

Electromagnetic 3D Tomography of the Elbrus Volcanic Center According to Magnetotelluric and Satellite Data

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Abstract—A geoelectric 3D model of the potentially active Elbrus volcano and its vicinities has been constructed using magnetotelluric data, which takes the volume model of the tectonic fragmentation field developed based on deciphering satellite photographs into account. An original method of searching for the correlation and determination of the character of the interrelation between the ground-based and satellite data has been used in this construction. The geoelectric 3D model constructed includes two conducting objects located at different depths. One of the objects, with a resistivity of 25–40 Ω m, located at depths of 0–10 km, is most intense at a depth of 5 km, where the object is quasi-isometric in shape and has a radius of 10 km along the 40–60 Ω m contour lines. Another object with a resistivity of 10–40 Ω m is located at a depth of ~45 km, where its dimensions along the contour line for 40 Ω m are 35 and 15 km in latitude and longitude, respectively. The thickness of the conducting core is approximately 20 km. The upper and lower objects can be interpreted as a volcano magma chamber and a volcano parent chamber, respectively.

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INTRODUCTION

Results of the geological–geophysical studies of volcanism in the Caucasian region performed for the last decade indicate that the level of tectonic stresses is increasing in the Earth's crust and especially within the Transcaucasian transverse uplift [4, 6], which could result in an activation of volcanic centers in the Great Caucasus.

Development of 3D models of the Earth's crust and upper mantle depth structure using data of the geophysical fields in the regions of active and potentially active volcanoes is an important problem from the standpoints of volcanic activity prediction, comparative geodynamics, and general tectonics. The present work is aimed at creating a geoelectric 3D model of the region in the vicinity of the potentially active Elbrus volcano located near densely populated regions of Russia and Georgia.

Electromagnetic (EM) measurements over the entire volcano surface should be used to construct a 3D model of the area but they are difficult to perform due to a complex surface topography and/or inaccessibility of individual regions near the volcano summit. This problem can be solved using a new approach combining the analysis of ground-based and satellite data. This approach is based on the method of maximal correlation similarity (MCS), which makes it possible to fill gaps in EM measurements on the Earth's surface using geological or geophysical data that correlate with rock resistivity.

The MCS method was used to construct a 3D model of the Elbrus volcano resistivity based on the magneto-

telluric (MT) data obtained on the submeridional profile that crossed the volcano summit [1]. To fill the gaps in the EM data, we used maps of the tectonic fragmentation of the Earth's crust which were constructed by Nechaev [11] by deciphering satellite photographs of the Earth's surface. An analysis of the distribution of the tectonic fragmentation coefficient (TFC) and the resistivity, specified at the same section sites of the submeridional profile, made it possible to distinguish the subset of sites where the correlation coefficient between these two parameters is maximal. The artificial neuronet was subsequently trained to correspond to the TFC parameters and resistivity and was used to reconstruct a 3D resistivity distribution over the TFC values in the entire region.

Thus, construction of the graph used to create the geoelectric 3D model of the Elbrus volcanic center (EVC) consisted of the following stages:

- (i) analysis of the TFC 3D model in the vicinity of the Elbrus volcano;
- (ii) determination of the character of the correlation between the TFC and resistivity values at the Cheget–Kislovodsk segment of the MT profile;
- (iii) construction of the 3D model of the lithospheric resistivity in the vicinity of EVC.

PREVIOUS GEOLOGICAL–GEOPHYSICAL STUDY OF THE REGION

The volcanic centers of the Great Caucasus, the largest of which is the Elbrus EVC (43°20' N, 42°27' E),

are located within the Central Caucasian tectonic block. This block was formed from a rigid crystalline rock mass during the Hercynian stage of tectogenesis. The tectonic boundaries of the Great Caucasus meganticlinorium are longitudinally extensive deep faults, which are adequately traced in geophysical data. The main of them are located in the Pshekish–Tyrnyauz zone in the north (with the EVC at the rear of this zone) and the Kakhetin–Lechkhum suture zone in the south, which separates the Great Caucasus from the Transcaucasian intermontane depression. The Pshekhin–Adler, Shtavler–Elbrus, and Samur faults are among the main transverse faults striking in the anticaucasian direction. The EVC at the northern slope of the Main Caucasian Range is confined to the intersection between the longitudinal Syltran fault zone and the transverse Shtavler–Elbrus fault. The network of longitudinal and transverse faults within the Great Caucasus meganticlinorium is responsible for the block character of this structure [5].

Activity of the Elbrus, Kazbek, Aragats, and other volcanoes accompanied formation of the folded–nappe Caucasian structures, which was most intense during the Middle Pliocene–Early Pleistocene Caucasian phase of the Alpine tectonic–magmatic epoch [15]. At present, Elbrus, with its western (5642 m) and eastern (5620 m) summits, is the highest mountain in Europe and one of the largest glaciation centers in the Caucasus. The Elbrus summits (which are crossed by the Syltran, supposedly magma controlling, fault) represent Neopleistocene–Holocene volcanic structures of different types, dimensions, and times of formation. Both summits, forming a common cone below 5400 m, are confined to a huge, supposedly Middle–Late Pleistocene, caldera of ~230 km² in area. A recent study of samples taken from lava sheets, ignimbrite horizons, and ash material, together with paleomagnetic and geological data, allows us to conclude that the Elbrus volcanic rocks were probably formed from the Late Pliocene–Early Pleistocene to the Holocene (inclusively). The last eruptions occurred in the 1st–2nd centuries, and catastrophic eruptions took place in the Late Pleistocene. During other periods the volcanoes were relatively quiet. The present-day high heat flow density for Elbrus (which is an order of magnitude higher than the background value for the Central Caucasus, 71–193 mW m⁻²), the high geothermal gradient below the volcano (100°C km⁻¹), rather high temperature of the deep carbonic-acid water (22–24°C), and fumaroles are possible manifestations of an uncooled magma hearth [6].

The Central Caucasian crystalline rock mass is part of the Transcaucasian transverse uplift (TTU), a large meridional zone, which is clearly defined in its topography, fault tectonic strength, and geophysical fields and is characterized by increased tectonic–magmatic activity. The TTU zone includes the Armenian and Dzhavakhet volcanic plateaus within the Little Cauca-

sus meganticlinorium and the Dzirul protrusion of the crystalline basement in the Transcaucasian intermontane depression. Further northward, the TTU separates the central and eastern sectors of the Great Caucasus meganticlinorium and includes the Mineral'nye Vody protrusion and the Stavropol uplift. High heat fluxes, thermal manifestations, Neogene–Quaternary volcanic activity, and high seismicity are, as a rule, typical of the above tectonic elements [6, 7].

Recent geophysical studies (using methods for processing video information obtained from satellites, as well as gravimetry, seismology, seismic tomography, and geoelectric studies) indicate that the Elbrus magma chamber is rather close to the surface (~7 km) [6]. Taking into account the fact that earthquake hypocenters in the greater part of the Caucasus, including the Elbrus environs, occur at depths of 5–15 km, we cannot rule out the possibility that increased seismicity within the TTU could initiate reactivation of the volcano and, after the prolonged period of quiescence (1700–1800 years), result in catastrophic consequences.

The possibility of TTU activation makes it necessary to study the structure of the lithosphere in the vicinity of the volcano in order to:

- (i) determine parameters of volcanic structural elements (magmatic hearth and chamber and magma transfer channels joining these elements) and
- (ii) predict zones of possible lava flows.

The knowledge of the parameters of volcanic structural elements makes it possible to efficiently organize a network of ground-based long-term observations of the evolution of the magmatic system, during which the geometric characteristics of the elements (dimensions, configuration and relative position) and the geophysical parameters (i.e., the reflecting variations in the chemistry and properties of the medium) are changing.

GEOELECTRIC SECTION OF THE ELBRUS ENVIRONS ACCORDING TO MT DATA

More than 60 MT soundings (MTs) at an interval of 2.5–3 km were performed in 2001–2002 on the Cheget–Elbrus–Kislovodsk–Essentuki–Aleksandrovskoe profile which is 192 km in length [1]. Electric exploration was included in the general complex of geological–geophysical studies aimed at studying the depth structure of the seismic zones and zones of tectonic–magmatic intensification in the Central Caucasus and adjacent southern periphery of the Scythian Platform. The studies were performed by FGUP Kavkazgeols'emka (TEM, FS–IP, and AMT electric exploration methods; magnetic exploration; repeated interpretation of previous studies, including gravity exploration and geological support), MGNPVP Sei-Eko-Geon (deep studies using CWMS), and Nord West Ltd (MT) [1, 8, 9].

MT data were interpreted in the class of two-dimensional models taking into account seismic, gravimetric,

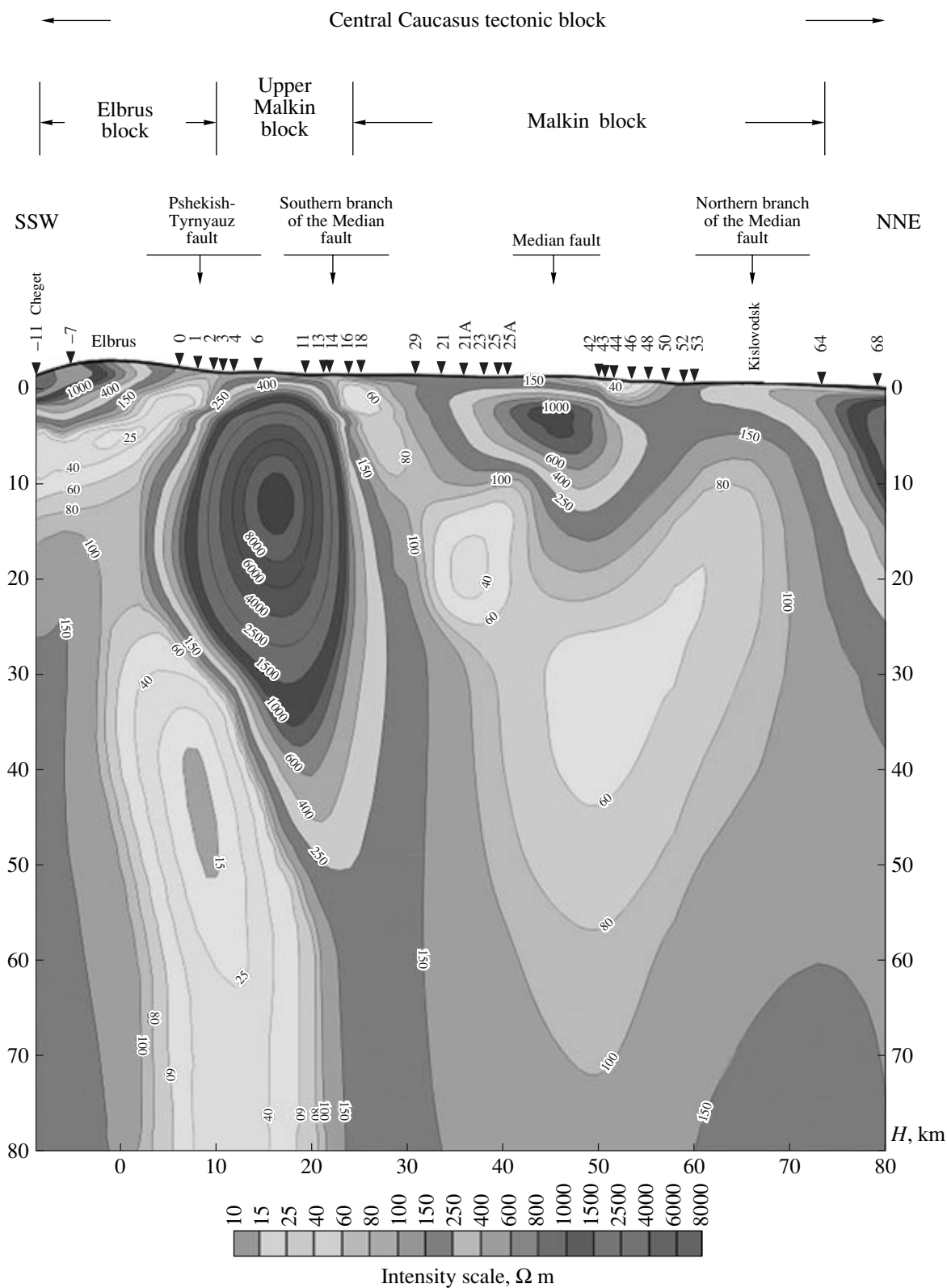


Fig. 1. Vertical section of the resistivity of the earth's crust constructed for the Cheget–Kislovodsk part of the Elbrus profile [1]. The profile is oriented across the Caucasus strike and includes the Elbrus volcano. The profile is referenced to the conventional coordinate system. Resistivity contour lines are given in Ω m.

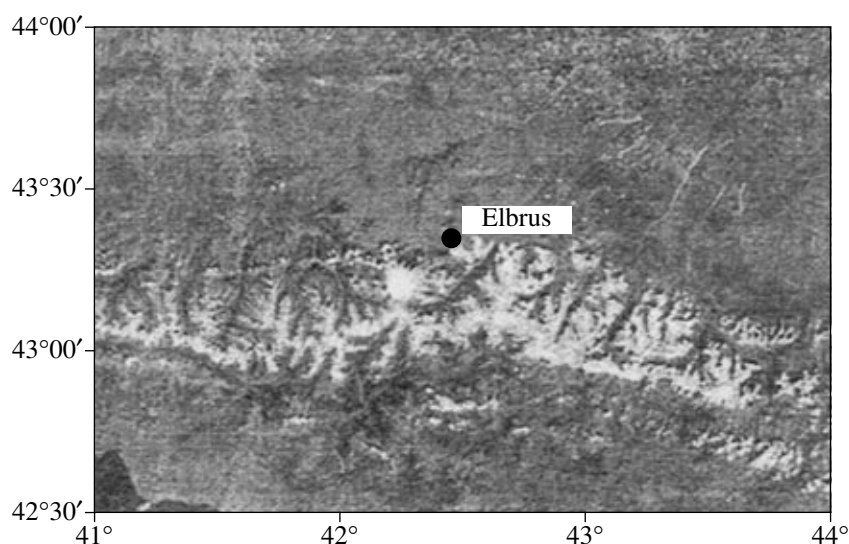


Fig. 2. Satellite photograph of the Northern Caucasus [11].

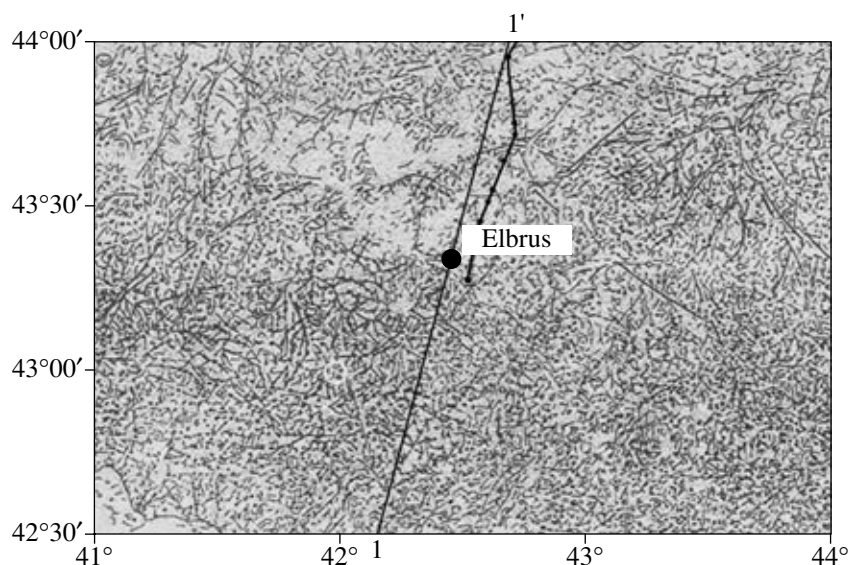


Fig. 3. Network of lineaments obtained as a result deciphering of satellite data [11]. The southern fragment of the Elbrus profile (Cheget–Kislovodsk, broken line) studied using the geoelectric methods [1]; (1–1') the profile of the tectonic fragmentation field [10].

and magnetic data. Figure 1 presents the southern fragment of the geoelectric structure of the considered region according to the MT version. The location of the southern section of the Elbrus profile is shown by a broken line in Fig. 3. The Cheget–Kislovodsk fragment (MT sites from –11 to 68) corresponds to the folded-block structure of the Great Caucasus. The depths and the location of MT sites in kilometers are plotted on the ordinate and abscissa, respectively, in Fig. 1. This paper uses the right-hand coordinate system, where the x , y , and z axes are directed northward, eastward, and downward, respectively. The origin coincides with the Elbrus location and is at sea level. The contour lines of resis-

tivity are digitized in Ω m. The section is constructed to a depth of 80 km.

In Fig. 1 the megablock of the Great Caucasus folded-block structure (composed of the most ancient Proterozoic metamorphic complexes, Lower–Middle Paleozoic sedimentary–volcanogenic sequences, and supposedly Middle–Upper Paleozoic ultrabasites and granitoids) is represented by three blocks with different geoelectric characteristics in the composition of the Central Caucasian tectonic block. These blocks are (from north to south):

- (i) the Malkin block of length ~50 km (MT sites 16–64),

(ii) the Upper Malkin block extending for ~15 km (MT sites 2–16),

(iii) the Elbrus block of ~18 km in length (MT sites from –11 to 2).

In the Malkin block, the upper crust resistivity is not higher than 1000 Ω m. The crust resistivity quickly decreases and is already only 150 Ω m at a depth of 15 km. The Malkin block is separated from the adjacent high-resistivity Upper Malkin block and Mineral'nye Vody block (joining the previous block from the north and not shown in Fig. 1) by low-resistivity zones corresponding to the northern (the boundary between the Malkin and Mineral'nye Vody blocks) and southern (the boundary between the Upper Malkin and Malkin blocks) branches of the Median fault. At a depth of ~25 km, both branches are combined into a region of decreased resistivity submerging into the subcrustal lithosphere.

In the high-resistivity Upper Malkin block, the resistivity of the upper crust (depths of 8–15 km) is higher than 10000 Ω m and decreases to 600–400 Ω m at depths of 40–45 km and to 150 Ω m at a depth of 65 km in the subcrustal lithosphere.

The Elbrus low-resistivity block, located in the profile southern section, is separated from the Upper Malkin block by a gradient zone coincident with the Pshekish–Tyrnyauz fault. Judging by the character of the resistivity contour lines in the geoelectric depth section and the contour lines of relative anomalies in *P*-wave velocity, constructed based on data of seismic tomography [8], the Pshekish–Tyrnyauz fault is bent. In the upper crust, a fault steeply (80°) dips southward to a depth of 17 km and then sharply bends and dips northward at an angle of 70°. The fault terminates in the lower crust at a depth of ~50 km.

According to the MT data collected on Elbrus slopes and in the immediate proximity of this volcano, the resistivity of the volcanogenic formations is higher than 1000 Ω m, and that of the volcano crystalline basement (composed of the Proterozoic metamorphic complexes and Paleozoic granites) ranges between several hundreds and thousands of Ω m.

The upper crust resistivity decreases to 40–25 Ω m at depths of 5–10 km. A region of decreased resistivity rises northward from a depth of 10 km to sea level. One more low-resistivity region, with a resistivity of 25–15 Ω m at its center, is located in the middle and lower crust (at depths of 25–55 km and lower). This ~10-km-wide region, located at the rear of the Pshekish–Tyrnyauz fault, steeply dips northward behind this fault and propagates to subcrustal depths, i.e., to depths larger than 55 km. Figure 1 indicates the upper and middle–lower crustal regions of decreased resistivity as if they contain the core of the Upper Malkin high-resistivity block.

The geoelectric section of the Elbrus lithosphere generally reflects a standard change in geoenvironmental resistivity with depth [3]. The upper crystalline crust

at depths of 0–(10–15) km is characterized by large resistivity values (10³–10⁴ Ω m), whereas resistivity decreases by two–three orders of magnitude (several hundreds of Ω m) in the middle–lower crust because of a rise in temperature and pressure (and, consequently, a change in the rock physical state and chemistry). Two types of different-origin anomalies are distinguished against the general background of the resistivity section.

Anomalies of the first type are confined to the zones of tectonic dislocations, which supposedly correspond to deep faults that submerge into the mantle and are traced along the contacts of high-resistivity/high-velocity and low-resistivity/low-velocity blocks of the Earth's crust [1, 8]. In Fig. 1 these are the zones of the Pshekish–Tyrnyauz fault and the southern and northern branches of the Median fault. A high environmental conductivity in the fault zones is of an electrolytic origin and depends on two factors:

(i) the degree of mineralization of fluids, which come from deep horizons of the upper crust, that are formed as a result of chemical reactions in the middle–lower crust, and are carried away from the mantle;

(ii) the volume of the fracture–pore space in the upper crust occupied by fluid and the volume of inter-related microfractures in the middle–lower crust [3].

In other words, we observe *direct dependence of environmental conductivity on the degree of environmental fragmentation and permeability*.

The upper and the middle–lower crust conductivity anomalies, which are present in the Elbrus block section and are identified with the magma and parent chambers, are most probably related to partial melting of rock [6, 8] and can be classified as conductivity anomalies of the second type. The fragile, high-resistivity upper crust in the high-temperature regions of the lithosphere (the magma chamber and its source) is replaced by a plastic low-resistivity environment. In this situation we observe *the inverse relationship between environmental fragmentation and conductivity* (or, which is the same, *a direct relationship between environmental fragmentation and resistivity*).

Conductivity anomalies revealed within the Elbrus block correlate with results from interpreting the field of lithospheric tectonic fragmentation determined using satellite photographs of the Central Caucasus [6], which suggested utilizing these data in order to develop the 3D geoelectric model of the volcano.

When constructing the 3D model, we used the results of the profile MT sounding characterizing the Elbrus, Upper Malkin, and Malkin blocks. The extension of the southern section of the Elbrus profile (MT sites from –11 to 68) is approximately 90 km.

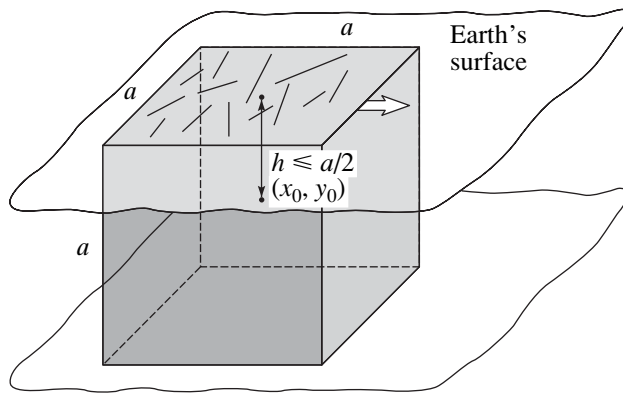


Fig. 4. Schematic processing of the lineament network map. Determination of the TFC for the considered volume of the geological environment: window with horizontal dimensions $a \times a$ moves over the entire scanned surface of the lineament network map; (x_0, y_0) coordinates of the sites for which a TFC value was calculated; (h) depth of study of the tectonic fragmentation field.

ASSESSMENT OF TECTONIC FRAGMENTATION OF THE ELBRUS LITHOSPHERE ACCORDING TO SATELLITE DATA

To fill gaps in electromagnetic data to be used to construct the geoelectric 3D model, we proceeded from the hypothesis that two characteristics of the geological–geophysical environment correlate in the EVC environs (namely, the resistivity of the environment and the degree of environmental fragmentation). This section considers the main principles for determining the coefficient of tectonic fragmentation of the environment and the specific features of the 3D field of TFC values of the volcanic system under study.

The tectonic fragmentation field of the lithosphere reflects the different types and orders of linear deformations of the environment which occurred during the entire process of geological evolution as well as the different materials which compose the lithosphere. This field was determined using the technique proposed by Nechaev [2, 11] which is based on the processing of data from satellite geological photographs of the surface of studied territories. In this case the lithosphere is represented as a hierarchically ordered 3D system of contact zones of rock blocks, fractures, ruptures, and faults of different rank and different predominant orientation, extension, and penetration depth in different regions of the Earth. On the Earth's surface, this system is represented as a network of lineaments, which is reconstructed using satellite photographs. The territory of our studies is located between $42^{\circ}30'–44^{\circ}$ N and $41^{\circ}–44^{\circ}$ E and occupied an area of 185×277 km centered at EVC (Fig. 2). The lineament network map presented in Fig. 3 was constructed as a result of the deciphering of these photograph in [11].

The TFC for the selected geoenvironmental volume was determined as the ratio of the total volume of inho-

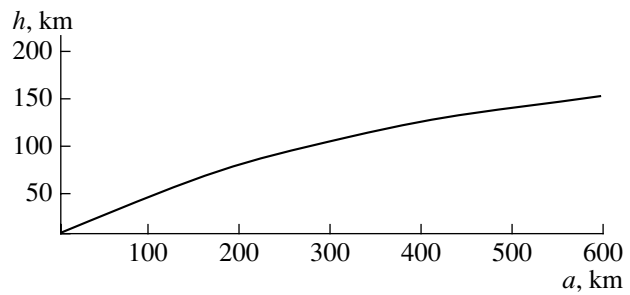


Fig. 5. Empirical dependence of the depth of study (h) on the survey scale (a) [11].

mogeneities (fractures) to the entire environmental volume and for a cubic object with a base side a (Fig. 4) is equal to:

$$(\text{TFC})_a = \sum_i \left(\gamma_i \frac{h_i l_i}{a^2} \right). \quad (1)$$

Here γ_i and l_i are the width and length of the i th lineament on the upper face of a cubic volume, respectively, and h_i is the depth of the i th fracture penetration into the chosen environmental volume.

If we assume that the fracture width is constant in the selected volume ($\gamma_i = \gamma = \text{const}$) and the fracture penetration depth within the selected volume is characterized by a certain average value ($h_i = h = \text{const}$), which can be treated as the depth of study, expression (1) can be rewritten in the form:

$$(\text{TFC})_a = C \cdot C_a \cdot l_a, \quad (2)$$

where $C = \gamma$ is a constant coefficient for the studied region, $C_a = h/a$ is a constant coefficient for the selected volume a characterizing the relative depth of study, and $l_a = (\sum_i l_i)_a / a^2$ is the specific length of lineaments, which is equal to the total length of all lineaments within the upper face of a cubic object with side a to the area of the side.

Thus, under the above assumptions, $(\text{TFC})_a$ is directly proportional to the specific length of the lineaments l_a and, consequently, can be considered as a measure of tectonic fragmentation of the lithospheric section at a depth h determined by a selected size a . For the selected site size $a \times a$, the depth h , to which a calculated $(\text{TFC})_a$ value should be related, is determined in [11] using the empirical relationship $h = f(a)$ constructed during the study of folded rock structures (Fig. 5).

The method for constructing 3D models of tectonic fragmentation fields proposed by Nechaev consists in the construction of slices at different depths by scanning the map of a lineament network with variable cells $a \times a$. Each slice constructed for fixed a presents information about distribution of the lithosphere tec-

tonic fragmentation field corresponding to the average level [11].

The fields of tectonic fragmentation of the Central Caucasus lithosphere, reflecting the lithospheric structure at different depths, are offered in [10, 11]. The minimal and maximal dimensions of a square cell (a) used for map scanning were 2 and 100 km, respectively. The TFC maps were constructed for depths of 1–50 km, and the values of the tectonic fragmentation field on these maps were calculated for a 1×1 km network. Vertical TFC sections were also constructed. All these materials, digitized using the same conventional units (hereafter, conv. units), form the 3D TFC model. The model reflects the regularities and specific features of the Central Caucasus lithospheric structure and therefore can be used to reconstruct the physical properties of rocks composing the lithosphere.

Figure 6 shows a vertical TFC section corresponding to the 1–1' profile oriented transversely to the Caucasus extension (Fig. 3), near which, and parallel to which, the Elbrus profile, which we studied using geoelectric methods, is located. The main components of the TFC section agree with those of the geoelectric section shown in Fig. 1. For convenience in comparing the sections, the location of the Elbrus, Upper Malkin, and Malkin crustal blocks and separating zones of tectonic faults are shown above the profiles in Figs. 6 and 1. Both the geoelectric and the TFC sections reflected the complex structure of the upper (fragile) crust (depths up to 10–15 km) which were represented by objects with average dimensions of 5–15 km. The TFC values of these objects changed by 20 to 120 conv. units and sometimes more.

The structure of the Elbrus lithosphere is simplified with increasing depth. In the southern part of the 1–1' profile, crossing the geological structures of the Great Caucasus southern flank, objects in the middle and lower crust were characterized by TFC values of 96–102 conv. units. In the northern part of the profile, the TFC values for the middle and lower crust objects were no greater than 70 conv. units. The Pshekish–Tyrnyauz fault zone, which is located in the central part of the 1–1' profile and separates the Elbrus and Upper Malkin blocks, manifested itself (as in the resistivity section) as a gradient zone. In the upper, narrowest, part of this zone, the TFC values were larger than 120 conv. units. With depth, the gradient zone widened and the TFC values decreased to 99–65 conv. units.

On the TFC vertical section, the region of decreased (90–20 conv. units) TFC values (14–0 km on the distance scale) was distinguished in the upper part of the Elbrus block upper crust (1–8 km on the depth scale) at the rear of the Pshekish–Tyrnyauz fault. This region of the map is shaded, and hachure marks were added to the 90 conv. units contour line. Based on the complex interpretation of the gravimetry, magnetometry, seismology, and geothermal data, as well as the data from other geophysical and geochemical studies, Nechaev interpreted

the region of decreased TFC values as the magma chamber of the Elbrus volcano [10, 12]. A zone of decreased resistivity (40–25 Ω m and less) corresponds to this region on the geoelectric section of the Elbrus profile.

The TFC slices for depths of 1–4 km [10] (Fig. 7) make it possible to follow the transformation of the anomalous region identified with a magma chamber along the section. This region can be understood as a system of closed concentric contour lines of TFC, the values of which change from the periphery toward the center from 90 to 20 conv. units. On the contour map for the depth of 4 km, the chamber shape, outlined by a contour line of 90 conv. units with hachure marks, is almost isometric, and the radius of the anomalous zone is ~5 km. In higher sections (e.g., depths of 3 and 2 km), the chamber shape extends submeridionally; the north-eastward branch, which extends from the main chamber body and is traced by the contour line of 100 conv. units, is clearly defined at a level of 2 km on the depth section. The map for a depth of 1 km indicates that the dimensions of the main chamber body decrease, and the chamber itself splits into channels [10].

On the slices for depths of 1–4 km, the Pshekish–Tyrnyauz fault zone appears as open TFC contour lines parallel to the north-northeastern map edge, i.e., along the strike of the Great Caucasus.

We now consider again the TFC vertical section of the lithosphere presented in Fig. 6. Objects that could be identified with the EVC parent chamber are not obviously visible on the section. We can assume that the volcanic source zone dimensions in the submeridional direction are smaller than the method resolution at depths of the possible location of this zone (less than 30–40 km). At the same time, the information from the 3D model of the Elbrus tectonic fragmentation field makes it possible to determine the region of probable localization of the magma chamber on the section corresponding to the submeridional profile. The geometry of the appropriate region can be determined from a joint consideration of the TFC map for the 30 km section (Fig. 6 in [11]) and the TFC vertical section along the sublatitudinal profile, i.e., the profile oriented along the strike of the Great Caucasus (Fig. 7 in [11]). The map makes it possible to determine the horizontal dimensions of the anomalous region (20 km in longitude and 40–65 km along latitude), and the TFC vertical section allows us to determine the depth of location (20 km) and vertical dimensions (20 km) of the anomalous zone. The zone of the probable location of the parent chamber, confined to the conjugation zone of the Elbrus and Upper Malkin blocks, is shaded and outlined by dashes in Fig. 6. The TFC vertical section in Fig. 7 in [11] also makes it possible to determine the intensity of the TFC anomaly, which is interpreted as a source zone: the center of this zone is within the closed contour lines

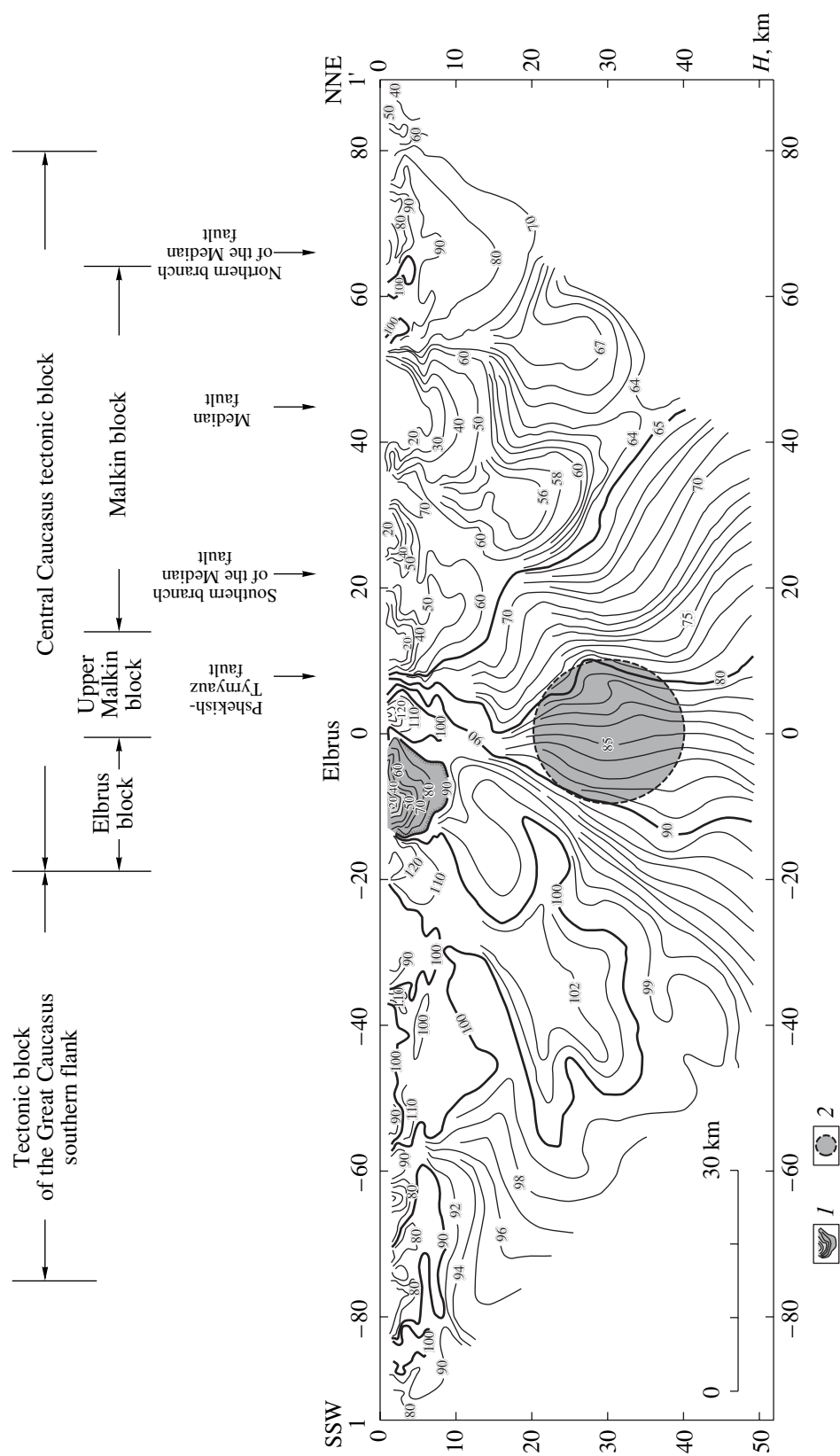


Fig. 6. Vertical section of the field of tectonic fragmentation (TFC) along the 1–1' profile [10] oriented across the Caucasus strike and crossing the Elbrus volcano cone. The horizontal location of the profile is shown in Fig. 3. The profile is referenced to the conventional coordinate system. TFC contour lines are given in conventional units. Contour lines without numerals show intermediate values. (1) The region of anomalously decreased TFC values identified with the Elbrus volcanic chamber [10, 12]; (2) the region of probable localization of the Elbrus volcano parent chamber determined from the data presented in [11].

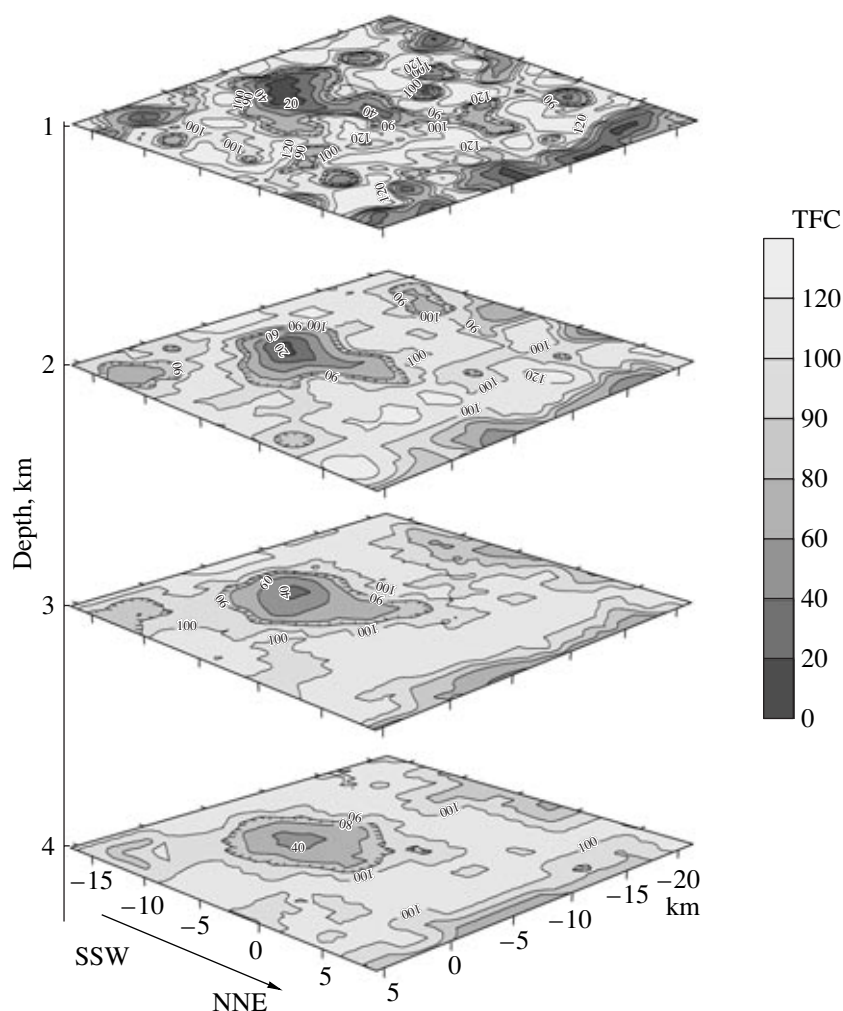


Fig. 7. TFC slices in the region of anomalously decreased values of the tectonic fragmentation field identified with the presence of the Elbrus volcano magma chamber in the upper Earth's crust. The maps correspond to depths of 1–4 km. The maps are referenced to the conventional coordinate system. TFC contour lines are given in conventional units. Hachure marks are added to contour lines of 90 conv. units.

for values of 84–87 conv. units, with background values of 95–96 conv. units for the TFC parameter.

The location of the described anomalous region of the TFC parameter is in good agreement with that of the low-resistivity zone distinguished on the geoelectric section of the Elbrus profile (the region where the resistivity decreased to 15 Ω m and lower at depths of 35–50 km).

Qualitative agreement between the TFC and the resistivity sections determined using principally different geophysical methods made it possible to jointly interpret these parameters in order to construct the 3D geoelectric model of the EVC.

To reconstruct the depth distribution of resistivity in the vicinity of the EVC, we selected the neuronet approach often used to recognize images and interpret different types of data.

NEURONET DATA ANALYSIS

For the last decade, data processing methods based on an analogy with the operation of human brain have been successfully used to solve similar problems in other fields of science, including the problems associated with geoelectric studies [13]. The following known properties of neuronets (NNs) are prerequisites for successful application of the neuronet approach:

- (i) NNs can extract rules of inference from incomplete and noisy data, both actual and model data can be used to derive and verify these rules;
- (ii) NNs can be used for interpolation and extrapolation based on the available database;
- (iii) NNs made it possible to integrate individual data series into a composite integral response, which allow one to complexly interpret different data obtained using various geophysical methods.

Below, we will briefly describe the neuronet approaches we used to construct the 3D geoelectric model of the EVC based on MT and satellite data.

Method of error back propagation (BP). The work uses one of the so-called methods of learning with a teacher: the method of error (BP) (see the methodology of application to geophysical problems of in [14]). Such an approach includes two stages of problem solution, which are the learning of a network and the recognition phase. At the learning stage, “a teacher” specifies the correspondence between certain input and output data, this stage is analogous to the mechanism by which humans learn. In the n -layer net, certain relations exist between each neuron in a particular layer and neurons in other layers. In this case a signal comes from outside the system to neurons in the input layer, whereas a signal value for neurons in other layers depends on the values of the signals and the connection weights of all neurons in the previous layer connected to a neuron. Moreover, as in biological systems, the total response of a neuron is described by a nonlinear function.

The present work used a three-layer neuronet, which consisted of a layer of input neurons (TFC values at sites of the net covering a two-dimensional section), a layer of hidden neurons (the number of which is, generally speaking, arbitrary and depends on the system complexity), and the layer of output neurons (resistivity function values at the same net sites). Connection weights w_{ij} , where i and j are the indices of neurons in the previous and next layers, existed between neurons in any two adjacent layers. The architecture of this neuronet provides such relations according to the principle “each to each” for every pair of adjacent layers.

In this net, the input signal propagated in the following way. Each i th neuron in the input layer received an input signal V_i equal to the value of the corresponding element of the input vector composed of the TFC values at grid nodes. Each i th neuron in two remaining layers received the total input signal from all neurons in the previous layer V_i^{inp} :

$$V_i^{inp} = \sum_k w_{ki} U_k^{out}, \quad (3)$$

where U_k^{out} was the output signal from the k th neuron in the previous layer, and summation was taken with respect to all neurons in the previous layer. This input signal (V_i^{inp}) was transformed by neurons in two layers into the output signal U_i^{out} with the help of the so-called neuron activation function $G(x)$:

$$U_i^{out} = G(V_i^{inp}). \quad (4)$$

A nonlinear function is, as a rule, used for this purpose. In the present study we used the hyperbolic tangent to specify the activation function $G(x)$:

$$G(x) = \frac{1}{2} Gf(1 + \tanh(x)), \quad (5)$$

where the values of the coefficient Gf (the so-called gain-factor, i.e., the parameter characterizing the activation function steepness) are selected separately for both the hidden and the output layers. The output signal U_i^{out} of the output layer is the resultant signal from processing of the input signal.

At the learning stage, it is necessary to obtain output signals U_i^{out} that minimize the rms error Er_p for each p th learning sample:

$$Er_p = \sum_{i=1} (U_i^{out} - U_i^t)^2, \quad (6)$$

where summation is taken with respect to all neurons in the neuronet output layer, and U_i^t is the value of a correct response that should correspond to this input signal. The error was obtained for each corresponding input and output signal. Such input–output pairs are determined by the teacher and compose the neuronet learning series. The total rms error to be minimized is:

$$Er = \left(\frac{1}{P} \sum_p Er_p \right)^{1/2}, \quad (7)$$

where summation is taken for all learning examples. The connection weights between the input–hidden and hidden–output net layers are the parameters that are responsible for signal propagation in the net and, consequently, for error value. Thus, the learning process in essence consists in selection of weights between neurons w_{ij} for each pair of matrix layers in order to minimize the error (7).

Learning begins with the use of small random values for the connection weights. The input signal propagates in the net toward the output. The output signal of the output layer is compared with a correct value, and the corresponding error is calculated. If the error value is larger than the threshold value specified by the teacher, the signal propagates backward toward the net input. In this case the values of the connection weights are determined by the standard BPE method, using an error gradient, (calculated at each step for each pair of adjacent layers) and taking into account the inertia term making a contribution from the previous step:

$$\Delta w_{ij}^{(n)} = -\alpha \frac{\partial Er}{\partial w_{ij}} + \beta \Delta w_{ij}^{(n-1)}, \quad (8)$$

where $\Delta w_{ij}^{(n)}$ is the weights matrix increment at the n th step, $\Delta w_{ij}^{(n-1)}$ is such the increment at the previous step, α is the learning rate, and β (learning momentum) is the persistence coefficient ($0 < \beta < 1$). This procedure is performed for the entire learning series and ends when a certain specified accuracy threshold eps is reached ($Er < eps$).

Method of maximal correlation similarity. The neuronet extrapolation accuracy substantially depends not only on quality and volume of data used to learn the net but also on the level of correlation between the values of the two considered functions. Therefore, prior to neuronet learning, it was necessary to select pairs of initial values for resistivity and TFC that gave the maximal correlation coefficient.

For this purpose, we developed a method for maximal correlation similarity, the concept of which is as follows.

Assume that the sample $E = \{\mathbf{x}\}$ includes n pairs $\mathbf{x} = (x_1, x_2)$ of, generally speaking, random values. The sample correlation coefficient between these values is:

$$r = \frac{n \sum_{\mathbf{x} \in E} x_1 x_2 - \left(\sum_{\mathbf{x} \in E} x_1 \right) \left(\sum_{\mathbf{x} \in E} x_2 \right)}{\sqrt{n \sum_{\mathbf{x} \in E} x_1^2 - \left(\sum_{\mathbf{x} \in E} x_1 \right)^2} \sqrt{n \sum_{\mathbf{x} \in E} x_2^2 - \left(\sum_{\mathbf{x} \in E} x_2 \right)^2}}. \quad (9)$$

We seek a subset $A \subseteq E$ of $m \leq n$ sites such that the partial correlation coefficient

$$r_A = \frac{m \sum_{\mathbf{x} \in A} x_1 x_2 - \left(\sum_{\mathbf{x} \in A} x_1 \right) \left(\sum_{\mathbf{x} \in A} x_2 \right)}{\sqrt{m \sum_{\mathbf{x} \in A} x_1^2 - \left(\sum_{\mathbf{x} \in A} x_1 \right)^2} \sqrt{m \sum_{\mathbf{x} \in A} x_2^2 - \left(\sum_{\mathbf{x} \in A} x_2 \right)^2}} \quad (10)$$

would be maximal.

This problem is solved in the following way. Let $\theta(\mathbf{x})$ be the characteristic function of the subset A ; i.e.,

$$\theta(\mathbf{x}) = \begin{cases} 0, & \text{if } \mathbf{x} \notin A \\ 1, & \text{if } \mathbf{x} \in A. \end{cases}$$

In such a case, the expression for the partial correlation coefficient can be rewritten in the form

$$r_A = \frac{\left(\sum_{\mathbf{x} \in E} \theta(\mathbf{x}) \right) \left(\sum_{\mathbf{x} \in E} x_1 x_2 \theta(\mathbf{x}) \right) - \left(\sum_{\mathbf{x} \in E} x_1 \theta(\mathbf{x}) \right) \left(\sum_{\mathbf{x} \in E} x_2 \theta(\mathbf{x}) \right)}{\sqrt{\left(\sum_{\mathbf{x} \in E} \theta(\mathbf{x}) \right) \left(\sum_{\mathbf{x} \in E} x_1^2 \theta(\mathbf{x}) \right) - \left(\sum_{\mathbf{x} \in E} x_1 \theta(\mathbf{x}) \right)^2} \sqrt{\left(\sum_{\mathbf{x} \in E} \theta(\mathbf{x}) \right) \left(\sum_{\mathbf{x} \in E} x_2^2 \theta(\mathbf{x}) \right) - \left(\sum_{\mathbf{x} \in E} x_2 \theta(\mathbf{x}) \right)^2}}.$$

We now assume that $\theta = \theta(\mathbf{x}, \mathbf{a})$ in the obtained expression is a smooth function of $\mathbf{x}$ and of a certain set of parameters $\mathbf{a}$ taking on values in the interval $[0, 1]$. In such a case the value r_A is not necessarily equal to the partial correlation coefficient of a certain subset $A \subseteq E$ since it is possible that $0 < \theta(\mathbf{x}, \mathbf{a}) < 1$ for certain $\mathbf{x}$ values. However, in this case the value r_A becomes a smooth function $r(\mathbf{a})$ of parameter $\mathbf{a}$, and we can find the $\mathbf{a}$ value, at which the $r(\mathbf{a})$ value is maximal, using standard algorithms for searching for the function maximum. Then, we can define the subset A by the condition: $\mathbf{x} \in A$ if and only if $\theta(\mathbf{x}, \mathbf{a}) > 0.5$. In this case we can hope that the corresponding partial correlation coefficient will be close to maximum. Since this mathematical problem has, evidently, no unique solution, a necessary subset is found by using the superposition of the natural requirement of one-to-one correspondence between two functions.

RECONSTRUCTION OF THE 3D LITHOSPHERIC RESISTIVITY DISTRIBUTION IN THE EVC ENVIRONS

The construction of the 3D geoelectric model included two stages. At the first stage, we determined the subset of sites with maximal correlation coefficients between the TFC on the 1–1' submeridional section of the tectonic fragmentation field and the resistivity in the space of resistivity values corresponding to the Cheget–Kislovodsk profile fragment. Subsequently, we determined the character of correspondence between these parameters for sites of the selected subset. The correlation dependence of the TFC and resistivity, (Fig. 8) with a correlation coefficient of 0.73, cleared the way to the second stage of construction of the 3D resistivity model. We note here that the obtained dependence is rather specific and is a feature typical of the Elbrus block. When we studied the correlation between the

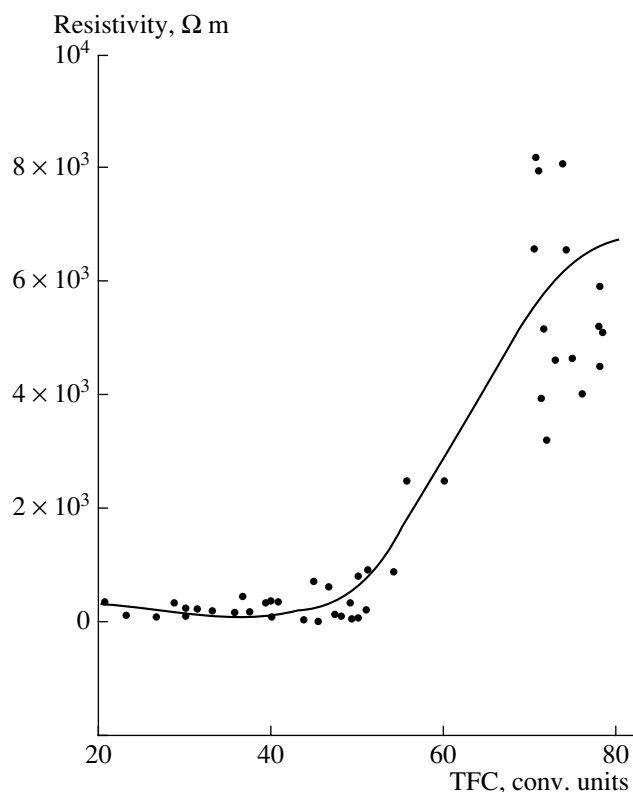


Fig. 8. Relationship between TFC and resistivity established for the submeridional profile (1–1') in the region of the Elbrus volcanic center. Experimental data (dots) and their spline-approximation.

TFC and resistivity in the Cheget–Kislovodsk geoelectric section, we also revealed the regions of direct correlation between the TFC and resistivity (anomalies of the first type). As was mentioned above, such a correlation is typical of fluid-saturated subvertical zones of fragmentation and tectonic faults, zones of lateral increase in fracturing in the intermediate layer of the earth's crust, etc. The application of the relationship between the TFC and resistivity which we revealed and show in Fig. 8, to the entire region, including the zones of propagation of the first- and second-type anomalies, would likely result in obtaining models that incorrectly represent the resistivity distribution within these regions. However, final conclusions on a 3D resistivity distribution in the entire considered region and mechanisms that are in the basis of correlation between the TFC and rock resistivity could most likely be made after obtaining additional data.

At the second stage, artificial neuronet learning of the correspondence between the TFC and resistivity was performed. In this case the input TFC values corresponded to the output resistivity values. The trained neuronet was subsequently used to predict resistivity at sites of the spatial net, covering the entire region under study, based on the known TFC values. Figure 9 shows the geoelectric model of the EVC constructed using the predicted resistivity values.

The 3D geoelectric model of the EVC we developed is presented as a set of slices for depths of 0, 5, 10, 20, 30, 40, and 50 km. The resistivity contour lines were digitized in Ω m. For convenience in reading and comparing of maps, hachure marks were added to the 60 Ω m contour lines.

The three upper slices show a change in the depth of the upper crustal low-resistivity anomaly identified with the magma chamber of the volcano. It is clear that the anomaly is most pronounced at a depth of 5 km. At this depth the anomaly shape along the contour lines of 60 and 40 Ω m is close to isometric, and the radius of the anomalous zone is 10 km. Resistivity decreases to 25 Ω m at the zone center. The upper crustal resistivity anomaly rapidly decays in the horizontal plane, as does the geoelectric section, (Fig. 1) while the resistivity increases by a factor of 100 (from 40 to 4000 Ω m) over a distance of ~ 10 km. In the vertical plane, the anomaly decays more slowly: at a depth of 20 km, the resistivity at the anomalous zone center is higher than 150 Ω m.

At depths of 30–50 km, the model includes a conducting object with a resistivity of 10–35 Ω m and dimensions (from the 40 Ω m contour line) of ~ 35 and ~ 15 km in latitude and longitude, respectively, in the high-resistivity (>300 Ω m) environment. A conducting object, compressed in longitude and located at middle-lower crust depths, can be interpreted as the region of the volcanic parent chamber, the shape of which corre-

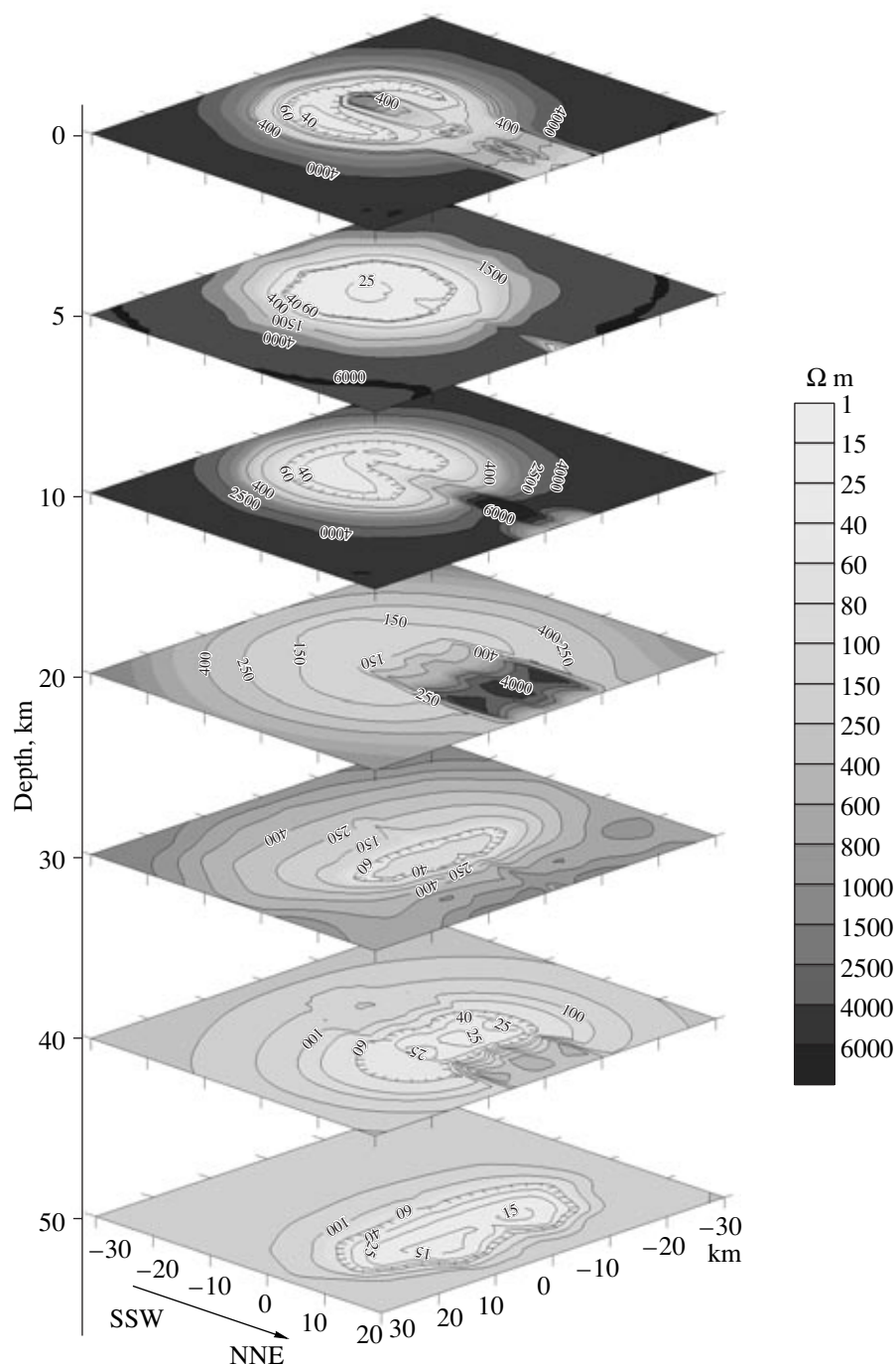


Fig. 9. Resistivity slices at the EVC background. The maps correspond to depths of 0, 5, 10, 20, 30, 40, and 50 km. The maps are referenced to the conventional coordinate system. Resistivity contour lines are given in Ω m. Hachure marks are added to contour lines of 60 Ω m on all maps.

sponds to the direction of compression stresses predominant in the region.

CONCLUSIONS

Based on a complex analysis of the ground-based MT data and information about the TFC of the Earth's crust, we developed a preliminary 3D model of the

EVC resistivity. Our predictive 3D geoelectric model includes two conductive entities spatially separated at depth. The upper crustal conductor with a resistivity of 25–40 Ω m, interpreted as a magma chamber of the volcano and located at depths of 0–10 km, is most pronounced at a depth of 5 km. Here, the conductor is isometric in the horizontal and is about 10 km in radius along the 40–60 Ω m contour lines. The conducting

object localized at middle–lower crust depths (with a resistivity of 10–40 Ω m), identified as the Elbrus parent chamber, is most pronounced at depths of 45–50 km, where the object dimensions are 35 km in latitude and 15 km in longitude along the 40 Ω m contour line of. The thickness of the conducting center of this object is 20 km. Our model can form a basis for solving the two most important problems of volcano EM monitoring: optimization of the observation network, and construction of the reference level to be used as the background against which the temporal and spatial anomalies related to regional tectonic activity can be distinguished.

To fill gaps in MT data, we proposed an original method for integrating ground-based and satellite data based on the developed method of maximal correlation similarity. This method makes it possible to fill gaps in ground-based EM data by finding correlations between resistivity (conductivity) and other geological or geophysical parameters. The proposed method can also be used to solve other problems where it is necessary to reconstruct absent geophysical information using available satellite and ground-based data.

Our results indicate that the neuronet approach can be effectively used in a complex interpretation of geological and geophysical data. Such an approach makes it seem possible to increase the set and the information value of parameters characterizing geological objects under study.

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