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Magnetotelluric investigation of the geothermal anomaly in Hailin, Mudanjiang, northeastern China

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ABSTRACT

To study the occurrence conditions and locations of geothermal bodies in Hailin, Mudanjiang, northeastern China, we conducted a magnetotelluric investigation to delineate the electrical conductivity structure of the area on three parallel profiles. The area to the west of the Mudanjiang Fault lies in the Hailang sag of the Ning'an Basin. The data were processed using the mutual reference technique, static shift correction, and structural strike and dimensionality analysis based on tensor decomposition. Moreover, a modified anisotropic-diffusion-based method was used to suppress noise for the magnetotelluric time series data. This method retains the advantages of conventional anisotropic diffusion and is superior in its discrimination ability. The method is characteristic not only of the inherited features such as intra-region smoothing and edge preservation, but also of the adaptive selection of the diffusion coefficient. Data analysis revealed that the electrical resistivity structure can be approximated by a two-dimensional characterization. Two-dimensional inversion and rendering visualization show that a highly resistive granite basement is covered with conductive sedimentary layers and that a relatively low-resistivity anomalous structure with a resistivity of approximately 100–600 Ω·m is imbedded in the high-resistivity background. The anomalous structure has a narrow top and a wide bottom (the bottom depth is at least 3500 m). The shape and electrical features of the structure indicate favorable storage space for hot subsurface water. Fault activities and magma intrusion may result in the fractures of the basement, which are filled with hot water and thus produce the relatively low resistivity. Based on a comprehensive analysis, we infer that the structure is indicative of a geothermal reservoir. An exploratory well drilled near the structure confirms the occurrence of high temperatures. Several geological factors (cap rock, basement, and major faults) determine the favorable geothermal conditions of the reservoir. Large areas of granite form the major thermal source for the study area. The Mudanjiang and Hailang River Faults and their subsidiary faults provide another heat source and movement channels.

1. Introduction

High electrical conductivity is one feature of geothermal sources. Geothermal-water-rich rocks commonly have relatively lower resistivity than initial rocks, and the variation in the resistivity is related to the water abundance, temperature, and degree of mineralization (Spichak et al., 2007). Hot subsurface water is closely related to structural fractured zones connected to medium-deep hot sources. Water-abundant (especially hot water) and fractured zones usually have lower resistivity. The resultant low-resistivity anomalies have generally been the main target for the geophysical exploration of geothermal resources (Simpson and Bahr, 2005). This is the geophysical basis of magnetotelluric (MT) soundings for geothermal resource exploration. The MT method can be used to detect the distribution of highly conductive geological bodies and faults. MT data, when combined with other geophysical anomalies and geological conditions, can be used to predict the distribution of thermal reservoirs (Spichak and Manzella, 2009). Since the late 1980s, the development of remote references, robust approaches, distortion corrections, multidimensional modeling and inversion methods has made the interpretation of magnetotelluric data more reasonable (Bahr and Simpson, 2005; Berdichevsky and Dmitriev, 2008;

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Chen and Wang, 1990; Telford et al., 1990). There have been many successful applications of the MT method in geothermal exploration (Bai et al., 2001; Corwin and Hoover, 1979; Johnston et al., 1992; Kong et al., 1991; Newman et al., 2008; Pellerin et al., 1996; Volpi et al., 2003; Wright et al., 1985).

Previous geophysical and geological studies suggest the presence of geothermal resources underneath the southern part of Mudanjiang and its adjacent areas in Heilongjiang Province, northeastern China (Qi, 2006; Sui et al., 2011; Ye, 2011; Wang and Huang, 2014). The activities of the Mudanjiang and Dunhua–Mishan Faults and their subsidiary faults have provided heat and favorable space for the geothermal resources. Hailin lies in western Mudanjiang and is close to the Mudanjiang Fault. Neither data nor cases of geophysical investigations in Hailin have been published. Therefore, no geophysical evidence can be referenced to reveal whether Hailin also has geothermal potential like the southern part of Mudanjiang. Some geological and hydrogeochemical investigations reveal that the basement of Hailin mainly consists of granites and granodiorites and is buried at shallow depths (Jing et al., 2008; Li et al., 2007). As a result, the basement is highly resistive. However, if the granites or granodiorites are fractured or filled with fluids, especially hot water, their resistivity will decrease dramatically. Such a resistivity contrast is to be expected for an MT investigation.

To study the possible occurrence conditions of Hailin, we conduct an MT survey on three parallel profiles at the village of Hailin to delineate the geoelectrical structure and provide geophysical evidence for the exploitation and evaluation of geothermal resources in the area. Reliable data are obtained through mutual reference, noise suppression, static shift correction, and dimensionality analysis based on tensor decomposition. A modified anisotropic-diffusion-based method is utilized to suppress noise for the MT time series. This method retains the advantages of conventional anisotropic diffusion and is superior in its discrimination ability. A 2-D inversion is used to provide better constraints on the conductivity structures of the three profiles. A rendering visualization of the inversion results is applied to represent the structures.

After the MT survey, an exploratory well was drilled where the MT results indicate favorable structures of geothermal water. The well confirms the occurrence of high temperatures. The geothermal sources are deduced based on the geological conditions of the area.

2. Geological and tectonic setting

2.1. Tectonic setting

The study area (see the red rectangle in Fig. 1) is located in the volcanic rock belt of Changbaishan Mountain, which is an important part of the Pacific Mesozoic volcanic chains. The area is next to the western side of the Mudanjiang Fault, in the Hailang sag of the Hailang Depression (belonging to the Ning'an Basin). The Hailang Depression is a relatively independent artesian basin (Li et al., 2007). Strata are widely outcropped, and intense magmatic activities and structures developed there. The structural evolution includes the Zhangguangcai Range epoch, Caledonian epoch, Indo-Chinese epoch, and Yanshan epoch. The deformation structures are mainly north–south linear compaction folds.

2.2. Stratigraphy

Fig. 2 is the regional geological map of the MT survey area. The outcrop strata are distributed in valleys and are composed of sandstones and glutenites, which mostly belong to the Neogene and Quaternary. Other outcrops close to the survey area are Cretaceous Hailang formation, migmatitic granodiorite of Variscan age, granite rock formation of Early Yanshanian age, alaskite granite rock formation of Late Variscan age, and granite porphyry rock formation of Late Yanshanian age. Because of the intensive magmatic activity in the area, the strata are seriously damaged and the remains are mainly xenoliths distributed in the intrusive rocks. The intrusive rocks are alaskite granite, granodiorite, gabbro, and granite porphyry of Yanshanian epoch, Indo-Chinese epoch, Late Variscan epoch, and Proterozoic. Their modes of occurrence

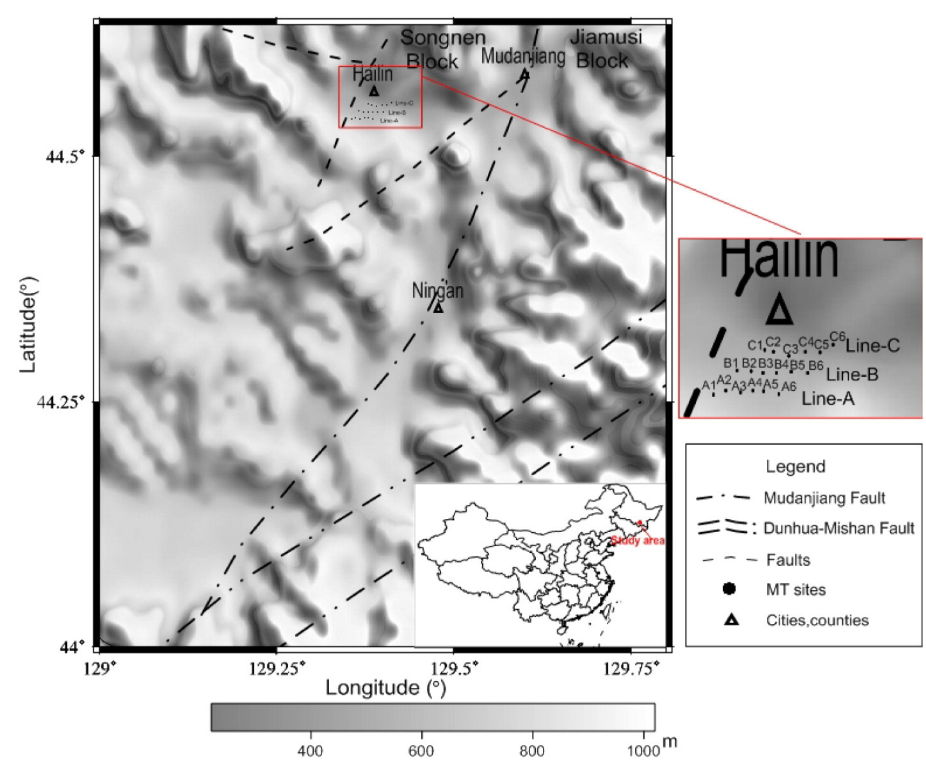

Fig. 1. Topographic map.