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Anomalous geomagnetic variations and their relationship with the geodynamics of the earth's crust in the Ferghana depression (Uzbekistan)

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ABSTRACT

Permanent magnetometer stations offer valuable insights into potential strong earthquakes when linked with tectonic activities. This paper aims to elucidate the relationship between certain electromagnetic variations recorded at stations in Uzbekistan and the geodynamic parameters of the Earth's crust during earthquake preparation. Two key aspects are explored: first, dilatancy, the expansion of the Earth's crustal volume upon reaching its strength limit, which induces changes in mechanical and electrical properties detected by various instruments; second, the earthquake source mechanism, whether brittle fracture or plastic slip, which affects the electromechanical properties of the earthquake source. Examples of concurrent variations in different physical fields during specific earthquakes are provided. Given that magnetometric anomalies appear well before other geophysical, hydrochemical, telluric, and other anomalies, integrating changes across various physical fields based on tectonic principles enables the practical identification of short-term earthquake precursors.

KEYWORDS

Earthquake; Geomagnetic anomaly; Precursor; Tectonic movements; Dilatancy; Crustal stress

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Introduction

The challenge of interpreting tectonic-related anomalous variations in the geomagnetic field within specific regions remains an unresolved problem in physics. Despite the fact that for more than 50 years in seismically active areas of the world, the search for magnetic precursors of earthquakes and ways of using them in practical forecasting has been actively studied, it is still impossible to say with certainty in advance which earthquake in preparation this or that observed anomaly may correspond to. Many short-term precursors, so as telluric currents, charged particles, ultramagnetic radiation, atmospheric electricity, geodetic manifestations, anomalies in the velocity of seismic waves, hydrochemical anomalous, appear, although not always, immediately before the earthquake in the source zone. To register them, advance knowledge of the geographic coordinates of the future earthquake will be required. Despite a fairly large number of scientific research on the search for earthquake precursors it is still impossible to link the geomagnetic medium-term anomalous variation in advance with a specific future earthquake source [1-9]. Based on the real state of affairs, the United States Geological Survey (USGS) was not afraid to openly state that there is no convincing evidence of earthquake precursors [10]. Similar statements have been made sporadically at different times [11-13]. Despite their harsh verdict, the authors were forced to admit that several cases of earthquake prediction using seismic electrical signals by the VAN method met the International Association of Seismology and Physics of the Earth (IASPEI) precursor criterion [11,12,14]. Retrospectively, such anomalies with a certain degree of probability can be attributed to one or another earthquake and relate to the size of tectonic units [15-20]. In proposed a partially encouraging method, the authors of which claim that the direction to the future epicenter can be determined using the phase-gradient components of ultra-low-frequency geomagnetic disturbances [21-24]. A group of researchers believe that in order to obtain more reliable information about upcoming earthquakes, magnetic anomalies must be combined with gravity and hydrogeochemical anomalies [25,26]. Moreover, according to the IASPEI criterion, precursors are considered more reliable when different precursors appear simultaneously.

Some geophysical changes within a certain radius around the source during the earthquake preparation period were studied post facto [27,28]. However, there are also examples that were reported anomalies in advance [14]. Variations such as geoelectric, geomagnetic, changes in the composition of radon, changes in the temperature of well waters in many parts of the world appeared within a radius of 100 km 3 months before earthquakes with magnitude M=5-6 [29]. This distance increased to 300 km closer to the earthquake and even to 500 km at magnitudes M=7. Similar manifestations of geomagnetic precursors were also recorded by magnetic stations on the territory of Uzbekistan [16,30]. Based on the results of many years of factual materials from Central Asia, statistical dependencies have been established between the duration of the manifestation of some mid-period bay-shaped precursors on the strength of the earthquake, as well as on the distance of the earthquake hypocenter [6,31]. Similar results were obtained for other countries of the world [7,28]. Subsequent analysis showed that the detected anomalous magnetic variations precede strong earthquakes and are most clearly visible in the differences in the corresponding magnetic components

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observed at separated magnetic stations. One of the unsolved problems in predicting earthquakes based on the characteristics of geomagnetic anomalous variations according to world data and, in particular, according to data obtained at the geodynamic test sites of the Fergana depression of Uzbekistan, is the question: why, it would seem, earthquake foci located at approximately the same distances from the station in some cases create a magnetic anomaly, but not in others. Also, the question of why the cove anomaly has a convex appearance in some cases and a concave appearance in others awaits resolution. The purpose of this work is to connect the listed features identified at the Chimyon station (Uzbekistan) with tectonic processes occurring in the earth's crust during the preparation of earthquakes, the source of which is located quite far from it.

Methods and Results of Studying Magnetic Anomalies

Studies of magnetic variations of tectonic nature on the territory of Uzbekistan have been carried out since 1970 using the methods of repeated route, area and stationary geomagnetic observations [15,16]. The total number of repeated route and area observations at testing sites in Uzbekistan exceeded 465 points, and more than 19 stationary observation stations (Figure 1). In addition, repeated observations are periodically carried out at more than 500 points located in the epicentral areas of strong earthquakes and man-made objects.

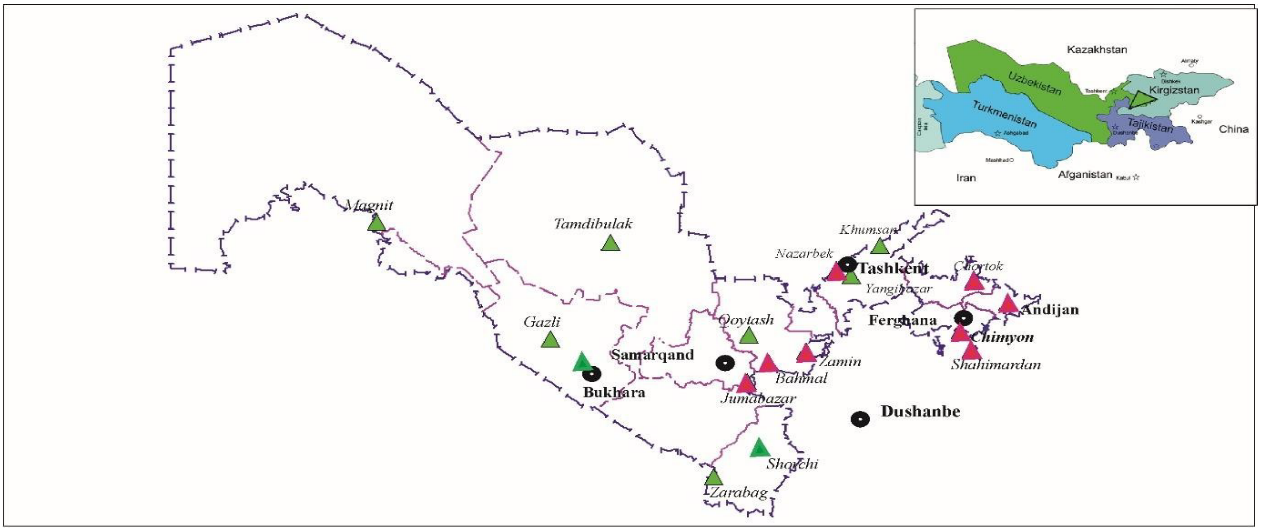

Figure 2. Location of stationary magnetometer stations (colored triangles) of Uzbekistan. The top corner shows the location of the territory of Uzbekistan.

Monitoring of geomagnetic variations at observation points was carried out relative to the reference station - the Yangibazar observatory, located near Tashkent city. The subjects of study of the time series of the geomagnetic field were inter-cycle and average daily difference values of the module of the total vector of geomagnetic induction ΔT of stations relative to the reference. Over the past period of research, numerous (more than 70 cases) geomagnetic precursors of earthquakes have been identified. The most significant and reliably identified of them are medium-term variations. Due to the significant impact of external electromagnetic variations on the studied difference magnetic field, short-period variations are less confidently identified, from which it has never been possible to identify operational precursors of earthquakes. Of the 54 cases of registration of a precursor signal, 17 cases (31.5%) were recorded at the Chimyon station, located in the Fergana depression. The remaining 68.5% of cases occur at other 18 stations in Uzbekistan. The magnitude of earthquakes from which a precursor signal can be expected at Chimyon station is more than 4.5. Statistics show that out of 11 cases of earthquakes that occurred within the radius of R up to 50 kilometers from the Chimyon station, precursor signals from only 4 events were recorded. The results of statistical studies of sensitivity to earthquake magnitude for the Chimyon station are shown in the Table 1 and Figure 2.

Table 1. Earthquake precursors to the total number of events in the South Tien Shan block.

Years of operation of stationary stations	*σ2	Ratio of detected earthquake precursors to the total number of events in the South Tien Shan block			
			M=5.1-5.5	M=5.6-6.0	M≥6
	(nTl)	M=4.5-5.0	1/1	1/1	0/0
1980 -1988	± 0.81	02-Aug	2/3	1/1	0/0
1989 – 1992	± 2.0-2.9	0/13	0/1	1/1	1/1
2006-2009	± 2.7	0/7	0/0	1/1	0/0
2014-2016	± 0.8-1.0	0/4	0/1	1/1	0/0
2017-2019	± 0,8-1.7	0/12	1/1	0/0	0/0
2019-2021	± 0.3-0.5	03-Jul	0/0	1/1	0/0
2021-2023	± 0.3-0.5	0/2	4/7	6/6	1/1
For the entire period		May-53	57,1%	100%	100%

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The work analyzed the dependence of the spatial location of recorded magnetic anomalies on the size of tectonic blocks [20]. Chimyon station is located in the South Tien Shan block with an average linear size of 1292 km, where earthquakes with M = 6.25-7.25 are possible. Over the period 1980-2023, excluding the periods 1993-2005 and 2010-2013, 67 earthquakes with M ≥ 4.5 occurred within the entire South Tien Shan block. It follows from the table 1 that indeed all earthquakes with M>5.6 that occurred within the Tien Shan block gave precursors at the Chimyon station. The lower the magnitude, the fewer earthquake warning signals.

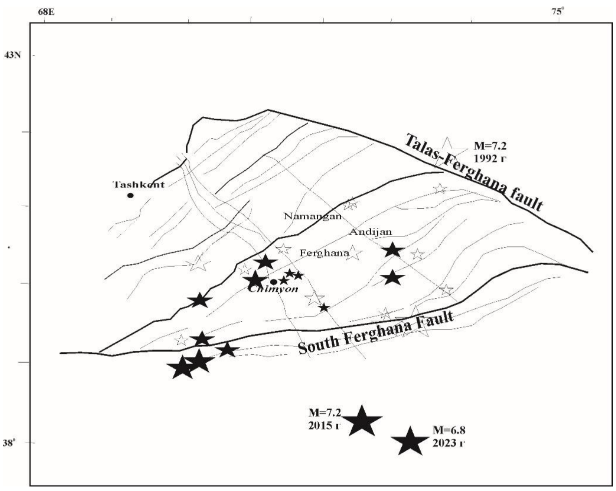

Figure 2. Geomagnetic bay-shaped precursors of earthquakes at Chimyon station for 1980-2023. Filled asterisks indicate cases where earthquake precursors with the corresponding magnitude appeared. Unshaded asterisks indicate cases where precursors have not appeared. Curved lines indicate active faults of different ranks.

There were isolated cases associated with weak earthquakes with magnitude M≤4.5 located near Chimion station, which gave anomalous changes shortly before the earthquakes. In these cases, the magnetic variation anomalies had a concave shape, in contrast to anomalies from stronger earthquakes, which usually have convex shapes. For example, at the Izbaskan station (Andijan region), the earthquake of May 15, 1992, M=6.4, appeared concave on the graph of magnetic variations. The Chimyon earthquake of 05 June of 1982 y., with M=5.5, manifested itself as a concavity at the Chimyon station. It should be noted that such dependence is typical especially for cases of seismic origin. In other cases, anomalies may have both a concave and convex appearance, or be completely absent [18]. Examples are measurements taken with portable magnetometers at different times in the areas of reservoirs and oil fields. Basically, an increase in the volume of water in the Charvak reservoir in most cases led to a positive change in the magnetic field, but during 1973-1978 the opposite picture was observed. The same can be said from data obtained in areas containing deep faults. It was assumed that on different sides of the fault, changes in the geomagnetic field would manifest themselves in opposite signs, and in this regard, a method for identifying faults using magnetometric measurements was even proposed [31]. Apparently, in such cases, various near-surface phenomena contribute differently to magnetic measurements. For example, creeping movement around a reservoir created by increasing water volume can change the orientation of the magnetic sensor. In this case, for example, as noted in, tilting the sensor by 0.01˚ leads to a change in the value of the horizontal magnetic component by 6.6 nTl [28]. Moreover, measurements under non-stationary conditions, when carried out at different times, give large errors ΔT. If repeated measurements are carried out once every 3-4 months or once a year then it is generally unknown how accurately the difference field is measured.

There are known cases when stations located in the Fergana depression responded to stronger earthquakes that occurred outside the Tien Shan block. These include: Gazli earthquakes of 1976 and 1984 with M=7.2 and M=7.3, the precursors of which were observed at some stations of the Pritashkent region and Southern Uzbekistan, the Alay earthquake of 1978 with M=6.8, which caused anomalous changes in various forecast fields of Eastern Uzbekistan and the recent earthquake of 23.02 [30]. 2023 in the area of Lake Sarez (Tajikistan) with M=6.8 and focal depth h=21 km (Figure 2). In the last case, before the earthquake, precursor anomalies appeared synchronously at 4 stations as Chortok, Andijan, Chimyon and Shakhimardan, located in the Fergana depression (Figure 3)

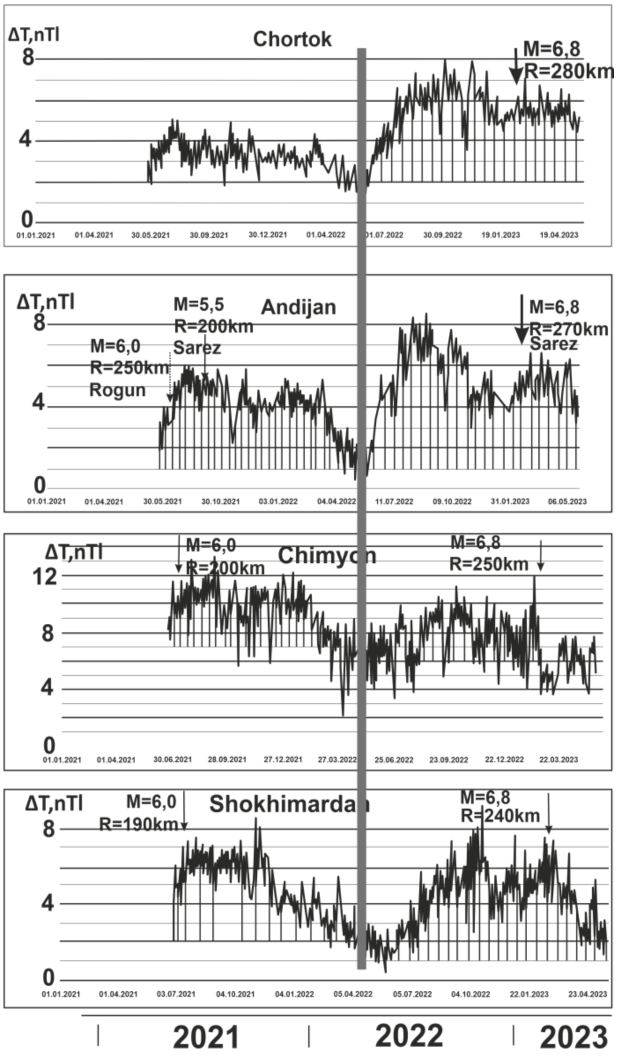

Figure 3. Synchronous manifestation of anomalies at 4 magnetometric stations of the Fergana depression, before the earthquake near Lake Sarez in 02/23/2023 (Tajikistan).

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Comparison of the features of magnetic anomalies with the physical properties of the earth's crust in the preparation of earthquakes

Let's try to connect the listed features of magnetic variations with changes in the physical properties of the earth's crust, particularly with the process of dilatancy. Dilatancy is a nonlinear decompression of a medium caused by the formation of cracks when the stress exceeds the material's interatomic bond strength threshold. Experiments have established that the process of dilatancy occurs for quite a long time under prolonged loading of rocks [32-35]. Changes in density during dilatancy are associated with the opening of cracks in the fragile part of the earth's crust. After the stress reaches a value of approximately half the strength, the cracking process begins, and the planes of the resulting cracks are approximately parallel to the plane of the lowest compressive stress [36]. On cracks, unlike dislocation-type defects, there is a jump in both tangential and normal stresses, which leads to increase in micro voids in rocks. During this period, the strength properties of rocks change dramatically. The consequence of this is electromagnetic emissions [37], a change in the ratio of longitudinal and transverse velocities of seismic waves shortly before the earthquake, etc [7]. This effect is attributed to moisture diffusion in brittle materials with manifestations of dry friction [38,39]. A small amount of moisture changes the intensity of the diffusion process in the earth's crust. Minerals dissolve under pressure and are redistributed. Violation of dense packing leads to under saturation of rocks. Under high voltage, water molecules begin to dissociate into ions, which under certain conditions can generate telluric currents. It should be noted that there are experiments that have been performed on gabbro samples saturated with an electrically conductive fluid similar to that observed in active seismic fault zones, and no electric currents were observed [40]. However, these experiments were carried out at low compressive pressure values equal to 0.22 kbar, at which dilatancy is not possible. A long time ago, many authors conducted experiments at stresses up to 8 kbar and noted that experiments like [40] may correspond to the behavior of faults during creep movements, and are not predictive [32,40-42,43]. Experiments fall into two categories: those based on fault constitutive relations, which predict the behavior of the fault but without changing the properties of the material surrounding the fault, and those based on bulk rock constitutive relations, which predict changes in physical properties in the volume surrounding the fault. The best known of the first type are models of nucleation and lithosphere loading, and of the second type is dilatancy models.

Measurements of electric currents and seismic velocities during the period of preparation of earthquakes in the vicinity of the source have been quite well studied in the Garm test site and at California landfills [7,38,44]. In Garm, most of the stations where anomalies were observed were located at a distance of 15 to 45 kilometers from the source of earthquakes with a magnitude of M=4.5. Similar manifestations have been demonstrated in laboratory experiments [43,45]. Magnetic anomalies were observed at a distance twice the distance at which seismic wave velocity anomalies were observed.

Apparently, the maximum distance where anomalies can be detected depends on the volume of the dilating medium. It would seem that all earthquakes in this radius should cause geophysical and geochemical anomalies. However, a statistical analysis of records carried out for the Chimyon station shows that more than 42.9% of earthquakes with a magnitude of less than 5.6 within a radius of up to 50 km from the station went unnoticed by magnetic observations. This may be due to the second type of mechanism of earthquakes listed above, namely, stick-slip on pre-existing faults, where the rock is in a plastic state [35]. In this case, changes in the physical parameters of the environment occur in a small volume around the earthquake source. When saturated rocks stick-slip, very small changes in physical parameters occur. Electrical resistance and seismic wave velocity ratios remain almost unchanged. Naturally, in this case no anomalies should be expected. Such cases of earthquakes have been described in Central California [38].

Based on the dilatancy process, earthquake preparation models have been developed: dilatation-diffusion and IPE (Institute of Physics of Earth), which are similar in mechanism, but differ in the presence or absence of moisture [38,46]. They provide a fairly good theoretical explanation of the step-by-step changes in the geophysical and geochemical parameters of the rock during the preparation of an earthquake: a decrease in the ratio of the velocities of longitudinal and transverse seismic waves, an increase in radon emission, foreshocks and aftershocks. The exception is electrical resistance. According to the first model, during the period of preparation for an earthquake, electrical resistance decreases, while the IPE model allows to consider two options: a decrease in moisture-saturated rocks and an increase in dry rocks. According to the IPE model, it could be considered that the concavity or convexity of the shape of magnetic anomalies is associated with undersaturation with fluids.

However, at the Chimyon station, the concavity of the magnetic anomaly was observed in a very specific way, namely only in the case of a source located directly or very close to the magnetometric station. It seems to us that this is most likely due to the characteristics of the dilating volume. From laboratory experiments it is known that for some time the stress in the source increases, after which dilatancy cracks develop. At the same time, moisture tends to the dilating volume from the environment. Accordingly, the electrical resistance increases, which leads to the appearance of a concave Calculations of the distances of dilation volumes were carried out based on the energy analogy of nuclear explosions and comparison of the elastic volume releasing energy during an earthquake. At the same time, an estimate was obtained for strong earthquakes up to 100 km [,33,38,47]. Mathematical modeling of the dilatancy process in terms of mechanics is very difficult. The occurrence of small cracks with their subsequent concentration along the predominant direction for inhomogeneous rocks is impossible in terms of continuum model. An attempt was made to calculate the dilatation region using the example of solving the problem of the influence of high pressure at some internal point of an elastic half-space [48]. The Schleicher-Nadai criterion usually used in plasticity problems is adopted as a criterion for the occurrence of dilatancy: $D\tau=\tau-\alpha P-Y\geq 0$. Here τ is the intensity of shear stress, P is pressure, α is the coefficient of internal friction, Y is rock adhesion. The zone, where tangential stresses dominate over compressive stresses ($D\tau\geq 0$), is interpreted as a dilatancy volume. Theoretically, dilatancy effects manifest themselves between the limits of strength and elasticity during strengthening and softening of the material until the level of residual strength is

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reached, so the mathematical formulation requires at least the solution of plasticity problems [49]. Moreover, the formation of dilatation volumes in the case of earthquakes is completely different in its mechanisms from those in a nuclear explosion. If in the latter case such a zone is formed due to a powerful short-term explosion of a charge, from uniform pressure, the preparation of an earthquake occurs for quite a long time, the mechanism of which is modeled by a double dipole without a moment. Since the seismic moment is an expression of the released elastic energy, stress changes after earthquakes can be used to calculate the dilatation zone. Numerical solutions of such problems in elastic formulation for Central Asia were carried out in [50,51].

Susamyr earthquake 08/19/1992 (42.1 N; 73.6 E; M=7.3; h=13 km) occurred at a distance of 320 km from Chimyon station. In Fergana, the tremors were felt with an intensity of 6 points. However, the lead-up to this earthquake, unlike other strong earthquakes, did not exhibit any magnetic precursors. From this point of view, this event requires a special interpretation. In contrast to the above cases, the source mechanism of the Susamyr earthquake (reverse fault with a right strike-slip to the north) manifested itself a little differently [52-54]. The source of the earthquake was located within the intersection of the Talas-Fergana and Tien Shan faults, which have a northwestern and near-latitudinal direction. The creep movements of the Talas-Fergana fault led to strong compression of the Aramsu tectonic block, which resulted in near-latitudinal reverse faults. It seems to us that in this case, dislocation movements along the Talas-Fergana fault limited dilation phenomena, and therefore magnetic precursors were not discovered in Chimyon.

Comparison of medium-term magnetic anomalies with other independent anomalies that occur during the preparation period for earthquakes can significantly increase the reliability of earthquake forecasts. The change in the ratio of longitudinal and transverse seismic waves vp/vs within the framework of elasticity is convincingly interpreted by the passage of seismic waves through a dilating volume. The manifestations of ultra-low-frequency magnetic anomalies during microfracture of rocks can also be explained: when a microcrack opens, a charge production can be intensified by the ionization of void space within the crack and by acceleration of unbounded electrons [37,55]. Possible geodetic anomalies, changes in hydrochemical parameters and other physical phenomena in the short period before earthquakes can also be associated with the penultimate stage of dilatancy. Redox processes expressed by the potential Eh and changes in the concentration of hydrogen ions pH occur as a consequence of the release of electrons not long before the main event of the formation of the main fault [56].

Here is an example to prove the reliability of some precursors with a specific earthquake. Let us compare the obtained magnetic anomalies (Figure 4) before the earthquake of July 19, 2011. (40.12 N; 71.45 E; M=6.2; h=18 km) in the village of Kan, Batken region, on the border of Kyrgyzstan, Tajikistan and Uzbekistan, 42 km southwest of Fergana with other anomalies manifested immediately before the earthquake [57].

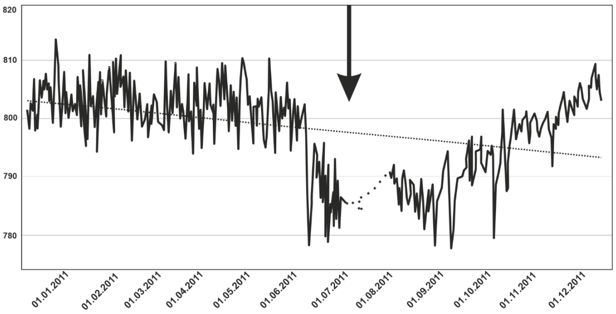

Figure 4. Magnetic anomalies during the preparation of the earthquake of July 19, 2011. in the village of Kan, Batken region, Kyrgyzstan.

Figure 5 shows vp/vs anomalies constructed before and after the Kan earthquake, the behavior of which is quite consistent with the earthquake preparation cycle described above.

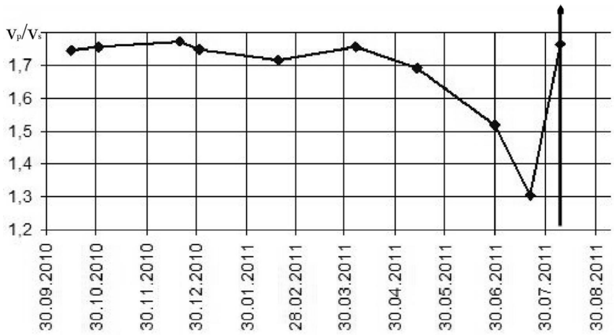

Figure 5. Change in vp/vs during the preparation period for the earthquake of July 19, 2011. in the village of Kan, Batken region, Kyrgyzstan.

Similar changes occurred in the composition of groundwater. Figure 6-7 shows sudden changes in the redox potential Eh and the concentration of hydrogen ions pH.

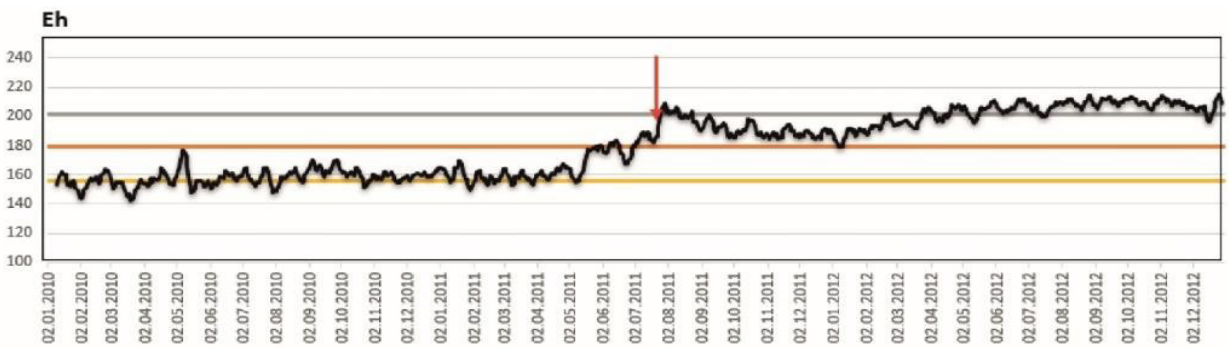

Figure 6. Change in Eh during the preparation for the earthquake of July 19, 2011 in the village of Kan, Batken region, Kyrgyzstan.

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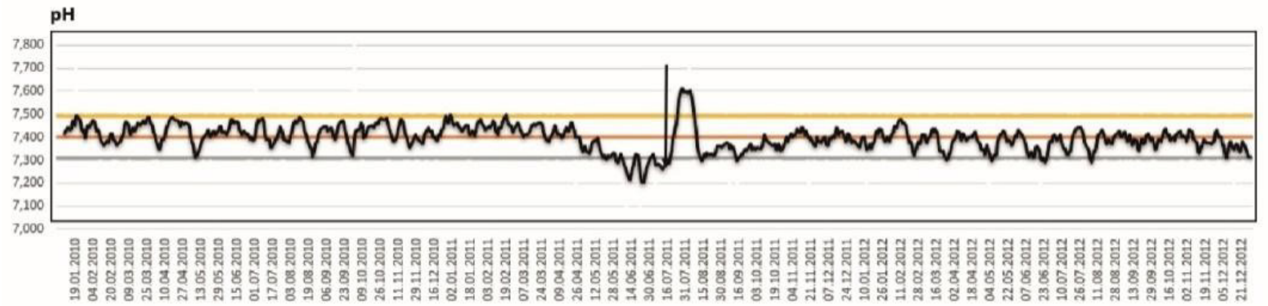

Figure 7. Change in Ph during the preparation for the earthquake of July 19, 2011 in the village of Kan, Batken region, Kyrgyzstan.

Similar comparisons took place with the recent earthquake on the territory of Tajikistan, near Lake Sarez on February 23, 2023, to which, long before the earthquake, 4 magnetometric stations of the Fergana depression responded synchronously (Figure 3). We obtained similar pictures of sharp changes in Eh and pH 10-12 days before the earthquake. A leap in telluric currents was also obtained (Figure 8) at the Yangibazar observatory (measurements of telluric currents in Uzbekistan have been carried out since 2013) 10-11 days before the earthquake.

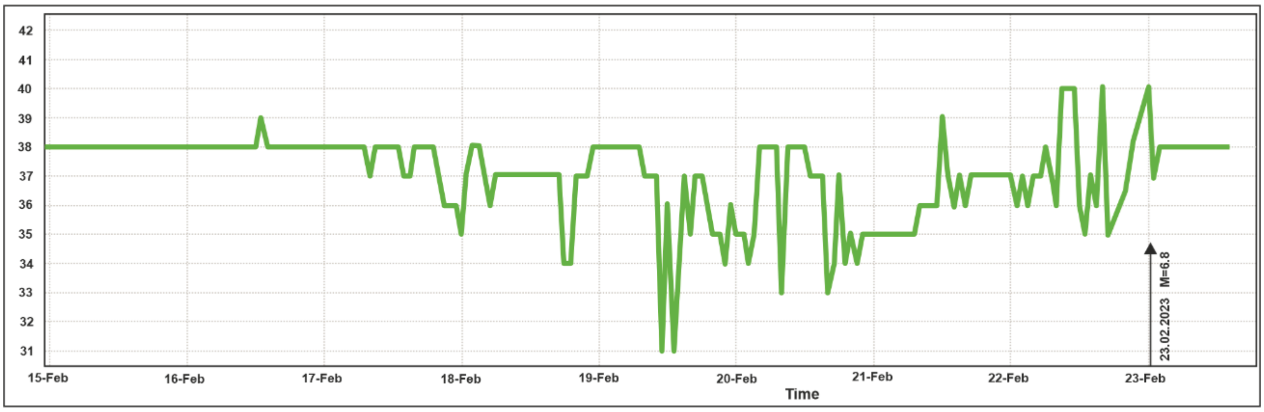

Figure 8. A surge of telluric currents long before the earthquake of 02/23/2023. near Lake Sarez, Tajikistan.

Thus, these examples show that stationary magnetic stations make it possible to continuously monitor magnetic anomalies of a tectonic nature, regardless of whether they manifest themselves or not. If such are detected, the phase-gradient method can be used to clarify the coordinates of the source. Additional monitoring of v_p/v_s behavior, telluric currents and hydrochemical parameters makes it possible to carry out a short-term earthquake forecast.

Conclusions

The identified geomagnetic precursors of earthquakes (including their timing and range of manifestation) at stations in the Fergana depression of Uzbekistan align well with established global data from other countries. Permanently operating magnetometry stations provide critical information about the potential for strong earthquakes. When correctly analyzed, this information can signal the detection of short-term precursors. The nature of the observed short-term prognostic signs for some significant earthquakes (e.g., the 07/20/2011 earthquake in Kan village, Batken region, on the Kyrgyzstan-Uzbekistan border, and the 02/23/2023 earthquake near Lake Sarez, Tajikistan, observed at the Chimyon station) aligns with medium-term magnetic anomalies recorded at stations in Uzbekistan. These anomalies can be interpreted as variations in the stressed state of the Earth's crust, related to the development of dilatancy at the earthquake source. Given that magnetometric anomalies appear well before other geophysical, hydrochemical, telluric, and other anomalies, integrating changes across various physical fields based on tectonic principles enables the practical identification of short-term anomalies in a timely manner.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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