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Interblock zones of the northwestern Baikal rift: results of geological and geophysical studies along the Bayandai Village–Cape Krestovskii profile

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Abstract

The structure of the Earth's crust at the junction of the Siberian craton and Sayan–Baikal Fold Belt was studied along the Bayandai Village–Cape Krestovskii profile (85 km long) by a set of geological and geophysical methods: structural survey, interpretation of long-distance photographs, emanation survey, electrical prospecting with self-potential (SP) and direct-current (DC) resistivity profiling, magnetotelluric sounding, magnetic survey, and hydrogeochemical sampling of water objects. Interpretation of the data refined the main features of the tectonic structure of western Cisbaikalia and revealed the disruption pattern and hierarchic zone–block structure of the Earth's crust. The Obruchev fault system (≈50 km wide), which is the northwestern shoulder of the Baikal Rift, is the main interblock zone of the studied region. It consists of the Morskoi, Primorskii, and Prikhrebtovyi interblock zones, traced from depths of tens of kilometers and widening near the surface owing to superior structures. The studies gave an insight into the regularities in the occurrence of interblock zones and the criteria for their identification in different geologic-geophysical fields. An efficient complex of methods for mapping the Earth's crust zone–block structure is proposed.

Keywords: interblock zone; faults; zone–block structure; Baikal Rift; electrical prospecting; magnetotelluric soundings; emanation survey

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Introduction

Now the most popular lithospheric models are those in which the lithosphere is a hierarchic structured environment consisting of relatively stable blocks, which are surrounded by zones of strong substrate deformation (Gatinsky and Rundquist, 2004; Gol'din, 2002; Jacobi, 2002; Krasnyy, 1984; Kurlenya et al., 1993; Makarov, 2007; Sadovskii et al., 1987; Seminskii, 2001; Shebalin et al., 2002; Viruete et al., 2003). This is evidenced directly by the existence of lithospheric plates with contacts along a network of divergent, convergent, and transform zones. The same patterns on a larger scale are confirmed by zone–block structure schemes for individual regions, including Cisbaikalia and the adjacent regions (Seminskii, 2008). Tectonically, interblock structures are represented by variously ranked faults, belts of faults and joints of different ranks, and jointing zones. This structural diversity complicates mapping when researchers assess interblock boundaries in terms of seismicity, Rn hazard, and ore, groundwater, and hydrocarbon potential. Therefore, zone–block structure is shown with unequal accuracy depending on the scale of the study and with almost unsatisfactory accuracy in poorly exposed and/or low-activity regions.

Under such conditions, the mapping quality can be improved by the use of an integrated geological and geophysical approach to distinguishing interblock zones. In this study we aim to develop such an approach, relying on the previous studies (Ben-Zion and Sammis, 2003; Schulz and Evan, 2000), which revealed differences in the manifestations of the same fault zone in geological and geophysical data of different origin. The geological and geophysical works were done in western Cisbaikalia. Since this region, including its tectonics, is well-studied, it can be regarded as a reference in developing a set of geological and geophysical methods for mapping

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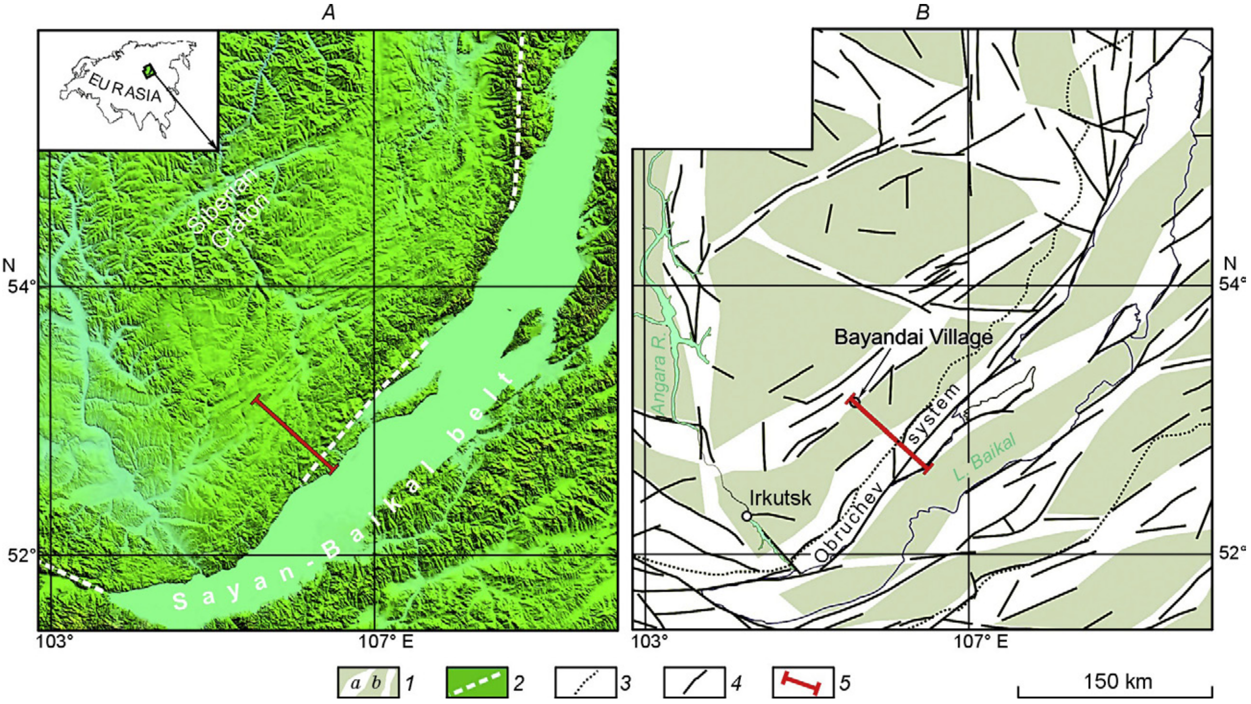

Fig. 1. 3D topographic model (*A*) and scheme of the zone–block structure of the crust in Cisbaikalia (*B*). *1*, areas occupied by mobile zones (*a*) and blocks (*b*); *2*, marginal suture of the Siberian Platform; *3*, Baikal Rift boundaries (Zolotarev and Khrenov, 1979); *4*, faults manifested in scarps and straight elements of river valleys; *5*, Bayandai Village–Cape Krestovskii profile.

interblock zones. The work focused on the Bayandai Village–Cape Krestovskii regional profile (Fig. 1), oriented across the strike of the tectonic structures at the junction of the Siberian craton and Sayan–Baikal Fold Belt. The activation of this tectonic boundary in the Cenozoic gave rise to the Baikal Rift, whose northwestern shoulder is crossed by the profile. This permitted studying the relationships between crustal zones and blocks marked by high tectonic activity at the present stage of tectogenesis.

The crustal deformation around Lake Baikal is generalized in the scheme (Fig. 1, *B*). The latter is based on the analysis of the distribution of straight topographic features (lineaments), which are distinct on the 3D model (Fig. 1, *A*). As a rule, these features are grouped in elongated linear zones; the blocks in- between contain considerably fewer lineaments, which are variously oriented and short. Thus, although the lineaments represent now-active faults only to some extent, the scheme reflects the general zone–block structure of the crust in the region. What is more, its structural hierarchy agrees with that on the previous similar large- and small-scale maps of western Cisbaikalia, on the one hand, and of the Baikal Rift and Central Asia in general, on the other (Seminskii, 2008).

In hierarchical analysis most of the interblock zones (Fig. 1) are of rank II, because the rank I interblock structure in this area is the Baikal Rift, which developed actively owing to interaction between the Siberian and Transbaikalian lithospheric blocks. Its boundaries, shown in the figure after (Zolotarev and Khrenov, 1979), correlate clearly (in the first approximation) with the zone–block structure of Cisbaikalia inferred from the lineament distribution. The approximation is reflected, for example, in an inconsistency between the boundaries of the rift and constituent rank II zones. This is, to some extent, due to ambiguity in individual zone–block units, whose scheme in this case was based on only one feature (lineament distribution).

This example illustrates the importance of the integrated study. Its main objectives were the following: studying the manifestation of interblock zones along the Bayandai Village–Cape Krestovskii profile in geological and geophysical data of different origin; ranking the interblock zones constituting the zone–block structure of the crust in western Cisbaikalia and determining their boundaries, types of movement, internal structure, etc.; assessing the potential of different methods for studying interblock zones and proposing an efficient set of geological and geophysical methods for studying the zone–block structure of the crust.

To meet the objectives, the following was done: faults in western Cisbaikalia were studied by structural methods, along with the morphotectonic analysis of the topography, based on field geomorphological observations and interpretation of long-distance photographs, magnetic survey, electrical prospecting with self-potential (SP) and DC resistivity profiling; magnetotelluric (MT) soundings, hydrogeochemical sampling of water objects, and emanation survey (Fig. 2). The set of methods was aimed at assessing the degree of crustal faulting, which dominates the internal structure of zones of active block interaction. Its efficiency is determined by a combination of direct fault mapping techniques and indirect ones, based on the high magma and fluid permeability of fault zones. We obtained important additional information about the structure of the well-studied territory of western Cisbaikalia by using

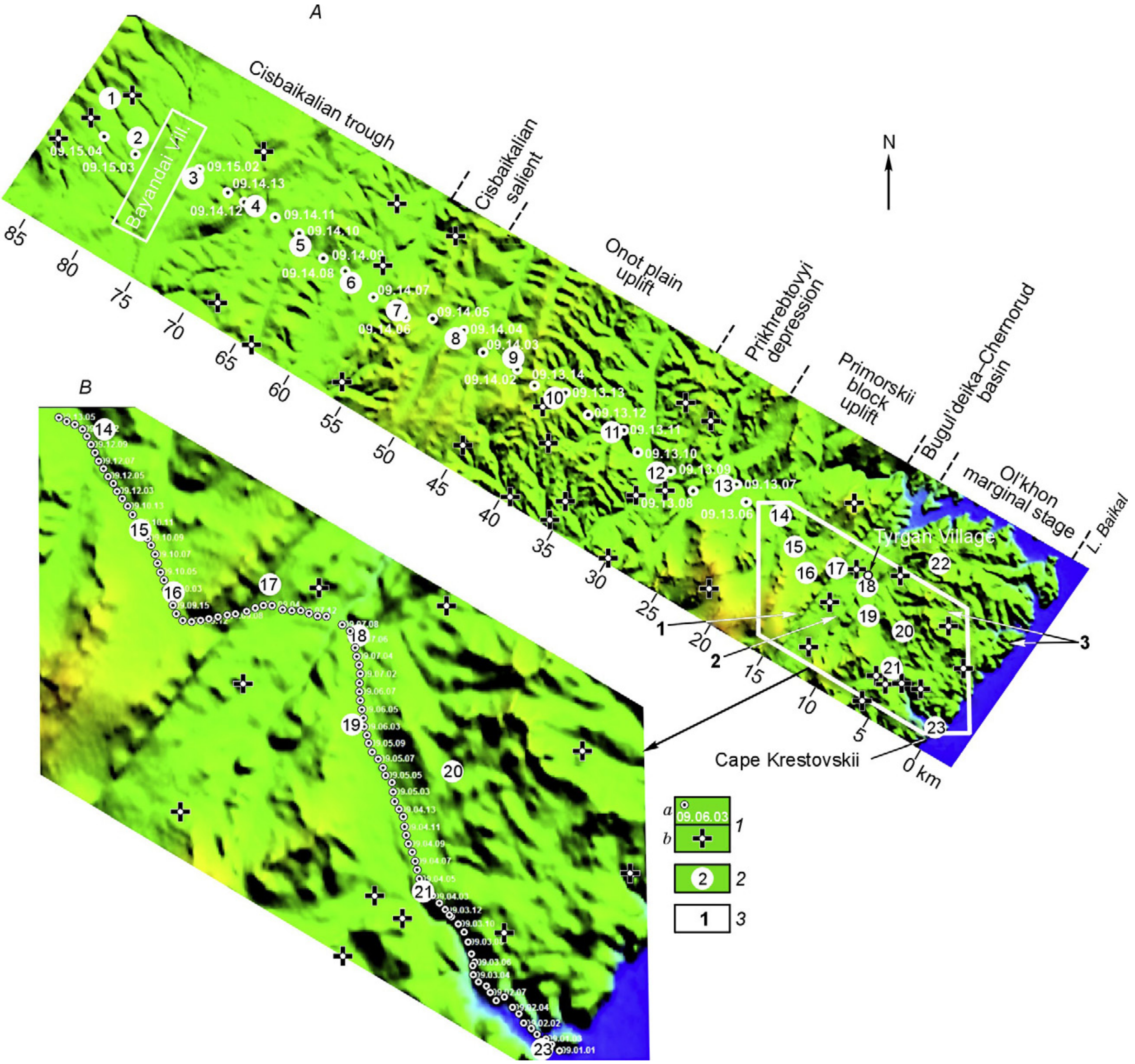

Fig. 2. General schemes showing the position of the Bayandai Village–Cape Krestovskii profile (*A*) and its part studied in detail (*B*) on a 3D topographic model for Cisbaikalia. *1*, Rn–Tn survey stations (the first figure shows the year; the second one, the route number; the third one, the site number) (*a*) and sampled springs (*b*); *2*, MT stations; *3*, faults described in the text (1, Primorskii fault; 2, reverse fault; 3, NW-trending transverse fault). The stations of the most detailed geophysical measurements (interval 50 m) were localized between sites MT-14 and MT-23 (DC resistivity and magnetic surveys) and between sites MT-6 and MT-23 (SP survey).

studies new to the region (Rn–Tn survey), more detailed studies (electrical and magnetic prospecting), and the newest equipment (MT). The high efficiency of our set permitted a quick compilation of a data bank on the distribution of geologic-geophysical fields along the Bayandai Village–Cape Krestovskii profile.

Methods and results

The 25-km-long southeastern part of the profile underwent the most complete and detailed geophysical study. Here, the magnetic, SP, and DC resistivity measurements had an interval of 50 m; the Rn–Tn survey, 250 m. Elsewhere on the profile, the self-potential was measured at intervals of 50 m and the Rn–Tn survey was conducted at intervals of 2500 m. The distance between the MT stations along the profile averaged 5000 m. The primary data are shown in Fig. 3 as plots of the geophysical fields observed. The smoothing of the original data by averaging in a sliding window permitted comparing variations in different parameters and yielded values for intervals of 2500 and 250 m (Fig. 4). An attempt at a direct correlation between the geologic and geophysical parameters (Fig. 4) did not reveal stable dependences. Therefore, the main analytical technique was comparing the variation in different fields along the profile. To do this, the field deviation from its mean was used, like in the previous geological and geophysical studies (Seminskii et al., 2008; Seminsky and Bobrov, 2009).

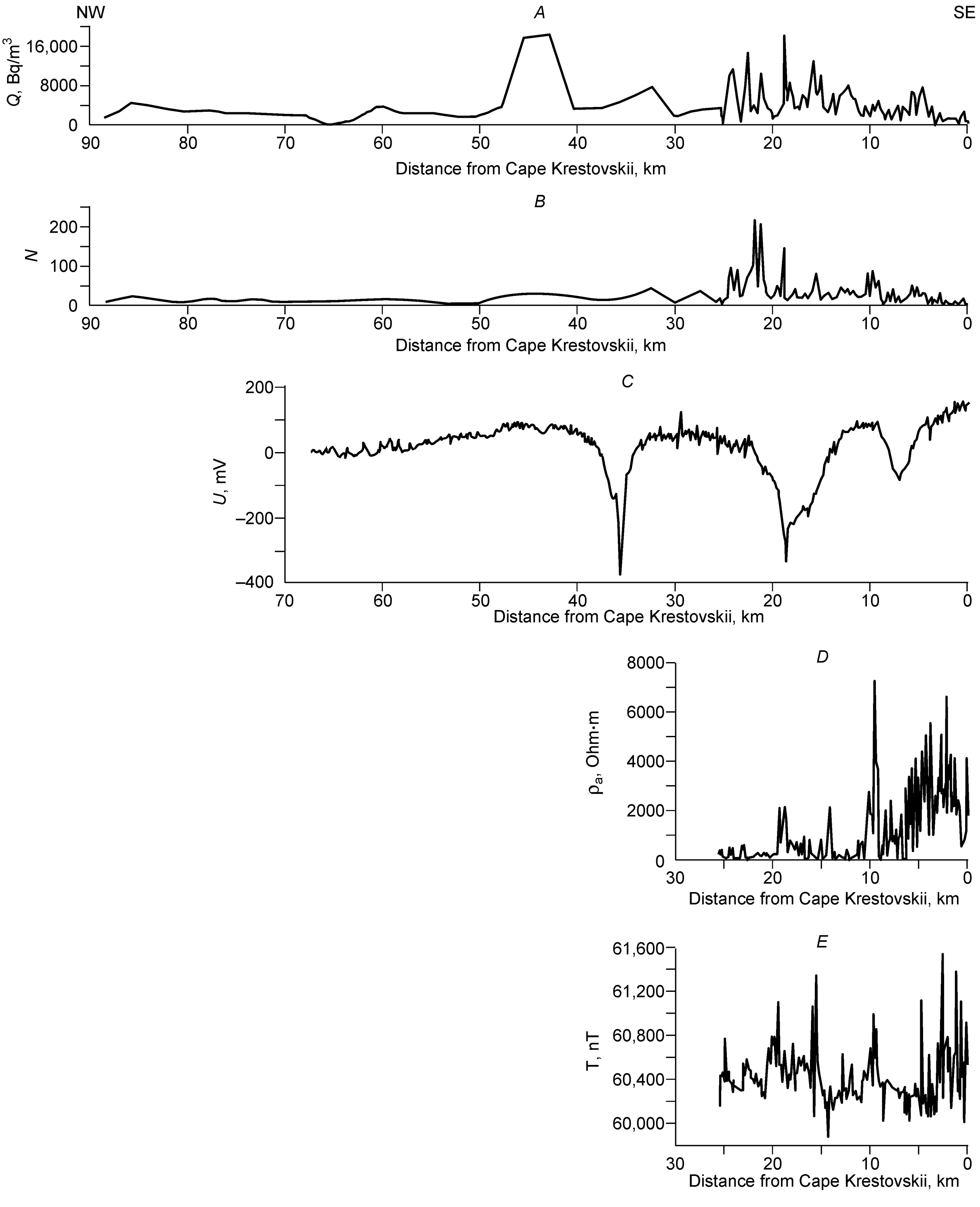

Fig. 3. Primary plots of the geophysical fields measured along the Bayandai Village–Cape Krestovskii profile: *A*, Rn volumetric activity (*Q*); *B*, number of Tn decays (*N*); *C*, self-potential (*U*); *D*, DC apparent resistivity (ρ_a); *E*, total intensity of magnetic induction (*T*).

Structural studies

The geologic structure of the study area is generalized in the section based on the State Geological Map, Scale 1 : 200,000, and the authors' data on the faults active at the neotectonic stage (Fig. 5, *B*). In the northwest, the section consists of different Siberian craton complexes. They show a relatively calm bedding at the profile periphery and are intensely dislocated near the Bugul'deika River (Cisbaikalian marginal trough). In the southeastern (Ol'khon) part, there are outcrops of the multiple-stage metamorphic complexes of the marginal uplifts of the Sayan–Baikal belt. Two large tectonic units of Central Asia have a contact along the fault system of a marginal platform suture (Primorskii segment) consisting of

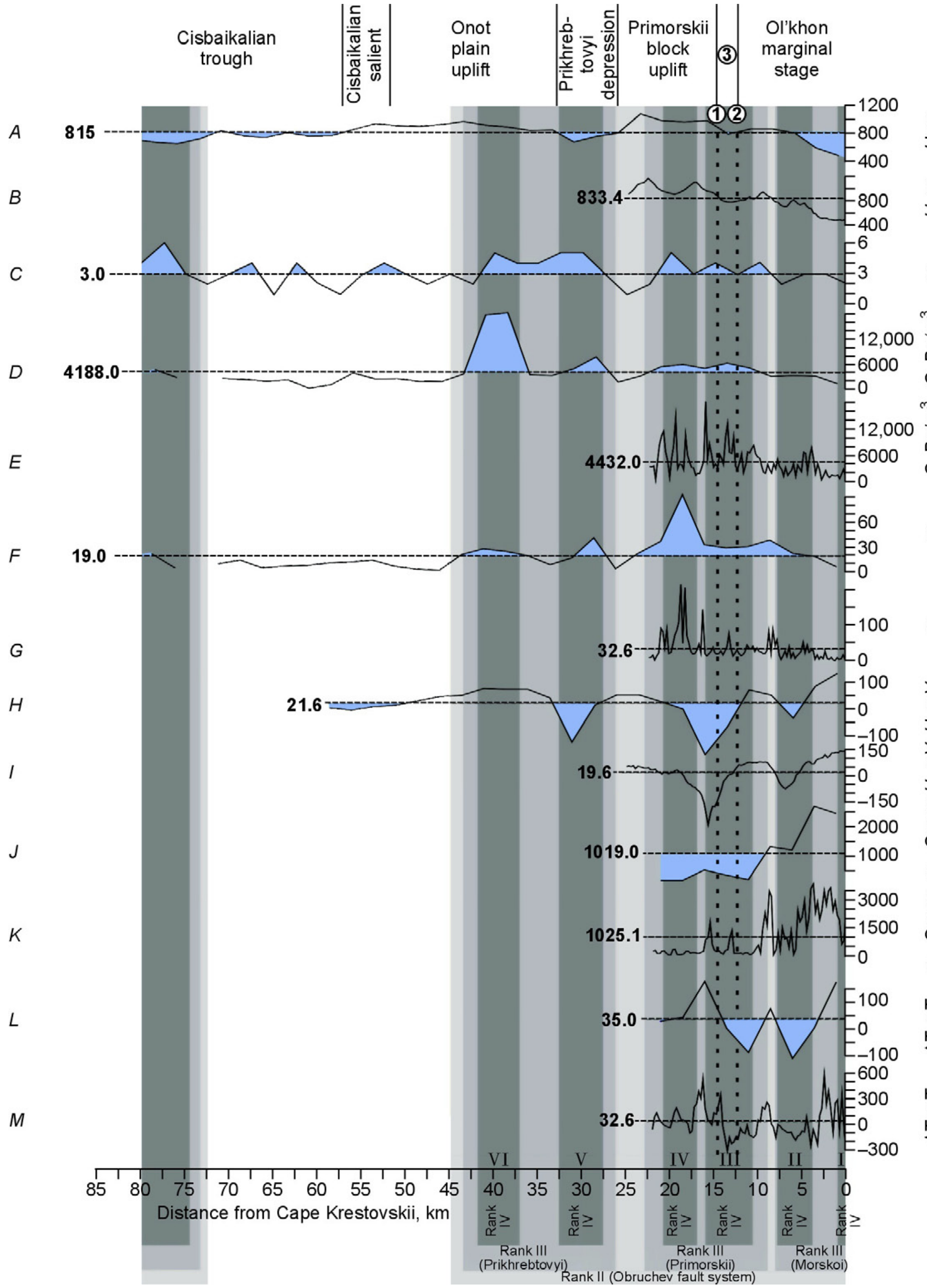

Fig. 4. Variations in the geologic-geophysical parameters along the Bayandai Village–Cape Krestovskii profile: altitude (*H*), lineament density (*D*), Rn volumetric activity (*Q*), number of Tn decays (*N*), SP (*U*), DC apparent resistivity (ρ_a), and increment of the total intensity of magnetic induction (ΔT). The distance between neighboring points on the plots is 2500 (*A*, *C*, *D*, *F*, *H*, *J*, *L*) and 250 m (*B*, *E*, *G*, *I*, *K*, *M*). Anomalies (higher or lower than the mean (dashed line)) on plots *A*, *C*, *D*, *F*, *H*, *J*, and *L* are shown in blue. The upper part of the figure (circled numbers) shows the morphostructures and faults intersected by the profile: 1, Primorskii fault; 2, reverse fault; 3, Bugul'deika–Chernorud graben. The lower part of the figure shows the position of interblock zones of three ranks; the zonal boundaries, shown by vertical strips in grays, were inferred from the integrated analysis of the data.

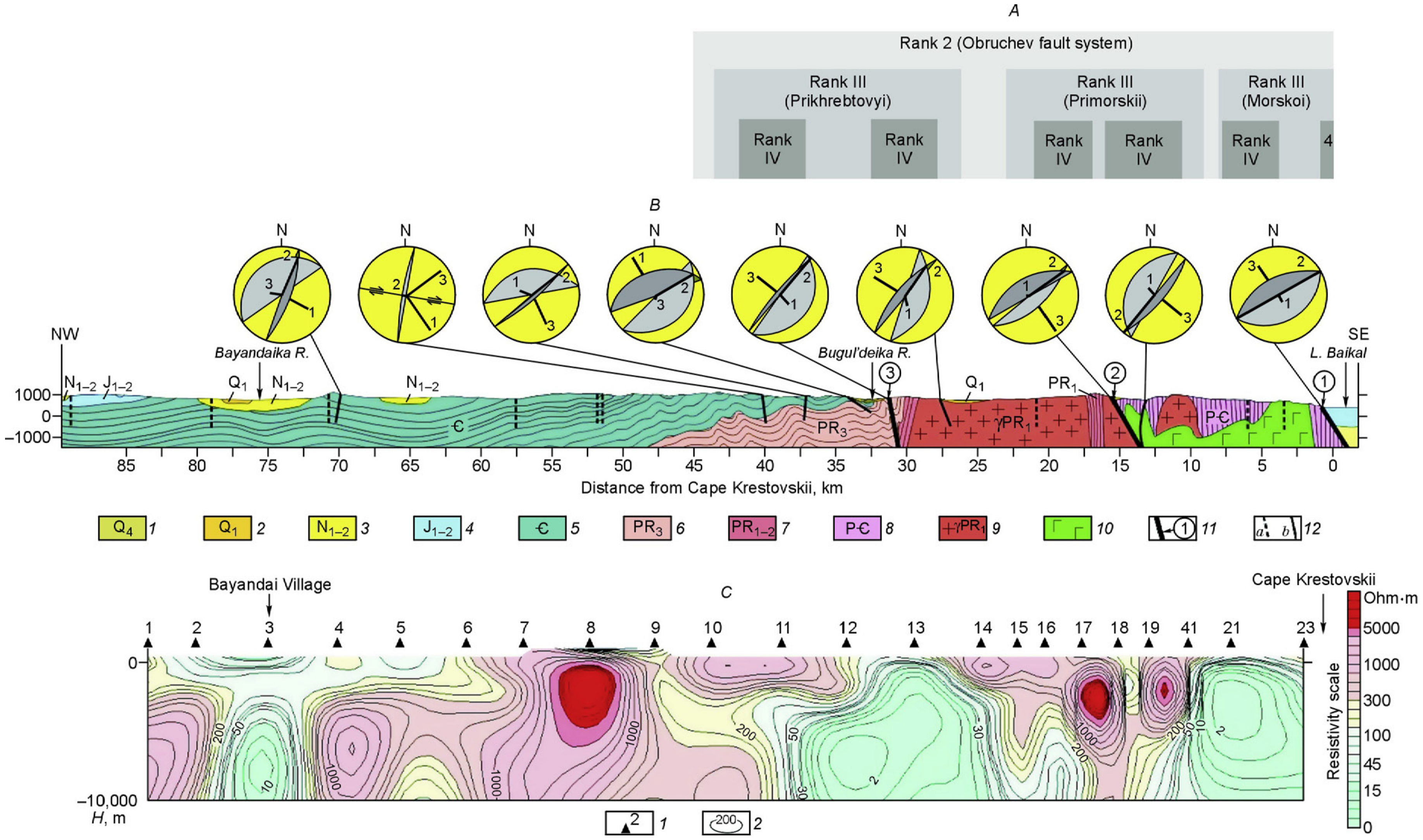

Fig. 5. Variously ranked interblock zones of western Cisbaikalia (*A*) in the geologic (*B*) and geoelectric (*C*) sections compiled along the Bayandai Village–Cape Krestovskii profile. *B*, *1*, Alluvium (Holocene): silt, pebblestone, sand, clay loam, peat; *2*, alluvial and alluvial-lacustrine sediments (Upper Pliocene–Eopleistocene): sand, pebblestone, gravel; *3*, alluvial-lacustrine sediments (Miocene–Lower Pliocene): sand, clay, pebblestone, coquina; *4*, Lower and Middle Jurassic platform sediments: sandstone, siltstone, mudstone, conglomerate, coal beds; *5*, Cambrian sedimentary cover of the Siberian Platform: sandstone, dolomite, limestone, marl, gravelstone, siltstone, shale and carbonaceous-argillaceous schist, rock salt; *6*, Neoproterozoic rocks: quartzite, gravelstone, phyllite, metamorphosed quartz porphyry, carbonacerous-argillaceous schist, limestone; *7*, Paleo- and Mesoproterozoic rocks: quartz-muscovitic, binary, muscovite-garnet, chlorite-sericitic, and other schists, metamorphosed gravelstone, quartzite, porphyrite; *8*, intensely metamorphosed rocks of the Ol'khon area: biotitic, hornblende, and other gneisses, schist, amphibolite, crystalline limestone, quartzite; *9*, *10*, intrusive plutons: *9*, granite; *10*, gabbro, gabbro-diorite, quartz diorite, diorite porphyry; *11*, large faults: 1, Morskoi; 2, Primorskii; 3, Prikhrebtovyi; *12*, faults detected by geomorphological (*a*) and proven by geological (*b*) methods. Diagrams plotted in the projection of the upper hemisphere show the fault planes (dark gray), the conjugated system of rank II faults (light gray), and the axes of principal normal stress: 1, shortening; 2, intermediate; 3, stretching; *C*, 1, MT stations; 2, resistivity isolines (Ohm·m).

a wide belt of blastomylonites and different intrusions, including the granitoids of the Primorskii complex (Naumov, 1974; Sklyarov, 2005; Zamaraev, 1967; Zamaraev et al., 1979).

The marginal structures were repeatedly activated, but the character of the destructive process is determined reliably only for the Early Paleozoic collision (Aleksandrov, 1990; Fedorovsky, 1997; Sherman et al., 1994; Sklyarov, 2005) and Cenozoic rifting (Delvaux et al., 1997; Lamakin, 1968; Levi et al., 1997; Logachev, 2003; Mats et al., 2001; Ruzhich, 1997; Sherman, 1977; Sherman et al., 1992; Zamaraev et al., 1979). This is due to their relatively young age and occurrence in "brittle" deformations: open joints and fault planes, represented by "loose tectonites." In both cases large northeastward faults are inclined toward the fold belt. However, the Cenozoic is dominated by high-angle faults, whereas the Paleozoic is dominated by thrusts (for example, where the profile crosses the Bugul'deika River valley). The main faults in the northwestern shoulder of the Baikal Rift are grouped in the Obruchev fault system, which consists, within the profile, of the Primorskii and Morskoi branches, which are the largest ones. The former inherits the southeastern boundary of the marginal platform structures, and the latter forms the Baikal continental slope of the Ol'khon area and Ol'khon Island (Fig. 5, *B*).

The structural studies within the Bayandai Village–Cape Krestovskii profile revealed now-active faults, and the stress field was reconstructed at some sites (Fig. 5, *B*). In the absence of direct evidence for displacement along the faults, mass measurements of the fissures in their limbs (44 observation sites in total) were processed by new (Seminskii et al., 2005; Seminsky and Burzunova, 2007) and well-known (Rastsvetaev, 1987) methods of paragenetic analysis together with kinematic techniques for restoring paleostress (Parfenov, 1984). The profile contains several intervals (0–6, 13–15, 27–40, 52–58, 70–78 km) within which the upper crust is intensely deformed by faults, which dip near-vertically or are inclined toward Lake Baikal.

Each of three southeastern areas is host to a large fault (Morskoi, 0 km; Primorskii, 15 km; Prikhrebtovyi, 31 km) with feathering structures. For example, detailed studies of the Bugul'deika–Chernorud graben (Fig. 5, *B*, 13–15 km) confirmed that it consisted of a series of northeastward-elongated blocks bounded by faults with different amplitudes (Mats et al., 2001; Pleshanov and Romazina, 1981). The graben, which is ~2.5 km wide, is bounded by the Primorskii fault in the northwest and by a reverse fault in the southeast. According to the structural models known (McCalpin, 1996), both faults might join at a shallow depth. The northward dip of the second fault along the profile (Fig. 5, *B*) is evidence for near-surface complication of the fault plane, which is inclined southeastward, as confirmed by measurements of the bedding elements of individual fault segments in the Ol'khon area (Mats et al., 2001; Pleshanov and Romazina, 1981; Seminskii et al., 2005). This complication might be due to the fact that a northwestward fault joins the fault in question within the site studied. The northwestward fault is manifested structurally and traced by straight topographic features up to the shore of Lake Baikal (Fig. 2, *A*).

The faults mapped in the Cenozoic sediments and crystalline rocks of site 3 (Fig. 5, *B*, 27–40 m) have zones of influence the first tens of meters in size, suggesting intense rift stretching. At the same time, northwestward-shortening environments were reconstructed here from conjugated strike-slip systems, though with lesser confidence. The fault networks which formed previously during the shortening (Aleksandrov, 1990; Sherman et al., 1994) were activated in the rifting epoch for stretching with the same orientation. Thrusts as such are not observed in the poorly consolidated sediments of the Bugul'deika–Anga interfluve; most probably, they took place only before the Cenozoic within the profile site under study.

Unlike the southeastern part of the profile, its northwestern flank is dominated by small reverse faults. Consequently, the boundary of the Baikal Rift is located at 40 km. This differs in ~10 km, but, in general, confirms the demarcation in (Mats et al., 2001; Perevoznikov, 1999; Zolotarev and Khrenov, 1979) along the northeastern segments of the Anga, Bugul'deika, and Kurtun Valleys. This conclusion is an important result of the structural studies (including the interpretation of geophysical data) along with the confirmation of the structural patterns of the junction between the Siberian craton and Sayan–Baikal belt and the specification of movement types along the large faults in the region.

Morphotectonic studies

The Cisbaikalian trough and Baikal arch are known (Mats et al., 2001; Perevoznikov, 1999; Ufimtsev, 1992; Zolotarev and Khrenov, 1979) to have smaller morphostructures in western Cisbaikalia, which are distinct in the topography of the Bayandai Village–Cape Krestovskii profile. As a rule, they comprise the Cisbaikalian trough, Cisbaikalian marginal salient (flexure), Onot plane uplift, Prikhrebtovyi depression, Primorskii block uplift, Bugul'deika–Chernorud basin, and Ol'khon marginal stage (Fig. 4, *A*). These structures are due to the movement of crustal blocks along Cenozoic large faults, which can be localized on the basis of the lineament distribution.

Lineament analysis was based on a conventional technique for morphostructural zoning (Rantsman, 1979) involving the use of topographic maps (1 : 25,000; 1 : 100,000; 1 : 500,000) and a digital model created by the GIS technique on the basis of SRTM-type space images (resolution up to 90 m). The use of topographic and 3D (Fig. 2) images was efficient in distinguishing straight or slightly curved scarps, straight valley segments, and some kinds of linear erosional forms, which mostly reflected the position of active faults.

The lineament scheme compiled for the study area was used for mapping the distribution of the lineament density (D) in isolines (Fig. 6). The values of D were calculated for the nodes of a square network by counting straight topographic features within the square grid cell, whose area (s) was determined statistically from the formula $s = 2\ S\ /\ n$ (S, study area; n,

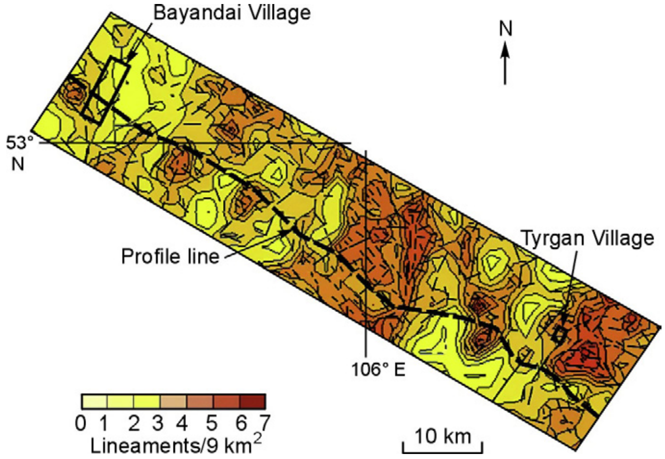

Fig. 6. Map of lineament density (black lines) in isolines near the Bayandai Village–Cape Krestovskii profile (Kogut, 2007). Sites with different lineament density are shown in different colors.

total number of lineaments within the study area) to be 9 km^2. As shown in Fig. 6 and the plot for the Bayandai Village–Cape Krestovskii profile (Fig. 4, *C*), *D* in the study area varies from 1 to 7 and has an extremely nonuniform areal distribution. Strongly deformed areas are elongated northeastward and separated by areas with a low *D*. The southeastern part of the profile is host to two largest sites, each being 14 km wide. The central one among three specific maxima of the extreme site (15 km) is associated with the Primorskii fault and Bugul'deika–Chernorud graben, whereas the southeastern maximum (10 km) marks off the northwestward fault described in the previous section. The second large site contains two maxima of *D*, the larger one (32 km) being associated with the Prikhrebtovyi depression. The northwestern half of the profile also contains a series of peaks, which are smaller (~4 km) and have a lower *D* than the maxima on the southeastern flank. Only the site associated with the axis of the Cisbaikalian trough has a fairly high density (6) and is quite wide (7 km).

Comparison between the hypsometric profile (Fig. 4, *A*) and the plot of *D* variation (Fig. 4, *C*) shows that the basins and low topographic features correspond to zones with the most mountain mass deformation, whereas the topographic peaks correspond to zones with a lower *D*. The same pattern is observed when we analyze a more detailed plot of topographic highs (Fig. 4, *B*). Thus, in low and the most faulted areas, the profile crosses mobile zones, along which relatively stable crustal blocks come into contact. The interblock zones are usually northeastward and of different scales. The largest ones are localized on the southeastern flank of the profile and have a heterogeneous internal structure.

Emanation survey

The advantage of Rn–Tn survey is the possibility of finding active faults open to gas migration within poorly exposed areas. This survey was conducted successfully in the study region (Seminskii et al., 2008; Seminsky and Bobrov, 2009; Seminsky et al., 2008). This work shows that a typical emanation anomaly is marked by a nonuniform increase in gas content from the periphery to the axis of the fault zone, accompanied by local maxima and minima, which mark the position of individual fault planes with permeable (dislocation breccia) or impermeable (fault gouge) tectonites. The Rn–Tn survey was conducted along the profile (Fig. 2, *B*; 124 measurement stations) by the previously developed technique (Seminsky and Bobrov, 2009) which permits measuring the volumetric activity of ^{222}Rn (*Q*, Bq/m^3) and counting Tn decays in the working cell of a radiometer (*N*) for each sample of underground air.

The *Q* and *N* parameters vary in the study area from 174 to 18,325 and from 1 to 215 Bq/m^3, respectively, and their general variations along the profile are similar (Fig. 3). Anomalies of these parameters, except that confined to the interval 75–80 km, are localized in the southeastern part of the profile (Fig. 4, *D*, *F*). They are similar in shape and size: the anomaly at 40 km is 7 km wide; that at 29 km, 5 km wide; that at 16 km, ~14 km wide. Unlike the shape of the anomalies, their intensities within the Rn and Tn fields differ considerably. This is because the Rn and Tn emanations characterize the permeability of the mountain mass at different depths, since the half-lives of Rn (3.8 days) and Tn (54.5 s) differ greatly. In the Rn field, the site associated with the Prikhrebtovyi depression is the most distinct; in the Tn field, the highest intensity is observed within the southeastern anomaly. Interestingly, *Q* and *N* are largest northwest of the Bugul'deika–Chernorud graben, which is geologically and geomorphologically distinct. This is explained by the data of a detailed emanation survey (Fig. 3, *A*, *B*, Fig. 4, *E*, *G*): *Q* and *N* minima correspond to the Primorskii fault and reverse fault, which bound the graben, because it was estabished (Seminsky and Bobrov, 2009) that the near-axis parts of the Ol'khon fault zones often consisted of rocks poorly permeable to gases.

In general, the distribution of gas exhalations over the Bayandai Village–Cape Krestovskii profile correlates with the faulting detected in the structural and morphotectonic studies. In the southeastern part of the profile, which is the most dislocated, two broadest *D* anomalies correspond to four paired sites with large *Q* and *N*. Note that the position of the local minima within these sites coincides with that of individual large fault planes.

Hydrogeological studies

The hydrogeochemical sampling was conducted by a standard technique at 18 water objects immediately near the profile. Water samples underwent a complete chemical analysis in the Hydrogeochemistry Laboratory of the Institute of the Earth's Crust.

According to the hydrogeological studies, the Primorskii Ridge and its southwestern spurs are marked by considerable precipitation (up to 400–500 mm/yr), which is a permanent source of fissure groundwater. The water discharges studied are swamps, whose mixed recharge was reflected in high mineralization (0.7–1.0 g/dm^3), predominantly in the calcium hydrocarbonate composition of water and neutral pH at silica and dissolved oxygen contents of 18–40 mg/dm^3 and 3.3–11 mg/dm^3, respectively.

The lowland territory of the Ol'khon area, adjoining the Primorskii Ridge in the southeast, has an arid climate with a long cloudless period, low precipitation (~160 mm/yr), and frequent variously directed winds, which do not favor snow accumulation. The water discharges sampled are springs and swamps with a mineralization of 0.3–0.55 g/dm^3 (1.0 g/dm^3 in the southeast), a predominantly calcium or calcium–magnesium hydrocarbonate or sulfate-hydrocarbonate composition, pH = 8–9, 40–60 mg/dm^3 silica, and 5.3–10 mg/dm^3 oxygen.

Thus, the variations in the local landscape-climatic conditions along the profile were reflected in the recharge and nonuniform areal distribution of groundwater. Note that Fig. 2 (which, along with the springs sampled within the area of detailed study, reflects the position of similar water discharges, according to the State Hydrogeological Survey, Scale 1 : 200,000) shows clearly that natural groundwater discharges are confined to low topographic features and the edges of the adjacent uplifted blocks northwest of the basins.

Along with groundwater mineralization in the processing of the electrical-prospecting data, this pattern was necessary for the integrated interpretation of the geological and geophysical data in the final part of the paper. Further studies will involve an in-depth compositional analysis of the water discharges sampled to determine the hydrogeochemistry and water exchange typical of different interblock zones in the northwestern shoulder of the Baikal Rift.

SP survey

The fixed-base SP measurements were taken with the help of nonpolarizable (porous-pot) electrodes (Semenov, 1980). The voltage between the reference and moving electrodes was measured by a digital millivoltmeter with an input impedance of 10 MΩ. When the voltage from 0 to ±200 mV was measured, the readability was 0.1 mV; outside this range, it was 1 mV.

The profile intervals 4.4–9, 14–22, and 34–38 km show negative SP anomalies with amplitudes of ~150, 350, and 400 mV, respectively (Fig. 3). These are similar in shape and amplitude to the anomalies measured previously in the Ol'khon area (Kozhevnikov, 1998; Kozhevnikov and Tezkan, 1998; Kozhevnikov et al., 2004). They are most probably associated with ancient high-angle fault zones with graphite mineralization, which forms electrically continuous systems with electron conductivity. Such electron-conductive systems, along with the enclosing ion-conductive ones, form so-called geobatteries (Bigalke and Grabner, 1997). However, the SP anomalies on the Bayandai Village–Cape Krestovskii profile are two to four times broader than those known in the Ol'khon area. The latter delineate the ancient Chernorud zone, within which the rocks of the Ol'khon complex are marked by the maximum tectonometamorphic reworking.

The SP plot within the interval 14–22 km, which contains the broadest anomaly, correlates negatively with the topography. This suggests that not only the geobattery contributes to the SP anomaly but also the electric field resulting from groundwater filtration from high to low altitudes (Komarov, 1994).

DC resistivity profiling

As mentioned above, the southeastern part of the regional profile was studied by electrical profiling. An A40M20N40B Schlumberger array was used; that is, the transmitter line was 100 m long to ensure an effective depth of about the first tens of meters. The voltage in the receiving line and current in the transmitter one were measured with an AE-72 instrument. The data were then converted to apparent resistivity ρ_a (Fig. 3, *D*).

Analysis of ρ_a profiles plotted with different levels of detail revealed two peculiarities of the resistivity distribution under study (Fig. 4, *J*, *K*). First, ρ_a in the Ol'khon area are much higher than those within the Bugul'deika–Chernorud basin and near the Primorskii Ridge. Second, the resistivity in a considerable part of the profile drops to the first tens of ohms per meter. These features cannot be explained only by a difference in the electric properties of the rocks exposed on the profile (Fig. 5, *B*); apparently, the variations in ρ_a depend considerably on the water reserves of the mountain mass. Note that precipitation is much lower in the Ol'khon area than in the Primorskii Ridge. Nevertheless, the presence of intensely deformed, permeable, and watered zones within some intervals is the cause of abnormally low ρ_a (Fig. 4, *J*, *K*). Anomalies occur within two intervals in the southeastern part of the apparent-resistivity profile (0–1.5, 4–8 km) and its entire northwestern flank, in which the side faults of the Bugul'deika–Chernorud graben are also marked by local ρ_a drops.

Magnetic survey

Like the resistivity profiling, the magnetic survey was conducted in the southeastern part of the regional profile (Fig. 3, *E*). The total magnetic-field intensity (T) was measured with an MMP-203 proton magnetometer.

Since the geomagnetic field reflects mainly the mineral composition of rocks and depends only slightly on the degree of deformation, the magnetic prospecting data were the most ambiguous when the interblock zones were mapped. Direct comparison between T plots (Fig. 4, *L*, *M*) and the rocks exposed on the profile did not reveal steady relationships. However, the intervals with T minima and maxima coincided in most of the cases with the sites with high and low ρ_a, respectively (Fig. 4, *J*, *M*). Although the cause of the ρ_a–T correlation remains unknown, there is no doubt that the interblock zones are reflected in the geomagnetic field despite the "masking" effect of composition. Evidently, further studies are required for more certain conclusions and recommendations.

Magnetotelluric studies

Magnetotelluric sounding is an important method in the set, because it permits studying the section in almost any environment from the first hundreds of meters to depths of >200 km. Note that it is efficient in now-deformed crustal areas, which are marked by low-resistivity areas owing to fluidization, as was shown clearly, for example, for large fault-type interblock zones (Ben-Zion and Sammis, 2003; Maercklin et al., 2005; Unsworth and Bedrosian, 2004; Unsworth et al., 1999).

Magnetotelluric soundings have been conducted in the southern Siberian Platform, including western Cisbaikalia, since the 1960s. The results were presented in (Gornostaev, 1967, 1972, 1979; Gornostaev et al., 1970; Popov, 1989; Popov et al., 1999) and other publications, in which MT data were generalized in the models for the deep geoelectric structure of Cisbaikalia and the Baikal basin (Berdichevskii and Dmitriev, 2008; Mats et al., 2001). The MT survey revealed conductors: the crustal (or lithospheric) one, with the top at depths of 12–14 km, and the mantle one at depths of 90–110 km. In accordance with the generally accepted view, the thickness and resistivity of these layers in individual parts of the section are determined by the substrate thermodynamics.

Unlike the previous MT studies, the MT measurements on the Bayandai Village–Cape Krestovskii profile was aimed mainly at the detailed study of the geoelectric structure of the Earth's crust at the junction of the Siberian Platform and Baikal Rift. This determined the interval between the MT stations, which was unusually small for conventional MT observations (5 km), with a concentration of up to 2.5 km near the Bugul'deika–Chernorud graben.

The MT field components were recorded in the period range from 3×10^{-3} to 5×10^{3} s with MTU-System-2000 instruments (Phoenix Geophysics, Canada) equipped with a program for primary-data processing (SSMT). The receiving lines were 100 m long, and the measurements lasted for 19–22 h. Quantitative interpretation was done within a 1D model. Different recommendations and conclusions exist in the literature as to which of the curves are the most informative for 1D inversion (Spichak, 2009). Finally, longitudinal (quasilongitudinal) curves were selected for the interpretation. This was because theoretical studies of the main 3D models (Berdichevskii and Dmitriev, 2008) revealed several levels with the inhomogeneities distorting the MT field in East Siberia. Most of the effects are galvanic. The top level of inhomogeneities is the near-surface part of the section; the second one comprises the subsalt-complex inhomogeneities; the last one comprises the upper-crust inhomogeneities. Under these conditions, the deep-section parameters were determined with the help of so-called "quasilongitudinal" curves. The technique for the selection of these curves was applied in the LineInterMT software, which is designed for the profile interpretation of MT data. The main purpose of the further processing of the 1D inversion data was to correct for the *S*-effect and prepare for compiling the final geoelectric sections.

The geoelectric section based on the 1D interpretation of the MT longitudinal curves is shown in Fig. 5, *C*. Its northwestern and southeastern parts differ, mostly not in composition but in the presence of near-vertical, strongly deformed, and, consequently, fluid-permeable zones with an abnormally low (5–30 Ohm · m) resistivity. The southeastern part of the profile (0–40 km) contains a group of such zones (or sites), whereas the northwest contains only one zone. The low resistivity of these zones and their crosscutting relationships with the compositional complexes found (Fig. 5, *B*) suggest that they formed owing to active tectonic processes at the block boundaries.

The position of the zones in the southeastern part of the profile differs from that of the pre-Cenozoic thrust sheets, but does not contradict that of the faults in the shoulder of the present-day rift (Fig. 5, *B*, *C*). Structurally, among three high-conductivity zones, the most important one is the first one from the southeastern end of the profile (0–8 km). It is a broad area with a resistivity below 10 Ohm · m. In all probability, it continues southeast, but studies in the lake area are required for the ultimate conclusions about the structure and position of this zone. The position of the second large zone near the surface coincides with that of the Prikhrebtovyi depression (28–33 km). In the geoelectric section, it is an area with an abnormally low (reduced to 4–7 Ohm · m) resistivity, widening considerably ≈3 km away from the surface. The third conductive zone (~30 Ohm · m) is delineated at depth near stations MTZ-18 and MTZ-19. It is considerably inferior to the first two zones in scale and character, but its spatial correlation with the Primorskii fault and Bugul'deika–Chernorud graben suggests a genetic relationship with the Cenozoic faulting.

Thus, the MT survey along the Bayandai Village–Cape Krestovskii profile permitted the first detailed studies of the deep structure of the junction between the Siberian craton and Sayan–Baikal Fold Belt in the central part of western Cisbaikalia. The complexity of this structure is determined by the proximity of the structural-compositional complexes reflecting different stages in the activation of the ancient tectonic boundary. However, the Cenozoic structure of the area is manifested quite clearly in a system of zones with an intensely deformed substrate, which penetrate to a depth of 10 km and even more if we consider the preliminary MT data under processing. On the northwestern flank of the profile (within the platform), such a zone cuts gently bedding ancient strata. As for the southeastern flank, it contains a series of disrupted zones, which have inherited the marginal-suture inhomogeneities and form the permeable structure of the Baikal Rift shoulder. As a result, the high-resistivity complexes (~10^3–10^4 Ohm · m) have a limited distribution on the southeastern flank of the profile.

Integrated analysis of the results

In the previous section, the geologic and geophysical data are described. Their analysis revealed abnormal intervals along the Bayandai Village–Cape Krestovskii profile. In most cases these anomalies correlate spatially (Figs. 4, 5), reflecting the presence of zones with the substrate deformed intensely by Neogene–Quaternary faults. Different-scale geological-geophysical surveys within the same profile permitted studying the crustal division in the region at five hierarchic levels (ranks); the Baikal Rift in general belongs to rank I. Lower down the section, these ranks are characterized successively from faults to the largest interblock structures; note that each next rank in Fig. 4 and Fig. 5, *A*, is shown by a darker shade of gray. We emphasize that these figures show the averaged position of the zones, because the demarcation of each is somewhat different depending on the parameter used.

Studies in the southeastern part of the profile with an interval of 50 m (Fig. 3, Fig. 4, *B*, *E*, *G*, *H*, *K*, *M*) reveal local interblock fault zones. However, considering that our studies are, to a large extent, experimental, we deem it reasonable to begin the description of the hierarchy with rank V. It consists of the fault planes bounding the Bugul'deika–Chernorud graben; their position and main properties were studied in detail by structural mapping. For example, the planes of the Primorskii fault and reverse fault have low Q, N, ρ_a, and T, and self-potential (U) fluctuations while this value increases regularly. Such a combination of parameters can be explained by the saturation of the axial parts of the faults with gouge, which is impermeable to gases, and low-resistivity weathered rocks poor in ferrimagnetic minerals. The fact that the southeastern site is wider than the northwestern one should not be attributed to the greater tectonic importance of the reverse fault than that of the Primorskii fault: the anomaly at the first site increases owing to a transverse fault joining the reverse one.

A block with high Q, N, ρ_a, and T is localized between two above-mentioned rank V fault zones. The small size of this block and the relatively small values of the parameters listed as compared with those typical of the blocks in the external parts of the zones (Fig. 4, *B*, *E*, *G*, *I*, *K*, *M*) suggest that the site under study belongs to a larger fault structure. Geomorphologically, this structure is represented by the Bugul'deika–Chernorud graben (Fig. 4, *A*, *B*) and is a rank IV interblock zone. In general, it has a high D (Fig. 4, *C*) and a high Rn content in the subsoil air (Fig. 4, *D*), combined with a relatively low resistivity (DC electrical profiling, MT), T, and self-potential. The minimum resistivity and T gravitate toward the southeastern part of the zone (Fig. 4, *J*, *L*, Fig. 5, *C*). The negative SP anomaly is localized in the northwest and, specifically, associated with the lying side of the Primorskii fault (Fig. 4, *H*), probably because the fault-line anomalies are of different origin.

Anomalies of D, Q, and N, similar in width, are localized at five more sites on the southeastern flank of the Bayandai Village–Cape Krestovskii profile (Fig. 4, *C*, *D*, *F*). In places of DC resistivity and magnetic surveys (Fig. 4, *K*, *M*), sites of this type correspond to ρ_a and T minima. Thus, the southeastern part of the profile contains six rank IV interblock zones. Their faulted substrate is highly permeable to water and gases, and the migration of the latter is one of the main causes of geophysical anomalies. At the same time, the rank IV zones in the above-mentioned geophysical fields show regular qualitative and quantitative differences. In most cases, zones II, IV, and VI (Fig. 4) have more distinct positive D, Q, and N anomalies than the other three. Nevertheless, these zones are manifested in smaller basins and faults, which belong to different morphogenetic types. In contrast, zones I, III, and V were formed by large SE-inclined faults, the movements along which gave rise to deep grabenlike basins. Also, these zones are marked by distinct anomalies in the upper part of the section (SP, MT).

According to these data, zones I, III, and V are deep faults, and three others (II, IV, VI) are relatively shallow. The zones are paired; note that those which are the most distinct in all the studied fields (III, IV; V, VI) are so close to one another that some plots show a single anomaly with two closely spaced extremums (Fig. 4, *C*, *F*, *J*). On the scheme based on the interpretation of space images and the analysis of the fault structure of the region, these sites are broad belts with a high degree of tectonic crushing (Arzhannikova and Gofman, 2000). Thus, the southeastern part of the Bayandai Village–Cape Krestovskii profile contains three rank III zones, which separate large crustal blocks. In the topography, these blocks are manifested in the Baikal basin, Ol'khon marginal stage, Primorskii block uplift, and Onot plane uplift. The zones mentioned were formed by the Cenozoic stretching; each of them is inclined southeastward and has a similar internal structure.

The most intense movements within the rank III zones gave rise to the largest faults (Morskoi, Primorskii, Prikhrebtovyi) as well as the deep and narrow Bugul'deika–Chernorud and Prikhrebtovyi basins. These fault structures are associated with belts of ancient tectonites. As pointed out above, they are marked by intense negative SP anomalies. The near-vertical zones under study intersect Paleozoic thrusts (30–35 km) in the section. Their position turned out to be less favorable to activation during the Cenozoic rifting. Additional stretching zones with a similar thickness formed at the back of each deep fault. They violate the southeastern faces of the blocks, mainly near the surface. Within these stretching zones, the crust is destroyed less intensely owing to the activation of an ancient network of conjugated N–S and E–W strike-slip faults and relatively small NE-trending faults (Fig. 5, *B*). The rear zones might not join the main faults at depth, but, in any case, they reflect the internal structure of three large interblock faults (Morskoi, Primorskii, Prikhrebtovyi).

At the next level (II), it is natural to combine three zones described in one structure spanning the entire southeastern (0–45 km) half of the profile. The reason for this combination is that the sites occupied here by the interblock zones are larger than those with less deformed blocks. According to the geological and geophysical data, this pattern is most distinct near the crustal surface (Fig. 4). The low-resistivity Prikhrebtovyi and Morskoi zones also occupy a considerable part of the section at depth (Fig. 5, *C*). Also, the area with high-resistivity intrusive rocks between them is not monolithic, because these rocks are deformed by the Primorskii fault. The latter, as compared with the other faults, is most distinct in the geologic and geophysical features reflecting the structure of the upper part of the section. Its indistinctness in the MT-based geoelectric section might be due to the sparse network of the MT stations, which did not permit the complete delineation of the narrow crushed zone of the well-formed fault plane, the inhomogeneous water depth in the fault zone, or the weak activity of the fault at the present tectogenesis stage (Lamakin, 1968). This issue can be the subject of a separate detailed investigation, but the intense activity of the Primorskii fault, combined with the Morskoi and Prikhrebtovyi faults, during the rifting is obvious.

Along with the above criterion, based on integrated geological-geophysical survey data, the assignment of the southeastern part of the profile to a large interblock zone is confirmed by the unity of its internal structure. The deformations within the zone show a distinct pattern in their localization (Fig. 4): the distance between same-rank zones decreases from the northwest southeastward, suggesting that the substrate deformation increases from the periphery to the main faulting surface (Morskoi fault). Note that three rank IV zones have a similar spatial orientation and show faulting; note that the Primorskii and Morskoi faults, joining near the Bugul'deika Village, form a continuous fault network. The features listed permit (Gibbs, 1990; Park, 1997) assigning the entire southeastern half of the profile to the Obruchev stretching fault system. Thus, as compared with the previous estimates, the Obruchev system is almost twice larger across. This system and the same-rank interblock zone on the opposite shore of Lake Baikal form the shoulders of the rift, which belongs to rank I in the hierarchy of the study region.

Unlike the southeastern part of the Bayandai Village–Cape Krestovskii profile, the main structural element on its northwestern flank is a weakly deformed crustal block without intense geophysical anomalies (except the extreme site) (Figs. 4, 5). Note also the profile part intersecting the Cisbaikalian marginal salient (transition from the Onot uplift to the Cisbaikalian trough). Here, a network of local faults was activated; emanation approaches the average; *U* is lower than the profile average; the geoelectric section contains a near-vertical discordant zone with a high resistivity (MT-8, Fig. 5, *C*). An ancient "healed" fault zone might be localized at this site and have concentrated strains in recent time, like the southeastern structures of this type. However, since this zone is localized at the periphery of the area of the Late Cenozoic activation, only shallow faults formed here owing to upper-crust warping. This does not permit assigning the structure to the same rank as the interblock zones considered.

As regards the extreme, northwestern part of the profile (Fig. 4, Fig. 5, *B*, *C*), this area (near the Bayandai Village), to all appearances, is host to the edge of the large interblock zone associated with the axis of the Cisbaikalian trough. Judging from the MT data and the localization of the epicenters of weak seismic events unrelated to industrial explosions (Seminskii and Radziminovich, 2007), the Bayandai segment of the Cisbaikalian zone is active now. Although the zone described is outside the actively developing rift, its activity also reflects the tectonic processes accompanying the contact of the Siberian and Transbaikalian lithospheric blocks.

Thus, the integrated analysis of the field geological and geophysical data confirms the spatial relationships between the Obruchev zone and the Cisbaikalian trough, detected when the scheme of the zone–block structure of Cisbaikalia was compiled on the basis of the 3D topographic model (Fig. 1). The hierarchy of the zone–block structure of western Cisbaikalia was reconstructed owing to the use of efficient methods and the fact that the geophysical fields associated with the interblock zones are controlled by the crustal structure rather than by its composition. Since this situation is not typical, it is reasonable to summarize the experience of using specific geological and geophysical methods to distinguish variously ranked block interaction zones.

Field structural, geomorphological, and hydrogeological observations as the most important source of information about faults and migrating waters are an obligatory component of the set of methods. However, for objective reasons, they can be conducted only at individual sites in the study regions. The other ones we used are express methods, simple and efficient in most environments. The measurements are an array of quantitative data, which can be processed and analyzed by different methods, including statistical ones. For example, the geological and geophysical studies on the Bayandai Village–Cape Krestovskii profile confirmed the results of similar studies at the local sites of the Ol'khon area (Seminskii et al., 2008; Seminsky and Bobrov, 2009). According to these local data, the initial quantitative criterion for the presence of an interblock zone is an increase in *D*, *Q*, and *N* and a decrease in ρ_a, *T*, and ΔU with respect to the averages. Significantly, the boundaries of the same zone determined with this criterion by different methods are the nearer to one another, the closer the relationship between this parameter and the degree of crustal faulting.

In general, the straight topographic features objectively reflect the position of the faults not only in the active part of the Baikal Rift but also on the platform edge, as confirmed by targeted studies (Seminskii and Radziminovich, 2007; Seminsky et al., 2008). On the other hand, abnormally high *D* might be typical not only of the deep interblock zones but also of the near-surface parts of the section (Fig. 4, *C*, 50–55, 61–63, 67–70 km). Active interblock zones clearly manifested in maxima are typical of gas-exhalation fields (Fig. 4, *D*, *F*), mainly those of Rn, which reflects deeper crustal structures than Tn, with its short half-life. At the same time, the fault planes filled with gouge correspond to minimum *Q* and *N*, thus making the interblock zone boundaries somewhat ambiguous (Fig. 4, *E*, *G*).

A good source of information in distinguishing variously ranked interblock zones both in the upper part of the section and at depth is the resistivity field, with minima over the intensely deformed and watered parts of the mountain mass

(Fig. 4, *J*, *K*, Fig. 5, *C*). The efficiency of electrical prospecting might depend considerably on the possibility of fluid supply to the interblock zone from depth or from the surface. However, considering that conditions for near-surface water exchange depend on the study locality (for example, they differ greatly in the Primorskii Ridge and Ol'khon Plateau), the relationship between resistivity anomalies and water exchange is a special subject of study. The magnetic-survey data are the most ambiguous in structural studies, because the magnetic field within the regional profile reflects mainly the substrate composition.

Unlike the fields considered above, the SP data reflect mainly the localization of the ancient fault zones, marked by graphitized dynamically metamorphosed rocks and, consequently, negative *U* anomalies (Fig. 4, *H*, *I*). Since the ancient tectonites, as a rule, concentrate strains and might cause resumed block movements, SP measurements are an important part of the set of methods. The prospects of its use for distinguishing local active interblock zones are related to the analysis of low-amplitude variations accompanying the regional *U* variations described above (Fig. 3, *C*).

Note that the results of different methods, irrespective of their geological-geophysical basis and depth, agree in distinguishing interblock zones. This unevident a priori fact shows that the interblock zones in the study area are "through"; that is, they are intensely deformed crustal areas with a high permeability, which are traced from the Earth's surface to depths of about several kilometers or, most probably, more.

Thus, interblock zones in general, as complex 3D structural elements of the crust, are distinct in different fields. However, the manifestation of an individual zone in the field depends on its structure and composition as well as the origin of the field. Therefore, the criteria for distinguishing interblock zones can differ even for one field (for example, depending on the rank). Owing to the integration of methods, the disadvantages of some methods in our study are compensated for by the advantages of others. The results show that the set of methods is efficient in mapping the zone–block structure of the Earth's crust. It is therefore recommended for similar studies in different geodynamic settings.

Conclusions

The main aim of the geological and geophysical works along the regional profile in western Cisbaikalia consisted in studying the tectonic division of the crust at the junction of the Siberian craton and Sayan–Baikal Fold Belt. The set of methods was oriented toward delineating active structures manifested in open faults and joints and, consequently, highly permeable to water and gases. The measurements on the Bayandai Village–Cape Krestovskii profile are more detailed (DC resistivity, SP, magnetic prospecting, MT, lineament analysis) than the previous geological and geophysical studies and use new equipment (MT). Within the section studied, the Rn–Tn survey was done for the first time.

The interpretation of the data helped specify the tectonic structure of western Cisbaikalia, reveal the crustal deformation pattern, and establish its correspondence to the tectonophysical ideas about the zone–block structure of the lithosphere. Two types of tectonic settings were distinguished, which alternate along the Bayandai Village–Cape Krestovskii profile and are represented by relatively stable blocks and dislocated crustal zones. Highly faulted rocks form a strict hierarchy of interblock zones. They make up five adjacent levels and fit into the scheme of the zone–block structure of Cisbaikalia, which, in turn, is a fragment of the smaller-scale maps reflecting the hierarchy of the zone–block structure of the Central Asian lithosphere (Seminskii, 2008).

The largest interblock structure in western Cisbaikalia is the Obruchev fault system. It determines the character of the geophysical fields in the entire southeastern half of the profile. It represents the northwestern shoulder of the Baikal Rift and is ~50 km wide, which is twice as much as the previous estimates (Mats, 1993; Mats et al., 2001). The Obruchev fault system comprises the Morskoi, Primorskii, and Prikhrebtovyi interblock structures. They are traced to depths of tens of kilometers and widen toward the surface owing to the appearance of superior zones. As a result, the deformed areas within the Obruchev system are larger than the same-rank blocks. On the northwestern flank of the profile, the ratio is the opposite, suggesting the attenuation of the tectonics on the edge of the Siberian craton. The Morskoi, Primorskii, and Prikhrebtovyi interblock structures, which are inclined southeastward and dip steeply, formed along the northeastern zones of ancient tectonites and cut the surface of pre-Cenozoic low-angle thrusts. Considering the faulting, all this reflects the formation of the Baikal Rift under crustal stretching.

Interblock zones as areas with a higher-than-average fault density are detected reliably in geophysical fields from positive or negative anomalies. The studies along the Bayandai Village–Cape Krestovskii profile show that the set of methods for studying the active zone–block structure of the crust is highly informative in distinguishing variously ranked interblock zones, permits time-saving field measurements, can be used in different environments, and is inexpensive.

The set comprises methods which supplement one another successfully. Lineament analysis reveals areas with a highly deformed near-surface part of the crust. Within a wide range of depths, DC resistivity profiling and MT soundings permit distinguishing and outlining conductive zones, which are crustal areas crushed as a result of active block interaction and permeable to aqueous solutions. Negative SP anomalies are typical of ancient faults with graphite mineralization, often affected by recent tectonics. Emanation survey reveals deep zones of intense degassing; note that local *Q* maxima and minima mark off the position of individual fault planes with gas-permeable or -impermeable tectonites. Along with the methods listed, the set includes field structural, geomorphological, and hydrogeological studies. On the basis of observations at individual sites, they permit determining the origin and tectonic characteristics of the zones distinguished during the geophysical works.

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