The deep structure of the Salair fold-cover structure according to magnetotelluric studies

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Abstract. The results of magnetotelluric studies (MTS) performed within the Salair cover-folded structure on two profiles are considered: the Zabrodino village – the Rodnikovy village (1) and the Smaznevo village – the Kotino village (2). The profiles are oriented crosswise along the main structures and intersect Salair and the western part of the Kuznetskiy trough. The analysis of the obtained data showed that a subhorizontal underlying conducting zone is distinguished in the Earth's crust of the Salair fold-cover structure, such zone is typical for intracontinental orogens. The zone is considered as a deep separation failure. The nature of the electrical resistance values distribution confirms the presence of the Salair thrust on the Kuznetskiy deflection. The Alambay ophiolite zone on the geoelectric section corresponds to a highly gradient region, indicating the suture zone of this structure. High resistivity values in the northern part of the Khmelevskoy trough are associated with the widespread development of granitoid massifs that are not covered by erosion.

1. Introduction
The Salair fold-cover structure (Salair) is located in the north-western part of the Altai-Sayan fold region of the Central Asian fold belt and is composed of Cambrian-Early Ordovician volcanogenic and sedimentary deposits. In terms of the Salair orogen, it has the shape of a horseshoe, facing the convex side to the North-East. In the inner part of this arc-shaped structure there is the Khmelevskoy trough, made by terrigenous deposits of the Upper Devonian-Lower Carboniferous. The Early Paleozoic Salair deposits are pushed over the Devonian-Permian execution of the Kuznetskiy trough by the scaly thrusts system. At the same time, it hasn’t been divided into blocks, but deformed as a single rigid block. Paleozoic thrusts were reactivated at the neotectonic stage in some places and are expressed in the modern relief by tectonic ledges.

In order to initially study the deep structure of the Salair orogeny using the deepest electrical prospecting method, magnetotelluric studies were performed on two profiles oriented across the strike of its main structures (figure 1).
Figure 1. Geological scheme of Salair and the position of the MTS profiles

1 – Cambrian–Early Ordovician folded basement, including volcanic rocks, volcanomictic sandstones and shales, limestones; 2 – ophiolite melange of the Alambay zone; 3 – lenses of serpentinized dunites and harzburgites in the ophiolite melange of the Alambay zone; 4 – Ordovician limestones and shales, the lower structural stage of the Epicaledonian sedimentary cover; 5 – Early–Middle Devonian carbonate deposits and volcanites, middle layer of the cover; 6 – Upper Devonian and undifferentiated Upper Devonian–Lower Carboniferous sandstones, siltstones, mudstones, limestone lenses, upper layer of the cover; 7 – Carboniferous sandstones and siltstones, the lower part of the sedimentary filling of superimposed Late Paleozoic deflections; 8 – Permian sandstones, siltstones, coals, the upper part of the sedimentary execution of superimposed Late Paleozoic deflections; 9 – Triassic basalts; 10 – Early–Middle Jurassic sandstones, siltstones. Conglomerates, coals, deposits of superimposed deflections; 11 – Cretaceous sandstones and siltstones of the Neninsk-Chumysh depression; 12 – undifferentiated granitoid intrusions; 13 – main thrusts; 14 – other discontinuous disturbances; 15 – numbers of tectonic structures not signed on the scheme: I – Kuznetskiy Alatau, II – Gornaya Shoria, III – Gorlovskiy trough, IV – Zarubinskiy trough, V – Doroninskaya depression, VI – Neninsko-Chumyshskaya depression; 16 – MTS points.

The inset shows the position of figure 1 in the structure of the Central Asian folded Belt.

2. The geological structure of the region
2.1. Salair fold-cover structure
From above, the Salair fold-cover structure has the shape of a horseshoe and can be divided into three parts: the middle – north-western stretch and the flanks of the south-western stretch. The middle part, with a length of about 250 km, is the frontal part of a complex-built allochthon and corresponds to the neotectonic uplift of the Salair ridge. The Early Paleozoic deposits of Salair are pushed over the Devonian-Permian sedimentary formation of the Kuznetskiy trough along the system of scaly thrusts. The thrust front is the north-eastern border of Salair. The central part of the structural arc is formed by the superimposed Khmelevskaya deflection, made by Late Devonian-Early carboniferous terrigenous deposits. In the southwest, the Salair Caledonids and the Late Paleozoic sediments of the Khmelevskiy trough are gently submerged under the Cenozoic cover of the Biysk-Barnaul depression, which is part of the West Siberian plate. The cover structure of Salair was formed in the Permian period, as a result of the collision of the Siberian, East European and Kazakhstan continents [3, 6] and sealed with late Permian polyphase granitoid batholiths of the Zhernovskiy complex [10].

The Alambay ophiolite suture zone passes through the Salair axial part. The following geological complexes are distinguished in its composition: Alambay basalt, Upper Alambay dunite-harzburgite and Shalap melange [4, 11, 12]. Salair is a block of juvenile Early Paleozoic crust formed as a result of suprasubduction magmatism. The Earth's crust is composed mainly of igneous rocks of basic and acidic composition.

2.2. Khmelevskaya deflection
The Khmelevskaya trough is composed of a complex of sediments dating from the early Ordovician to the early Carboniferous, with a total thickness of more than 4200 m [2]. The lower part of the Devonian section is composed of limestones with interlayers of bauxite of the Berdsko-May series of the Lower-Middle Devonian age. The upper part consists of carbonaceous clay shales and sandstones of the Middle Devonian Khmelevskaya formation and the Upper Devonian-Lower carboniferous Paiinsky formation. The deposits of the Paivin formation form the core of the deflection and cover most of it. The folded Early Paleozoic basement comes to the surface within the Salair. The folding of the Khmelevsky trough is characterized by north-eastern vergence and, according to its morphological features, can be attributed to the structures of the folded-thrust paragenesis [11, 12].

2.3. The joint zone of the Salair and Kuznetskiy deflection
The Salair deposits are pushed over the sedimentary execution of the Kuznetskiy trough with the formation of a wide system of scaly thrusts in the sedimentary cover of the trough. The thrust character of the boundary is confirmed by data from the study of mining workings and drilling wells [1, 8]. Neotectonic activation was expressed in the formation of the modern Salair uplift, the eastern boundary of which is a series of ledges with a height of up to 100 m and is a geomorphological expression of reactivated Late Paleozoic thrusts. Seismic events are associated with the thrusts of the Prisalair zone [7], which allows us to consider neotectonic faults as active at the present time.

3. Methods of work
The MTS studies were carried out on two profiles during two field seasons (figure 1). The first profile is the Zabrodino village – the Rodnikovy village, 175 km long, crosses the middle part of the Salair orogen. The second one is the Smaznevo village – the Kotino village, 125 km long, passes to the South and crosses the Alambay ophiolite zone.

The work was carried out by the equipment of the Canadian company “Phoenix Geophysics Ltd” in the range of 3·10^-3-10^4 s periods. Two MTU-5 measuring modules were used. Four components of the magnetotelluric field were recorded: E_x, E_y, H_x, H_y. The average observation step was 4-5 km, the recording duration was 19-22 hours. A cruciform installation with a length of electric lines of 100 m was used, oriented according to the scale of magnetologists: the X – axis is North, the Y – axis is East. Field data were processed in the program “SSMT-2000”, 1D-and 2D-inversion – in the software package “WinGLink”.

4. Research results

Based on the results of the conducted studies, deep geoelectric sections were constructed (figure 2, 3), on which zones of increased and decreased electrical resistivity values are contrastingly distinguished. For description ease, they are numbered with numbers in circles. The most contrasting structure, expressed on both geoelectric sections, is the joint zone of the Salair folded-cover structure and the Kuznetskiy trough. The zone is characterized by a high resistivity gradient: from the first units of Ohm·m in the sedimentary formation of Kuzbass to tens and thousands of Ohm·m in the dislocated rocks of Salair. Resistivity isolines sink in a south-westerly direction under the Salair, which is in good agreement with the geological data on the thrust character of the zone [2, 9].

4.1. Profile between Zabrodino village – Rodnikoviy village (Profile 1)

In the central part of the profile (points 8-30), two areas with high resistivity values (1 and 2) are distinguished, amounting to 2000-7000 Ohm·m and a width of 6 km. In the area of points 18-19, they are separated by a subvertical conducting zone (3) marking the Kinterpskiy fault. According to V. I. Belyaev and co-authors [2], the Kinterpskiy fault within the Khmelevskoy trough is traced by a chain of narrow fault uplifts (gorst-anticlines) formed by Middle and Lower Devonian rocks in the field of distribution of Late Devonian-Early Carboniferous deposits. The north-eastern wings of the uplifts are steep, folded up by ups, the south-western ones are flat, with normal contacts. In the interval of the section of 6-20 km, a lateral conducting inhomogeneity is distinguished (4). In the western part it is limited by a high resistance block (7), and in the eastern part it rises gently in the direction of the conducting zone (5) corresponding to the sedimentary deposits of the Kuznetskiy depression. The conducting zone is interpreted as a zone of separation failure at the base of the Salair allochthonous plate. Its increased electrical conductivity is most likely associated with tectonic disintegration and fluid saturation of the separation failure zone. It is also impossible to exclude the presence in this depth range of fragments of the tectonically overlapped Upper Paleozoic sedimentary cover of the Kuznetskiy trough. The geological position of the subvertical conducting zone, spatially corresponding to the Kinterpskiy fault, is in good agreement with this structural interpretation (figure 2) [5, 9].

High resistivity values at depths up to 7 km in the western part of the profile are evidence of the widespread distribution of weakly dislocated granitoids of the Zhernovskiy complex in this sector of the Khmelevskiy trough. The presence of undiscovered granitoid massifs in the central part of the Khmelevskiy trough is confirmed by the results of geochemical studies [2]. The main characteristic of the section is the subhorizontal occurrence and the flattened shape of crustal geoelectric inhomogeneities, emphasized by the presence of lateral conducting inhomogeneity (4) in the lower part of the upper crust of the folded-cover structure of Salair.

4.2. Profile between Smaznevo village – Kotino village (Profile 2)

The geoelectric section along the profile of the Smaznevo village – the Kotino village is also characterized by a contrasting distribution of resistivity values (figure 3).
Figure 2. Deep geoelectric section along the profile of the Zabrodino village – the Rodnikoviy village.

The central part of the section (points 26-8) is represented by a block with high resistivity values (11), which vary from $10^3$ Ohm·m to $10^4$ Ohm·m (figure 3). According to geological studies, igneous rocks characteristic of this part of the Salair orogen are widely distributed within the block. The highly gradient zone (points 27-22) forming its western border corresponds to the main Salair ophiolite suture – the Alambay zone. The field of development of ophiolite melange (points 27-22) is characterized by high values of UES [5]. The western part of the ophiolite zone (points 26-30) is manifested by a conducting zone (9) with resistivity values of 50-200 Ohm·m. Low resistivity values in this zone are due to the presence of carbonaceous quartzite shales in sedimentary deposits, which form a fine graphite substance during tectonic processing.

Figure 3. Deep geoelectric section along the profile of the Smaznevo village – the Kotino village.

5. Conclusions
1. In the Earth's crust of the Salair fold-cover structure, a subhorizontal conductive inhomogeneity characteristic of intracontinental orogens is distinguished. The zone is interpreted as a deep separation breakdown (decollement). The nature of the deep electrical conductivity distribution confirms the presence of an advance of the Salair orogen on the Kuznetskiy trough. From the analysis of geoelectric sections, it follows that in the area of the junction between Salair ridge and the Kuznetskiy depression, the boundary of the high-resistance block sinks in a south-westerly direction under the Salair fold-cover structure. This is in good agreement with the geological and geomorphological data on the north-eastern vergence of the Paleozoic and Neotectonic thrust structures. The amplitude of the thrust of the allochthonous Salair plate is a debatable issue. According to [3, 4], the horizontal thrust amplitude is estimated at 200-250 km. The zone of a sharp resistivity gradient between the conducting zone (4) and the high-resistance block (7) may correspond to the transition to the tectonic cover edge region. In this case, the amplitude of the horizontal displacement of the Salair allochthon can be estimated at 100-120 km [5];

2. The Alambay ophiolite zone on the geoelectric section according to profile 2 (the Smaznevo village – the Kotino village) is expressed by the zone of the junction between high-resistance and conductive blocks. This is evidence of the suture nature of the zone;

3. The conducting inhomogeneity identified in the north-western part of the Khmelevskiy trough corresponds to the Kinterespiy thrust zone, which may indicate modern activity. The northern part of the Khmelevskoy trough is characterized by high resistivity values, which is probably due to the widespread development of granitoid massifs of the Zhernovskiy complex that have not been exposed by erosion here;

4. The geoelectric section of the Kuznetskiy trough is characterized by low resistivity values of both the sedimentary cover and the upper part of the consolidated Earth's crust. The low values of the latter are due to its fragmentation and fluidization at the neotectonic stage of the territory's development.

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