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THE USE OF HIGH-PRECISION MAGNETOMETRY IN SOLVING VARIOUS SCIENTIFIC AND PRODUCTION PROBLEMS

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Abstract. *In the article named "the use of high-precision magnetometry in solving various scientific and production problems" the data of analysis of long-term observations of the geomagnetic field are presented, and the specialists engaged in magnetometric work are familiarized with the methods of high-precision magnetic surveys developed at the Institute of Seismology and some results of magnetometric work obtained at geodynamic testing sites in Uzbekistan.*

Keywords: *geomagnetic field, technogenic and geodynamic processes, reservoir, seismicity, operation, variations.*

Introduction. Over the last decades, due to the emergence of new high-precision absolute magnetometers and the development of high-precision magnetic surveying methods, the capabilities of magnetometric research in solving various scientific and production problems have increased dramatically. In Uzbekistan, high-precision magnetometry is successfully applied in the study of the seismomagnetic effect, the influence of the operating mode of man-made objects on variations in the geomagnetic field, the search and exploration of mineral deposits, the separation of zones with abnormal electrical conductivity of rocks and many other areas. Numerous anomalous changes in the magnetic field caused by the preparation and implementation of earthquakes, the operating regime of underground gas reservoirs, high-altitude reservoirs and oil and gas fields have been identified at the geodynamic testing sites of Uzbekistan. In recent years, high-precision magnetometry has also been successfully applied in the search and exploration of mineral deposits with poor differentiation of the magnetic properties of rocks located in closed areas. In all the above areas, very interesting and noteworthy scientific and practical results have been obtained. The above results of magnetometric research have been obtained by repeated route and field magnetic surveys and stationary observations.

The purpose of this article is to familiarize specialists involved in magnetometric work with the methods of high-precision magnetic surveys developed at the Institute of Seismology and some results of magnetometric work obtained at geodynamic testing sites in Uzbekistan.

At the Institute of Seismology of the Academy of Sciences of the Republic of Uzbekistan, magnetometric work was started in 1968 to study anomalous variations in the geomagnetic field associated with earthquakes (seismomagnetic effect). Later, these works were expanded and conducted in man-made objects, in the epicenters of strong earthquakes, in areas with anomalous electrical conductivity of rocks and for the search and exploration of mineral deposits [1-3]. Below we will briefly talk about the methods of magnetometric work and the results obtained.

Table 1

Table 1 shows the types of high-precision magnetometer surveys in various modifications.

1. Routine surveys	**2. Stationary methods of magnetic observations**	**3. Land surveying**
1.1 Repeated route observations	2.1 Supervisory observations	3.1 Detailed magnetic prospecting works

1.2 Identification of areas with abnormal electrical conductivity	2.2 Seismic predictive observations	3.2 Repeated site surveys for seismic effect studies
1.3 Magnetic Exploration Work	2.3 Observations at points of centuries of passage	3.3 Repeated site surveys at man-made facilities

The success of experimental scientific research depends primarily on the correct organisation of fieldwork methods, including: selection of the research area, selection of equipment used, measurement methods, survey scale, assessment of measurement accuracy, accounting for variations in the geomagnetic field, etc.

The main methodological issues were developed in 1970-80s. In 1977, V.P.Golovkov, N.A.Ivanov, I.M.Pudovkin and others published the "Instruction on search and study of anomalies of a century course of a geomagnetic field". [4]. A new instruction was developed at the Institute of Seismology in 2019 due to the appearance of new, more highly sensitive instruments and processing methods [5]. The developed method of high-precision magnetic surveys has also been successfully applied in high-precision magnetic surveys [6,7]. The present work is devoted to outlining the main issues of the methodology and the results obtained from high-precision magnetic surveys carried out at geodynamic testing grounds, at man-made facilities and in areas of magnetic exploration.

Selection of the research area. In the case of magnetometer surveys, the success of the survey primarily depends on the selection of the survey area. Stationary points and profiles must be laid along active faults or geological structures... One of the profiles must go into the crosshairs of geological structures and active faults. Areas of exploited gas and oil fields, water reservoirs, underground gas reservoirs, epicenters of major earthquakes, etc. may also be surveyed. Points should be laid away from industrial disturbances, railways, high-voltage lines, gas pipelines, etc. [2, 5].

Choice of measurement method. There are methods for stationary observation, repeated routing and site surveys [2, 3, 5]. Stationary observations can be continuous or discrete, depending on the task at hand. The frequency of repeated routing or site surveys is also selected depending on the purpose and objectives of the observations.

In order to study long-term earthquake precursors, repeated observations should be made 3-4 times a year.

For the study of medium-term harbingers, the frequency of surveys should be at least once a month. For the study of short-term harbingers, measurements should be taken continuously or at intervals of between several and 20 minutes.

When performing magneto-exploration work, the scale of the survey should correspond to the goals and objectives of the tasks to be performed.

Evaluation of the accuracy of the Earth's magnetic field measurements. Selected abnormal changes in the magnetic field can only be firmly judged when there is no doubt about the accuracy. The mean square error of measurement at a point (σ) for each area varies depending on the geographical location of the study area, its geological structure, the measurement methods used, the equipment used and a number of other factors, and is the sum of a number of errors: instrument errors caused by non-identity of variations at different points, magnetic or stationary stations caused by interference, etc.

Instrumented errors. Passport accuracy of measurements with proton magnetometers MPP, TMP, MV-01, G-816, G-856, etc. is about 0.3-0.5 nTl. Proton magnetometers have random and systematic errors. The first ones within a series of counts are automatically excluded. Systematic errors occur in constants and variables. Constant systematic errors are related to the inaccurate determination of the frequency of quartz oscillators, the gyromagnetic ratio and certain features of the instrument circuit. Variable systematic errors are related to the operating conditions of the devices: temperature, power supply voltage, ageing of circuit elements, signal level, etc. Years of research have shown that when the influence of temperature on the frequency of quartz generators is taken into account more strictly than is provided for in the factory instruction, and the systematic monitoring of this frequency, and the constant maintenance of power quality, these errors can be taken into account or significantly reduced.

Constant instrument errors can be taken into account when checking several similar instruments or when checking against a reference. Only a detailed examination of each instrument can determine the individual RMS error (σ_{ins}). This is done by checking several proton magnetometers by comparing a series of at least 150-200 counts per instrument. Moreover, the test instruments are tested at different supply voltages (maximum allowable, optimum and minimum) and in the range of temperatures that may be encountered during fieldwork. Thus, at the end of the study, the total instrument error is averaged (σ_{ins}).

Mistakes due to different variations (σ_{var}) may occur for three reasons. First, if two points are at a different distance from the source of the variations, the changes in the field will be different. Secondly, in the local electrical conductivity of the earth's crust and upper mantle, geomagnetic variations induce electric currents that distort the flow of variations at a given point. Thirdly, if research is carried out near industrial cities, industrial disturbances may occur. In all cases, the difference in variations between the two points is determined by the difference in distance from these points to the source of the variations or the source of the distortion.

1. The differences in variations due to the first cause can be assessed using the example of solar day s_q -variances. Since the variations depend on local time, they will not occur simultaneously at two points, in the east before. For Uzbekistan's latitudes (φ=38°-43°N) the value of σ_{var} at a distance of 100 km is about 1nTl.

2. The value of σ_{var} may increase significantly due to local heterogeneity in the area under study. There are known cases when σ_{var} at a distance of 100 km during bay-shaped variations reached 5-6 or more nTl [2, 5]. The distance from electrical inhomogeneities in the Earth's crust usually plays a significant role. Our studies in the Fergana Valley and western Uzbekistan have shown that during bay-shaped disturbances, the amplitude of the latter can change by only 20-40 km at distances of 20-40 km, and during seismic activation by 70-75% [3, 5].

3. Industrial disturbances (stray currents, moving masses, radio waves) can also cause significant errors. The magnitude of σ_{var} can only be realistically estimated by examining the impact of each of the above factors. The magnitude of the standard error for the difference between variations and industrial disturbances is determined by the expression

$$\sigma_{var} = \sqrt{\frac{\sum \Delta T^2}{n}}$$

Where n- number of definitions

ΔT - difference in definitions.

The value of σ_{var} depends significantly on the time of measurement. Night hours are the most favourable time for measurements.

Therefore, the value of σ_{var} depends on a number of factors and therefore requires a detailed survey for each particular location.

Evaluation of shooting accuracy. With fairly simple sequential operations, you can confidently assess the accuracy of measurements. To assess accuracy, the most reliable way is to compare the actual error distribution with the normal law

$$\varphi_x = \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{x^2}{2\sigma^2}}$$

Regardless of the normal law, an actual error distribution curve is constructed [2, 5]. The calculated mean square error of measurement σ_{calc} is only taken as the actual measurement evaluation when the actual error distribution curve lies within the normal law.

Average annual change in the magnetic field at a given point is referred to as the century's course of the geomagnetic field. The age-old course of the geomagnetic field is caused by various internal and external processes connected [2, 5]:

- with the very processes of creating the Earth's main magnetic field, i.e. with the sources lying in its core;
- with external processes - changes in currents in the Earth's magnetosphere (ionosphere, radiation belts, etc.);
- with changes in the Earth's crust: a) independent or active, b) induced or passive.

Global and regional changes in the magnetic field are caused by processes in the Earth's core and external sources, while local changes are related to different processes in the Earth's crust.

Changes in the geomagnetic field have a very wide time spectrum, from fractions of a second to hundreds and thousands of years. The amplitudes of these changes can be comparable in magnitude and even significantly larger than the local ones. The characteristic times of change are also close to different variations in external and internal origin. It is therefore impossible to isolate local geomagnetic field features from a series of observations at individual points in geodynamic polygons by applying different frequency and time filters.

Only their spatial distribution can be used to highlight changes in the field associated with different processes in the earth's crust.

It is therefore only possible to isolate local changes in the geomagnetic field by applying various spatial filters.

The method of high-precision routing surveys is used to study the seismomagnetic effect, to identify areas with abnormal electrical conductivity of the earth's crust and to conduct magnetic surveys.

1.1 Repeated route observations

In 1968, three profiles were laid out at the Tashkent Geodynamic Range together with the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) [2,3]. The distance between points is 5 km. Measurements were made using proton magnetometers and led to the baseline T-variometer of the Yangibazar Observatory. Since 1968, 3-4 cycles of repeated routing measurements have been performed annually.

The first and most significant were abnormal changes in the magnetic field associated with the Abaibazar earthquake of 10 February 1971 with a magnitude of M=4.2 [2]. The earthquake occurred in close proximity to points along the Western Route. The abnormal change in profile was a classic magnetic anomaly over a magnetized body. In the centre there were positive and negative changes along the edges.

The result related to the Tavaksay earthquake of 6 December 1977, obtained at one of the points on the Sequential route, is extremely valuable. Measurements were started in 1968 and repeated 3-4 times a year. Against the background of minor oscillatory changes, intensive anomalies of a long-term and medium-term nature have been identified. From 1968 to 1975 there were slow long-term anomalies and from 1976 until the earthquake there were medium-term changes. This result is extremely valuable and unique. Because it covers two stages in the earthquake preparation process (Figure 1).

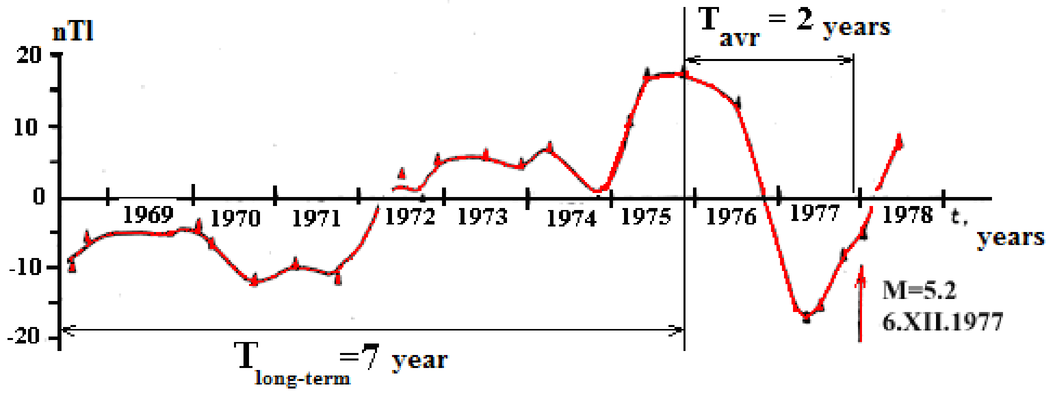

Fig.1. Anomalous variations in the magnetic field caused by the Tavaksay earthquake on 6 December 1977 ($T_{long-term}$ = 7 years; $T_{medium-term}$ = 2 years).

The research was soon extended. The Fergana, Kyzylkum, Charvak and Poltorak polygons were organised. In 1975-80, a total of 400 ordinary sites were measured in Uzbekistan. Since this period, numerous anomalous changes in the magnetic field associated with earthquakes and other processes in the Earth's crust have been detected [1-3].

Identification of areas with abnormal electrical conductivity. Special work was also carried out in Uzbekistan to identify areas with abnormal electrical conductivity, which are important in the study of the deep structure and peculiarities of manifestation of geodynamic processes and other phenomena in the Earth's crust. The method proposed by Ural geophysicists was used to identify zones with abnormal electrical conductivity [6,7]. It is known that the amplitudes of daily and bay-shaped variations of the geomagnetic field in zones with abnormal electrical conductivity are strongly distorted. In order to find the anomalous conductivity zones, ground magnetometer profiles are set up and forward and reverse magnetometer measurements are made in the morning hours. Above the anomalous conductivity zones, the difference in field size between forward and reverse is very different. In the Fergana Valley, geomagnetic routes were set to cross the South Fergana Deep Fault every 50-100 kilometers, and as a result of these surveys, a zone with anomalous electrical conductivity was identified that stretches in a sub-latitudinal direction from east to west, several thousand kilometers long[6].

Magneto-exploration works. In recent years the Institute of Seismology has been conducting detailed magnetic exploration work in various parts of Uzbekistan for the purpose of prospecting and exploration of mineral deposits [8, 9]. Detailed magneto-exploration work has been carried out in the areas of Tashkent, Jizzakh and other regions. Dozens of promising sites have been identified on the basis of contractual and innovative grants [8, 9].

Fixed observations. Stationary observations of variations in the geomagnetic field are carried out in geomagnetic observatories, at reference points, at points of complex seismic forecast stations, at points of centennial course of the geomagnetic field and for other purposes.

Geomagnetic field variations are monitored in specially equipped geomagnetic observatories. The horizontal (H), vertical (Z), declination (D), inclination (J) and full magnetic field vector module (T) are recorded. There are currently about 200 geomagnetic observatories operating worldwide. Data from the world network of geomagnetic observatories are stored in the World Data Centres and used to address a range of global challenges. It should be noted that one of the world network's geomagnetic observatories is located in Yangibazar (Tashkent Oblast), which has been operating since the early 20th century. Based on the analysis of average annual data from the world network of geomagnetic observatories, K.N. Abdullabekov and V.P. Golovkov [2, 3] have identified anomalous variations of the century's course with a characteristic time of 15-25 years and intensity from tens to the first hundreds of nTl. It should be noted that the "anomaly of a century course" was first identified by V.P.Orlov in the late 1950s [6].

Seismoprognostic observations. Seismic prognostic observations are conducted at a network of stationary magnetometer stations. The network of stations registers long-term, medium-term and short-term magnetic precursors of earthquakes. Variations in the magnetic field related to aftershocks are also investigated. It is also possible to construct relationships between the duration of the variations and the magnitude of earthquakes or between the radius of the harbinger and magnitude, etc.

Fixed observations. Stationary observations at points of century-old travel are usually made in order to study the manifestation of a century-old travel of the geomagnetic field in time and space. As is known, the age-old course of the geomagnetic field is commonly referred to as the average annual change of field at a given point. The age-old course of the magnetic field is caused by deep processes in the core and mantle of the Earth and has a wide time spectrum from 10-20 to 60 years and more. The amplitude of the century's variations also varies greatly over time and can range from tens to several hundred nTl. The study of the age-old course of the magnetic field is connected with the solution of regional and global problems of earth magnetism. Their linear sizes also have large sizes and fluctuate from several hundreds to tens of thousands kilometers. However, in nature there may also be anomalies of the century-old course that have local dimensions and surface sources (11). When studying the seismomagnetic effect, this type of variation must also be taken into account.

High-accuracy magnetic surveys are carried out for detailed field magnetic surveys (3.1), investigation of the seismomagnetic effect by repeated field surveys (3.2) and on technogenic objects by repeated field surveys (3.3).

The results of the experiment at the East Ferghana Geodynamic Range are of exceptional interest. Here, from 1976 to 1989, repeated on-site magnetic surveys were carried out over a 13-year period. The research area is approximately 10,000 square kilometers. Repeated site magnetic surveys were carried out regularly at 40 sites located evenly over the area with a frequency of 15 days. Routine measurements were complemented by 3 stationary points, Tashata, Andijan and Madaniyat. At the stationary points the measurements were carried out almost continuously at a discrete rate of 10 or 20 minutes round the clock. During the period of research, several strong and tangible earthquakes occurred on the territory of the site and in close proximity to the observation points (Alay November 2, 1978, M=6.8; Chimyon May 6, 1982, M=5.8; Pop February 18, 1984, M=5.5, etc.). It was possible to trace the appearance, development and disappearance of several magnetic field anomalies associated with specific earthquakes. In our opinion, similar magnetic field anomalies have not been detected anywhere else. This is why the results of the research at the East Fergana test site are also of global novelty and undoubtedly deserve close attention.

Numerous short-term magnetic anomalies with intensities ranging from several to 23nTl are also highlighted here. They were obtained at the stationary stations in Tashata, Andijan, Madaniyat and later at the network of other stationary stations. The most interesting is the anomaly obtained at Andijan station at a distance of 120-130 km from the epicenter of the Alay earthquake on November 2, 1978, with an intensity of 23nTl. Characteristic time is 1 week. The earthquake was predicted from these and other complex observations six hours before the shock [13].

Long-term geomagnetic observations at stationary stations and repeat survey points in the geodynamic testing areas of Uzbekistan have made it possible to identify local changes in the geomagnetic field associated with anthropogenic processes, the preparation of major earthquakes and geodynamic processes in various depths of the Earth's crust and upper mantle.

Repeated site surveys at man-made facilities. In 1969, at the intersection of two routes West and Current, an anomalous 23nTl intensity change was detected at one of the points of the Tashkent test site located above the dome of the underground gas storage. For the first time in world practice, an abnormal change in the magnetic field associated with the mode of operation of the underground gas storage was identified [1-3].

Later on, similar studies were organized in the areas of Charvak reservoir, gas and oil fields (Shurtan, Pamuk, Zevarda, Kokdumulak, etc.), epicenters of major earthquakes that occurred (Tavaksay, 1977), Isfara-Batken 1977, Nazarbek 1980, Gazli 1976, 1984, Chimyon, 1982, Pop, 1984, Hamzaabad, 1985, Izbaskan, 1992, Kamashi, 1999, 2001, Kan, 2011, etc.), the epicenters of the strong earthquakes that occurred.

Research at Charvak Testing Ground is unique in the world in terms of volume and duration compared to others. In total, more than 135 measurement cycles were carried out between 1973 and 2020. A local change in the geomagnetic field related to the reservoir operation regime has been detected. The amplitude of the abnormal changes ranged from 1-2 nTL to 4-6 nTL, and they are reversible, i.e. when the volume of water increases, the value of the geomagnetic field decreases and returns to its level when it decreases. [1,2].

Similar research has been carried out on the territories of the gas and oil fields under development. The dynamics of spatio-temporal anomalous changes in the magnetic field over field structures were studied. In 1990-1991, geomagnetic measurements were performed over the Shurtan field dome at 30 repeat survey points and two stationary magnetic stations. One station (Shurtan-1) was installed above the field dome, while the other (Shurtan-2) was 25 km north of the first station (Abdullabekov et al. 1994). Changes in the local geomagnetic field at the Shurtan-1 station and the repeat survey points are clearly correlated with the volume of gas produced (Q) and changes in reservoir pressure (P). The correlation coefficient between changes in the local magnetic field and operational parameters is 0.98 and 0.95 for Q and P respectively. Anomalous local variations in the geomagnetic field are observed in the main gas extraction zone. The results of repeated geomagnetic studies in 2006-2007 confirmed a trend of abnormal changes in the main gas extraction zone, although reservoir pressure has decreased to 12.1 MPa during this time (Abdullabekov et al. 1994).

Similar results were obtained during geomagnetic surveys in the Pamuk-Zevarda group of oil and gas bearing structures, Kokdumulak and Khauzak-Shady fields. The only difference was the intensity of abnormal changes, which depended on the intensity of hydrocarbon selection from the fields (Tuichiev, 2007).

Conclusion. Therefore, many years of magnetometric research at the geodynamic sites of Uzbekistan have revealed the peculiarities of manifestation of anomalous variations in the magnetic field of anthropogenic and seismo-geodynamic nature:

-anomalous variations in the anthropogenic nature associated with the mode of operation of underground gas reservoirs, high mountain water reservoirs and oil and gas fields were identified.

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