

Deep Structure and Dynamics of the Issyk-Ata Fault (Northern Tien Shan)



Anatoly Rybin , Elena Bataleva , and Kseniia Nepeina 

Abstract The identification of hidden areas of active faults in the Earth's crust that can generate earthquakes is the most urgent problem in assessing the seismic hazard of various regions. The main goal of this study was a detailed study of the geophysical characteristics in the zone of individual segments of active faults in the Northern Tien Shan with electromagnetic geophysical methods. The structural line of the Issyk-Ata fault is clearly, but fragmentary, revealed on the surface by geological methods, since the tectonic disturbance is hidden by loose deposits of the Cenozoic age. The results of inversion of detailed magnetotelluric soundings in the fault impact zone of the fault made it possible to determine the position of the upper edge, width, depth, strike and inclination of the fault zone. At the stage of complex construction of 2D geoelectric models of the Issyk-Ata fault zone, the results of field profile soundings by the method of surface electrical resistivity tomography were used. To study the dynamics of the constructed block model of the fault zone, we considered variations in the following electromagnetic parameters that reflect the response of the geomedium to a change in its stress–strain state: impedance and tipper components, apparent resistivity and impedance phase, time–frequency series, and anisotropic properties. Based on this, estimates of the correlation between variations in electromagnetic parameters and lunar-solar tides and the spatiotemporal distribution of seismicity were made. This work was supported by the Russian Science Foundation under grant No. 22–27-00567.

Keywords Active fault · Magnetotelluric sounding · Electrical resistivity tomography · Seismicity · Variations in electromagnetic parameters · Northern Tien Shan

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1 Introduction

At the beginning of the last century, Reid [1], in his most famous work, was the first to put forward a hypothesis about the confinement of earthquakes to the fault structures of the Earth's crust, which attracted the attention of geophysicists to a more detailed study of the patterns of localization of seismic events in fault zones. However, the relationship between earthquake epicenters and tectonic faults, established as a result of geological studies, is not always manifested. First, earthquake sources can be confined to fault structures that are not vertical or subvertical, but have a listric shape. Since such faults are characterized by flattening at depth, the nature of the distribution of earthquakes is more complex. Secondly, the hypocenters of seismic events can be localized in fault zones, which are fixed by geologists on the day surface only by indirect signs, or they are not manifested at all and represent the so-called hidden faults [2]. The confinement of earthquakes to hidden tectonic faults identified by a complex of geological and geophysical methods is typical for many seismically active regions, including the Tien Shan.

In this paper, we use such terms as “fault”, “fault structure”, “zone of tectonic faults”, “zone of increased fracturing” as synonyms. We pay special attention to the study of active fault structures, since modern geodynamic processes are associated with them.

“An active fault (also a “living fault”) is a fault in the Earth's crust or the entire lithosphere, along which in historical time or in the Holocene (the last 10 thousand years) displacements occurred or earthquake sources were localized; in geophysics, a zone of anomalous changes in deformation, geophysical, and fluid-geochemical fields” [<https://ru.wikipedia.org/wiki/>]. Various researchers invest in the concept of “active fault” a different temporal meaning. We will be in solidarity with the authors who consider active faults to be those structures along which displacements are currently occurring and, at the same time, they are revealed instrumentally. To isolate the entire near-fault area, which includes the fault zone and the zones of discontinuous plumage framing it, the term “zone of dynamic influence of the fault” or simply “fault impact zone” is usually used.

Thus, S. I. Sherman and his colleagues [3] believed that fault impact zone is the area of deformation associated with the mechanical formation of the fault and movements along it. It is within this zone that rocks undergo physical and mechanical (crushing, brecciation, shearing, formation of plumage faults), rheological (changes in physical properties with depth or in connection with the duration of fault development), petrographic (metamorphism of different stages) and structural changes (thickening plumage breaks, fault folding, boudinage). On this basis, it can be concluded that the fault zone is an area containing rocks with anomalous physical characteristics, and is a zone of concentration of the stress–strain state of the geological media. The most effective tools for studying fault zones characterized by increased electrical conductivity compared to the host rocks due to their increased fracturing and fluid saturation are electromagnetic methods.

2 Materials and Methods

2.1 Geological Structure

According to modern concepts based on the results of trenching (a method for studying seismic deformations in ditches) [4, 5] and structural and geological constructions [6–8], it has been established that the Late Quaternary structure of the Northern Tien Shan is characterized by the presence of an almost continuous zone of active faults. It consists of the transpressive left-lateral strike-slip Kemin-Chilik zone [9], passing to the west into the active thrust thrusts of the southern framing of the Chu basin (Issyk-Ata and Shamsy-Tunduk faults), and from the east it is limited by the Chundzha-Kapchagai system of active faults of northwestern strike. This zone separates the isometric blocks of the Kyrgyz part of the Northern Tien Shan from the blocks convex to the south (Zaili and Chu-Kendyktas), enclosing the Ili basin. The Chu basin is an intermountain depression whose Paleozoic basement is overlain by a thick cover of Meso-Cenozoic and Quaternary sedimentary rocks [10–12]. Therefore, the search and refinement of the territorial position and structure of active faults, both visually observed and hidden, is carried out according to geophysical research data, and the identification of areas of active faults in the Earth's crust that can generate earthquakes of various strengths is the most urgent problem in assessing seismic hazard at present.

The fragmented structure of the Northern Tien Shan is clearly expressed in the cross-lattice nature of the fault system—in the Late Quaternary, its main blocks were formed: the Kyrgyz, Zaili, Chu-Kendyktas, Charyn and Issyk-Kul. It is along the fault limits of these blocks that the main seismicity of the region is concentrated and, accordingly, when assessing the seismic hazard, these blocks should be chosen as areal sources. The article [5] shows the segmentation of the Issyk-Ata fault, which was divided by the authors into segments based on such parameters as seismic, behavioral, structural and geometric. The characteristics of the selected segments and the relationship between them are described. Rebetsky Yu. L. (Institute of Physics of the Earth RAS) and Kuzikov S. I. (Research Station RAS in Bishkek) in [10] presented the results of tectonophysical zoning of active faults in the Northern Tien Shan. The authors identified and digitized 102 faults and built a map of active faults in the Northern Tien Shan. It is noted, that most of the study area is represented by reverse faults with a left right strike-slip component. The calculated kinematics of faults for the present stage of deformation of the upper part of the crust of the Northern Tien Shan generally corresponds to the data of geological observations of displacements of fault limbs in near-surface layers. It has been established, that only some of the faults in the Earth's crust (about 20–30%) can be classified as active in the current stress field [10]. However, this conclusion concerns only those tectonic faults that come to the surface, but in the territory under consideration there are also hidden fault structures of the basement and their intersection zones, which can also be active.

The objects of our study were impact zone of the Issyk-Ata fault, which is an active thrust of the southern framing of the Chu basin and controls the junction zone of the Kyrgyz ridge with the basin in a compression setting. The Issyk-Ata fault is located almost on the surface of the earth and goes deep into 20 or more kilometers. Its length is 150 km. At the moment, it is believed that it starts from the Tokmak city and stretches up to Sosnovka. Accordingly, it passes through the southern part of Bishkek and the villages adjacent to the capital. Studies have shown that during each major earthquake, of which there may have been four over the past 5 thousand years with $6.9 > M < 7.4$ [13], the southern part of the fault rose by 2–2.5 m. Now the ledge is about 7 m. The displacement rate of the fault itself is 2.9 mm per year. That is, in 10 years the fault shifts by 2.9 cm.

2.2 Research Methods and Data

In recent years, significant progress has been made in studying impact zones of the fault structures of the Northern Tien Shan by electromagnetic methods [14–20]. At the moment, monitoring studies in the Chu basin are being carried out in several areas (Figs. 1 and 2): (1) on the northern slope of the Kyrgyz Range in the junction zone with the Chu basin (Baitik basin), between the Norus and Almaly rivers—Kentor minipolygon—in fault impact zone of the Shamsy-Tunduk fault; (2) at the stationary points Aksu and Chon-Kurchak, located in the immediate vicinity of the Issyk-Ata and Chon-Kurchak faults, respectively; 3) in the regime point No. 9 (Boom) and the profile of the same name, crossing the alleged hidden segment of the Issyk-Ata fault.

The method of magnetotelluric sounding (MTS), is one of the leading methods of electromagnetic monitoring of the Bishkek Geodynamic Polygon (BGP), and allows monitoring hidden fault structures that do not appear in the sedimentary cover, but are zones of increased fracturing and fluid permeability of the basement and manifest themselves as anomalies in geophysical fields. Electromagnetic monitoring in geodynamic active areas with MTS is quite widely used, e.g. [21, 22]. Previous electromagnetic studies confirm both the existence of hidden fault structures and geoelectric segmentation of the study area [15–17], which reflects the main elements of the block structure of the junction zone of the Chu basin and the Kyrgyz ridge. These features must be taken into account when building a complex geological and geophysical geodynamic model for the development of the Tien Shan as a vivid example of an intracontinental orogen. At the same time, the geoelectric model of the active Issyk-Ata fault, which controls the junction zone of the Kyrgyz Range with the Chu basin in a compression setting and which, according to geological data, represents 6 tectonic segments, does not exist today.

There are also no data on the manifestation of fault lineaments in electromagnetic parameters. Thus, the determination of the values of electromagnetic parameters characteristic of each specific lineament of the fault structure is relevant, and studies of the dynamics of their variations can form the basis of a new approach for assessing the stress–strain state of the fault zone.

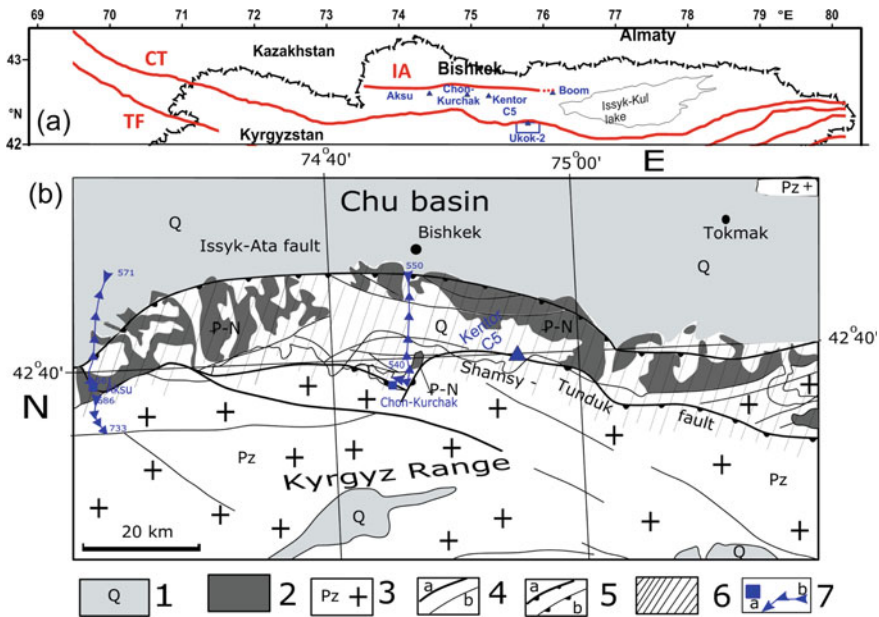


Fig. 1 Scheme of location of fault structures and monitoring points with magnetotelluric soundings (blue triangles) in the basins of the Northern Tien Shan: **a** general scheme with red lines for faults: CT—Central Terskey, TF—Talas-Fergana, IA—Issyk-Ata; **b** Chu basin. The junction zone of the Kyrgyz Range and the Chu Basin: 1—Quaternary deposits; 2—Paleogene-Neogene deposits; 3—Paleozoic basement rocks; 4—active faults: main (a) and secondary (b); 5—reverse faults and overthrusts: main (a) and secondary (b); 6—zone of alpine activation; 7—points of electromagnetic monitoring: stationary (a), regime (b) [19]

The identification of hidden active faults can contribute to solving the problems of modern geodynamics, in view of the fact that a relationship has been established between the development of tectonic faults and the distribution of seismicity [18]. The two largest seismic events are the Kemin-Chu in 1938 ($M = 6.9$; 42.70° N, 75.80° E; $K = 16$) and the earthquake in 1968 ($M = 6.4$; 42.70° N, 75.90° E, $K = 15.5$) occurred in the area (Fig. 3), which is located in the immediate vicinity of the Issyk-Ata fault and may be its continuation. Considering this, in 2021 the Boom profile was laid and repeated in 2022, cutting across the zone of the proposed fault. Figure 4 shows the distribution of seismic events recorded by the KNET network, consisting of 10 broadband telemetry stations, which shows a high degree of spatial confinement of seismic events to the fault zones of the Issyk-Ata and Shamsy-Tunduk (or simply Shamsy) faults. Both fault structures appear in the distribution of seismicity, but the Shamsy-Tunduk fault is more pronounced. At the same time, we would like to pay attention to the nature of the distribution of earthquake epicenters in the eastern part of the Issyk-Ata fault (Fig. 4), where we assume the presence of its seventh segment J (?) in Fig. 3. To confirm our assumption a local Boom profile (Fig. 1a) 4 km long was laid.

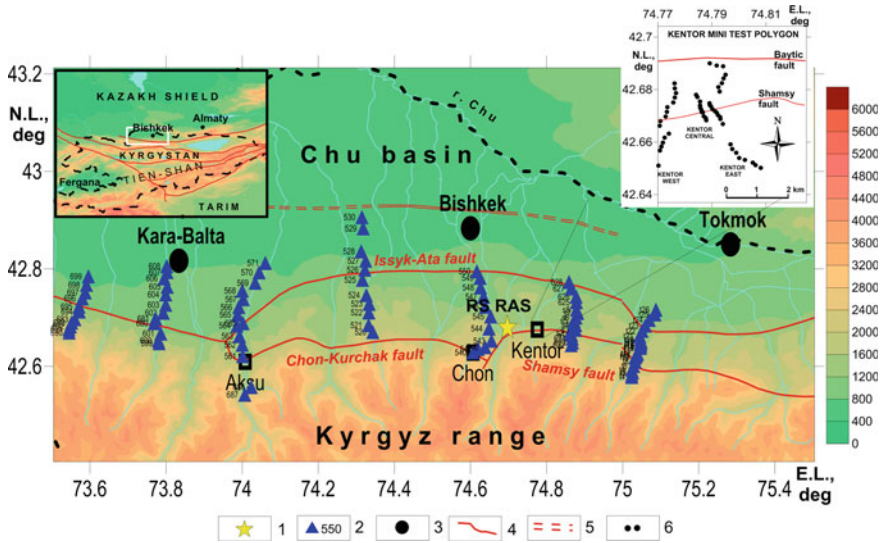


Fig. 2 Map-scheme of the Kyrgyz Tien Shan: 1—Research station of the Russian Academy of Sciences in Bishkek; 2—points of magnetotelluric soundings; 3—cities and towns; 4—main fault structures; 4—earthquakes according to the KNET catalog; 5—flexural-discontinuous zone; 6—state border of the Kyrgyz Republic. In the inset in the left corner the Bishkek Geodynamic Polygon (BGP) is shown by the white rectangle; the inset in the rights corner shows minipolygon Kentor

To build a geoelectric model, the results of nine soundings were used, performed in the period range of 0.01–1600 s, with a step of 350–370 m, using the Phoenix MTU-5 equipment. Correction and interpretation of field data distorted by the influence of near-surface inhomogeneities was carried out based on the results of magnetovariational sounding (MVS) and a three-level 2D MVS/MTS data inversion algorithm using TE and TM modes and taking into account their different sensitivity to surface and deep structures and susceptibility to the effect static offset. Within the Tien Shan, this approach ensures the construction of reliable geoelectric models in a wide range of exploration depths.

The interpretation of the results of magnetotelluric sounding was performed using the Rodi-Mackie 2D inversion algorithm [23]. The program implements the non-linear conjugate gradient method, which tries to minimize the objective function, which is the sum of normalized residuals, data, and model smoothness. The tradeoff between data residuals and model smoothness is controlled by the regularization parameter τ . The parameter τ is set manually by the user. Analysis of MTS data obtained by Belyavsky and Spichak [24] within the southern border of the Chu Basin has showed that not everywhere and not at all frequencies 2D inversion corresponds to the distribution of asymmetry parameters. However, our experience and previous works [15, 17, 19, 20] strongly reveal, that the asymmetry parameters N and $skew$, characterize the degree of horizontal inhomogeneity of the medium, are explicit. The

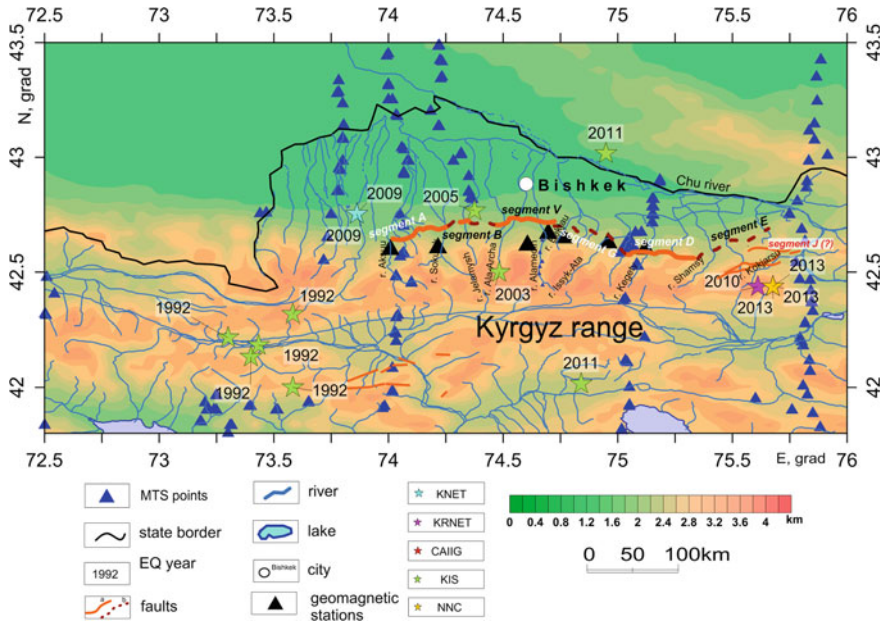


Fig. 3 Segmentation of the Issyk-Ata fault based on geological and geophysical data. Geologic evidence of segments for Issyk-Ata fault upon [5]

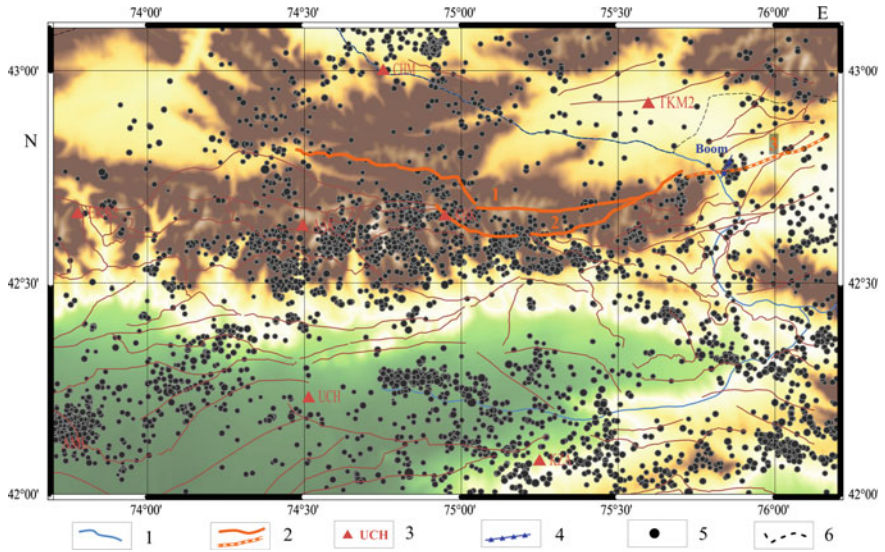


Fig. 4 Distribution of seismicity for the territory of the Bishkek Geodynamic Polygon. Legend: 1—rivers; 2—faults (under the number 1, 2—established, 3—assumed); 3—seismic stations; 4—Boom profile; 5—seismic events for the period 1994–2020; 6—border of the Kyrgyz Republic

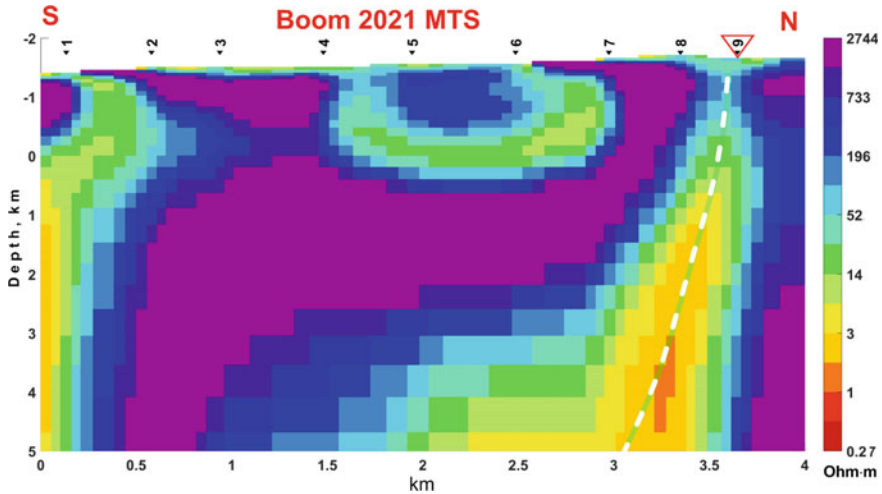


Fig. 5 Geoelectric cross-section MTS profile Boom by Phoenix MTU-5 (2D model). Fault impact zone ~2.5–3 km. Point 9 is a regime point

values of *skew* to significant depths are 0.1, which means the possibility of using 2D inversion of MT S data.

The input data of the inversion are the longitudinal and transverse apparent resistivity and impedance phase curves for 9 observation points in the interval of periods from 0.01 to 1600 s. The grid of the approximation model consists of 78 cells horizontally, sparse at the edges of the model and more frequent in the vicinity of sounding points, and 73 cells vertically, increasing in size with depth. When building a grid, the terrain is taken into account. The resistivity of the starting model is 100 Ω·m. The error limits of the inverted data are as follows: apparent resistivity modulus (TE mode) –100%, apparent resistivity modulus (TM mode) –10%, impedance phase (TE mode) –5%, impedance phase (TM mode) –5%, tipper –0.01%. As a result of several test calculations of the inversion, the value of the regularization parameter 3 was chosen. As a result of 200 iterations, the 2D model shown in Fig. 5 was obtained. The value of the RMS error was 1.76.

3 Analysis and Discussion of Results

The geoelectric section (Fig. 5) is characterized by a contrasting distribution of areas of different electrical conductivity, where a number of electrical conductivity inhomogeneities are distinguished: conductive zones along the edges of the cut; (2) a subhorizontal conductive zone (points 4–6) occurring at depths of 0–2 km in the central part of the section.

In the north of the profile, under the sedimentary cover, whose thickness reaches 400 m, there is a subvertically dipping conductive structure (point 9), which acquires a southward slope at a depth of about 2 km, gradually flattens and merges with a subhorizontal conductive zone lying on depth of 5 km or more. The thickness of the conductive structure varies from a few hundred meters in the upper part of the section to 2.5 km at a depth of 5 km; the resistivity in the fault impact zone varies from 1 to 200 $\Omega\cdot\text{m}$. Thus, as a result of the studies performed, a geoelectric section was constructed, in which a subvertically dipping conductive structure was found under the sedimentary cover, which may be a continuation of the Issyk-Ata fault and represent its hidden seventh segment. Detailed MTS in the fault impact zone made it possible to determine the position of the upper edge (400 m), width (max $-2.5-3$ km), depth (up to 15–17 km), strike (sublatitudinal) and inclination (75°) of the fault zone.

A promising direction for further electromagnetic research, in our opinion, is to conduct monitoring observations in the zone of a hidden fault structure by various electromagnetic methods.

The relationship between the behavior of variations in geophysical fields and the stress–strain state of the Tien Shan earth's crust in seismically active regions is considered in this paper based on the analysis of correlations between the components of lunar-solar tidal effects, variations in electromagnetic parameters, and the distribution of seismic events for MTS regime points in the Northern Tien Shan (Fig. 6). An example of such an analysis, presented in this paper, is the observation point Boom (point 9).

To detect and study fracture zones, we use both the analysis of traditional electromagnetic parameters (apparent resistivity, impedance phase, etc.) and new ones—anisotropic changes in the electrical conductivity of the geological media, which is evaluated based on methodological approaches specially developed over the past decade for conducting monitoring studies.

The geological media, in general, and the fault structure, in particular, are subject to periodic effects of lunar-solar tides, as a result of which its parameters (electrical conductivity, fluid saturation, elasticity, etc.) also periodically change [25]. Figure 6 shows the results of monitoring observations at the regime point 9 on the Boom profile. On this profile, monitoring studies are carried out in two modifications—profile monitoring and regime observations from 2020. As a result of the performed studies, a detailed model of the deep geoelectric structure was built along the profile that cuts the supposed zone of the active Issyk-Ata fault (Fig. 5). On the basis of the obtained geoelectric model, the location of the fault impact zone was determined and a regime monitoring point was selected. The nature of the distribution of seismicity over the observed period of time (9 days) (Fig. 6) indicates the confinement of the hypocenters of seismic events to certain deep levels: (1) near the day surface; (2) the corresponding upper crustal conductor (2–5 km) and (3) confined to the conductive layer at depths (8–12 km). Changes in apparent resistivity in orthogonal directions are observed for almost all earthquakes presented in Fig. 3, for azimuths of $0-75^\circ$, the maxima of lunar-solar tidal influences correspond to an increase in apparent resistivity, and minima—a decrease. Most of the hypocenters of seismic events recorded

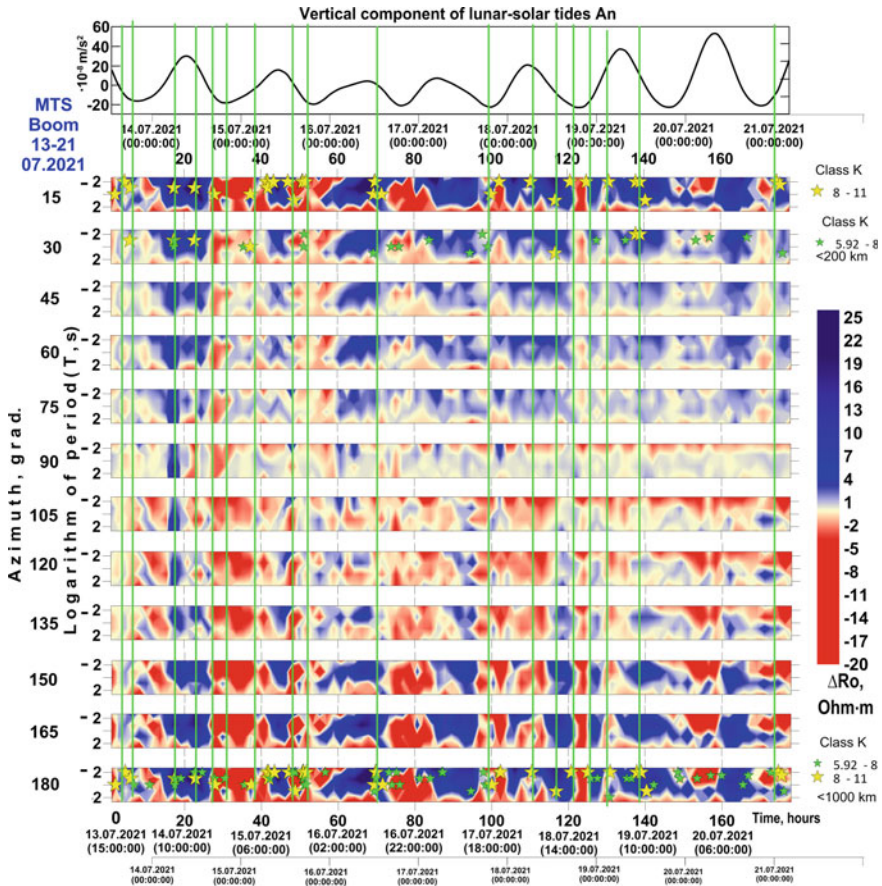


Fig. 6 The results of azimuthal MTS monitoring at the regime point No. 9 of profile Boom (13.07.2021–21.07.2021): above—the vertical component of lunar-solar tides A_n , below—pseudosections with a rotation over step of 15° (TFS $\Delta\rho_{app}$). Seismic catalogs: Kyrgyzstan (KNET + KRNET) and Kazakhstan (NNC)

by the KNET network (shown on a 30° pseudosection) during monitoring work at the Boom observation point are confined to a low-resistivity layer occurring at depths of 2–5 km. Earthquakes themselves occur either during a change in apparent resistivity in orthogonal directions, or are confined to gradient zones of resistivity change.

A shallow electromagnetic method, which is in demand in regions with high seismic activity when studying the active fault impact zones and the modern geodynamic processes associated with them, is electrical resistivity tomography [26, 27]. Electrical resistivity tomography (ERT) is based on the use of multi-electrode electrical spit connected to equipment capable of switching current and measuring electrodes to arbitrary outputs of the spit [28]. This technology increases the productivity and resolution of resistivity studies by an order of magnitude, especially if the

equipment has several measuring channels that allow one to determine the potential difference simultaneously from several receiving lines. Equipment “Skala-48” (LLC “Design Bureau of Electrometry”, Novosibirsk)—48-electrode electrical exploration equipment—designed to perform electrical exploration using the methods of resistivity and induced polarization in the modes of electrical profiling (EP), vertical electrical sounding (VES) and electrical resistivity tomography (ERT) [29]. The Skala-48 equipment set includes two electrical streamers with 24 contacts each, connectors (from the streamer to the electrode), electrodes, a battery, cables for an external battery, a USB cable, a flash drive, SIBER TOOLS and RiPPP programs. To verify the position of the fault structure in the upper part of the geoelectric section (Fig. 5), in 2021–2022, the Research Station of the Russian Academy of Sciences in Bishkek carried out work by direct current electrical resistivity tomography in a modification of the standard Schlumberger array. The step between the electrodes was 5 m, the total length of the spit was 240 m, which provided the necessary detail when constructing the near-surface geoelectric section. Preliminary processing of the results of field observations was carried out using the RiPPP program, which is included with the station. The program visualizes and allows you to edit the data obtained by the Skala-48 equipment in *.d2d (measured data file) and *.top (relief height file for each electrode) format. For two-dimensional modeling, we used the RES2DINVx64 program, which is based on the Gauss–Newton least-squares method [30]. It is fully automated, and the user does not need to work on compiling the starting model. On a modern personal computer, the inversion of a single pseudo-section is typically completed within a few seconds (up to several minutes). Based on the results of the inversion of the field ERT data performed in 2021–2022, the distribution of geoelectric characteristics along the Boom profile was obtained (Fig. 7).

The profile has a rather complex relief and the height difference along it is about 200 m. The distribution of electrical resistivity is mosaic and sharply differentiated. We paid special attention to the vicinity of point No. 9 of the MTS profile—the manifestation of a fault zone in the geoelectric section, its geometric dimensions, and the range of electrical resistivity variations (Fig. 8).

In our case, a significant decrease in resistivity values relative to the host medium is observed, which may indicate in favor of the presence of a fault structure. Taking

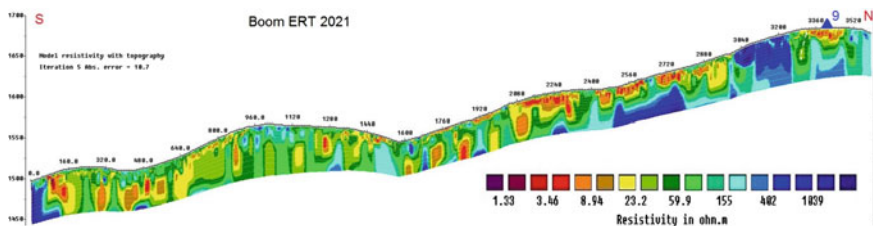


Fig. 7 Geoelectric cross-section ERT profile Boom by Skala-48 full 3.5 km profile

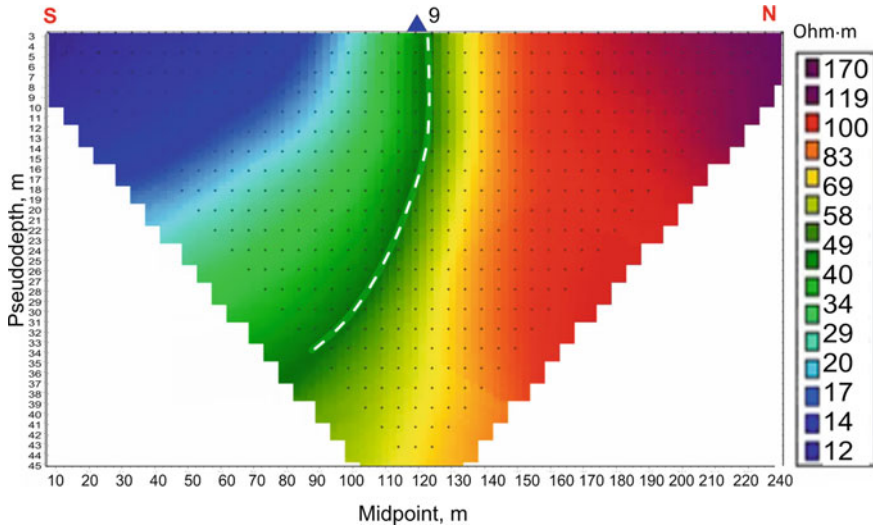


Fig. 8 Monitoring of dynamics of the impact fault zone near site point No. 9 profile Boom—geoelectric ERT cross-section by Skala-48

into account that the fault structure on the Boom profile, identified by a set of electromagnetic methods, is characterized by significant variations in electromagnetic parameters during monitoring studies, the fault can be attributed to active structures.

4 Conclusions

Thus, the monitoring observations carried out within the southern sides of the Chu basin and the zones of their junction with the Kyrgyz Range allow us to draw conclusions about the hidden segment of the major faults (Issyk-Ata and Shamsy-Tunduk) regarding changes in apparent resistivity.

- Within the Northern Tien Shan, this approach ensures the construction of reliable geoelectric models in a wide range of exploration depths. Detailed MTS in the dynamic impact fault zone allowed to determine the position of the upper edge, width, depth, strike and inclination of the fault zone.
- The work performed showed that the electromagnetic method is effective for studying the fault impact zone in seismically active regions.
- The results of field profile soundings by the shallow ERT were used at the stage of complex construction of 2D geoelectric models of the Issyk-Ata fault zone.
- An analysis of modern, ongoing in real time, geodynamic processes in the zones of active faults, identified from the data of electromagnetic observations, performed with increased spatial and temporal detail, is presented.

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