in Southwest Indian Ridge, seven hydrothermal regions in the East Pacific Rise equatorial area, and two hydrothermal regions in the South Atlantic Ridge. China submitted an application for exploring 10,000 km^2 of polymetallic sulfide regions in Southwest Indian Ridge, which was approved by the International Seabed Authority at their 17th meeting on July 19, 2011. Only 25% of the contract area will be retained in 2021. This region is the second contract area that China possesses in addition to the area of polymetallic nodules in the Pacific Ocean.

3. Quantitative prediction theory and method

Under the guidance of the scientific prediction theory, we comprehensively examined the geological, geophysical, geochemical and other metallogenic characteristics of polymetallic sulphide deposits in order to improve the effectiveness of prospecting studies and to enhance exploration efficiency (Zhao et al., 2006). Zhao firstly proposed a basic theory for metallogenic prediction in 1990, which incorporates information from analogous genetic models the combination of geological conditions, and geo-anomalies.

Analogous genetic models provide important information because by comparison with the ore-forming model obtained from known deposits, potential deposits may be discovered in similar geological conditions to those experienced by known deposits. The combination of geological conditions is important because the form and merit of a deposit is dependent on the interaction of a variety of ore-forming factors. Therefore, we need to comprehensively investigate and account for all geological, chemical, physical and biological factors that are associated with the ore-forming process. Geo-anomalies occur when there is a distinct difference between the material components, structure, or genetic sequence of a geological body and its surroundings (Zhao and Chi, 1991). Any deviation from the background range constitutes the geological anomaly. It is represented by a numeric range (or threshold) that has a definite space and time, and comprehensively reflects the crustal heterogeneity.

If we consider the exploration survey to be a large system that contains numerous subsystems, then metallogenic prediction is one of the dynamic subsystems. Corresponding to the four stages of exploration survey—reconnaissance, prospecting, general exploration, and detailed exploration (GB/T 13908-2002, 2003) — metallogenic prediction is also a study that is performed in stages; the specificity of the ore-controlling factors and the difference in the prediction methods in each stage should be considered. Many theories about process-oriented prediction and prospecting exist. In this paper, we employ the theory of "5P" ore-finding areas (Zhao et al., 2000) (Fig. 1) and adopt the method of weights-of-evidence during the quantitative prediction.

Weights-of-evidence is the most extensively applied linear model in mineral prospectivity mapping. It employs Bayes' theory of conditional probability to quantify the spatial association between a set of predictor maps and a set of known mineral deposits (Agterberg, 1989; Agterberg et al., 1990; Bonham-Carter and

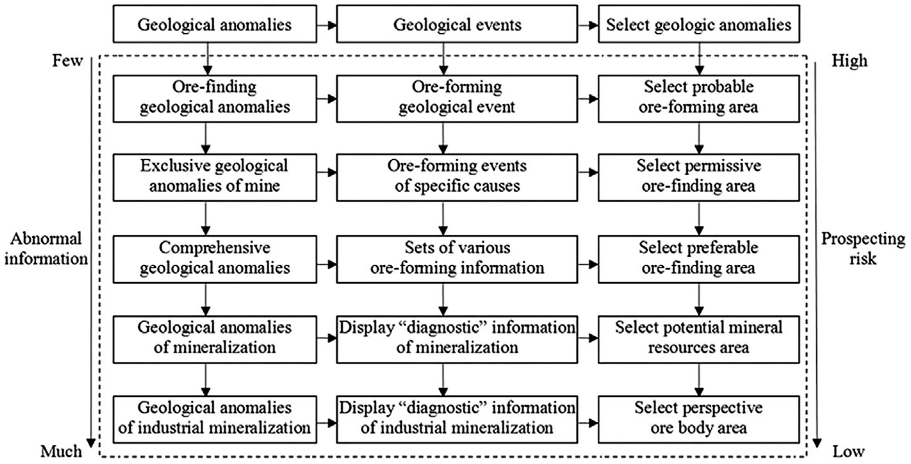

Figure 1. Procedure chart of geo-anomalies for locating ore-bodies (Zhao et al., 2000).