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On the Long-Term Prediction of Strong Earthquakes in Central Asia and the Black Sea–Caspian Region

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Abstract—This paper discusses the long-term prediction of two strong, $M \approx 7.5$ (intensity of 9–10), Central Asia earthquakes of 1976 and 1992 that occurred in the Gazli (Turan plate) and Suusamyr (North Tien Shan) areas, respectively. Long before each of the events, earthquakes of such strength were predicted in this region, and three main prognostic parameters, namely, the earthquake magnitude ($M > 7.0$), position of potential sources, and expectation time intervals, were determined. In both cases, the potential sources were located in areas where earthquakes of such magnitudes had not occurred previously and where seismic intensities did not exceed an MSK-64 value of 6. The prediction studies within the Turan plate, distinguished by very weak seismicity, were based on long-term strainmeter observations of the recent tectonic fracturing process near the epicentral zone of the expected earthquake. The prediction studies in the seismically active North Tien Shan region were based on the analysis of its seismic regime patterns and prevailing distances between earthquake epicenters. A new method is proposed for the monitoring of regional seismogeodynamic processes, and results of studying time variation patterns in the occurrence of earthquakes of various magnitudes are discussed. The current prediction of $M > 7.0$ earthquakes in Central Asia and the Black Sea–Caspian region is presented.

INTRODUCTION

Starting the development of the earthquake prediction problem in the first half of the last century, Academician G.A. Gamburtsev was convinced that the nature and conditions of earthquake occurrence can be successfully studied solely on the basis of a multidisciplinary approach using geological, geophysical, and seismological data. Believing that a close relation exists between the earthquake prediction research and seismic zoning, he emphasized that particular attention should be paid to the diversity of seismic and tectonic conditions in a given region. In his last publication devoted to this problem, Gamburtsev [1955] wrote: "Seismological data should be checked and complemented by tectonic analysis and deep geophysical survey (analysis of gravity and magnetic anomalies and deep seismic sounding of crust). Tectonic and seismological studies play the main role in the seismic zoning of large territories… The current state of seismology, dominated by seismic statistics, is unnatural. Later, as our knowledge of the nature of earthquakes and conditions of their origination will be improved, the role of seismic statistics should decrease and, accordingly, well-established physical and geological criteria should play the principal role." In his note "The Problem of Earthquake Prediction" written in March 1954, Gamburtsev suggested that "the earthquake prediction criteria … should be established on a new basis provided by the physical approach to the study of the general deep process involving the development of crust" both in individual regions and throughout the Earth.

Further research in seismic zoning and earthquake prediction showed that spatial–temporal and seismogeodynamic features indicating the preparation of large seismic events should actually be treated within the framework of a system encompassing various hierarchical levels of seismic activation on global, regional, local, and source scales [Ulomov, 1983, 1993a, 1993b]. Larger seismic sources and accordingly higher magnitudes of related earthquakes imply larger volumes of the geological medium involved in the preparation process of these earthquakes. Therefore, the study of the source-seismicity seismic regime and the assessment of seismic hazard in a given territory should take into account specific dimensions of genetically interrelated geostructures of seismically active regions. As regards the largest seismic sources, such geostructures can extend for a few thousands of kilometers and their width can reach a few hundreds of kilometers [Ulomov, 1993b]. In any case, the size (diameter) of a territory that can include the source of an earthquake of a given magnitude is at least four times larger than the dimensions of the source studied.

The temporal development of seismic and seismological processes is also studied on long- and short-term levels: the higher the magnitude of earthquakes studied, the longer the time interval to be analyzed.

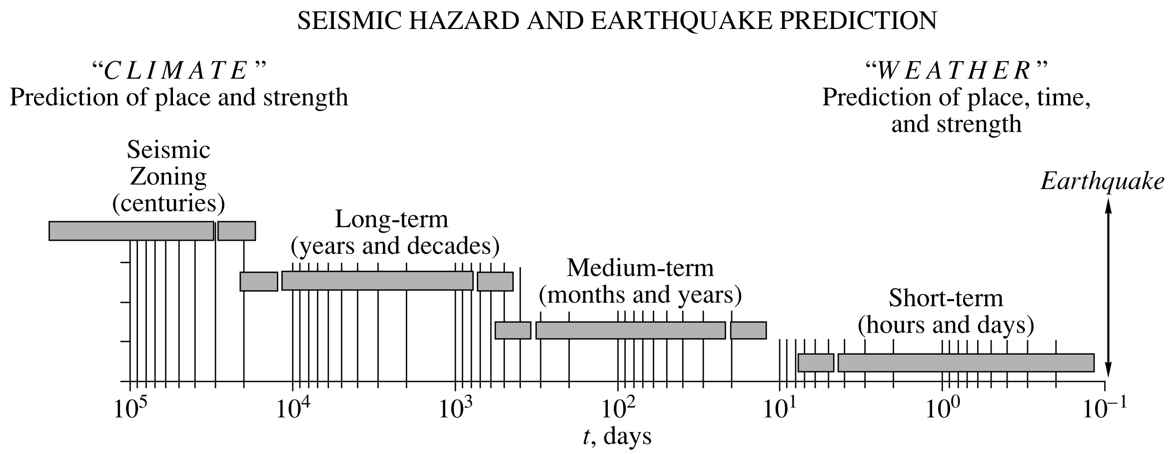

Fig. 1. Types of the seismic hazard prediction. The bidirectional arrow indicates the occurrence time of the predicted earthquake. Horizontal bars show the expectation time (given in parentheses) of prediction realization.

By analogy with meteorology and with regard to space–time scales, a region as a whole is usually characterized by a "seismic climate," whereas the "seismic weather" of the region appreciably varies over certain time intervals (Fig. 1). (Other similarity features between seismology and adjacent areas of Earth sciences are also known. Thus, meteorology deals with motions of air fluxes; oceanology, with motions of water masses; and seismology, with motions of lithospheric plates and deformation of solid shells of the Earth.)

The mapping of the seismic climate imitates seismic zoning, which predicts the place and maximum strength of earthquakes possible within a given region. Because the seismic hazard assessment is based in this case not on the prediction of each individual seismic event but on the seismic effect created by the set of such events, the knowledge of their occurrence times seems to be unnecessary. However, the probabilistic approach underlying the construction of new maps of general seismic zoning of North Eurasia (GSZ-97 maps) involves the presence of the time factor in the form of the probability of seismic events occurring within given time intervals [Ulomov and Shumilina, 2000].

The prediction of seismic weather implies that, along with the place, magnitude, and intensity of a future earthquake, its occurrence time should also be predicted. Three types of prediction are usually dealt with:

long-term prediction, if an earthquake is expected to occur in a large area, and its expectation time is as long as years and decades;

medium-term prediction, if an earthquake is expected to occur in a relatively small area, and its expectation time is a few months or years;

short-term prediction, if the time moment of an earthquake must be predicted with an accuracy of a few days or even hours.

On a log scale, these time intervals are similar in length (see the abscissa axis in Fig. 1). The relations between earthquake characteristics (magnitude, source size, etc.) and dimensions of areas involved in their preparation obey similar (power and fractal) laws (e.g., see [Ulomov, 1974, 1983, 1998]).

Seismic zoning is the best-developed approach. As regards the earthquake occurrence time, its short-term prediction is least effective, notwithstanding the large body of experimental data on very diverse precursors accumulated over many decades [Mogi, 1985; Ma Zongjin *et al.*, 1989; Sobolev, 1992]. Evidently, successful solution of the seismic prediction problem is, in a broad sense, directly related not only to the progress in theoretical and applied studies of the three types of prediction but also to their proper coordination. Accordingly, prognostic observations should be successively conducted, starting from seismic zoning through the identification of potential earthquake sources and further to the search of their precursors.

Such successive studies were conducted in Central Asia in relation to the monitoring of the Gazli earthquakes of 1976 within the Turan plate [Ulomov, 1972, 1974, 1983] and identification of potential sources and long-term prediction of a large seismic event in the Tien Shan region [Ulomov, 1990a, 1990b, 1991], where the Suusamyr earthquake of 1992 occurred afterward. In this connection, the seismic regime was also studied in Central Asia regions involved in the preparation of such strong events as the Karatag (1907), Chatkal (1946), Khait (1949), and Markansu (1974) earthquakes, comparable in magnitude with the Gazli and Suusamyr earthquakes [Ulomov, 1990a, 1990b].

All these investigations were based on a regional approach including the deep structure, geological history, seismotectonics, and seismogeodynamics of each seismically active region, as well as prevailing distances between epicenters of earthquakes of various magnitudes and their recurrence periods [Ulomov, 1987, 1993].

Various "extraregional" and "formal," small- and large-scale methods and techniques of localizing potential earthquake sources have been extensively studied [Reisner and Ioganson, 1993; Polyakova and Medvedeva, 1991, 1999; Polyakova *et al.*, 1992, 1993, 1995]. Applying the method of analogies to the recognition of potential sources, some authors used 0.3° × 0.5° and smaller map cells, whereas rather large (about 4° × 4°) "elementary cells" were used by others. The expectation time of seismic events was not predicted in most of these works, and the structure of the medium often is not discussed at all.

Below we focus on the Gazli and Suusamyr earthquakes, which are similar not only in magnitudes but also because their prognostic indicators appeared about ten years before their occurrence times (which is incidentally consistent with their magnitudes). Moreover, in both cases, not only possible areas but also expectation times of these events were involved in prediction studies. It is also important that the occurrence areas of these earthquakes (the Turan platform and North Tien Shan Mountains) substantially differed in geological and seismogeodynamic conditions.

Results previously derived by the authors and used in this study included data obtained within the framework of the international program "Assessment of Seismic Hazard in Countries of the Black Sea basin and Central Asia" of the Ministry of Industry and Science of the Russian Federation.

DYNAMICS OF THE TURAN PLATE CRUST AND THE LONG-TERM PREDICTION OF THE GAZLI EARTHQUAKES

The geological history of Central Asia, whose crust was almost completely derived from the material of the young Turan platform (plate), makes this territory unique with respect to seismogeodynamic research; the region includes nearly all types of geodynamic interactions between lithospheric plates, ranging from rift-like Turan structures and Tien Shan transforms to collisional structures subduction zone relics in the Pamir–Hindu Kush and mid-Caspian areas [Ulomov, 1974]. The Turan plate extends from the mountainous Tien Shan structures in the east, encompasses the northern Caspian area in the west, and reaches mountainous Kopet Dag structures in the south. Being a kind of buffer zone between the Eurasian, Indian, and Arabian lithospheric plates, the Turan plate is successively involved in geodynamic movements developing from the Tien Shan in the southeast and from the Kopet Dag in the southwest. These movements accommodate the pressure exerted by the Indian and Arabian plates, respectively. Seismogeodynamic processes of the recent and neotectonic activation manifest themselves most clearly in such frontal transitional zones.

A high-magnitude swarm of the Gazli earthquakes of 1976–1984, which were the largest seismic events known in the Kyzyl Kum Desert, occurred in the Turan plate in the southern part of the area between the Amu Darya and Syr Darya Rivers, in the zone of the NE-trending Central Kyzyl Kum faults orthogonal to the NW continuation of the South Tien Shan (Fig. 2). The table presents main parameters of these earthquakes: occurrence time, epicentral coordinates, focal depth H (km), surface wave magnitude M_s, and strike azimuth of main seismic source faults Az^0. Until the Gazli earthquakes, all of the officially adopted maps of general seismic zoning (GSZ) of the former USSR attributed this area to the 5-intensity zone of seismicity. The same estimates were adopted by the editorial board of the GSZ map that was prepared in the Institute of Physics of the Earth for publication in 1976 but was *ad hoc* (and formally) updated and was published only in 1978 under the name GSZ-78 [*Karta* …, 1984]. New studies devoted to the construction of basically different, probabilistic GSZ-97 maps were carried out under the guidance of V.I. Ulomov [Ulomov, 1999]. According to the GSZ-97 map, the Turan plate and many other regions of North Eurasia are seismically more hazardous than was suggested by the GSZ-78 map [Ulomov and Shumilina, 1999–2000].

The Gazli earthquakes were felt as far as 1000 km from their epicenters, and their ground motions were observed nearly all over the territory of Central Asia and even in the East Caucasus. Their intensity associated with the second, strongest earthquake of May 17, 1976, reached 4 on the eastern coast of the Caspian Sea. An MSK-64 intensity of 9–10 was observed in the epicentral area. Another significant aspect of the Gazli earthquakes is that a unique accelerogram of an underground $M = 7.3$ shock was obtained in their epicentral area and recorded ground motion accelerations exceeded the gravity acceleration for the first time in the worldwide seismological practice (the vertical and horizontal components amounted to 1.26g and 0.9g, respectively).

The Kyzyl Kum Desert in the central part of the Turan plate is characterized on the whole by very weak seismicity, although the Chiili (1929, $M = 6.4 \pm 0.3$), Tamdy-Bulak (1932, $M = 6.2 \pm 0.3$), and two Kyzyl Kum (1968, $M = 5.1 \pm 0.2$) earthquakes were recorded in the northern part of the Amu Darya and Syr Darya interstream area.

The geological structure of the Turan plate is relatively simple. A thick sedimentary cover overlies a folded basement, the depth to which varies from 1–3 km in the north of the plate to 2–5 km in its central part and reaches 6 km along the Kopet Dag in the south. Low rock masses continuing the South Tien Shan to the west (the Nuratau, Tamdytau, and Bukantau ridges) are occasionally exposed in the central Kyzyl Kum Desert. The topography of the crust base, which is a parameter characterizing the tectonic development of the region,

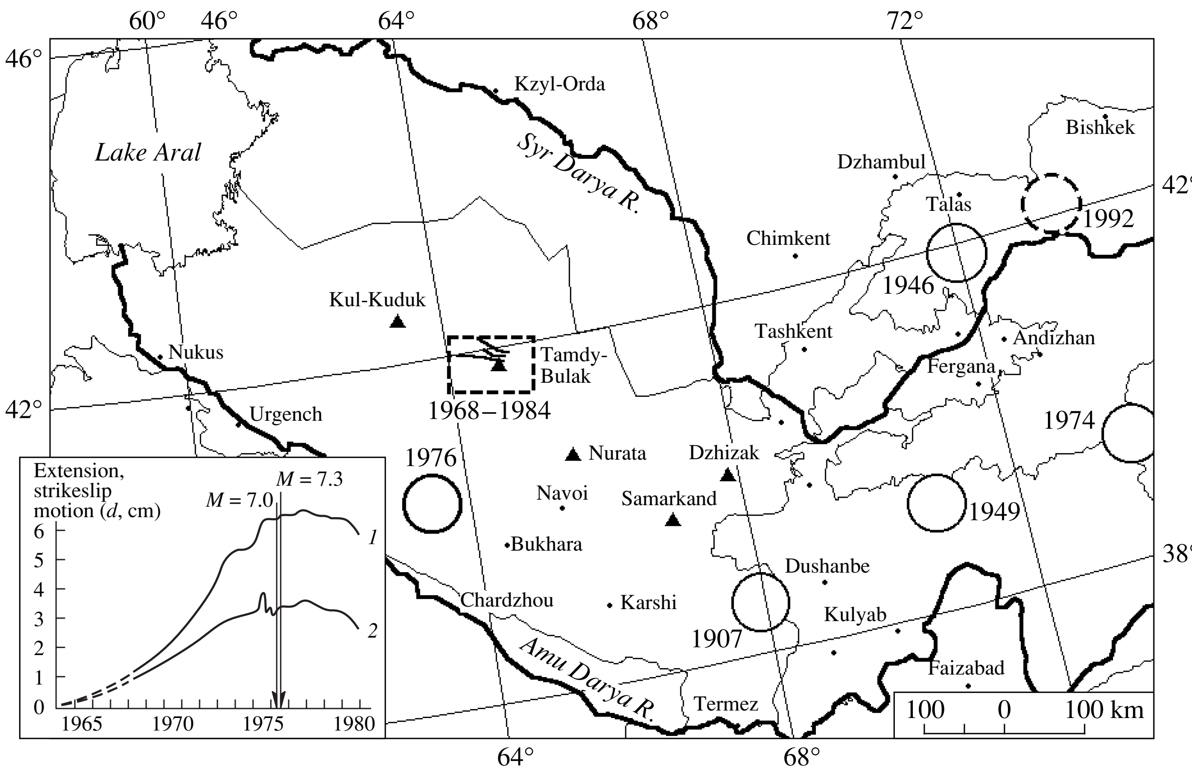

Fig. 2. Long-term prediction of the Gazli earthquakes of 1976. The circles are sources of earthquakes of similar magnitudes ($M = 7.5 \pm 0.2$) that occurred before the Gazli events: Karatag, 1907; Chatkal, 1946; Khait, 1949; and Markansu, 1974. The dashed circle is the source of the Suusamyr earthquakes of 1992. The dashed rectangle is the Tamdy-Bulak prediction research area; three lines within this area surface fissures that were observed visually from 1965 through 1967 and instrumentally from 1968 through 1984. Plots showing time variations in the relative motions of walls of these fissures: (*1*) extension; (*2*) strike-slip motion. Vertical arrows mark the time moments of the Gazli earthquakes. The solid triangles are seismic stations.

reaches depths of 45–50 km here. Interaction and deformation of geoblocks in this transitional zone is directly related to the dynamics of the lithosphere underlying the Pamirs, Tien Shan, and Kopet Dag region. As shown below, the complex interaction of lithospheric plates surrounding the Turan plate can finally produce rift-like extension structures and strike-slip faults in the central Kyzyl Kum area [Ulomov, 1974].

Anomalies of recent slow deformations of the crust and lithosphere are known to be the most promising prognostic indicators of forthcoming earthquakes. They are primary in relation to all (or nearly all) other of the known precursors of seismic events. As is evident from observations, recent deformations can be most informative in earthquake prediction studies in low-seismicity regions such as the Turan plate. The most remarkable success of strainmeter observations is the long-term prediction of the Gazli earthquakes of 1976 published ten years before their occurrence; afterward, this prediction was further developed and updated until the very earthquakes [Karzhauv and Ulomov, 1966; Ulomov, 1974; and others].

Thus, an active fracturing process of tectonic origin started developing in the vicinity of the Tamdytau Ridge and in the surface area of the Tamdy-Bulak settlement, and the analysis of this process provided a basis for the prediction of a large earthquake in this region [Karzhauv and Ulomov, 1966]. In this connection, a special research area was adjusted in 1968 for strainmeter observations here, and seismic stations at the Tamdy-Bulak, Kulkuduk, Nurata, and Dzhizak localities were installed for the first time in this region (see Fig. 2). Giant fissures of ancient origin were discovered in the northern part of the Tamdy-Bulak research area; these fissures are perfectly preserved in the sandy desert due to their periodical rejuvenation. These fissures, as well as less significant ones on the surface of the Tamdy-Bulak settlement, were found to be very sensitive indicators of recent slow tectonic movements in the region. All of the fissures studied yield evidence of horizontal extension and right-lateral

Table

Date	φ °N	λ °E	H, km	M_s	Az, deg
April 8, 1976	40.33	63.67	25	7.0	95
May 17, 1976	40.28	63.38	30	7.3	15
March 20, 1984	40.38	63.36	15	7.2	45

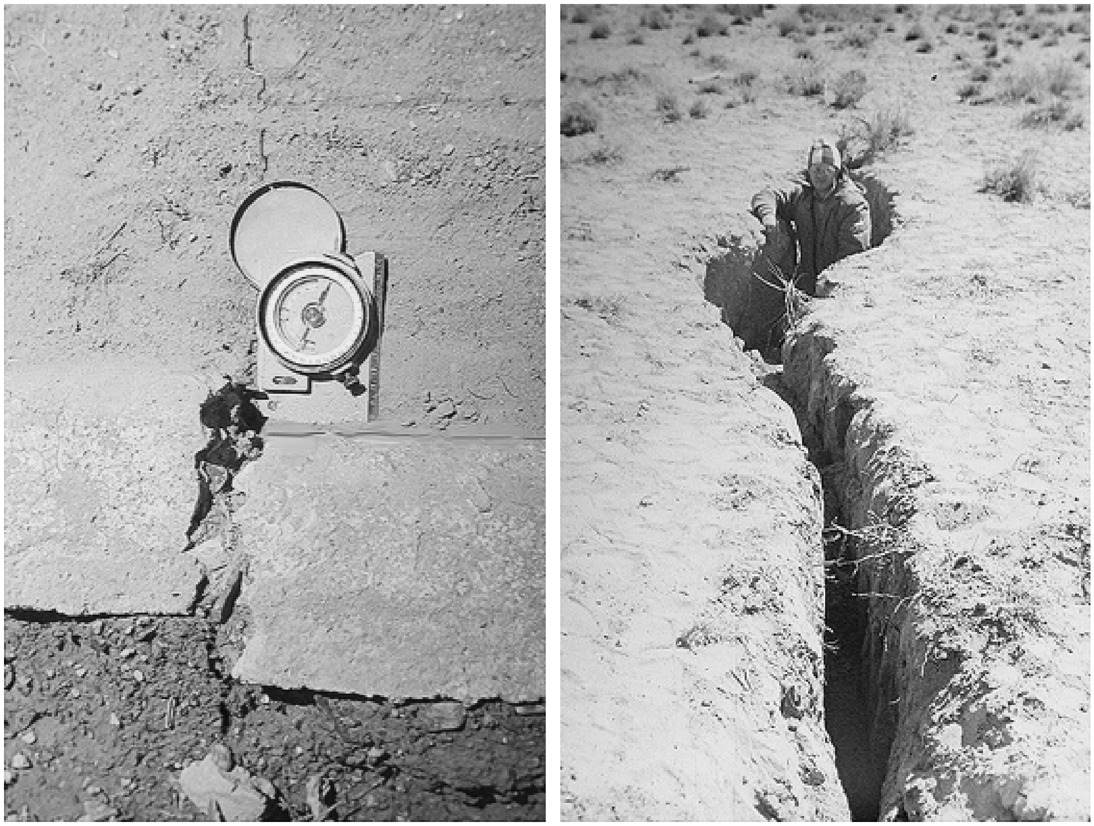

Fig. 3. Extension and right-lateral shear deformations visible at the pavement border crossed by one of numerous fissures present on the territory of the Tamdy-Bulak settlement (left plate) and giant fissures in the research area (central Kyzyl Kum desert) north of the settlement.

deformations prevailing in this part of the Turan plate (Fig. 3).

Based on the method of reduction of Neogene–Quaternary geodynamic movements, maps showing vector and scalar fields of recent and contemporary geodynamic crustal movements in the Pamirs–Tien Shan and Turan regions were constructed and published long before the Gazli earthquakes [Ulomov, 1972, 1974]. These studies established that these fields closely correlate with the regional structure of seismicity and gravitational field and interpreted the relationship between the shape of the earthquake recurrence plots and strength and dynamic properties of crustal and lithospheric rocks. Ulomov [1972, 1974] also emphasized that the SZ-78 map of seismic zoning adopted at that time was at variance with the actual seismogeodynamic conditions in this area of western Uzbekistan, and the seismic hazard of the Turan plate was underestimated.

Seismometric and strainmeter observations revealed a regular development pattern of the active fracturing process in the central Kyzyl Kum Desert. As seen from the plot at the bottom left corner in Fig. 2 illustrating the development of this process in time, the Kyzyl Kum fissures widened by 5 cm over the 1966–1973 period, and the relative displacement of their walls (right-lateral slip) amounted to 3 cm. During the next year, the widening of the fissures slowed down, rapidly increased in 1975, and slowed down again a few months before the Gazli earthquakes of 1976, when some of the fissures started to intensely close, which was accompanied by left-lateral slips. The anomaly in the strike-slip component of the fissure wall displacement was particularly pronounced in 1975 (a rapid right-lateral slip followed by an equally rapid left-lateral one). A series of shocks with magnitudes of 3.5–4.0 was recorded over the same short time interval in the future epicentral area; these shocks can be classified as manifestations of very weak foreshock activity. The recent tectonic movements changed their sign about a year before the Gazli earthquakes of 1976 separated by 40-day interval; the earthquakes occurred within the aforementioned central Kyzyl Kum orthogonal seismogenic zone described in [Ulomov, 1972, 1974].

As seen from Fig. 2, the earthquakes occurred not within the research area, as was previously expected, but 150 km to the south. However, the source preparation area of the Gazli earthquakes had a diameter δ (km) nearly four times as large as the size of the source itself

L (km), which is consistent with the relations [Ulomov, 1987]

$$\delta_M = 10^{(0.6M - 1.94)}, \quad (1)$$

$$L_M = 10^{(0.6M - 2.5)}. \quad (2)$$

Thus, if a cumulative magnitude of M_c = 7.5 is accepted for the three Gazli earthquakes (i.e., representing them as one event), we obtain L = 100 km and δ = 363 km. This size (a radius of about 200 km) of the preparation area is corroborated by distinct manifestation of strain precursors in the Tamdy-Bulak prediction research area.

Therefore, it is evident that the published long-term prediction of large earthquakes in the central Kyzyl Kum area has proven correct.

We should note that double and triple earthquakes are characteristic of sources located within the solid crust typical of platform regions and orogen-to-platform transition zones. Here, peculiar dynamics of the crust and lithosphere as a whole creates and destroys the strongest bonds between rocks at disjunctive nodes of intersecting or branching faults [Ulomov, 1974, 1988]. For example, such were even moderate Kyzyl Kum earthquakes with $M = 5.1 \pm 0.2$ that occurred on March 13 and 14, 1968, immediately north of the Tamdy-Bulak research area. The Karatag earthquake of 1907, which occurred in the transition zone between the South Tien Shan orogen and the Turan plate, also consisted of two shocks with M = 7.4 and 7.3 separated by a 20-min interval. Among the most significant seismic events of this type are the three well-known New Madrid earthquakes with magnitudes of more than 8.0 that occurred successively in the period from December 16, 1811 to February 7, 1812, on the plain territory of the United States. It is noteworthy that they occurred within rifting structures of the Mississippi River valley. Other examples can also be cited.

The multiyear fracturing process nearly stopped after the seismic events of 1976, and strainmeters, even with a tenfold sensitivity, recorded no strain variations at all. Subsequent, much weaker deformations were recorded about a year before the third, M = 7.2, Gazli earthquake, which took place after eight years nearly in the same source and apparently released the residual elastic stresses and deformations in this source area.

Repeated high-precision geodetic measurements made in the epicentral zone before and after the Gazli earthquakes revealed three local surface uplifts with amplitudes of 83, 76, and 75 cm; these uplifts, spaced at about 20 km and displaced relative to each other in the western direction, were located above the respective sources of the successive earthquakes. The horizontal amplitude of tectonic movements occasionally exceeded one meter. According to seismological data, focal mechanisms of the Gazli sources extending to depths of 20–25 km are thrust/strike-slip faults motions on which are due to horizontal compressive and nearly vertical tensile stresses. The faults of the first (April 8, 1976) and third (March 20, 1984) earthquakes appear to have ruptured in the NW direction, whereas a southwestward motion on the fault plane of the main shock of May 17, 1976, has been reliably established, which coincides with the strike of the orthogonal central Kyzyl Kum seismogenic fault zone [Ulomov, 1972, 1974]. Apparently, the strike-slip component was right-lateral in the sources of the first and third earthquakes, and it was left-lateral in the source of the main earthquake, which also agrees with the direction of compressive stresses exerted by the Arabian plate (via the Kopet Dag Range).

The origin of the rift-like structure of fissures in the central Kyzyl Kum area north of the epicentral zone of the Gazli earthquakes may be due to strike-slip motions of the same type as those responsible for the creation of pull-apart fractures and the Baikal rift zone [Molnar and Tapponier, 1975]. The presence of horizontal tensile stresses is supported by both the observed fracturing process and focal mechanisms of the aforementioned Kyzyl Kum earthquakes of 1968 that occurred immediately north of the Tamdy-Bulak research area. Their sources are characterized by normal faults and by clearly expressed horizontal tensile and nearly vertical compressive components of tectonic stresses.

THE SEISMICITY VARIATION AND THE LONG-TERM PREDICTION OF THE SUUSAMYR (NORTH TIEN SHAN) EARTHQUAKE

The Suusamyr, M = 7.5, earthquake of August 19, 1992, occurred on the southern slope of the Suusamyr Ridge on the territory of Kyrgyzstan (Figs. 2 and 4). Various aspects of this earthquake were extensively studied [Dzhanuzakov *et al.*, 1997; Mellors *et al.*, 1997; Ghose *et al.*, 1997; and others]. Its epicenter determined from instrumental data was located at (42.07° N, 73.63° E), and its hypocentral depth was 25 km, which agrees well with its macroseismic consequences. The seismic fault motion of an E–W strike was of the reverse/strike-slip type and took place on a fault plane steeply dipping south [*Regional* …, 1992; Dzhanuzakov *et al.*, 1997]. Similar to many other earthquakes (e.g., the Spitak (1988), Racha (1991), and Neftegorsk (1995) events), the source of the Suusamyr earthquake arose not along the main tectonic faults, as might be expected, but at an angle with them and was located in less significant structures. Supposedly, creep motions producing the most intense deformations and "skewing" adjacent faults prevail in such cases along main faults. A similar example is the Chatkal earthquake of 1946, which arose on the secondary Atoinok fault rather than along the major Talas-Fergana strike-slip fault (Fig. 4).

The Suusamyr earthquake was felt throughout Central Asia. The 5-intensity zone extended for more than 800 km and included Tashkent (the capital of Uzbekistan) in the west and Almaty (the former capital of

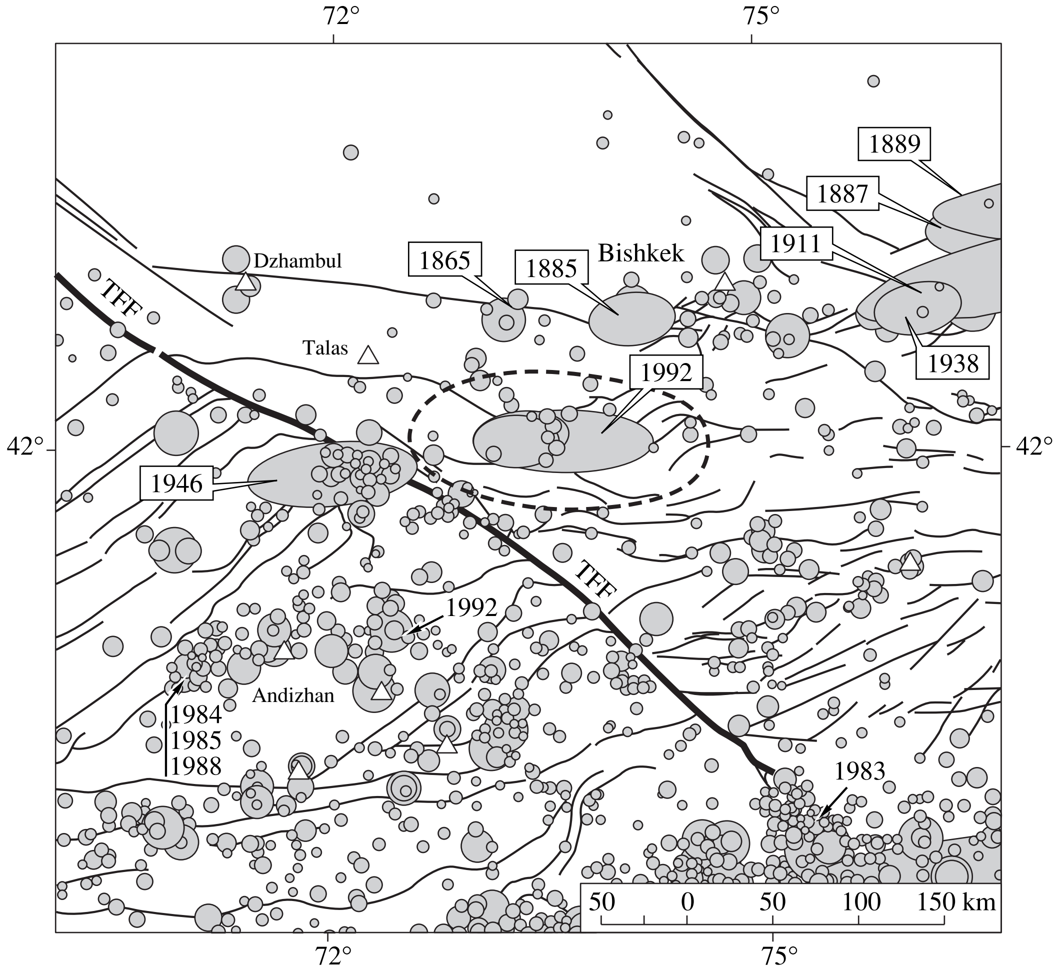

Fig. 4. Seismic setting in the source area of the Suusamyr earthquake of 1992. Ellipses are sources of earthquakes with $M = 7.0 \pm 0.2$ (extending for 50 km), $M = 7.5 \pm 0.2$ (100 km), and $M = 8.0 \pm 0.2$ (200 km) known from ancient times through 1993. The occurrence years of these earthquakes are shown within rectangles. The circles of decreasing diameters are sources of earthquakes with magnitudes of 6.5 ± 0.2 and less. The arrows show the position of weak earthquake swarms that arose before the Suusamyr earthquake. Their origination times (in years) are also shown. The broken line bounds the area of seismic quiescence. The thick line shows the trace of the Talas-Fergana fault (TFF); the thin lines are smaller, seismically active faults; and the triangles are towns.

Kazakhstan) in the east. The seismic intensity reached 9–10 in the epicentral area, and this indicated once more the imperfection of the then-adopted SZ-78 map of the former USSR, according to which the epicentral zone of the Suusamyr earthquake was located at the boundary between 7- and 8-intensity zones [*Karta* …, 1984] (Fig. 5). The imperfection of the SZ-78 map is also indicated by the Spitak (1988), Zaisan (1990), Racha (1991), Khailinskoe (1991), and Neftegorsk (1995) earthquakes, whose intensities exceeded the values shown in the map by 2–3. Our studies related to the creation of a new set of North Eurasia GSZ maps (GSZ-97) showed that a main drawback of the SZ-78 map was the fact that its creation was not based on a systematic approach to the assessment of seismic hazard and any fundamental seismogeodynamic model of earthquake sources [Ulomov, 1999; Ulomov and Shumilina, 1999–2000]. At that time, each republic of the former USSR and each region of the Russian Federation created its own fragment of the SZ-78 map, applying its own approach and analyzing only its own territories. Afterward, these separate and sometimes mismatching fragments were somehow joined at the Institute of Physics of the Earth (Moscow).

According to its magnitude, the Suusamyr earthquake was the largest seismic event in the western part of the North Tien Shan, and the only stronger event here was the Chatkal ($M = 7.5$) earthquake of 1946; as mentioned before, the latter occurred on the Atoinok fault, which is a branch of the major Talas-Fergana right-lateral fault located at the junction of geological structures of Caledonian and Hercynian ages. Only two historical earthquakes (Belovodsk, 1885, $M = 6.9$ and Merke, 1865, $M = 6.4$) took place within a 200-km radius from the Suusamyr earthquake epicenter, determining the zone responsible for such an earthquake; their sources

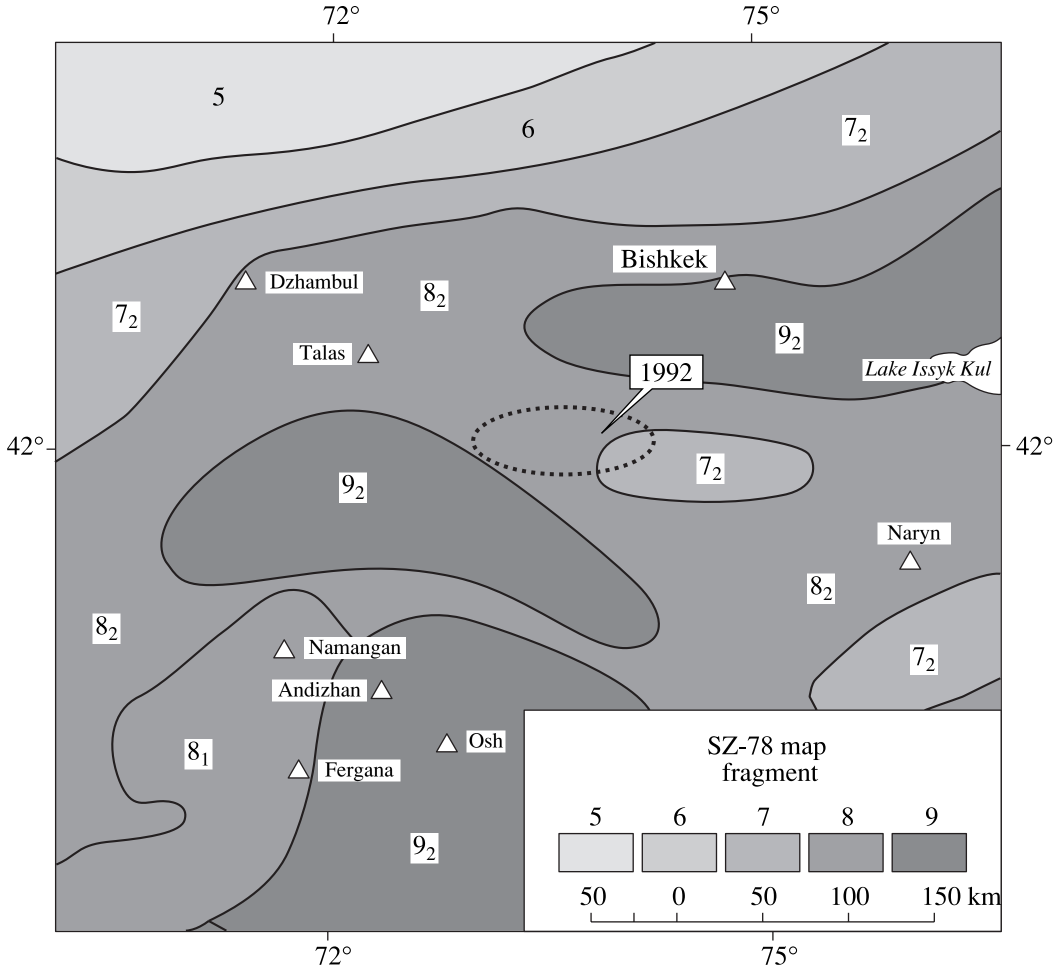

Fig. 5. Position of the Suusamyr, 1992 earthquake source (ellipse) in the seismic zoning map of the former USSR (SZ-78). Indexes 1 and 2 of the seismic intensity values indicate the average recurrence periods of the respective events equal to one event per 100 years and one event per 1000 years, respectively. The triangles are towns.

were located west and southwest of Bishkek (see Fig. 4). (Here we should note that the most reliable data on the seismicity of Central Asia are available only since 1865, i.e., since Russia's annexation of Turkestan.)

In the recent past, the most significant earthquakes in the North Tien Shan region took place east of Bishkek in offshoots of the Zailiiski and Kungei Alatau, north of Lake Issyk Kul. Some of their sources are seen in the upper right quadrant of Fig. 4: the Vernyi (1887, $M = 7.3$), Chilik (1889, $M = 8.3$), and Kemin-Chu (1911, $M = 8.2$) earthquakes; a weaker ($M = 6.9$) earthquake of 1938 occurred southeast of Bishkek.

The Central Asia region is characterized by a 40-year periodicity of seismic activation, best constrained by $M \geq 7.0$ earthquakes (Fig. 6) [Ulomov, 1974, 1990a]. About 25 years are seismically active (rectangles *I*, *II*, and *III* in Fig. 6), and 15 years are relatively quiescent (cross-hatched intervals). A similar 40-year cyclicity was noted farther to the south in the Himalayas [Mogi, 1985], which is additional evidence of a close seismogeodynamic relationship between these two large regions and is beneficial to the long-term prediction of strong earthquakes in Central Asia.

Ulomov [1990a] illustrated the seismic activation periodicity in the form of a plot (see Fig. 6) and estimated the occurrence probability of an $M \geq 7.0$ earthquake in Central Asia for the period from 1989 through 1995. He also calculated the probability that an earthquake will occur at a time moment t_2 (years) after the preceding real event occurring at a time moment t_1:

$$P(t_1, t_2) = 1 - \exp[-n(t_2 - t_1)]. \quad (3)$$

Here, n is the average flux density (recurrence) of seismic events per unit time (year) within the two last cycles (II and III). A thick horizontal bar indicates the 1989–1995 period of expectation for such an earthquake to occur in the region. By the moment of publication of the aforementioned paper, the probability of such an earthquake $P(t)$ is seen to have been close to

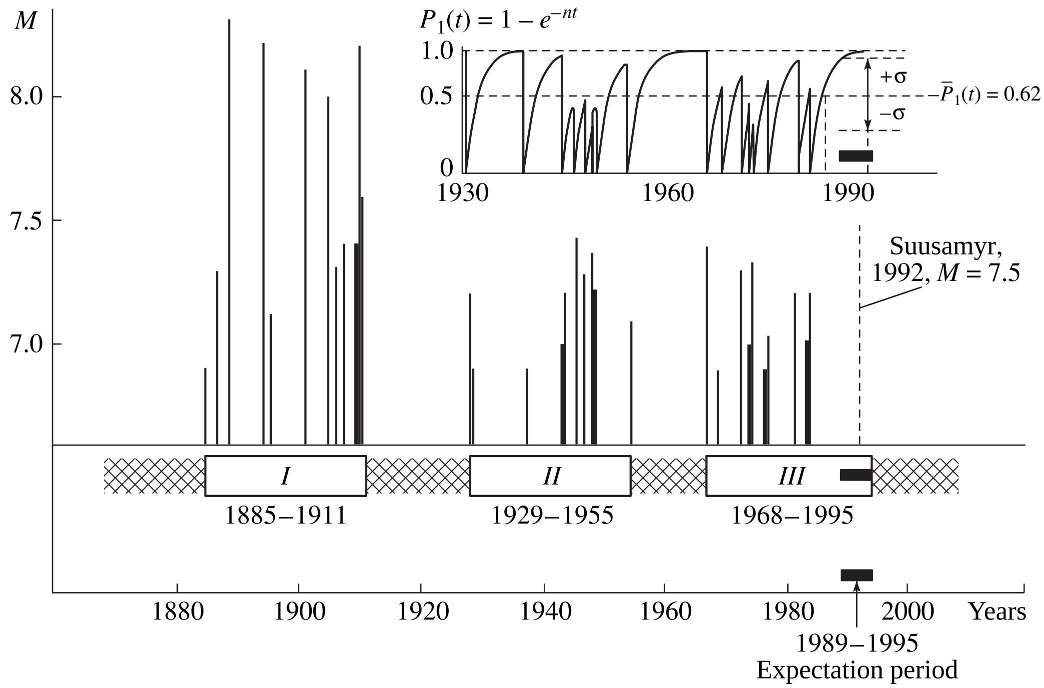

Fig. 6. Periodicity of seismic activation and the probability of earthquakes with $M \geq 7.0 \pm 0.2$ to occur in the Central Asia region [Ulomov, 1990a]. The vertical bars mark earthquake times, and their height is proportional to the magnitude; the broken vertical line shows the Suusamyr, 1992 earthquake. The upper plot is the occurrence probability of the next earthquake $P_1(t)$ in sequences II and III; ±σ is the standard deviation from the average $P = 0.62$. The horizontal black bar shows the expectation time of this earthquake (1989–1995).

unity and substantially exceeded both the statistical average $P(t) = 0.62$ and its rms deviation σ.

The prediction was realized as the Suusamyr earthquake of 1992 (the broken vertical line in Fig. 6, which was absent in the original diagram), which occurred well within the 1989–1995 expectation time interval. Moreover, the source of this earthquake was located in the close vicinity of the respective potential source (at a distance not greater than the size of the source) that was localized two years before the Suusamyr earthquake among other similar sources of such a rank in the territory considered (Fig. 7) [Ulomov, 1991].

Figure 7 shows a fragment of the seismotectonic map presented in the aforementioned paper. (The complete diagram illustrating the fractal hierarchical structure of the spatial distribution of seismic lineaments of various ranks in Central Asia was presented in [Ulomov, 1993b; Sobolev, 1992].) The black circles show the sources of earthquakes with $M = 7.5$ that were known by that time (the chosen magnitude value is similar to that of the Suusamyr earthquake of 1992); these are the Vernyi (1887), Karatag (1907), Khait (1949), Chatkal (1946), Markansu (1974), and Gazli (1976) earthquakes. The white bands are seismic lineaments (boundaries between geoblocks, or sutures after Gamburtsev [1955]) of the respective rank ($M_{max} = 7.5 \pm 0.2$). The shaded circles are potential sources of earthquakes of a similar magnitude that were localized by the method of predominant inter-epicenter distances based on the grid regularization of the source seismicity [Ulomov, 1987a, 1987b, 1998]. This method essentially reduces to the fact that the statistically average distances δ_M (km) between epicenters of the nearest pairs of seismic sources having a size L_M (km) obey the same hierarchical dependence on the magnitude M. As seen from (1) and (2), the value δ/L is independent of magnitude, indicating that the distance between sources of neighboring earthquakes of the same magnitude is approximately four times as large as the size of these sources. The larger the source, the farther it is from its neighbor of the same magnitude.

Figure 7 indicates that an $M = 7.5 \pm 0.2$ earthquake could likewise occur during the predicted period at any other potential source shown in this figure, because the prognostic plots presented in Fig. 6 are valid throughout the Central Asia territory considered. However, it is important that the Suusamyr earthquake confirmed that we correctly predicted the position of such a large potential source in a region where no significant earthquakes had been known previously. This is why many local geologists and seismologists regarded the position of this potential source as absurd.

In view of the new unified Specialized earthquake catalog (SEC) of North Eurasia [Kondorskaya and Ulomov, 1995] and recent data on weak seismicity of the territory considered [Dzhanuzakov *et al.*, 1997; Mellors *et al.*, 1997; Ghose *et al.*, 1997; Gorbunova *et al.*, 2001], we thought it interesting to retrospectively trace

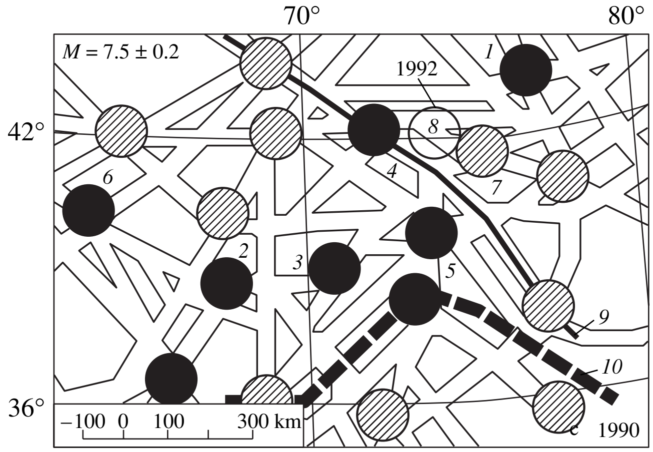

Fig. 7. Real (solid circles) and potential (shaded circles) sources of $M = 7.5 \pm 0.2$ earthquakes and seismic lineaments (bands) in eastern Central Asia: (*1–6*) earthquakes: (*1*) Vernyi, 1887; (*2*) Karatag, 1907; (*3*) Khait, 1949; (*4*) Chatkal, 1946; (*5*) Markansu, 1974; (*6*) Gazli, 1976; (*7*) potential source in the epicentral zone of the Suusamyr earthquake; (*8*) source of the Suusamyr, 1992 earthquake; (*9*) Talas-Fergana fault; (*10*) Pamir-Hindu Kush deep fault marking the boundary between the Eurasian and Indian lithospheric plates.

the space–time development of the seismic process in the preparation area of the Suusamyr earthquake source.

Figure 8 presents yearly maps of $M < 3$ earthquakes over the 1982–1993 time period. The Suusamyr earthquake source determined from the epicentral field of its numerous aftershocks (see the fragment for the 1992–1993 period) is shown as an open oval.

Whereas data on $M \geq 3.5$ earthquakes from the North Eurasia catalog yield no evidence of any seismic activity in the source area of the Suusamyr earthquake and complete quiescence was observed from 1981 until the main event, some evidence for a forthcoming event could be gained from weak earthquakes. Starting apparently in 1983, the amount of weak shocks was largest in 1986, after which (and particularly since 1990) the activation was followed by quiescence. At the same time, swarms of both weak and moderate earthquakes arose at great distances from the source. The first swarm appeared in 1983 at the southeastern end of the Talas-Fergana fault; the second, in 1984–1985 and 1988 at the North Fergana fault; and the third, in 1992 at the East Fergana fault (see the circles in Fig. 8 and the arrows with dates in Fig. 4). The position and time

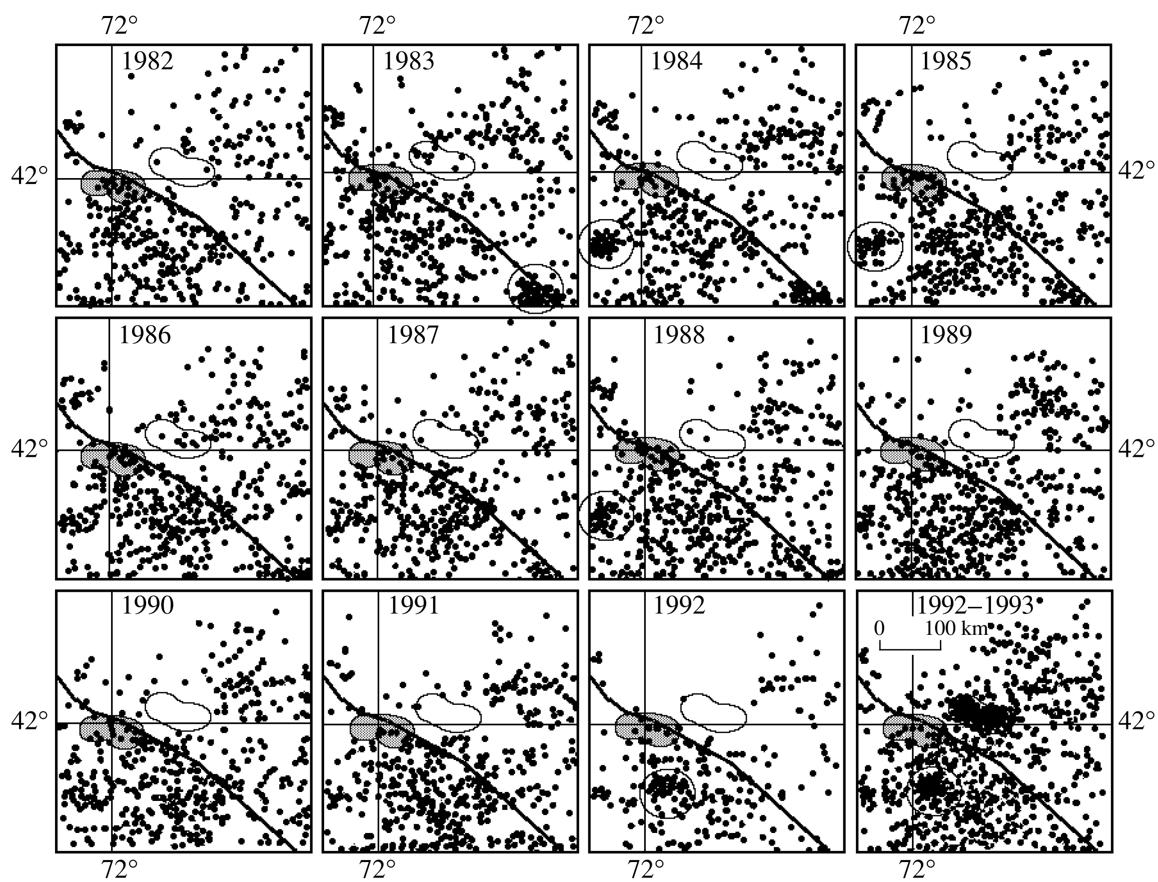

Fig. 8. Space–time development of the weak ($M < 3$) seismicity process. The open and shaded ovals are the sources of the Suusamyr and Chatkal (1946) earthquakes, respectively. The dots are epicenters of $M = 1.5$–2.5 earthquakes. The thick line is the Talas-Fergana fault. The circles delineate swarms of weak earthquakes that took place in 1983, 1984–1985, 1988, and 1992. Epicenters of the first half of the year (before the Suusamyr earthquake) are only shown in the fragment of 1992. The fragment of 1992–1993 shows events postdating this event; the aftershock activity is clearly observable in this fragment.

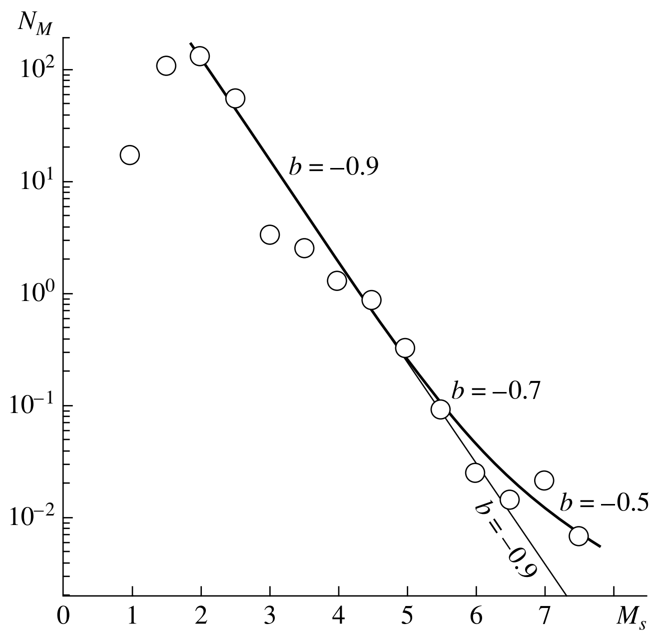

Fig. 9. The earthquake recurrence plot for the territory studied (see Fig. 8). N_M is the annual average number of earthquakes with the magnitude M_s determined from surface waves, and b is the slope of the plot and its fractal dimension [Ulomov, 1990b].

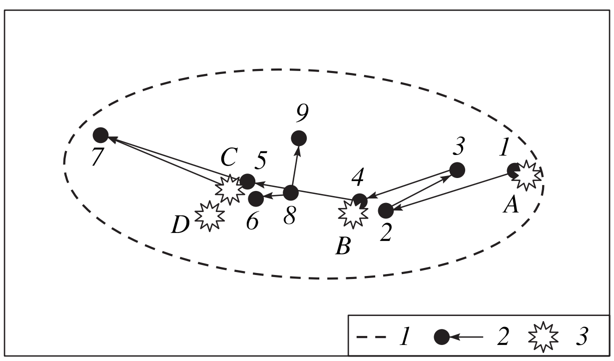

Fig. 10. Development of the seismic process in the source of the Suusamyr earthquake (see Figs. 4 and 8) in 1986 and 1992: (*1*) source outline; (*2*) epicenters of weak earthquakes and directions of their migration (arrows); (*3*) epicenters of the foreshock (*A*), main event (*B*), and two strong aftershocks (*C* and *D*).

sequence of these swarms may indicate a deformation wave propagating from the south, i.e., from the Pamirs and Indian plate.

The representativeness of the general catalog joining the SEC and data on weak earthquakes is illustrated in Fig. 9, showing the earthquake recurrence plot in a magnitude interval of 1.0–7.5 normalized to a year and reduced to a fixed area. As seen, the plot is nonlinear and gradually flattens out, changing its slope from the "classical" value $b = -0.9$ in the upper part to $b = -0.5$ in the lower part. Earthquakes with $M = 2.0$ and 2.5 lie on the linear segment of the plot. Shocks with $M = 1.5$ and 3.5 can also be considered more-or-less representative. Data on earthquakes with $M = 1.0$ and 3.0 are less reliable. However, the general shape of the plot coincides with the nonlinear configuration of a similar plot constructed for the entire territory of the North Tien Shan, and this is evidence of its reliability and additionally supports the idea according to which the recurrence plots of earthquakes of various magnitudes have different configurations in regions differing in their fragmentation extent [Ulomov, 1974]. Similar to the plot for the entire North Tien Shan, the upward departure from the straight line with the slope $b = -0.9$ is evidence that strong earthquakes in this region occur much more frequently than is suggested by the linear (exponential) extrapolation of the weak-earthquake plot toward larger events (the thin line in Fig. 9).

Figure 10 illustrates in more detail the development of the source itself as constrained by weak seismicity ($M < 3$). The figure shows an episode of 1986 (as mentioned above, the trace of the future rupture in the Suusamyr earthquake source became recognizable) and the sequence of seismic events observed in 1992 in the same (western) direction (weak foreshock–main event–two aftershocks with $M = 6.9$ and 6.8).

SEQUENCES OF SEISMIC EVENTS AND PREDICTION OF LARGE EARTHQUAKES IN THE CENTRAL ASIA AND BLACK SEA–CASPIAN REGIONS

Figure 11 presents sequences of earthquakes in magnitude intervals of (1) $M = 8.0 \pm 0.2$, (2) $M = 7.5 \pm 0.2$, and (3) $M = 7.0 \pm 0.2$ that occurred in the Tien Shan and Turan plate regions from 1880 to the present time (years on the vertical axis). The ordinal numbers (N) of earthquakes in each of the time sequences are plotted on the abscissa axis. Straight lines approximate the whole sets of events in each of the sequences, and the approximating curves are obtained by the B-spline interpolation of the data. If seismic events occurred regularly in time, they would lie strictly on straight lines and the earthquake occurrence time could be easily predicted. The real situation, albeit imperfect, is characterized by distinct regular patterns. Thus, the largest events with $M = 8.0 \pm 0.2$ (plot *1* in Fig. 11) forming a dense group occurred within a 20-year time interval. These are the Chilik (1889, $M = 8.3$), Kashgar (1902, $M = 8.1$), and Kemin-Chu (1911, $M = 8.2$) earthquakes. Since then (over more than 90 years) no earthquakes of such magnitudes have occurred in Central Asia, so that there are no grounds to discuss the occurrence time of similar events. As regards the two other sequences (plots *2* and *3* in Fig. 11), their regular patterns are beyond doubt.

The time moments of $M = 7.5 \pm 0.2$ earthquakes insignificantly deviate from their approximating straight line corresponding to an average recurrence period of $T = 15$ years, and the majority form three groups separated by 40- and 25-year intervals, each group consisting of two closely spaced events. Two isolated events of the same magnitude are symmetrically located on the sides of extreme groups. A slightly undulating spline line deviates insignificantly from the approximating straight line and has slopes that vary within narrow limits corresponding to T = 12.5 and 17.5 years. Extrapolating this line toward later times suggests that the future earthquake with $M = 7.5 \pm 0.2$ in the study area should occur within a 2002–2015 time interval and may coincide with one of the potential sources shown in Fig. 7.

The plot of successive events with $M = 7.0 \pm 0.2$ (plot 3 in Fig. 11) exhibits an equally ordered pattern. The spline curve resembles a sinusoid showing a complete (100-year) cycle and having an amplitude corresponding to a nearly 15-year time interval with respect to the approximating straight line with a slope of about T = 8.5 years, which can be considered as an axis of the sinusoid. The recurrence periods of $M = 7.0 \pm 0.2$ earthquakes vary within fairly wide limits (from 2.5 to 20 years). The upward extrapolation of the sinusoid and its intersection with the ordinate N = 17 indicate a high probability of an earthquake (no. 17) to occur in the next decade.

The hatched horizontal band in Fig. 11 marks the time interval (2002–2015) of the probable occurrence of large earthquakes in the region considered. The black circles are the occurrence times of the next large earthquakes.

Figure 12 illustrates an example of mathematically more rigorous prognostic calculations that we carried out for the Black Sea–Caspian region embracing the Crimea, the Caucasus, the Kopet Dag, northeastern Turkey, and northern Iran, where the statistics of large seismic events is much more representative than in Central Asia. Thus, reliable data are available here over a 2000-year period for earthquakes with $M = 8.0 \pm 0.2$, over a 500-year period for $M = 7.5 \pm 0.2$, and over the last 200 years for $M = 7.0 \pm 0.2$. Accordingly, a denser time scale on the ordinate axis was chosen. It is noteworthy that earthquake pairs are clearly observable here even for magnitudes $M = 8.0 \pm 0.2$, and the sinusoid, for events with $M = 7.5 \pm 0.2$. Earthquakes with $M = 7.0 \pm 0.2$ occur rather regularly, although on a larger time scale in Fig. 12 also reveals a somewhat sine-like behavior here.

Figure 12 also presents the equations approximating the observed data and predicting earthquakes for each of the 8.0 ± 0.2, 7.5 ± 0.2, and 7.0 ± 0.2 magnitude intervals. Also shown are the correlation coefficients (R^2) of the initial data with the approximating curves, standard deviations (SD), and the expected occurrence years (Y_M^P) of current earthquakes (solid circles) estimated by the given formulas.

The first and third equations describe the straight lines obtained by the least-squares method, and their

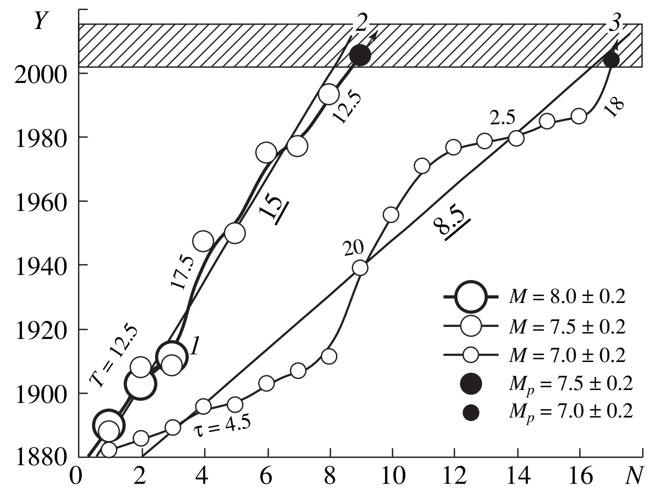

Fig. 11. The sequence of intracrustal earthquakes with M = 8.0 ± 0.2, 7.5 ± 0.2, and 7.0 ± 0.2 in the Central Asia region. The black circles are potential earthquakes expected to occur in the time interval shown as a hatched band in the upper part of the figure. For other explanations see the text.

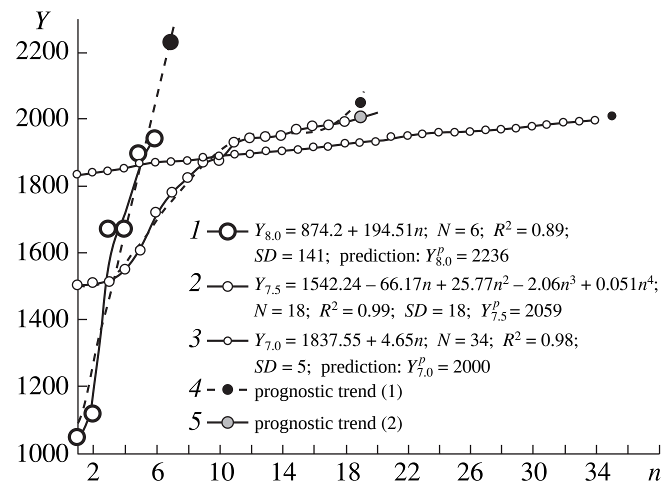

Fig. 12. The sequence of intracrustal earthquakes with M = 8.0 ± 0.2, 7.5 ± 0.2, and 7.0 ± 0.2 in the Black Sea–Caspian region: (*1*–*3*) occurrence times of earthquakes of respective magnitudes and the approximating B-spline formulas (Y is the year, n is the number of an earthquake, N is the number of seismic events of respective magnitudes, R^2 is the correlation coefficient, and SD is the standard deviation); (*4*, *5*) approximations of the initial data by various methods and the predicted earthquakes of the respective magnitudes.

extrapolation toward later times is simple. The sequence of $M = 7.5 \pm 0.2$ earthquakes had to be approximated by a fourth-degree polynomial. The extrapolation of the latter toward later times predicts an earthquake in the year 2059 ± 18 (*4* in Fig. 12). If the initial data are interpolated by a B-spline, such an earthquake should have occurred in 2000 (*5* in Fig. 12).

In this respect, of interest is the recent strong earthquake that occurred on December 6, 2000, in western

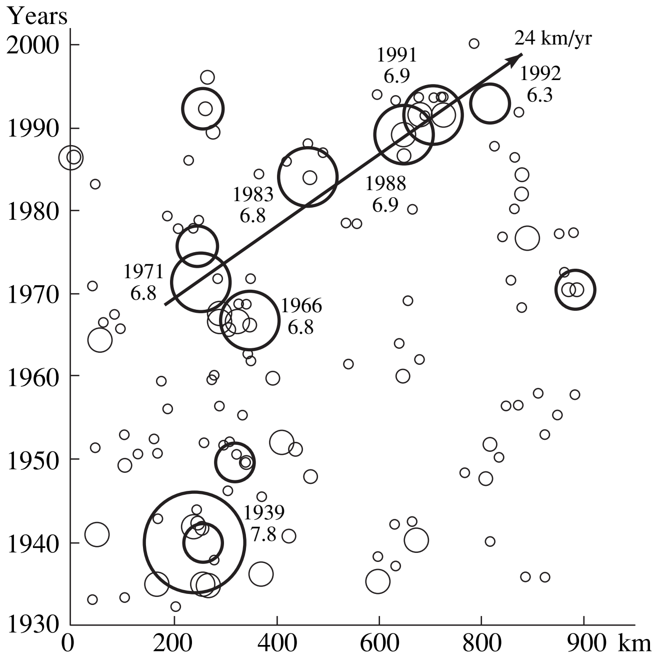

Fig. 13. Spatial–temporal development of seismic processes along the trans-Caucasian lineament extending for about 900 km. The magnitude and year of large earthquakes are given near the sources shown as open circles. The arrow shows the direction and rate of seismic migration. For other explanations see the text.

Turkmenistan near the eastern Caspian coast at the boundary between the Central Asia and Black Sea–Caspian regions. This earthquake is consistent with each of the plots in Figs. 11 and 12, which were constructed without regard for this event. Unfortunately, very scarce data are available on the epicentral zone and disastrous consequences of this Turkmenian earthquake. (To the best of our knowledge, it was not studied even by Turkmenian seismologists due to circumstances beyond their control.) Data on the seismic source parameters are also contradictory. Thus, the magnitude and epicentral coordinates as estimated by the Geophysical Survey of the Russian Academy of Sciences are $M = 7.4$ and (39.66° N, 54.84° E), the hypocentral depth being conventionally accepted equal to 33 km. On the other hand, according to data of the Mediterranean Seismological Center (CSEM), this earthquake had $M = 7.0$–7.4, epicentral coordinates of (39.78° N, 54.49° E), and a hypocentral depth of 10 km. Divergences between the focal mechanism determinations are less significant. Both nodal planes strike northwest, which is consistent with the Cheleken-Kumdag fault orientation. The reverse fault component is predominant, and nearly horizontal axes of compressive stresses are oriented along an N–S direction.

Judging from its location, the source of this earthquake can belong to both the Turan plate (Central Asia) and Kopet Dag Range (the Black Sea–Caspian region). Supposedly, such an intermediate position of the source accounts for reasonable agreement between times of this Turkmenian earthquake and potential $M = 7.0 \pm 0.2$ events in each of the prognostic plots of Figs. 11 and 12, as well as the predicted time of an $M = 7.5 \pm 0.2$ earthquake obtained by interpolating initial data by a B-spline in the Black Sea–Caspian region (the shaded circle in Fig. 12).

As regards the epicentral area of this earthquake, we should note that previous investigations of fluctuations in the seismic regime of the Caspian region and anomalous variations in the Caspian Sea level revealed regular features indicating a deep origin common to both types of phenomena [Ulomov, 1999]. The author supposed that a strong earthquake was prepared in the region studied. In this context, the same processes may have caused the earthquake of 2000 on the eastern Caspian coast.

In conclusion, it is important to note that additional constraints on the position of potential sources of forthcoming earthquakes can be gained by studying the migration of seismic activation due to the passage of deformation waves along the related fault structures [Ulomov, 1993a]. As an example, Fig. 13 shows an ordered migration of seismic sources with $M \approx 7.0$ along the trans-Caucasian seismically active NE-trending structure. Such sources originated in 1966–1971 near the epicentral area of the Erzindzhan, northeastern Turkey earthquake of 1939 ($M = 7.8 \pm 0.3$; 39.8° N, 39.4° E) and started to migrate northeast along this structure at a rate of 24 km/yr. This event was followed by the Khorasan (1983), Spitak (Armenia, 1988), and Racha (Georgia, 1991) earthquakes. If the observed migration does not stop, the next earthquake of a similar magnitude should be expected in the North Caucasus, most likely, in its eastern part.

CONCLUSION

The study of recent geodynamics and seismic regime patterns on both regional and seismic source scales contributes much to our knowledge of the seismogenesis, as well as to the improvement of seismogeodynamic models and earthquake prediction methods. The inferred regular patterns in the dynamics of crust and seismicity manifestations enabled the long-term prediction of earthquakes that were the largest in Central Asia over the last quarter of the century.

The studies showed that ordered patters in the development of seismicity, such as grouping of earthquakes in time and the sinusoidal shape of the curves describing sequences of seismic events, are evidence of the existence of very-long-period deformation waves involving whole regions.

Further research on the ordered patterns in the development of seismic sources in both time (earthquake recurrence) and space (distances between sources) is required for more reliable localization of potential sources and assessment of seismic hazard. The modern

GPS-assisted methods of surface strain measurement and the development of new approaches described in this paper are beneficial to this research. Satellite observations and deployment of continuous monitoring systems in seismically active regions can provide high-precision results even in regions where traditional geodetic observations are scarce.

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