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Magnetotelluric sounding in the Western Transbaikalia segment of the Central Asian fold belt

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Abstract

This paper presents the results of magnetotelluric (MT) studies performed within the Western Transbaikalia segment of the Central Asian fold belt along the Selenga River delta–Krasnyi Chikoi Village profile. The data are interpreted using the results of recent geological, petrological, geothermal, tectonic, and geochronological studies of the Mongolia-Transbaikalian part of the Central Asian fold belt, including large heterochronous igneous provinces and zones. The studies have shown that the investigated area has a complex geologic and tectonic structure produced by extensive rifting leading to the formation of large crustal blocks and by intense magmatic fluid activity along deep fault zones. The investigated profile is characterized by a combination of blocks with different types of geoelectric section—mountain ranges and intermontane basins separated by long-lived deep fault zones.

Keywords: magnetotelluric sounding; electrical resistivity; geoelectric section; deep rift; rift trough; mountain range; magmatism; granitoids; Earth's crust; rift zone; Western Transbaikalia

Introduction

Magnetotelluric (MT) soundings performed along the Selenga River delta–Krasnyi Chikoi Village profile are part of integrated geological-geophysical studies of the zone-block structure of the Earth's crust in the south of East Siberia. MT sounding is one of the main methods to obtain information on the deep structure of the Earth. MT sounding is widely used in many parts of the world to solve a wide variety of problems—from mineragenic zoning of areas to investigating the geodynamic state of the lithosphere. This method is also effective for identifying fluid-saturated areas and active fault zones in the Earth's crust.

The aim of the present study was to investigate the deep conductivity distribution features that reflect the development and tectonic evolution of Western Transbaikalia. This included the following tasks:

– identification of the main features of the geoelectric structure of the Earth's crust of the Baikal (southeast flank) and Western Transbaikalia rift zones and their relationship to the intensity of tectonic processes;

– zonation of the study area according to the types of geoelectric section, with emphasis on the key portions of the transition areas from mountain ranges to intermontane basins;

– identification of fault systems in the crust that are active at the current stage of tectogenesis.

Geological setting

The study area is located in the Western Transbaikalia segment of the Central Asian fold belt, whose structure formed as a result of Early Paleozoic accretion–collision events accompanied by the closure of the Paleo-Asian Ocean (Dobretsov and Buslov, 2007). A consequence of these processes was the accretion of geodynamically different terranes (microcontinents, intraoceanic systems, and island arc systems to the marginal parts of the Siberian craton (Belichenko et al., 2006; Bulgatov et al., 2004; Parfenov et al., 1996, 2003; Tsygankov 2005; Zonenshain et al., 1990) and the formation of collision belts along its margins (Donskaya et al., 2000; Gladkochub et al., 2010).

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In the Late Paleozoic and Mesozoic, Western Transbaikalia was a region of within-plate magmatism resulting in the formation of large igneous provinces with batholith cores in the center (the Angara–Vitim and Hentiyn–Daurian) and rift zones on the periphery (Kovalenko et al., 2003; Vorontsov et al., 2007; Yarmolyuk et al., 2002). Batholiths are composed of granitoids varying widely in composition—from tonalites and plagiogranites to granosyenites and rare-metal granites dominated by normal granites (Yarmolyuk and Kovalenko, 2003). Most of the granitoids of Western Transbaikalia of different types and different ages belong to the Angara–Vitim batholith, whose diversity of rocks reduces to two complexes—Barguzin and Zaza (Gordienko et al., 1978; Litvinovsky et al., 1992). The formation of granitoids of the Barguzin complex took place in two stages: the rocks of the early stage are represented by quartz monzonites, monzo-syienites, and quartz syenites, and the rocks of the late (main) stage by normal granites, which, according to (Gordienko et al., 1978; Litvinovsky et al., 1999), are interspersed with allochthonous (predominant fraction) and autochthonous varieties. Both granite varieties correspond to different levels of batholith formation, separated by a depth interval of many kilometers and corresponding to the magma formation level (autochthonous granitoids) and the levels of intrusion of displaced (allochthonous) melts (Litvinovsky et al., 1992). The time of formation of the Angara–Vitim batholith rocks was interpreted quite widely—from the Late Precambrian to the Late Paleozoic. Recently, clear evidence for the Late Paleozoic (Late Carboniferous–Early Permian) age of the batholith has been provided, and many types of granites identified as complexes of different ages were formed in intervals of 340–270 million years (Litvinovsky et al., 1999; Tsygankov et al., 2007; Yarmolyuk et al., 1997, 2003).

Granitoids of the Hentiyn–Daurian batholith (Fig. 1), varying widely in composition—from granodiorites to leucogranites, are widespread in the southeastern part of the study area. Granodiorites and melanocratic and leucocratic biotite granites dominate (Koval', 1998; The Mesozoic..., 1975). Gabbro and diorites are present in subordinate amounts, composing separate bodies corresponding to early phases of intrusion or forming unevenly distributed segregations in main-phase granodiorites corresponding to synplutonic intrusions of mafic magmas (Koval', 1998; Yarmolyuk and Kovalenko, 2003). Small dike-like and boss-like bodies of leucogranites, including rare-metal lithium-fluoride, are the most recent in the batholith structure. The age of the Hentiyn–Daurian batholith, according to (Yarmolyuk and Kovalenko, 2003) is 230–195 Ma (Late Triassic–Early Jurassic).

The formation of batholiths is associated with the overlap of the North Asian continent with a number of hot spots of the Paleo-Asian ocean mantle and the subsequent interaction between mantle plumes and the lithosphere in the active continental margin setting (Vorontsov and Yarmolyuk, 2004; Yarmolyuk and Kovalenko, 2003). Mantle plumes initiated within-plate activity and contributed to the occurrence of rift splits and the formation of alkaline basic and alkaline salic associations. The rifting zones located at the batholith margin are identified by zones of grabens and basins and their separating uplifts and horsts. The magmatism of these zones is determined by bimodal basalt–trachyte comendite (pantellirite) or substantially basalt (alkaline basaltoid) volcanic associations; intrusive rocks are dominated by alkaline syenites and granites, granosyenites, and leucogranites (Vorontsov et al., 2007; Yarmolyuk and Kovalenko, 2003).

One of the structures where Early Mesozoic within-plate magmatism was most intense is the Western Transbaikalia segment of the Northern Mongolia–Western Transbaikalia (NMWT) rift zone situated on the northern flank of the Hentiyn–Daurian regional igneous province. The Western Transbaikalia segment, within which a large part of the MT profile is located, extends from the confluence of the Selenga and Dzhida Rivers through the basin of the Uda, Tunga, and Khilok Rivers to the upper reaches of the Vitim River and has a length of over 800 km. Large volcanoplutonic structures up to 2000 km^2 in area formed within this zone in the Early Mesozoic. They consist of volcanic fields, trachybasalt and alkaline bimodal associations, alkaline granite and syenite massifs, and extended dyke fields associated with systems of longitudinal faults, grabens, and horsts (Kovalenko et al., 2003; Litvinovsky et al., 2001; Vorontsov et al., 2007; Yarmolyuk et al., 2001). The bimodal strata are composed of trachybasalt, comendite-pantellirite, trachyrhyolite-trachydacite, and trachyte of the volcanic Tsagan–Khurtei Formation (Shergina et al., 1979; Vorontsov et al., 2004).

The further development of magmatism in the Mesozoic occurred almost continuously within both pre-existing and newly formed grabens until the beginning of the Late Cretaceous, when the scale of volcanism decreased significantly (Yarmolyuk et al., 2000). Various, mostly highly alkaline, magmatic associations formed in these areas (grabens) at different stages of their development. A common feature of the magmatic associations of all stages is the absolute predominance of mafic rocks (Vorontsov and Yarmolyuk, 2004).

Research method

Magnetotelluric soundings were performed at periods from 0.003 to 10,000 s using equipment produced by the Phoenix Geophysics Ltd Canadian company. Five components (E_x, E_y, H_x, H_y, H_z) of the magnetotelluric field (MT field) were measured with two MTU-5 measuring units. The observation step was 4–5 km. A cross-shaped array with an electric dipole length of 100 m was employed. Magnetotelluric field components were recorded for 19–22 h.

The field data were processed with the Phoenix Geophysics software, and 1-D and 2-D inversions of the experimental data were carried out using the WinGLink software. Qualitative and quantitative interpretations were performed according to the procedure described in detail in (Epov et al., 2012). During qualitative interpretation, an analysis of magnetotelluric data was performed, showing that the study area is a northeast-trending regional two-dimensional structure:

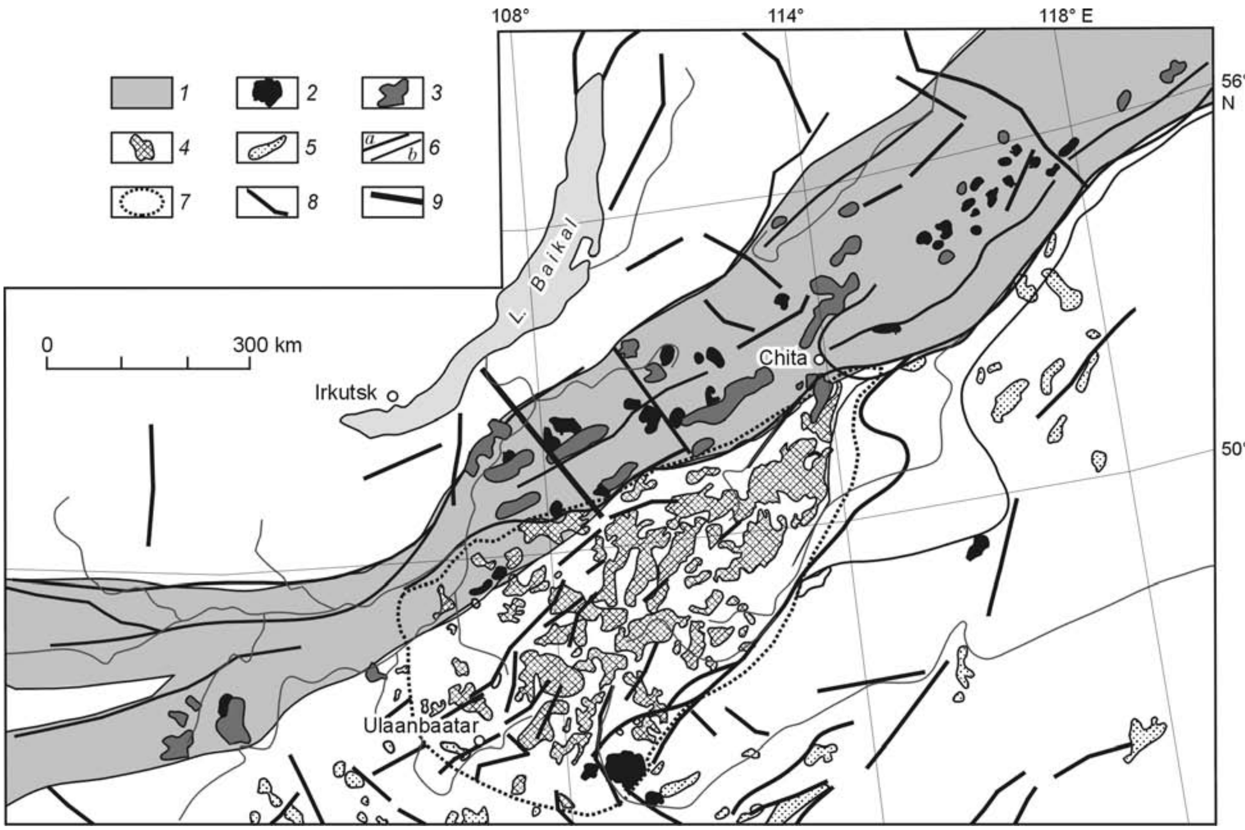

Fig. 1. Schematic of the position of the Northern Mongolia–Western Transbaikalia rift zone in the structure of the Early Mesozoic igneous area with the Hentiyn–Daurian batholith core in the center and rift zones on its periphery (Vorontsov et al., 2007). *1*, Northern Mongolia–Western Transbaikalia rift zone; *2*, alkaline granitoid massifs; *3*, bimodal trachybasalt-comendite and trachybasalt magmatic associations; *4*, *5*, rocks of the zonal igneous area: *4*, granitoids of the Hentiyn–Daurian batholith, *5*, rift volcanic associations of the framing of the Hentiyn–Daurian batholith; *6*, belt of major faults classified as a suture (*a*) and the boundaries of the Northern Mongolia–Western Transbaikalia rift zone (*b*); *7*, boundaries of the Hentiyn–Daurian batholith; *8*, faults; *9*, MT profile.

$$\mathrm{Nmt} \gg \delta \to \mathrm{scew_S} \le \delta \to \mathrm{scew_B} \le \delta,$$

where Nmt is the heterogeneity parameter (Berdichevskii et al., 1997), $\mathrm{skew_S}$ is the skew parameter (Swift, 1967), and $\mathrm{skew_B}$ is the phase-sensitive skew parameter (Bahr, 1988). The exception in the data set is the soundings across the Khamar-Daban Range, which is composed of a large granitoid massif and is a typical three-dimensional structure.

Deep rift faults predominantly have a northeast strike, coincident with the strike of regional structures. In places where they cross northwest- or roughly east-west-trending faults at a certain critical period, there is a rotation of the polar diagrams by 90° (Fig. 2) and in the $M = f(\sqrt{T})$ and $\theta = f(\sqrt{T})$ plots, there is a sudden change in the values of θ by 90° and M becomes much smaller than 1. Here M is the ratio of the magnitudes of the longitudinal and transverse impedances, and θ is the angle between the positive X direction and the maximum impedance. Starting from this "critical" period, the branches of the curves are replaced (Z_{xy} by Z_{yx} and φ_{xy} by φ_{yx}) in order that the curves of ρ_k correspond to the longitudinal and transverse directions of all the structures studied.

Another important objective of the MT studies was to identify distortions in the sounding curves associated with the horizontal heterogeneity of the section. Geologically, the study region belongs to the Barguzin igneous province—an extensive area of Late Paleozoic granitoids in Western Transbaikalia, where the electrical resistivity can reach more than 30,000 Ohm·m. Therefore, the distortions here are predominantly galvanic in nature. It is known that in the abstract two-dimensional model, only the transverse MT component experiences galvanic distortions manifested in a static shift of transverse apparent-resistivity curves (Berdichevskii and Dmitriev, 2009). However, in real geological settings, there is often a superposition of regional quasi-dimensional structures and local three-dimensional subsurface heterogeneities, which distorts both MT components, resulting in a static shift of both transverse and longitudinal curves. A certain reference is needed to identify the static shift and evaluate its magnitude. As such a reference we used a global magnetovariational (MV) sounding curve plotted from generalized data on global electromagnetic sounding (Fainberg et al., 1977). Later, these data were revised in terms of mathematical statistics and interpretation based on the joint use of amplitude and phase MT curves (Pospeev, 1979; Pospeev and Mikhalevskii, 1981), making it possible to determine the boundaries of abrupt conductivity change in the global sounding curve. These boundaries are located at depths coincident with the phase-transition depths in the mantle inferred from geophysical and petrological data (Pushcharovskii and Pushcharovskii, 2010;

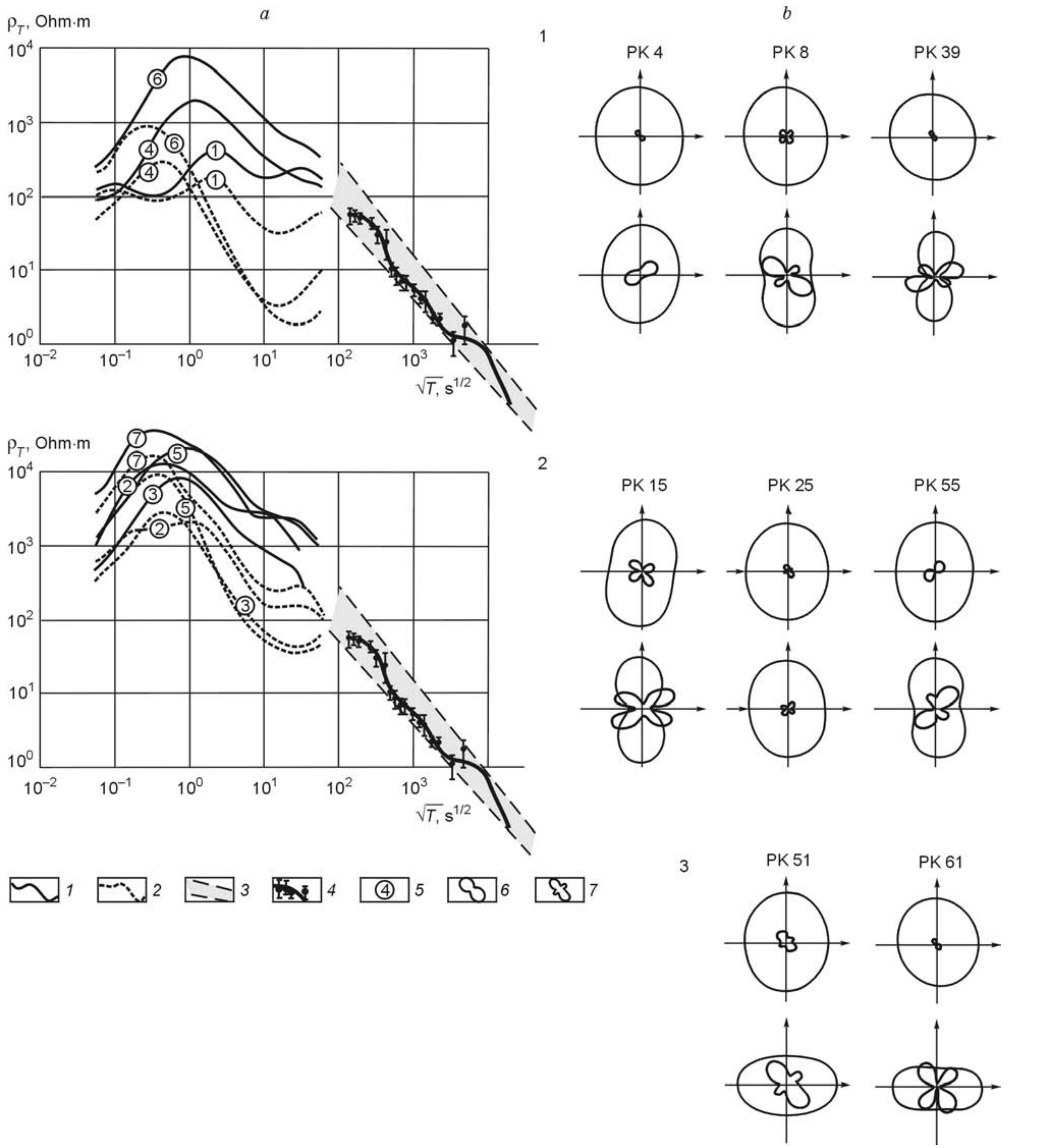

Fig. 2. *a*, Semicharacteristic MT curves of the study area. *b*, Typical polar diagrams of the impedance tensor: 1, within tectonic depressions; 2, within mountain ranges; 3, in fault zones. *1*, transverse MT curves; *2*, longitudinal MT curves; *3*, GMV curve (Pospeev, 1979; Pospeev and Mikhalevskii, 1981); *4*, lines bounding the region of experimental values of ρ_k; *5*, block numbers: 1, Selenga, 2, Khamar-Daban; 3, Tsagan-Daban; 4, Tugnui depression; 5, Zagan Range; 6, Khilok–Chikoi basin; 7, Malkhan Range; *6*, principal polar diagrams of the impedance tenzor; *7*, additional polar diagrams of the impedance tenzor.

Ringwood, 1981; Zharkov, 1983). We evaluated our data exactly for this model of electrical conductivity distribution with depth.

Figure 2*a* shows the family of mean curves from different blocks of the investigated profile—rift basins (Fig. 2*a*, 1) and mountain ranges (Fig. 2*a*, 2). Within the basins, the ascending branches of transverse curves practically merge with the ascending branches of longitudinal curves, and their descending branches are shifted upward along the resistivity axis (Fig. 2*a*, 2). Longitudinal curves have well-defined lows, reflecting the presence of conductive zones (crustal conductive layer and conductive heterogeneities confined to fault zones) in the crust. Within the mountain ranges, a static shift of transverse curves is observed over the entire frequency range. Their descending branches are shifted relative to the MV curve by almost a decade. Because of strong galvanic screening, the sensitivity of the transverse MT component is too low to study the underlying section of the crust with low resistivity values, and information on this section can be derived only from the longitudinal MT component (Berdichevskii and Dmitriev, 2009).

Discussion

The MT profile traverses blocks of the Western Transbaikalia segment of the Central Asian fold belt that differ in geoelectric structure, age, and the nature of underground processes (Fig. 3). The blocks correspond to northeast and roughly east–west-trending granite-gneiss ranges and their separating intermontane basins.

The modern ranges of Transbaikalia are usually regarded as gentle anticlinal folds, and intermontane basins as synclinal basins. Their occurrence is associated with the Young-Cimmerian folding because Jurassic continental deposits accumulated in the already formed intermontane basins (Bulnaev 2006; Gordienko and Klimuk, 1995; Gordienko et al., 1999). The correspondence of the modern topography of Western Transbaikalia to the main elements of its structure indicates a continuous restoration of disrupted tectonic forms by repeated movements of the Earth's crust throughout the Neogene–Quaternary, when active uplift of mountain ranges and subsidence of intermontane basins took place (Zhavoronkin, 2007).

The northwestern segment of the MT profile (sites 3–17) crosses the southwestern margin of the Barguzin igneous province within the boundary of the Angara–Vitim batholith and completely belongs to the Baikal Rift Zone. The results of the study indicate the presence of two large blocks—Selenga and Khamar-Daban—in the crust of the study area (Fig. 4).

The Selenga block (sites 3–11) includes the southeastern part of the Selenga River delta in the region of Cenozoic deposits overlying the moderately acidic granite massifs of the Barguzin complex and the overlain Selenga–Itantsy rift basin. The basin is composed of Jurassic and Cretaceous deposits, overlain by deposits of all epochs of the Quaternary Period. The sedimentary deposits are divided into three generalized resistivity horizons, whose total thickness decreases in the southeast direction from 3500 to 300–500 m, in the Fofonovo crystalline bridge. The most subsiding part of the Fofonovo crystalline bridge is characterized by resistivity highs (above 2000 Ohm·m), which decrease to 150 Ohm·m with depth and are less than 30 Ohm·m at depths of 18,000–30,000 m.

A feature of the crustal section of the Selenga block is the presence of northeast- and northwest-trending deep rift faults, which determine the high fluid reworking of the crust and hence low resistivity. The Deltovyi and Bortovyi major deep faults are well-known rift-forming normal faults dipping toward the axis of the Baikal Rift (Ryazanov et al., 2004; Seminsky et al., 2013). They appear in the geoelectric section (sites 3–4, sites 10–11) as low-resistivity zones with a pronounced dip of the lateral boundaries (Fig. 4). The boundary between the Selenga and Khamar-Daban blocks passes along the northeast-trending Bortovyi fault.

A fragment of a crustal conductive layer with a resistivity of 5–10 Ohm·m is identified at depths of 8–16 km in the northwestern part of the block considered (sites 3–6) (Figs. 4, 5). Inferring the parameters of the layer in other parts of the investigated profile is extremely difficult and impossible in most cases due to the presence of anomalously low-resistivity zones and high-resistivity long vertically extended formations in the crust.

The top and bottom of the conductive layer in structures of different ages are at depths corresponding to isotherms of 350–400 °C and 750–800 °C. The temperature range 300–750 °C and the pressure range 2.5–6 kbar covers the granite-metamorphic rocks of the crust from greenschist to amphibolite facies, inclusive. With increasing *P-T* parameters, a series of metamorphic solid-state reactions occur, resulting in stepwise dehydration of rocks to release most of the bound water and to form metamorphic solutions and supercritical fluids separated by the critical water point (374 °C) (Kissin, 2009; Pokrovskii, 2006). The intergranular fluid phase is considered to play a special role in the formation of the conductive crustal layer (Brown and Shankland, 1981; Kissin, 2009; Ringwood, 1975). A source of water generation is also the oxidation of reduced mantle fluids (Letnikov 2000; Marakushev and Perchuk, 1971; Niko'lskii, 1987; Perchuk, 2000). The depth of the top of the conductive layer correlates well with the magnitude of the heat flux. In tectonically stable areas with normal heat flux magnitudes, the top of the conductive layer is located at greater depths (35–40 km) than in tectonically active structures (16–20 km) (Adam, 1987; Berdichevskii et al., 1999; Jones, 1981; Kovtun, 2004; Moroz et al., 2008; Pospeev and Mikhalevskii, 1975).

The uplift of the top of the conductive layer to depths of 8–10 km in the Selenga block, compared to 15–10 km in the other parts of the Baikal rift zone (Berdichevskii et al., 1999; Popov, 1977, 1990; Pospeev and Mikhalevskii, 1975; Pospeev et al., 1978), is due to the increased tectonic activity of this block of the Earth's crust. This finding is consistent with the geothermal data on the heat flux and temperature distributions at depths of 20 and 40 km in a 100–km zone along the MT profile (Duchkov and Sokolova, 2015, oral report; Duchkov et al., 2004; Golubev, 2009). Within the block considered, the heat flux is increased to 60–75 mW/m^2, with a maximum of 80 mW/m^2 in the Selenga River delta. The temperatures at the calculated depths are 450 °C and 900 °C, respectively, and correspond to the upper and lower boundaries of the conductive crustal layer. In the rest of the profile, the heat flux and temperatures at depths of 20 and 40 km are in the ranges 50–55 mW/m^2, 350–400 °C, and 550–650 °C, respectively.

The high permeability of the lithosphere of the Selenga block due to extensive disruption by active faults causes venting of their associated mantle fluids. The heat contained in the fluid at depth is completely transferred to rocks, i.e., is transformed to the conductive form of heat and mass transport as the fluids move to the Earth's surface (Golubev, 2007). The

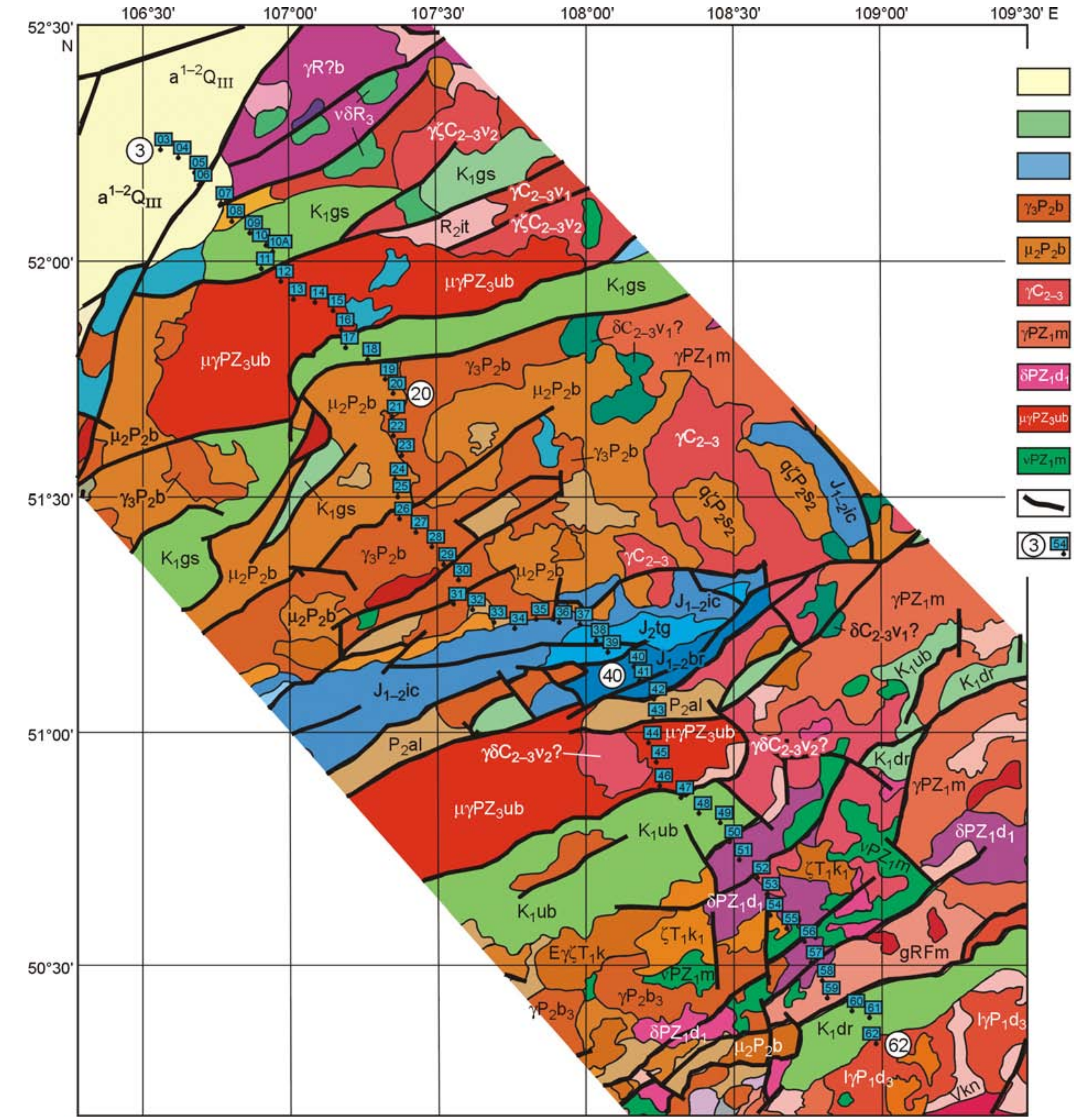

Fig. 3. Geological map of the MTS area compiled on the basis of geological maps of the Russian Federation, scale 1:1,000,000 (third generation): sheets N-48, M-48, N-49, M-49 (http://vsegei.ru/ru/info/pub_ggk1000-3/). *1*, Quaternary deposits; *2*, Cretaceous deposits; *3*, Jurassic deposits; Permian deposits: *4*, *5*, Bichurin gabbro–monzonite–granite complex; *6*, Carbonaceous deposits, Daurian granodiorite complex; Paleozoic deposits: *7*, Malkhan granite complex; *8*, Dzhida diorite–granite–plagiogranite complex; *9*, Ulan-Burga metamorphic complex; *10*, Monostoi gabbro complex; *11*, faults; *12*, MT sites with numbers.

main features of the geothermal field of the Selenga block fit the conductive-convective model of the Baikal rift zone (BRZ) developed by Golubev (2007). According to this model, the positive thermal anomalies of the rift basins of the BRZ are caused by heat transport of the ascending branches of the regional hydrothermal convection cells (whose wide downward branches are located in water and heat removal zones on mountain ranges). This model easily satisfies the sustainability requirement. The formation of thermal anomalies of the BRZ from the thermal resources of its regional thermal field will take place under two conditions: the existence of groundwater-driving forces caused by the difference in groundwater level on ranges and in basins; permeability of faults in the upper crust, sustained by crust tension and recurrent earthquakes (Golubev, 2007).

The Khamar-Daban block (sites 12–22). The Khamar-Daban block includes three major structures: the eponymous mountain range, the Ivolga–Uda rift basin, and the Ganzurinskii Ridge. These structures are considered within a single block primarily because the latter two structures were insufficiently investigated in the present work. The second, more important reason, is that based on the results of stress field

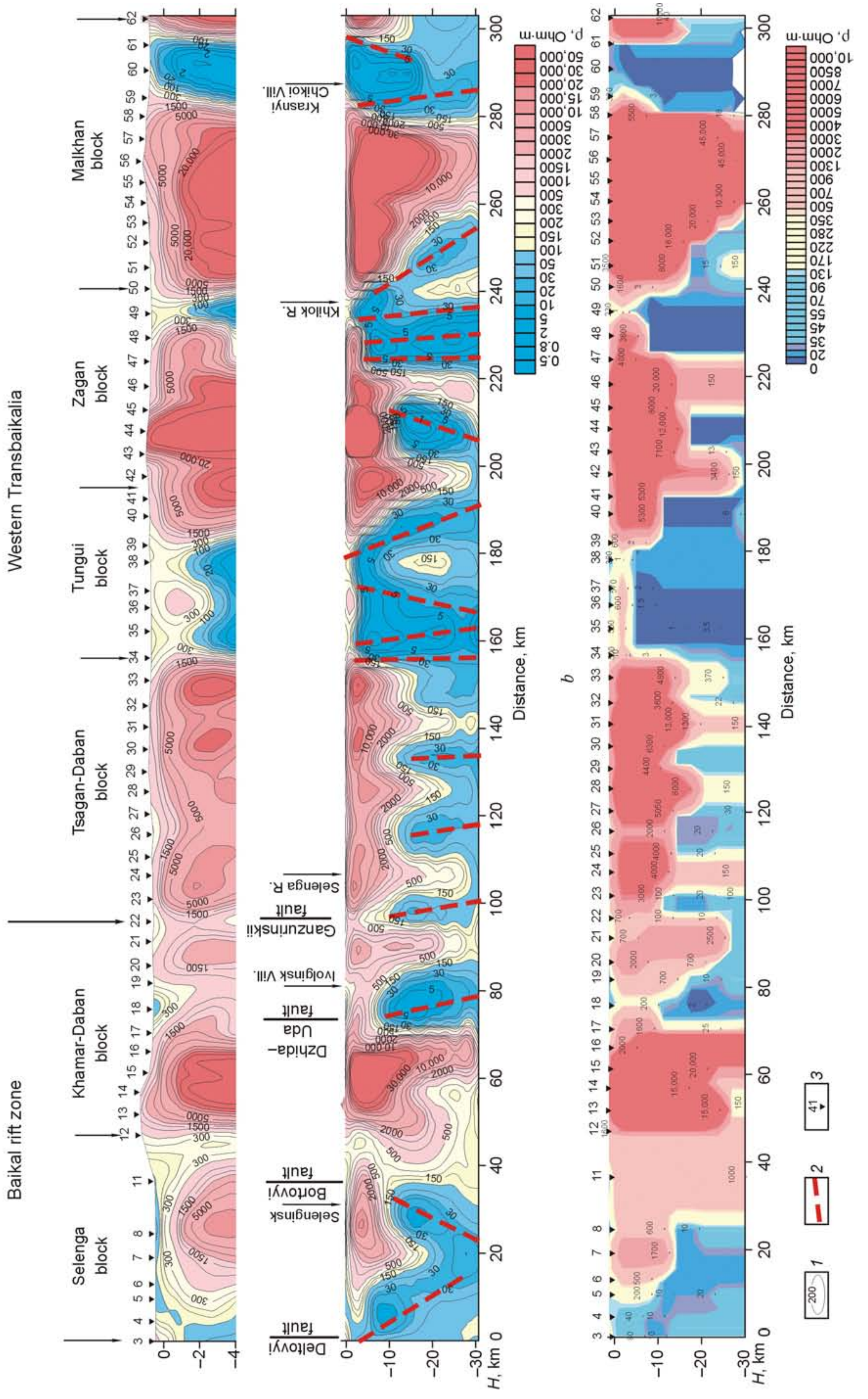

Fig. 4. Geoelectric section along the Selenga River delta–Krasnyi Chikoi Village profile. *a*, From the results of inversion; *b*, model; *1*, resistivity isolines; *2*, inferred deep faults; *3*, magnetotelluric sounding stations.

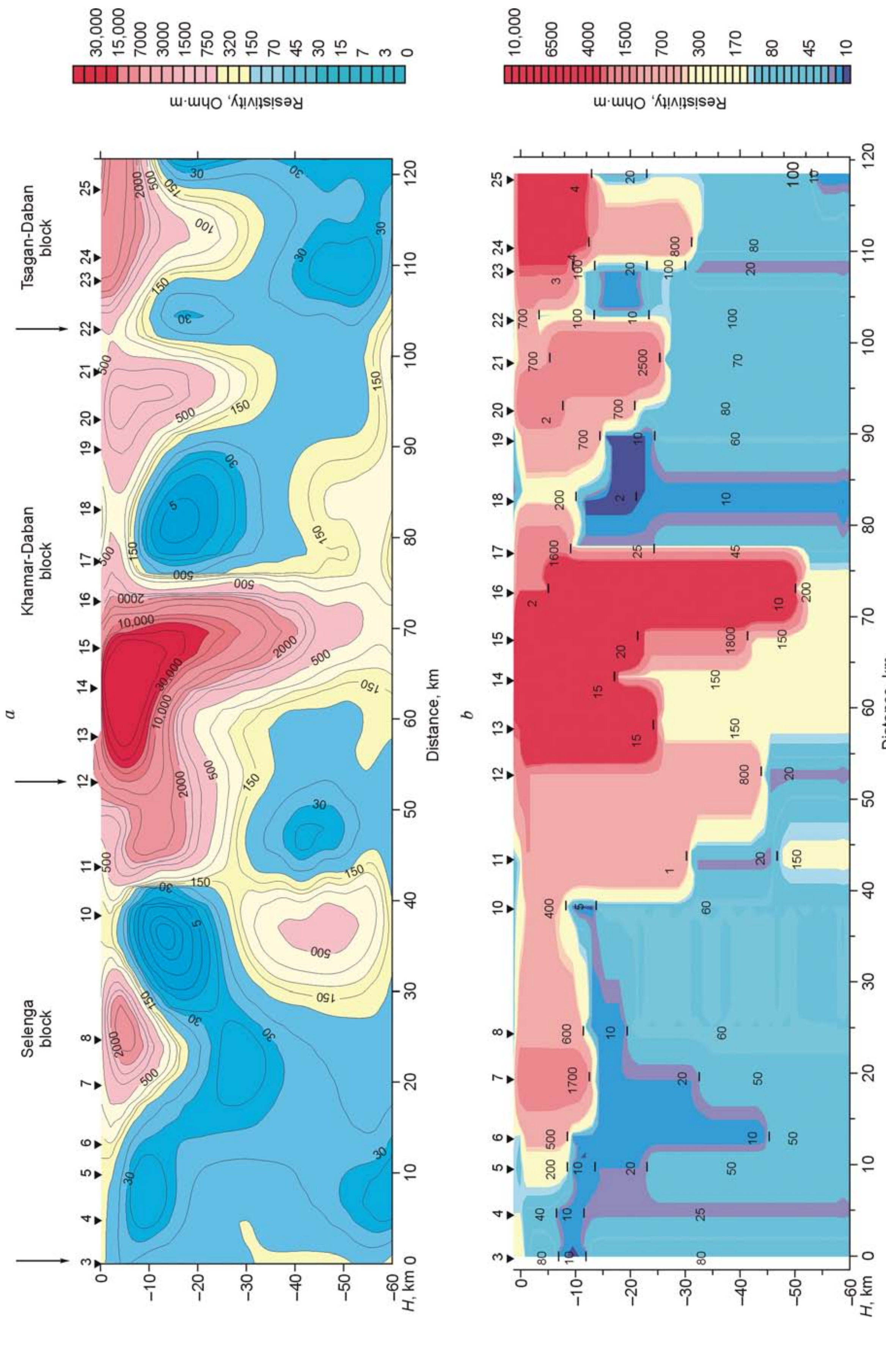

Fig. 5. Deep geoelectric section along a portion of the MT profile (sites 3–25). *a*, From the results of inversion; *b*, model. See Fig. 4 for the legend.

studies and tectonic reconstructions, they belong to the Baikal rift zone (Delvaux et al., 1997; Levi et al., 1997; Logachev, 1984; Seminsky, 2009; Seminsky et al., 2013). According to tectonic data (Seminsky, 2009; Seminsky et al., 2013), this crustal block is characterized by three main types of dynamic setting: compression, left shear, and extension. Similar settings dominate in the central part of the Baikal Rift and are associated with the Early Paleozoic (compression), Early Cenozoic (shear), and Late Cenozoic (extension) Stages of development of the crust of the Baikal region (Seminsky et al., 2013).

The Khamar-Daban Range (sites 12–17) is a structurally complex geoelectrical heterogeneity with high electrical resistivity. According to the distribution of geoelectrical parameters (thickness and resistivity), it is divided into three smaller blocks: northwestern (sites 11–13), central (sites 14–15), and southeastern (sites 16–17) (Fig. 5). In the northwestern block, heterogeneity can be traced to a depth of 30–45 km and the resistivity is lower than 1000 Ohm·m. The central block is characterized by resistivity highs of 15,000–20,000 Ohm·m and a capacitance of about 25 km. In the southeastern block, significant variations in the geoelectric parameters are observed in both the vertical and the lateral directions. In the depth interval from 800 to 10,000 m, the resistivity values are 1600–2000 Ohm·m, increasing by almost an order of magnitude (10,000–20,000 Ohm·m) in the deep parts of the crustal section (10–50 km). In the area of influence of the Dzida-Uda deep fault, the thickness of high-resistivity formations is reduced to 10 km (Fig. 5).

The distribution of electrical resistivity within the Khamar-Daban Range is due to the compositional diversity of its constituent granitoids of different ages. Based on the age and composition, they belong to the Early Paleozoic S-type syncollisional formations (Antipin and Gorlacheva, 2013; Antipin et al., 2014). These are basically crustal formations originated from gneisses and schists of the Khamar-Daban metamorphic strata. The granitoids are mainly migmatites, plagiogranites, granite-gneisses, and Ka–Na granites. The Late Paleozoic igneous area of the Khamar-Daban Range is characterized by the development of sub-alkaline granitoids (monzodiorites, quartz syenites, and leucogranite) and intrusive subvolcanic rare-metal Li-F granites on its periphery. They are post-collisional formations and mark the transition to within-plate magmatism with manifestations of various geochemical rock types (Antipin and Gorlacheva, 2013).

The low resistivity of the cross section lying below the high-resistivity rocks of the Khamar-Daban Range (100–150 Ohm·m) is due to the same processes as in the Selenga block discussed above, namely the high fluid reworking of the crustal section.

The Ivolga–Uda basin is a large Mesozoic structure extending from northwest to southeast and bounded by the Khamar-Daban and Ulan-Burgasy Ranges in the northwest and by the Ganzurinskii Ridge in the southeast. According to morphostructural features (Florensov, 1960), it is a Transbaikalia type intermontane basin, with a characteristic smooth transition from the bottom of the foothills to the well-developed mountain frame. The southern margin of the basin is made up of Upper Jurassic clastic deposits of the Galgatai Formations, and the central part is composed of the Lower Cretaceous Gusinoe Ozero argillo-arenaceous coal-bearing deposits. Continental margin molassoid deposits of the Sotnikov Formation are developed along its relatively steep northern boundary.

A determining factor in the formation of the modern morphostructure the Ivolga–Uda basin and its mountain frame is the structural continuity of roof-block movements and ruptural deformations. The axial part of the mountain ranges rose faster than their margins, which led to the asymmetry of the "wings" of its frame with characteristic step-block structures bounded by faults. In the modern intracontinental rifting setting, there is an expansion of the basins due to their surrounding mountain ranges, as exemplified by the Ivolga–Uda basin and its surrounding Khamar-Daban and Ganzurinskii Ranges. The results of this process are clearly seen in the geoelectric section (sites 17–20, Figs. 4 and 5). In the area of influence of the Dzhida–Uda rift fault adjacent to the steepest northern margin of the basin, there is a sharp uplift of the marginal part of the Khamar-Daban Range (from –50,000 m to –10,000 mm) and the resistivity decreases by almost an order of magnitude. In the area of junction of the basin with the Ganzurinskii Ridge, this interval of the crustal section is characterized by values of 500–700 Ohm·m (Figs. 4 and 5). Within the ridge, composed of intrusive formations of the Dzhida complex (Viktorova, 2001), the resistivity varies from 2000 to 2500 Ohm·m. The Ganzurinskii fault separating the Khamar-Daban and Tsagan-Daban blocks is the southeastern flank of the Baikal rift zone.

The Tsagan-Daban block (sites 23–33), covering the territory of the eponymous mountain range, is located within the Western Transbaikalia segment of the rift zone and is an extensive area of granitoid magmatism. The granites are extremely diverse in composition: gneiss and alaskite granite, syenite, quartz diorite, diorite, granodiorite, alkaline aegerine-arfvedsonite and riebeckite granites, granite-porphyry, quartz porphyry, and acid volcanics.

A feature of this block is that it is dissected by recent regional deep faults (mainly northeast- and southwest-trending) into smaller blocks with identical structure characterized by a two-layer section of the Earth's crust (Fig. 4). The upper part of the section in the depth range of 1000–15,000 m has the highest resistivities (2000–10,000 Ohm·m), with the maximum corresponding to the central part of the block. In the root parts of granitoid bodies, the resistivity is reduced to 500 Ohm·m. The lower part of the crustal section with a resistivity of 150 Ohm·m is complicated by a series of low-resistivity (below 30 Ohm·m) blocks, marking areas of neotectonic faults (Fig. 4).

The Tsagan-Daban block is bounded in the northwest and southeast by zones of regional long-lived northeast-trending faults (Fig. 4). According to (Bulgatov et al., 1978; Ochirov, 1976), the Transbaikalia block structure formed as a result of activation of faults of this trend.

The Tugnui block (sites 34–41) comprises one of the largest Mesozoic structures of the Western Transbaikalia—the Tugnui rift basin (graben). The basin is east-west trending, about 35–40 km wide, and stretches more than 140 km away from the lower reaches of the Khilok River in the west to the upper reaches of the Tugnui River in the east. Its northern and southern margins are the Tsagan-Daban and Zagan Ranges, respectively, made up of Precambrian Paleozoic rocks metamorphosed in the Late Mesozoic (Fig. 4).

The basin is mainly made up of Late Jurassic and Cretaceous volcanic and sedimentary strata, dominated by Middle Jurassic Ichetui Formation rocks. Along with dominating subalkaline basalts, they contain single beds and lenses of trachyte and trachydacite lavas and tuffs, interspersed with alkaline trachyriodacites and pantellirites (Gordienko and Klimuk, 1995; Gordienko et al., 1999; Vorontsov and Yarmolyuk, 2007). The Ichetui Formation is underlain by the Berezovskaya Formation conglomerates. The overlying section consists of coal-bearing clastic deposits of the Tugnui, Galgatai, Murtoi, and Selenga Formations, which accumulated until the Early Cretaceous (Tsekhovskii, 2013).

The studied part of the Tugnui basin is dominated by the Lower and Middle Jurassic desposits of the Berezovskaya, Ichetui, and Tugnui Formations. The geoelectric structure of the western and central parts of the basin (sites 34–39) is simple. Here the volcanic-sedimentary sequence is divided into three resistivity horizons (Fig. 6): $\rho_1 < \rho_2 < \rho_3$.

The first horizon (ρ_1), represented by Quaternary and Middle Jurassic deposits of the Tugnui Formation stands out only in the central part of the basin (sites 36–39). Quaternary deposits pinch out in the direction of its both margins and are completely replaced by the Tugnui Formation deposits in the vicinity of site 39 (Fig. 6). The second (ρ_2) and third (ρ_3) resistivity horizons, confined to the Ichetui and Berezovskaya Formation deposits, can be traced throughout the section and are characterized by laterally stable resistivity and thickness (Fig. 6). In the eastern part of the basin, bounded by a steep marginal bench, its disruption and erosion resulted in accumulation of coarse deposits of the Berezovskaya Formation with high resistivity (200–300 Ohm·m). Here the thickness of the sedimentary cover is reduced to 350–400 m, and the underlying section consists of ancient Paleozoic basement granitoids. In the area of site 40, the Berezovskaya Formation deposits are intruded by granitoids of the Late Permian Sogotin complex, represented by subalkaline granitoids, quartz syenite, and syenite porphyry. Here the resistivity is 3000 Ohm·m (Fig. 6).

The basement of the Tugnui basin, made up of predominantly Paleozoic granitoids, has a complex block structure (Bulnaev, 2006). It is divided by tectonic faults of varying trend into different-sized blocks which have been displaced

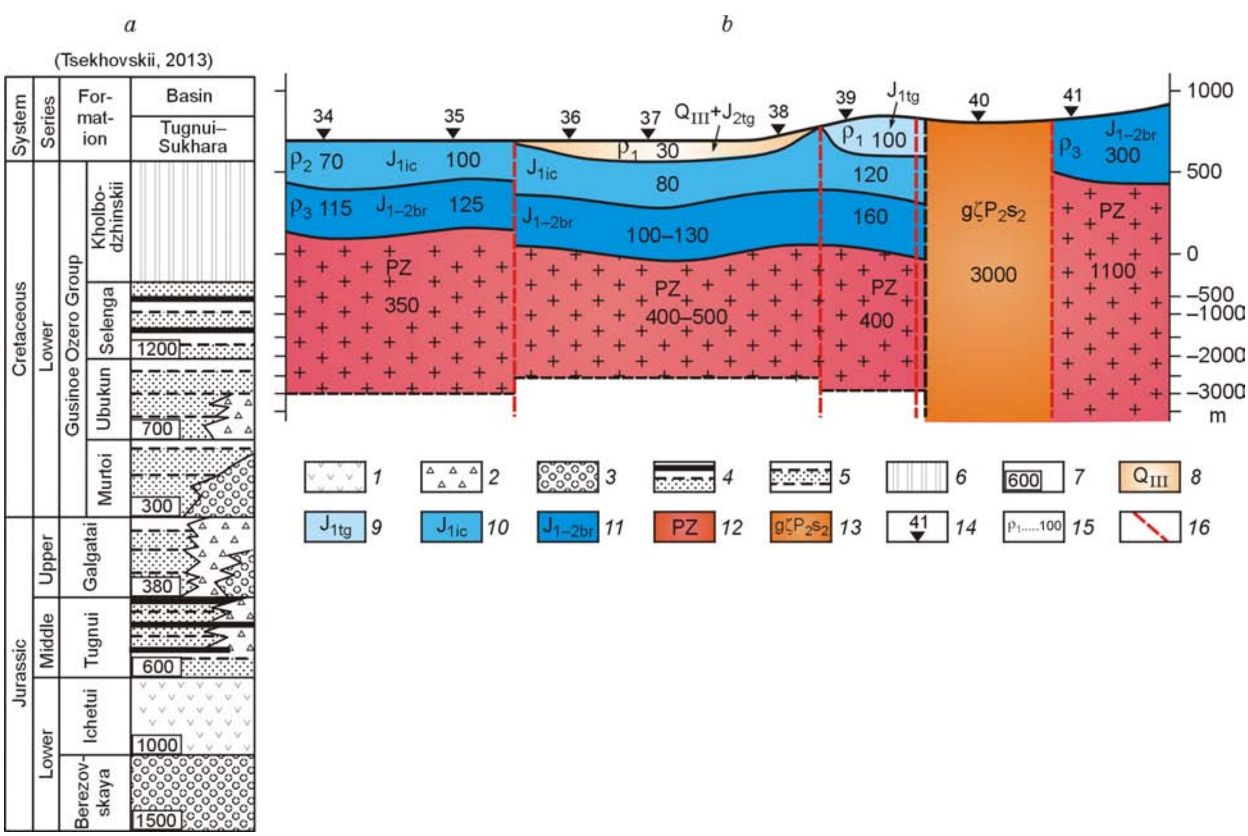

Fig. 6. *a*, Schematic structure of the formations of the Jurassic–Cretaceous deposits of the Tugnui–Sukhara rift basin (Tsekhovskii, 2013); *b*, geoelectric section of volcanic-sedimentary deposits of the Tugnui basin. *1*, effusive rocks; *2*, breccias with boulder lenses and rotten stone; *3*, boulder conglomerate, conglomerate, and gravelstone; *4*, interbedded sandstone, siltstone, and shale with coal beds; *5*, interbedded sandstone, siltstone, and shale, often coal and sometimes weakly coal-bearing; *6*, large interruptions in sedimentation; *7*, numbers at the corner of the columns indicate the maximum thickness of deposits in meters; *8*, Quaternary deposits; *9*, Tugnui Formation; *10*, Ichetui Formation; *11*, Berezovskaya Formation; *12*, basement; *13*, granitoid intrusion of the Sogotin complex; *14*, MT sites; *15*, resistivity horizons and resistivity values in Ohm·m; *16*, faults (from the 1:1,000,000 geological map of the Russian Federation, the third generation).

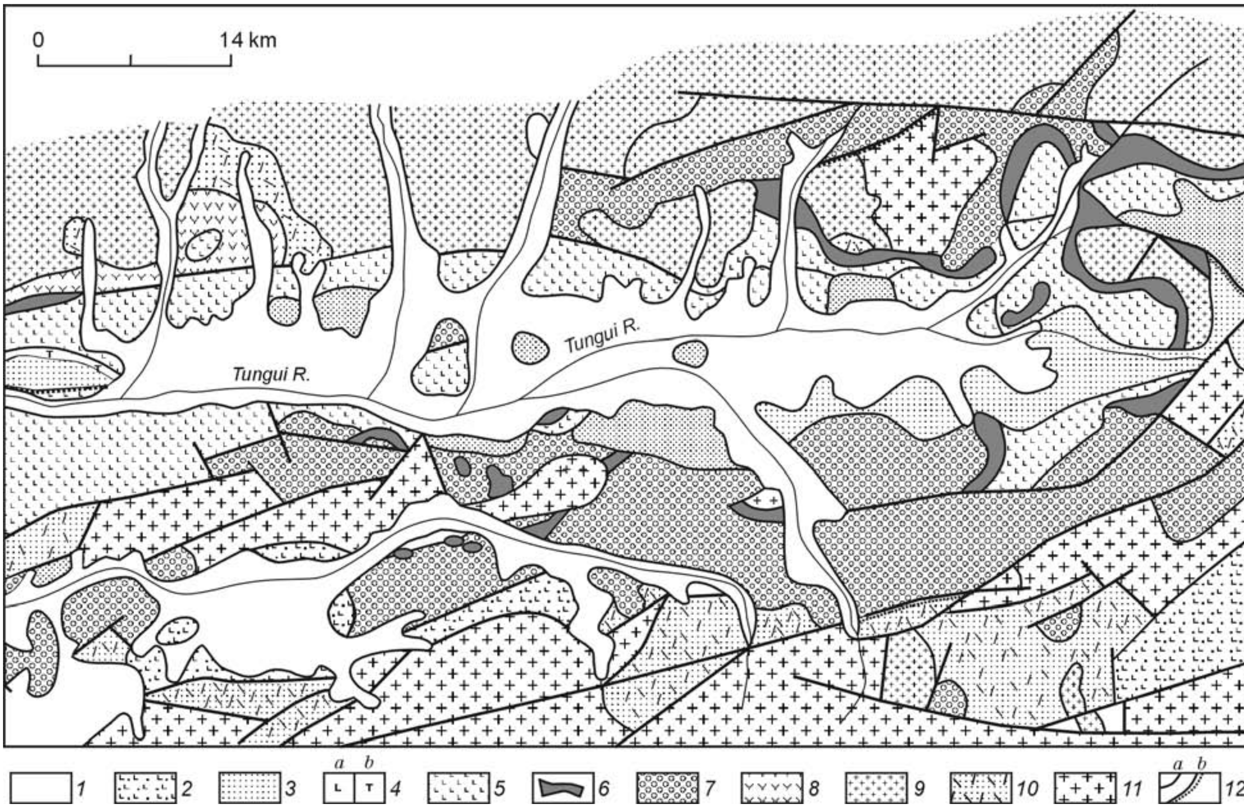

Fig. 7. Geological structure of the Tugnui rift basin (Western Transbaikalia) (Gordienko and Klimuk, 1995). *1*, Quaternary deposits; *2*, Khilok Formation (J_3–K_1): sandstone, siltstone, coal seams, conglomerate, trachybasalt sheets; *3*, Tugnui and Galgatai Formations (J_{2-3}): conglomerate, sandstone, siltstone, coal beds; *4*, upper subformation of the Ichetui Formation (J_2^2): trachybasalt, trachyte-trachyrhyodacite (*a*), subvolcanic trachyte and syenite-porphyry bodies (*b*); *5*, lower subformation of the Ichetui Formation (J_1^1): trachydolerite, trachybasalt, trachyandesite-basalt; *6*, Kapsal Formation (J_{1-2}): ignimbrite, tuff, breccia lavas, and trachyrhyodacite tuff lavas, acidic volcanic glass (perlite), conglomerate, sandstone, siltstone; *7*, Khonkholoi Formation (J_1): conglomerate, gravelstone, sandstone, siltstone; *8*, Chernoyar Formation (T_{2-3}): trachybasalt and trachyandesite basalt and their tuffs and tuff-breccias, tuff-conglomerate, tuff sandstone and tuff aleurolite, subvolcanic bodies of trachydolerite and trachyte; *9*, Upper Paleozoic granites; *10*, Upper Permian volcanic strata; *11*, Precambrian and Lower Paleozoic granitoids; *12*, faults (*a*), including thrusts (*b*).

relative to each other by different magnitudes. Some of them, observed on the surface of the structure, cross the entire section of the basin deposits (Fig. 7). These tectonic disruptions, along with long-lived deep marginal faults improve the interaction of groundwater of various geological complexes and related hydrogeological structures (Yas'ko, 1982). These venting areas provide vertical and horizontal movement of groundwater due to changes in its chemical and gas composition, temperature, and salinity. These processes lead to a sharp decrease in the resistivity of the basin basement to 400–500 Ohm·m (see Fig. 6).

The crustal section of the Tugnui block absolutely is dominated by absolutely low resistivities (10–30 Ohm·m). The exception is the depth range from –12,000 to –22,000 m near site 38, where they are increased to 150 Ohm·m and are in agreement with the resistivity level of the crustal sections of neighboring blocks (Fig. 4).

The occurrence of high electrical conductivity in the crustal section of the block considered and the nature of its permeability are related to the structural evolution, magmatism, and general geodynamics of the Tugnui rift basin. It formed in an extensional setting caused by the rise of the mantle plume in the Tugnui–Konda system of long-lived deep faults (Gordienko and Klimuk, 1995; Vorontsov and Yarmolyuk, 2007). Rifting was accompanied by Late Jurassic bimodal and Late Jurassic–early Early Cretaceous trachydacite-pantellirite volcanic lava eruptions localized within the basin. The absence of similar products of magmatism outside the basin indicates that the system of effluent channels feeding magmatic activity was located directly under the basin and sustained throughout the subsequent geological history (Vorontsov and Yarmolyuk, 2007). Highly permeable faulted areas of the Earth's crust cause its saturation with fluids and gases, which, in turn, leads to the formation of a high-conductivity area. Subvertical zones with resistivity lows (<5 Ohm·m) are formed within the basin, which mark recent faults disrupting both margins of the basin and their feathering second-order faults (Fig. 4).

The Zagan block (sites 42–50) includes the eponymous range and the Khilok–Chikoi rift basin (included in the block because of insufficient MT data on this basin, sites 48 and 49) and considered as a complementary structure to the Zagan Range.

The northeast-trending *Zagan Range* is bounded in northwest and southeast by the Tugnui and Khilok–Chikoi rift basins (Fig. 4). It is composed of the Zagan metamorphic core complex and has a zonal structure consisting of a core zone and a zone of brittle-plastic flow (Mazukabzov and Sklyarov, 1995; Mazukabzov et al., 2011; Sklyarov et al., 1997). Most of the core is composed of various granitoids, including syenites and granosyenites, gneiss granites, medium-grained granites, and granodiorites. The core of the complex is flanked by a gently-dipping zone of dynamometamorphic formations (mylonites) marking the detachment zone. Dynamometamorphic formations are widespread mainly along volcanic-sedimentary sequences of Late Paleozoic and partly Early Mesozoic rocks (Mazukabzov et al., 2011). The mylonite rocks vary in the degree of metamorphism and comprise protomylonites, mylonites, mylonite schists, blastomylonites, and pseudotachylites, and ultramylonites (Mazukabzov and Sklyarov, 1995). In addition, the slopes of the range contain Late Paleozoic–Mesozoic volcanic-sedimentary formations common in the associated basins: the Tugnui basin in the northwest and the Khilok–Chikoi basin in the southeast.

The zonal structure of the Zagan Range, with the variety of its compositional associations, is reflected in the resistivity distribution pattern. In general, the high resistivities characteristic of the upper crust of the block differ significantly in its central and marginal parts (Fig. 4). The central high-resistivity area (sites 43–46) corresponds to the rock spectrum of granite-metamorphic formations of the core. Here the resistivities are maintained at 12,000–20,000 Ohm·m over the entire range of depths (from 600–15,000 m). They decrease to 4000–5000 Ohm·m toward the margins and are 600–1000 Ohm·m in the area between the range and the basins (Fig. 4). The marginal parts of the Zagan Range, comparable in resistivity, differ in vertical length. The eastern part of the range is the most elevated. In the western part, it is traced to depths of 22,000 meters and uplifts sharply to 15,000 m in the area of transition to the Tugnui basin.

The lower crust with a resistivity of 150 Ohm·m is disrupted by a series of subvertical conductive zones, associated with a system of longitudinal faults and marginal rift faults and range-associated basins (Fig. 4).

The formation of the Zagan metamorphic core complex and its complementary Tugnui and Khilok–Chikoi basins is related to rifting processes, which in Western Transbaikalia began with the occurrence of a mantle plume in the base of the region (Mazukabzov and Sklyarov, 1995; Mazukabzov et al., 2011; Sklyarov et al., 1997; Vorontsov and Yarmolyuk, 2007). Extension processes were accompanied by the formation of separate basins (grabens), including the Tugnui basin. Adjacent areas of the Earth's crust, affected by enhanced heat flow, undergo anatexis and metamorphism, resulting in areas of increased plasticity. In the extensional setting, these plastic crust fragments contributed to the formation of a hollow detachment zone with a southeastern vergence, expressed as a mylonite zone (Sklyarov et al., 1997). The surface of the detachment zone restricted the access of mantle melts to the Tugnui basin and was bulged up by the buoyant hot crustal mass of the Zagan Range. The Khilok–Chikoi basin formed above the steep branch of the detachment zone subsiding to the plume. This promoted the formation of a stable system of effluent channels under the basin and the displacement of sites of active magmatism into its area (Vorontsov and Yarmolyuk, 2007).

The Khilok–Chikoi basin, like the Tugnui basin, extends roughly east–west over a distance of 150 km at a width of 20–30 km. The basin is made up of Cretaceous (Gusinoe Ozero Sequence and Khilok Formation) and Cenozoic volcanic and sedimentary strata. The Early Cretaceous Khilok Formation rocks (K_1hl) are dominant. They appear as almost continuous thick series of lava flows over the entire length of the basin.

A crucial role in the formation of the modern structure of the Khilok–Chikoi basin was played by marginal rift faults and transverse faults dissecting the basin and producing the distinct block structure of the basin (Fig. 8). The formation of steeply dipping faults is probably related to the period of isostatic buoyancy, i.e., with the establishment of the Zagan dome. According to geological features, this event occurred after the formation of shallow mylonite zones (Sklyarov et al., 1997).

The Khilok–Chikoi basin appears in the geoelectric section as an area with a very low crust resistivity (≤5–10 Ohm·m) (Fig. 4). Its marginal parts have subvertical zones with resistivity lows (5 Ohm·m or less), associated with marginal rift faults. Low resistivities of the basin basement (200–250 Ohm·m) are due to the venting of fracture-vein waters at the sites of intersection of marginal and meridional faults.

The Malkhan block (sites 51–62) is located within the southeastern flank of the MT profile and includes the Malkhan Range and the Chikoi basin; the basin is not identified as a separate block because of a lack of sufficient MT data on it.

Within the *Malkhan Range* (sites 50–59), almost the entire crustal section, explored to depths of 30,000 m is characterized by high resistivity, which ranges from 5000 to 45,000 Ohm·m (Fig. 4). The high resistivity is due to the extensive development of various igneous complexes throughout the crustal section. These are primarily granitoids differing in composition and structure, including granitoids of the Malkhan metamorphic core complex, whose central part is composed of Early and Middle Paleosoic granitoids interspersed with metamorphic xenoliths. A special feature this complex is the much wider occurrence of diorite rocks (Sklyarov et al., 1997).

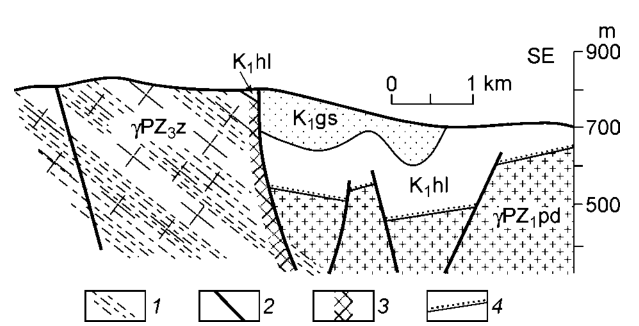

Fig. 8. Correlation between the Khilok–Chikoi basin and the Zagan Uplift. (Sklyarov et al., 1997). K_1gs, Gusinoe Ozero Formation; K_1hl, Khilok Formation; γPZ_3z, Upper Paleozoic granitoids; γPZ_1pd, Early Paleozoic granitoids; *1*, mylonitization; *2*, faults; *3*, increased fracture zone; *4*, thrust.

The outer zone, facing the Early Cretaceous Chikoi basin, is composed of Middle Paleozoic foliated granites and Early Cambrian and Carboniferous metamorphic sedimentary and volcanic deposits. A significant part of these deposits is dynamically metamorphosed in a wide fault zone gently dipping to the southeast (Mazukabzov et al., 2011; Sklyarov et al., 1997).

The granitoid fields are extensively penetrated by mafic intrusions of rocks of the Lower Paleozoic Monostoi gabbroic complex. The rocks of this complex (gabbro, gabbro, diorite and gabbro-diorite) contribute significantly to the formation of the high-resistivity region of the central part of the Malkhan Range. Here the resistivity varies between 12,000 and 45,000 Ohm·m. Resistivity highs correspond to outcrops of mafic intrusions. On the margins of the range, the resistivity is reduced to 5000–8000 Ohm·m, and in the areas of transition to the Khilok–Chikoi and Chikoi basins, it is 500–1500 Ohm·m (Fig. 4).

The Chikoi basin, like the Tugnui and Khilok–Chikoi basins discussed above, is a Transbaikalia type basin formed in an extensional setting in a system of long-lived deep faults (Bulnaev, 2006; Gordienko and Klimuk, 1995; Vorontsov and Yarmolyuk, 2007). It is roughly east-west trending and extends over a distance of about 130 km with a width of 1–2 to 8 km. The basin is bounded in the north by the Malkhan Range and in the south by the spurs of the Asin, Ulentui, and Mergen Ranges (Fig. 4). Geologically, it is a sedimentation basin filled with Early Cretaceous terrigenous rocks with a total thickness of 700 to 1600 m. It originated in the Mesozoic and developed during the Neogene–Quaternary under the influence of neotectonic movements in the south of the Khilok–Vitim structural-facies zone.

Low resistivity values from 3–5 to 30–50 Ohm·m were measured virtually throughout the crustal section within the Chikoi basin. This is due not only to its deep structure but also to the insufficient exploration of this region. The profile traversed the basin only at two sites (60 and 61) in the marginal fault zone, which did not allow us to estimate the upper crust. In the geoelectric section, the Chikoi basins corresponds to a low-resistivity region complicated by subvertical conductive zones (less than 5 Ohm·m) related to marginal rift faults (Fig. 4). The southeastern termination of the Malkhan block (and, in general, the entire investigated profile) are the high-impedance (10,000 Ohm·m) formations of the Chikoi Mountains.

Conclusions

The study area has a complex geological-tectonic structure produced by extensive rifting, leading to the formation of large crustal blocks, and by intense magmatic fluid activity along deep fault zones. These processes are manifested in the deep electrical conductivity distribution as follows.

1. The significantly lower tectonic activity of the Western Transbaikalia rift zone, compared to the Baikal region of modern rifting, is reflected in the contrast of the resistivity distributions in the northwestern and southeastern parts of the studied profile. The high permeability of the Baikal rift lithosphere due to active Cenozoic faulting allows venting of mantle fluids and provides additional heat transport. Areas with maximum disruption of the Earth's crust and hence with increased permeability to fluids and heat are characterized by broad resistivity lows (Selenga block). The increased tectonic activity of the Selenga block is indicated by the parameters of the crustal conductive layer. The depths of the top and base of the layer correlate with the temperature distribution in this part of the crustal section.

2. Both parts of the profile are characterized by a combination of structures with different types of geoelectric section—mountain ranges and intermontane basins separated by areas of long-lived deep faults. The ranges are complex resistivity heterogeneities with a two-layer section of the crust. The upper part of the section, composed of granitoids of different age and composition, has high resistivity values. They are distributed in descending order from the central parts of mountain ranges to their margins. The sharp decrease in resistivity in the underlying section of the crust is associated not so much with the rock composition as with its high permeability to fluids and gases due to intense regional faulting zones. The exception is the Malkhan Range, within which the entire studied section of the Earth's crust is characterized by high resistivity due primarily to the mafic magmatism widespread within the Earth's crust and upper mantle.

3. Intermontane basins are large Mesozoic rift structures formed in an extensional setting in a system of long-lived deep faults. In the geoelectric section, they correspond to low-resistivity crustal blocks complicated by subvertical conductive zones associated with marginal rift faults.

4. The regional deep faults separating blocks of different sizes appear in the geoelectric section as distinct subvertical zones with resistivity lows. The dips of their lateral boundaries coincide with the position of the fault planes determined from geological structural data on the surface (Boartovoi, Dzhida–Uda, Ganzurin). The conductive zones within the Tsagan-Daban block mark recent fault zones.

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