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Implication of Horizontal Tectonic Movements for Seismogeodynamics and Seismic Hazard Prediction

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Abstract—Analysis of the horizontal component of tectonic movements is shown to be vital to the examination of the seismicity structure and seismic hazard assessment in a case study of the Pamirs–Tien Shan and the Turan platform of the Central Asia seismically active region. Such investigations are of particular importance in flat platform regions, including the Scythian-Turan plate and the East European Platform, where vertical movements are negligible. Comparison of vector and scalar fields of the horizontal Neogene–Quaternary movements of the Central Asia crust previously constructed by the author with the results of GPS measurements shows that these fields are similar to contemporary movements of the Earth's surface in the region studied. The presence of a rotational component of tectonic motions is confirmed on the scale of general seismogeodynamics of the region.

INTRODUCTION

Results of GPS measurements that have been obtained over recent years (in particular, on the territory of Russia and Central Asia) convincingly point to an important role of the horizontal component of tectonic movements in the evolution of the crust and the lithosphere as a whole. Global satellite geodesy provides high-quality information on contemporary geodynamics and its spatial–temporal variations, which is of particular significance for adequate seismic zoning and long-term prediction of strong earthquakes.

The first steps in the study of horizontal geodynamic movements in Central Asia were taken by the author as early as the 1960s and 1970s on the basis of the method of reduction of crustal dynamics to the Neogene–Quaternary [Ulomov, 1966, 1972, 1973, 1974]. At the same time, the role of horizontal and rotational components of the movements in seismic hazard prediction was noted and the new notion of *seismogeodynamics* was introduced. As distinct from seismotectonics, which mainly characterizes static properties and geometrical links of seismic sources to the deep structure, seismogeodynamics considers the seismicity origin as a result of dynamics of the crust and the lithosphere as a whole, with due regard for their hierarchical structure, strength properties, and failure processes at various scale levels (from a local earthquake source to regional and global seismogenic structures).

The reduction method made it possible to reconstruct the vector and scalar fields of neotectonic and recent movements in Central Asia. In addition, a close correlation of these fields with the seismicity pattern and the gravity field was confirmed and nonlinearity of earthquake recurrence plots and their association with strength and dynamic properties of crustal rocks and the lithosphere as a whole were explained. The important role of the underestimation of seismic hazard on the Turan plate and the necessity of a new map of seismic zoning of this territory (considered at that time as aseismic) were emphasized. In this context, new seismic stations were established in 1967 and 1968 on the Turan plate. Seismological and strainmeter observations of local seismicity, horizontal extension, and recent fracturing processes on the surface of the Central Kyzyl Kum area allowed the author to state that the nucleation of a large earthquake was in progress in this region [Karzhauv and Ulomov, 1966; Ulomov, 1972, 1974]. This long-term prediction was confirmed by the series of three Gazli earthquakes of 1976 ($M = 7.0$ and $M = 7.3$) and 1984 ($M = 7.2$), which were the strongest on the platform and occurred in the same source in the Central Kyzyl Kum [Ulomov, 1986].[1]

The following statement by the well-known geologist B.A. Petrushevskii illustrates the negative attitude of most geologists of that time to the role of horizontal tectonic movements. Disclaiming the concept of new global tectonics and disbelieving the potential of geophysical methods in the study of crustal dynamics (in particular, the dynamics of the Turan plate, on which he was an expert), he wrote indignantly "… as regards this territory, we face not only a significant violation of the equilibrium between geological and geophysical approaches to earthquake research, with focus being placed on geophysical methods. The situation is aggravated by the fact that, in recent years, geophysicists,

[1] Here and below, the magnitude M means the value M_S determined from surface waves with the use of the Specialized Earthquake Catalogue for North Eurasia (http://socrates.wdcb.ru/scetac/).

primarily V.I. Ulomov, have been resorting to the concept of tectonic control of the Kyzyl Kum seismicity. It is he who began to put forward 'up-to-date' (from the viewpoint of adherents of the plate tectonics hypothesis) ideas on the relation of Kyzyl Kum earthquakes to complex movements of large crustal blocks that are thrust over or under neighboring blocks including Pamir and Hindu Kush structures .... In this respect, we should mention his monograph[2] devoted to the whole of Central Asia and widely describing more complex rotational movements that are allegedly characteristic of this Asian region" [Petrushevskii, 1977, p. 50].

The estimates and reconstructions described in [Ulomov, 1974] and other publications of the author have stood the test of time. Recent investigations of crustal dynamics conducted in the Tien Shan by German, American, Russian, Kazakh, and Kyrgyz researchers have provided nearly the same pattern of horizontal movements of the Earth's surface (including block rotations) as that reconstructed by the author about 30 years ago. This fact was properly noted in [Abdrakhmatov *et al.*, 1996].

In order to compare the results of our investigations of the Neogene–Quaternary dynamics of the Central Asia crust with GPS data on contemporary horizontal movements of the Earth's surface, the reduction technique and results obtained in [Ulomov, 1972, 1973, 1974] in relation to seismic hazard assessment for the region under study are briefly described below. We also present GPS data recently obtained for the Tien Shan. It is shown that such investigations are of particular significance in flat platform regions, including the Scythian-Turan plate and the East European Platform, where the vertical component of the movements is negligible and the seismic potential is high.

SEISMOGEODYNAMICS AND SEISMICITY OF CENTRAL ASIA

Geologically, Central Asia is an epiplatform orogen formed in the Neogene–Quaternary in the place of an epi-Hercynian platform the western part of which is presently represented by the young Turan plate. This region is characterized by high intracontinental seismicity due to geodynamic interactions between the large European, Asian, Iranian, Indian, and Chinese plates (Fig. 1).

Analysis of the distribution of earthquake sources in western Central Asia reveals some regular features of the seismic field in this territory consisting, in particular, in the confinement of seismogenic structures to large fault zones and areas of high gradients of the isostatic anomalous gravity field (Fig. 2) [Ulomov, 1966]. On the whole, the anomalous gravity field in this region is a low centered at the Pamirs. The field intensity decreases toward the Pamirs nonmonotonically, zones of higher gradients (gravitational steps) reflecting the

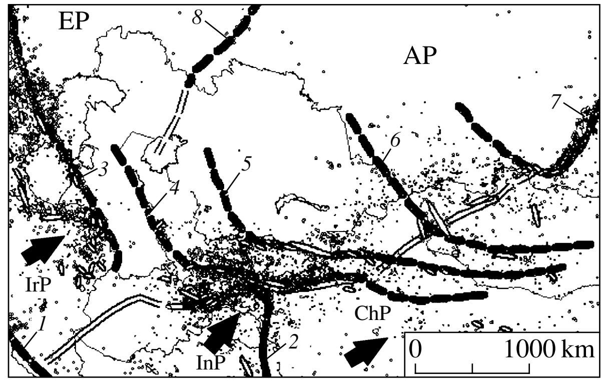

Fig. 1. Seismogeodynamics of Central Asia. Shown are fragments of the European (EP), Asian (AP), Iranian (IrP), Indian (InP), and Chinese (ChP) lithospheric plates. The double lines are plate boundaries and the arrows show the directions of plate motions. The thick broken lines are axes of regional seismogenic structures (relics of island arcs of subduction zones): (*1*) Zagros; (*2*) Pamir–Himalaya; (*3*) Crimea–Caucasus–Kopet Dagh; (*4*) South Tien Shan; (*5*) North Tien Shan; (*6*) Altai; (*7*) Sayany-Baikal; (*8*) the Urals. The notation for earthquake sources is explained in Fig. 2. The thin lines are national borders.

deep topography of major crustal interfaces. Thus, gravity anomalies reflect the deep structure and the vertical component of geodynamic movements. They correlate well with the seismicity structure, primarily characterized by thrust motions in earthquake sources, whereas horizontal strike slips are insignificant. An example is the Talas-Fergana strike-slip fault (the largest in Central Asia) except for its northwestern part exhibiting significant vertical displacements along the Karatau ridge.

Three main regional lineament zones, the North Tien Shan, South Tien Shan, and Pamirs–Hindu Kush, are seismically most pronounced. Each of these zones belongs to geological formations differing in age and characterized by various strength and dynamic properties and is a consequence of a collision of subduction origin that occurred in this region. The length of the North Tien Shan and South Tien Shan zones is comparable to the statistically mean length of all arclike convergence zones of the world and amounts to 3000 ± 500 km [Ulomov, 1974, 1993, 1999].

The North Tien Shan is represented by Caledonides, and the South Tien Shan, by Hercynides. Alpine structures of the South Pamirs and Hindu Kush are the NW termination of the Himalayan arc, which in turn is a part of the extended Alpine-Himalayan belt. Clusters of deep sources of local earthquakes still persist at both ends of this relatively young arc (in the Pamir–Hindu Kush and Myanma regions). Seismic sources in the Pamirs–Hindu Kush, where the whole lithosphere is not in equilibrium and continues sinking into the upper mantle, reach a depth of 300 km. In the rest of the Central Asia territory, they are located within the upper crust, mostly at depths of up to 15–20 km.

[2] [Ulomov, 1974].

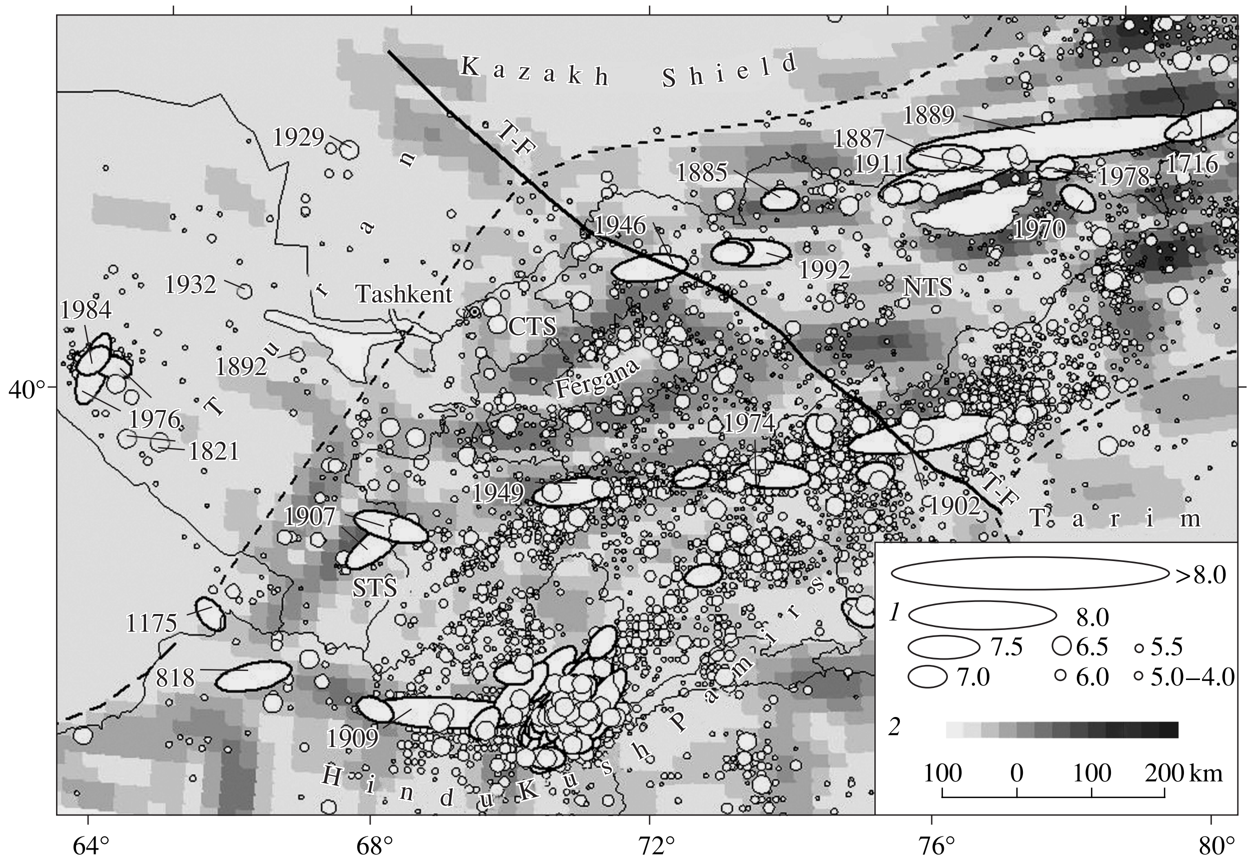

Fig. 2. Seismicity of western Central Asia: (*1*) earthquake sources with $M = 4.0 \pm 0.2$ increasing at a step of 0.5; sources with $M \geq 7.0$ are shown as ellipses of realistic orientations and length; the years of the strongest and some moderate earthquakes (on the Turan plate) are shown; (*2*) gradients of isostatic gravity anomalies of various intensities (darker shades correspond to higher gradients) [Kaban *et al.*, 1998]); T-F, Talas-Fergana right-lateral fault; NTS, Caledonian North Tien Shan; CTS and STS, Central and South Hercynian Tien Shan. The thin broken line shows the tentative boundary between the Tien Shan orogen, Kazakh Shield and Turan and Tarim plates. The thin lines are national borders.

The seismogenic structure of the North Tien Shan is characterized by the largest earthquakes that occurred here against the background of a relatively low seismic activity. Among these are the Chilik (1889, $M = 8.3$), Kebin (1911, $M = 8.2$), Vernyi (1887, $M = 7.3$), Belovodsk (1885, $M = 6.9$), Chatkal (1946, $M = 7.5$), and Suusamyr (1992, $M = 7.5$) earthquakes [Ulomov *et al.*, 2002]. The North Tien Shan zone extends eastward as far as the Mongolian Altai and coincides in its NW part with the Talas-Fergana fault, characterized here by a relatively low seismic activity. Seismic lineaments of a lower seismic potential bounding the Fergana basin are reliably identified to the west of the central segment of the Talas-Fergana fault, on the territory of the Hercynian Central Tien Shan. They are characterized by thrusts and have distinctive signatures in the gradient field of isostatic gravity anomalies (Fig. 2). The Southern Fergana fault zone is also clearly traceable in the gravity field of the Turan plate.

The largest seismic events that occurred along the South Tien Shan arc are the Kashagar (1902, $M = 7.8$), Karatag (1907, double shock with $M = 7.3$ and 7.4), Khait (1949, $M = 7.4$), and Markansu (1974, $M = 7.3$) earthquakes. In distinction to the North Tien Shan zone, nearly all of the aforementioned earthquakes occurred against a very high seismic activity typical of the central South Tien Shan zone. In the east, this zone controls the northern boundary of the Tarim plate, crosses the Turan plate in the west, and apparently extends as far as the Mangyshlak Plateau. The Gazli earthquakes of 1976 ($M = 7.0$ and 7.3) and 1984 ($M = 7.2$), which are the largest for platform regions, occurred here in the central Turan plate. They had intensities of 9–10 and arose in the intersection area of the southeastern extension of the South Tien Shan zone and the Central Kyzyl Kum zone, identified by the author well before these events [Ulomov, 1972, 1973, 1974].

Historical data are available on other rather strong (intensity of 8–9) earthquakes that occurred along the South Tien Shan zone and within the Turan plate; they caused damage and casualties in ancient cities of this region (Bukhara, Samarkand, and Urgench). Seismic events of lower intensity occurred along the Central Kyzyl Kum zone as far as the Kopet Dagh Mountains in the vicinity of Ashkhabad and extended farther into the Iran territory.

The S-shaped Pamirs–Hindu Kush zone is seismically the most active in Central Asia. The largest earthquake known here occurred in the Hindu Kush in 1909 and had the magnitude $M = 8.0$; its source was located at a depth of about 230 km. A few tens of earthquakes of magnitudes $M = 7.0–7.5$ and thousands of less significant events occurred at nearly the same depth after this earthquake.

Fields of elastic stresses and strains are important characteristics of crustal dynamics and its seismicity. Geodynamic stresses supplementary to the lithostatic pressure have various origins. However, tectonic deformations caused by large horizontal movements of the lithosphere relative to the asthenosphere play a main role. As follows from geological and geophysical data, Neogene–Quaternary deformation of the crust and lithosphere in Central Asia was mostly due to the tangential pressure exerted by masses located outside this region. Maximum tangential stresses in the upper crust amount to a few hundreds of kilograms per square centimeter. This quantity is of the same order of magnitude as the excessive shear stresses released in sources of tectonic earthquakes. An activation of young platforms, as is observed in the western Turan plate, is favorable to an increase in maximum tangential stresses at their bases due to enhancement of orogenic movements [Ulomov, 1974].

As was noted by the author more than 30 years ago, distinctions between seismic regimes of the North and South Tien Shan are due to different stages of the accumulation of tectonic disturbances in these regions. Recent crustal weakening in Central Asia develops from south to north, i.e., from Alpine structures to Hercynides and farther to Caledonides. Depending on the structure and strength properties of the medium, a substantial differentiation of crustal force fields and the seismogeodynamic regime is observed throughout the Tien Shan. Thus, the amount of elastic energy released in the North Tien Shan, characterized by a low activity of weak earthquakes over the last 150 years, is a few tens of times higher than the energy released in the South Tien Shan, characterized by a high seismic activity. This phenomenon was attributed by the author to a greater consolidation of the crust in the Caledonian North Tien Shan as compared with the weaker crust of the Hercynian South Tien Shan. The fairly consolidated crust of the eastern Turan plate also has experienced a young stage of deformation in the recent geological epoch.

The weakened South Tien Shan crust, fractured by faults and subjected to intense deformations, is incapable of accumulating elastic stresses in large volumes of rocks sufficient for the initiation of very large earthquakes. Exceptions are stronger peripheral areas of the orogen–platform transition. Thus, the aforementioned Karatag (1907) and Kashgar (1902) earthquakes occurred at the boundaries between the South Tien Shan and, respectively, the Turan and Tarim plates, where the seismic activity of weak and moderate earthquakes is relatively low. The average density of elastic energy of tangential stresses accumulated in rocks of the North Tien Shan is probably higher than 10^4 erg/cm^3, while it is about 10^3 erg/cm^3 in the South Tien Shan [Ulomov, 1974].

HORIZONTAL NEOGENE–QUATERNARY CRUSTAL MOVEMENTS

The deep topography of the crust base, as well as the crustal surface structure, is one of the main indicators of the tectonic evolution of the crust. Seismological, geological, and geophysical investigations of the last decades have shown that horizontal movements are a major factor controlling the tectonic evolution and seismicity of the entire outer shell of the Earth. Ideas of the existence of large horizontal shear movements in Central Asia over distances of 100–200 km and more are shared by many specialists [Ulomov, 1974]. The Talas-Fergana fault is considered as the largest strike-slip fault. Extended thrusts are characteristic of the Central and the South Pamirs. However, researchers still encounter methodological difficulties in studying horizontal crustal movements, particularly in flat regions. Therefore, the method of crustal reduction proposed by the author can be considered as a tool suitable for the study of horizontal crustal movements.

Investigations have shown that the crustal thickening, as well as the entire Pamir–Tien Shan neotectonics, results from residual lithospheric deformations produced by intense horizontal geodynamic stresses due to the interaction with the ancient Indian and Tarim platforms. As a result, the crust of the young epi-Paleozoic Turan plate, which occupied the vast territory of the present Central Asia in the pre-Neogene period, experienced a substantial reorganization over a relatively short time interval (3×10^7 years). A thin (35–45 km) crust was transformed into sequences 50–70 km thick (Fig. 3). This reorganization was not accompanied by any significant manifestations of magmatism, implying that the crustal thickening was unrelated to intrusion of large portions of a young magma into the crust.

In order to reconstruct the pattern of crustal deformation and formation of the epi-platform orogen, we considered residual deformations in their kinematic and dynamic aspects. In other words, the crust was reduced to its pre-Neogene 35–40-km thickness of the epi-Paleozoic platform under the assumption that orogenic structures, as well as the topography of the crustal base, were mainly produced by horizontal movements of the lithosphere.

Strains were measured from a fixed vertical surface passing through an arched profile (Fig. 2) within the platform part of the consolidated Turan plate crust (in the west) and the Kazakh Shield (in the north). The

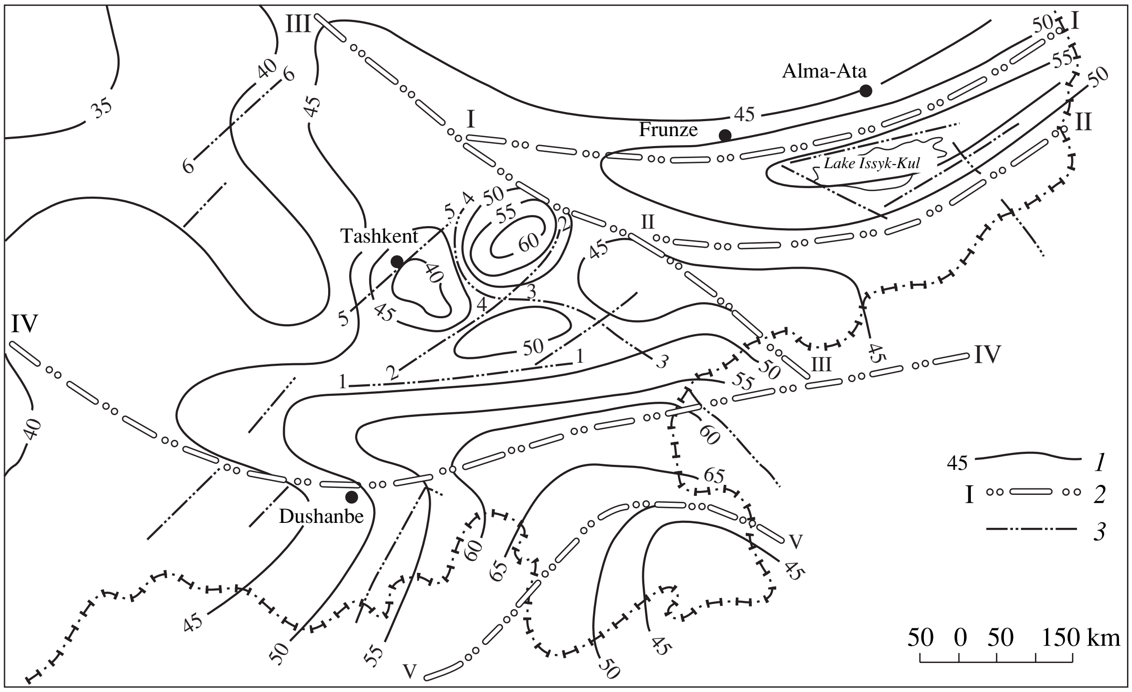

Fig. 3. Deep crustal structure of western Central Asia [Ulomov, 1966, 1973]: (*1*) depth contours of the crustal base (in km); (*2*) axes of deep fault zones: I, North Tien Shan; II, Naryn; III, Talas-Fergana; IV, South Tien Shan; V, Pamirs–Hindu Kush; (*3*) axes of secondary fault zones: 1, South Fergana; 2, North Fergana; 3, East Fergana; 4, Kumbel; 5, Karzhantau; 6, Central Kyzyl Kum.

average depth of the Moho discontinuity on this profile is about 40 km and the Moho itself is nearly horizontal (Fig. 3). In other words, the crustal region located to the north and west from the profile, which did not experienced any significant tectonic activation, serves as a peculiar barrier for the intensely deforming orogenic crust.

In accordance with the principles of continuum mechanics and under the assumption of laminarity of a rock flow, the orogen crust was "straightened out" and "stretched" in the direction orthogonal to the reference surface (the aforementioned barrier) and linear folds of mountain structures that were encountered in the stretching direction. Taking into account the arched configuration of the barrier, the age of geostructures, and the fact that the extended Talas-Fergana fault distinctly separates the Caledonian and Hercynian Tien Shan from the remaining territory, we started the crust reduction from the northern part of the barrier. The reconstruction of the western orogen crust was conducted in the direction orthogonal to the barrier segment of the Turan plate and along the strike of the Talas-Fergana fault, which became, after its straightening, a directing lateral barrier for moving crustal masses.

Figure 4 shows individual paths (flow lines) along which the Pamir–Tien Shan crust was reduced. Figure 5 illustrates the technique of reduction along vertical sections crossing the real deep relief by their transformation into a section of a constant thickness (40 km). The reduction was implemented graphically by the successive and continuous transfer of crustal volumes (in this case considered, areas of vertical sections) located below the 40-km level into an imaginary 40-km layer. The process of such a transfer resembles the rolling out of dough between two parallel rollers (rolling pins) 40 km apart. The rate and amplitude of the horizontal movement of excessive subcrustal masses depend on the amount of the real crustal thickening in concrete areas. The thicker the crust, the more rapid the horizontal movement of the deformation front in these areas (and in front of them). Finally, new areas (volumes) arising due to such straightening and shown in Fig. 5 by an oblique hatching must be quantitatively consistent with areas (volumes) located under the straightened plate (in Fig. 5 they are shown by cross-hatching as part of the contemporary real crust).

Continuity of the reduction makes it possible to reconstruct not only the paleokinematics of the crust but also its paleogeodynamics. In this case, the transformation of the crust is performed in the reverse order (similarly to the reverse projection of a film).

Undoubtedly, the deformation processes under consideration involve the entire lithosphere rather than the crust alone. However, the absence of detailed information on the topography of the lithosphere base precludes the application of the reduction technique. The well-defined Moho discontinuity within the lithosphere serves as a good indicator of all these geodynamic movements (including the lithosphere).

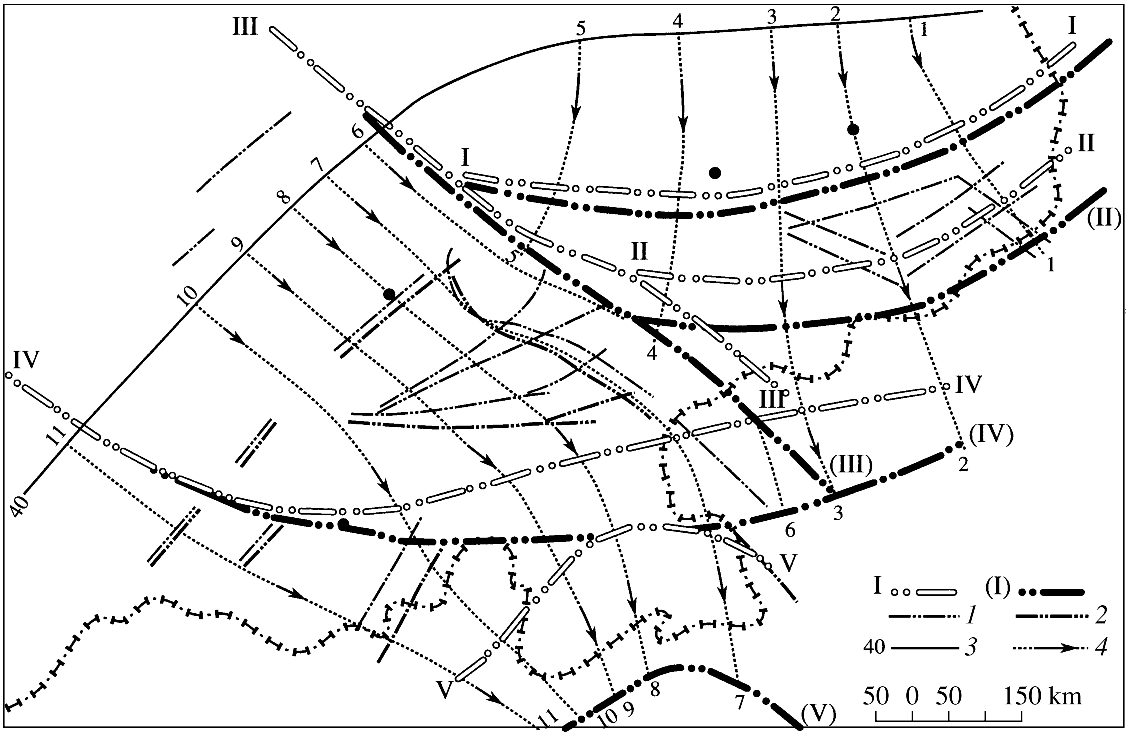

Fig. 4. Reduction scheme for the Central Asia crust: (I, *1*) the same as *2* and *3* in Fig. 3; (*2*) position of the same axes before the neotectonic activation; (*3*) trace of the vertical surface taken as a fixed strain reference origin; (*4*) paths (streamlines) along which the reduction of the crust was performed. The dots are cities (see Fig. 3), and the thick dot-and-dash line is the border of the former USSR [Ulomov, 1973, 1974].

Thus, the reduction provided a schematic image of the structure of the pre-Neogene Central Asian crust in plan view. As seen from Fig. 4, the axes of main deep fault zones had initially a more regular arched shape consistent with relics of oceanic island arcs of the North Tien Shan in the Caledonian period and of the South Tien Shan in the epoch of the Hercynian tectogenesis. As distinct from the Tien Shan arcs, the Pamir arcs apparently were not individual island arcs and manifested themselves only in the Neogene–Quaternary due to large northward thrusts. The latter arose in response to the deformation of the entire Asian mobile belt and, first of all, to the neotectonic activation of crustal movements in the Himalayas, represented by a huge Tethys island arc in the Mesozoic and Early Cenozoic. Clusters of seismic sources that are symmetric relative to the Himalayas and are observed in the Hindu Kush and Myanmar regions at intermediate depths suggest that these zones may be considered as evidence for incomplete healing of fragments of the ancient Himalayan subduction zone [Ulomov, 1966, 1974].

In distinction to a scalar field of 1-D vertical movements, 2-D horizontal crustal movements are represented by a vector field. In order to construct the vector field in the study region over the Neogene–Quaternary period, it is sufficient to convolve the reduced orogenic crust of Central Asia (Fig. 4) in the reverse order. This operation inverts the signs of displacement vectors, whereas their moduli are determined by the length of trajectories of individual points (benchmarks) moving in the process of reduction.

As seen from Fig. 6, the vector field of horizontal crustal movements in Central Asia is inhomogeneous.

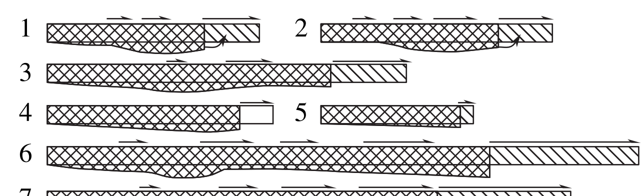

Fig. 5. Reduction of vertical crustal sections along paths shown in Fig. 4. Vertical sections of the real crust along each path are shown by cross hatching and 40-km thick straightened sections are shown by an oblique hatching. Reduction path directions of crustal masses are shown by arrows. The paths are enumerated in accordance with Fig. 4. The topography of the Earth's surface is not shown.

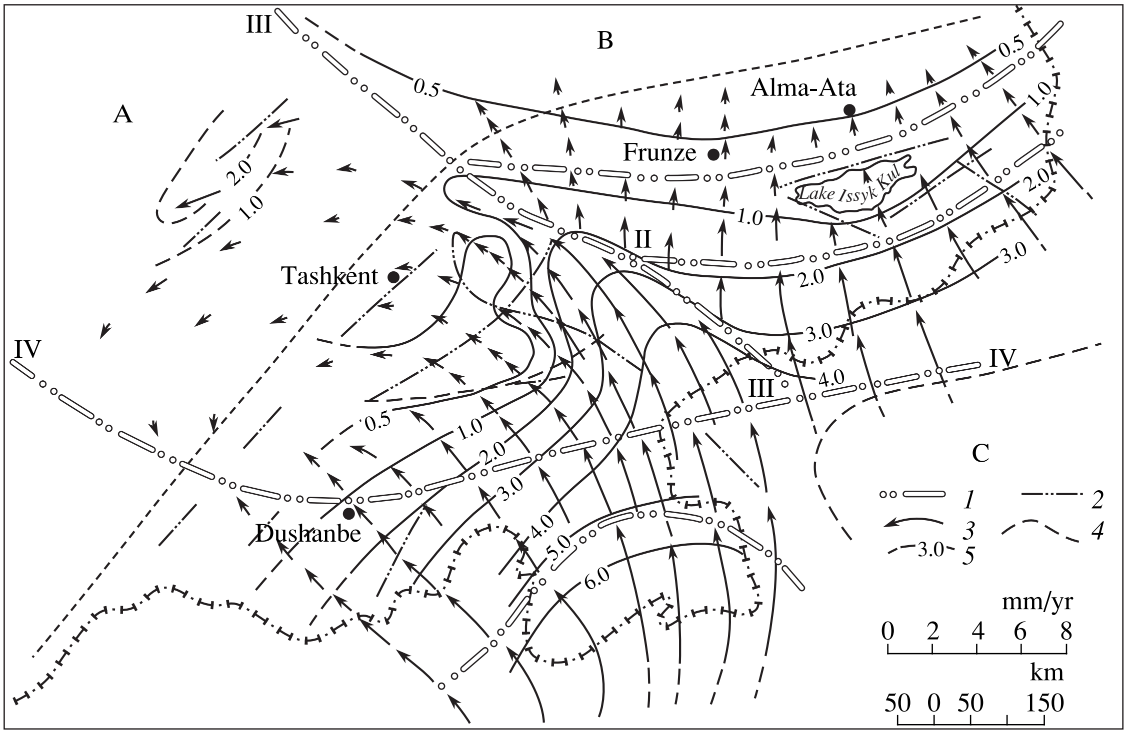

Fig. 6. Vector field and average velocities of horizontal movements of the Central Asia crust over the neotectonic period [Ulomov 1973, 1974]: (*1, 2*) the same as *2* and *3* in Fig. 4; (*3*) vectors of horizontal movements; (*4*) tentative boundaries of the orogen with the Turan plate (A), Kazakh Shield (B), and Tarim plate (C); (*5*) contours and values of velocities of crustal horizontal movements (mm/yr) in accordance with the scale in the bottom right-hand corner.

On the whole, it is characterized by a negative divergence (div < 0), indicating a decrease in the volume of the crust toward the platform. A negative divergence is observed most clearly in the North Tien Shan, where the crust was subjected to horizontal compression, thrust deformations, and significant transverse shortening in the neotectonic period. The average rate of the Neogene–Quaternary horizontal movements decreases rather monotonically in the northward direction (from 3.0 to 0.5 mm/yr).

The vector field of the horizontal crustal movements in the Pamir–Hindu Kush and Central Tien Shan regions is characterized by a significant negative divergence and very substantial positive rotation (rot > 0). Velocities of neotectonic horizontal movements are highest in the South Pamirs (more than 6.0 mm/yr), and intense bending deformations are observed in the South Tien Shan. The latter are most evident from the counterclockwise rotation of the South Tien Shan zone of deep faults and its kink in a Gissar Ridge area (surrounding the city of Dushanbe). This area is characterized by right-lateral faults, normal faults, and (in its central part) thrusts.

A significant gradient of neotectonic movement velocities in the E–W fault zone of the Central Pamirs is associated with the presence of a sink here in the form of an intense subsidence of the crust base and the entire Pamir–Tien Shan lithosphere into the asthenosphere (Fig. 7). This is also responsible for an intense negative gravity anomaly in this region.

The Central Tien Shan, particularly its region west of the Talas-Fergana fault, is characterized by intense counterclockwise rotations (rot ⩾ 0). Velocities of horizontal movements vary here from 4–5 to 0.5 mm/yr and rapidly decrease in the northwestward and westward directions. A high velocity of the crustal block bounded by the Talas-Fergana and West Fergana faults can be attributed to the presence of a sink in the thickened crust of the Chatkal block, where the Moho subsides to a depth of 60 km and a system of thrusts is developed in upper horizons. A similar accommodation of horizontal movements by a vertical subsidence of the crust is observed in the southern part of the Fergana intermontane basin and in other regions.

We should note that the thickening of consolidated crustal blocks during Neogene–Quaternary movements is very insignificant (≈45 km) within large intermontane basins of Lake Issyk Kul and the Fergana valley arising in back parts of Caledonian and Hercynian structures. These blocks only subsided to depths of 10–15 km and were overlain by Mesozoic–Cenozoic deposits. Apparently, the subsidence occurred not due to gravitational forces, which are not in equilibrium here, but due to tangential forces pressing intra-arc blocks inward. The blocks were displaced vertically along bounding deep

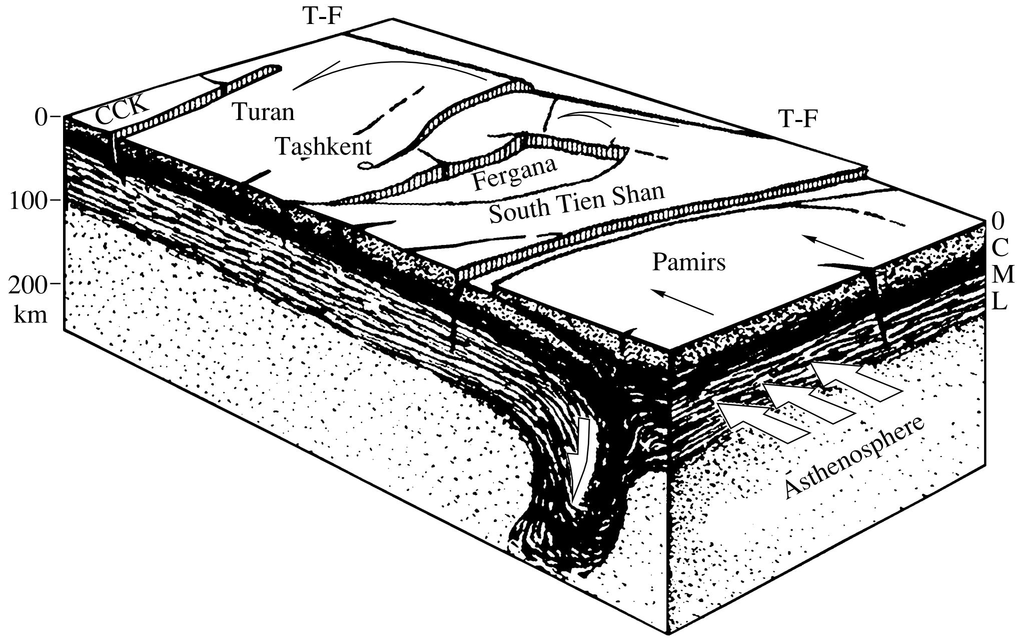

Fig. 7. Fragment of the 3-D fault–block deformation model for the lithosphere of the Pamirs, Tien Shan, and eastern Turan plate [Ulomov, 1973, 1974]: 0, Earth's surface; C and M, Conrad and Moho discontinuities; L, base of lithosphere; T-F, Talas-Fergana fault; CKK, Central Kyzyl Kum fault zone, within which the Gazli earthquakes of 1976 and 1984 occurred. The open arrows show the pressure exerted by Hindustan, and the black arrows show the directions of forced movements of geoblocks. The vertical scale is about two times larger than the horizontal scale.

fault zones inclined (along the dip) away from the blocks.

The western Turan plate is also involved in rotational motions producing here tensile forces, normal faults in the NW part of the Talas-Fergana fault zone, and strike-slip faults along the Central Kyzyl Kum zone of seismically active faults that have signatures in geophysical fields and, in particular, in magnetic field anomalies [Ulomov, 1974]. As mentioned above, the eastern Turan plate, located between the NW continuations of the South Tien Shan and Talas-Fergana zones of deep faults, displays, in plan view, a left kink. It is likely that the same rotational motions account for the circular migration of seismic activation on the periphery of the Fergana basin noted in [Butovskaya *et al.*, 1961].

We note once more that all these calculations and reconstructions were accomplished and published by the author well before the Gazli earthquakes of 1976 and 1984, which corroborated the validity of these reconstructions [Ulomov, 1973, 1974].

A fragment of the 3-D fault–block deformation model of the Pamirs, Tien Shan, and Turan plate lithosphere, which was published for the first time in 1973, is shown in Fig. 7. The pressure exerted by Hindustan on deep structures is a controlling factor responsible for the fragmentation and dynamics of the crust and lithosphere of the Pamirs and Central Tien Shan. A considerable NW displacement of the left wall of the Talas-Fergana fault and a rapid decay of its amplitude away from the fault produces a torque in the area of the Fergana basin and, as a result, a counterclockwise rotation of the entire system of adjacent blocks. Crustal blocks adjacent to the eastern Turan plate are subjected to a similar effect.

The Pamir crust overrides for about 200 km the Alai valley and the South Tien Shan, thereby producing the large thrusts characteristic of the Pamirs. The thrust amplitudes decrease eastward, which is also supported by a gradual decrease in depths of local earthquake sources from 300 to 70 km and less. These deformation processes led to a twofold thickening of the crust and deep downwarping of the Pamir–Hindu Kush lithosphere into the underlying ductile asthenosphere. A relatively high rate of the lithosphere subsidence hinders the relaxation of the related elastic stresses. Nearly complete reworking of lithospheric material takes place at depths exceeding 300 km, where discrete seismic motions cannot occur and ductile deformation starts, mixing the lithospheric material with the asthenospheric substrate. Since the lithosphere has been moving for at least 3×10^7 years, our estimates show that a plate section about 1000 km in length was "dissolved" over this period, given a subsidence rate of few centimeters per year [Ulomov, 1974]. This estimate does not contradict data on the contemporary convergence of the Asian and Indo-Australian plates.

An idea of crustal deformation in Central Asia can also be gained from the spatial migration and the distribution in time of earthquake hypocenters, as well as

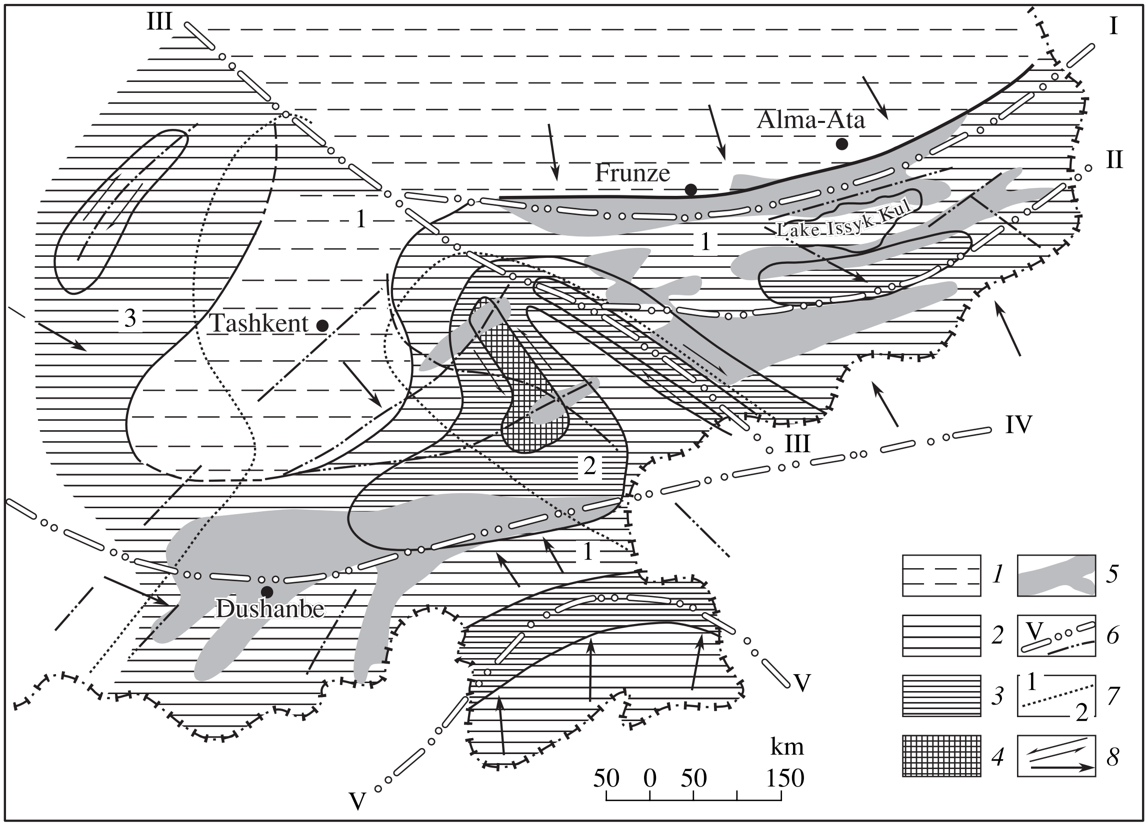

Fig. 8. Schematic map showing average velocity gradients of neotectonic movements [Ulomov, 1973, 1974]: (*1–4*) gradient values: (*1*) lower than 10^{-8} yr^{-1}, (*2*) $(1–2) \times 10^{-8}$ yr^{-1}, (*3*) $(2–5) \times 10^{-8}$ yr^{-1}, and (*4*) $(5–10) \times 10^{-8}$ yr^{-1} and higher; (*5*) areas of high velocity gradients of vertical movements ($(5–10) \times 10^{-9}$ yr^{-1}); (*6*) the same as (*2*) and (*3*) in Fig. 4; (*7*) tentative boundaries of areas dominated by (1) compressive, (2) tangential, and (3) tensile stresses; (*8*) directions of stresses.

from the pattern of motions in earthquake sources. The migration phenomenon is clearly observed at edges of consolidated crustal blocks (the Kuramin–Kyzyl Kum, Fergana, and other blocks) and along major seismogenic structures of the Tien Shan and the Pamirs.

VELOCITY GRADIENTS OF HORIZONTAL TECTONIC MOVEMENTS AND SEISMIC HAZARD PREDICTION

Velocity derivatives of crustal movements are of major significance for seismogeodynamics. The most important of them are gradients characterizing the strain rates. Maps of the velocity gradient modulus were constructed for the vertical velocity component *Vv* in [Gzovskii, 1967; Nikolaev and Shenkareva, 1967]. Maps showing horizontal strain rates did not exist until 1973, when the work [Ulomov, 1973] was published. This was a serious disadvantage in seismic hazard assessment for flat territories with their typically horizontal movements (the Fergana valley, the Turan plate, and other regions).

Comparing either horizontal or vertical components of tectonic movements with seismicity, one should bear in mind that the neotectonic crustal velocities and their derivatives can differ from the values averaged over the neotectonic period. Thus, the average velocity of contemporary (Holocene) crustal movements can be about tenfold higher than the average over the Neogene–Quaternary. Rheological processes ensuring relaxation of crustal elastic stresses over 10^4 years, the elastic stress fields under study should be related to the contemporary (Holocene) period. The unique correspondence of crustal strains averaged over the neotectonic period and seismic fields shows that they were inherited by contemporary deformations.

The first scheme showing average velocity gradients of horizontal crustal movements for the contemporary period was constructed in [Ulomov, 1973]. A map showing the moduli and directions (shown by arrows) of grad V_H is presented in Fig. 8. A gradient being a vector quantity, its scalar field (Fig. 8) should be considered together with the vector field (see Fig. 6), or another representation should be adopted. The scalar field was calculated as usual. A linear velocity variation was assumed between adjacent contours V_i and V_{i+1}. The gradient value was calculated by the formula

$$|\text{grad}\, V_H| = (V_i - V_{i+1})/\Delta_{i,\,i+1},$$

where $\Delta_{i,\,i+1}$ is the distance between contours and V_i is the velocity value on the ith contour.

Areas of large gradients of average vertical velocities of neotectonic movements gradV_V are also shown in Fig. 8 for comparison. The velocity gradient of horizontal movements is seen to exceed that of vertical movements by ten times or more.

The highest gradients of V_H and V_V are observed in deep fault zones and can be said to complement each other. Areas of small values of gradV_V have large values of gradV_H and, vice versa, small crustal uplifts and subsidences correspond to large horizontal movements. However, one should bear in mind that the gradient field has discontinuities in deep fault zones, where velocity values on both sides of a fault should be dealt with rather than gradient values (especially if a fractured zone is narrow).

The highest gradients of horizontal movements are observed most clearly in the western Fergana basin along the Western Fergana zone and partly along the eastern Southern Fergana zone of deep tectonic disturbances characterized by high seismicity (grad$V_H \geq 1 \times 10^{-7}$ yr^{-1}). The smallest values ($\leq 1 \times 10^{-8}$ yr^{-1}) are characteristic of the Kazakh Shield and the flat territory of the Tashkent area. In Central Kyzyl Kum area, the gradient of the shear strain rate increases again and reaches 5×10^{-8} yr^{-1} and more. The Gazli earthquakes of 1976–1984 occurred, as mentioned above, in the southeastern continuation of this zone.

Similar values of the gradient of horizontal motions are observed south of the Fergana basin in the South Tien Shan, south of the Issyk Kul basin in the North Tien Shan, and along the Pamir–Hindu Kush fault zone in the Central Pamirs, where horizontal movements are rapidly transformed into vertical subsidence of the entire lithosphere.

Three types of geodynamic tangential stresses playing a decisive role in the development of the crust and seismicity in Central Asia were identified from the analysis and comparison of scalar and vector fields of velocities and their gradients. The whole North Tien Shan, a considerable part of the Central and South Tien Shan, and the whole Pamirs are predominantly subjected to compressive stresses. The western Fergana and Central Kyzyl Kum crust experiences intense shear stresses and deformations.

As follows from analysis of neotectonic and recent geodynamics, the study of seismicity and the assessment of seismic hazard in orogenic regions should be based on combined analysis of vertical and horizontal crustal movements; in flat regions, particular attention should be paid to the identification of horizontal movements and calculation of their gradients.

Results of our research in seismic hazard assessment of the Turan plate conducted long before the Gazli earthquakes of 1976 were used for the constriction of a seismic zoning map of Uzbekistan in 1978, and this map was included in the composite SZ-78 map of the former USSR. A 7-intensity zone bordering the NE-striking Central Kyzyl Kum zone of deep faults, characterized by high gradients of Neogene–Quaternary horizontal movements (see Fig. 8), was identified for the first time in the flat territory of the Turan plate, considered at that time as nearly aseismic.

Our recent studies of seismic zoning in North Eurasia confirm a high level of seismic hazard in the Turan plate and the entire Tien Shan. Based on a new methodology taking into account characteristic features of the Neogene–Quaternary and neotectonic geodynamics, a large group of specialists of the Institute of Physics of the Earth (IPE), Russian Academy of Sciences (RAS), in cooperation with other CIS institutions, created in the period from 1991 to 1997 the GSZ-97(A, B, C) set of probabilistic maps of general seismic zoning for North Eurasia, which characterize various degrees of seismic hazard and are intended for the design and construction of objects varying in the category of significance and service life [Ulomov and Shumilina, 1999]. This set was included in the official building code "Building in Seismic Regions."

Figure 9 shows a fragment of one of these maps (GSZ-97-A) showing the 90% probability that the seismic intensity will not exceed the value (shown in the map in units of the macroseismic MSK-64 scale) during 50 years (or the 10% probability that this value will be exceeded). Calculations showed that the seismic hazard in the eastern Turan plate, as well as in many other regions of North Eurasia, is higher than that accepted previously. A considerable part of the Central Kyzyl Kum zone is classified as an 8-intensity zone, and zones of intensities 7 and 9 were considerably enlarged.

Active faults and ring structures identified on the basis of geological evidence (the GSZ-97 database) are shown in Fig. 8 by thin lines. Three thick lines north of the town of Tamdy-Bulak show large riftlike gaping joints that were activated ten years before the Gazli earthquakes of 1976 [Karzhauv and Ulomov, 1966; Ulomov, 1972, 1974; Bykovtsev *et al.,* 1984; Ulomov *et al.*, 2002].

The GSZ-97 maps were constructed on the basis of a fundamentally new methodology and a unified seismological and geological–geophysical database compiled for North Eurasia. A unified 3-D lineament–domain–source model of the development of earthquake source zones was developed for the first time. This model deals with extended, rather than concentrated, sources of earthquakes and employs up-to-date

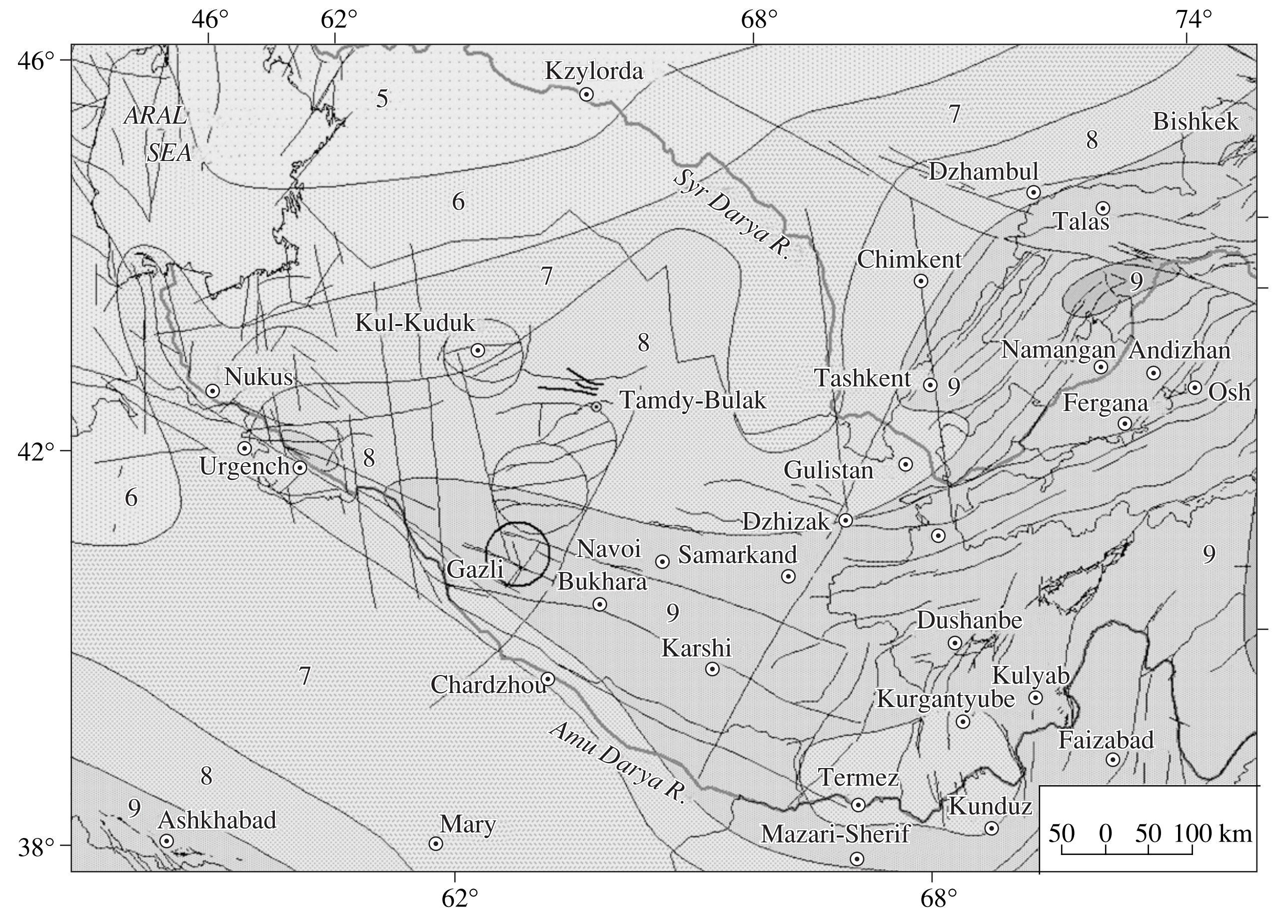

Fig. 9. Fragment of the GSZ-97-A map of general seismic zoning of North Eurasia [Ulomov and Shumilina, 1999]. Seismic intensity values (in units of the MSK-64 scale) are shown in each seismically hazardous zone. The thin lines are active faults and ring structures visible on the Earth's surface, and the thick lines are large pull-apart fractures north of Tamdy-Bulak. The bold circle is the source zone of the Gazli earthquakes of 1976–1984.

concepts of nonlinear effects of seismogeodynamic processes.

RECENT HORIZONTAL CRUSTAL MOTIONS

GPS measurements of contemporary horizontal movements of the Earth's surface in Central Asia were pioneered by the Scientific Station and Experimental–Methodological Electromagnetic Expedition of the Institute of High Temperatures of the RAS, the RAS Geological–Engineering and Geoecological Research Center, the RAS Institute of Astronomy, and the Georesearch Center of Germany (Potsdam). Specialists from IPE RAS, the Institute of Seismology of the National Academy of Sciences of Kyrgyzstan, the Institute of Seismology and the Institute of Astronomy of the National Academy of Sciences of Uzbekistan, and the geodetic surveys of these countries also participated in these investigations. The GPS network was further developed with the participation of Russian, American, Kyrgyz, and Kazakh specialists. GPS sites were mainly established on the territory of the North Tien Shan in Kyrgyzstan and Kazakhstan, where their number now exceeds 400.

Several GPS sites were located on both sides of the Talas-Fergana fault, crossing the territory of Kyrgyzstan. The average distance between the GPS sites is about 25 km in the orogenic region and about 200 km in Central Kazakhstan. Results of measurements on this network were presented in [Abdrakhmatov *et al.*, 1996; Zubovich, 2001]. These data were used for comparison with results obtained in [Ulomov, 1973, 1974].

A well-known disadvantage of fields of horizontal surface movements constructed in the vector form is their dependence on the choice of a reference frame. In this respect, the comparison between our results obtained by the method of reduction of Neogene–Quaternary crustal movements (Fig. 6) and contemporary movements of the Earth's surface determined from GPS data (Fig. 10), which is described below, is correct because calculations were conducted with reference to the same fixed structure (the Kazakh Shield).

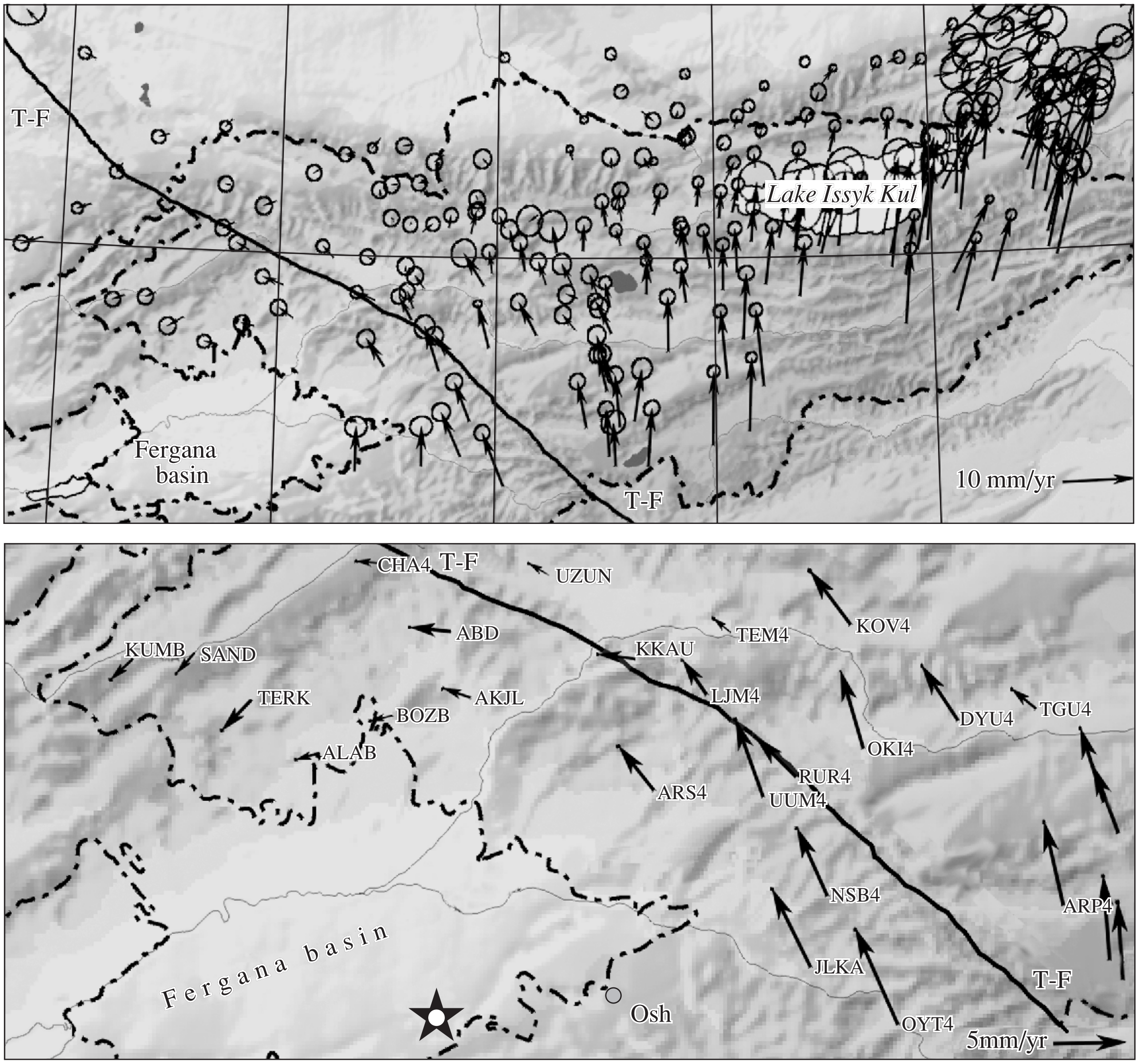

Fig. 10. Velocity vector field of recent horizontal movements from GPS data measured in Kyrgyzstan [Zubovich, 2001]. GPS sites are shown by arrows, with the arrow length being proportional to the year-averaged velocity of the movements in accordance with the scales shown in the bottom right-hand corners of the maps. The arrowhead circles are 95% confidence circles. T-F stands for the Talas-Fergana fault. The enlarged fragment of the map (at the bottom) illustrates the rotation of the Earth's surface northeast of the Fergana basin (the center of rotation is shown by a star) [Zubovich, 2001].

As seen from Fig. 10, velocity vectors of recent and Neogene–Quaternary movements are mainly directed N–S, and their absolute values decrease northward, which is in good agreement with our data presented above (see Fig. 6). The maximum velocity of recent movements reaches, according to GPS data, 10–12 mm/yr and exceeds the Neogene–Quaternary velocity by about two times in the same areas of the North Tien Shan, which is quite natural, as noted above. A.V. Zubovich believes that more intense deformations in the western part of the region under consideration modified the surface topography, producing here the mounts Khan Tengri (6995 m) and Pobedy (7439 m), the highest mountain structures of the Tien Shan. Zubovich also arrived at our conclusion that the observed pattern of the velocity field has existed for a rather long geological period.

Figure 10 shows (at the bottom) a somewhat enlarged fragment of the map showing velocities of recent movements in western Kyrgyzstan. The movements of GPS sites in this territory have a well-defined counterclockwise rotation pattern, which convincingly confirms our results obtained previously (see Fig. 6) and criticized severely by Petrushevskii and his adherents. Analysis performed by Zubovich showed that the rotation occurs at an angular velocity of 0.5–1.5 ms/yr about a center located in the southwestern Fergana basin ((72.00° E, 40.55° N), Zubovich's data; see Fig. 10). Absolute velocities of the rotational move-

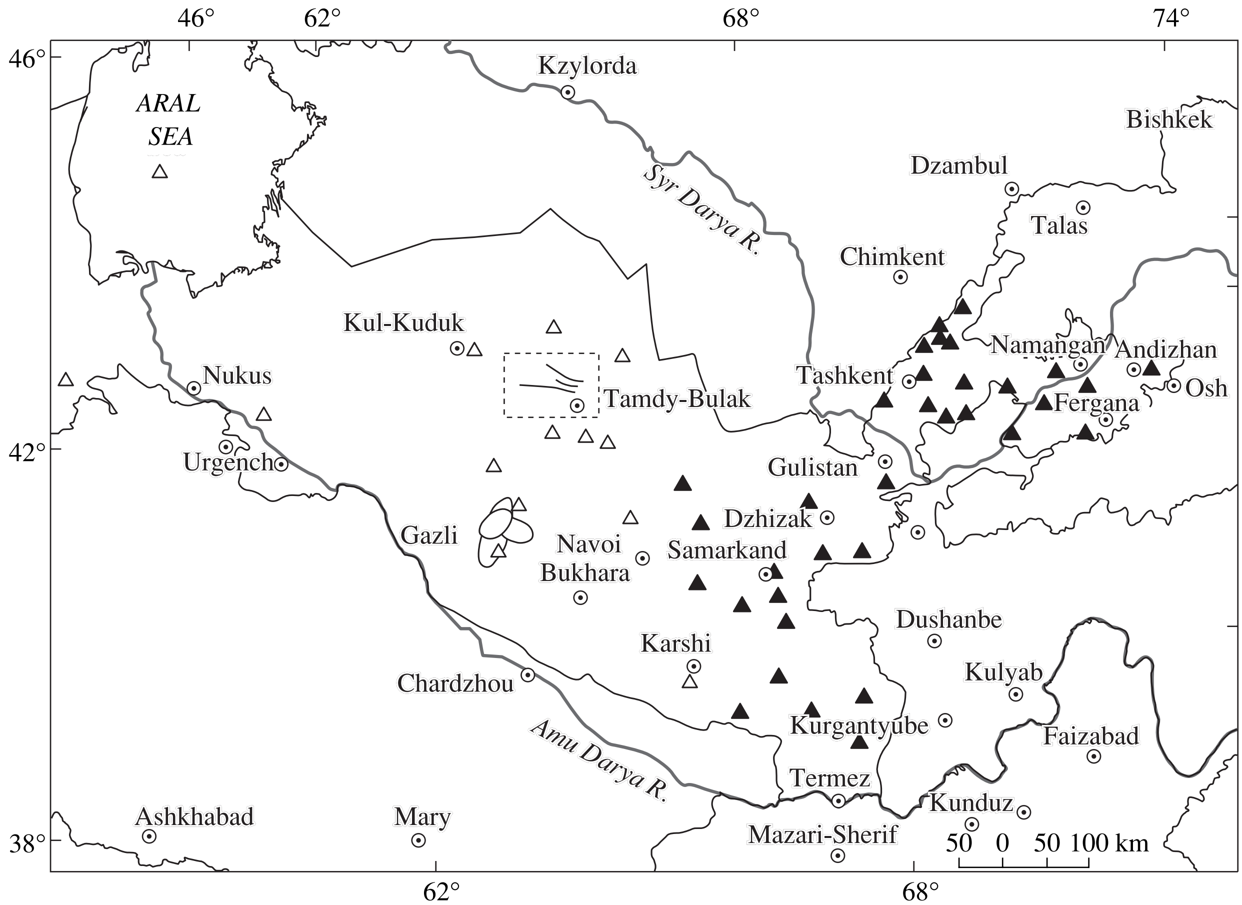

Fig. 11. GPS observation system in Uzbekistan. The existing GPS sites are shown by solid triangles (data of A.R. Yarmukhamedov) and the sites proposed by the author to be installed on the Turan plate are shown by open triangles. The area of development of giant joints (thick lines) in the Central Kyzyl Kum region is bounded by a broken line. The sources of the Gazli earthquakes of 1976 (M = 7.0 and 7.3) and 1984 (M = 7.2) [Ulomov, 1984, 1986; Ulomov *et al.*, 2002] are shown by ellipses.

ments decrease northwestward from 5–6 to 2–3 mm/yr. Zubovich also noted a probable relationship between the rotational component of horizontal movements and the circular migration of seismic activation along the periphery of the Fergana basin [Butovskaya *et al.*, 1961; Ulomov, 1974].

In order to determine the relative values of yearly averaged strain increments, Zubovich interpolated the velocity field to a uniform grid and calculated the divergence at each of its nodes in a manner similar to our calculations.

As noted above, all aforementioned results were obtained on the territories of countries participating in the project. In this connection, the information on the GPS network in eastern Uzbekistan, developed in 2002 on the initiative and with the participation of the National Institute of Seismology (A.R. Yarmukhamedov and others), is presented in Fig. 11. No significant results have been obtained as yet from the GPS measurements due to a short observation period. GPS sites proposed by the author and extending the Uzbekistan network westward are also shown in this figure. These sites would be helpful for obtaining new instrumental constraints on recent movements of the Turan plate and linking the Uzbekistan system of GPS sites to the GPS networks already existing in the Mediterranean and Caucasus regions.

CONCLUSION

Movements of the crust and the entire lithosphere are three-dimensional. Depending on the geodynamic stress state, some regions are dominated by vertical movements and others, by horizontal movements. The vertical component is best reflected in the topographies of the crustal base and of the Earth's surface in orogenic regions. This component can readily be studied by geological, geodetic, and other methods. Horizontal movements manifest themselves less evidently, particularly in flat areas, where the vertical component is small, and it is very difficult to identify them by traditional methods. In this respect, GPS measurements open new possibilities for such investigations.

The agreement between GPS data and results obtained through the application of the reduction method to the crust throughout its thickness indicates that the neotectonic deformations have inherited the Neogene–Quaternary movements and GPS can provide constraints on the contemporary deep geodynamics of the crust and the whole lithosphere.

Analysis of schemes and maps characterizing neotectonic and recent tectonic movements and their comparison with the geological–geophysical setting and seismicity in the study region point to the predominant role of horizontal movements in the geodynamics of the Pamirs, the Tien Shan, and the Turan plate. The horizontal and vertical velocity fields are complementary to one another. Territories of low velocity gradients of vertical movements are characterized by high velocity gradients of horizontal movements. Within such territories, seismically active areas coincide with areas of the highest gradients of horizontal velocities.

Consistent crustal deformation in the zone of transition from the epi-platform Tien Shan to the young epi-Hercynian Turan plate and the counterclockwise horizontal rotation of the eastern part of this plate are due to the fact that platform territories involved in tectonic movements enlarge.

Platform regions are typically characterized by a very weak seismic activity. However, a number of very large earthquakes occurred in these regions, and the position of sources of such events is virtually unpredictable at present because of a lack of reliable data on recent horizontal movements and paleodynamics. Apart from the series of Gazli, Uzbekistan, earthquakes of 1976–1984 (M = 7.0, 7.3, and 7.2); three New Madrid, United States, earthquakes of 1811–1912 ($M \approx 8.0$), the Tangshan, China, earthquake of 1976 ($M = 7.8$); the Ahmadabad, India, earthquake of 2001 ($M = 7.7$); and a series of other no less significant earthquakes are examples of such “exotic” seismic events. It is noteworthy that the sources of nearly all of these earthquakes were confined to rift or riftlike structures characterized by predominantly horizontal tensile stresses and strains.

As regards the territory of southern Russia, the Scythian plate, which is a genetic continuation of the Turan platform, and the adjacent territory of the West European platform cannot be regarded as an exception to the necessity of reassessment of their potential seismic hazard toward a higher level. The Scythian plate and southern European Russia continue to be increasingly involved in the orogenic movements of the Caucasian mountain structures. The danger of new destructive earthquakes in this densely populated area is high. Social, economic, and ecological consequences of strong local earthquakes can be aggravated by the presence of atomic power plants and other installations of particular significance prone to possible seismic effects.

Detailed studies (including GPS observations) of the seismicity structure and recent geodynamics in the zone of transition from the Crimea–Caucasus–Kopet Dagh fold system to the Scythian–Turan plate are of particular importance for seismic hazard prediction in the Northern Caucasus and adjacent Russian areas.

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