Geophysical exploration of submarine massive sulfide deposits based on integration of multimodal geophysical data

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Summary

In this paper, we introduce an innovative integrated approach to geophysical exploration of submarine massive sulfide deposits. The developed approach is based on three-dimensional inversions of multimodal geophysical data guided by other geophysical data and known geological information. The developed approach was applied to the quantitative interpretation of multimodal geophysical data acquired over a known hydrothermal deposit in Izena area, offshore Japan. There are good correlations between multimodal geophysical anomalies and known hydrothermal deposits. This paper demonstrates that integrated interpretation of the multimodal geophysical data can be effectively used for exploration of the seafloor hydrothermal (massive sulfide) deposits.

Introduction

In order to satisfy the demand for securing mineral reserves not only on land but also offshore, geophysical explorations have been conducted offshore Japan from 1980s, and several seafloor hydrothermal fields with massive sulfide deposits have been successfully discovered.
The Council for Science, Technology, and Innovation (CSTI) started the "Cross-ministerial Strategic Innovation Promotion Program (SIP)" in 2014, which included the development of "Next-generation Ocean Resource Exploration Techniques" from 2014 to 2018. The Research and Development Partnership for Next Generation Technology of Marine Resources Survey (J-MARES) was established by four companies (JAPEX, JGI, NSENGI, and MMTEC) in order to participate in this program with the aim of developing a "Multi-stage and integrated approach for seafloor massive sulfide exploration" through highly efficient and cost-effective geophysical exploration methods, focusing mainly on seismic and electromagnetic methods, and the combination of existing exploration tools and systems (Asakawa et al, 2017). Figure 1 shows the general concept of the multi-stage and integrated approach.

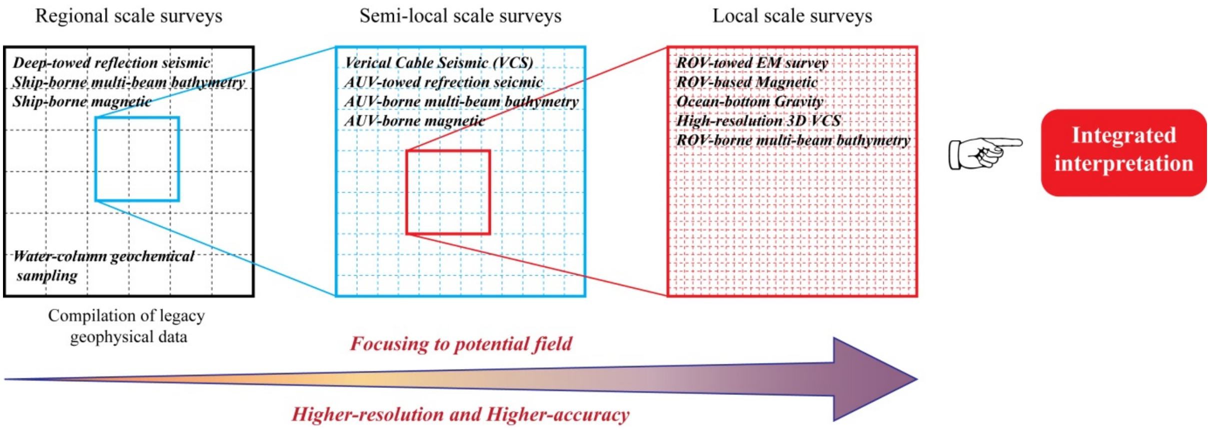

Figure 1 *Overview of the multi-stage and integrated approach.*

J-MARES and Japan Marine Surveys Association (JAMSA) have deployed several research surveys such as seismic, electromagnetic (EM), resistivity, magnetic, gravity, rock sampling (including petrophysical analysis), etc., over known seafloor hydrothermal fields, e.g., Izena area, offshore Japan. It is required to develop and standardize a multi-stage and integrated approach, which combines multiple geophysical and geological exploration methods, for the exploration of seafloor massive sulfide deposits.
In the current paper, we present our developed integrated geophysical approach based on the 3D inversions of multimodal geophysical data guided by known geophysical and geological information, and its application to the multimodal geophysical data acquired over Izea area, offshore Japan.

Multimodal geophysical data in Izena area, Japan

General geological setting and petrophysical analysis

Several research surveys have been carried out in Izena area, offshore Japan. There are several known hydrothermal deposits in the survey area. The typical deposit in the area forms a mound with massive sulfides, and many chimneys and hydrothermal ejection holes are observed on or around the mound. Except for these mounds, ocean bottom sediments cover the entire area (Figure 2).
There is a known hydrothermal deposit (mound) at around the center of the survey area. We have also studied the petrophysical and mineralogical characteristics of rock samples collected in the same survey area (Endo, et al., 2016). The mineralogical analysis of rock samples was performed using the quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) system. The results show that the rocks from the survey area include large amount of sulfides (ex. sphalerite, pyrite, and barite). The complex resistivity measurements of rock samples were performed in order to

clarify the electrical properties of rocks. As expected, strong induced polarization (IP) effect was observed, mainly caused by the large amount of sulfide minerals. This electrical property has to be taken into account for the interpretation.

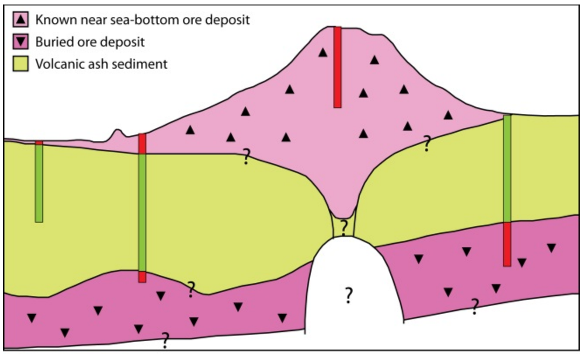

Figure 2 *General geological model (after METI, 2013).*

Multimodal geophysical data

The following geophysical surveys were deployed in the research survey area:

- Seismic survey
- Electromagnetic survey
- DC resistivity and self-potential surveys
- Magnetic survey
- Gravity survey

Figure 3 shows the maps of these multimodal geophysical surveys.

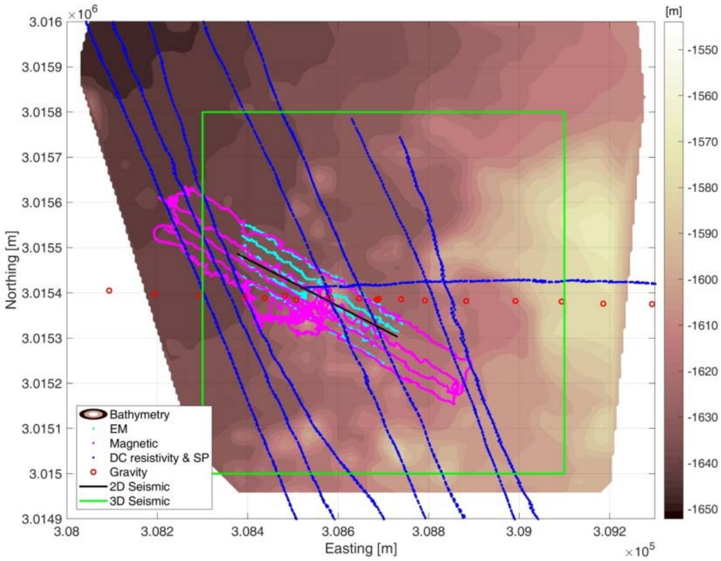

Figure 3 *A map of multimodal geophysical surveys in the survey area.*

Integrated geophysical approach

We have developed an integrated geophysical approach for quantitative interpretation of multimodal geophysical data. Three-dimensional (3D) inversion of geophysical data for the corresponding physical properties is required for the quantitative interpretation. In a general case, geophysical inverse problem is ill-posed, i.e., non-unique and unstable. The a priori information can help reducing non-uniqueness and increasing stability of this ill-posed problem. Figure 4 presents the general workflow of the integrated interpretation.

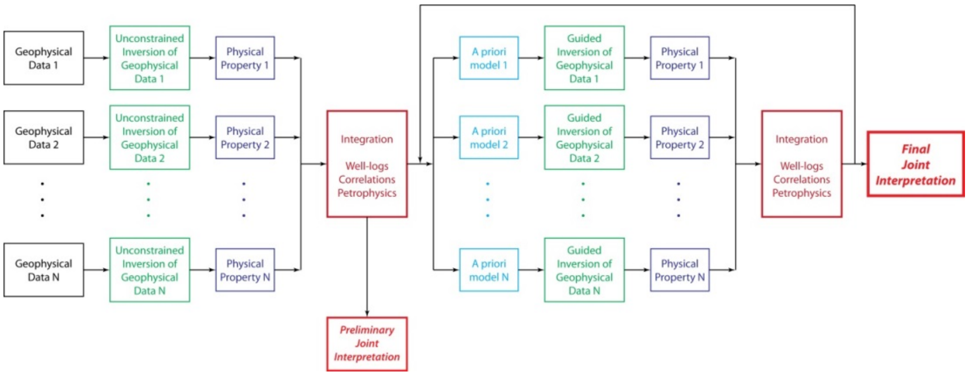

***Figure 4** General workflow of the integrated interpretation.*

Our developed integrated geophysical approach to interpretation of the multimodal geophysical data in Izena area, offshore Japan consists of the following steps:

1) Unconstrained 3D inversions:
    a. Unconstrained 3D inversion of time domain EM data with taking into account the IP effect (IP model);
    b. Unconstrained 3D inversion of magnetic (TMI) data for magnetization vector model.
2) Guided 3D inversions:
    a. Guided 3D inversion of time domain EM data with 3D a priori model constructed from seismic data, well information, and the result of unconstrained 3D inversion;
    b. Guided 3D inversion of magnetic with 3D a priori model constructed from seismic data, well information, and the result of unconstrained 3D inversion.
3) Integrated interpretation.

Results of the integrated interpretation

Figure 5 presents a vertical cross section of 3D resistivity and 3D magnetization models recovered by the guided 3D inversions overlaid with seismic data. Figure 6 shows a vertical cross section of 3D chargeability and 3D magnetization models recovered by the guided 3D inversions overlaid with seismic data.

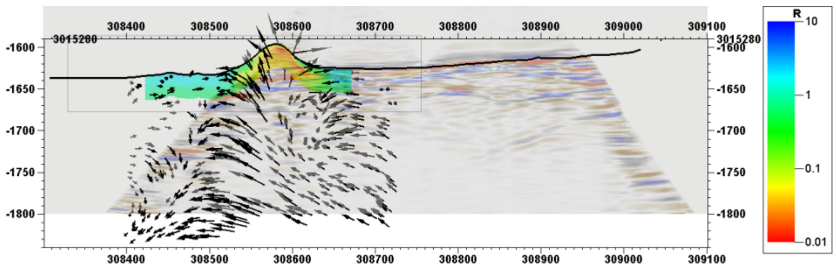

Figure 5 Vertical cross section of 3D resistivity and 3D magnetization vector models recovered by the guided 3D inversions overlaid with seismic data.

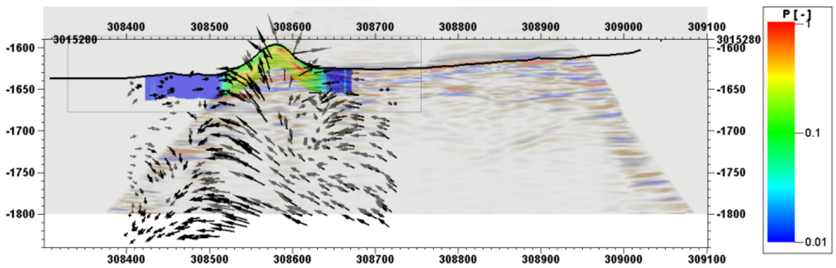

Figure 6 Vertical cross section of 3D chargeability and 3D magnetization vector models recovered by the guided 3D inversions overlaid with seismic data.

From these results integrated with borehole information, we have interpreted the sea-bottom structure as shown in Figure 7. The conductive and chargeable anomaly recovered from EM data agrees very well with the known hydrothermal deposit, and the recovered magnetization vector clearly indicates a vertical hydrothermal activity below the mound, and the remanent magnetization which seems to be caused by sulfides covered by the sea-bottom sediment. Further, boundaries of geological units can be estimated by the integrated interpretation.

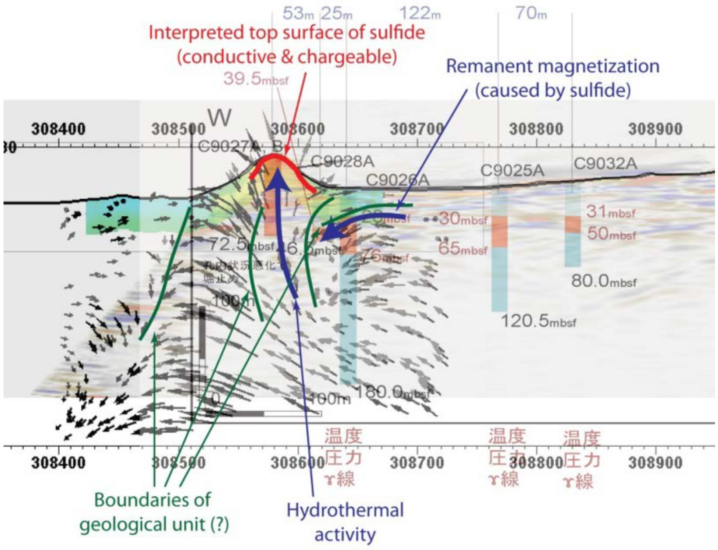

Figure 7 *Vertical cross section of the interpreted structure.*

Conclusions

We have developed an innovative approach to the integrated quantitative interpretation of multimodal geophysical data based on guided (constrained) 3D inversions. This approach has been applied to the multimodal geophysical data acquired in Izena area, offshore Japan. Because there are good correlations between multimodal geophysical anomalies and hydrothermal deposits, multimodal geophysical methods can be effectively used for exploration of the seafloor hydrothermal (massive sulfide) deposits.

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