Electromagnetic soundings of the earth crust and deformation processes in geosphere of the Bishkek geodynamic polygon (BGP)

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Abstract. A new processing of materials on variations of seismicity of the Bishkek geodynamic polygon (BGP) under effect of electromagnetic (EM) soundings of geological medium has been carried out. The revision of these materials is topical due to following issue. During the period of 1983-1989 the discharges of the capacitor battery (so-called cold runs) were used for supply for EM soundings in addition to the MHD generator launchs (hot, or fire runs). Moreover, alternative source of EM soundings by bipolar current pulses (namely, the ERGU-600-2 equip) was used in the times of 90s. But previous studies paid low attention to electric injection to Earth Crust besides MHD generator hot runs. Motivated by such state of the art we have analysed temporal dependence of Benioff strain on the territory of the BGP in the overall period of EM soundings (from 1983 up to now). The alterations of EM soundings sources and operational modes have been taken into account. But our approach has reveal no no noticeable change seismic regime (by the Benioff strain data) during the nineties in close surrounding of the injecting dipole.

1. Introduction
A dipole-injector installed in the central part of the BGP in 1983 has been used for electromagnetic soundings as a load. The electric dipole is oriented along the north-south line. The dipole is manufactured of an AVVG insulated cable with a total cross section of 1200 mm²; the wire is immersed in 1 m depth. The distance between the grounding electrodes is 4.2 km. The total weight of the cable is 40 tons. The earth connection of each pole is a metal grid manufactured from rods with a diameter of 20 mm. The cell size is 6 meters. The vertical electrodes of 2 meters lengths are welded to the grid with a spacing of 12 meters. The entire system is immersed in a depth of 2 meters. The earth connection is located in clay soils with specific electrical resistance 10 Ohm·m. The thickness of enclosing layer of soils is of 100 m for the place of one pole and 70 m for the second. The total electrical resistance of the dipole was initially equal to 0.4 Ω. It was being increased monotonously in time up to 0.5 Ω, and this last value remains presently [1]. These technical parameters are able to display the difference between groundings of currents during lightning discharges and that of EM soundings. No correlation of lightning discharges and seismicity were found at the BGP territory.

During the performance of deep EM soundings by the frequency sounding method, the Prognoz-1 and Pamir-2 MHD generators (hot runs) and a capacitor battery (cold runs) were used as the sources of electric current supply. The first launch of the MHD generator was made on 10.29.1983. The number of
hot runs was as follows: 6 runs in 1983, 20 ones in 1984, 30 ones in 1985, 23 ones in 1986, 11 - in 1987, 12 - in 1988 - 12, 11 in 1989, and 1 hot run in 1990. Total number of MHD generator launches was 114. The energy of a launch injected to the earth via the dipole was from 1 to 30 MJ, the average energy was about 20 MJ, and the total energy input was \( 1.6 \cdot 10^9 \) J. The pulse duration was from 2 to 12 seconds.

Beside MHD generators a capacitor battery of the initial excitation system of the MHDs was used for regular EM soundings. When using a capacitor battery of large capacitance, larger amplitudes of the current in the high-resistance loads can be achieved in comparison with the case of MHD generator launch, although the pulse duration and total energy transferred to the load are significantly less. The capacitance of a capacitor battery located at the EM soundings site was \( C_0 = 0.1 \) F. The mean value of energy input during the discharge (the cold run) was from 0.06 MJ per day to 8.32 MJ per day. The total energy contribution of all cold runs is \( 2.34 \cdot 10^{12} \) J.

The high cost of MHD generators launches ultimately limited the frequency of their hot runs. Therefore, the work began in 1983 on the development of low-cost electric pulses generators, that are able to generate sequences of current pulses with amplitude of several hundred amperes. Several specialized thyristor blocks called by electric pulse systems were developed for the BGP. The designation of these systems: EIS-100 (1983), EIS -300 (1984), EIS-630 (1986), ERGU-600-2 (1987) was to induce the current pulses of the value (respectively) 100, 300, 630 and 1400 A in the active load. Up to now 6 series of soundings of 90-120 bipolar pulses are produced daily with the use of that systems (mostly ERGU-600-2) for monitoring the apparent resistance of the BGP crust. The daily energy input is up to 1000 MJ. The total energy input of soundings supplied by the ERGU-600-2 unit is \( 4.51 \cdot 10^{12} \) J. According to the available data, the estimate of the energy input of soundings since the dipole depleting time is \( 6.84 \cdot 10^{12} \) J. The characteristics of the sounding modes are given in the table.

| Table. EM soundings on BGP territory using the injecting dipole |
|---------------------------------------------------------------|
| Electric current sources | Work period | Energy, J | Note |
|-------------------------|-------------|-----------|------|
|                         | Start       | End       | One exposure per day | Over the entire period of work |                         |
| MHD generator           | "Hot" runs | 29.10.83  | 30.03.90 | 2 \cdot 10^7 | 1.6 \cdot 10^9 | 1983 – 6; 1984 – 20; 1985 – 30; 1986 – 23; 1987 – 11; 1988 – 12; 1989 – 11; 1990 - 1 |
|                         | “Prognoz-1”, “Pamir-2” | 17.08.84  | 30.03.90 | (0.06-8.3) \cdot 10^6 | 2.34 \cdot 10^{12} | Launches are held from 1 time per day (250 per year) in 1985, up to 5 times per day (1250 per year) in 1989. |
| MHD generator           | "Cold" runs, Battery capacitor | 1983       | until now | 10^9 | 6.84 \cdot 10^{12} | EIS-100 (1983), EIS-300 (1984), EIS-630 (1986), ERGU-600-2 (1987) |
| Electric pulse sources  | Continuous soundings | 2000       | 2005     | (1.5–7) \cdot 10^8 | 2 \cdot 10^{10} | 53 sounding: 1 time in 35 days (36 sessions) 1 time in 53 days (17 sessions) |
| Electric pulse sources  | Experiment, unipolar pulses | 2000       | 2005     | (1.5–7) \cdot 10^8 | 2 \cdot 10^{10} | 53 sounding: 1 time in 35 days (36 sessions) 1 time in 53 days (17 sessions) |
The effect of the increment of microseismicity after electromagnetic soundings of the earth crust with geophysical MHD generators was discovered by N. Tarasov et al. at the end of the last century [2,3]. The first results of field experiments were obtained at the Garm (Tajikistan, Pamir) and Bishkek (Kyrgyzstan, Northern Tien Shan) test sites. The effect of local seismicity triggering (increment of events amount) was revealed to take place under the action of electric current pulses (EM soundings) supplied by geophysical MHD generators during hot runs [2,3]. Triggering effect manifested itself in a short-term increase in weak (low magnitude, minor energy) seismic events after the dates of soundings. Thereafter, a number of works was devoted to such triggering [4-8]. These works reviewed the data on the action of electric current pulses generated during launches of geophysical MHD generator as well as the changes in local seismicity. The important results were represented in [4], concerning a modification of the spatio-temporal structure of seismicity under the action of powerful electromagnetic pulses. The authors of [4] noted, in particular, that the distribution of the daily number of earthquakes N_t had varied in the temporal interval from 20 before the day zero (the dates of MHD generator launches) up to 20 days after this day. The number of daily seismic events increases with some delay after days of EM soundings.

Other numerous works (the review is in [9]) have witnessed that discharges of an MHD generator with pulse duration of 9 s and more, giving the highest energy input to the ground, were accompanied by an increase in the number of events in cumulative dependencies (Figure 1). The course of the plots in Figure 1 follows the plot of the cumulative distribution of the events daily number constructed in [4] for all MHD generators hot runs (or very close to it).

![Figure 1](image)

**Figure 1.** Cumulative distributions with separation by classes, constructed for experiments with MHD generator launches with a pulse duration of 9 s or more. The dotted line shows the average value found for the first 17 days before hot runs of the MHD generator and the standard deviation from it, according to [9].

The effect discovered previously was confirmed in subsequent works [10-13]. The works revealed the variations of seismicity during deep sounding of the earth's crust by monopolar current pulses produced by the ERGU-600-2 installation (named so because of the Russian abbreviation: Electric Prospecting Generator Unit). In first years after the millennium the monopolar pulses of duration of 5, 10 or 20 seconds each were supplied to the primary (injecting) dipole in addition to the usual soundings for everyday monitoring (see Table 1). The experiment with the injection of monopolar pulses was performed to verify following hypothesis. Since the main result on the stimulating effect of MHD generator discharges was obtained with coherent superposition of periods before and after MHD hot runs (soundings), a similar effect of seismicity increase should manifest itself with a larger number of soundings periods. The soundings with monopolar pulses of ERGU-600-2 involved greater total energy input and electric charge transfer than that with MHD generator runs. Analysis of data on variations of weak seismicity during periods of crust soundings by those monopolar pulses (“experimental” soundings) should confirm or disprove the “activation” hypothesis.

The information on dates of additional experimental soundings as well as usual ones (to control apparent resistivity) was used together with the catalog of seismic events based on KNET data. Digital seismological network KNET working in real time since 1998 allowed to record events of small energy classes, K, in the territory of the BGP. The method of coherent summation of earthquakes within the time windows of 35 days length was used to reveal the change in seismicity regime associated with experimental
soundings. For this purpose the dated of the experimental soundings (electric injections) were superimposed and put in the middle of the 35 days period.

Figure 2 shows the cumulative dependencies of the daily number of events with different energy classes. The plots show that the increase in the number of events of energy classes 7.5–8.5 begins after the day of electric pulses action, but earlier than the activation of events with energies corresponding to the range 8.5 < К < 9.5. The delay time of activation is different and varies from 2 to 8 days after the “day-zero” when electric impacts occur. However, the largest increase (exceeding 2 standard deviations) is observed for events of energy classes 8.5–9.5. This result has been obtained for the entire period of experimental soundings, 2000–2005.

![Figure 2](image1.png)

Figure 2. The cumulative dependences of the daily number of events before and after days with experimental discharges of the ERGU-600-2, according to [9]. The dashed line is the same as in Figure 1.

The sensitivity of geological medium to electric impacts may differ somewhat depending on the duration of the pulse, i.e. from the energy input to the crust. Soundings by pulses with the different duration are correspondent with the stages of the electric injection experiment of 2000-2005. Change in the state of the geological medium may occur while growth of the pulses duration and energy input to the crust [9]. One can see in details of the reaction of seismic events of different energy classes due to electric pulses action, with the aids of plots in Figure 3. Two plots have been built in this figure giving the cumulative number of earthquakes, N, that occurred during 10 days before (blue line) and 10 days after (red line) the electric impact versus energy class, K, of these events.

![Figure 3](image2.png)

Figure 3. Dependence of the number of seismic events in the 10-days intervals before and after the day of energy impact on the earthquake class, K, according to [9].

The part of the red plot corresponding to the range of K 6.5–8 is above blue plot, which denotes the activation in this range of energy classes. The comparison of the plots built in the figure 3 with the cumulative curves constructed for earthquakes of different energy classes (figure 2) leads to full compliance of the results. So, the response of events with energy classes 8.5–9.5 is contrasting with respect to prehistory. The increment of such events number exceeds twice the mean deviation from the average level determined by prehistory, but the number of events in this range of classes is still less than that of lower energies.

The response of the geological medium in the form of activation of the weakest events (energy class K = 6.5–7.5) occurs likely in the immediate vicinity of the injecting dipole. The next relaxation scenario could be as follows: the first is the stress redistribution in the similar form (the increment of events with K = 6.5–7.5) but in enlarged area, and then the activation of the events of classes 8.5-9.5 occurs with some delay (7-8 days), accompanied by partial stress unloading.
2. Results
To analyze the seismic processes occurring on the territory of the BGP, a catalog of the Institute of Seismology of the Kyrgyz Republic was used. This catalog included earthquakes on the territory of the BGP in the period 1980-2017. Previously, various catalogs were taken into considerations when revealing changes in seismic regime due to electromagnetic soundings. There were catalogs of the Institutes of Seismology of Kyrgyzstan and Kazakhstan for the period of MHD generators launches. It was the KNET catalog of the RS RAS that was used in the case of experimental EM soundings with ERGU-600-2 unit.

Accumulations of conditional Benioff strains. Trying to establish a connection between the energy of individual earthquakes, following each other in a certain area, and the strains resulting from these earthquakes, \( \varepsilon_i \) [14], Benioff derived that, \( \varepsilon_i \sim \sqrt{E_i} \). The conditional Benioff strain in large temporal intervals is determined as simply arithmetical sum of these separate “scalar” strains over seismic consequences:

\[
\varepsilon_{\Sigma} = \sum_{ii} \varepsilon_{ik} = \sum_{m} \sqrt{E_k} = \sum_{m} \sqrt{\sum_{i=1}^{n} E_i},
\]

where \( m \) is the number of earthquakes in a short period of time, and \( n \) is the number of such intervals in the total observation period. Using this expression, a plot of Benioff’s conditional strains (Figure 4) was built for earthquakes near the injecting dipole (the hypocenters are inside a circle with a radius of 100 km). Thereby, the studied circular zone does not overlap the territory of the strongest earthquake (Suusamyrskoe Eq, August 19, 1992, \( M = 7.3 \)) occurrence and its aftershocks.

The plot of the Benioff strain gives qualitative rather than quantitative results. Nevertheless some details in Figure 3 are of interest. One can treat such change in the strain rate as a modification of seismic energy release. So, during the impacts of both: hot and cold runs the MHD generators (highlighted by grey background in Figure 3) the trend of the Benioff strain plot becomes steeper. It is combined effect of the hot and cold runs that lead to such increment of the strain rate. Similarly, the mean angular coefficient of the strain curve growths during the final stage of experimental soundings (pointed out also in the same figure). The increase in the rate strain is associated with energy released by moderate earthquakes. This means the possible enhancement of stress relaxation in the area near the supplying dipole.

The data on the focal mechanisms of the sources of 1287 earthquakes that occurred in the considering territory from 1994-2015 were used for the computation of seismotectonic stress (STD). The main part of the catalog consists of weak events (\( M = 1.5–2.0 \)), occurring from 1999 to 2015. The most oh hypocenters of these events are immersed at depths of 5-15 km. Half of the solutions for focal mechanism presented in the catalog were obtained using the maximum number of possible (in KNET network conditions) of first arrivals signs (9–10).

Figure 4. The plots of energy input during EM soundings and Benioff conditional strain in 1980–2017. The energy input plot shows the energy of soundings by day, before 1996 - the average passport values, and after 1996 - daily soundings for each “action” in accordance with the table.
Seismotectonic strain rate tensor $<\theta_{ij}>$ [15] is the result of summation of the seismic moment tensors normalized to time, volume and shear modulus:

$$<\theta_{ij}> = \frac{1}{\mu V T} \sum M_0^{(\alpha)} m_{ij}^{(\alpha)},$$

where $\mu$ is the shear modulus; $V$ – elementary volume; $T$ – period of study; $M_0^{(\alpha)}$ – seismic moment of the earthquake with the number ($\alpha$), ($\alpha = 1,2,\ldots,N$); $m_{ij}$ – tensor of focal mechanism.

The dominant direction of the seismotectonic deformation results from average processing the initial data on focal mechanisms. In the processing of this averaging, the territory of the region was subdivided into elementary structural zones with a definite radius. The centers of these circular zones are located at the nodes (focal points) of a specially selected grid. The computation of STD has been performed by summing up the matrices of individual focal mechanisms within each cell. A grid with $0.1^\circ$ step (~10 km) is chosen for nodal points, and the radius of the elementary zones put equal to $r = 0.2^\circ$ (~20 km) in this work. Such selections ensure that the local STD features are proper throughout the studied area. The lower limit of the depth of the investigated layer is 30 km (the depths of earthquakes hypocenters in the Northern Tien Shan do not exceed 30 km, according to [16]).

The strain and the distribution of the surface deformation. The strain intensity is calculated by summing up the scalar seismic moments within each cell, see equation (1), [17]. The strain field of the area change is defined as the sum of the horizontal components of the strain rate tensor multiplied by the strain intensity in the cell at hand. This field is presented in Figure 5. The same map contains events from the catalog of dynamic parameters of the sources, with 183 earthquakes included [18]. The symbols of mapped events are differently colorized against the value of earthquakes stress drop $\Delta\sigma$, of the earthquakes: $\Delta\sigma > 10$ MPa - red (20 events); $1<\Delta\sigma <10$ MPa green (113 events) and $\Delta\sigma<1$ MPa - blue (50 events).

**Figure 5.** The areal distribution of the surface deformation changes, and the location of the studied earthquakes. The unit of deformation is $10^{-9}$ per year. The color of the event depends on the level of $\Delta\sigma$ (see text). Triangles denote network stations KNET. Rectangles: yellow – the position of Bishkek, crimson – that of the RS RAS, black – receiving stations of EM monitoring.
Figure 5 legend shows that, almost entire territory is characterized by shortening, with the exception of individual fragments in the western and eastern parts. The shunk area is characterized by maximal shortening, “red” events do not fall into this area, and the number “green” events is small. In general, the “red” events are infrequent and distributed throughout the territory, while the “green” ones (more than 60% of total) are compactly located in two areas: on the northern slopes of the Kyrgyz ridge and the Karamoynok and Sandyk ridges. The “blue” events are also rare, and they are evenly spaced in the shortening and shear zones except the eastern part. The “red” events absence in the zone of maximum shortening could be explained by following circumstance. The pink square in Figure 5 indicates both: the position of the Research Station of the Russian Academy of Sciences, and that of the generator installation ERGU-600-2. The publications [9-12] on trigger effects related to the use of ERGU-600-2 unit observed that the higher is the level of weak seismicity in the surrounding of the dipole, the lower is the number of events of moderate magnitudes. The stress unloading is more probably to occur due to weaker seismicity in the zone of maximum shortening. Thus, there are no conditions for stress concentration in this zone, at least in the range from the surface to the depth of 15 km.

Lode – Nadai coefficient. The Lode – Nadai coefficient $\mu_\sigma$ is used to specify the main characteristics of the strained state of the crust. This coefficient does not depend on the coordinate representation of the tensor and can be regarded as the invariant. The method of Lode – Nadai coefficient computation was described in details in [19-20]. Figure 6 shows the distribution of the Lode – Nadai coefficient, and the location of the same 183 events as in the figure 5, according to [18].

Figure 6. The distributions of the Lode – Nadai coefficient ($\mu_\sigma$) and the epicenters of events with small and large $\Delta \sigma$. See the legend on Figure 5. The saturation of the color of the square corresponds to the value of $\mu_\sigma$ at the nodal point according to the legend.

A large part of the studied area (central and partly eastern zones) is characterized by the straining mode of simple compression ($\mu_\sigma > 0.2$). A minor part of the earth’s crust (western part only) is under simple shear conditions ($-0.2 < \mu_\sigma < 0.2$), except a small subarea of extension, $\mu_\sigma < 0.2$. The area colorized from white to pink on the map in Figure 6 (according to the figure legend) is characterized by maximal horizontal compression. One zone with maximal value of the compression ($\mu_\sigma > 0.6$) is located in the central part of the foothills of the Kyrgyz range and the second zone is beyond the Kyrgyz range on the Karamoynok ridge and Sandyk mount. The “green” and “blue” events are grouped in the first zone, but the “red” and “green” ones are concentrated in the second zone. A compression area with a shear component ($-0.2 < \mu_\sigma < 0.6$) is located on the right side from the first zone. The events with $\Delta \sigma > 1$ MPa gathered themselves in this area. The absence of
events with $\Delta\sigma > 10$ MPa in the central part of the Kyrgyz ridge (the closest zone to the place of the injecting dipole at the RS RAS, see Figure 6) can also be explained by the effect of EM soundings with the ERGU-600-2 unit. The effect involved the increase of weak events amount, due to which the stress relaxation seems to occur.

3. Conclusion
Prolonged electromagnetic soundings of the earth crust at the Bishkek geodynamic polygon (Northern Tien Shan) were accompanied by partial stress relaxation, the manifestation of which was the increase in the number of weak earthquakes. Two episodes of considerable growth of the energy input to the crust during EM soundings appeared to correlate with the growth of the Benioff strain rate on the territory around the injecting dipole. The first was the period of the MHD generators launches with the electric current pulses of duration of 9 s or more (growth of the energy input resulted from sounding with such lengthy pulses, 1987-1988). The second episode was in the temporal interval of experimental EM soundings with the use of ERGU-600-2 s in 2003-2005. The transition from EM soundings with monopolar pulses (hot and cold runs of the MHD generators) to bipolar ones supplied by electropulse systems in the end of 80 th decade gave no noticeable effect in the Benioff strain accumulation.

The partial unloading of the stress on the territory around injecting dipole has occurred due to low energy seismic events. Such events make to contribute to the stress unloading despite the fact that this area is characterized by enhanced values of Lode-Nadai coefficient and changes in the surface deformation.

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