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Tectonomagnetic Effects in the Tajikistan's Seismic Regions

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Observations of local variations of the geomagnetic field in the seismic regions of Tajikistan during the last two decades exhibit regular anomalies prior to earthquakes with a magnitude of 5.0 or greater. These anomalies may be a valuable predictive tool, and important step forward in earthquake hazard mitigation. Four main types of anomalies have been found, depending on how far they are from the epicentral zone; namely in the focus, near, intermediate or far zone. Analyses of the characteristics of the anomalies have been carried out in terms of the piezomagnetic and electrokinetic mechanisms. The dominance of electrokinetic effects in the generation of tectonomagnetic anomalies is suggested by: (1) a phase delay effect in the local geomagnetic field from the far to the near zone; (2) coincidence of the main earthquake shock with the time when the anomaly begins to return to the background level; (3) relatively low magnetic properties of rocks in the region of observation; and (4) detection of tectonomagnetic signals from the deep crust, below the active magnetic layer.

KEY WORDS AND PHRASES: earthquake prediction, tectonomagnetism, rock magnetism, electrokinetics.

Introduction

Based on the high accurate geomagnetic observations for about fifty years, mainly after the implementation of proton precession magnetometers, the geomagnetic method was proved as being very effective to discriminate background noises and to identify pure signals generated by tectonic processes [1–4]. As it is well known, the Earth's magnetic field is composed of a number of constituents with global (1,000–10,000 km, of the order of magnitude), regional (1,000 km) and local (1–100 km) scales. These constituents are generated by electric currents and rock magnetization of the Earth as a whole, and continents, platforms, or a plain geology structure (geoblocks and faults). There are global variations like secular ones generated by the Earth's core and mantle with extremely long periods of hundreds year and more, solar stipulated variations with period of 1 day, 27 days, annual, 11, 22 years and longer periodicities, and by ionospheric and magnetospheric sources as well. These variations have taken place worldwide, not in the seismic active regions only. In the Tajikistan territory, there are specific variations in Earth's magnetic field generated by tectonic processes; that is, the local effect. The special term “tectonomagnetism” was introduced by Nagata before for these variations with tectonic origin [5]. To underline tectonic processes related to seismicity, some authors used terms “seismomagnetism”, and “seis-motectonomagnetism”, “volcanomagnetism”. Tectonomagnetic researches have been conducted in the Tajikistan's seismic regions since early 50s starting with the works by Kalashnikov [6]. There have been found out different kinds of such variations both in space extensions and time variations generated by tectonic and seismic processes. Some of them have a bay-like shape of long-, medium- and short-term effect (depicting space-time strain accumulation and redistribution) and some are step-like (depicting crust offsets).

In almost all cases of detection of tectonomagnetic anomalies a question has arisen on what their nature is. There are several suggestions on the nature of tectonomagnetic effects observed in the Tajikistan seismic regions, mainly of piezomagnetic and

electrokinetic origin [1,6–8], but no definite conclusions have been made about it. The purpose of the present paper is to investigate the origin and nature of the tectono-magnetic anomalies observed in the seismic active regions in Tajikistan.

1. Magnetometric Network and Methods of Observations

The purpose of high accurate magnetic observations is to identify the features of the local geomagnetic field variations which are originated from the seismotectonic processes, in particular earthquake preparation. Network of magnetic field observations was arranged in the high seismic active areas of Tajikistan covering three main geological structures of South Tan-Shan, Tajik Depression and Pamirs. The region of observations includes also Hindu-Kush, Afghan Depression. The following observation sites were operating in the network: Hissar (1), Simiganj (2), Shar-Shar (3), Garm-Rasht (4, the former site of the Institute of Physics of the Earth, Academy of Sciences, USSR), Darband (5), Sultanobod (6), Djerino (7), Chuyangaron (8), Arjinak (9), Djir-gatal (10), Gezan (11), and Shaartuz (12). The number of each observing site is also indicated in Fig. 1 as the corresponding number attached to each black triangle. Here the first order faults are shown, I — Hissar-Kokshaal, II — Darvaz-Karakul, III — Ilyak-Vakhsh, IV — South-Fergana, V — North-Fergana, VI — Vanj-Akbajtal, VII — Pshart-Bartang. These faults are also indicated in Fig. 1. A number of other faults pass far away, so that they are not depicted. Circles mark the epicenters of the most powerful earthquakes with the energy classes $K \geq 12$. The connection between earthquake energy class K and magnitude M was accepted according to the formulas of Rautian [9]. Date, month and year of each earthquake are indicated near the circle of the earthquake epicenter in Fig. 1.

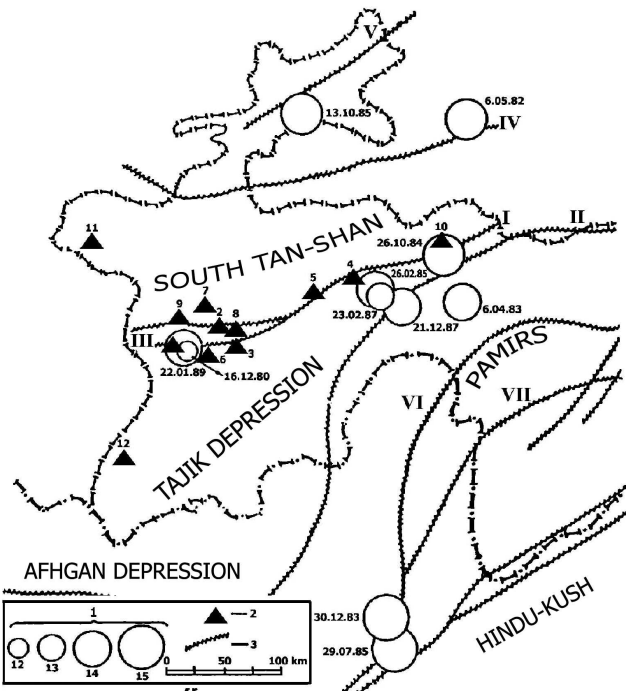


Figure 1. Magnetometric network in Tajikistan: 1 — White circles indicate epicenters of earthquakes for the period of 1980–1990 with K greater than 12, with the radius proportional to the magnitude. The connection between earthquake energy class K and magnitude M was calculated according to the formulas of Rautian (1964). Date, month and year of each earthquake are indicated near the circle of the earthquake epicenter; 2 — Magnetometric sites are indicated by black triangles; 3 — Major faults are indicated with black squiggly lines.

Annually about hundreds of people felt earthquakes occurring in the Tajikistan territory, and several tens of earthquakes in the region of observations are found to exceed the magnitude 5.0. Almost all epicenters are located along the fault zones. In the South Tan-Shan, Tajik and Afghan Depressions all earthquakes are shallow, they can be shallow and intermediate in Pamirs and deep focus in Hindu-Kush. Each site was equipped by the high sensitive magnetometer MPP-1 type (Proton Precession Magnetometer), designed by the Construction Bureau of the Institute of Earth Physics, Russian Academy of Sciences (IEP RAN) in the late 70s and widely used in the Tajikistan's seismic regions. The magnetometers have an excellent stability of the basis, reference level, the 0.1 nT sensitivity and accuracy in measurements of the total intensity of the Earth's magnetic field.

There are special and well-developed methods to eliminate global, extraterrestrial, regional geomagnetic variations and then identify pure signals generated by local tectonic processes, in particular of earthquake preparation. Because tectonic process of an earthquake preparation has been limited in space (local character) [10,11], relevant anomalies in geomagnetic field variations have so far a local character too [1–3]. Variations of local geomagnetic fields exceeding background discrimination level are the anomalies of variations of local geomagnetic field. These anomalies are detected as exceeding of temporal evolution of local geomagnetic field variations by 2 sigma (sigma; standard deviation) criterion. The variations in local geomagnetic fields exceeding the geomagnetic background discrimination level are defined as the anomalies. Local geomagnetic field variations generated by local tectonic processes are named tectonomagnetic effect. Geomagnetic noise stipulates the standard deviation and is mainly a result of differences in electromagnetic induction effects on sites under comparison. Sampling with the intervals 2–10 minutes and averaging of the difference local geomagnetic field on the sites provide the accuracy not worse than 1.0 nT in the identification of anomalies in local geomagnetic field variations [1, 12].

2. Regularities in the Appearance of Tectonomagnetic Anomalies

There were the following regularities found out in the appearance of anomalies in Tajikistan's seismic regions [1, 7, 8, 13]

- 1) Values of the effects are within 10 nT .
- 2) There are different zones of tectonomagnetic effects; focus, near, intermediate and far zones in the sense of appearance of tectonomagnetic effects. The time duration of the anomaly for the definite earthquake is decreasing while moving from the focus zone to the far one (see Figs. 2–4).
- 3) In the near, intermediate and far zones the temporal dependence of a tectonomagnetic anomaly has a bay-like shape and the main shock moment is when the anomaly begins to return to the background level.
- 4) In the focus zone the shape of an anomaly can be either bay-like or sign-alternative bringing space mosaic distribution.
- 5) In the near zone the duration of an anomaly and its mean radius where it appears, are increasing loglinearly versus the magnitude M of a preparing earthquake. This provides a basis to attribute these anomalies to medium ones according to the classification by Rikitake [14].
- 6) In the middle zone the duration of an anomaly for the definite earthquake descends with distance of preparing earthquake's epicenter.
- 7) In the far zone the duration of an anomaly for the definite preparing earthquake is shorter than in the middle and it is less than one month.
- 8) The anomalies exhibit space anisotropy.
- 9) Sometimes anomalies appear that have a trapeze shape or an offset with sharp variations up to the first nT during the first days, which reflect assumingly earth crust creep processes.
- 10) In the vicinity of large water reservoirs there is an amplification of the tectonomagnetic anomalies stipulated assumingly by ground electrokinetic currents.

The anomaly in the variations of local geomagnetic field started in April-May 1980 at the sites of Hissar, Simiganj, Shar-Shar, and Sulatnobod before the Sultanobod earthquake on 16 October 1980, whose results are shown in Fig. 2. Darband site did not fall in the near zone, so that it was chosen as a reference. Hissar site (1 in Fig. 2) was only the west side station relative to the epicenter on the Ilyak-Vakhsh fault and the sign of the anomaly turned up positive in contrast to the ones at other sites.

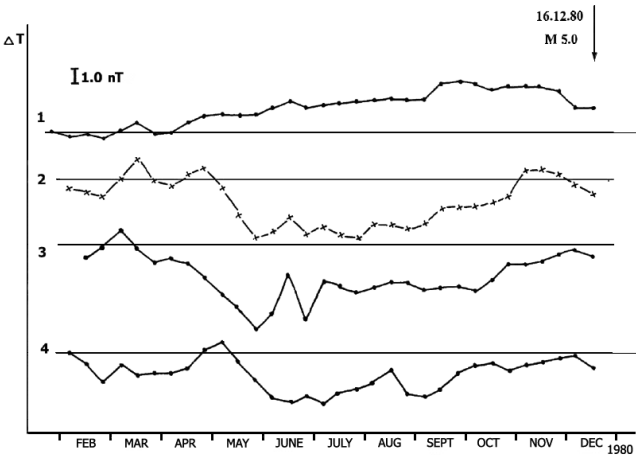


Figure 2. An example of the temporal variation of tectonomagnetic anomalies in the near zone for the Sultanobod earthquake on 16 Dec. 1980 with magnitude $M = 6.0$: Arrow indicates occurrence of the main shock. The numbered curves depict geomagnetic data for four different sites: 1 — Hissar, 2 — Simiganj, 3 — Shar-Shar, and 4 — Sultanobod. Darband is the reference site. See Fig. 1 for site locations. Bar shows 1 nT, which is also the 2 sigma interval.

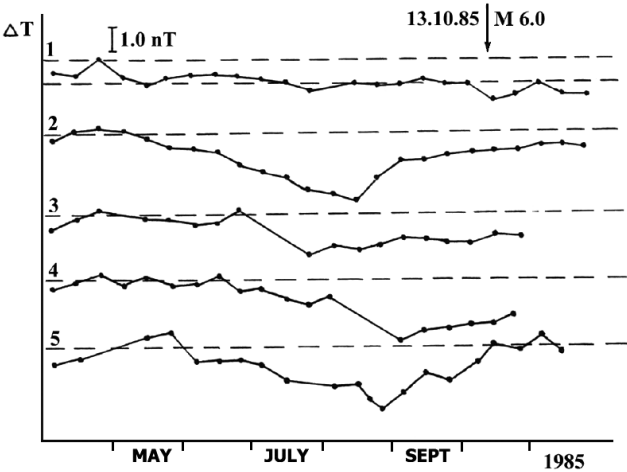


Figure 3. An example of the temporal variation of tectonomagnetic anomalies in the middle zone for the Kayrakkum earthquake on 13 Oct. 1985: Arrow indicates occurrence of the main shock. The numbered curves depict geomagnetic data for four different sites: 1 — Darband, 2 — Djerino, 3 — Chuyangaron, 4 — Arjinak, and 5 — Sultanobod. Hissar is the reference site. See Fig. 1 for site locations. Bar shows 1 nT, which is also the 2 sigma interval.

Anomalies in the variations of local geomagnetic field before the Kayrakkum earthquake on 13 October 1985 ($M = 6.0$) are found to start in May–July 1985 and were registered at the sites at Darband, Djerino, Chuyangaron, Arjinak, and Sultanobod. Fig. 3 illustrates the temporal evolution of geomagnetic field data at different observing sites. The farthest Hissar site was chosen as the reference. In spite of larger

earthquake magnitude, the Sultanobod station exhibited relatively shorter time duration of the anomaly. Kayrakkum earthquake epicenter was not in the near zone, but in the intermediate zone. It took some time for the tectonomagnetic signal to propagate from the focus to the sites, while stations will begin to register coming anomalies.

Fig. 4 illustrates the anomalies in the local geomagnetic field variations, which show bay-like temporal variations before strong earthquakes with magnitude greater than 5.0. The anomalies were registered at the sites of Darband, Djerino, Chuyangaron, and Sultanobod. Hissar site was taken as the reference. Almost all of these anomalies are found to precede earthquakes with magnitudes greater than 5.0 with the epicenters in the Hindu-Kush zone. One anomaly precedes an earthquake on 23 August 1985 ($M = 7.2$) with the epicenter in Takla-Makan. No sizable local earthquakes have been taken place during this period. The duration of anomalies turned out to be even shorter than that for the anomalies before the Kayrakkum earthquake on 13 October 1985. It can be stipulated by a very far distance of the focus preparation zone from the magnetometric sites, and it is a far zone for the registration of anomalies in the local geomagnetic field. It takes more time for the geomagnetic signal to propagate from the focus preparation zone to magnetometric sites which begin to register the anomalies with significant delay.

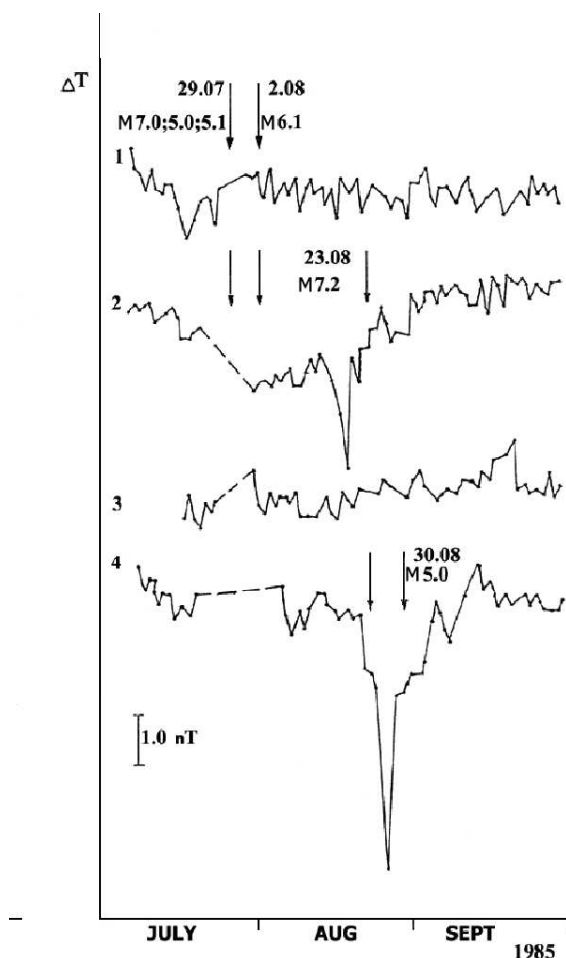


Figure 4. Pamirs-Hindu-Kush earthquakes and an example of the temporal variations of tectonomagnetic anomaly in the far zone. Arrows indicate occurrences of the main shocks: The numbered curves depict geomagnetic data for four different sites: 1 — Darband, 2 — Djerino, 3 — Chuyangaron, and 4 — Sultanobod. Hissar is the reference site. Bar shows 1 nT, which is also the 2 sigma interval.

In the first and fourth curves in Fig. 4 sharp variations up to several nT during the first days have been taking place along with the bay-like anomalies. It can be suggested that such an anomaly runs depict Earth's crust creep events. It is a striking fact that the main shocks coincide with the time when the anomaly begins to return to the background level independently of the zone where anomalies have appeared: near, intermediate, or far.

3. Analysis of Piezomagnetic and Electrokinetic Mechanisms

Let us consider possible mechanisms of the tectonomagnetic anomalies on the basis of contemporary representations on the seismic tectonic processes [10, 11]. Tectonomagnetic anomalies are stipulated by two general classes of phenomena; piezomagnetic and electrokinetic effects under the action of mechanical, tectonic stresses [1–3, 7, 15].

According to the general representations about seismic tectonic process, the integrant stress in the earthquake preparation zone has a bay-like shape [10, 11]. Starting from some moments after the beginning of earthquake preparation, when stresses will be increasing up to high enough values, we would expect the appearance of a tectonomagnetic anomaly. Stress accumulation in the preparation zone is conveyed by the anomaly's growth in space. After stress accumulation reaches critical values "inclusion" begins decay on two space parts. Outer one with reducing stresses and inner with continuing rising stresses. In local geomagnetic variations it depicts as extreme point. Integrant "inclusion" stresses became reducing at the expense of outer part. Integrant field intensity reduces accordingly. In the inner stresses continue rise compressing pores and cracking medium. In the local geomagnetic field it depicts as returning of the anomaly to a background level of a regular state. Inner part going on concentrate in shear zone where further shifting of adjacent geoblocks at the main earthquake shock takes place after large enough stress have accumulated. The main shock pertains to the stage of approaching of anomaly to this level. Therefore behavior of an anomaly in the near zone straightly reflects tectonic stresses in the preparation zone. Time delay in anomaly's appearance in the middle zone and more delay in the far one mean that one observes an effect of the anomaly source propagation. Magnetometric site in the near zone begins to register an anomaly immediately so far as tectonic stresses reach enough intensity. Later on, when anomaly sources are approaching the middle zone, the tectonomagnetic anomalies turn up appearing now over here. Anomalies in the far zone turn up later because sources are required more time to propagate and reach this zone. Besides would it these effects are effects of propagation, then the main shock moment in the middle and far zones would not be coinciding with the anomaly run to a regular state level. In that case the moment of earthquake shock would be coincided with the times when the anomalies are already over. Thus the tectonomagnetic effects are short distance effect rather than long distance one [7].

For the Kairakkum earthquake, by using the empirical dependencies [1, 7] one can obtain 140 km for the average radius R of the area of anomaly appearance and duration of the anomaly T in the near zone would have to be 630 days. Because of retarding effect the duration turned out to be less. The speed turns out to be from 30 to 150 m/day, reflecting anisotropy in source propagation. The highest propagation speed was found in the direction where the sites (6–9) are grouped, lowest speed is in the direction only to the south site (5) (Fig. 1). Besides, site (5) is located closer to the transition from Tajik depression to Pamirs and therefore where earth crust is several times thicker than in the sites (6–9). Probably that is why source propagation in the direction to the site (5) is constrained. For the Hindu-Kush earthquakes the tectonomagnetic anomalies registration sites are turning up located in the far zone at the distances about 300–400 km. It follows that speeds of anomaly propagation are within the interval from 40 to 1,000 m/day.

Rock magnetizations and magnetic susceptibilities in the area of investigation are relatively low, not exceeding 10–5 CGS and 10–4 CGS respectively, piezomagnetic coefficient is about 10–4 bar⁻¹ (1 bar = 100 kPa). Stresses in the focus and near zones

amount to about 104 bars, which are enough, in principal, to generate piezomagnetic effect up to the first nT. But these values under the tectonic stress descend in the stress inhomogeneous space within the radius r [10, 11]

$$\lg r[\text{km}] = 0.43M, \quad (1)$$

r is equal to about 120 km for the earthquake with M equal to 5. So as Eq. (1) shows, they are insufficient to generate such anomalies in the middle and in the far zone. Besides, the preparation zone of the deep focus Hindu-Kush earthquakes with the hypocenters in the depth 100–300 km, scarcely comprises magneto active layer located in the upper crust 20–40 km width where temperatures do not exceed Curie point for the natural magnetite, titanomagnetites, etc.

Electrokinetic mechanism of tectonomagnetic anomalies is stipulated by the underground fluid filtration through porous and fractured crust medium. There are a plenty of both surface and underground waters in the Tajikistan region. There are both pure and mineral waters widespread. The waters salt concentration is up to 600 mg/liter at some sites. The natural underground waters are very good electrolytes and promote appearance of electrokinetic phenomena. In terms of underground water filtration from the earthquake source preparation space the delay of tectonomagnetic effects in the near and far zones can be interpreted by limitedness of filtration speed.

There were natural observations carried out in the vicinities of Nurek water reservoir [7] and Surkhob river [1, 12] to investigate local magnetic field variations. It was found that seasonal variations of the water reservoir level from about 220 m in summer to about 270 m in winter were correlating, with the coefficient 0.85, with the local geomagnetic field variations up to 5 nT in the sites 4 km aside. Variations of the river water level within 5 m correlated, with the coefficient about 0.9, with the local geomagnetic field variations up to 4 nT at the sites 200 m aside the river bed. Obviously, the several meter layer water weight loading on the water reservoir and the river bottom ground is very low to create anomalies up to 1 nT in the order of magnitude generated by means of piezomagnetic effect. In contrast, the underground active water filtration and high water mineralization in the vicinities of Nurek water reservoir and Surkhob river, allow us to explain tectonomagnetic anomalies observed as simple calculations based on double electric layer terms [1, 12] or ion concentrations difference [7] confirm.

Conclusions

Researches on the variations of local geomagnetic field anomalies carried out in the Tajikistan seismic region, have demonstrated that they are correlating with the tectonic earthquake preparation processes. Investigations of the regularities obtained and analysis of piezomagnetic and electrokinetic mechanisms for these tectonomagnetic anomalies have shown that low rock magnetization and magnetic susceptibility make piezomagnetic mechanism insufficient to explain the tectonomagnetic anomalies. But, natural explorations in the vicinities of Nurek water reservoir and Surkhob river and calculations have confirmed that electrokinetic mechanism is effective enough to interpret tectonomagnetic anomalies observed in the Tajikistan seismic region.

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Тектономагнитные эффекты в сейсмических районах Таджикистана

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Наблюдения над вариациями локального геомагнитного поля в сейсмически активных районах Таджикистана привели к обнаружению аномалий перед землетрясениями с магнитудой 5,0 и выше, которые в соответствии с современными классификациями предвестников землетрясений относятся к среднесрочным. Обнаружено четыре основных типа аномалий соответственно тому, как далеко расположен пункт наблюдения от эпицентра готовящегося землетрясения, именно, в очаговой, близкой, промежуточной или дальней зонах. Анализ параметров аномалий был выполнен на основе представлений о пьезомагнитном и электрокинетическом механизмах. Превалирование электрокинетического эффекта в генерации тектономагнитных аномалий в сейсмоактивных районах Таджикистана обусловлено следующими фактами: (1) — аномалии в вариациях локального геомагнитного поля при переходе от близкой к дальней зонам отстают по фазе; (2) — моменты землетрясений совпадают с заключительной фазой возвращения аномалии к фоновому уровню в её временном ходе во всех четырёх зонах; (3) — магнитная восприимчивость и индуктивная намагниченность горных пород в районе наблюдений имеют относительно низкие значения; (4) — регистрируются тектономагнитные эффекты глубокофокусных землетрясений, очаговые области которых расположены глубже магнитоактивного слоя, где температуры выше температур Кюри основных естественных магнитных минералов.

Обнаруженные аномалии в вариациях локального геомагнитного поля вместе с другими соответствующими геофизическими данными могут быть включены в системы прогнозирования землетрясений.