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Inversion of magnetotelluric data in fault zones of Gorny Altai based on a three-dimensional model

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Abstract

Results of magnetotelluric sounding (MTS) in Gornyi Altai are interpreted on the basis of a numerical model of MTS curve distortions in a 3D earth. The distortions are modeled using the Trefftz method permitting the application of models of different degrees of similarity to the test medium (depending on available computational resources). The main advantages of this approach are demonstrated. There is no need to choose between different MTS curves (transverse and longitudinal, minimum and maximum, undistorted and distorted). Procedures of normalizing these curves become unnecessary. All recorded curves are fully used as input data for their inversion. Optimization of the model of the medium taking into account the distortions of MTS curves caused by surface and depth inhomogeneities improves the reliability of geoelectric sections.

Keywords: magnetotelluric sounding; electrical conductivity; distortions and normalization of MTS curves; surface and depth inhomogeneities; geoelectric section; recent faults; Cenozoic activation

Introduction

Identification and study of active fault zones helps to solve problems of modern geodynamics and is an essential element of seismic zonation and seismic hazard evaluation. Faults as dominant geological structures of different scales are assigned a key role in the structural control of fluid permeability and recent phenomena in the upper part of the Earth's lithosphere. In seismology, the relationship between earthquakes and faults has long been established: the development of fault zones is accompanied by seismicity and is associated with deformations of the crust and lithosphere, which contribute to tectonic movements (Sherman and Seminsky, 2010) and are identified in the surface relief. Faults with a long geological history, latent faults of the basement, lineaments, and their intersection nodes are seismically active (Kalinina, 2005; Kalyagin and Abramov, 2003). Deep faults are in fact through channels penetrating into the lower crust and upper mantle, as well as alkaline ultrabasic and carbonatite magma fluid columns reaching hypabyssal depths and even the Earth's surface (Kadik, 2006). Major earthquakes are almost always confined to active faults. This is confirmed by experimental data showing that a sudden rise of fluids in fault zones initiates an earthquake (Aptikaev, 1995).

One method for studying active faults is magnetotelluric sounding (MTS). Deep fluid-saturated faults form conductive channels which intersect the high-ohmic lithosphere to provide vertical redistribution of excess currents and are fixed in the magnetotelluric field in the form of subvertical conductive geoelectric inhomogeneities (Batalev et al., 2013; Berdichevsky et al., 1999; Epov et al., 2011; Maercklin et al., 2005; Nevedrova et al., 2014; Pospeeva et al., 2014; Unsworth and Bedrosian, 2004; Unsworth et al., 1999). The identification of earthquake patterns in relation to geological-tectonic features and neotectonics has motivated magnetotelluric studies in Gornyi Altai, which is one of the most dangerous seismic regions in Russia. An important aspect of these studies is to choose a valid methodological approach to the interpretation and analysis of the data obtained.

The complex geoelectric structure of the medium near faults complicates the analysis of the behavior of magnetotelluric curves. In particular, one has to use various coefficients to check the two-dimensionality conditions of geoelectric structures, to choose undistorted curves or perform their normalization (Moroz and Moroz, 2012; Nevedrova et al., 2011).

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At sounding stations near a fault, the maximum and minimum curves usually differ in resistivity, and additional minima and maxima appear, depending on the sounding period. However, this behavior of magnetotelluric curves is quite typical of distortions that occur in the presence of surface and subsurface inhomogeneities of electrical conductivity (Plotkin and Gubin, 2015).

By distortions are usually meant differences between recorded magnetotelluric curves and the local curve corresponding to a horizontally layered section with the electrical conductivity dependent on the depth under the sounding station. Lateral changes in this dependence lead to various distortions of the electromagnetic field and additional contributions to the impedance tensor. The response of the medium becomes nonlocal, but due to the diffusion nature of field propagation in a conductive medium, the distortions of the curves are determined by the confined volume of the medium near the sounding station (Plotkin, 2012). Neglect of the possible distortions of the curves may lead to misinterpretation of MTS data on the deep structure of faults. In particular, distortions caused by near-surface inhomogeneities may be interpreted as a deep conductive layer.

On the other hand, modeling of these distortions in the interpretation of MTS data using all available magnetotelluric curves (longitudinal, transverse, phase) for several stations can narrow the equivalence regions of the inverse problem solutions. In (Plotkin and Gubin, 2015), distortions are modeled using the Trefftz method (Egorov, 2011), a feature of which is that the software code allows using models of varying degrees of similarity to the test medium. Changing the detail of representation of the medium, it is possible to find a compromise between the achievable quality of experimental data interpretation and the computational cost of processing. At the same time, the similarity of the inverse problem solutions in these cases confirms their accuracy and a decrease in the equivalence region.

It should be noted that at high latitudes or in the equatorial zone where there are powerful ionosphere currents—electrojets (Zhdanov, 1986), the approximation of a primary source by a vertically incident plane wave ceases to hold. The inhomogeneous structure of the source should be taken into account. The difficulties that arise can be overcome by using synchronous areal sounding. In this case, there is no need to know the origin of spatial harmonics of the fields (from the source or from the medium) on the Earth's surface, and the magnetic or electrical field component distributions recorded on the Earth's surface can be used as the upper boundary conditions (UBC). The inverse problem solution can be found by matching these distributions on the surface to each other (Plotkin, 2012) and without using and calculating MTS curves.

In the mid-latitudes, there is no need to use synchronous probing because in the far-field zone of the primary source, it is valid to assume that the medium is excited by a vertically incident plane wave. This implies that lateral changes of the field on the Earth's surface are due only to the inhomogeneity of the medium. Therefore, it is possible to use UBC (Plotkin and Gubin, 2015) which take into account that the spatial harmonics of the field excited in the medium are attenuated deep in the atmosphere. This case is the subject of the present paper.

Data used and inversion procedure

To analyze the possibilities and implementation of this approach, we used the results of magnetotelluric profiling performed within the Ulagan Plateau located in the East-Altai facies zone. This zone is between the Gorny Altai and West Sayan folded systems and is often included in the latter (Kuznetsov, 1963). In the southwest, it is bounded by the Kurai–Teletsk deep fault, whose eastern part breaks into a series of feathering faults. The upper structural level of the East-Altai structural zone is formed by basins composed of terrigenous sedimentary rocks, in particular, Devonian clastic sediments. Metamorphic ridges, previously considered as basement rocks, are currently interpreted as Lower–Middle Paleozoic metamorphosed rocks with a complex laminated-overlapped tectonic structure (Novikov, 2004). The profile in question is located in the interfluve between Bashkaus and Yoldu (Fig. 1*a*), within which the upper structural level rocks are primarily sandstones and siltstones of the Gorny Altai Formation ($Є_3$–O_{1gr1}) and metamorphic schists of the Lower Proterozoic Terekta Formation ($PR_{tr?}$). These formations are characterized by high electrical resistivity, which varies from 2000–2500 Ohm·m in the southwestern part of the profile to 7000–10,000 Ohm·m in the northeast. In the middle part of the crustal section, there is a conductive layer with the upper edge at a depth of 10–12 km and a resistivity of less than 50 Ohm·m. The layer is complicated by a series of subvertical conductive inhomogeneities within which the resistivity is about 5 Ohm·m. The inhomogeneities are spatially associated with a system of recent northwest-trending faults reconstructed from the results of geomorphological studies (Novikov, 2001). According to these studies, the faults, active in the Cenozoic, form a block system with significant (hundreds and thousands of meters) displacement amplitudes during the Late Cenozoic time and form the basis of the modern orographic structure (large relief forms such as ranges and intermontane basins).

In Fig. 1*a*, faults are shown by wide black and gray stripes. MTS stations 7–18 of the profile are located along one of these faults (black). The profile is intersected by two other faults (gray) in the vicinity of stations 9 and 13.

In the simulation using the Trefftz method, the computational domain of the inhomogeneous medium is represented by a set of several finite elements in the form of parallelepipeds, in which the medium is homogeneous. As an example, Fig. 1*b* shows a diagram of the polygon and the projections of the parallelepipeds onto the surface. The coordinate system is placed at the location of the base station 13 (the *OX* and *OY* axes are arranged in a horizontal plane, and the OX axis is directed along an azimuth of 45° with respect to the geographic north, i.e., along the selected profile, the *OZ* axis is directed downward, and the Earth's surface $z = 0$). In Fig. 2, the apparent resistivity curves at the stations of the profile are