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GEOPHYSICS

Sensitive Zones of the Earth's Crust as a Manifestation of Dynamics of the Interaction of Blocks

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"Sensitive zones" of the Earth's crust, where high-amplitude distant earthquake forerunners and postseismic effects are observed in different geophysical (geochemical and hydrogeodynamic) fields, were distinguished for the first time two decades ago [1, 2]. Voluminous data gathered by the present time confirm and provide new insights into our understanding of "sensitive zones" as specific structures confined to the most mobile contacts between major blocks of the Earth's crust. Responses of these structures to weak perturbations are manifested as very intense, high-gradient variations in parameters of different geophysical fields. New data on sensitive zones are considered in this work in the light of an actively developing line of investigation, namely, dynamics of the deformation of block massifs (see [3] and others). These investigations are based on instrumental observations of deformation during underground nuclear explosions and mining. Peculiarities of geophysical fields in interblock contact zones may serve as good indicators of such processes and supplement direct measurements of deformation.

To distinguish sensitive zones of the Earth's crust, one should analyze data on amplitudes and epicentral distances of earthquake-related effects. We studied forerunners of earthquakes mainly based on hydrogeodynamic parameters—groundwater level variations, for which numerous observations are available. These parameters can be determined by methods of noise registration and elimination, as well as determination of the deformation component and the strain-sensitive effect [4]. High-amplitude effects include forerunner- and earthquake-related parameters, deviation of which, relative to background values, are one to two times higher than the amplitude of the majority of such effects. The analysis of more than 180 forerunners, which preceded 112 of the strongest earthquakes (M from 4.5 to 7.8) in different regions, showed that amplitudes of groundwater level variation did not exceed 0.3 m in the majority of observations. Therefore, groundwater level variations exceeding 3 m were taken as high-amplitude effects. Such effects account for 6.2% of the total number of observations. We have introduced the notion "distal effects" for effects observed beyond a zone where calculated strains during the earthquake preparation or manifestation period exceed the value of earth tide strains (10^{-8}).

To date, several sensitive zones are known in the territory of the former Soviet Union and northern China [2, 5, 6], e.g., the Kopet Dagh zone (Turkmenistan,) the Fergana zone (Uzbekistan), central and southern zones of Armenia, and northeastern China. The table presents the main parameters of high-amplitude and distal effects related to strong earthquakes in the mentioned zones. In addition to the effects registered by groundwater characteristics, intense variations in different parameters (surface inclination, nontidal gravity variations, geomagnetic field gradient, helium release, and so on) were observed in these zones before and after earthquakes.

Especially strong response of different fields to distortions of the stress-and-strain state of the medium was detected only in sensitive zones. This effect is not an integral feature of all the high-seismicity areas. Let us cite some examples. Short-term forerunners of two events (the Petrovsk earthquake; February 26, 1983; $M = 5.2$, and the Dzhirgatal earthquake, October 26, 1984; $M = 6.4$) were registered at the Garm test site (Tajikistan), where groundwater level was monitored in six boreholes [7]. At epicentral distances of 13–40 km, the amplitude of groundwater level variations was 2–8 cm before the Petrovsk earthquake and did not exceed 32 cm during the earthquake. Before the Dzhirgatal earthquake, groundwater level variation of 3 cm was registered only in one borehole, located at the epicentral distance of 75 km, and was absent in the closer borehole. However, the effect of the Dzhirgatal earthquake, with an amplitude of 16 m, was registered in the Fergana sensitive zone at a distance of 180 km (table).

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Principal characteristics of earthquake-related high-amplitude variations in groundwater level, discharge, and temperature

Borehole	Filter or shaft depth, m	Variation time	Amplitude of variations in groundwater level (*H*), discharge (*Q*), and temperature (*T*)	Variation mode	Earthquake date	Magnitude	Epicentral distance, km
			Kopet Dagh zone				
Nizhnyaya Firyuza, 2g [5]	57–1210	Aug. 31, 1975–Apr. 20, 1976	$H = 7.2$ m	Abrupt fall in groundwater level with partial recovery	Apr. 8, 1976	7.0	560
″	″	Apr. 25, 1976–Oct. 27, 1976	$H = 8.4$ m	Abrupt fall with recovery	May 17, 1976	7.3	560
″	″	July 28, 1990–Aug. 18, 1990	$H = 15.2$ m	Abrupt then gradual fall without recovery	Aug. 18, 1990 Aug. 30, 1990 Sept. 9, 1990	5.7 5.1 5.6	220 90 90
Dzhanakhir, 3v [5]	1300–1600	Aug. 16, 1988–Aug. 17, 1988	$H = 11.4$ m	Abrupt fall with partial recovery	Aug. 16–17, 1988	4.7	200
Kazandzhik, 1gs [10]	513–958	Dec. 11, 1986–Jan. 8, 1987	$H = 8.6$ m	Fall with recovery	Dec. 26, 1986	5.0	220
″	″	Jan. 18, 1987–Sept. 7, 1987	$H = 57.0$ m	Fall without recovery	Sept. 7, 1987	5.4	70
			Fergana zone				
Andizhan, 1 (A. N. Sultankhodzhaev et al., 1986)	550	Oct. 24, 1984–Oct. 27, 1984	$H = 16$ m	Peak rise and fall	Oct. 26, 1984	6.4	180
Khodzhaabad, 745 (G. A. Mavlyanov et al., 1981)	1860	Sept. 28, 1978–Nov. 2,1978	*Q* at 12 l/s to 0	Cessation and recovery of water discharge	Nov. 2, 1978	6.8	160
			Armenia				
Kadzharan [6]	–	Aug. 17, 1999	$Q = 0.8$ l/s	Peak rise of discharge	Aug. 17, 1999	7.4	1380
			Northeastern China				
Yue, 42 [5]	540–707	May 21, 1976–July 28, 1976	$H > 10$ m	Groundwater level fall with subsequent abrupt rise and discharge	July 28, 1976	7.8	12
Ksyun, 3 [5]	974–1020	May 20, 1976–May 24, 1976, July 20, 1976–Aug. 1, 1976	$T = 5.2$°C $T = 5.4$°C	Abrupt decrease and recovery of temperature	July 28, 1976	7.8	200
Mo, 1 [5]	3173–3184, 3341–3343	July 21, 1976–July 27, 1976	$H = 20$ m	Sudden oil gusher	July 28, 1976	7.8	240
Din, 8-1 [5]	146–293	Mar. 3, 1988–Nov. 15, 1989	$H = 6.7$ m	Fast fall in water level accompanied by a slower fall	Oct. 19, 1989	5.8	370

In another high-seismicity region (central Japan), observations in a series of boreholes showed that groundwater level variations related to strong earthquakes generally did not exceed 0.5 m. The groundwater level only fell in one borehole, which started before the earthquake and continued after the event with a greater amplitude [8].

The sensitive zones are characterized by a common tectonic setting—located at conjugations of more or less large blocks of the Earth's crust with different structures and recent movements in various directions. Such zones are marked by a high concentration of stress in the crust. High-amplitude or distal effects of earthquakes may appear in response to strong stresses and corresponding strains and/or high strain-sensitivity. For parameters cited in the table, we calculated strains inferred during the earthquake preparation period. It was found that strains during the preparation period were ~10^{-4} only in the epicentral zone of the Tien Shan earthquake (July 28, 1976; $M = 7.8$), in the area of Borehole Yue 42. In Boreholes Ksyun 3 and Mo 1, where high-amplitude earthquake forerunners were observed, calculated strains slightly exceeded 10^{-6}. In Boreholes Nizhnyaya Firyuza 2g (September 9, 1990; $M = 5.6$) and Kazandzhik 1gs (September 7, 1987; $M = 5.4$), such deformation during the preparation period was 10^{-7}. In all the remaining cases, the calculated values are lower or close to the values of strains caused by earth tides (10^{-8}). Such strains may induce only a very weak response of groundwater. The values mentioned above show that high-amplitude effects could in most cases be caused only by strains substantially greater than the calculated values. These strains should act in fault zones, where the observation boreholes are located.

The influence of strain sensitivity is especially high in the manifestation of high-amplitude and distal effects, which can be produced under certain conditions by rather weak strains that, nonetheless, exceed the value of earth tide strains. Elevated strain sensitivity is often observed in fault zones. This is characteristic of sensitive zones of the Earth's crust confined to contacts of major blocks. These blocks are characterized by individual features of different geophysical fields. However, interblock contact zones are marked by high gradients of parameters in each field and favorable conditions for high strain sensitivity.

The discussed behavior of sensitive zones is well manifested in the comprehensively investigated Kopet Dagh zone, which extends from west-northwest to east-southeast along the northern margin of the Kopet Dagh Range (Fig. 1). The Kopet Dagh zone, where epicenters of many strong earthquakes are concentrated, is related to the Main Kopet Dagh fault, which separates the alpine fault region of the Kopet Dagh Range from the epi-Hercynian Turan Platform. Figure 1 demonstrates epicenters of some strong earthquakes and boreholes located in the fault zone, where high-amplitude hydrogeodynamic forerunners of these earthquakes were registered. A previous analysis of short-term hydrogeodynamic effects registered in the Main Kopet Dagh fault showed that short-term motions, which generated these effects, are caused by the disturbance of block stability in the course of preparation of (or owing to) earthquakes, and by other geodynamic processes [9]. It is particularly remarkable that rather high groundwater level variations (up to 1 m) were in many cases related to weak earthquakes ($M = 3$–4), which took place 200–450 km away from the observation boreholes.

Among the voluminous data on hydrogeodynamic effects registered in the Kopet Dagh zone, the results of observations in the Kazandzhik borehole group carried out in five boreholes located on a 2-km profile intersecting the Main Kopet Dagh fault are of particular interest [10]. Forerunners of earthquakes were registered only in Borehole 1gs, which penetrated the fault, and responses to earthquakes were not revealed in other boreholes located in different blocks on each side of the fault (Fig. 2). Two forerunners with relatively small magnitudes (5.0 and 5.4) were registered in Borehole 1gs (table, Fig. 2). The groundwater level dropped by 57 m prior to the second earthquake. Such substantial amplitude of a hydrogeodynamic forerunner is a unique phenomenon in worldwide research. The observation results were confirmed by a thorough testing, which involved the drilling of a complementary borehole. The mechanism of this effect is related to interaction of major crustal blocks.

Figure 3 demonstrates schemes of variations in strains and hydrogeodynamic conditions in this sector of the Main Kopet Dagh fault. As shown in Figs. 2 and 3, absolute heights of groundwater levels measured in boreholes make up 104–107 m in the Kopet Dagh high-pressure system and 0–22 m in the low-pressure system of the foredeep. The fault separates two hydrogeodynamic systems. Judging from variations in groundwater levels, preparation of the earthquakes of December 26, 1986, and September 7, 1987, was accompanied by tensile strains. The strains resulted in the disturbance of the barrier function of the fault, and a hydraulic connection appeared between two hydrogeodynamic systems. Tension prior to the first earthquake caused an 8.6-m groundwater level fall in Borehole 1gs. When the fault recovered the initial state (this is demonstrated by almost complete restoration of the level), the groundwater level continued to fall intensively and the amplitude reached 57 m by the time of the second earthquake. The last groundwater level fall to the position occupied in the low-pressure system was an irreversible process, suggesting the retention of residual tensile strains in the fault.

The quoted scheme surely gives only a general characteristic of strains in the fault zone. Such an interpretation based on the analysis of the hydrogeodynamic regime complies with ideas on neotectonics of the Kopet Dagh fault zone that underwent shear strain

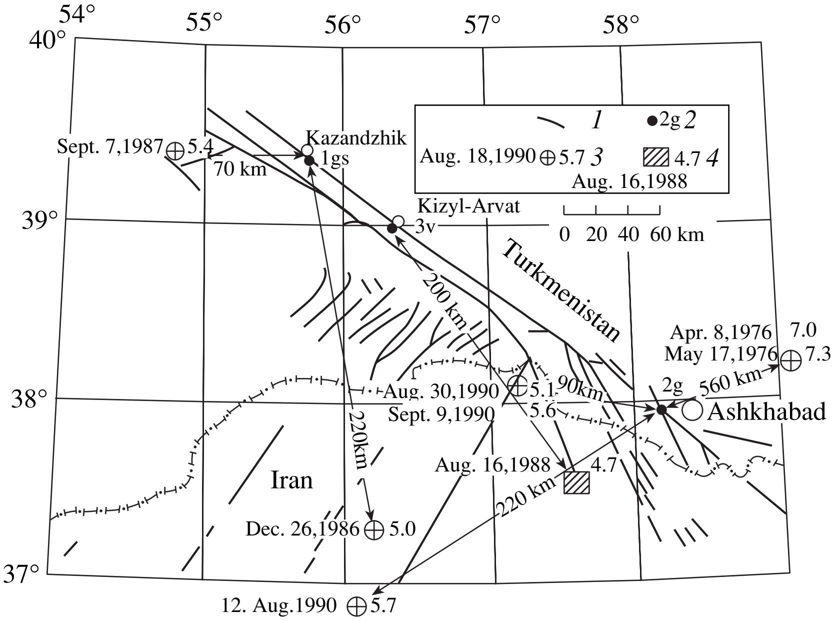

Fig. 1. Scheme of the Kopet Dagh "sensitive zone". (*1*) Deep-seated faults (after V.N. Krymus and M. Berber'yan); (*2*) observation borehole and its number; (*3*) earthquake epicenter, its date, and magnitude; (*4*) epicenter of the Bondzhnurd earthquake swarm, its date, and magnitude of the strongest shock.

owing to convergence of the Turan and Iran (Arabian) plates (V. N. Krymus and V. I. Lykov, 1969; V. A. Sidorov and Yu.O. Kuz'min, 1989; and others). The mentioned tensile strains should be considered in correlation with long-term compression of the fault zone. Such interpretation of hydrogeodynamic effects of both earthquakes suggests that strains in the fault zone substantially exceeded the calculated values. Second, the very high amplitude of the forerunner is caused by specific conditions of the fault zone (very high strain-sensitivity of the hydrogeodynamic field).

Thus, data on sensitive zones of the Earth's crust indicate that they represent the most dynamic contacts of blocks subjected to great strains. Such structures are characterized by instability and nonlinear characteristics shown up in responses to stresses. Geophysical fields in the studied zones are characterized by a very high strain-sensitivity. Therefore, they exhibit strong responses to even weak strains. The sensitive zones also include mobile contacts between blocks, where responses of geophysical fields to weak strains are lacking due to low strain-sensitivity and only responses to strong strains at contacts between blocks is manifested.

Deformation characteristics of sensitive zones correspond to their counterparts in the dynamics of block massifs [3]. Intense deformations in interblock spaces are caused by faults (interlayers of lesser strength or higher jointing and porosity). Interblock contacts are characterized by nonlinearity of strain characteristics at low-amplitude impact [11]. This is also confirmed by responses of hydrogeodynamic and other types of fields to preparation and aftershocks of distal or weak earthquakes, as in the cases mentioned above.

The data available show that responses of different geophysical fields to seismicity-related disturbances in sensitive zones of the Earth's crust are mostly manifested at contacts between the largest blocks. One such example is the Kopet Dagh sensitive zone, located at the junction of major blocks and marked by the most intense responses of geophysical fields to the preparation and manifestation of earthquakes with great epicentral distances. This feature of sensitive zones—dependence on a hierarchy of blocks and interblock contacts—corresponds to the inference based on instrumental observations, suggesting an inverse relationship between rigidity of interblock contacts and dimensions of relevant blocks [11]. For instance, normal rigidity of interblock boundaries decreases from 350–450 MPa/mm in small blocks (10–20 m long) to 0.03–0.06 MPa/mm in major faults separating large blocks (100–200 km long).

New data confirm that interblock junctions can lose stability even at weak external strains [12]. The loss is also possible at a small energy contribution related to the preparation of a distal earthquake. Preparation of a strong earthquake probably can be accompanied by relative displacements of rather large blocks. In this case, forerunners with great amplitude appear at interblock contacts in sensitive zones, but such effects are weaker or absent within the blocks.

The author of the present paper previously identified forerunners of the second type, which appear if stability at interblock contacts is violated over a vast area [2]. Such forerunners are a response of geophysical fields to rearrangement of the stress-and-strain state rather than signs of destruction prior to seismic fracture. This kind of rearrangement accompanies the preparation of a

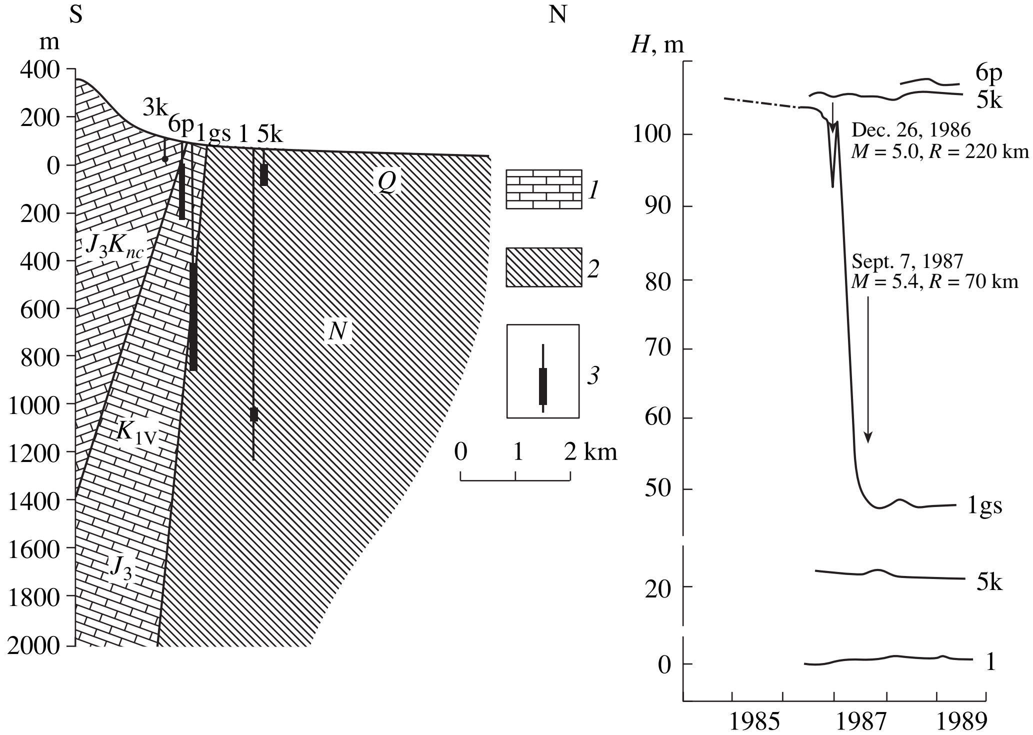

Fig. 2. Geological section of the Main Kopet Dagh fault zone near Kazandzhik and variations in the groundwater level (based on observation boreholes in 1985–1989). Geological section (at the left): (*1*) Limestones; (*2*) sandy–clayey deposits; (*3*) filter or shaft position; Diagrams of groundwater level prior to and after earthquakes (at the right).

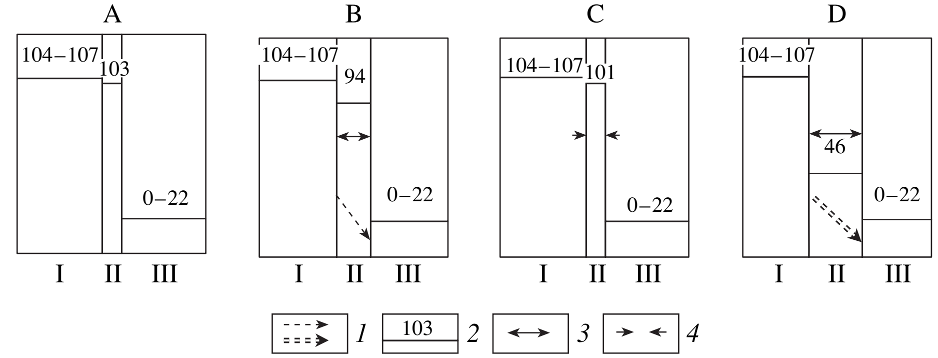

Fig. 3. Scheme of the hydrogeodynamic regime in the Kazandzhik sector of the Main Kopet Dagh fault and its state in 1985–1989 (not to scale). (I) Kopet Dagh block; (II) Main Kopet Dagh fault zone; (III) block of the Kopet Dagh foredeep and Turan plate. (*1*) Seepage of variable intensity; (*2*) groundwater level, absolute height (m); (*3, 4*) strains: (*3*) extension, (*4*) compression. Periods: (A) 1985 (Aug.)–1986 (Sept.); (B) earthquake of December 26, 1986; (C) 1987 (early January); (D) after earthquake of Sept. 7, 1987.

strong earthquake and proceeds over a vast area of the Earth's crust. The data on sensitive zones of the Earth's crust, related high-amplitude and distal effects, and specific features of the dynamics of interblock contacts confirm the existence of forerunners of the second type. The study of high-amplitude effects in sensitive zones showed that *such effects are inevitably followed by strong earthquakes over the surrounding vast area.* The most intense phase of such effects is usually observed within some days or months prior to the earthquake at an epicentral distance of 70–560 km (table). Hence, such effects may serve as rather reliable short- and medium-term forerunners of strong earthquakes.

REFERENCES

1. I. G. Kissin, Dokl. Akad. Nauk SSSR **281**, 304 (1985).
2. I. G. Kissin, Fizika Zemli, No. 6, 3 (1988).
3. G. G. Kocharyan and A. A. Spivak, *Dynamics of the Deformation of Block-Type Rock Massifs* (Akademkniga, Moscow, 2003) [in Russian].
4. I. G. Kissin, Fizika Zemli, No. 8, 58 (1993).

5. I. G. Kissin, V. M. Belikov, G. A. Ishankuliev, et al., Earthquake Predict. Res. **2**, 89 (1993).
6. S. Yu. Balasanyan, Geol. Geofiz., No. 1, 83 (2005).
7. L. I. Bokanenko, O. N. Galaganov, and V. P. Perederin, Fizika Zemli, No. 5, 72 (1999).
8. C.-Y. King, S. Azuma, G. Igarashi, et al., Geophys. Res. **104** (B6), 13073 (1999).
9. I. G. Kissin, V. M. Belikov, and G. A. Ishankuliev, Tectonophysics **265**, 313 (1996).
10. I. G. Kissin, V. M. Belikov, and G. A. Ishankuliev, Dokl. Akad. Nauk SSSR **314**, 1099 (1990).
11. V. M. Kostyuchenko, G. G. Kocharyan, and D. V. Pavlov, Fiz. Mezomekhanika, No. 5, 23 (2002).
12. G. G. Kocharyan, A. A. Kulyukin, V. K. Markov, et al., Fiz. Mezomekhanika, No. 1, 23 (2005).