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His professional career includes extended service in Russian Academy of Sciences. Presently he heads the Geoelectromagnetic Research Institute RAS, which undertakes research and development activity in the field of theoretical and applied geoelectrics. Dr. Spichak is nationally and internationally recognized for contribution in the theory, analysis and three-dimensional interpretation of magnetotelluric fields. He works at the problem of forward modeling and inversion of electromagnetic data in three-dimensional media and has a vast experience in the use of computer science in the solution of geophysical problems.

Dr. Spichak has presented a number of lectures and seminars on advanced methods of electromagnetic data interpretation at Universities and Geological Surveys of many countries. He is a member of several professional societies and continues to take an active part in committee and meeting organization activities. Currently his membership includes Academy of Natural Sciences of Russia. He has published more than 100 works including 2 monographs.

V. Spichak

CONSTRUCTION OF THREE-DIMENSIONAL GEOELECTRIC MODELS FROM ELECTROMAGNETIC DATA

Abstract

Advanced interpretation methods developed recently enable construction of three-dimensional geoelectric models both without prior geological/geophysical information and taking into account not only such data, but also the results of past observations and formalized human experience. Conductivity models of the Juan de Fuca subduction zone, MinamiKayabe geothermal area, Mino a fracture zone are constructed basing on array of electromagnetic data measured at the Earth surface. Numerical modeling and inversion of EM fields in hypothetical models of volcanoes and freshwater aquifer demonstrate the resolution power of magnetotelluric data with respect to the parameters of both deep and nearsurface complicated geoelectrical structures.

Introduction

Electromagnetic induction in the Earth by sources of the natural origin, located in the Earth magnetosphere and ionosphere, as well as by controlled sources, enables understanding the physicochemical state of the Earth interior through its influence on the electrical resistivity. Measurement of the electromagnetic fields in the Earth at the surface or in the atmosphere may serve as unique tools for both deepening our knowledge about the Earth's interior and monitoring geodynamic processes.

Variations in the natural electromagnetic field that are generally used in geoelectrical investigations can be classified by their sources into four basic types: (a) pulsations, (b) polar substorms, (c) quiet solar diurnal variations, and (d) world storms. All these fields can be approximated with some errors by model fields. A scheme of such approximation is presented in the Table 1 [1]. The purpose of the paper, is to demonstrate how the electromagnetic (EM) fields induced in the Earth may provide information about three-dimensional geological structure of the regions considered. With this aim we will restrict ourselves mainly by considering EM fields induced in the Earth by pulsations and polar substorms in low and middle latitudes, that is by plane wave model of the source.

<table>
<thead>
<tr>
<th>VARIATIONS</th>
<th>MODELS</th>
</tr>
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<tbody>
<tr>
<td>I. PULSATIONS in low and middle latitudes</td>
<td>a) Arbitrarily oriented fixed horizontal electric dipole; b) arbitrarily polarized non-uniform or uniform plane wave</td>
</tr>
<tr>
<td>II. POLAR SUBSTORMS</td>
<td>Arbitrarily polarized non-uniform or uniform plane wave</td>
</tr>
<tr>
<td>a) low and middle latitudes</td>
<td>Infinitely long rectilinear ionospheric current</td>
</tr>
<tr>
<td>b) high latitudes</td>
<td></td>
</tr>
<tr>
<td>III. QUIET SOLAR DIURNAL VARIATIONS</td>
<td>Fixed current eddy of fixed configuration</td>
</tr>
<tr>
<td>IV. WORLD STORMS</td>
<td>Arbitrarily oriented moving magnetic dipole</td>
</tr>
<tr>
<td>a) sudden commencement</td>
<td>Arbitrarily oriented uniform magnetic field</td>
</tr>
<tr>
<td>b) main phase</td>
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</table>

Let us consider alternative electromagnetic fields induced in some Earth region Ω by external currents localized in the region Q (Fig.1). If the dimensions of the studied domain (L) are small enough in comparison with both the Earth radius (R) and the wavelength, the EM fields generated by the external current systems can be treated as planar ones propagating downwards. For the considered frequencies it is correctly reasoned that \( \sigma/\varepsilon \omega \gg 1 \) (where \( \varepsilon \) - dielectric permeability, \( \sigma \) - electrical properties)
conductivity, \( \omega \) - frequency). It is also supposed that magnetic permeability is equal to those in the vacuum \( (\mu = \mu_0) \) Under these conditions the EM field is described by Maxwell equations in the following form:

\[
\nabla \times \vec{E} = \sigma \vec{H} + \vec{E}_{ext}, \quad \nabla \times \vec{H} = i \omega \mu_0 \vec{H},
\]

where \( \vec{E} = \vec{E}^p + \vec{E}^S, \vec{H} = \vec{H}^p + \vec{H}^S, \vec{E}^S, \vec{H}^S \) - secondary field due to the Earth inhomogeneity, \( \vec{E}_{ext} \) - external current.

Below we shall give some examples of both real and synthetic magnetotelluric data interpretation in a class of three-dimensional models by means of advanced imaging and inversion methods developed recently in [11, 13, 17-20].

3-D geoelectric model of the Juan de Fuca subduction zone

The Electromagnetic Sounding Experiment EMSLAB was aimed to study the geoelectrical structure of the lithosphere and asthenosphere beneath the Juan de Fuca oceanic plate and its subduction under the Western margin of North American continent. With this aim the electrical, magnetic and electromagnetic data were measured totally in 86 sites distributed in the territory restricted by latitudes 40° and 50 °N and meridians 116° and 132° W (Fig.2).

Fig. 1. Model of the electromagnetic field source.

Fig. 2. The scheme of observations in the EMSLAB experiment [23]. Rectangle is the boundary of the modeling domain.

The results of the experiment were analyzed then by means of 2D forward modeling and inversion tools. In particular, the EMSLAB Group constructed the resistivity cross-section beneath the Lincoln Line [24] (Fig.3).

However, some inconsistencies between the synthetic responses and experimental data required application of 3-D interpretation tools aimed at elimination of local 3D effects and more precise detection of the Eastern margin of the Juan de Fuca plate beneath the North American continent taking into account prior geological information about the considered region.

The domain restricted in the Fig.2 by the rectangular line was studied using 3D forward modeling [25] with starting model being based on all geological information as well as on the results of 2D inversion carried out for Lincoln Line data [24].
The main features of 3D conductivity structure of the land region were: the Coast Range, Willamette Valley, High and Western Cascades, Puget Sound (on the North) and High Lave Plateau (to the South-East). The dimensions of the modeling domain were; 320km x 500km x 250km and calculations were carried out for periods 17.9, 19.2, 27.0 and 40.2 min.

Fig.4 shows isolines of the horizontal magnetic field component $H_z$ at the Earth surface at the period $T = 27$ min. It is seen from these map that, in spite of different 3D features included into the starting model, the resulting configuration of isolines is almost two-dimensional. The exceptions are only for the region to the south from the Puget Sound, where a conductive body (conductance 500 S) at the depth of 5 km is located, and, in a lesser extent, the North-West corner of the High Lave Plateau. Similar behavior of other horizontal field components resulted in conclusion that local 3D effects do not greatly disturb the general two-dimensionality of the structure, so, the interpretation of the data in this area could be carried out using 2D interpretation tools.

Fig.5 demonstrates the maps of induction vectors based on synthetic data. Their length and the sign reverse approximately coincide with the experimental data, published by EMSLAB group, and indicate the horizontal projection of the Eastern margin of the Juan de Fuca plate beneath the North American continent. Fig. 6 demonstrates 3D conductivity model of the whole domain considered with two vertical cross-sections, one of which is along Lincoln Line. It is well seen both the subduction and high-conductive asthenosphere zones.

Thus, constructed geoelectrical model takes into account all prior geological and geophysical information available at the moment of study, as well as two-dimensional inversion results along Lincoln Line obtained on [24]. Numerical experiments on this model have confirmed the stated earlier hypothesis about the subduction of the Juan de Fuca plate under the North American continent. At the same time, forward modeling of MT-fields indicates that at the interpretation of EMSLAB experiment data along the Lincoln Line it is possible to use two-dimensional approximation with a sufficient degree of reliability.
Fig. 5 In-phase (a) and quadrature (b) induction vectors for $T = 19$ mm [25].

Fig. 6. Volume conductivity model of the Juan de Fuca subduction zone [25].

Detection of high-conductive zone in Minami Kayabe area (Hokkaido, Japan)

Interpretation of data measured simultaneously over a regular 2D array of sites at a number of frequencies may enable to get very detailed information about the deep geoelectrical structure. At the end of 1980 the Minami Kayabe area at the North of the Hokkaido Island (Japan) was studied by geological, gravimetric, geochemical, magnitotelluric and other methods [21] in order to detect and, possibly, map the source of geothermal energy. Highly precise MT measurements
were carried out in a square area with dimensions 1.2 x 1.2 km² with a step 100 m in a frequency range from 0.001Hz up to 20 kHz (Fig.7).

**Fig. 8. Volume resistivity image of the MinamiKayabe zone [11].**

Based on the results of well logs and 2D modeling it was supposed that some conductive zone is located between 100 and 600m [22]. However, in order to determine more precisely its spatial location and dimensions 3-D interpretation tools were required. With this aim in [11] 3-D MT imaging of the MinamiKayabe area was carried out and its conductivity structure was defined.

Fig. 8 shows the 3D resistivity distribution with two vertical sections along the lines passing through well logs (MK-2 and MK-6) drilled in this area. From the results of 3-D imaging a high conductive zone (with resistivity less than 6 Ohm-m), which could be treated as a geothermal reservoir, was mapped (Fig. 9). It is well seen from the latter Figure that conductive areas are concentrated in a southern part of considered region and that with depth their horizontal sizes at first increment, reaching maximum at depths approximately from 200 up to 800m, and then are again moderated.

**Fig. 9. High conductive domain (with resistivity less than 6 Ohm-m) [11].**

**Imaging Volcanic Interiors with MT Data (numerical modeling)**

Magnetotelluric sounding has been used to monitor volcanic activity and to help understand the processes leading to eruptions [3,7, etc.]. Modeling of these applications, however, has been relatively crude. For example, Newman et al. [9] modelled a homogeneous prism in a layered Earth with a 3-D integral equation method to study the detectability of a magma chamber, whereas Moroz et al. [8] built a more elaborate scale model to study the distortion of MT fields by a volcanic cone, but the conductivity of all conductive elements of the structure was equal to 10⁶ S/m. In papers [12, 14] the resolving power of MT data in more realistic models of volcanic zones is studied and guidelines aimed at efficient MT surveying depending on the aim of the data interpretation are suggested.

In particular, in the paper [12] 3-D geoelectrical model of a typical volcano of Hawaiian type was used. The model represents a shield volcano, characterized by low and flat summit formed by homogeneous basaltic rocks (Fig. 10). Its flanks stretch down into the ocean; the conductivity of the ocean water was taken to be 3.6 S/m. The volcano’s summit, 0.5 km thick, is formed by basaltic lavas with conductivity \( \sigma = 0.001 \) S/m. There is a small layer, 0.8 km thick, with conductivity \( \sigma = 0.01 \) S/m at the boundary between the air and the ocean. Below are porous volcanic lavas, which are characterized by high content of salty water (this zone is 1.7 km thick and has a conductivity \( \sigma = 0.17 \) S/m). Then, at 3 km depth from the volcano summit, there are dense lava formations 5.5 km thick with conductivity \( \sigma = 0.01 \) S/m, underlaid by the crystalline crust with conductivity \( \sigma = 0.001 \) S/m. Other details of the geoelectrical structure are not important for this study.

MT fields for this model were synthesized for two polarizations of the primary field at periods \( T = 0.1; 1, 10 \) and 100 sec. Then, a number of the MT field transformations were calculated and analysed at different levels in the atmosphere to find those that are most sensitive to the parameters of the model.
Fig. 10. Vertical cross-section of 3-D geoelectrical model of a Hawaiian-type volcano [12].

It was found that 3-D isosurfaces (or 2-D maps of the isolines) of the data transforms based on the impedance phases and or the in-phase and quadrature parts of the horizontal electric fields are the best for imaging the complicated geoelectrical structure of the volcano (Figs. 11 and 12).

Fig. 11 (a, b) show the vertical cross-sections of the volcano overlapped by the maps of isolines of the transformed impedance phases \( \phi_{xy} \) and \( \phi_{det} \), correspondingly. Although the values attached to these isolines hardly could be interpreted in reliable terms, then spatial gradients clearly indicate the location of the magma chamber and of the conductive formation above it. The gradient of \( \phi_{det} \) delineates not only the magma chamber but also the flanks of the volcano (Fig. 11 b). This result matches the findings of Park and Torres-Verdin [10] and Zhdanov and Spichak [25] from the interpretation of the impedance phases in array MT data.

Transforms of the in-phase and quadrature parts of the horizontal electrical field component parallel to the incident electrical field are even more sensitive to gradients of conductivity. Fig. 11c shows the vertical cross-section of the model overlapped by the map of the isolines of the Re\( E_y \) transformation. The bunching of isolines correlates with gradients of the conductivity; the local extrema mark upper and lower edges of the magma chamber. Isolines of the Im\( E_y \) transformation are shown in Fig. 11d. There is a strong extremum located at the lower boundary of the magma chamber while the isolines delineate it. 3-D pseudo-structure of the medium is especially well seen from the volume image constructed basing on Im\( E_y \), (Fig. 12).

Thus, 3-D MT imaging basing on transforms of the in-phase and quadrature parts of the horizontal electrical field and also on the impedance phases appears to be a useful tool for determination of the geometric parameters of the complex volcanic environments. Methodologies of data interpretation aimed at 3-D imaging and monitoring conductivity variations in the magma chamber were elaborated in [14]. It is important to note that the obtained results allow three-dimensional imaging of the medium on the basis of the data measured not only on a surface of the Earth, but also at different levels, which are higher than the top point of a relief, that, in turn, makes possible the remote sounding of regions difficult of access.

Reconstruction of geoelectrical parameters of the Minou fracture zone (northern part)

The Minou fracture zone is an active fault system and runs from the East (Kurume City) to the West (Ukiha Town), North Kyushu, Southwest Japan [2]. The Minou fault is one of the components of the Imari-Matsuyama Line (IML) situated at the boundary between the northern and central parts of Kyushu Island. The fault runs on the northern foot of the Minou mountain range which is composed mainly of metamorphic rocks and located at the boundary between the mountain area and an alluvium plain extending along Chikugo river (Fig. 13).

Prominent low gravity anomaly is recognized at the northern side of the fault beneath the plain [6]. It is extending to the East along the IML [4]. The depth of the metamorphic formation is subsided abruptly in the northern side of the fault and its maximum depth was estimated to be approximately 1.5 km at the deepest zone [6]. The depth of the formation turns to be shallower at the northern side of the deepest zone. This structure could be considered as a graben buried in a thick Quaternary sediment.

No marked displacement of the basement was detected by the gravity data measured above the fault. It seemed to have been active at the southern wail of the graben before the Alluvium time. The active part moved then to the south and a new activity has been started at the topographic discontinuity in recent times. This fault displacement suggests that extensional movement has been prevailing in this area during Quaternary.

In order to determine the geoelectrical structure beneath the northern part of the Minou area as well as the parameters of a dipping seam presumably located in this zone a scalar controlled source audio - MT survey was carried out. CSAMT data collection in the studied area was arranged in four major measurement lines, which cover the surveyed area around the fault zone (Fig. 14).

The electromagnetic field of the controlled source (electric dipole) was approximated in a far zone by a plane wave. 3-D image of the resistivity beneath the northern part of the Minou fault zone was obtained by a synthesis of Bostick transforms of the apparent resistivity component \( \rho_{xy} \) beneath each site along profiles L1 - L4 (restricted by the rectangle in a Fig, 14) for 14 frequencies ranged from 2 Hz up to 16384 Hz in a binary step [16].
Fig. 11 Pseudo-sections of $\phi_{\text{det}} \times 10^{-1}$ (a), $\phi_{xy} \times 10^{-1}$ (b), $\text{Re} E_s \times 10^1$ (c) and $\text{Im} E_s \times 10^1$ (d) for volcano model shown in Fig. 10 [12].
distance 2300 m from the northern edge. It is manifested mainly beneath the profile L1 and gradually goes to pieces in the western direction. The dip angle is about 45 degrees, the resistivity contrast between the seam and surrounding medium is approximately 2-5, while the resistivity of the near-surface layer (its thickness equals to 300 - 400 m) is approximately 150 Ohm-m and the resistivity of the basement is around 100 Ohm-m.

In order to check the inversion result independent interpretation of the data in the frames of quite different inversion paradigm was carried out. It is based on Artificial Neural Network (ANN) recognition method extended to 3-D electromagnetic data interpretation in [15, 19, 20].

So that the ANN learns the correspondence between data and desired geoelectric parameters, it is first necessary to formulate the hypothesis on the class of inversion models. This is difficult in the general case, but quite possible in some practically important situations. It is worth to note that it is meant only the assumption on the class of models for which the solution is sought rather than considerably more stringent constraints on the parameters values (1-D layering and/or target geometry) used in the applications of the known inversion methods.

Fig. 15 shows the volume apparent resistivity distribution in the considered area. It is seen that in spite of the general 3-D resistivity distribution in the plane part of the Minou area is rather complicated, some dipping low resistive seam (with resistivity less than 35 Ohm.m) could be revealed. It starts from the depth 250-300 in in a northern part of the considered region and ends at the depth 1000 m approximately at distance 2300 m from the northern edge. It is manifested mainly beneath the profile L1 and gradually goes to pieces in the western direction. The dip angle is about 45 degrees, the resistivity contrast between the seam and surrounding medium is approximately 2-5, while the resistivity of the near-surface layer (its thickness equals to 300 - 400 m) is approximately 150 Ohm-m and the resistivity of the basement is around 100 Ohm-m.

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Fig. 16. 3-D class-generating model used for ANN interpretation of electromagnetic data: C, C1 and C2—conductivities of the fault, first and second layer, correspondingly; D, L, W and A—its depth, length, width and dip angle, correspondingly [16].

Expert System MT-NET trained in advance [18, 20] was applied to the reconstruction of these geoelectrical parameters given scalar CSAMT data collected in a northern part of the Minou area. Apparent resistivities \(\rho\), and phases \(\phi\), measured along profiles L1 - L4 on five frequencies (8Hz, 32Hz, 128 Hz, 256 Hz, 1024Hz) practically coinciding with those in the synthetic data were used for ANN reconstruction. The results of ANN data interpretation of the northern part of the Minou fault zone are summarised in the Table 2 [16].

Table 2. ANN reconstruction of the seam parameters in the Minou fracture zone (northern part).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>C1/C2</th>
<th>Width (m)</th>
<th>Length (m)</th>
<th>C/C2</th>
<th>Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>308</td>
<td>0.36</td>
<td>641</td>
<td>1461</td>
<td>5.92</td>
<td>45</td>
</tr>
</tbody>
</table>

Comparison of these results with those obtained by 3-D EM imaging and with other geophysical data indicated that parameters of the Minou geoelectrical structure were detected quite reliably in spite of the insufficiency of the data used [19].

Mapping of saltwater intrusion zone using AMT-data (a model study)

The problem of fresh waters of lakes and other reservoirs salinity becomes more and more pressing, so the development of effective methods of remote control over the level of their salinity becomes more and more urgent. Since with the change of a level of the salt content in a fresh water its electrical conductivity also changes, one of the possible ways of the solution of this problem is the pursuance of magnetotelluric monitoring of an electrical conductivity of water. Depending on selected matter for inquiry the details can vary, but the key basis of the approach can be shown on the following hypothetical task [11].

Statement of the problem

It is necessary to detect with the help of audio-MT sounding the fact of seawater intrusion into the freshwater aquifer and, if possible, to map the border of the salted water. The geoelectric model relevant to such problem is given in a Fig. 17. The values of \(\sigma = 0.05\) S/m and \(\sigma = 0.4\) S/m correspond to an electrical conductivity of the ground, saturated with fresh and salted water, accordingly. The electrical conductivity of sea water is equal to 4 S/m.

The data

MT data were calculated at frequencies 50, 100 and 200 Hz at two polarizations of a primary field. It was assumed that in practice the data can be measured only on the ground surface, so during the solution of the inverse problem the values of synthetic electric fields on the land surface (in area, restricted by projection to a surface of horizontal boundaries of the domain of search) were taken into account only.

Prior information

In the solution of the set problem it was supposed, that
1) 1-D layering in considered region is known from other geophysical methods;
2) zone of a probable ground water salinity is restricted to area, which in a Fig. 17 is marked by a dashed line;
3) inside the domain of search the electrical conductivity of water with equal probabilities can take the values \(\sigma = 0.05\) S/m (conductivity of the ground saturated with a fresh water) and \(\sigma = 0.4\) S/m (conductivity of the ground saturated with salty water), that corresponds to uncertainty of an expert estimation of the fact of the freshwater salinity.

3-D inverse problem was solved in [11] using the INVERS-3D program, implementing the Bayesian approach developed in [17, 18]. Fig. 18 shows vertical \((a)\) and horizontal \((b, c, d)\) slices of a posterior distribution of an electrical conductivity at depths 2, 4 and 6 m, accordingly. In the lowest layer of salted water (from 6 to 8 m, see Fig. 17) the posterior electrical conductivity did not exceed an average prior estimation \((0.225\) S/m). On the other hand, three high layers were detected and contoured quite well. In a Fig. 18 the boundaries of the salted zone both in vertical and in horizontal projections are precisely visible.

Thus, the audio magnetotelluric sounding method can be successfully applied to mapping salty water intrusion zones and to monitoring variations in physical properties of the near-surface layer (first tens meters), which lead to its electrical conductivity alteration.

Conclusions

Thus, it is demonstrated that electromagnetic induction
data could serve as an important carrier of information about the Earth's geological structure. Advanced interpretation methods developed recently enable construction of three-dimensional geoelectric models both without prior geological/geophysical information and taking into account not only such data, if available, but also the results of past observations and formalized human experience.

Fig. 17. Geoelectrical model relevant to problem a/ground water salinity with a marine water a - vertical section in a symmetry plane, b - horizontal cross-section in a bottom layer of the domain of search, border of which is designated by a dashed line [11].

Three-dimensional geoelectric models of the Juan de Fuca subduction zone, MinamiKayabe geothermal area, Minou fracture zone are constructed basing on array data. On the other hand, computer analysis of EM fields behavior in hypothetical models of volcanoes, freshwater aquifer, etc., allows to determine in advance, first, the most effective surveying strategy and, second, the interpretation tools to be used depending on the quality and volume of both prior information and the data.

Acknowledgements

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Fig. 18. Vertical (a) and horizontal (b, c, d) sections of a posterior conductivity distribution in the domain of search [11].

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