Modern problems and prospects for the development of magnetotelluric monitoring on the territory of the Bishkek geodynamic test site

E A Bataleva
Research Station of RAS in Bishkek, Bishkek, Kyrgyz Republic
E-mail: bataleva@gdirc.ru

Abstract. The high sensitivity of the electromagnetic parameters of the geological environment to the influence of geodynamic processes for the territory of the Bishkek geodynamic test site is shown. An assessment of the characteristics of the stress-strain state of the geological environment and the behavior of variations in electromagnetic parameters has been carried out in order to identify patterns in their relationship for seismically active regions of the Tien Shan. The promising objects for monitoring observations are identified and the results obtained are presented. The experimental results obtained indicate that the position of the regions of stable correlation (clusters) on the polar correlation diagrams is associated with the geoelectric structure of the observation point and corresponds to the orientation of the main tectonic elements in the vicinity of this point. A detailed geological and geophysical interpretation of geoelectric sections was carried out in order to separate modern active faults and weakened zones of the Earth's crust, for example, the Kochkor basin. The relationship between the manifestation of geoelectric inhomogeneities and the spatial distribution of the epicenters of seismic events is revealed; it is shown that a significant part of earthquake epicenters is confined to structural inhomogeneities of the Earth's crust; the depths of the geoelectric section, most sensitive to the influence of geodynamic processes, have been determined. The behavior of variations in the electrical conductivity of the earth's crust in a wide range of periods has been investigated according to the data of profile magnetotelluric soundings (MTS) at the Kentor geophysical monitoring minipolygon. Field experiments confirm the concept of the relationship between the stress-strain state of the medium and the change in apparent resistivity through the redistribution of saline solutions between fracture systems. The problems and trends in the development of magnetotelluric monitoring of modern geodynamic processes in the Northern Tien Shan are shown. To solve the tasks set, a methodology for conducting monitoring studies is proposed, which most fully takes into account the specific features of the deep structure and distribution of seismicity of the Bishkek geodynamic test site.

1. Introduction
The study of the modern geodynamic activity of the Earth's crust of inland orogens, which includes the territory of the Northern Tien Shan, is one of the topical directions in the field of earth sciences [1-5]. Observations of variations in geophysical fields are traditionally used in systems of integrated geophysical monitoring at geodynamic testing sites of seismically active regions [6, 7]. Carrying out
such work involves a quantitative assessment of the stress-strain state of the geological environment during the preparation of seismic events using data on electromagnetic, acoustic, tidal and other responses of the Earth's crust. Systematization of the precursors of catastrophic natural phenomena and the development of scientific and methodological foundations of monitoring studies are the main goal of the system of integrated monitoring of modern geodynamic processes.

2. Data and methods
The Research Station of the Russian Academy of Sciences is quite actively developing and mastering new methods of geophysical monitoring of the stress-strain state of the geological environment, focused on short-term forecasting of earthquakes. As part of these works, at several points of the Bishkek geodynamic test site (BGTS) (41.5°–43.5° N, 73°–77° E), continuous and regime measurements of the natural electromagnetic field are currently being carried out [6, 7]. In 2017, for example, a gradient installation was developed for recording the seismic field, and in 2021, monitoring studies of the upper part of the geoelectric section by the resistance method began. A number of time measurements of other types of geophysical observations are also carried out - sounding by the formation of the field, GPS observations, as well as seismic monitoring performed using the digital network KNET.

Monitoring magnetotelluric (MT) observations have been carried out on the territory of the BGTS since 2003, when the Canadian company Phoenix Geophysics, together with the Research Station of the Russian Academy of Sciences, installed two Phoenix MTU-5D stations at the stationary points Ak-Suu and Chon-Kurchak [6, 7]. Both stations are located on the territory of the BGTS, which, in turn, is part of the North Tien Shan seismic generating zone (Fig. 1); data recording is carried out around the clock in the period of 0.01-1000 s. In the process of recording continuous MT observations, at least once every 3 months, such as characteristics of the measuring system as the stability of the channel transmission coefficient and the shape of the amplitude-phase frequency response are monitored [6]. Experimental observations are carried out at strain-sensitive (regime) points of magnetotelluric monitoring (zones of dynamic influence of faults), such as ukok, for example, to study the relationship of variations in electromagnetic parameters, seismic events and lunisolar tidal effects.

Of greatest interest to us is the vertical component of the lunisolar tide. The calculation of lunisolar tidal variations of the gravitational field is carried out by the TIDE_3.exe program, which is freely available on the Internet. The theoretical calculation of the tidal deformation of the planet's surface is based on the fact that the tidal potential is represented by the sum of spherical waves expressed in terms of Legendre polynomials. Each wave has a constant period and amplitude, and the phase depends on the local latitude and current ephemeris of cosmic bodies. The decomposition used by H.G. Wenzel (1996) for the theoretical tide includes more than 1000 waves. Theoretical calculations of gravitational tidal effects are confirmed by experimental observations for the territory of BGTS in [8, 9]. To verify the calculated data, the Research Station of RAS performs observations using the Scintrex CG-5 Autograf gravimeter, which is installed in an adit with a constant temperature of +8° on the territory of the RS RAS (30 km from the Bishkek city) [8, 9]. Observations are carried out with an interval of 12 s, and then, during processing, they are averaged with an interval that is necessary for the tasks set and the required data sampling. The very high quality of the observed data should be noted (about 0.001 mGal).

In this case, the interference is seismic events, which are clearly recorded by a gravimeter, which is a Golitsin pendulum. The algorithm for calculating the tidal variation implemented in the Scintrex CG-5 gravimeters can be considered very accurate.

To analyze the results of monitoring MT-observations, the catalogs of the networks KNET (Research Station of the Russian Academy of Sciences), KRNET (Institute of Seismology of the National Academy of Sciences of the Kyrgyz Republic) are used. The main purpose of monitoring magnetotelluric studies is to identify geodynamically active (strain-sensitive) zones on the territory of the Bishkek geodynamic test site. Taking into account the high sensitivity of the electromagnetic parameters of the geological environment to the influence of geodynamic processes in seismically
active regions [6, 7], it can be expected that MT-monitoring will be effective in solving the problems listed below, which determine the main scientific and applied directions of further monitoring research. Another direction of our work is associated with a detailed study of the deep geological structure of the selected strain-sensitive objects, for example, tectonic faults, which are indicators of increased seismic activity.

Figure 1. A schematic map of the Central Tien Shan with the location of the points of the DMTS of the Research Station of the Russian Academy of Sciences in Bishkek: 1- stationary points of MT-monitoring; 2 - settlements; 3- fault structures; 5- sounding points of DMTS; 6- points of DMT sounding, for which the relationship of the anisotropy of electrical resistance with seismic events is considered.

3. Results and Discussion
Let us consider the main results obtained in solving the problems of geophysical monitoring:

1) Identification of the relationship between the nature of modern geodynamic activity and variations in geophysical fields, as well as geoelectric inhomogeneities of the Earth's crust and upper mantle. A striking example, reflecting the nature of the relationship between modern geodynamic activity and changes in apparent resistivity and other geophysical parameters, is the study of the response of the geological environment to the industrial Kambarata explosion [7]. The results are shown in Fig. 2.

2) Identification of active fault structures, including hidden faults, based on the study of the anomalous behavior of the electromagnetic field [7] and the determination of indicator signs of the allocation of geodynamically active zones [10]. An example of identifying active fault structures is shown in Fig. 3.

3) Detailed geological and geophysical interpretation of geoelectric sections in order to separate modern active faults and weakened zones of the Earth's crust, for example, caused by the cataclase of granites [7, 10]. Currently, the main objects for detailed magnetotelluric survey are the territory adjacent to the Chon-Kurchak station and the southern side of the Kochkor depression [11]. Figure 4 shows a geoelectric section through the southern flank of the Kochkor basin.

4) Analysis of seismological data recorded by the KNET network (Fig. 5), which makes it possible to estimate the following parameters: a) the thickness and depth of the seismically active layer, and its
location on the geoelectric section of the study area; b) periods of repetition of swarms (clusters) of seismic events; c) levels (quantitative characteristics) of seismic activity of fault structures [7].

Figure 2. Time series of variations in apparent resistance, presented in the form of pseudo-sections in the 0° and 90° directions (xy and yx) during the Kambarata experiment.

Figure 3. Panel on the left is a fragment of the geological map near the location of the regime point of MT-monitoring No. 906; the panel on the right is the distribution of the correlation coefficient (additional impedance Zxx and the vertical component of tidal forces An) in polar coordinates, where the T (T-period) is shown along the axis of the radii. The color and contour lines show the values of the correlation coefficient.

The location of MTS points is shown in the diagram in Fig. 1. The numbers from 1 to 10 in the figure indicate the numbers of the packs (description in the text). Circled numbers (1 to 6) indicate electrically conductive structures. 1- top (bottom) of the packs, 2- bottom of red-colored deposits of the Kyrgyz series, 3- faults, 4- fractured zones, 5- MTS points.

5) Development of integrated monitoring of seismically active areas using the monitoring geophysical data of the Kentor minipolygon (Fig. 6) for comparison and substantiated identification of modern deformations and movements of significant amplitude along the zones of active faults [10];

6) The attraction of materials from repeated geodetic observations, which make it possible to establish the patterns of movements of the Earth's surface, including the activity of faults, as well as the nature of movements along them. Using the method of re-leveling to find out the directions and estimate the speeds of modern horizontal movements on the territory of the BGTS.
Figure 4. Geological interpretation of the geoelectric model along the profile through the southern side of the Kochkor depression. Color gradation of electrical resistance on the scale on the right.

Figure 5. Layout of active faults and earthquake clusters: 1-points of electromagnetic monitoring; 2-epicenters of earthquakes, 2007; 3-fault structures; 4-borders of the Kyrgyz Republic. The circles indicate clusters of earthquakes: 1-Chumysh; 2-Shamsi; 3-Chon-Kurchak; 4-Kegety; 5-Ala-Archa; 6-Kemin; 7-Ukok; 8-Susamyr; 9-East-Suiek;
Figure 6. Correlation polar diagrams for the Kentor mini-polygon: a) - location of monitoring points and faults: 1 - Shamsi regional fault, 2 - local faults, 3 - MT-monitoring point, 4 - points of remote-ranging observations. Correlation diagrams for variations of apparent resistance (dRo) at FT-0 and: b) by the northern component of lunar-solar tidal effects (Av), c) by changes in the lengths of the base lines between points K5 and K2 according to the results of distance ranging observations.

7) Use of data on geothermal anomalies, the presence of which indicates zones of modern permeability or areas of heat and mass transfer.

8) Identification of the features of the development of mutually perpendicular directions of geodynamically active zones (fluid flows), the diagram is shown in Fig. 7. We believe that such zones serve as a key to understanding the mechanism of the relationship between the stress-strain state of the medium and the change in apparent resistance.

Figure 7. The scheme of fluid redistribution between systems of fractures in rock mass, causing an increase in electrical conductivity along the compression axis and a decrease in electrical conductivity in the orthogonal direction [13-14]

4. Conclusions
The main problem in studying the correlations of lunisolar tidal effects with modern geodynamic processes is seismic noise, which is generated both directly by tidal deformations of the Earth's crust and by processes occurring in the planet's atmosphere [15]. The endogenous useful signal caused by the preparation of seismic events is weak and it is very difficult to separate it from this noise.

An integrated approach to solving the problems of complex geophysical monitoring, which is a unique hardware and software complex for recording, collecting, storing and processing geophysical
data, makes it possible to create new methods for studying ongoing geodynamic processes (identifying and preventing dangerous geological processes), including seismic events.

As a result of the research, the relationship between the manifestation of geoelectric inhomogeneities and the spatial distribution of the epicenters of seismic events was revealed; it is shown that a significant part of earthquake epicenters is confined to structural inhomogeneities of the Earth's crust; the depths of the geoelectric section, which are most sensitive to the influence of geodynamic processes, have been determined.

The development of monitoring studies on the territory of the Bishkek geodynamic test site is determined, first of all, by the introduction of new specialized hardware and software systems, which will ensure reliable registration of signals from geophysical fields and an assessment of variations in the stress-strain state of the geological environment.

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