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The Effect of High Energy Electromagnetic Pulses on Seismicity in Central Asia and Kazakhstan

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The effect of high-energy electromagnetic pulses emitted by a magnetohydrodynamic (MHD) generator on the seismicity of former Soviet Central Asia and Kazakhstan is examined. The seismicity was found to be appreciably higher in the area of study after the MHD-generator start-ups than before them. A sharp increase in the local seismicity rate began 2–4 days after the start-ups and continued during a few days afterward. It is shown that electromagnetic pulses initiate the release of the energy, stored in the earth during tectonic processes, in the form of comparatively small earthquakes.

INTRODUCTION

Recently N. T. Tarasov [8] studied the effect of high-energy electromagnetic pulses emitted by an MHD generator, used as a source for deep electrical sounding of the crust, on the seismicity of a highly seismic area in former Soviet Central Asia, Garm District in Tajikistan. He found that a starting of the MHD generator in this area was followed after 6–7 days by appreciably more frequent local earthquakes of 8–13 energy class. The total seismic energy release initiated by the MHD generator starting was 1.1×10^{12} J on the average, which is five orders of magnitude greater than the energy transmitted by the MHD generator to the radiating dipole. This suggests that electromagnetic pulses initiate the release of the energy, previously stored in the earth during tectonic processes, in the form of low-magnitude seismic events.

Since the results derived by N. T. Tarasov [8] provide evidence of new, still little known properties of the crust and may possibly open new prospects for the development of means for earthquake and rockburst prevention or weakening, it is very important to test whether the effect in question manifests itself under different geological and geophysical conditions.

This study is concerned with the effect of sounding pulses (SP) emitted by an MHD generator operated at the Bishkek Site, Institute of High Temperatures, Russian Academy of Sciences, on seismicity in Kirghizia and southern Kazakhstan.

METHODS OF STUDY

The Bishkek Site is situated in the junction area of the North Tien Shan and Chuya Basin structures. Its southern part consists of Paleozoic crystalline rocks and the northern, of Mesozoic/Cenozoic sedimentary deposits. The Tien Shan is a highly seismic region of the Earth. The North Tien Shan earthquake-generating zone, where the Bishkek Site is situated, contains deep crustal faults. Three earthquakes with magnitudes greater than 8.0 occurred there during the past 100 years. One conspicuous feature of the Site is that, even though large earthquakes occur there, its seismicity rate per unit area per unit time is rather low [3].

Deep electrical sounding of the crust was carried out at the Bishkek Site in 1983 to 1989. The source of energy was an MHD generator, and the load was an electric dipole of 0.4 Ω resistivity whose electrodes were 4.5 km apart. When the generator was started, the load current was 0.28–2.8 kA, the sounding pulses had durations of 1.7 to 12.1 s, the energy being mostly in the range 1.2–23.1 MJ. The dipole was installed within those structural features in the North Tien Shan which were adjacent to the boundary of sedimentary deposits in the Chuya Basin. A total of 128 start-ups were carried out during the time of the MHD operation. A detailed description of the MHD installation and of the sounding procedure can be found in [2], [10].

The observation area was confined within the coordinates 41.0° to 45.4°N and 74.0° to 81.4°E. Our analysis of its seismicity was based on an earthquake catalog for the North Tien Shan and adjacent areas [5], [6] containing earthquake data for the period of 1975 to 1987. The catalog was converted to an electronic form and stored as a file suitable for digital processing. It contained data on 7622 earthquakes with energy classes of 4 to 15. Of these, 12 events had $K > 13$, and the largest two had $K = 15$ and 15.3 (the last occurred during the electrical sounding experiment reported here). The recurrence curve based on all events is linear in the class range 8 to 15.

Figure 1 presents a map of all earthquakes the catalog contains. The epicenter density is seen to vary widely over the area. There are several zones of high seismicity rate in the middle and south, while the density in the northwest is significantly lower. This pattern of earthquake distribution generally persists in time.

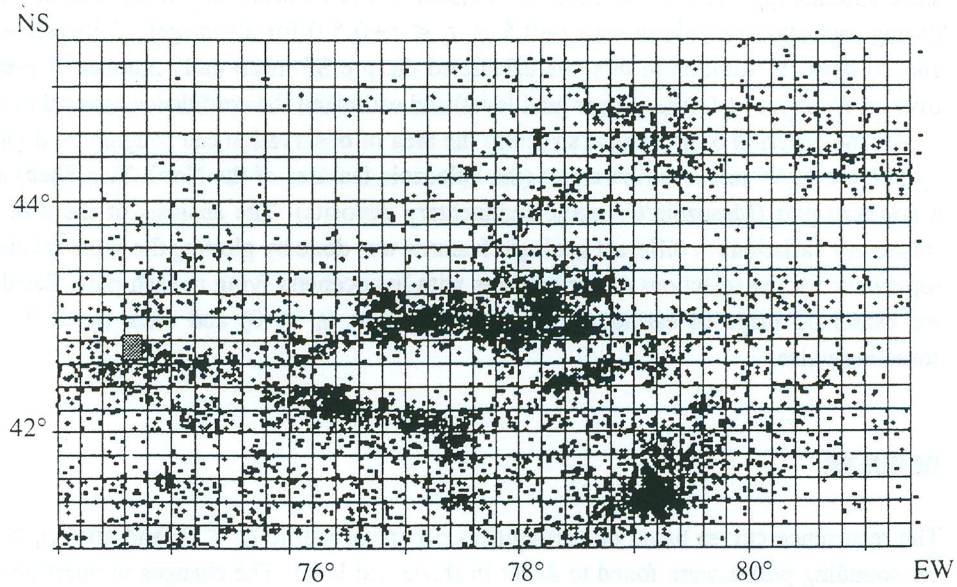

Figure 1 A map of earthquakes for the North Tien Shan and adjacent areas. The square is the site of the MHD generator installed at the Bishkek Site.

Eighty five start-ups had been made during the catalog period. The associated seismicity changes were identified upon the background of the natural variation by the coherent summation of seismic events in time windows of ± 20 days about the time of each start-up. (The events occurring during 20 days before the start-ups were used to estimate the natural seismicity rate immediately before the transmission of sounding pulses). We superposed all 85 windows in time, i.e., a selection of earthquakes was made for each MHD-generator start-up in the interval $[t_j-20, t_j+20]$, where t_j is the absolute time (in days) of the jth sounding pulse (SP) (j = 1, 2, 3,..., 85); their absolute times T_i were replaced with the times $t_i = T_i-t_j$ measured from the time of the starting; after this all selections were combined into a general catalog containing more than 3000 local earthquakes of energy classes 5 to 13. The events with times $t_i < 0$ occurred during 20 days before an SP and those with $t_i > 0$, during the same interval after it.

The resulting subcatalog was used to assess how the sounding pulses affect the shape and level of recurrence curves. This was done by calculating n_k/m_k (the ratio of the number of earthquakes occurring after and before SP) as a function of the relevant energy class K. The values of n_k and m_k were found for K = 5, 6, 7,..., 13 by counting the numbers of events with $t_i > 0$ and $t_i < 0$, respectively, and classes between K$-$0.5 and K+0.5.

The post-SP seismicity change was also examined over time. To do this, we used the same subcatalog to find N_t, which is the number of events occurring in the area of study during each day, i.e., those with $t-0.5 \leq t_i < t+0.5$ 0 for all integer t between -20 and 20 days. In addition to this, we calculated the pre-SP mean daily number of events over all N_t with $t < 0$ (the background level) and estimated the confidence interval of 3σ.

By the criterion of geological structure the area of observation can roughly be divided by latitude 42.9° into a southern part (the Paleozoic features of the North Tien Shan) and a northern part (Mesozoic/Cenozoic sedimentary deposits). The analysis of the post-SP seismicity variations in different geologic features was done by plotting the same relations separately for the selections of earthquakes with hypocenters lying in each part. Besides, we examined maps of earthquakes occurring before ($t_i < 0$) and after ($t_i > 0$) the sounding pulse.

RESULTS

The recurrence curves based on earthquakes occurring before ($t_i < 0$) and after ($t_i > 0$) the sounding pulses were found to differ in shape and level. The changes in question are clearly seen in the plot of n_k/m_k (the ratio of the number of events before and after the start-ups) against earthquake energy class K shown in Fig. 2, *a*. Except for the events with K = 6 ($n_k/m_k = 1$), this ratio varies from 1.12 to 3, demonstrating some post-SP seismicity increase.

Figure 2, *b* shows a similar relation for the northern part of the area mostly composed of Mesozoic/Cenozoic sedimentary rocks. The values of n_k/m_k are fluctuating about unity in this plot. This behavior demonstrates that some rearrangement of earthquakes over energy occurred in the north of the area, but the overall seismicity rate remained nearly the same in this part of the area. On the other hand, there was an appreciable growth in n_k/m_k for the southern part of the area (Fig. 2, *c*) composed of Paleozoic crystalline rocks, the ratio varying from 1.4 to 6, except for the K = 6 events. It follows that the electromagnetic pulses mainly caused the seismicity growth in the southern part of the study area.

An analysis of the post-SP seismicity variations at different depths showed that the seismicity in the upper crust within 5-km depth was most strongly affected. Figures 2, *d* through 2, *f* show similar relations based on the selection of events occurring in that layer. It appears that n_k/m_k mostly varies between 1.3 and 2 for the area as a whole (Fig. 2, *d*), fluctuates about unity in the north, even though with a smaller amplitude, and varies between 1.4 and 3 for almost all energy classes in the south. This demonstrates that the seismicity increase for the area was controlled by that in the upper 5-km layer in the south, which belongs to the North Tien Shan, although some rearrangement of seismicity over energy was observed throughout the area of study.

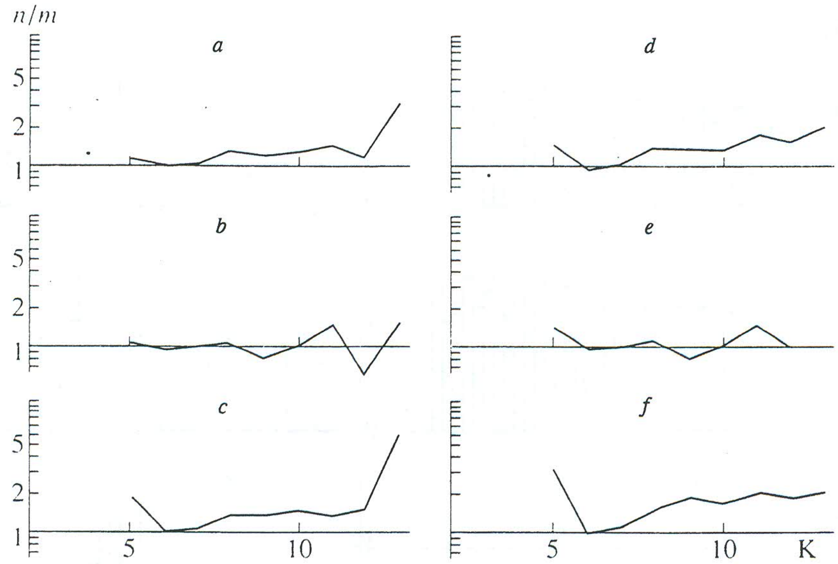

Figure 2 The ratio n_k/n_m of the numbers of earthquakes occurring after and before the MHD-generator start-ups as a function of earthquake energy class K for the entire area of study (*a*), its northern (*b*) and southern (North Tien Shan) part (*c*), and for the upper 5-km layer: for the entire area (*d*), northern (*e*) and southern (*f*) part. The values of n_k/n_m are plotted on a log scale.

We examined the variation of post-SP seismicity over time. Figure 3, *a* presents the pre- and post-SP distribution of daily rates of earthquakes N_t for the entire area. The values of N_t are seen to be appreciably higher a few days after the start-up than before it. The maximum rate occurred on the fourth day after SP with an amplitude nearly 6σ above the background. When the north alone is considered, no significant SP-related changes in N_t can be detected (Fig. 3, *b*), whereas a well-pronounced maximum can be seen in the south (Fig. 3, *c*) occurring on the fourth day after SP, nearly 9σ above the mean background, to be followed by a gradual falloff in N_t during a few days.

The initiating effect of sounding pulses was most active in the upper 5-km layer. Figures 3, *d* to 3, *f* show the distribution of earthquakes occurring within the layer in the entire area, in the north, and the south, respectively. A post-SP increase in N_t is clearly seen, even for the area as a whole (Fig. 3, *d*), even though the northern seismicity which shows no increase (Fig. 3, *e*) contributes to enhance the "noise". A still clearer pattern is observed for the south. It is apparent from Fig. 3, *f* that the post-SP values of N_t remained at the background level for two days more. This was followed by a sharp seismicity increase seen as a well-pronounced two-day maximum and a subsequent gradual falloff to the background level during three days. The maximum is more than 10σ above the pre-SP mean daily rate (i.e., above the background level).

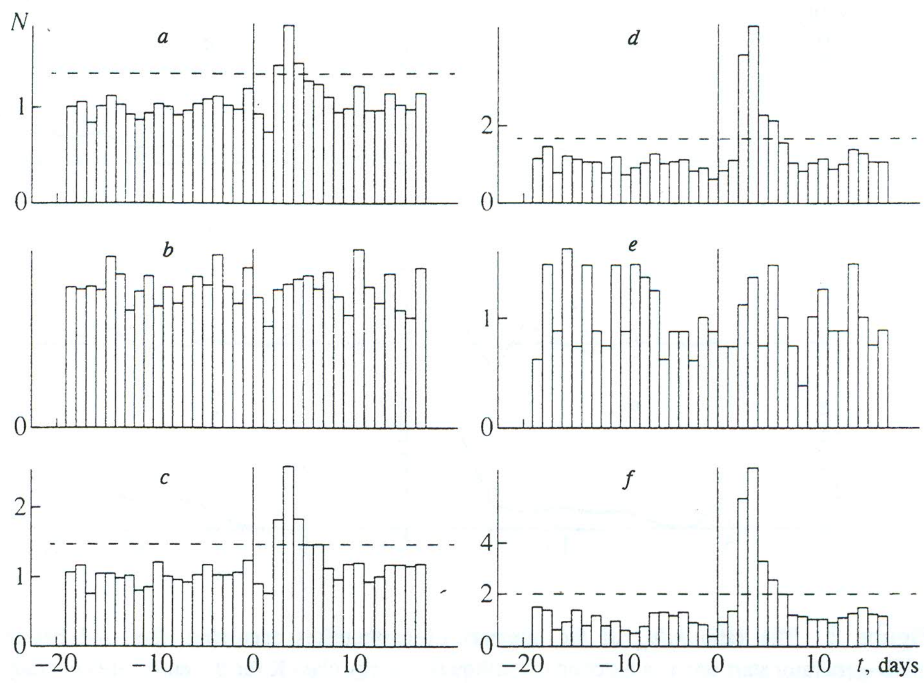

Figure 3 Distribution of earthquakes in the area before ($t < 0$) and after ($t > 0$) MHD-generator start-ups plotted against time: for the entire area (*a*), its northern (*b*) and southern (North Tien Shan) part (*c*), and of $K \geq 8$ events occurring in the upper 5-km layer: for the entire area (*d*), northern (*e*) and southern (*f*) part. The vertical axis shows the daily rate of events divided by the mean pre-SP rate; the horizontal axis shows the time measured from the start-up date. The dashed line indicates a confidence interval of 3σ.

A careful examination of the seismicity behavior revealed that a significant contribution into the distributions presented above was due to the January 24, 1987, $K = 15.3$ earthquake and its aftershocks. Proceeding strictly according to the method used, that event should be classed as one initiated by sounding pulses. It cannot however be ruled out that this coincidence in time of the event and the initiating start-up was fortuitous, so it was necessary to verify how the initiating effect of sounding pulses would work after that earthquake had been excluded from the consideration.

With this end in view, we restricted the catalog by the date of January 23, 1987, just before that earthquake, and carried out all calculations again. The number of start-ups under analysis was reduced to 75, and the number of seismic events, to 5962. Nevertheless, in this case too, an appreciable post-SP seismicity increase was found to confirm our previous conclusions. Figure 4 presents the distribution of pre- and post-SP seismicity rate over the time of the truncated catalog. A noticeable seismicity increase was now observed on the second day after the start-ups. The amplitude of the associated maximum in N_t was 4σ above the background level. However, the increase was less pronounced, probably because the most significant seismic event had been artificially removed from the natural flow of earthquakes. The maximum seismicity rate occurred on the second day now, while earlier it had been observed four days after the sounding pulses.

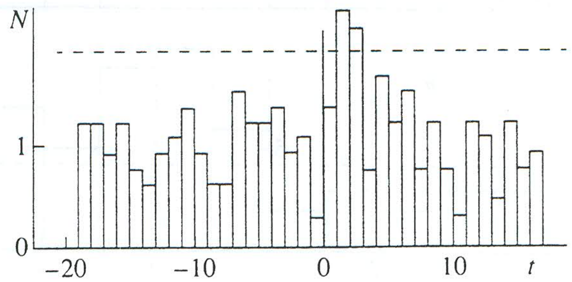

Figure 4 Distribution of earthquakes occurring in the upper layer of the southern part of the study area versus time based on the catalog truncated at the date just before the January 24, 1987, K = 15.3 earthquake. The notation is as in Fig. 3.

In their analysis of seismicity variations in the Garm area during the seismic effects of Semipalatinsk nuclear tests, N. T. Tarasov and N. V. Tarasova [9] showed that the delay of seismicity increase after the blasts had been different for different geologic features. Assuming the same phenomenon to take place after the sounding pulses, it can be postulated that the rock masses in the epicentral area of the January 24, 1987, earthquake had a typical delay of about 4 days. When that area had been excluded from the earthquake catalog, the delay of post-SP seismicity increase began to be controlled by the time characteristics of some other geologic features of the area whose delays were shorter.

The pattern of daily seismicity rate over time might become less pronounced, when the time windows centered on the starting times were spaced at short (compared with the window length) intervals. We hoped to reveal the time variation of N_t more clearly, when windows of ± 5 days were used instead of 20 days and when all SPs spaced at less than 10 days were excluded from the consideration.

Figure 5, *a* presents the distribution of the daily seismicity rate based on the unabridged catalog. A well-pronounced maximum can be seen lasting three days with a delay of 3–4 days relative to the sounding pulses. Figure 5, *b* shows a similar distribution based on the shorter catalog. The increase here is lower, but longer. It can be concluded that this pattern resulted from a superposition of several seismicity increases that had occurred after the sounding pulses in different geologic features having different delays.

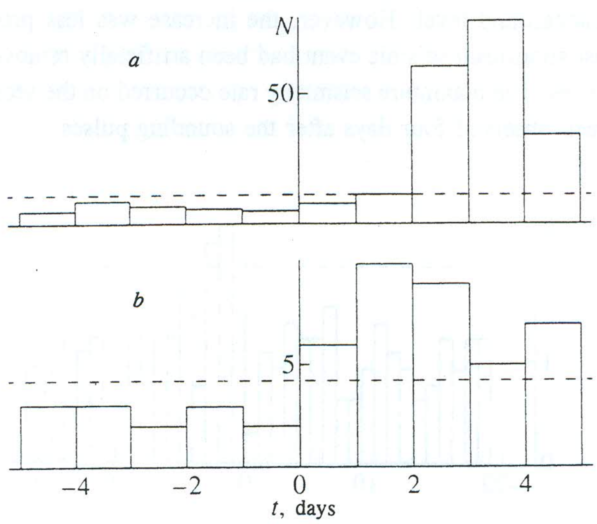

Figure 5 Distribution of K ≥ 8 earthquakes occurring in the upper 5-km layer of the southern part of the study area before ($t < 0$) and after ($t > 0$) start-ups over time: *a* – based on the entire catalog from 1983 to 1987; *b* – based on the catalog truncated at the date of the January 24, 1987, K = 15.3 earthquake. All MHD-generator start-ups spaced at intervals of less than 10 days were excluded from consideration. The notation is as in Fig. 3.

Sounding pulses also caused a spatial rearrangement of earthquakes. Figure 6 presents the maps of earthquakes that had occurred within the Bishkek Site area during 8 days before and after the sounding pulses. These local earthquakes are seen to be aligned in two chains. One chain trends east-west, and the other extends from northeast to southwest, probably because these earthquakes had been associated with the deep-seated North Tien Shan and Kara Koi faults. It is only a few post-SP earthquakes that can be classified as associated with these faults. Most of the epicenters are dispersed over the area in a kind of a ring surrounding the radiating dipole of the MHD installation.

Table 1 gives the estimates of the total seismic energy released during 20 days before all 85 MHD-generator start-ups (E_b), the total energy released during the same period after the start-ups (E_a), the post-SP increase in total seismic energy release ($E_a - E_b$), and the energy increase normalized to the number of the start-ups ($(E_a - E_b)/85$). These estimates are based on all earthquakes of the area, on the events occurring in the north, and on those in the south. Also given in the table are estimates for all events regardless of their focal depths and for the event from the upper 5-km layer.

An analysis of the above values shows that the total earthquake energy released in the area during 20 days after all 85 start-ups was 2.03×10^{15} J greater than the energy released for a period of the same length before them, the bulk of the release being due

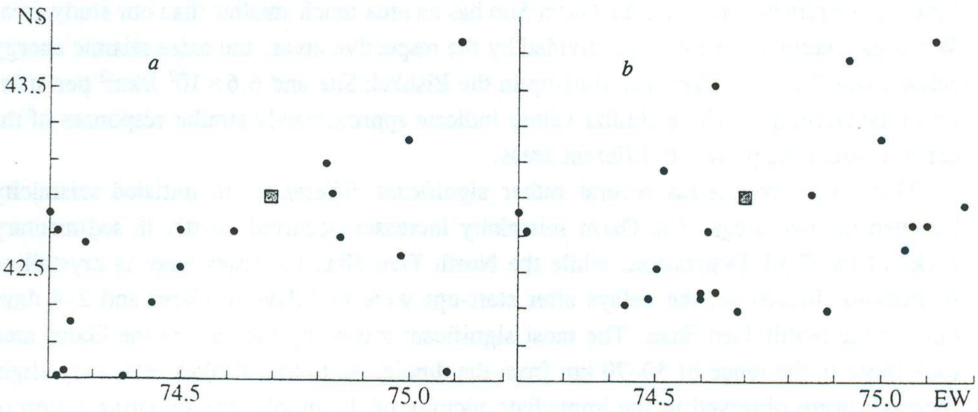

Figure 6 Epicenters of K $\geq$ 8 earthquakes with $h \leq$ 5 km that occurred in the Bishkek Site area during 8 days before (*a*) and during 8 days after (*b*) the start-ups. The square indicates the position of the MHD-generator dipole.

Table 1 Total seismic energy released in earthquakes in the area of study before (E_b) and after (E_a) MHD-generator start-ups.

Depth of focus, km	Area	E_b	E_a	$E_a - E_b$	$E_a - E_b$ per start-up
		10^{13} J			
All	Entire area	22	213	191	2.2
All	North	15	2.7	−12.3	−0.15
All	South	6.9	210	203.1	2.4
0–5	Entire area	7.2	210	202.8	2.4
0–5	North	0.8	0.85	0.05	0.0
0–5	South	6.4	210	203.6	2.4

to the earthquakes occurring in the upper 5-km layer in the southern part of the area which belongs to the crystalline rocks of the North Tien Shan. At the same time, the total energy transmitted by the MHD generator to the radiating dipole for all 85 start-ups was 1.1×10^9 J, i.e., six orders of magnitude smaller. Consequently, the high energy electromagnetic pulses radiated by the MHD generator initiated the release of energy that had been stored in the crust due to other sources.

The mean energy of initiated earthquakes per one start-up was 2.2×10^{13} J. N. T. Tarasov [8] investigated the initiating effect of MHD-generator sounding pulses on the seismicity of the Garm area in Tajikistan and concluded that the average increase in total energy release through local seismicity had been 1.1×10^{12} J per start-up. It should however be remembered that the Garm Site has an area much smaller than our study area. When the energy estimates were divided by the respective areas, the extra seismic energy release was 7.3×10^7 J/km^2 per start-up in the Bishkek Site and 6.6×10^7 J/km^2 per start-up in the Garm Site. These similar values indicate approximately similar responses of the earth to sounding pulses in different areas.

There are nevertheless several rather significant differences in initiated seismicity between the two areas. The Garm seismicity increases occurred mostly in sedimentary rocks of the Tajik Depression, while the North Tien Shan increases were in crystalline formations. Moreover, the delays after start-ups were 6–7 days in Garm and 2–4 days only in the North Tien Shan. The most significant seismicity increase in the Garm area took place in the range of 50–70 km from the dipole. As to the Bishkek Site, very slight increases were observed in the immediate vicinity of the dipole, the initiating action of sounding pulses being much higher farther than 100 km from the dipole. It can be surmised that this pattern was due to the low energy content of the earth in the site area or to the relatively low seismicity rate compared with the other earthquake-generating zones in the area of study.

The above results were tested using the data for 23 MHD-generator start-ups made in the Bishkek Site in 1988–1989. Since this time period was not covered by the catalog "Earthquakes of North Tien Shan and Adjacent Areas", we did a similar analysis for the catalog "Earthquakes of Soviet Central Asia and Kazakhstan", which contains more than 1200 events for 1988–1989. The spatial boundaries of this catalog are somewhat broader, being displaced southwest compared with the former catalog. This circumstance lent a certain show of independence to this analysis in relation to the previous one.

Figure 7 presents time variations in the post-SP daily seismicity rate obtained by the coherent summation of seismic events in 23 time windows corresponding to the MHD-generator start-ups made in 1988–1989. The picture here is not as clear-cut as in Fig. 3, probably because of fewer start-ups. It is nevertheless clearly seen that, similarly to the previous case, a noticeable post-SP seismicity increase occurred, best discernible for the upper 5-km layer in the southern part of the area. The delay between maximum activation rate and SP was 2–3 days, which is also consistent with the previous results.

DISCUSSION OF RESULTS

The above results demonstrate that high energy electromagnetic pulses emitted by MHD generators give rise to an appreciable increase in the rate of local earthquakes, occurring some 2–4 days after the pulses, in a wide range of earthquake energy. This process is accompanied by the rearrangement of events in energy and of hypocenters in space. The effect of start-ups may strongly vary between different geologic features.

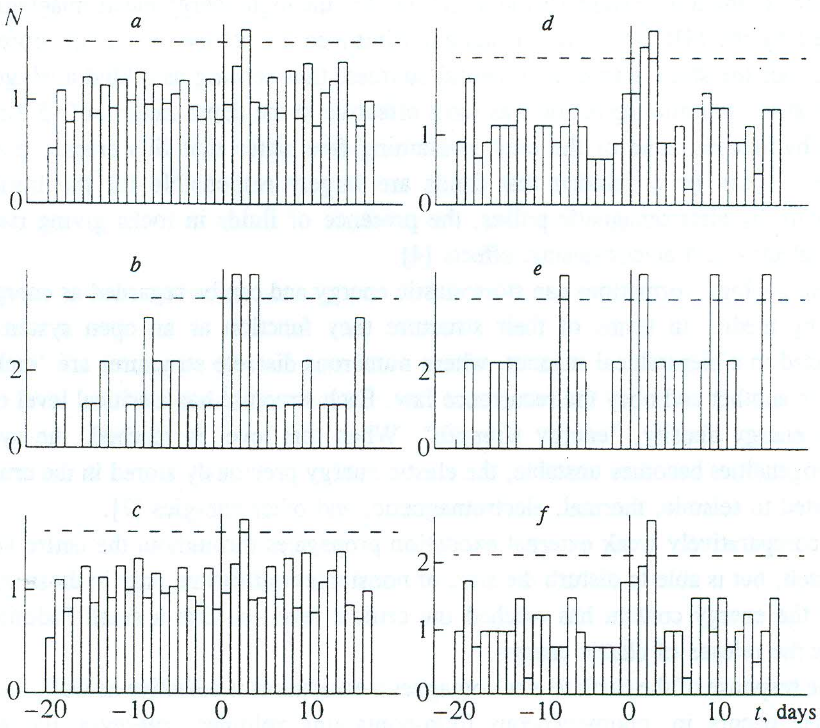

Figure 7 Distribution of the daily rate of local earthquakes over time for former Soviet Central Asia and Kazakhstan before ($t < 0$) and after ($t > 0$) start-ups of MHD generator in 1988–1989: *a* – for entire area of study; *b* – for its northern part; *c* – for southern part (North Tien Shan); *d–f* – same as *a–c*, respectively, but for the upper 5-km layer. The notation is as in Fig. 3.

These conclusions were verified using two independent sequences of MHD-generator start-ups at the Bishkek Site with two different earthquake catalogs. The results confirmed the initiating effect of action by electromagnetic pulses on the seismicity previously identified [8] in the Garm area in Tajikistan.

The Garm seismicity increases mostly occurred in the sedimentary rocks of the Tajik Depression, while in the North Tien Shan crystalline Paleozoic formations were affected. What was common for both areas was the fact that radiating dipoles of MHD generators were installed there. This shows that the highest seismicity increase must probably take place in geologic features that are under immediate action of electromagnetic pulses.

It can on the one hand be hypothesized that it was the extra energy imparted to the earth by electromagnetic excitation that was radiated in the form of earthquakes, and on the other, that sounding pulses initiated the release of energy stored in the crust due to natural geodynamic processes. The fact that the increase in total earthquake energy release after start-ups was six orders of magnitude greater than the total energy transmitted by the generator to the dipole suggests the inference that the high energy electromagnetic pulses radiated by the MHD-generator installation initiated the release of energy stored in the crust under the study area due to natural sources, thus serving as a kind a trigger.

Because the initiating action was most effective in the depth range of 0–5 km, which is the hydrostatic zone of the crust containing free water that fills cracks, pores, and cavities, it can be concluded that fluids are largely responsible for the initiation of seismicity by electromagnetic pulses, the presence of fluids in rocks giving rise to the seismoelectric and electroseismic effects [4].

Real geologic formations can store elastic energy and can be regarded as energy-accumulating media. In terms of their structure they function as an open system that is organized in a hierarchical manner, where numerous discrete structures are "embedded" into one another and obey the recurrence law. Each structure has a critical level of stored elastic energy density, "energy strength". When that level is reached, the system of inhomogeneities becomes unstable, the elastic energy previously stored in the crust being converted to seismic, thermal, electromagnetic, and other energies [7].

A comparatively weak external excitation propagates throughout the entire volume it can reach, but is able to disturb the state of nonstable equilibrium only in those structures where the energy content has reached the critical level, so that a small "addition" can initiate the release of elastic energy.

The response of the earth to electromagnetic excitations is selective as well; the highest response occurs in inhomogeneous fluid-containing volumes (energy-active zones of electrokinetic nature) and is controlled by electrokinetic phenomena occurring at solid–liquid interfaces within the associated double electrical layers. This makes the region of double layers thermodynamically unstable when external forces act on it [1].

When an electromagnetic disturbance is traveling in the earth, the associated electric field will interact with surplus volume charges in the double layer region, producing pressure gradients in the fluid and thereby exciting macroscopic mechanical disturbances. A pressure gradient disturbs the equilibrium of a system and gives rise to a rearrangement of structural stresses, thereby causing the rearrangements and subsequent release of elastic energy at the inhomogeneities whose energy-content levels are "critical".

The fact of delays of a few days between a maximum seismicity rate and an MHD-generator start-up observed both in the Garm area and in the North Tien Shan can probably be explained by inertial transition of the system to a stable state when an extra source of disturbance appears in it. This is consistent with the well-known patterns observed in natural and induced seismicity (including those caused by nuclear blasts).

It should be pointed out that the mechanism proposed here seems to be the most likely one at the present state of knowledge. The fact that some other physical phenomena might have accounted for the results obtained calls for more research to elucidate the mechanism of SP-induced seismicity.

CONCLUSIONS

The results of this study show that the action of high energy electromagnetic pulses radiated by MHD generators causes substantial changes in the seismicity of earthquake source zones by accelerating the release of energy stored in the crust due to the activity of natural tectonic processes in the form of comparatively small seismic events.

Based on the considerations of energy balance to be preserved in the crust, it can be conjectured that a man-induced increase in the ratio of seismic energy radiated in the form of small earthquakes leads to an additional release of tectonic stresses, thereby diminishing the likelihood of catastrophic events (or at any rate, reduces the energy of such events).

The high efficiency of electromagnetic excitation combined with the relative simplicity and small size of an MHD installation suggests the conclusion that the effect discussed can be used to help in the development of earthquake prevention techniques.

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