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Neotectonics of eastern Gorny Altai: Evidence from magnetotelluric data

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Abstract

According to 2D magnetotelluric (MT) data from northeastern and southeastern Altai, numerous neotectonic faults cut the Gorny Altai territory as a whole, as well as large basins within its limits, into blocks. Large neotectonic faults are traceable depthward in MT-based cross sections as zones of very low resistivities (below 0.5 Ohm·m). The MT data generally confirm the fault geometry inferred previously from morphotectonic and geological evidence. Fault plane dips are vertical in normal and strike-slip faults and inclined in reverse faults. The nearly vertical and dipping zones of neotectonic faults crosscut a horizontal conductivity anomaly at depths of 10–15 km. The anomaly makes a natural divide between the zones of brittle crustal failure above and ductile downward pressing of material below. It may be responsible for the high tectonic and seismic activity potential of the upper lithosphere in Gorny Altai associated with growth of mountains and crust thickening. Beneath the Chuya and Kurai large basins, the conductivity anomaly occurs at a shallow depth of 10 km and has a resistivity below 10 Ohm·m.

Keywords: magnetotelluric soundings; neotectonics; Gorny Altai

Introduction

Neotectonic activity sculptures the modern Earth's surface and controls the shape and location of major landforms. Correspondingly, Late Cenozoic tectonic structures are commonly studied by morphotectonic and geomorphological methods (Bogachkin, 1981; Devyatkin, 1965; Masarskii and Moiseenko, 1962; Moiseenko, 1969; Novikov, 2001, 2004). These methods are however restricted to the surface 2D distribution of neotectonic faults and folds but cannot see their behavior in depth. Therefore, morphotectonic 3D models stem from fragmentary data and can give only a tentative idea of fault slip geometry and depths of neotectonic structures. Geophysical surveys are required for obtaining more faithful 3D images, which is especially important for highly seismic and tectonic active areas. Seismic profiling is the most commonly used method (Novikov et al., 2008, 2014; Nevedrova and Pospeeva, 2009; Nevedrova et al., 2011), while resistivity and gravity surveys are more rare (Dobretsov et al., 2016). Electromagnetic soundings with natural or controlled sources are progressively becoming ever more popular alternative due to multiple proxies of deep-seated tectonic movements. Among the existing resistivity methods, magnetotelluric soundings (MTS) of the Earth's natural electromagnetic field provide the greatest depth penetration. Electrical conductivity in deep earth is sensitive to temperature, phase state, fluid content, and other parameters and thus can bear the respective information.

The Altai–Sayan region in Russia is remarkable by its high seismicity, as well as the Baikal rift system, the Kuriles–Kamchatka arc, and the Caucasus. Gorny Altai belongs to the Altai–Sayan orogenic area which is currently a scene of active mountain building and, presumably, high seismicity. Seismic activity within Gorny Altai was believed to be moderate, proceeding from instrumental and historic records, until extrapolation of seismotectonic data from the adjacent territories of Mongolia and China (Reisner and Ioganson, 1996; Reisner et al., 1993; Rogozhin et al., 1995) led to the inference of high seismic risk with the highest possible magnitude of $M = 7.5 \pm 0.2$. The inference was proven valid when the $M = 7.3$ Altai earthquake shock the area on 27–28 September 2003 and became an impetus for new studies of crustal dynamics. Setting up MT surveys in Gorny Altai was motivated by the discovered correlation of earthquake activity with geological and neotectonic features. Since the first steps in this direction

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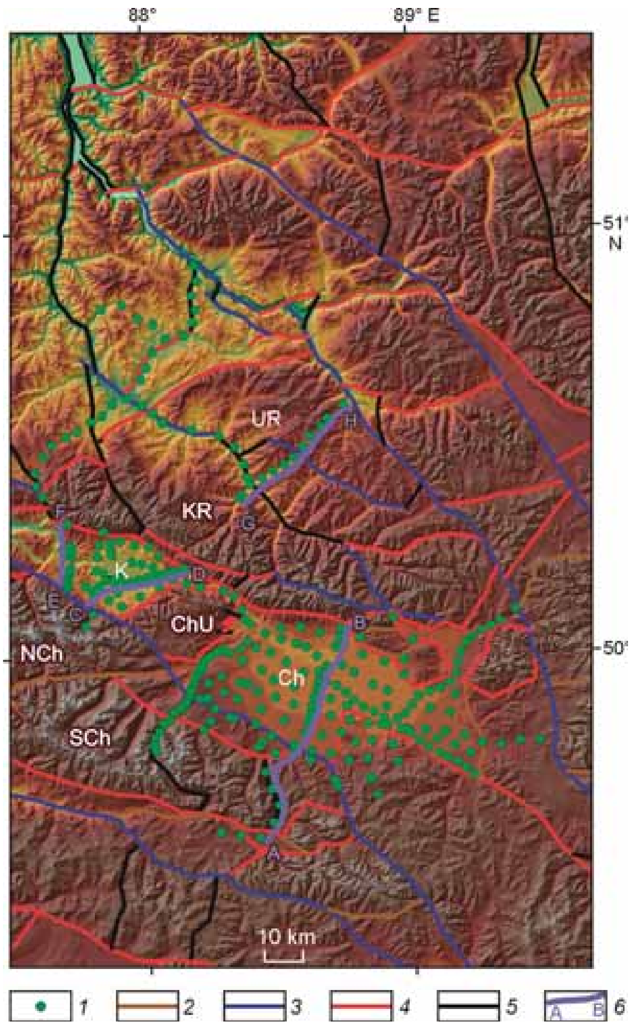

Fig. 1. Morphotectonic model of western Gorny Altai, with MTS points. *1*, MTS points, *2–5*, neotectonic faults: uncertain slip geometry (*2*), right-lateral strike-slip faults and reverse faults with a strike-slip component (*3*), reverse and thrust faults (*4*), normal faults and grabens (*5*); *6*, profiles shown in Figs. 2, 4, 6, and 7. Abbreviations stand for: NCh, North Chuya Range; SCh, South Chuya Range; KR, Kurai Range; UR, Ulagan Range; ChU, Chagan-Uzun Mountains; K, Kurai basin; Ch, Chuya basin.

undertaken recently (Lunina et al., 2008; Novikov et al., 2008), a wealth of MT evidence has been collected, with a focus on the depth and resistivity of large crustal conductivity anomalies, as well as on the pattern of Cenozoic active faults. Joint analysis of MT and faulting data can provide clues to understanding the current tectonism, seismicity, and deep-seated fluid regime.

Methods

MT data were acquired with a *Phoenix Geophysics Ltd* system (made in Canada) at periods from 0.003 to 10000 s. Two MTU-5 measurement units could record five components of the MT field (E_x, E_y, H_x, H_y, H_z), at a spacing of 4–5 km, reduced to 1 km in the epicentral area of the Chuya (Altai) earthquake. The system consisted of 100 m long crossing electric lines, with the X and Y axes oriented in the northern and eastern directions, respectively. The sounding duration was 19–22 hr on average.

The field data were processed with the *Phoenix Geophysics* software and inverted in 1-D and 2-D with the *WinGLink* software, using the Nmt inhomogeneity (Berdichevskii et al., 1997) and the skewness parameters Skew_S and Skew_B of Swift (1967) and Bahr (1988), respectively, as well as impedance polar plots. The impedance tensor analysis images the study territory generally as an NW regional 2D structure. Distortion to ascending branches of MT sounding curves was checked against TEM data (Nevedrova and Pospeeva, 2009; Nevedrova et al., 2011; Pospeeva et al., 2014) and the descending branches were normalized to the global magnetovariation (MVS) curve (Fainberg et al., 1977; Pospeev, 1979; Pospeev and Mikhalevskii, 1981). To improve the interpretation reliability, the data were inverted using the Trefftz method with reference to the numerical model of distorted MT curves (Plotkin and Gubin, 2015). The approach ensures good inversion quality even in the presence of 3D inhomogeneities and strong distortion to MT curves. It allows avoiding analysis of standard 2D approximation applicability in the choice between different types of MT curves (transversal/ longitudinal, minimum/maximum, distorted/nondistorted), and makes unnecessary the normalization of curves. All MT curves can be used as input data for inversion, while taking into account all their distortions improves significantly the quality of the resulting resistivity sections.

By the present, more than 270 soundings have been performed in the area, along profiles and in 2D arrays (Fig. 1). Data collected by survey teams from the Krasnoyarsk Research Institute of Geology, Geophysics, and Mineral Resources (KNIIGGiMS) and from the RAN Science Station in Bishkek were used additionally for reference in geological modeling.

Tectonic background

Gorny Altai is an NW–SE striking system of generally low-grade active- and passive-margin complexes cut by intrusions, with sporadic high-grade metamorphism. The area has existed in a continental setting since the Late Devonian–Early Carboniferous collision of the Kazakhstan–Baikal and Siberian continents (Buslov et al., 2013). The collision zone remained active and responded by faulting and mountain growth to far-field processes on the margins of newly formed Eurasia. Activity events repeated in Late Paleozoic, Mesozoic, and Cenozoic time, judging by molasse of the respective ages preserved in tectonic wedges and basins (Novikov, 2013). The latest activity as an echo of the India–Eurasia collision has occurred in the Neogene and Quaternary. Currently the compression within Gorny Altai is directed northward, while West Siberia and Junggaria on its both sides are converging at ~4 mm/yr (England and Molnar, 1997, 2005; Yang et al., 2005) which leads to faulting along existing and new planes. Cenozoic active faults with large amounts of displacement

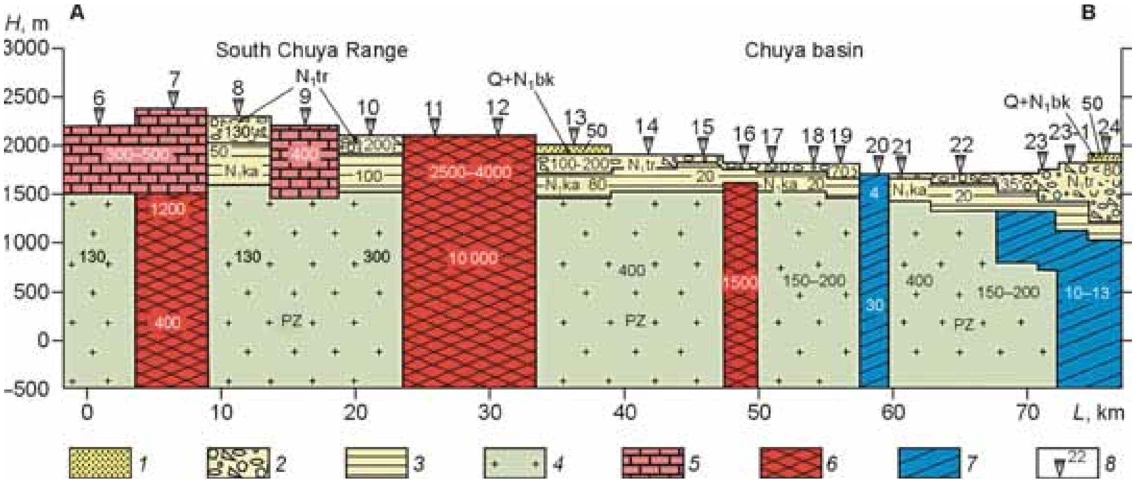

Fig. 2. Resistivity cross section of sediments along profile A–B (South Chuya Range–Chuya basin). *1*, Quaternary sediments of the Pliocene Bashkaus and Beken Formations; *2*, Lower Pliocene–Upper Miocene Tueryk Formation; *3*, Middle–Lower Miocene Koshagach Formation; *4*, Paleozoic basement; *5*, plutonic and metamorphic complexes in mountains; *6*, high-resistivity zones corresponding to low-porosity massive rocks; *7*, low-resistivity zones corresponding to deformation zones of neotectonic faults; *8*, points of MTS soundings. Numerals are resistivity values (Ohm·m).

(hundreds and thousands of meters) control the present framework of ranges and basins between them, i.e., methods of geomorphology are applicable to reconstruct the neotectonic framework (Novikov, 2001). The N–S compression, along with NW-oriented fault boundaries between accretionary complexes of different ages, form a system of major NW neotectonic right-lateral strike-slip faults with pinnate faults of compressional (reverse and thrust) and extensional (normal faults) geometries. Deformation of rheologically heterogeneous crust has produced a northward opening fan-shaped system of faults, more complicated than it was assumed in the classical tectonophysical studies, with backbone strike-slip zones and pinnate compressive and extensional faults.

The Gorny Altai surface topography consists of regularly alternating high mountain chains, valleys of large rivers, and ramp or half-ramp intermontane basins.

Results of MT surveys

MT surveys within the Chuya and Kurai tectonic basins and the flanking mountains have provided depth-dependent resistivity/conductivity patterns which record a complex structure of faults that cut both basins and ranges into blocks. The crust in the mountains is rather highly resistive till the depths 15–18 km, which is consistent with the predominance of consolidated sedimentary, plutonic, and metamorphic complexes. Resistivity is the highest (5000 Ohm·m) within the South Chuya Range, the southern border of the Chuya basin. The range, a block uplift upon a folded Paleozoic basement, comprises 3000–4500 m asl Alpine-type mountains composed of high-grade rocks. The resistivity within the North Chuya and Kurai Ranges, as well as in the Chagan-Uzun Mountains, is from 1500 to 2000 Ohm·m. The mountains are separated from the basins by neotectonic faults which coincide in plan view with nearly vertical zones of low resistivity (<2 Ohm·m). Consolidated rocks buried under soft Cenozoic sediments within the Chuya–Kurai system are mostly low resistive.

The Chuya and Kurai basins evolved concurrently with the uplifts around them. They are ramp (Kurai) or half-ramp (Chuya) basins like most of present intermontane basins in Gorny Altai.

The *Chuya basin*, the largest one in Gorny Altai, accommodates up 1200 m of Paleogene, Neogene, and Pleistocene continental sediments (Devyatkin, 1965). The MT section across the Chuya basin and the South Chuya Range, in the N–S direction along the A–B profile (Fig. 2), reveals three resistivity layers in Late Cenozoic sediments. They correspond to (1) the Quaternary (Upper Pliocene) Bashkaus, Kyzylgir, and Beken Formations, varying in thickness from 400 m to 130 m and to zero and exceeding 300 Ohm·m in resistivity; (2) the Lower Pliocene–Upper Miocene Tueryk Formation, 140 m thick on average, <300 Ohm·m; (3) the Middle–Lower Miocene Koshagach Formation, from 200 to 250 m thick, 25–30 Ohm·m.

The resistivity image shows no single large block at the base of the Chuya basin which would subside at the account of converging ridges. On the contrary, it lies upon a system of multiple small subsided blocks surrounded by uplifted blocks (ranges) of highly resistive Paleozoic basement rocks. The orogeny involved the Chuya basin itself and caused faulting in its base and formation of linear neotectonic troughs which evolved while the flanking mountains were growing. Rapid deformation began in the earliest (Vetrov et al., 2016) or latest (Devyatkin, 1965) Pliocene. The same processes led to motion of blocks producing a hilly terrain with basement uplifts marked by high resistivity (200–400 Ohm·m) in the central part of the basin where the Paleozoic basement uplifted along neotectonic faults (though not reaching the ground surface) divides the basin into almost equal halves. The sediments are the thinnest along the basin axis but much thicker on its northern and southern margins. The basement

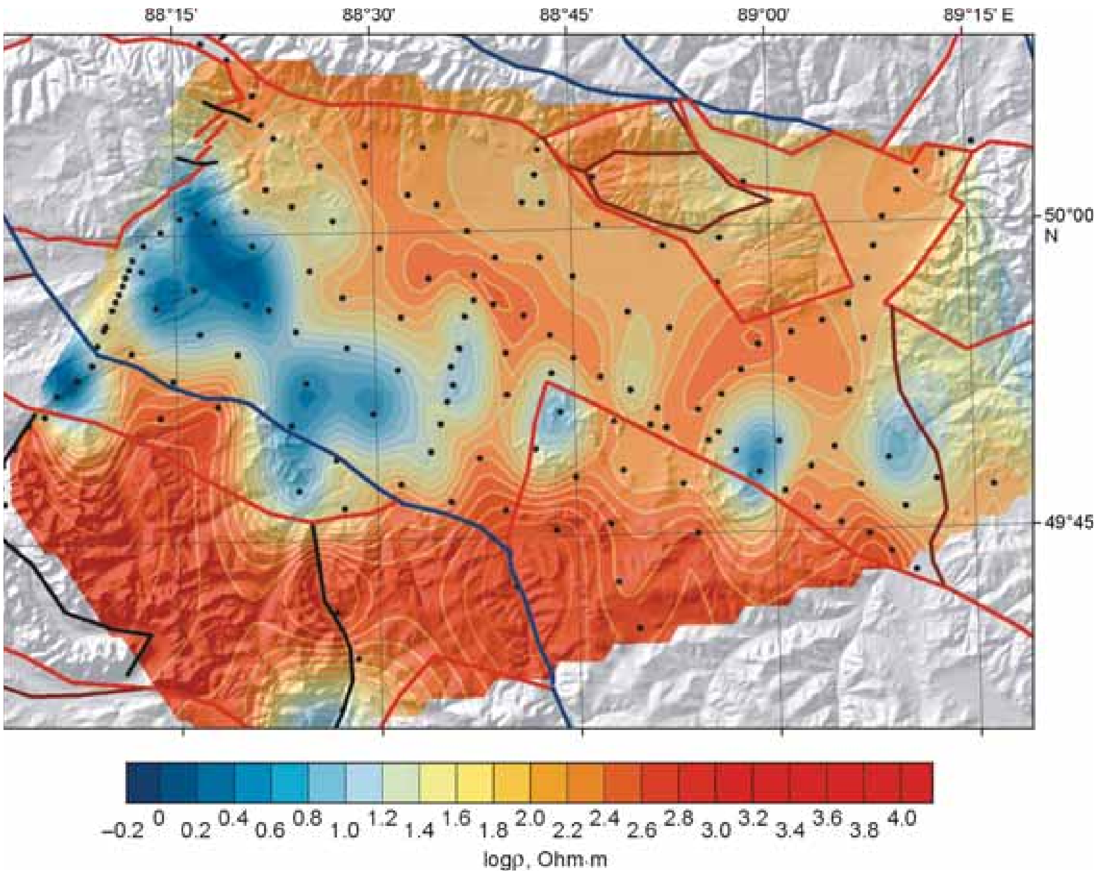

Fig. 3. Resistivity pattern to a depth of 5 km in the Chuya basin. Lines are neotectonic faults inferred from geological and geomorphological data. Corresponds to faults in Fig. 1. Symbols of slip geometry are as in Fig. 1.

uplift is traceable in the resistivity field to a depth of 5 km (Fig. 3).

The *Kurai basin* is a large intermontane basin with fault borders of reverse slip geometry (pure reverse slip or with a strike-slip component). The basement composed of Paleozoic and Late Proterozoic volcanic and sedimentary rocks crops out in its western part while the eastern part has been a basin of Cenozoic deposition. The resistivity pattern in the Kurai basin was imaged along the C–D and E–F MT profiles that cross it in the W–E and N–S directions, respectively. The profile C–D (Fig. 4) has a shallower penetration but a higher resolution. It shows three resistivity layers in basin sediments: (1) Middle–Late Pleistocene fluvioglacial deposits with uniformly low resistivity (15–20 Ohm·m) reducing in thickness northeastwards from 150 m (points 17–20) to zero; (2) slightly more resistive (50–70 Ohm·m) undifferentiated Early–Middle Pleistocene deposits and Middle Miocene rocks of the Tueryk Formation, 250 to 300 m thick; (3) the most conductive (10–20 Ohm·m) layer of the Lower Miocene Koshagach Formation and Upper Oligocene Karachum Formation sediments, 350 m thick.

The basement consists of Upper Riphean, Vendian, and Cambrian rocks (Buslov et al., 2013) varying in resistivity from 70 to 400 Ohm·m, the highest at Paleozoic outcrops. A basement uplift separates the southern part of the basin, with much thicker Cenozoic sediments, from its northern part where the neotectonic fault border of the basin dips northward to beneath the Kurai range. A large neotectonic fault in the southern part of the basin appears in the resistivity section as an almost vertical broad conductive zone (1–15 Ohm·m) standing out against the resistive basement. The reverse-slip southern fault border is beyond the profile.

The Cenozoic tectonics of Gorny Altai has left a prominent imprint on structures produced by active deep processes marked by regional-scale conductivity anomalies associated with circulation of fluids through faulted crust. The Chuya–Kurai system of basins falls within one such zone extending in the NW direction along the strike of accretionary complexes that make up the Paleozoic structure of the region. Resistivity in the middle part of consolidated crust in this zone is below 300 Ohm·m and reduces to 50 Ohm·m in the area of the Chuya earthquake and in the central Kurai basin. Linear conductivity anomalies (1 Ohm·m) striking in NW and SE directions at the same depths may correspond to faults buried under sediments (Fig. 5). Deep faults in the lithosphere can channel fluids in periods of their activity. They reach the lower crust and mantle depths and act as conduits along which mantle fluids rise to shallow levels (Kadik, 2006). Such faults can generate the largest earthquakes, which is consistent with experimental evidence of earthquakes triggered by abrupt ascent of fluids (Aptikaev, 1995). In Gorny Altai, neotectonic faults follow Paleozoic fault zones only within limited areas and commonly

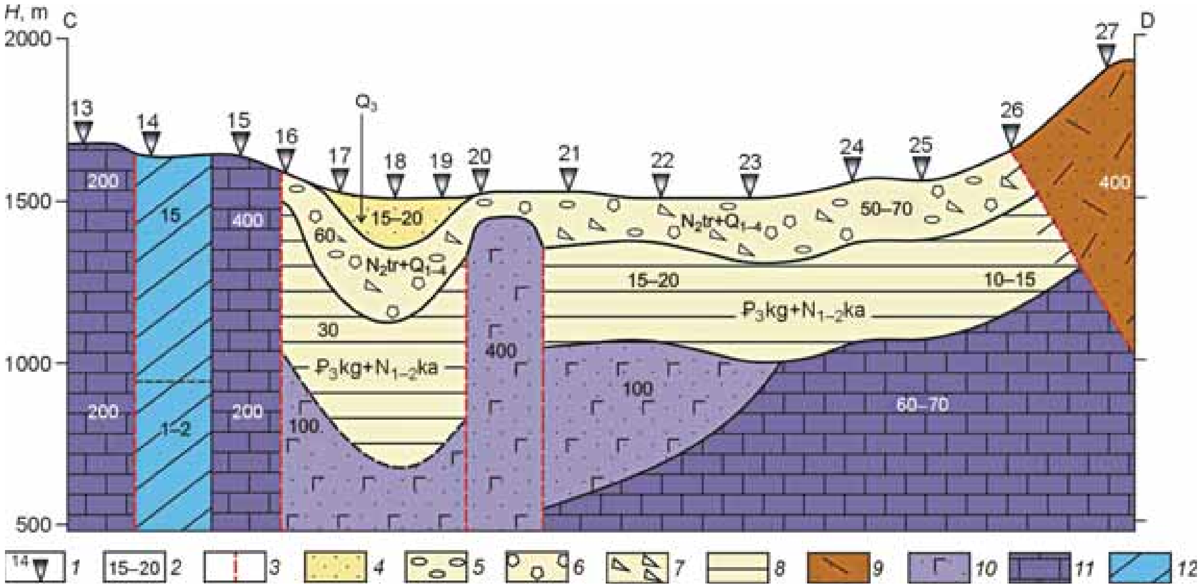

Fig. 4. Resistivity cross section along profile C–D (Kurai basin). Basement complexes are according to (Buslov et al., 2013). *1*, MTS points; *2*, resistivity values in Ohm·m; *3*, faults marked by abrupt resistivity changes in MT data; *4–8*, fluvioglacial (*4*), alluvial-lacustrine (*5*), glacial (*6*), alluvial-proluvial (*7*), clay, marl, clay silt, silt, and brown coal (*8*) Cenozoic deposits; *9*, active-margin Early–Middle Devonian volcanic-sedimentary rocks; *10*, Vendian volcanics; *11*, Cambrian carbonate rocks; *12*, faults recorded as low-resistivity zones in MT data.

crosscut them at different angles (Novikov, 2004). The intersections of reactivated faults appear in the MT field as nearly vertical low-resistivity zones with one lateral boundary dipping (Fig. 6) which are well pronounced in the N–S profile across the western Kurai basin. Such features may correspond to combination of reverse and strike-slip faults along separate zones of neotectonic faults.

The presence of local conductivity anomalies in consolidated crust associated with neotectonic faulting impedes or even rules out constraining the position of the regional-scale crustal high-conductivity zone as an indicator of the geothermal regime and fluid saturation. Its top in structures of different ages is located at different depths corresponding to the 350–450 °C isotherms and its base is delineated by the 750–800 °C isotherm. The ranges of temperatures between 300 and 750 °C and pressures from 2.5 to 6.0 kbar span crustal rocks from greenschist to amphibolite facies, inclusive. As the pressures and temperatures increase, a series of solid-phase metamorphic reactions leads to multistage dehydration whereby most of bound water releases and forms saline aqueous solutions and supercritical fluids separated by the water critical point at 374 °C (Kissin, 2009; Pokrovskiy, 2006). The intergranular fluid phase plays a special role in the formation of the crustal conductivity anomalies (Kissin, 2009; Ringwood, 1975; Shankland et al., 1981). Water may also release by oxidation of reduced mantle fluids (Letnikov, 2000; Marakushev and Perchuk, 1971). There is good correlation between the depths to the conductor top and heat flux: it shallows as heat flux increases (Adam, 1987; Batalev et al., 2013; Klemperer et al., 1987; Pospeev and Mihalevskii, 1981; Rybin et al., 2001). Therefore, the geothermal regime controls the position of large conductivity anomalies.

The regional conductive zone is fragmentary within the study area, except for the G–H profile across the Ulagan Range (Fig. 7) where it continues over a long distance at depths 10–15 km. The profile traverses two large vertical faults in northeastern Altai which are traceable to depths greater than 20 km. A zone of extension covering the middle part of the Bashkaus River valley is slightly less prominent in the resistivity section unlike the clearly pronounced neotectonic strike-slip zone in the middle of the Ulagan Range with the total amount of Late Cenozoic displacement as large as 9000 m, according to geomorphological data (Novikov, 2004).

The conductivity anomaly reaches the 18–20 km depths and has an average resistivity of 30–50 Ohm·m in the mountains flanking the Chuya–Kurai system of basins but is shallower (8–10 km) and more conductive (<5 Ohm·m) within the basins themselves. Most of earthquakes fall within this area which may indicate that the shallow top of the conductive zone may separate rigid upper crust from more ductile fluid-saturated lower crust, and most of stress releases at the interface. The MT results obtained through the recent decades from different parts of the world have revealed correlation of processes in seismic zones with crustal and upper mantle conductive features (Adam, 1987; Bryksin and Khlestov, 1980; Epov et al., 2011; Grachev, 2000; Jackson et al., 2002; Kissin, 2009; Moroz et al., 2008; Moroz and Moroz, 2009; Nikiforov et al., 2013; Pospeeva et al., 2014; Rodnikov et al., 2002). Synthesis of the data allows an inference on the location of crustal earthquakes with respect to the conductive zone. Namely, seismic activity most often occurs at junction of structures with different resistivities. Earthquakes commonly originate above large conductivity anomalies or in their upper parts where they abruptly become shallower and where

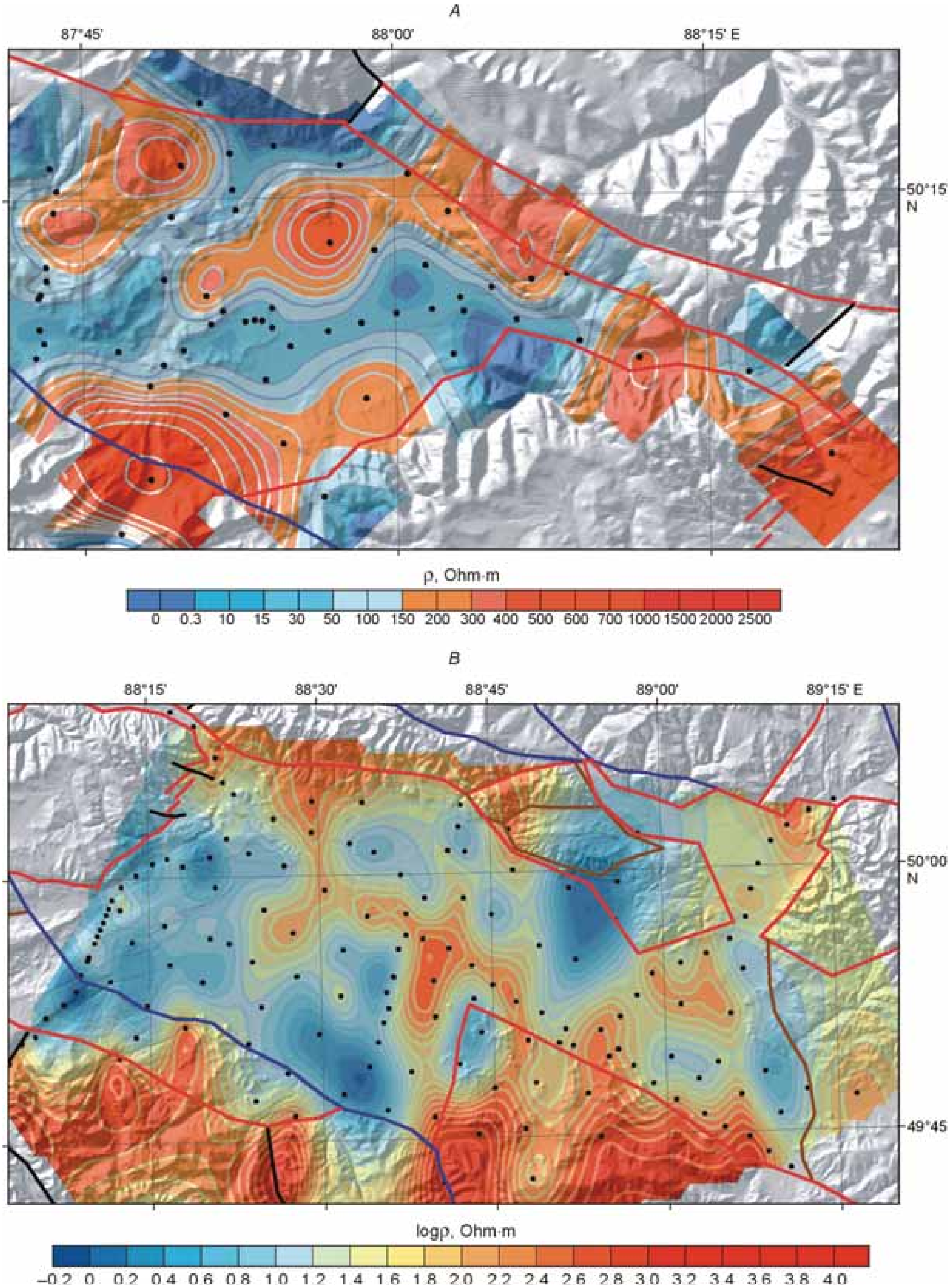

Fig. 5. Resistivity pattern to a depth of 10 km: *A*, Kurai basin; *B*, Chuya basin. Lines are neotectonic faults inferred from geological and geomorphological data. Corresponds to faults in Fig. 1. Symbols of slip geometry are as in Fig. 1.

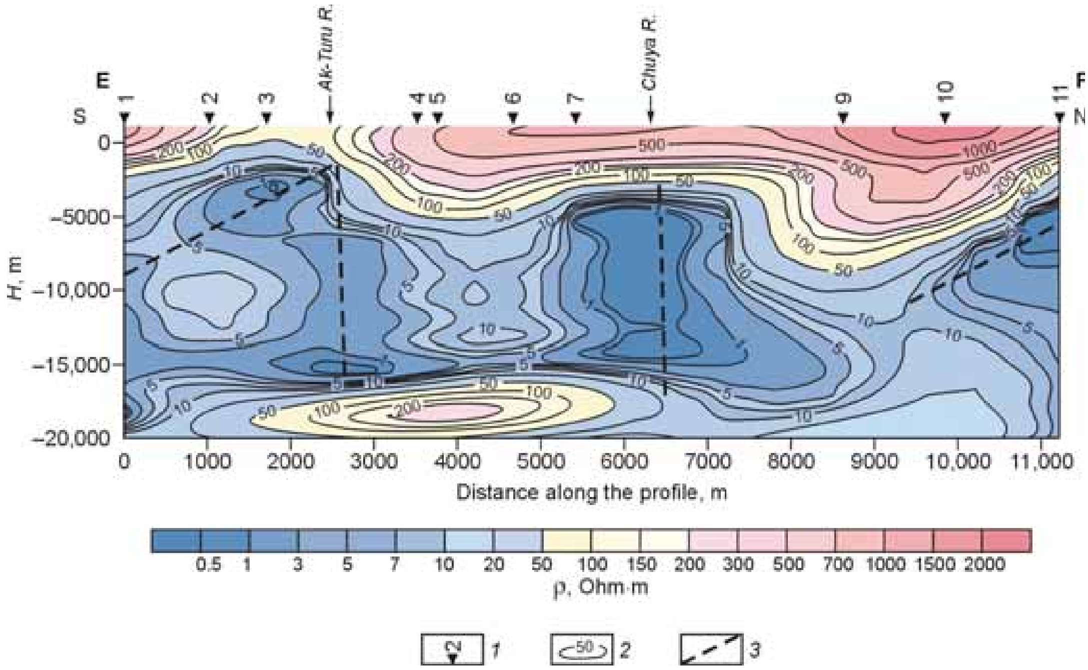

Fig. 6. Resistivity cross section along profile E–F (Kurai basin). *1*, MTS points; *2*, resistivity values in Ohm·m; *3*, Cenozoic active faults.

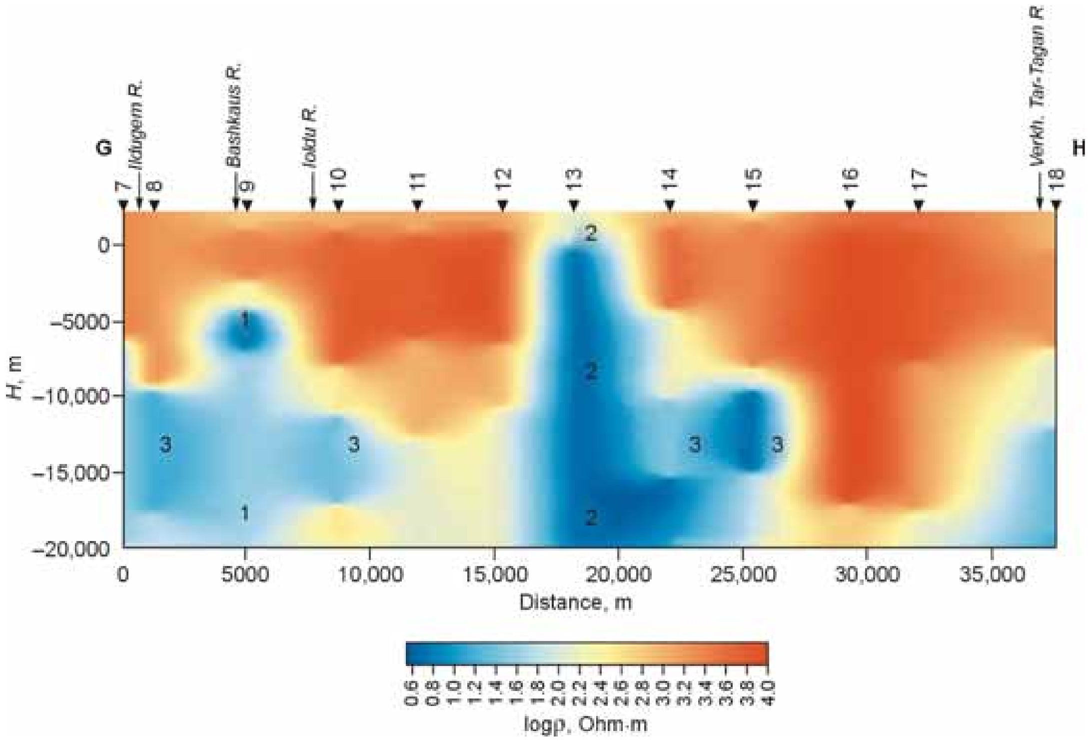

Fig. 7. Resistivity cross section along profile G-H (Ulagan Range). 1, extension zone in the middle part of the Bashkaus valley; 2, right-lateral strike-slip fault along the axis of the Ulagan Range; 3, crustal conductivity anomaly.

the total conductance is higher. The conductor top is as shallow as 8–10 km beneath the source areas of many known earthquakes, in the Altai (Epov et al., 2011; Nevedrova and Pospeeva, 2009, 2012), Trans-Dunai (Adam, 1987), and South-Caspian (Grachev, 2000; Jackson et al., 2002; Rodkin, 2003) areas, as well as at the junction of the Pripyat basin and the Belorus uplift (Results…, 2007), and in many other places. This setting agrees with the model of active seismic zones by Kissin (2001, 2009). According to this model, metamorphic reactions of dehydration in a crust block produce additional stress at its fault boundary with a block where no such reactions occurred; high pore pressure (approaching the lithostatic value) leads to hydraulic fracture and injection of pressurized fluids into the fault zone, which triggers earthquakes. Fluids influence strongly the deformation conditions: stress and strength of material (Kissin, 2009). Earthquake sources were inferred to occur most often above nearly horizontal fluid-saturated zones or in their upper parts. Thus, the parameters of the regional crustal conductivity anomaly influence seismic activity.

Conclusions

Interpretation of MT data from northeastern and southeastern Altai reveals heavily faulted crust over the whole territory and within large basins, like Chuya or Kurai, which are thus not related to subsided rigid blocks. MT cross sections allow tracing the behavior of major faults to depths of 20 km as they correspond to zones of very low resistivity (<0.5 Ohm·m). Generally, MT data confirm the slip geometry of faults inferred previously from morphotectonic and geological data. Fault planes are vertical in normal and strike-slip faults and dipping in reverse faults. The zones of neotectonic faults intersect with a nearly horizontal conductivity anomaly at depths 10–15 km.

The presence of the horizontal conductivity zone indicates high potential for tectonic and seismic activity in the brittle upper crust of Gorny Altai. Within the study area, the upper crust may be shifted with respect to the lower crust along the horizontal zone of high conductivity which makes a natural divide between the domains of brittle deformation above and ductile downward pressing of material below. However, the shift is relatively small, judging by the presence of vertical faults below the conductivity zone. Regional-scale compression induces growth of mountains and crust thickening. According to MT data, the top of the conductive zone is as shallow as 10 km and its resistivity is below 10 Ohm·m in the basement beneath the Chuya and Kurai large basins.

The work was carried out on the themes of the Scientific and Research Works "Continental sedimentary paleobasins of various tectonic and sedimentation environments" (0330-2016-0015) and "Geoelectrics in geological environment studies: technologies, field experiment and numerical models" (IX.128.1.2).

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