Numerical modeling of fault structures in the Kurai basin of Gorny Altai based on data from direct current methods

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Abstract. The southern site is located in the junction zone of the Southwestern and Eshtykel bench, where vertical electrical soundings were performed, and a preliminary fault-block depth model was built based on the results of field data interpretation using a horizontally layered model. Comparison of geoelectric and seismological data showed that the epicenters of significant earthquakes (M> 4) are concentrated in the identified faults. In the central site, three profiles of electrotomography were made through a bench, well expressed in the relief. Three-dimensional modeling was used to verify and clarify the structural features of both sections. Modeling is performed using programs EMF_DC3Dmod (GPU) - an accelerated version of the program EMF_DC3Dmod for vertical electrical sounding and SCALA-48 (GPU) for the method of electrotomography. The study is relevant for the tasks of geodynamics, seismic zoning and seismic hazard assessment.

1. Introduction

The Kurai basin belongs to the large, inhabited depressions of the Gorny Altai. It is part of the Chuya-Kurai seismically active zone with a high probability of strong earthquakes. Geological and geophysical studies have shown that from the south the depression is limited by the deep Eshtykel bench with fractured sides. Faults of various lengths and strikes are traced throughout the entire territory of the depression and its mountainous framing. At present, according to seismological data, an increased seismic activity is observed in the southern part of the depression. Geoelectrical exploration works were carried out on the territory of the depression in different years. In particular, according to the TEM data, we obtained up to the reference horizon (basement) for the entire territory of the Kurai depression, since the depth of the VES method is limited in some areas with high-resistivity deposits. Application of electrotomography at the top of the incision. Thus, an area survey was created using electrical prospecting methods, which allows the use of three-dimensional programs. In figure 1 shows the profiles and measurement points, blocks and faults identified by geologists, earthquake epicenters, and the study areas are marked with blue rectangles.

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The purpose of numerical three-dimensional modeling is to clarify the structure of individual sections of the Kurai depression, within which there is an increased seismic activity. Particularly important is the task of determining the true position of the fault structures and the determination of the possible angle of inclination of the displacer. Such information is necessary to build a realistic model of the study areas and is important for geodynamic problems, for example, to clarify the stages of the formation of a depression. In particular, it is the significant inclination of the fault displacer that determines the degree of thrusting of the mountain massifs that bound the depression onto its sedimentary filling and the formation of a sedimentary basin as a ramp-type structure [1]. The ongoing tectonic processes affect the modern structure of the depression. Faults are often distinguished and characterized by the chains of earthquakes confined to them. The number of events, their magnitudes in the fault area affect the magnitude of the resistivity variations and ultimately determine their amplitude, by which one can judge the fault activity and estimate the seismic hazard of the territory.

2. 3D Modeling software for direct current methods
For the study of intermontane depressions, given the complexity of their structure, it is three-dimensional programs that are constantly being improved are relevant. Three-dimensional modeling for direct current problems by the methods of vertical electrical sounding and electrotomography is reduced to modeling the distribution of the electric potential of a point source in a complexly constructed environment.

Figure 1. Block scheme of the Kurai basin (Deev) with measurement points. The blue rectangle marks the 3D modeling area.
We represent the potential of the electric field $U$ as the sum of the anomalous potential $U^a$ and the primary potential $U^0$ associated with a field source located in a homogeneous medium with conductivity $\sigma_0$:

$$U = U^0 + U^a.$$  \tag{1}

For the anomalous potential $U^a$, the Poisson equation is valid

$$\text{div}(\sigma\nabla U^a) = -\text{div}((\sigma - \sigma_0)\nabla U^0)$$  \tag{2}

$\sigma(r, \varphi, z)$ - conductivity in the medium. With distance from the source, the potential attenuates as $1/R$, therefore, for the function $U^a$ away from sources $U^a\big|_{r=R} = 0$, $U^a\big|_{z=\pm z} = 0$.

A parallel algorithm for solving equation (2) for the lateral logging method is described in detail in [2]. For the method of electrotomography and vertical electrical sounding, fast parallel algorithms are described in [3]. The process of solving these problems consists in discretizing equation (2) by the finite difference method using a conservative scheme on inhomogeneous grids and then iteratively solving a system of algebraic equations. The method of conjugate gradients with its own preconditioner is used, which provides full parallelism and speed of computations on the GPU [4].

A fast solver significantly speeds up the work, but for solving practical problems, especially for areas with a particularly complex structure, this is not enough. To eliminate errors when compiling a starting model manually, it is necessary to initially create a digital model of the study area, and also be able to promptly make changes to the model - options for possible vertical, sub-vertical (inclination of the displacer up to 15 degrees) and inclined faults (> 15 degrees). For this purpose, 2 interfaces were written. Using the first one, it is possible to construct an input model based on previously constructed options using one-dimensional and two-dimensional inversion programs according to the data of each VES point. To create a model, you need to enter the coordinates of the VES point, as well as the thickness and resistivity of each layer. Further, the input model will be automatically built with a partition, as in [5]. The use of the second interface allows introducing faults both vertical and with different inclination of the displacer into the already constructed model.

The method of electrotomography differs from VES in the methods of obtaining field data; by changing the configuration of the installation, it is possible to obtain profiles of the length required for the study. For ERT, an interface was also written, with the help of which the apparent resistivity is calculated for the main and overtaking profiles with specified settings and spacing.

3. Modeling based on VES data in the Eshtykel bench

The modeling area is shown in figure 2 with a red rectangle. The starting model is formed from one-dimensional models of the first stage of interpretation within the framework of a horizontally layered model using 22 VES points. It should be noted that the curves obtained at points 51, 52, 40, 120 do not allow determining the depth to the foundation, since they do not go to the right asymptote. Therefore, the depths to the basement for these points were obtained from the results of interpretation of the TEM data, for points located nearby. At the first, three models were considered within the area of equivalence (Table 1), of which the optimal one was selected based on the results of calculations and analysis of residuals.
Figure 2. Modeling area in the Eshtykel bench.

Table 1. Equivalent Models.

| Model 1 | Model 2 | Model 3 |
|---------|---------|---------|
| Resistivity, Ohm∙m | Thickness, m | Resistivity, Ohm∙m | Thickness, m | Resistivity, Ohm∙m | Thickness, m |
| 1913 | 26 | 1200 | 8 | 795 | 6 |
| 410 | 28 | 1800 | 26.3 | 1913 | 26 |
| 10000 | 5 | 410 | 30 | 410 | 28 |
| 69 | 276 | 90 | 276 | 10000 | 5 |
| 3600 | 3600 | 69 | 276 | 3600 |
Then, two faults were added to the optimal model. The position of the faults was initially chosen according to the geological data of the fault-block structure of the depression [1]; the location of earthquake epicenters was also taken into account (figure 1).

Examples of 3D modeling results are presented in figures 3(a), 3(b) for VES points 54, 118. For each VES points, several models are considered, including a fractured model. Comparison of the theoretical and field curves, the obtained residuals show that the existence of faults is quite justified. Thus, the structure in the area of the Eshtykel trough has been clarified, and the reliability of geological data on the identification of faults has been confirmed.

![Figure 3](image)

**Figure 3.** (a) Comparison of 3D modeling results with different models and field data of VES point 54. Average discrepancy - 6.02%, minimum - 5.71%. (b) Comparison of 3D modeling results with different models and field data of VES point 118. Average discrepancy - 4.99%, minimum - 4.04%.

4. **Modeling according to electrotomography data in the central part of the Kurai basin bench**

In the second area of investigation, an extended bench with a height difference of 10 m is clearly traced on the surface (figure 4). There are two hypotheses of its origin based on the results of geological studies. The bench can be attributed to both the fault structure and the result of surface denudation processes.

To clarify the structure of the bench through this structure, measurements were made on four profiles by the method of electrotomography (figure 4).
As a result of three-dimensional inversion of the ERT field data, a model was obtained in which an inclined zone with low resistivity values (less than 400 Ohm·m) is clearly distinguished in relation to a higher-resistive host medium. For the inversion, the DiInSO [6] program was used. The lowest resistivity values are observed at depths of more than 20 m, which most likely indicates the presence of a fault (figure 5). Fault zones are usually manifested by a significant decrease in resistivity, which is confirmed by works in other parts of the Altai depressions, where electrotomography was performed in conjunction with trenching [7]. Measurements at the study area were carried out annually in the period 2015-2018. The inversion results for different years show that the resistivity of the fault zone changes over time, which may be associated with variations in the seismic activity of the area (figure 5(a),(b),(c)).
Figure 5. Models in the area of the bench based on the results of three-dimensional inversion of the field data of ERT using the DiInSO program. (a) for 2016 (b) for 2017 (c) for 2018.
To verify the structure in the area of the bench, three-dimensional modeling was carried out using the SCALA-48 (GPU) program for a model built using geoelectric parameters averaged over different years. In figure 6 shows a comparison of the VES-ERT curve, extracted from the field data of electrotomography, with a theoretical calculation. Table 2 shows the discrepancies in the percentage of field and theoretical data, it can be seen that the maximum values were obtained at separations greater than 50 m, which corresponds to depths of more than 20 m, i.e. in the fault zone.

![Figure 6. Comparison of the VES-ET field curve with the theoretical one for model 1, profile 1.](image)

**Table 2. Discrepancies of field and theoretical data.**

| AB/2, m | Field data Resistivity, Ohm-m | Theoretical Resistivity, Ohm-m | Discrepancy, % |
|---------|-------------------------------|--------------------------------|----------------|
| 7.5     | 2272.71                       | 2066.408                       | 9.077362       |
| 12.5    | 2314.74                       | 1962.758                       | 15.20613       |
| 17.5    | 1990.58                       | 1713.648                       | 13.91212       |
| 22.5    | 1638.37                       | 1404.817                       | 14.25522       |
| 27.5    | 1387.79                       | 1145.874                       | 17.43174       |
| 32.5    | 1217.26                       | 945.6836                       | 22.31047       |
| 37.5    | 1036.05                       | 888.1571                       | 14.27469       |
| 42.5    | 941.299                       | 767.2743                       | 18.48772       |
| 47.5    | 876.046                       | 677.8912                       | 22.61922       |
| 52.5    | 816.019                       | 609.4015                       | 25.32019       |
| 57.5    | 773.044                       | 553.8478                       | 28.35494       |
| 62.5    | 714.521                       | 510.3811                       | 28.57017       |
| 67.5    | 674.304                       | 495.5183                       | 26.51412       |
| 72.5    | 629.43                        | 473.8376                       | 24.71958       |
| 77.5    | 595.933                       | 456.4383                       | 23.40779       |
| 82.5    | 565.883                       | 448.6472                       | 20.71731       |
| 87.5    | 519.02                        | 452.3901                       | 12.83764       |
| 92.5    | 475.573                       | 446.07                         | 6.203672       |
| 97.5    | 447.417                       | 440.7083                       | 1.49942        |
| 102.5   | 419.79                        | 428.2563                       | 2.016796       |
| 107.5   | 400.879                       | 414.7158                       | 3.451605       |
Then, a three-dimensional inversion of the model data was performed. Its result is shown in figure 7. The use of average geoelectric parameters for three years of measurements and the chosen perspective of the figure well reflect the presence of a low-resistivity fault zone.

![Figure 7. Three-dimensional inversion of model data without taking into account the relief (DiInSO program).](image)

5. Discussion and conclusion

In our study we used the data of two direct current methods – vertical electrical soundings and electrotomography. Despite a common theoretical basis, these methods have different capabilities. First of all, they differ in the depth of research. For VES, it shows several hundred meters, depending on the spacing of the generator set and the parameters of the geological section. For electrotomography, the depth is limited not only by the parameters of the section, but by the capabilities of instrumental developments, for example, for the most common domestic devices it is 50 - 100 m. range of tasks. But the clear advantages of ERT are in high detail and advanced software, therefore, the method is currently widely used for a very wide range of tasks.

For the southern site of the Kurai basin, field work was carried out using the VES method. Based on the results of the first stage of interpretation using a horizontally layered model, it is not possible to confirm or deny the presence of faults in this area. It can only be considered that the results do not contradict the geological data. Calculations with three-dimensional models showed that the insertion of faults improves the discrepancy between the field and theoretical data, thereby justifying the insertion of faults that limit the Eshtykel bench.

Modern mobile technologies of electrotomography are used in two classes of tasks, first of all, for studying the structure of the upper part of the section, and secondly, for monitoring the geological environment. When working in seismically active areas, using this method, it is possible to obtain detailed geoelectric characteristics of the fault zone (distribution of resistivity, geometric parameters) and then observe the changes in the selected parameter over time. Such observations make it possible to identify active and, possibly, seismogenic faults, which is extremely important for the problem of seismic safety in populated areas, which include the intermontain depressions of Gorny Altai.

The results of interpretation of field data by the method of electrotomography in the central part of the Kurai basin showed that a low-resistivity zone was identified, which, taking into account the results of three-dimensional modeling, can be attributed to a fault zone. The used approach to the analysis of materials allows us to conclude that changes in resistivity for three years of measurements in the fault zone reach 20% or more. The reasons for such significant variations in resistivity are still
not fully understood, which may be associated not only with seismicity, but also with the hydrogeological regime, for example. Nevertheless, taking into account the amplitude of the resistivity variations, it is recommended to continue regular observations in the central area.

The developed three-dimensional software tools make it possible to quickly carry out calculations even for the most complex models, are effectively used for verifying constructions, choosing the optimal model from several possible ones. Additionally, the created interfaces are aimed at the automated construction of starting models, which eliminates errors, facilitates and accelerates the work of interpreters.

The results obtained in the article make it possible not only to clarify the structure of territories with probable fault zones, but they are also important for the interpretation and analysis of monitoring data for changes in geoelectric parameters under the influence of geodynamic processes in any seismically active regions.

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