The role of electromagnetic sounding in the assessment of hydrothermal resources of the Northern Tien Shan

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Abstract. This work presents the results of the electromagnetic study of thermal water deposits, conducted in the territory of the Bishkek geodynamic test area (Northern Tien Shan). The heat flow in this territory is quite high, which testifies in favor of the development of geothermal energy in the region. The objects with high electrical conductivity isolated in the geological environment by various electrical prospecting methods are fractured basement rocks saturated with a heated fluid (in a different aggregate state) in the upper part of the Earth's crust, promising for the development of geothermal energy.

1. Introduction
Due to the decrease in fossil fuels supplies and the simultaneous increase in energy requirements, as well as to preserve the environment, renewable alternative energy sources are becoming increasingly involved in energy circulation. Despite the large number of sunny days per year, the Kyrgyz Republic is characterized by a sharply continental climate and, consequently, large temperature fluctuations. At the same time, the Tien Shan Mountains contain a tremendous energy resource in the rocks and hydrothermal sources heated by the deep heat flow, therefore, the use of the Earth’s deep heat is most acceptable. The water temperature at the deposits of mineral springs, including world-famous health resorts (Isyk-Ata, Alamedyn, Ak-Suu (Teploklyuchenka), Jalal-Abad, Altynt-Arashan, Boz-Uchuk, Juukuchak, Keregetash, Joopay, Chaek, Jergalan and others), reaches +50 to +90 °C, and at depths of 2000–3000 m, water with a temperature of +70 to +100 °C or more is discovered in wells [1]. With the improvement of existing technology for drilling wells, the extraction of this heat can become quite cost-effective. In this case, Kyrgyzstan will receive an almost inexhaustible energy resource for providing heat and electricity not only to high-mountain villages, but also to small cities.

Geothermal resources are ideal objects for electromagnetic methods, since they are clearly reflected in the deep distribution of geoelectric heterogeneities of the geological environment. The high concentration of dissolved salts in thermal springs is the first reason leading to a significant decrease in electrical resistance both in conductive fluids filling the pore-fissure space and in the rock matrix. The second reason for the decrease in volume resistivity is a rise in temperature. The most interesting and detailed review of the use of electromagnetic soundings for studying hydrothermal deposits was made in [2].

2. Materials and methods
Electrical exploration works in the junction zone of the Kyrgyz ridge and the Chuy Basin were carried out by various electrical exploration methods - vertical electric sounding (VES), frequency sounding
(FS) and magnetotelluric sounding (MTS). Fieldwork was carried out in a remote mountainous area (altitude 3000 ~ 1100 m) from the 2000s to the present.

The work considered in the article was carried out in three stages:

- vertical electric sounding according to the regional profile;

The VES method is the most widely used electrical exploration technology designed to solve a variety of problems associated with the study of the geological environment at shallow depths (hundreds of meters - the first kilometers). The VES method measures an artificial constant electric field, the results of which are used to construct models of the distribution of electrical resistivity in the Earth's crust.

- detailed work by the method of frequency sounding along the Tuyuk profile (Fig. 1),

The method of frequency sounding is one of the most commonly used induction methods of electrical exploration in the study of the regional structure of sedimentary cover and crystalline basement. Information on the distribution of medium resistance with depth is obtained by analyzing the frequency dependences of the components of the electromagnetic field created by an artificial source. The depth of the study in the FS method is associated with the phenomenon of the skin effect, which consists in the fact that the higher the frequency of the electromagnetic field, the more it damps with depth. Thus, at high frequencies, the fields are examined near the surface of the geological environment, at low – in the lower part of the section.

- detailed areal works using magnetotelluric sounding along the Tuyuk profile (Fig. 1).

In the method of magnetotelluric sounding, the components of the Earth's natural variable electromagnetic field are recorded [3]. Unlike other electromagnetic methods of induction sounding (for example, frequency sounding), it does not require the use of generator sets, which is especially important for in-depth studies. The results of the processing and interpretation of MT field data are geoelectric models of the geological environment, reflecting the distribution of apparent electrical resistance in the context or volume.

Rock electromagnetic parameters depend on the mineral composition, PT conditions, and fluid regime of the Earth's crust. For example, filling the pore-fissure space with fluids or the presence of zones of partial melting of rocks leads to a sharp decrease in resistance. Processes such as granite cataclase, hydrothermal activity of mineral springs also contribute to an increase in the electrical conductivity of the medium [4].

All of the above indicates good prospects for using electromagnetic sounding methods to study geothermal resources in such a tectonically active region as the Tien Shan. The use of a complex of electromagnetic methods in the study of hydrothermal deposits makes it possible to increase the accuracy of determining the electromagnetic characteristics of the medium at various spatial-scale levels. In particular, the FS technology expands the possibilities of magnetotelluric research by obtaining additional information about the properties of rocks and the possibility of working in conditions of a high level of industrial interference.

In this article, the author will show the results of complex electromagnetic soundings performed on the Tuyuk profile, and consider the prospects for the use of electromagnetic soundings in the regional forecast and operation of hydrothermal resources.
Figure 1. Scheme of points of electromagnetic observations in the territory of the Bishkek geodynamic test area "1-1" - "8-8" - numbers of profiles of the complex of electromagnetic soundings (VES, FS, MTS); 8'-8' - profile of magnetotelluric sounding "Tuyuk"

3. Results and Discussion
Based on the results of electrical exploration studies, geoelectric models of the study area were built (Fig. 2). Below, the geoelectric sections along the regional profile are shown (Fig. 2a), worked out at the first stage of electromagnetic research. Within the upper part of the section (at depths of up to 2 km), an anomalously low-resistivity horizon was identified, presumably associated with granitoid waterlogged formations. Detailed information was obtained on the morphology of the roof and sole of this horizon, as well as on the distribution of lateral heterogeneities of electrical conductivity within it.
Figure 2. Combined geoelectric sections for the Tuyuk profile: a) - section along the profile of electromagnetic sounding 8''- 8''; b) - a section along the profile of electromagnetic soundings 8-8; c) - section along the MTS 8'-8' profile. The numbers in the circles indicate geological bodies (blocks) with different conductivity.

The following blocks can be distinguished within the Tuyuk profile by electromagnetic methods of VES, FS, MTS (Fig. 2b):

1) High-resistance block, Kindik ridge (fissured granitoids); 2) low resistivity, confined to the zone of the East Kyrgyz Epicaledonian volcanogenic-terrigenous trough (Kindik mega-anticline) (fracture zone confined to the fault zone); 3) a high-resistance block located to the left of the watershed of the Kyrgyz ridge (fractured granitoids); 4) an abnormally low resistance block under the Kindik mega-anticline (either fissured granitoids filled with a heated fluid, or an upper crust partial melting center with a resistance of 1 - 10 Ohm • m). In the central part of the profile, the brightest of the anomalous regions of the low-resistance complex (blocks 5 and 6), associated with the accumulation of hot mineralized water -5, is low-localized, located under the watershed of the Kyrgyz Range (fractured granitoids filled with a heated fluid); 6) a layer of reduced resistance (fractured granitoids filled with a heated fluid). In particular, the presence of a relatively conductive subvertical channel connecting the upper crustal conductive region with the near-surface conductivity anomaly described above is noted.
7) a block of increased resistance, representing the slope of the Kyrgyz ridge (strongly fractured granitoids); 8) high resistance block (slightly altered granitoids); 9) overthrow of the Kyrgyz ridge or diving of the Chuy basin under the Kyrgyz ridge (strongly fissured granitoids); 10) a block of reduced resistance, confined to the southern side of the Baitik depression (zone of increased fracturing, confined to the fault zone). Between objects 9 and 10, the Shamsi-Tyunduk fault zone is located, which is confidently traced to depths of about 10 km. The increased electrical conductivity of rocks can be due to several factors, for example, the degree of crushing (fracturing) of the medium and the connectivity of the cracks among themselves. The deep part of the constructed model indicates the heterogeneity of the geoelectric structure of the Paleozoic base of the section, but, overall, is highly resistive [5].

The authors of the work [6] established a significant differentiation of the resistance of granitoids. “Unchanged granitoids (2000-3500 Ohm*m), altered granitoids (1000-2000 Ohm*m), fissured granitoids (500-1000 Ohm*m) and strongly fissured granitoids (100-500 Ohm*m) are distinguished. On geoelectric sections in granitoids, “bundles” of thin layers of low resistance are distinguished. They have increased fracture and are apparently filled with thermal water.”

It should be noted that mineral springs were found along the entire Kyrgyz ridge (the so-called “Tien Shan thermal line”), some of them in geoelectric sections appear as subvertical conducting zones (Issyk-Ata thermal water deposit, Goryachy Klyuch, etc.) or objects. Taking into account that in the area of the Issyk-Ata thermal water deposit (a neighboring gorge with respect to the Tuyuk profile), the temperature in the bottom of the wells at a depth of 100 m is ~ 80 °C, at the outlet - 53 °C), we can assume inflow of heated fluid along subvertical fractured zones (red arrow in Figure 2a) from the lower crust conducting horizon to the upper part of the geoelectric section. I also note that the projections of subvertical conducting zones on the earth’s surface are marked with mineral springs along the entire Kyrgyz ridge, where several wells have been drilled, which are characterized by the release of carbonic thermal (up to 80 °C) mineralized waters.

In the geoelectric model constructed according to the MTS data, two objects with anomalously low resistances are noteworthy - a subvertical low-resistance section (10 - 20 Ohm*m) in the southern part of the section, identified with the thermal carrier (recharge) zone of the thermal water deposit. High resistance granodiorite intrusion (400 - 1000 Ohm*m), which goes to considerable depths, is highlighted to the right of it. In the southern upper part of the models, sections constructed by various induction methods are somewhat different from each other. The low-resistance layer in the southern part of the geoelectric section of the MTS Tuyuk profile ends rather sharply, being framed by high-resistance rocks of the Kyrgyz ridge with a resistance of about 3000 Ohm*m. The layer of the Earth's crust, lying below the considered depths, has a significantly different structure. In the section of the Tuyuk profile in the depth interval from 5 km and deeper, an alternation of vertically oriented zones of high and low electrical conductivity is observed. Noteworthy is the low-resistivity zone in the southern part of the section, which, like the Shamsi-Tyunduk fault, is rather hollow plunging southward under the uplift of the Kyrgyz ridge, probably representing a large crustal zone of tectonic disruption, softening, and increased fluid and gas permeability of the medium with properties waveguide. The middle and northern parts are represented by a rather powerful high-resistance block, with a specific resistance varying from 500 to 5000 Ohm*m. The thickness of this block increases from south to north and is 5–10 km in the southern part of the section and 20–25 km in the northern. The resistance in the block is also unevenly distributed: from 400–1000 Ohm*m in the south to 2000–4000 Ohm*m in the north. The thickness and significant lateral extent of this high-resistance block allow us to suggest that it seems to correspond to buried blocks of an ancient crystalline base. It is necessary to note the influence of another factor on the conductivity of the medium — the degree of crushing (fracturing) of the medium and the connectivity of the cracks among themselves.

According to the drilling data from well No.920-923 [1], productive intervals were discovered at relatively small depths - from 700 to 1200 meters. At the same depths in geoelectric models a) and b), lenticular objects with an extremely low level of resistivity of units of Ohm*m are distinguished.
According to the complex of geological and geophysical features, these abnormal objects can be attributed to a kind of natural reservoir filled with superheated water.

At the stage of detailed surveys, only shallow geophysics is often used in the development of deposits of thermal mineral springs. However, many electrical conductivity anomalies correspond to areas of increased heat and mass transfer in the earth's crust and upper mantle [7, 8], which causes the formation of geothermal deposits in the upper part of the earth's crust. Therefore, data on the distribution of crustal conductivity must be taken into account when searching and exploring the thermal resources of the Tien Shan. The geological-geoelectrical model, constructed according to the complex of electromagnetic methods, will reveal abnormal low-resistance objects, latent tectonic disturbances and make a preliminary estimate of the depth of the anomalous zones.

4. Conclusion

Thus, the use of a complex of electromagnetic methods for the joint analysis of data obtained in geothermal areas can provide a more reliable determination of the parameters of a thermal field. Thermal water reservoirs are associated with deep permeable zones providing active fluid regime and increased heat and mass transfer, which are reflected on geoelectric models as zones of abnormal electrical conductivity. At the same time, some of the anomalies may indicate modern tectonic activation, which is not manifested on the surface in the form of a tectonic disturbance or anomaly in the heat flux.

The examples presented in the work illustrate the possible applications of electromagnetic methods for solving problems of mapping geothermal deposits in such complex regions as the Tien Shan. In the upper part of the section, according to the results of deep-seated electromagnetic soundings, a low-resistance horizon with a resistance of 3-40 Ohm*m is highlighted. Its thickness is significant and amounts to 500-1200 m. A thin horizon (150 - 250 m) with an abnormally low resistance level (1-6 Ohm*m) is distinguished in its thickness.

Modern methods for conducting field research and interpretation of electromagnetic data allow more reliable construction of geoelectric models and, therefore, more reliable determination of the parameters of geothermal deposits and indicate the location for future wells. Thus, the use of electromagnetic methods in the exploration, assessment and operation of thermal reservoirs of folded areas can significantly reduce the cost of deep heat sources and make thermal energy competitive compared to traditional ones [9, 4].

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