New options to study irreversible deformations in the Tien Shan lithosphere

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Abstract. The paper describes application of an approach according to which the endogenous-nature electromagnetic field (EM) is included in the impedance relationships in an additive way, which allows distinguishing the EM field recorded on ground surface by the positions of sources. The case-studies of the endogenous EM field identification in the magnetotelluric sounding records obtained in the Tien Shan region are presented. The characteristics of the identified endogenous EM field are compared with the lunar-solar tides parameters and anisotropic properties of electrical resistivity. The found interconnections point at new options to study irreversible lithospheric deformations in the Tien Shan using magnetotelluric sounding data.

1. Introduction
This study aims to improve the stress–strain analysis of a geological medium in the conditions of north–south-oriented compression. The study was greatly inspired by the Kambarata Experiment on Dec 22, 2009, including seismic, electromagnetic (EM) and GPS observations (Figure 1).
Figure 1. Schematic map of the Central Tien Shan, stationary monitoring points, regime monitoring points, deep magnetotelluric sounding points of the Research Station RAS in Bishkek and Kambarata Experiment site: 1—stationary monitoring points Ak-Suu and Chon-Kurchak, Kentor mini test polygon and regime monitoring point Ukok; 2—cities; 3—regional faults; 4—border of Kyrgyzstan; 5—Kambarata Explosion Experiment; 6—deep magnetotelluric sounding points.

2. Electromagnetic field of endogenous origin
The distance between the shot point and magnetotelluric Phoenix MTU-5D system was 5.7 km. The yield of the industrial explosion was 2.8 kt of TNT equivalent. The Kambarata Explosion appeared a unique seismic event due to its yield comparable with the seismic effect of underground nuclear blasts and tectonic earthquakes; it was recorded as an earthquake by 30 seismic stations across the globe. The seismic test data allowed detecting explosion-induced movements along the fault nearby the explosion site. Furthermore, a series of induced weak seismic events was recorded 16 km away from the explosion site 12 s after the explosion. The explosion and the induced events are clearly distinguishable in the time-frequency series (Figure 2).

Figure 2. Comparison of variations in anisotropy of electrical resistivity (Kambarata point) with variations of the energy characteristics of electromagnetic field of endogenous origin: (a) $S_q$-variations in magnetic field; (b) energy characteristics of EM field of endogenous origin; (c) vertical component of lunar-solar tides $A_v$; (d) apparent resistivity ($\rho_a$) along different azimuths. Vertical lines mark the moments of seismic events nearby the Kambarata Experiment site.
Bishkek Geodynamic Proving Ground is equipped with a system of magnetotelluric (MT) monitoring composed of [1] (see Figure 1):

—stationary monitoring points Ak-Suu and Chon-Kurchak for the continuous MT field recording over a period of 20 days as a rule, after which the data are reloaded to laptop from flash memory; the instrumentation undergoes maintenance service and resetting;

—two-dimensional survey network of Kentor mini test polygon for seasonal observations governed by research tasks (two sessions in spring and autumn);

—MT regime monitoring points in the most strain-sensitive and interference-resistivity zones, intended for various-modification MT or deep MT sounding in the range of the MT field recording interval from few hours to few days, which defines the depth and details of sounding. The monitoring uses MTU systems manufactured by Phoenix Geophysics, Canada: 5-channel measurement MTU-5 and MTU-5A systems designed for recording of electric \((E_x, E_y)\) and magnetic \((H_x, H_y, H_z)\) MT-field components. The results are interpreted using the azimuthal MT-monitoring procedure [2] and KNET and KRNET seismic network data (available at: http://www.gdirc.ru/uki/napravlenija-issledovanij/sejsmologicheskie-nabljudenija; https://seismo.kg/ru) (Figures 2–4). In the test area, KNET sensitivity is sufficient for recording events of Rautian energy classes \(K \geq 7\) (magnitude not less than 1.7) without interruption.

The MT monitoring experiments implemented since 2017 are novel for Bishkek Geodynamic Proving Ground. These experiments represent an attempt to identify electromagnetic field of endogenous origin in the in-situ the field MT sounding records. Theoretically, for MT sounding data processing with a view to the geodynamic analysis of a geological medium, it is required to know the lower impedance \(Z\) determinable in the geodynamic calm period from the relation [3]:

\[
E_0 = ZH_0 + Y, \tag{1}
\]

where \(E_0, H_0\) are the tangential components of the electric and magnetic fields on the surface of a stratified section; \(Y\) is the electromagnetic field of sources in the lower half-space.

Both \(Y\) and \(Z\) change with time, therefore:

\[
E_0 = (Z_0 + \Delta Z(t))H_0 + Y = Z_0H_0 + \Delta(Z(t)H_0 + Y), \tag{2}
\]

and this change is related with low-frequency ionospheric flows, while \(\Delta Z(t)H_0\)—with higher frequency ionospheric flows.

The inverse problem of passive electromagnetic monitoring of modern geodynamics is finding the EM field of sources in the lower half-space, \(Y\), using the known lower half-space impedance \(Z\):

\[
Y = E_0 - ZH_0. \tag{3}
\]

The latter equation is valid for any sources and any parameters of the lower half-space (nonobligatory stratified). Then, using \(Y\) calculated on ground surface, damaged rock zone is located and damage intensity is evaluated.

One of the tasks of the experiments is to compare the energy characteristic of the identified electromagnetic field of endogenous origin with the lunar-solar tides. The endogenous electromagnetic field of endogenous origin energy characteristic is understood as the integral of the frequency \(\int Y(\omega) d\omega\) relative to obtained from the Fourier transform of of the recorded signals in a time domain for 1 h.

The key factor to affect daily variations in the apparent resistivity \(\rho_s\) can be the lunar-solar tides [2]. The change in the physical properties of rocks in the impact zone of a fault, as well as the fluid flow regime rate variations condition the geoelectric effects, for example, electrokinetic phenomena in the upper crust. For this reason, the curves of tidal accelerations under the actions of the Moon and Sun were computed in TIDE.exe for each observation point.
Magnetotelluric monitoring of variations in the natural electric fields in the area of Bishkek Geodynamic Proving Ground shows seismolectric effects associated with the events (energy class $K > 6$) spaced from the observation point at 200 km and farther [2]. The first-kind seismolectric effect features a long relaxation period, up to a few days [2]. It has been concluded that this effect is reflective of irreversible geological transformations in fractured rocks [4]. The further considerations are based on the assumed shift of electric charges in rocks as a consequence of disclosure and closure of fractures.

Identification of the EM field of endogenous origin in the monitoring records of stationary monitoring points and deep magnetotelluric sounding points in the area of the northern Tien Shan (see Figure 1) is illustrated using the Ak-Suu and Ukok records. From the first hour-long record of EM field, we determined the magnetotelluric impedance later on use for processing of the deep magnetotelluric sounding data in each subsequent hour. Then, we calculated the modulus vector of horizontal components of EM field of endogenous origin, $|Y|$, to be further averaged over 5 points in hourly observations and over 100 points with respect to frequency. As a result of processing of 8 daily deep MT sounding records at Ak-Suu and Ukok, the endogenous EM field was identified and the energy distribution of this field within 3 days was obtained for all sounding frequencies (Figures 3 and 4). After that, the identified energy characteristic of EM field of endogenous origin was compared with the lunar-solar tidal parameters.

**Figure 3.** Comparison of variations in anisotropy of electrical resistivity (Ak-Suu point) with variations of the energy characteristics of electromagnetic field of endogenous origin: (a) energy characteristics of seismic field of endogenous origin; (b) energy characteristics of EM field of endogenous origin; (c) vertical lunar-solar tidal component $A_{ts}$; (d) apparent resistivity ($\rho_a$) in different azimuths. Vertical lines mark the moments of seismic events nearby the Kambarata point.
The time-frequency series (TFS) describe variation in the structure of the EM field components (logarithm of sounding period) at rotation of the coordinate system at a certain angle (in degrees) [1, 2]. Figures 3 and 4 show TFS with step of 30° for the change in the apparent resistivity (ρ_a), i.e. the difference between the averaged and current a certain azimuth, and the related energy characteristic of the seismic and EM field of endogenous origin. The interconnection between the geomedium parameters, the earthquake spacing and the earthquake magnitude is evident.

Figure 3 shows the TFS of variations in electrical conductivity and the corresponding changes in energy characteristics for the electrical component of the electromagnetic field and the seismic field of endogenous origin. The result of the comparison leads us to a clear relationship between of the geomedium parameters, depending on the distance and magnitude of the earthquake, as well as on the place of observation. The study was conducted on October 11-30, 2018 on the territory of the Bishkek Geodynamic Proving Ground at the Ak-Suu stationary monitoring point.

First, the moments of earthquakes gravitate to the regions of decrease in the energy characteristic of the electromagnetic field of endogenous origin. Second, negative deviations of the apparent resistivity (ρ_a), with clear boundaries with respect in time, are governed by the change in the stress—
strain state behavior of the medium. Third, the variations of the energy characteristics contain detectable periodic components associated with the lunar-solar tides.

For the purpose of complexing of research techniques, in August 2018, Bishkek Geodynamic Proving Ground was equipped with a three-component seismic gradient system of grouped one-component velocimeters GS-20DX manufactured by Geospace Technologies, USA. The system dimensions are 1×1×1 m. The installation description and operating principle can be found in [5]. According to the adapted procedure for calculation of the energy characteristic for the seismic field of endogenous origin $E$ [5], only impulses recorded in the subvertical direction relative to the observation point on the surface are selected in the continuous record. The values of $E$ are averaged over the time window of 1 h. The variations in the energy characteristics of the seismic (Figure 3a) and electromagnetic (Figure 3b) fields are reflective of the processes running deep in the crust. However, the response in the geophysical fields is different. The day and ‘fuzziness’ of anomalies are apparent. Probably, this is connected with multiplicity of geological–geophysical relations and variety of causes.

The crosscovariance analysis shows that the cause of change in the energy characteristic of the endogenous electromagnetic field is the lunar-solar tides. Thus, there exists a cause-and-effect relation between the lunar-solar tides and the energy characteristic of the EM field of endogenous origin.

3. Conclusions
For the first time, in terms of Bishkek Geodynamic Proving Ground, the electromagnetic field of endogenous origin is included in the impedance relationships in an additive way, which allows distinguishing the EM field recorded on ground surface by positions of sources.

On the basis of MT field experiments, examples of the separation of an EM field of endogenous origin (calculation of the energy characteristic) are shown.

The comparison of the energy characteristics of EM field of endogenous origin, lunar-solar tides, apparent resistivity variations and seismicity (earthquakes distribution) made it possible to establish that: (1) moments of earthquakes mostly tend to the to the areas of decrease of the energy characteristics of the EM field of endogenous origin; (2) seismic events occur nearby the gradient zones of variation in the apparent resistivity; (3) variations of the energy characteristics contain detectable periodic components associated with the lunar-solar tides.

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