ISSN 0016-8521, Geotectonics, 2013, Vol. 47, No. 1, pp. 31–51. © Pleiades Publishing, Inc., 2013.
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The Geodynamics of the Pamir–Punjab Syntaxis

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Received December 19, 2011

Abstract—The collision of Hindustan with Eurasia in the Oligocene–early Miocene resulted in the rearrangement of the convective system in the upper mantle of the Pamir–Karakoram margin of the Eurasian Plate with subduction of the Hindustan continental lithosphere beneath this margin. The Pamir–Punjab syntaxis was formed in the Miocene as a giant horizontal extrusion (protrusion). Extensive nappes developed in the southern and central Pamirs along with deformation of its outer zone. The Pamir–Punjab syntaxis continued to form in the Pliocene–Quaternary when the deformed Pamirs, which propagated northward, were being transformed into a giant allochthon. A fold–nappe system was formed in the outer zone of the Pamirs at the front of this allochthon. A geodynamic model of syntaxis formation is proposed here.

DOI: 10.1134/S0016852113010020

INTRODUCTION

The tectonic processes that occur in the Pamir–Punjab syntaxis of the Alpine–Himalayan Foldbelt and at the boundary of this syntaxis with the Tien Shan have attracted the attention of researchers for many years [2, 7–9, 13, 15, 28]. The range of problems under discussion includes the kinematics and dynamics of these processes and their quantitative parameters, including offset and shortening of the Earth's surface and the rotation angles of tectonic elements. These data have been obtained as a result of research on the regional fold–nappe structure, seismic and seismological studies, investigations of recent movements of the Earth's crust, paleomagnetism of rocks, etc.

The Pamir–Punjab (Western Himalayan) syntaxis is an arc (orocline) that rounds the Punjab prominence of the Hindustan continent. The Vakhsh–Transalay (Vakhsh–Kazykart) thrust fault and the right-lateral South Gissar Strike-Slip Fault are located at the front of the Pamir–Punjab syntaxis (Fig. 1). Both boundaries of the syntaxis are complicated by large-offset strike–slip faults: the Chaman and Darvaz left-lateral faults at the western boundary and the Pamir–Karakoram and Momuk right-lateral faults at the eastern boundary.

The disharmonic inner Hindu Kush–Karakoram and the outer Pamir arcuate systems are distinguished within the syntaxis. The Pamir arc is delineated by structural elements of the Pamirs, Kunlun, and Badakhshan. The eastern limb of the Pamir arc is conjugated with structural units of the western Kunlun and northern Tibet via the right-lateral horizontal flexure associated with the Pamir–Karakoram and Momuk strike–slip faults. The western limb of the Pamir arc is conjugated with the system of right-lateral strike-slip faults that comprises the Harirod, Zebak–Mujan, Bandi-Turkestan, Andarab, and Albruz–Mormul faults (Fig. 1).

The Pamir arc is more compressed as compared with the Hindu Kush–Karakoram arc. Disharmony of these arcs arose in the western part of the syntaxis due to the offset along the right-lateral Zebak–Mujan Strike-Slip Fault, which is also named the Zebak–Anjoman, Panjshir, or Afghan–South Pamir Fault. The offset along the strike-slip fault diminishes in the eastern direction, so that the disharmony of the arcs smooths.

DEFORMATION OF THE EARTH's CRUST IN THE SYNTAXIS

The Northern Pamirs

Northern, central, and southern provinces are recognized in the Pamirs (Fig. 2). The northern Pamirs consist of inner and outer tectonic zones. The inner zone is thrust over the outer zone along the Karakul (North Pamir) Fault (Fig. 1). In the western segment of the Pamir arc, the Karakul Thrust Fault passes into the left-lateral Darvaz Strike-Slip Fault. In the eastern segment of the Pamir arc, the Karakul thrust fault passes into the Momuk Thrust Fault [5], which is known in Kunlun as the Main Pamir Thrust Fault [84].

The outer zone of the northern Pamirs (the outer zone of the Pamirs) is composed of folded Mesozoic and Cenozoic rocks. The deformation of the outer zone is a part of a structural rearrangement that took place in the boundary region between the Pamirs and Tien Shan in the Late Cenozoic.

The nearly meridional Late Cenozoic graben of Lake Karakul and the Tashkorgan–Tagarma–Muji system of basins are situated in the inner zone of the northern Pamirs, which are composed of Paleozoic

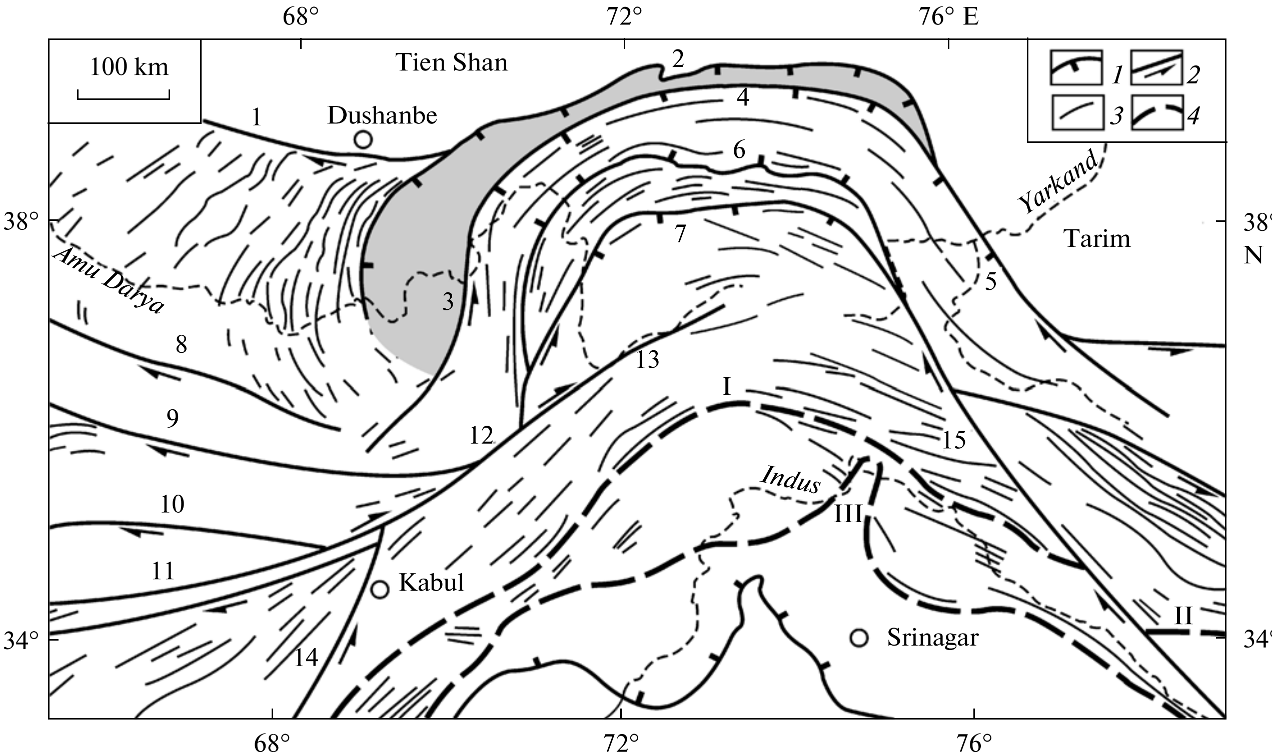

Fig. 1. Structural grain of the Pamir–Punjab syntaxis. The outer zone of the Pamirs is gray; rivers are shown as dashed lines. (*1*) Thrust fault; (*2*) strike-slip fault; (*3*) axial lines of folds; (*4*) oceanic sutures (Roman numerals in figure): I, Shyok; II, Bangong (Cretaceous); III, Indus–Zangpo (Paleogene). Faults (Arabic numerals in figure): 1, South Gissar; 2, Vakhsh–Transalay; 3, Darwaz; 4, Karakul; 5, Momuk; 6, Tanymas; 7, Rushan–Pshart; 8, Albruz–Mormul; 9, Andarab; 10, Bandi-Turkestan; 11, Harirod (Herat); 12, Zebak–Munjan; 13, Panjshir; 14, Chaman; 15, Pamir–Karakoram.

and older rocks (Fig. 3). The basins were formed in the transtensional stress field [91]. The Kongur Tagh granite-gneiss dome also occurs in the inner zone (Fig. 3). According to the geochronological and thermobarometric data, the gneisses were exhumed in the late Miocene [84]. The fission-track age of zircons from bedrock and detritus in the Kongur Tagh and Muztagh Mountains confirms the episode of basement exhumation in the Late Miocene 9–7 Ma ago and shows that the most intense exhumation took place in the Holocene: 2–1 Ma ago the exhumation rate was 7.4 km/Ma [54].

The Central Pamirs

The northward dipping Tanymas Fault (Fig. 4, *TN*) is a boundary between the northern and the central Pamirs. In the east this fault is conjugated with the northern branch of the Pamir–Karokaram Strike-Slip Fault.

In the Late Cenozoic, the Phanerozoic rocks of the central Pamirs were detached from the basement with the formation of multistage assemblies of nappes and tectonic sheets (Fig. 4), which consist of autochthon, parautochthon, and several tectonic nappes [6, 36–38]. The autochthons that crop out in the anticlinoriums are formed of the Vendian and Lower Paleozoic rocks. The para-autochthonous tectonic sheets consist of Silurian to Oligocene rocks. The allochthon has a multistage structure. The tectonic sheets are formed of Paleozoic rocks (Akbaytal and other nappes), as well as of Mesozoic and Cenozoic rocks (Yazgulem, Muzkol, etc.). The main nappes that developed after the deposition of the Paleogene sedimentary rocks, which occur in various facies in the section of the para-autochthon and allochthon. During the nappe emplacement the tectonic sheets underwent deformation with the autochton.

As follows from the palinspastic reconstruction of the nappe assembly in the Yazgulem Range by reconstruction of folds composed of Mesozoic and Paleogene rocks in four sections, the assembly was shortened by 28–45% [39]. The direction of nappe motion in the central Pamirs and the location of its root zone is a matter of debate. Ruzhentsev [38] supposed that the root zone occurs in the north of the central Pamirs and estimated the offset at 70–80 km. Other authors [21, 25, 39] suggested that the allochton moved from the south northward. In particular, it was assumed [35] that the root zone of the nappes in the central Pamirs occurs in the Karakoram and their offset reaches 150 km. The formation of multistage nappes resulted

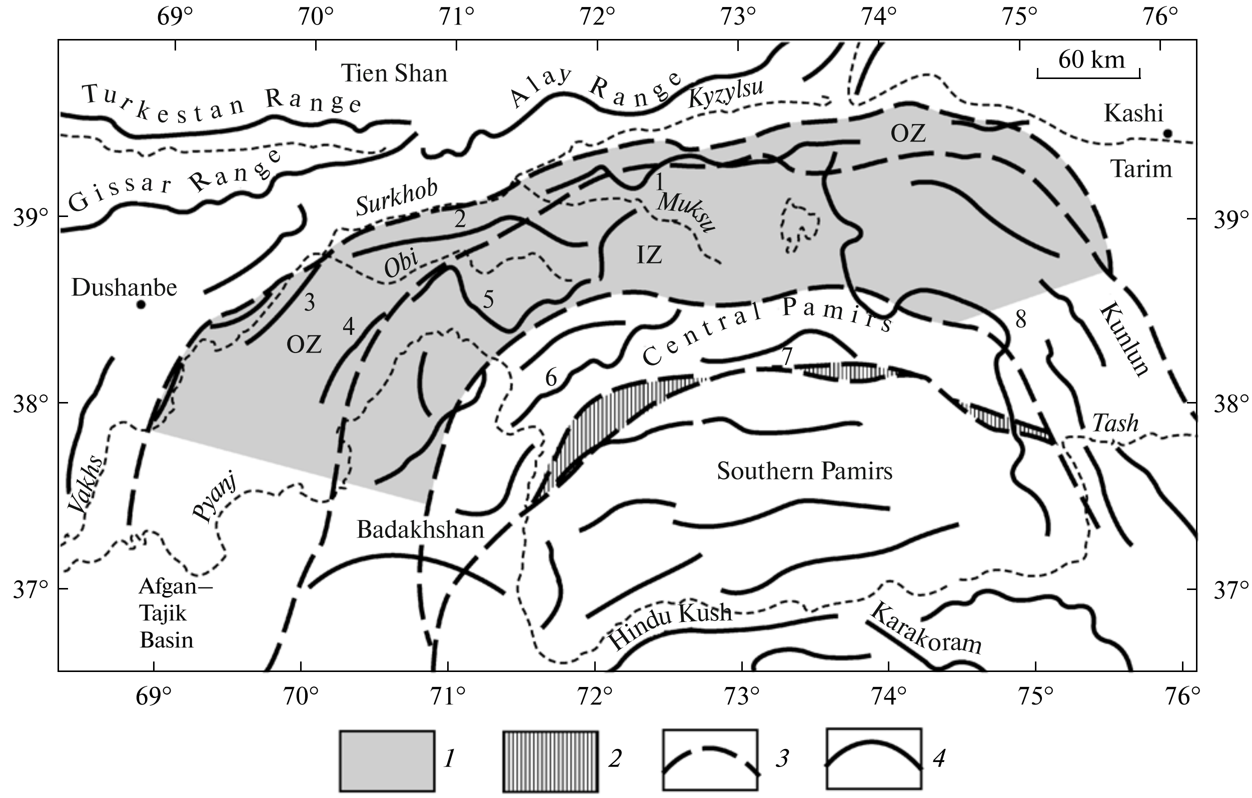

Fig. 2. Main tectonic zones of the Pamirs. (*1*) Northern Pamirs: OZ, outer zone of the Pamirs; IZ, inner zone; (*2*) Rushan–Pshart Zone; (*3*) boundaries between tectonic zones; (*4*) mountain ranges (numerals in figures): 1, Transalay; 2, Peter the First; 3, Vakhsh; 4, Khozretishi; 5, Darwaz; 6, Yazgulem; 7, Muzkol; 8, Sarykol; rivers: *Obi*, Obihingou; *Tash*, Tashkorgan.

in significant shrinkage of the basement of the central Pamirs. The transverse shortening of the central Pamirs in the Cenozoic by 100 km that was suggested in [53] is apparently underestimated.

The structure of the central Pamirs assumes that detachment of the Phanerozoic cover and formation of Cenozoic nappes was a result of thrusting of the basement of the central Pamirs under the southern Pamirs along the faults of the Rushan–Pshart tectonic zone and under the northern Pamirs along the Tanymas Fault. This process was accompanied by warping of the basement. The exhumation of the Muzkol and Sarez granite-gneiss domes in the Miocene (Fig. 3) was probably related to these deformations. Underthrusting and deformation of the basement led to a decrease in the area of the central Pamirs and the formation of antiforms, which , in turn, initiated gravitational geological processes that accompany thrusting.

The Southern Pamirs and Karakoram

The Rushan–Pshart Thrust Fault Zone separates the southern and the central provinces of the Pamirs (Figs. 2, 4). The zone reaches 25 km in width and has a northward vergence. The tectonic sheets are composed of rocks that relate to the margins of the Mesozoic oceanic basin [35]. In the east, the Rushan–Pshart thrust faults are conjugated with the Eastern Pamir System of right-lateral strike-slip faults, which are the branches of the Pamir–Karakoram Strike-Slip Fault Zone.

Extensive nappes occur in the southern Pamirs (Fig. 4). The autochthon and parautochthon consist of ancient metamorphic rocks and Mesozoic–Cenozoic igneous and sedimentary rocks. The Upper Paleozoic, Mesozoic, and Cenozoic rocks make up the allochthon. The youngest rocks of the autochthon and parautochthon are Oligocene or Miocene in age. The nappes moved northward; their root zones presumably occurred in the northern Karakoram [34, 35, 37]. The width of the allochthon in the southern Pamirs measured perpendicular to the front of nappes is more than 100 km. The bottom of the allochthon is affected by several gentle folds. The emplacement of the nappes was accompanied by internal deformations of both the allochthon and autochthon.

The fold–nappe structure of the southern Pamirs shows that the basement of this province underwent significant shortening in the Neogene. This shortening is estimated at 160 km [53] but could be much greater. The postcollision granites of the Karakoram and southern Pamirs are Oligocene and mostly Miocene in age [86].

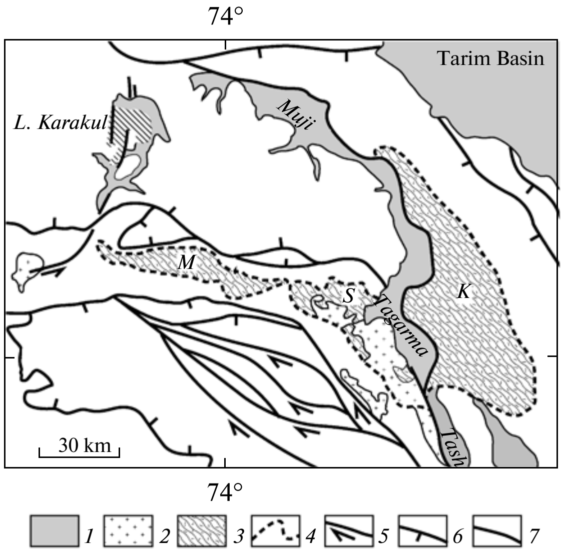

Fig. 3. Tectonic units in the eastern Pamirs active in the Late Cenozoic, modified after [84]. (*1*) Quaternary sediments; (*2*) Cenozoic granites; (*3*) Miocene granite-gneiss domes (letters in figure): *K*, Kongurshan; *M*, Muzkol; *S*, Sarez; (*4*) roof of granite-gneiss domes; (*5*) strike-slip faults; (*6*) thrust fault; (*7*) normal fault; *Tash*, Tashkorgan valley.

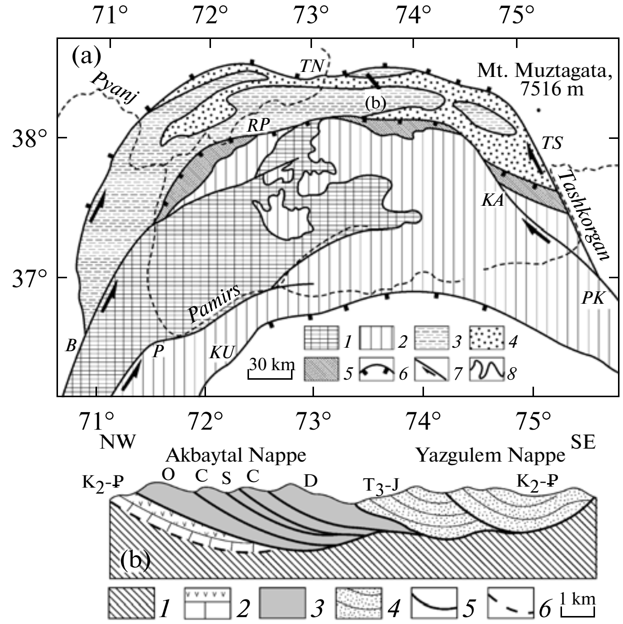

Fig. 4. Nappes of the southern and central Pamirs: (a) map, after [6, 35, 37, 38] and (b) geological section of nappe assembly of central Pamirs in the Zortashkol River valley, modified after [38]; see panel (a) for section line location. Panel (a): (*1, 2*) southern Pamirs: (*1*) autochthon and parautochthon, (*2*) allochthon; (*3, 4*) central Pamirs: (*3*) autochthon and parautochthon, (*4*) allochthon; (*5*) Rushan–Pshart tectonic zone; (*6*) thrust and underthrust faults; (*7*) strike–slip faults; (*8*) overthrust. Faults (letters in figure): *B*, Baharak; *KA*, Kalaktash; *KU*, Kunar; *P*, Pandsher (South Pamirs); *PK*, Pamirs–Karakoram; *RP*, Rushan–Pshart; *TN*, Tanymas; *TS*, Tashkorgan. Panel (b): (*1*) autochthon: Upper Paleozoic–Jurassic metamorphic rocks; (*2*) parautochthon: Upper Cretaceous–Paleogene; (*3, 4*) allochthon: (*3*) Paleozoic, (*4*) Mesozoic and Cenozoic; (*5*) overthrusts; (*6*) lower tectonic contact of parautochthon.

The Western Himalayas

The initial width of the tectonic zone between the Indus–Zangpo Suture and the Main Thrust Fault of the Himalayas, which is a boundary between the Alpine Foldbelt and the Hindustan Platform, was estimated in the western Himalayas using the method of balanced cross sections. As a result of folding and thrusting, this zone underwent threefold shortening for 470 km [59].

The Pamir–Karakoram Strike-Slip Fault

The Pamir–Karakoram Strike-Slip Fault (Fig. 1, unit 15), which complicates the eastern boundaries of both limbs of the Pamir–Punjab syntaxis, plays an important role in its kinematics.

Offset in the Holocene. According to the GPS data, the contemporary slip rate along the Pamir–Karakoram Fault is 7.4 ± 0.7 mm/yr [56]. The slip rate along the Karakoram segment of this fault is 11 ± 4 mm/yr [47] or 3.4 ± 5 mm/yr [64] (GPS data). The Tagarma–Tashkorgan chain of the late Pleistocene and Holocene pull-apart grabens extends for ~150 km along the northern branch of the Pamir–Karakoram fault. The width of particular grabens is less than 10 km. The faults that bound the grabens bear signs of vertical separation and horizontal offsets of moraines, terraces, and other landforms. A scarp that is visible for 30 km in its extent and is up to 3.5 m high arose during the Tashkorgan 1895 earthquake. The right-lateral offsets of the moraines that are related to the last glaciation (10–12 ka) are 150–250 m [69] and the average slip rate is ~20 mm/yr. In the fault segment between 31° and 34° N, the strike-slip offsets of morphostructures, which postdate the last glaciation, reach 200 m in the south and 400 m in the north [68]. At 32° N, two morains that are displaced along the fault contain fragments that have been dated at 21000 ± 1000 and 140000 ± 5500 years on the basis of cosmogenic beryllium. The offsets of moraines along the fault are 220 ± 10 and 1520 ± 50 m; the average rate of displacement is 10–11 mm/yr [57]. According to other data, the sediments that were dated at 11000–14000 years were displaced for 40 ± 5 m with an average rate of ~4 mm/yr [51].

The magnitude and the age of displacement. The offset along the Pamir–Karakoram Strike-Slip Fault in the Cenozoic was initially estimated at 170–250 km [12, 73]. Various estimates given in subsequent publications (1000 km [74], 600 km [66], 400 km [85, 94], 300 km [70], 200 km [77], etc.) are based on the geological markers in fault walls, whose choice has not always been appropriate. The Indus Valley and the Miocene pluton were displaced in the Late Cenozoic for 90–120 km along the Pamir–Karakoram Fault [87]. In the northern segment of the fault, the offset reaches 150–160 km [83].

The offset along the Pamir–Karakoram Strike-Slip Fault is mostly accommodated by thrusting along the Rushan–Pshart Fault Zone (Fig. 1, unit 7); the remainder is compensated by the Tanymas Thrust Fault (Fig. 1, unit 6). Geological maps of Xinjiang and Tibet [78, 79] show that the significant offset of the Pamirs relative to Tibet is related to rheological deformation within a wide shear zone by means of a horizontal flexure at the eastern limb of the syntaxis. This shear zone extends over the northwestern Kunlun, the eastern Pamirs, and the Karakoram. The offsets of various tectonic zones in the Pamirs differ due to the formation of the afore-mentioned horizontal flexure, horizontal folds, and partial compensation of the horizontal offset by thrusting. The front of the northern Pamirs is displaced relative to the front of the western Kunlun for a distance of ~300 km. The northern Pamirs is also shifted for 600 km relative to the extension of this tectonic zone in Tibet. The Cretaceous Bangong–Shyok Suture in the apex of the Hindu Kush–Karakoram arc is located 300 km to the north relative to its location in Tibet.

The onset of displacement along the Pamir–Karakoram Fault is dated by the age of mylonites in the fault zone. Such data have been obtained with isotopic and fission-track methods for the southern segment of the fault. According to this evidence, the displacement began 11 Ma [70], 13 Ma [72], 15 Ma [75, 83], 18 Ma [89], or 22–25 [66, 94] Ma ago. The links of mylonites to the onset of faulting are not obvious [88, 92]. It has also been suggested that the offsets could have started 35–37 Ma [63, 66] or 50 [74] Ma ago.

The ages of leucogranite dikes that extend parallel to the strike-slip fault and that are foliated in the same direction have been determined with U–Pb method at 15.7 ± 0.5 and 13.7 ± 0.3 Ma, respectively [75, 92]. The ruptured granitic batholiths in the Ladakh that had completed their crystallization 15 Ma ago [88] and then were offset along the Pamir–Karakoram Fault are considered to be direct evidence for the beginning of strike-slip dislocations in the middle Miocene or later.

Uplift of the Pamirs

The formation of the Pamir–Punjab syntaxis was accompanied by uplift of the Pamirs, which began from the late Oligocene. This process gave rise to the development of contrasting topography and the deposition of clastic material in foredeeps. The acceleration of uplifting took place in the Holocene. The average rates of vertical growth of the eastern Pamirs in the late Pleistocene and Holocene are estimated at 2–4 and 15–20 mm/yr, respectively [4]. As follows from the archeological data, the northern Pamirs grew in the Holocene at a rate of ~100 mm/yr.

Comparison of the Glenny and the isostatic gravity anomalies makes it possible to distinguish isostatic and tectonic components in the neotectonic uplift of the Pamirs [1]. The tectonic component of the uplift of the Pamirs is ~4 km; this value is twice as great as the tectonic component of uplift in the southern Tien Shan.

Recent Deformation of the Syntaxis

According to the GPS data (Fig. 5; Table 1) the shortening rate between the Peshawar GPS station at the boundary of Hindustan and the Garm station at the northwestern boundary of the Pamirs is estimated at 31.8 ± 1.5 mm/yr [71]; the meridional component of shortening is 26.6 mm/yr. This value illustrates the shortening rate of the Pamir–Punjab syntaxis as a whole. As follows from the data obtained at the Khorog station at the southern boundary of the Pamirs and the Garm station at the northwestern boundary of the Pamirs, the Pamirs shorten with a rate of 16.2 ± 1.6 mm/yr [71]; the meridional component of the rate is 13.4 mm/yr. This implies that half of the shortened syntaxis area falls on the territory to the south of the Pamirs. The territory between the Khorog and Osh stations (the latter is located in the Ferghana Valley) is shortening at a rate of 11.8 ± 2 mm/yr. Most of this shortening occurs at the boundary between the Pamirs and the Tien Shan. The difference between the rates of northward displacement of GPS stations located in the Transalay Range and Ferghana Valley is ~10 mm/yr [19]. According to other calculations that are based on GPS data, the Pamirs converge with the Alay Range at a rate of 15 mm/yr [20] or 17.5 ± 0.8 mm/yr [96].

The convergence of the Khorog and Shaartuz stations in the southern Pamirs and in the Tajik Depression, respectively, is probably related to the westward expansion of the Pamirs with a rate of 6.2 ± 1 mm/yr. Comparison of the data on displacement of the Tashkorgan and Khorog stations indicates that the Pamirs expands in the latitudinal direction with a rate of 8.8 ± 2 mm/yr [71]. The displacement of the Peshawar and the Kabul stations provides evidence for the left-lateral offset with a rate of 18.1 ± 1 mm/yr in Balochistan at the western boundary of the Pamir–Punjab syntaxis.

The GPS stations located in the Pamirs, the northwestern Kunlun, and Tarim migrate northward with similar rates of 15–20 mm/yr [20, 71]. This shows that the Pamirs and Tibet currently move jointly toward the Tien Shan. At the front of this convergence, Tarim is thrust under the Tien Shan, while the Pamirs thrusts over the Tien Shan.

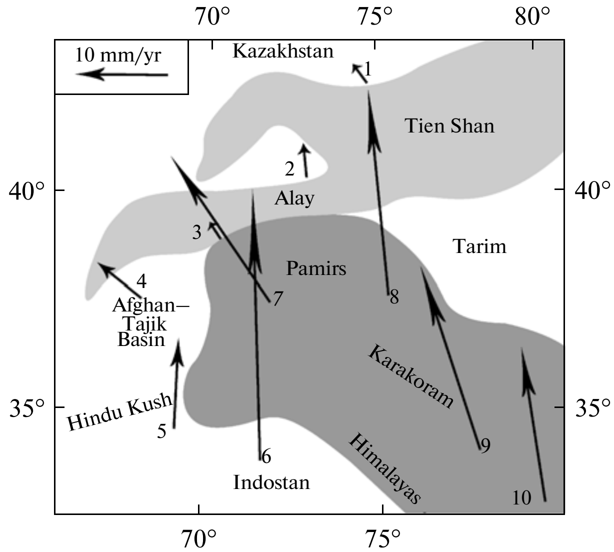

Fig. 5. Vectors of motion velocity of GPS stations relative to the stable part of Eurasia, after [71]. GPS stations: 1, Bishkek; 2, Osh; 3, Garm; 4, Shaartuz; 5, Kabul; 6, Peshawar; 7, Khorog; 8, Tashkorgan; 9, R; 10, I. Dark grey colour marks the territory of High Asia, light grey colour marks the territory of Tien Shan Mountains.

DEFORMATION IN THE BOUNDARY ZONE BETWEEN THE PAMIRS AND THE TIEN SHAN

The concept of dynamic interaction between the Pamirs and the Tien Shan was first stated by Mushketov [28]. Argand [46] considered the Tien Shan–Pamir boundary as a zone, where ductile flows in the Earth's crust of Indo-Africa and Eurasia interacted with each other. Nalivkin [30] suggested that this tectonic boundary is the front of a giant nappe. At present, the idea of dynamic interaction of the Pamirs and the Tien Shan is supported by a set of comprehensive arguments.

The region of the nearest Pamir–Tien Shan convergence, which covers the Alay Valley and Surkhob river valleys and their mountainous framework, is called the Pamir–Alay area. The Alay Valley is a narrow depression in front of the overthrusting Pamirs. The seismic profiles across the valley show that the cover of recent sediments overlaps a system of northward-verging thrust faults that disturb Mesozoic and Cenozoic rocks. The reconstructions obtained with the method of balanced cross sections indicate that the meridional shortening of the valley under the effect of tectonic deformation is 33–37% [58]; the average rate of transverse shortening is about 1 mm/yr. The onset of the deformations was marked by the appearance of conglomerates in the Upper Oligocene–lower Miocene Massaget Formation.

In the west, the Pamirs and the Tien Shan are separated by the Afghan–Tajik basin, which is filled with Mesozoic and Cenozoic sedimentary rocks. The northern part of the Afghan–Tajik Basin is called the Tajik Depression. This is a folded mountainous land with a range of topography that reaches thousands of meters, which looks like a depression only relative to the adjacent giant mountainous ranges. In the Tajik Depression, the Tithonian Stage of the Jurassic, which is composed of rock salt, gypsum, and anhydrite up to 800 m in thickness, overlies with unconformity older Jurassic sequences. Evaporites occur at a depth of 8–10 km and locally reach the surfaces as salt domes. They bound the fold system of the Tajik Depression and the outer zone of the Pamirs from below [15, 17].

The Cretaceous, Paleogene, and Neogene rocks of the Tajik Depression occur as the tectonic sheets that are thrust from the west eastward over the Vakhsh ramp (Fig. 6, unit 4). Bekker [3] combined these tectonic sheets into six structural units (tectonic nappes). Units 1, 2, and 3 are eastward verging, whereas units 5, 6, and 7 are westward verging (Fig. 6). The folds of structural unit 7 extend from the Tajik Depression to the Pamir–Alay area of the maximum Pamir–Tien Shan convergence. The folded Cretaceous and Cenozoic sedimentary rocks in the eastern part of the Tajik Depression (structural units 5, 6, 7 in Fig. 6), the Pamir–Alay area, and the foothills of the northwestern Kunlun make up the fold–nappe system of the outer zone, which surrounds the Pamirs in the north as a structural arc (Fig. 1).

The Boundary Zones of Active Faults

The Darwaz–Transalay zone of active faults is traced from the western boundary of the Tajik Depression to the northern slope of the Transalay Range. These faults were active in the late Pleistocene and Holocene. In the southwest, the zone extends along the older Darwaz Fault. A Pleistocene pull-apart graben is located in the Pyanj River valley and in the lower reaches of the Obiminou River (Fig. 7, unit 1). A left-lateral 300-m offset of the late Pleistocene landform, a 120–150-m offset of the early Holocene terraces and fans, and a 20-m offset of the late Holocene landforms took place along the western boundary of this graben [44]. The left-lateral offsets of young landforms for several tens of meters are known in the Darwaz Fault Zone at the headwater of the Obiminou River (Fig. 7, unit 2). Numerous left-lateral offsets of the late Holocene dry channels for a distance of a few meters to 100 m were found to the north (Fig. 7, unit 3). An offset of 21 m of a defensive wall that probably surrounded a mediaeval gold mine was also noted. The offset of landforms along strike-slip faults in this area reached 160 m in the Holocene, and 800–1200 m over the late Pleistocene and Holocene. Offsets of late Pleistocene landforms of 1500–1800 m and of the lower Pleistocene sediments of distances up to 3000 m were described in the Saryob River valley, a left tributary of the Obihingou River (Fig. 7, unit 4). The average rate of the Holocene slip along the Darwaz Fault Zone was 5–16 mm/yr and 4–

12 mm/yr over the late Pleistocene and Holocene [24, 31, 44].

In the basin of the Obihingou River, the zone of active faults crosses the Peter the First Range (Fig. 7, unit 5), reaches the Vakhsh–Transalay Thrust Fault, and extends further to the northeast along this fault. The left-lateral offset of a trough valley and late Pleistocene moraine for 170 m is seen in the Karashura River valley (Fig. 7, unit 6). In the Muksu River valley, the moraine ridges are displaced for 50 m along the left-lateral strike-slip fault [44]. Further to the northeast, the strike of the Darwaz–Transalay Zone of active faults smoothly deviates to the east–northeast and strike-slip offsets along longitudinal faults disappear. On the northern slope of the Transalay Range, the active dislocations include thrust faults, seismogenic ditches, and scarps (Fig. 7, unit 7). The radiocarbon age of 5150 ± 150 yr was determined for the Fore-Transalay Thrust Fault with displacement for 15 m; the thrusting rate is 3 mm/yr [32].

The Surkhob branch of the zone of active faults, which is associated with the Cenozoic Vakhsh–Transalay Thrust Fault, extends along the northern slope and foothills of the Peter the First Range and the left wall of the Surkhob River valley Fig. 7). The displacement of Pleistocene thrust faults reaches 500 m here [33]. The results of ground-based geodetic research on the northern slope of the Peter the First Range [16] show that the offset along the Vakhsh–Transalay Fault changed in the 1960s from thrusting to strike–slipping (Fig. 7, inset).

The Boundary Seismofocal Zone

The seismofocal zone plunges beneath the Pamirs from its boundary with the Tien Shan [53, 61]. The double belt of epicenters of earthquakes, which are at a medium depth in the south and are shallow in the north, marks the location of this zone in plan view (Fig. 8a). The seismofocal zone dips to the south at an angle of ~45° in the northern Pamirs and at 30°–35° in the northwestern Pamirs. The seismofocal zone is traced for about 300 km from the front of the Pamirs to a depth of 150–200 km (Fig. 8b).

Convergence of the Pamirs and the Tien Shan in the Late Cenozoic

The folds and faults that formed in the Cretaceous and Cenozoic in the frontal part and at the flanks of the Pamir Plate during its convergence with the Tien Shan bear quantitative information on this process.

Deformations of the outer zone of the Pamirs. The paleomagnetic data on the Cretaceous rocks in the outer zone of the Pamirs, which were obtained with use of low-temperature cleaning, indicate that the structural elements of the Transalay Range underwent clockwise rotation through an angle above 90° relative to the structural features of the Darwaz Range [11].

Table 1. The motion velocities of GPS stations, after [71]

Station	Number in Fig. 5	vN, mm/yr	vW, mm/yr
Bishkek	1	2.1 ± 0.8	1.8 ± 1.6
Osh	2	4.0 ± 1.3	0.6 ± 1.3
Garm	3	2.4 ± 1.2	1.2 ± 1.2
Shaartuz	4	3.9 ± 1.1	5.5 ± 1.1
Kabul	5	10.0 ± 1.1	0.1 ± 1.1
Peshawar	6	29.0 ± 0.9	0.8 ± 0.9
Khorog	7	15.8 ± 1.1	10.7 ± 1.1
Tashkorgan	8	22.5 ± 1.7	1.9 ± 1.8
R	9	20.3 ± 1.2	5.7 ± 1.2
I	10	16.6 ± 1.6	1.7 ± 1.6

Note: vN and vW are meridional (northward) and latitudinal (westward) components of the motion velocities of GPS stations relative to the stable part of Eurasia.

Later, more detailed and reliable paleomagnetic data on the Cretaceous and Eocene–Miocene rocks (Table 2) confirmed and specified this conclusion. The collections from GPS station R (Fig. 9) and several other stations were initially studied with the use of paleomagnetic thermal cleaning up to 400–500°C [2, 48] and then were subjected to a follow-up study using high-temperature cleaning and component analysis [49, 93]. The follow-up study insignificantly changed the initial result (Table 2). It was shown that the interpreted paleomagnetic component is stable in the temperature range of 250–680°C; this made it possible to use the data on collections that had been studied earlier with paleomagnetic cleaning up to 400–500°C and were not subject to follow-up study. These are paleomagnetic directions at stations V and Y (Fig. 9) in the Cretaceous rocks and at stations U, W, and Z in the Eocene–Miocene rocks (Table 2). The paleomagnetic declination at station J for the Miocene and the paleomagnetic declination at station K for the Early Cretaceous are local paleomagnetic reference directions (Fig. 9; Table 2), which are located beyond the territory that is involved in intense rotation. The rotation angles of the sites relative to these reference directions are given in Table 2.

The paleomagnetic data show that the tectonic units of the Tajik Depression and the outer zone of the Pamirs were turned after the early Miocene relative to the southwestern Gissar Range, the southern Tien Shan Mountains, and the Tarim Platform, which surround these units in the west, north, and east. The Kulyab segment of the outer zone of the Pamirs, which strikes in the near-meridional direction, was turned anticlockwise through 49° ± 12°, on average (Fig. 9, *a*). Structural units 5 and 6 underwent similar rotation in the eastern part of the Tajik Depression. The Petrovsky segment of the outer zone of the Pamirs (Fig. 9, *b*), which

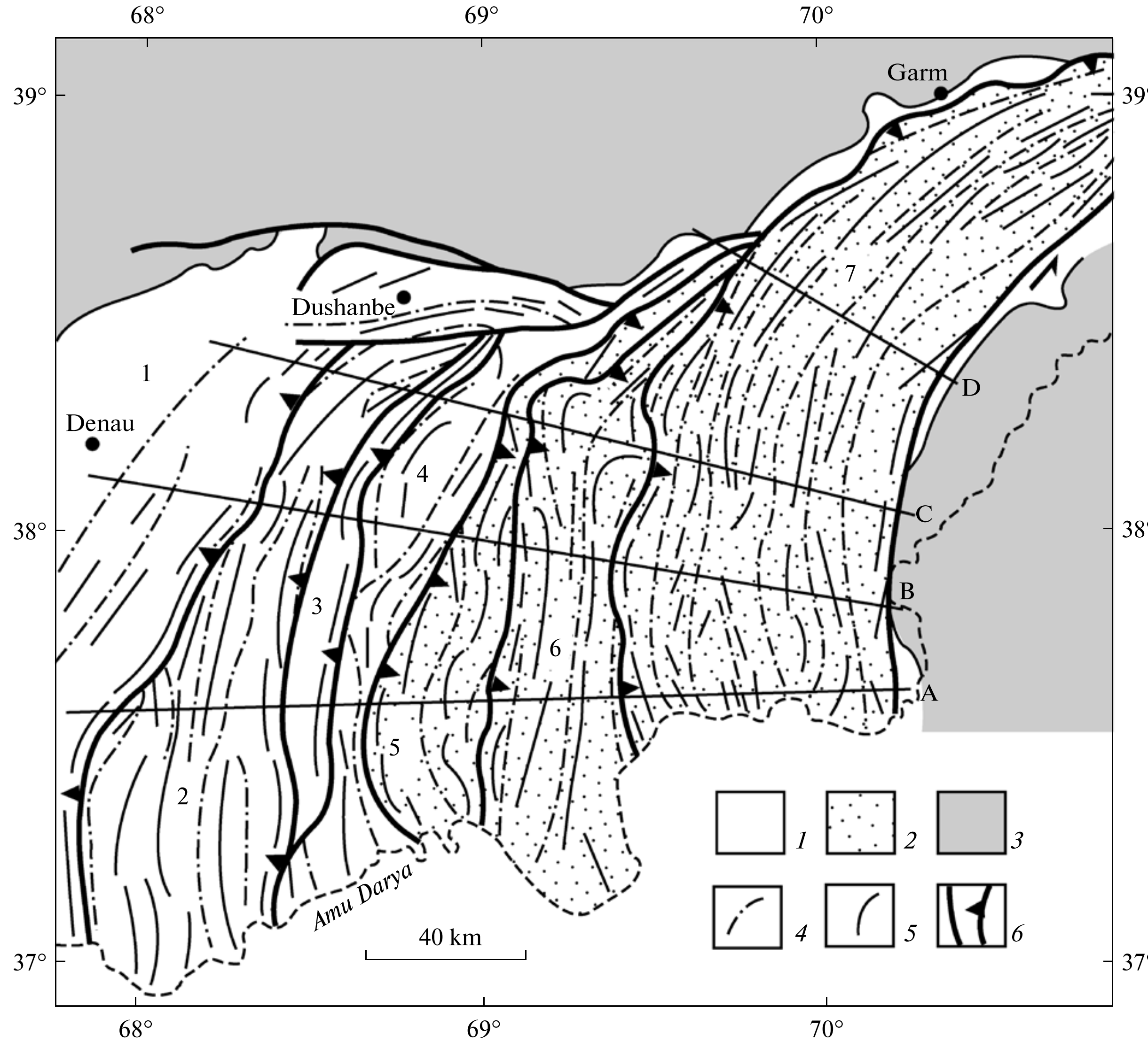

Fig. 6. Tectonic units of the outer zone of the Pamirs and Tajik Depression, modified after [3]. (*1, 2*) Cenozoic and Mesozoic: (*1*) Forland, (*2*) outer zone of the Pamirs; (*3*) Paleozoic; (*4, 5*) axial lines of (*4*) synclines and (*5*) anticlines; (*6*) main faults. Structural units (numerals in figure): 1, Babatagh; 2, Rengan–Kyzymchek; 3, Dagana-Kiik–Aruktau; 4, Vakhsh; 5, Karatau; 6, Sarsariak–Sanglak; 7, Kulyab–Transalay.

has the present-day east–northeast strike, has retained its initial orientation. The Transalay segment, which currently strikes in the latitudinal direction, has been turned clockwise through 34° ± 7° (Fig. 9, *c*). The reconstruction of the outer zone of the Pamirs on the basis of paleomagnetic data shows that this zone was almost rectilinear in the early Miocene and is oriented to the northeast in the present-day coordinate system.

Reconstruction of the Tajik Depression in the Pliocene. The structure of the Tajik Depression that separates the Pamirs and the Tien Shan has been well studied by geological mapping, geophysical surveying, and drilling. This provided a high reliability of geological sections across the Tajik Depression and the western part of the Pamir–Alay area prepared by Bekker [3]. These sections were the basis for estimation of the shortening of the territory and for palinspastic reconstructions [8, 52]. Comparison of the results (Table 3) obtained for sections A, B, and C (Fig. 6) allowed us to draw the following conclusions. The degree of shortening of tectonic units in the Tajik Depression decreases southward from 51% along section C to 33% along section A. Furthermore, the degree of shortening of the tectonic units in the Tajik Depression relative to their initial widths is much higher in the western part of the depression (Fig. 6, units 1–3) than in the eastern part (Fig. 6, units 5–7). The Vakhsh ramp (Fig. 6, unit 4) underwent the maximal shortening due to overlapping by the adjacent units, whereas shortening caused by internal deformation is relatively small. The shorten-

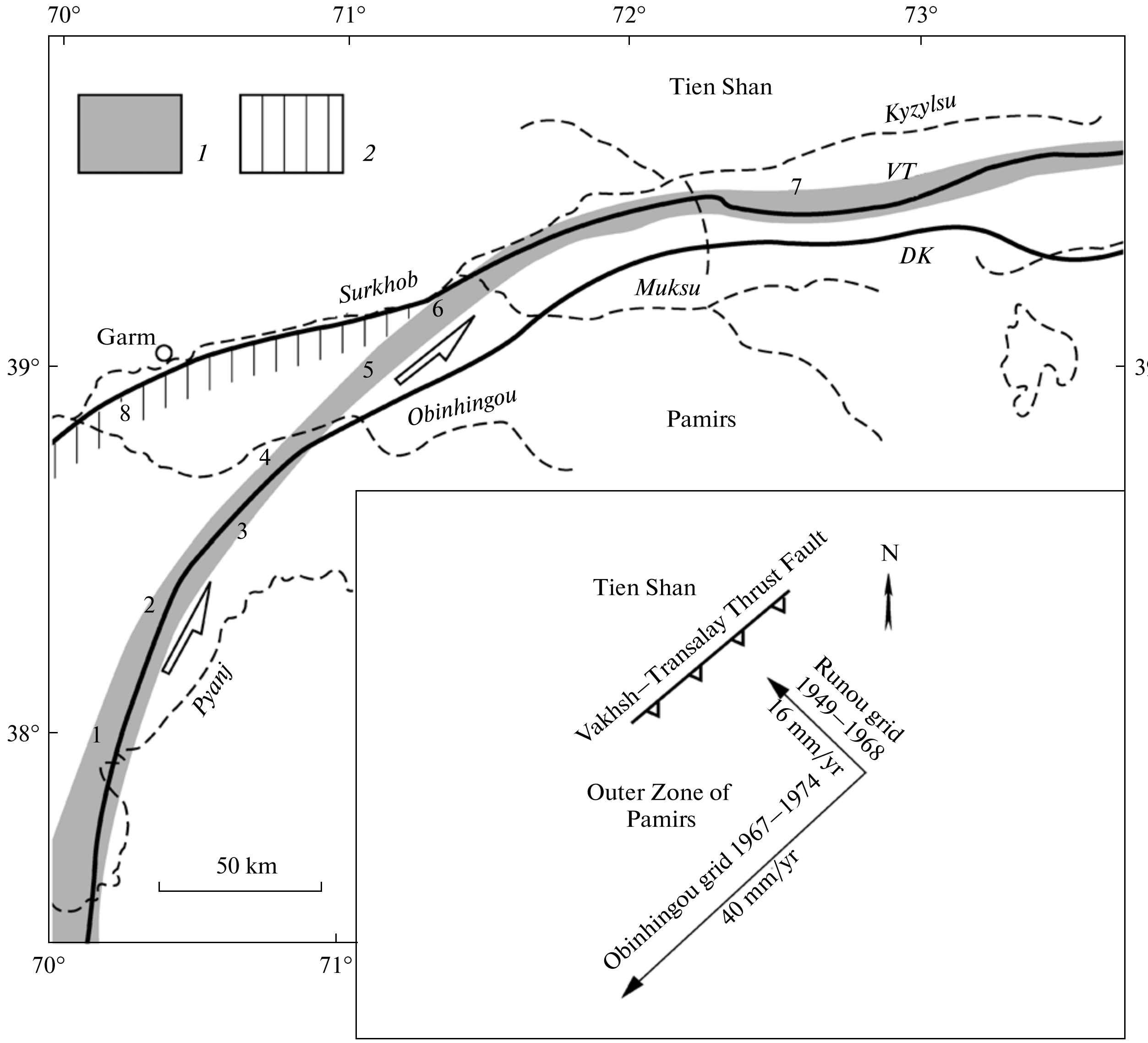

Fig. 7. The Darwaz–Transalay (*1*) and the Surkhob (*2*) active fault zones. The Cenozoic faults (solid lines): *VT*, Vakhsh–Transalay; *DK*, Darwaz–Karakul. Inset: offset direction and rate of the Runou–Obihingou area of the outer zone of the Pamirs relative to the southern Tien Shan estimated from the results of recurrent triangulation. See text for 1–7 numbers.

ing of the outer zone of the Pamirs related to the internal deformation reaches 100 km (59% of the initial width) along section D (Fig. 6) in the western part of the Pamir–Alay area. The results of independent verification of Bekker's geological sections were published in [45]. These estimates of shortening in the Late Cenozoic are close to my conclusions [8, 52].

The palinspastic reconstruction of the Tajik Depression based on the data on shortening of its surface along sections A, B, C, and D due to tectonic deformation (Table 3) is given in Fig. 10. In this reconstruction, the Kulyab–Transalay tectonic unit (Fig. 10, unit 7) is turned relative to its present-day position through 55°. That is in compliance with the paleomagnetic data on the rotation of this unit. The rotation angles of other tectonic units are also consistent with the paleomagnetic data. The convergence of the Pamirs and the Tien Shan (the distance between points *a* and *a*' in Fig. 10b) is ~300 km. A vast gap arose in the reconstruction between the northeastern part of the Vakhsh tectonic unit and the Tien Shan. Along section D, the width of this tectonic opening is more than 100 km. Shortening of this area is not supported by the data on the regional structure. A gap appears between sections C and D, where the western structural units of the Tajik Depression disappear from the Earth's surface, providing evidence for continental subduction beneath the Pamirs [53].

The existence of a seismofocal zone between the Pamirs and the Tien Shan (Fig. 8), the overthrusting of the Pamirs and the disappearance of a part of the crust

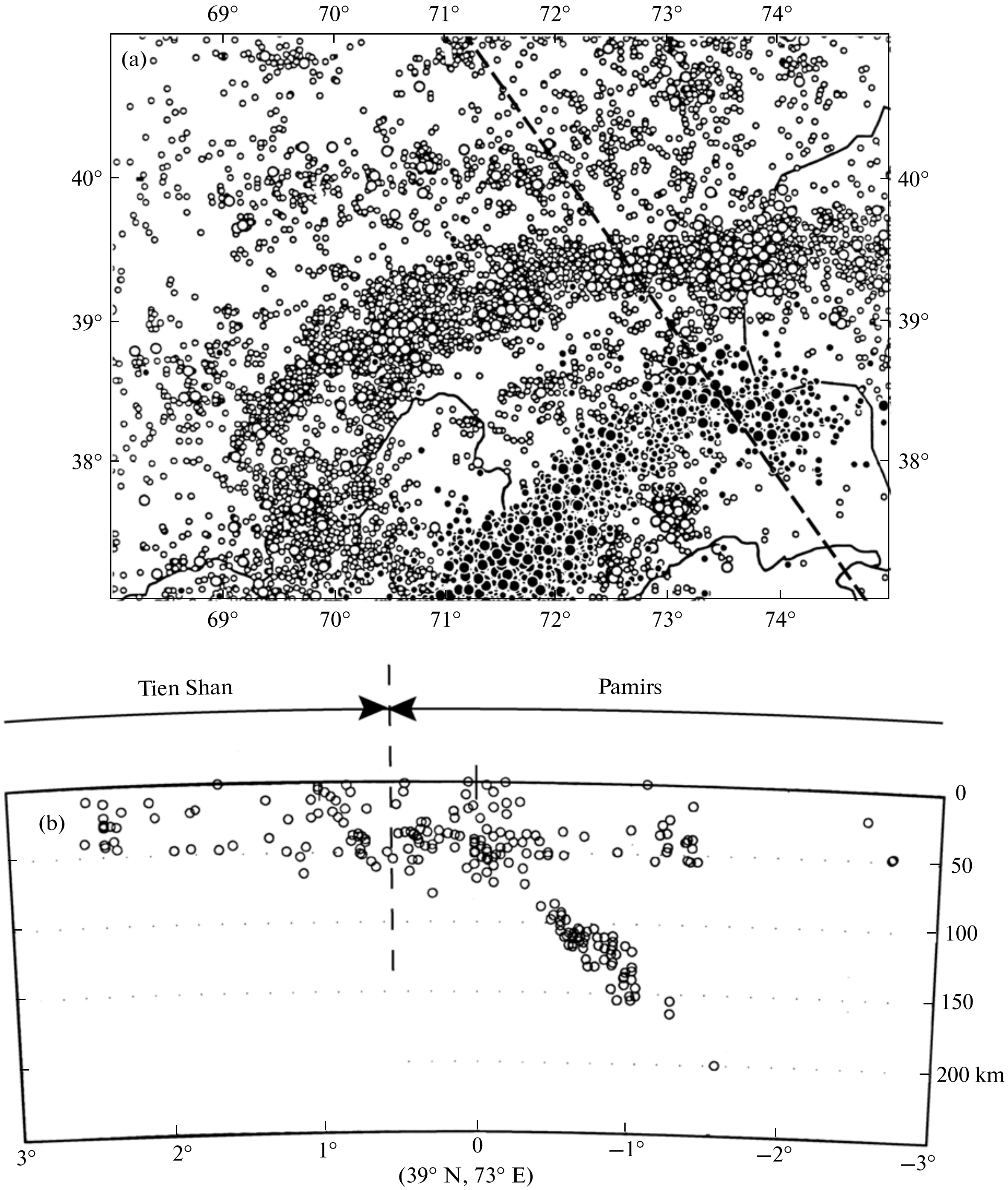

Fig. 8. (a) Earthquake epicenters in the Pamirs and the Pamir–Alay area and (b) seismofocal zone plunging beneath the Pamirs. The epicenters of the earthquakes that occurred in 1964–1980 at depths above 70 km (open circles) and below 70 km (filled circles) [61] are shown in panel (a). The earthquakes with magnitudes >4 and <4 are shown by large and small circles, respectively. The line of profile (b) is dashed; dotted lines are state borders between Tajikistan, Afghanistan, and China. Earthquake hypocenters that occurred in 1964–1985 in the belt 400 km wide [53] are shown in panel (b). The belt strikes at 145° SE; the line shown in panel (a) is located amidst the belt; the center of the section (0°) has coordinates 39° N and 73° E.

beneath it (Fig. 10) allow us to draw the conclusion that the seismofocal zone corresponds to the zone of subduction of the continental crust of the Tien Shan beneath the continental crust of the Pamirs.

Interpretation of the facies analysis results. The Vakhsh–Transalay fault separates different facies of the Cretaceous and Paleogene sedimentary rocks of the Tajik Depression and the Pamir–Alay area [15].

Table 2. Paleomagnetic declination in the Lower Cretaceous, Eocene, Oligocene, and Miocene rocks at the sites located in the southwestern Gissar Range, Tajik Depression, and outer zone of the Pamirs

Area	Station	Age	D°	a95°	ΔD°	R°/reference direction	Source
Eocene, Oligocene, and Miocene							
Dekhkanabad (reference direction)	J	Mio_1	3	9	10	0	[55]
Pulkhakim	L	Mio_1	349	13	16	(+) 14 ± 15	[93]
Payryagatau	M	Mio_1	336	12	14	(+) 27 ± 14	[93]
Aksu	N	Mio_1	347	15	18	(+) 17 ± 16	[93]
Kalininabad	O	Oli_2–Mio_1	310	9	11	(+) 53 ± 11	[93]
South Darwaz	R	Eoc_2–Mio_1	312	11	13	(+) 52 ± 13	[93]
		Eoc_2–Mio_1	305	7	8	(+) 58 ± 7	[2]
Tukaynaron	S	Oli_2–Mio_1	317	11	13	(+) 46 ± 14	[93]
Childara	U	Oli–Mio_1	352	7	8	(+) 11 ± 8	[2]
Khipshun	W	Eoc_4–Mio_1	329	7	9	(+) 34 ± 9	[2]
Kyzyl-Art	Z	Eoc_3–Mio_1	37	5	7	(–) 34 ± 7	[2]
Cretaceous							
Derbent (reference direction)	K	K_1	6	3	5	0	[94]
Aksu	N	K_1	356	3	5	(+) 10 ± 6	[49]
Nurek-2	P	K_1	355	12	21	(+) 11 ± 17	[76]
Nurek-1	Q	K_1	324	5	9	(+) 42 ± 7	[76]
South Darwaz	R	K_1	321	5	7	(+) 45 ± 7	[94]
		K_1	314	3	5	(+) 52 ± 5	[2]
Rogun	T	K_1	359	4	6	(+) 7 ± 7	[76]
Mionadu	V	K_1	8	3	4	(–) 2 ± 5	[2]
Guloma	Y	K_1	40	12	14	(–) 34 ± 12	[2]

Note: D°, declination of paleomagnetic vector; a95° radius of confidence circle for paleomagnetic vector; ΔD° confidence half interval for paleomagnetic declination; R, rotation angle: (+) anticlockwise or (–) clockwise relative to paleomagnetic declination of regional reference directions Dekhkanbad (**J**) for the Paleogene and Neogene and Derbent (**K**) for the Lower Cretaceous; Oli, Oligocene; Eoc, Eocene; Mio, Miocene. See Fig. 9 for the station location.

This implies that the outer zone of the Pamirs thrusts over the Cretaceous and Paleogene sedimentary rocks for 10–18 km. As was shown in [41], the eastern continuations of the facies zones are overlapped by the Vakhsh Thrust Fault for 100 km. New data exist for a more extensive territory [8, 52, 53]. The facies maps of the Cretaceous and Cenozoic sedimentary rocks that occur in the Pamirs and their eastern framework provide evidence for overlapping of a significant part of the Tajik Basin by the Pamirs. The facies zones of the southern wall of the Tajik basin are located now in the outer zone of the Pamirs, being deformed (compressed and bent) and advanced far to the north into the facies area of the northern periphery of the Tajik Basin. The offset is estimated at 300–400 km. The reconstruction of the paleogeographic and paleotectonic settings shows that in the Eocene the Tajik marine basin cut inland for 1000 km and had a width of 600 km. The sea left the region provisionally in the Priabonian and completely in the Oligocene.

THE GEODYNAMICS OF THE SYNTAXIS

The Earth's Crust

According to DSS, the thickness of the Earth's crust beneath the Transalay Range of the Pamirs is 68 km and reaches 70 km in the central Pamirs [40]. The Moho discontinuity in the northern and the southern Pamirs was established with the earthquake converted-wave method at a depth of 65–80 and 65–75 km, respectively [23, 65]. The Earth's crust in the Pamirs has a layered structure. A 5–10 km thick waveguide was detected at a depth of 10–20 km [23]. According to the seismological data, the lower boundary of the Earth's crust in the Tajik Depression occurs at a depth of 32–50 km. The lowest thickness of the

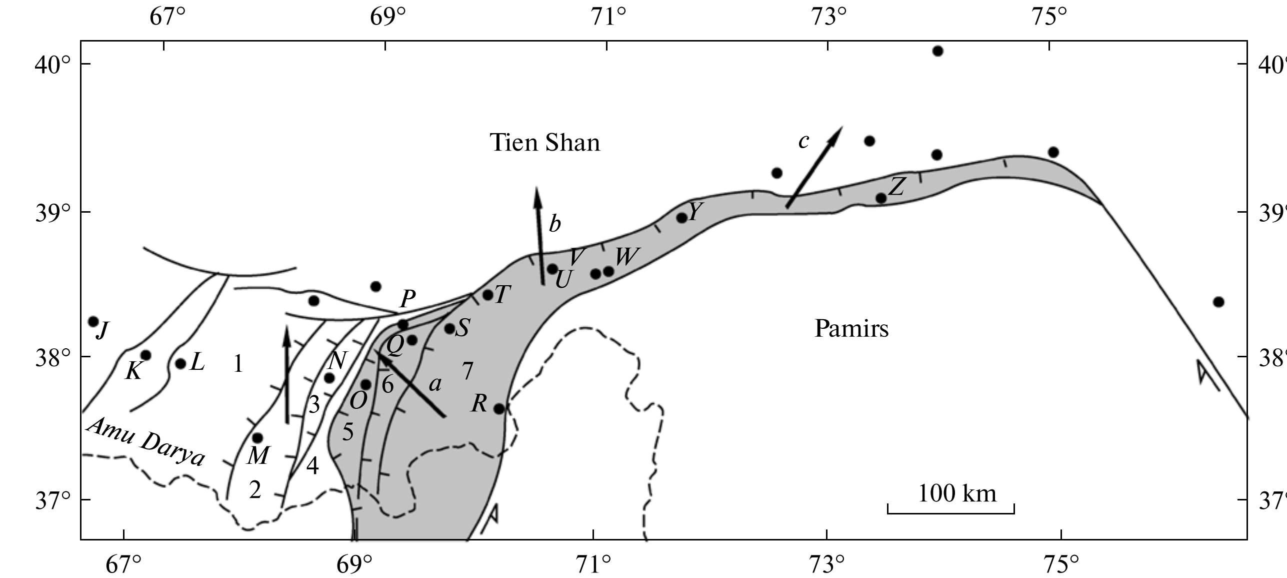

Fig. 9. The stations of paleomagnetic study of Cretaceous, Paleogene, and Miocene rocks denoted by large dots and labeled as in Table 2. 1–7 are tectonic units (see Fig. 6). Arrows indicate average directions of paleomagnetic declination. See text for *a–c*.

crust is established in the southern part of the depression and increases to the east and northeast. The roof of the waveguide, at a depth of 12–24 km, corresponds to the bottom of the upper crust [43].

The data on focal mechanisms in the sources of shallow earthquakes show that the compressive stresses at depths above 15 km in the northern Pamirs are oriented NW–SE and differ in the orientation from the compressive stresses in the southern Tien Shan. The seismotectonic deformations in the northern Pamirs have a transpressional reverse–strike-slip character [42].

Table 3. Late Cenozoic transverse shortening of the tectonic units in the northern Afghan–Tajik basin along the lines of geological sections A–D in Fig. 6

Section	Tectonic unit	LQ, km	LR, km	Σ, %
A	1–3	73	115	37
	4	6	25	76
	5–7	134	166	19
	1–7	213	316	33
B	1–3	65	123	47
	4	25	49	49
	5–7	108	158	32
	1–7	198	329	40
C	1–3	82	175	53
	4	6	47	87
	5–7	104	164	37
	1–7	192	382	51
D	4–7	69	170	59

Note: LQ, present-day width of tectonic units at the level of 0 masl; LR, reconstructed initial width of tectonic units in the early Miocene; Σ, transverse shortening of tectonic units, % of their initial width.

The Lithospheric Mantle

The thickness of the lithosphere beneath the Pamirs is 150–200 km; it has a relatively low density [27]. Data on the lithosphere was obtained from the seismic tomography of P-waves [65, 81, 95]. The section along meridian 75° E (Fig. 11a) shows a relatively high position of the lithosphere bottom (up to 160 km) at the northwestern end of Tarim and its southward plunging beneath the Pamirs at angles of 20°–30° to a depth of 270 km. This boundary is traced southward to a latitude of 37° N. The location of the lithosphere bottom beneath the Pamirs (Fig. 11a) indicates that the entire Tien Shan lithosphere participates in the intracontinental subduction. According to the seismological data, the length of the seismofocal zone is about 300 km (Fig. 8) and probably corresponds to the length of the lithospheric slab.

The high-velocity anomalies detected with seismic tomography of the Pamir–Punjab syntaxis are interpreted as the continental lithosphere and the lithospheric mantle. Jut C in the seismic sections (Fig. 12) is regarded as a lithospheric slab of the Indian Plate that has sunk into the mantle. This implies that the Hindustan lithosphere is thrust under the Pamirs for a distance of 300 to 500 km from the Indus–Zangpo suture.

The region of mantle earthquakes. The Hindu Kush–Pamir region of earthquakes occupies the

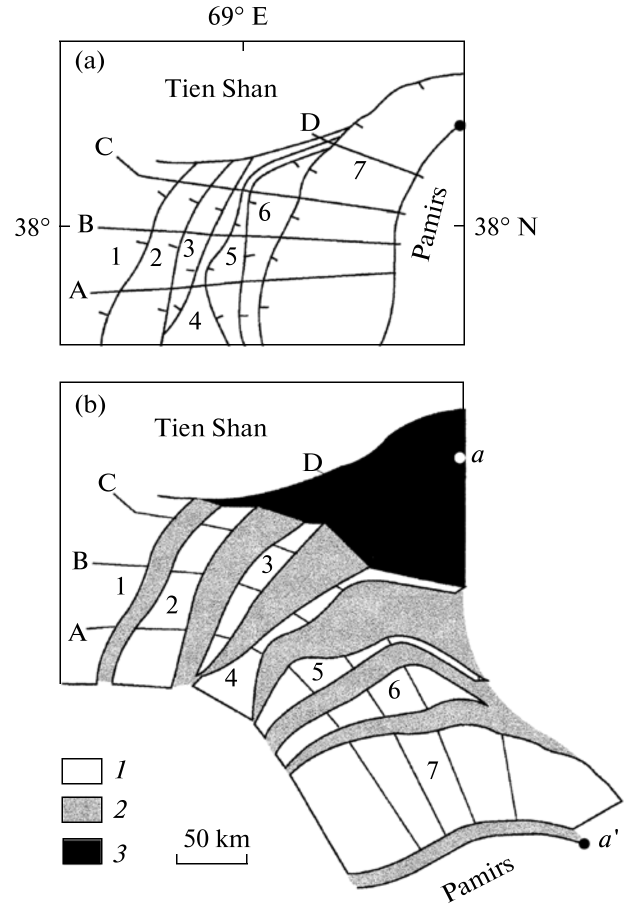

Fig. 10. Palinspastic reconstruction of the Tajik Depression: (a) present-day position of tectonic units 1–7 in the Tajik Depression; (b) position of these tectonic units before the Late Cenozoic folding as follows from shortening of the Earth's crust along geological sections A–D (see Fig. 5 and Table 2). (*1*) Territory of present-day tectonic units; (*2*) surface shortened due to folding and faulting; (*3*) tectonic gap, i.e., an area, the shortening of which is not compensated by the observed structural features.

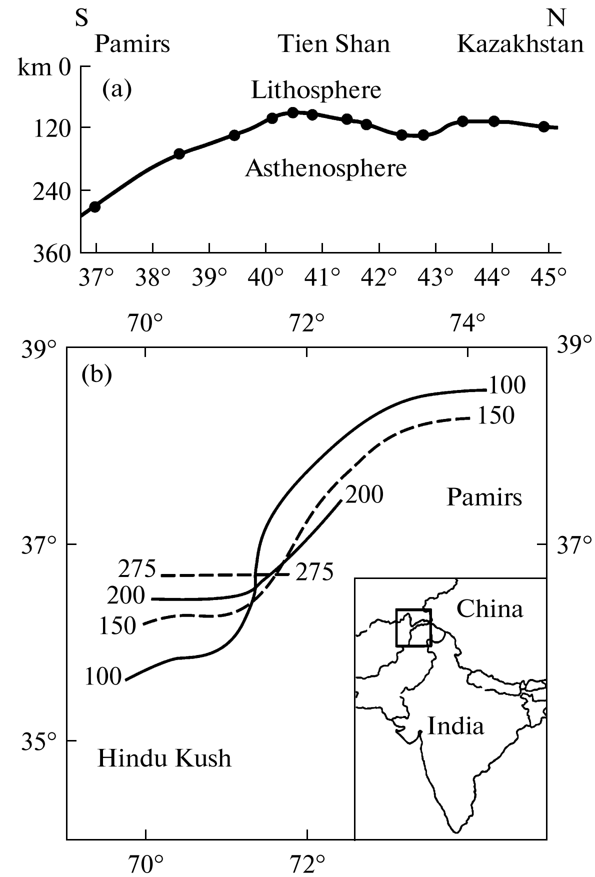

Fig. 11. (a) The boundary between the lithosphere and asthenosphere beneath the Tien Shan and the Pamirs along meridian 75° E from the results of seismic tomography [65]; (b) iso-depth contour (km) map of the Hindu Kush–Pamirs hypocentral zone of mantle earthquakes [50].

southwestern part of the Pamirs and the adjacent territory of the western Hindu Kush foothills. The earthquake hypocenters are located in the mantle at depths of 100–300 km. The focal zone is interpreted as a subduction zone of the continental lithosphere [26, 50]. The subduction zone experiences deviation and flip in subduction polarity along its strike (Fig. 11b). The focal zone beneath the western Hindu Kush foothills strikes in the latitudinal direction and dips northward. To the east, at meridian 71.5° E, the focal zone, which strikes in the meridional direction, becomes vertical or steeply dipping to the east. Beneath the northern Pamirs, the focal zone again acquires latitudinal orientation but plunges to the south. In the segment of the vertical focal zone, its kinematics corresponds to the scissor strike-slip fault. The projection of the mantle seismofocal zone on the Earth's surface is similar in configuration to the crustal structure (Fig. 1), where latitudinal thrust faults of the northern Pamirs and the Hindu Kush are separated by a near-meridional strike-slip fault zone. All this data shows that the Pamir block is a minor lithospheric plate. The subduction zones of the continental lithosphere in the region are displayed in Fig. 13 as a block diagram with sight holes.

Geodynamic Models

According to the proposed models, different processes take part in the formation of the Pamir–Punjab syntaxis. Let us consider the probability of their participation.

(1) Convergence of the Tarim and Tajik rigid blocks. According to some authors, e.g. [21, 60], this process was crucial or substantial in the formation of the structural arcs of the Pamirs.

The deformation of the body into an arc under compression of its flanks should be accompanied by right-lateral strike-slip faulting at the western limb of the Pamir arc and by left-lateral faults at the eastern limb (Fig. 14b). The actual pattern is, however, the

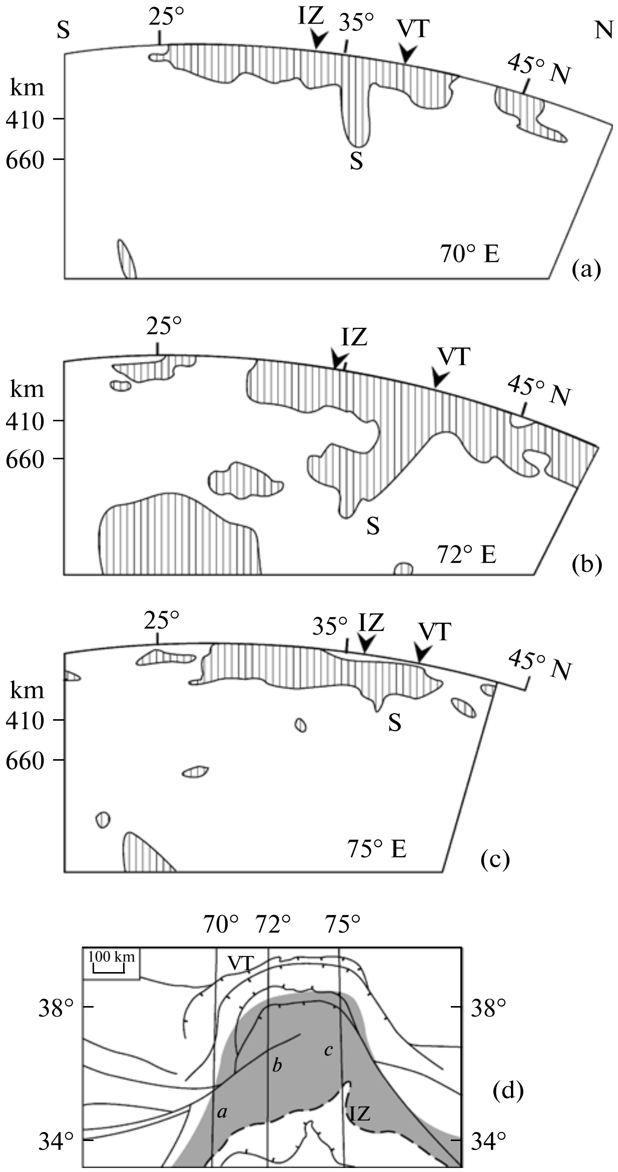

Fig. 12. High-velocity anomalies (hatched) in seismic tomographic sections along 70°, 72°, and 75° E meridians, after (a) [80], (b) [95] and (c) [81]. The section lines are shown in the schematic map of the Pamir—Punjab syntaxis (d); the region of Cenozoic granites is shown in gray; IZ, the Indus—Zangpo oceanic suture; VT, the Vakhsh—Transalay Fault at the Pamir—Tien Shan boundary; S, slab of the Hindustan lithosphere.

inverse: left-lateral offsets are typical of the Darwaz—Badakhshan limb, whereas right-lateral slip is established at the Kunlun limb (Fig. 14c). According to this model, the left-lateral offsets should be expected at the boundary between the Tajik Block and the Tien Shan; however, right-lateral thrusting actually develops here. Thus, this model (Fig. 14b) is inconsistent with the data.

(2) The role of indentors. The Punjab (Jhelum) prominence of Hindustan plays the role of a rigid

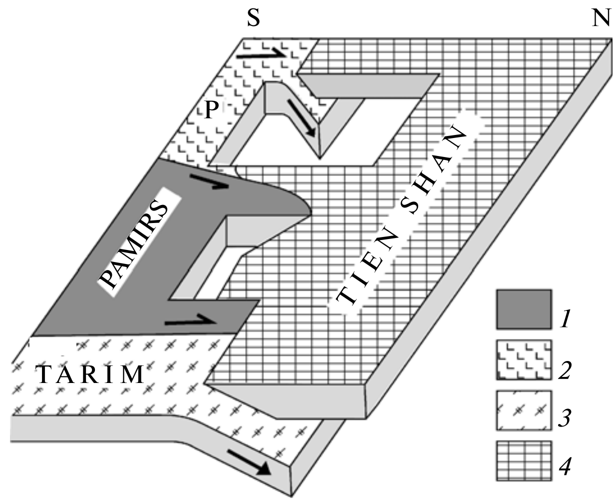

Fig. 13. Recent interaction of minor lithospheric plates in the northern Pamir—Punjab syntaxis. (*1*–*4*) Minor plates: (*1*) Pamirs, (*2*) Persian (P), (*3*) Tarim, (*4*) Tien Shan.

indentor, intrusion of which into the rigid—plastic Eurasian Plate gave rise to stacking of the crust and the arcuate structure of the Pamirs. Hauden [62], Nalivkin [29, 30], as well as Mushketov [28], D. Vadia, and other geologists shared this concept.

The emplacement of a rigid wedge into a plastic body is accompanied by the formation of arcuate folds, which surround the wedge. The degree of compression of the arcs decreases with distance from the wedge (Fig. 14a). The geometry of the Pamir—Punjab syntaxis is in conflict with this mechanism of deformation, because the Pamir arc is more compressed as compared with the Hindu Kush—Karakoram arc.

The Pamir indentor. The Pamir Block, which overthrusts and propagates northward, was an indentor that controlled the nature of the upper crustal deformation in the Tajik Depression and the southwestern Gissar Range. The structural grain of the Turkestan—Alay mountain system shows that the role of the Pamir indentor in the formation of this mountain system was insignificant, most likely, because of its insufficient thickness, which was limited by the basal detachment, along which the Pamirs thrust over the Tien Shan.

(3) The gravitational expansion of the Pamirs. The average height of the Pamirs is more than 4 km; the mountain summits at its margin exceed 7 km in height. According to the archeological data, the rate of uplifting of the Pamirs in the Holocene was about 100 mm/yr [14]; the geomorphic estimates yield 20 mm/yr [4]. The Tajik Depression to the west of the Pamirs is less than 2 km in height; the basement of the Tarim Basin to the east of the Pamirs lies at a depth of ~1.5 km above sea level. The Alay Valley is located at a height of 3.0—3.5 km to the north of the Pamirs. It is reasonable to suggest that the Pamir highland underwent gravity expansion (dulling) under these conditions.

The formation of young meridional normal faults, as well as the graben of Lake Karakul and other structural forms, provides evidence for extension of the Pamirs in the latitudinal direction [91]. The extension of the Pamirs and its rate are established by means of cosmic geodesy. The latitudinal extension as a natural response to the meridional compression is enhanced by its gravitational dulling, the effect of which increased with the growth of the Pamir Highland at the late stage of syntaxis formation.

(4) The flowing down of the crust of the Pamirs from above the underthrusting Hindustan. Delamination of Hindustan's crust during the subduction of the Indian Plate and the thrusting of the detached crust under the Pamir's crust could have induced gravity transfer of the masses that streamed down and their stacking. This mode of crust thickening was considered in [18]. The hypothesis of the gravity flow of the crust from the underthrusting and northward propagating Hindustan prominence explains the high degree of tectonic stacking of the crust in the Pamir–Punjab syntaxis, abundant nappes in the Pamirs, and the thrust-fault character of its outer boundaries. The cosmic geodetic data show that underthrusting of the Hindustan Plate beneath the Pamirs is occurring at present. The rate of the northward displacement of Hindustan is twice as high as the rate of the displacement of the Pamirs in the same direction.

(5) The influx of masses from the Himalayan collision zone. The pattern of magnetic anomalies in the Indian Ocean and paleomagnetic data indicate that the Hindustan continent underwent anticlockwise rotation before its collision with Eurasia and continued after the collision [95]. Such a path of movement of Hindustan relative to Eurasia resulted in the transpressional character of their collision. The stresses increased southeastward along the Himalayan zone of plate convergence. The stress gradient that was maintained during a million years must have induced a transfer of the crustal masses along the Himalayan Foldbelt in the northeastern direction toward the Pamir–Punjab syntaxis. Asymmetry of the syntaxis and disharmony between the Pamir and the Hindu Kush–Karakoram structural arcs is probably a consequence of the influx of crustal masses from the southeast.

The idea of the tectonic flow of the Earth's crust along the Himalayan collision zone due to pumping of rocks into the Pamir–Punjab syntaxis was stated in [7]. The subsequent cosmic geodetic data confirm that such a flow is developing now. The rate of displacement of GPS stations along the strike of the Himalayas gradually increases in the northwestern direction (toward the Pamir–Punjab syntaxis) from 0 in the central Himalayas to 2 cm/yr in the western Himalayas and Karakoram [90]. The influx of masses into the Pamir–Punjab syntaxis from the southeast can also be a consequence of the oroclinal belt of the Himalayas [22].

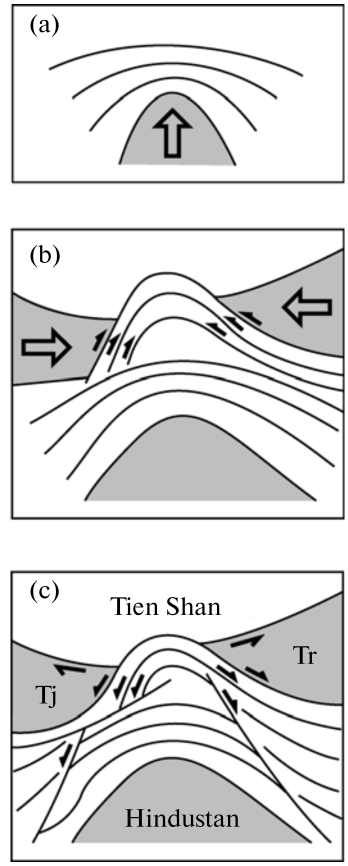

Fig. 14. Schemes (in plan view) of the formation of structural arcs (a) under effect of invasion of a rigid body into the plastic mass and (b) by convergence of lateral rigid massifs; (c) scheme of the Pamir–Punjab syntaxis. Massifs: Tajik (Tj) and Tarim (Tr).

The gravity flow from above the underthrusting prominence of Hindustan and the tectonic flow along the Himalaya–Tibet collision zone readily explain the structural features of the Pamir–Punjab syntaxis, including the structural disharmony and nappe structure of the Pamirs.

(6) Mantle flows and mantle convection. The suggestion that the upper mantle flow beneath the Pamirs brings about compressive stresses in the Earth's crust and offsets along faults was stated by Ritsema [82]. Desio [60], developing these views, saw an analogy with a block of ice (the continental block of the Pamirs), which is entrained by flow into the bay between the Tarim and Tajik–Karakum massifs. The syntaxis narrows in the northern direction. The effect of this funnel could have led to an acceleration of the flow in the narrower frontal Pamir segment of the syntaxis relative to its rear segment [22].

Mantle flows and especially mantle convection are at the heart of the contemporary geodynamic models that explain the origin of High Asia. These are sup-

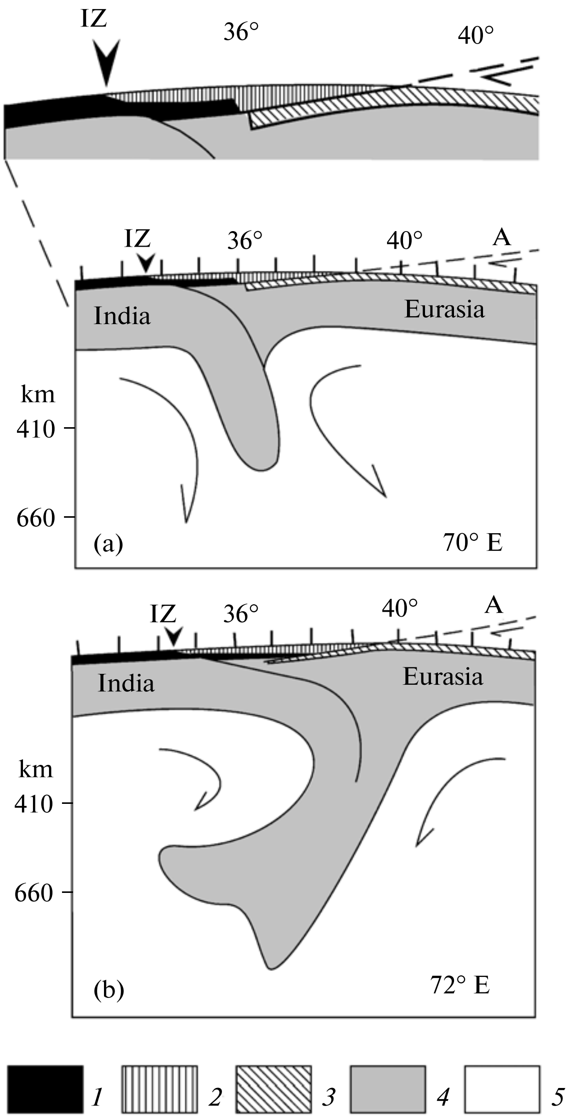

Fig. 15. Model sections of the Earth's crust and upper mantle along (a) 70° E and (b) 72° E meridians. (*1–3*) Earth's crust: (*1*) Hindustan, (*2*) Pamirs and Karakoram, (*3*) Tien Shan and Tarim; (*4*) lithospheric mantle; (*5*) asthenosphere and layer C of the upper mantle (arrows indicate direction of mantle convection). A, undertrusting of the Tien Shan and Tarim crust beneath the Pamirs; IZ, the Indus–Zangpo oceanic suture.

ported by the seismic tomography of the crust and mantle of the Pamir–Punjab syntaxis. Comparison of the data along the 70°, 72°, and 75° meridians (Fig. 12) indicates that the length of the slab, and correspondingly, the subduction rate of the Hindustan lithosphere, widely vary through the syntaxis, probably owing to the pattern of mantle convection. Because of the different rates of vertical mantle convection, the flows of mantle matter also must develop in the lateral and sloped directions with the formation of horizontal convective cells. The latter may be a cause of the rotation of the lithospheric blocks. Such a lateral convective cell could have initiated rotation of the Ferghana Block in the Tien Shan.

The schemes that reproduce the structure of the crust and lithospheric mantle of the syntaxis (Fig. 15) display the Hindustan continental crust, which was detached from the plunging lithospheric mantle during subduction of the Indian Plate and thrust under the Eurasian crust of the Karakoram–Pamir mountains. It cannot be ruled out that only the upper crust detached from the lower crust of Hindustan was involved in this process. It is quite possible that the origins of the magma sources and Cenozoic granitic magmatism of the Karakoram and Pamir mountains were related to underthrusting. The Cenozoic granites that extend from the southern boundary of the syntaxis to the central Pamirs and the eastern part of the northern Pamirs (Fig. 12d) can be regarded as evidence for thrusting of the Hindustan crust up to latitude 38° N in the eastern segments of syntaxis and 36° N at its western margin. The crust of the Tien Shan, which has been thrust under the Pamirs, is shown in the model section as well.

Summary. The model of the counter subduction of the continental lithosphere at the southern and the northern boundaries of the Pamir–Punjab syntaxis is consistent with the distribution of earthquakes, the thickness and structure of the Earth's crust, and the offsets caused by over- and underthrusting at these boundaries.

The geological and geophysical data on the structure of syntaxis assume that factors 2–6 (see above) operated during the formation of the Pamir–Punjab syntaxis in the geological past and are operating now.

The mantle convection is probably a driving force of the process (factor 6). The influx of masses from the Himalayan collision zone (factor 5) gave rise to the structural asymmetry of the syntaxis at the level of the lithosphere. Thrusting of the Hindustan sheet under the Karakoram–Pamirs leads to thickening of their crust and its northward gravity flow (factor 4) with the formation of the fold–nappe structure of the upper crust.

The highly uplifted Pamir crustal block undergoes gravity expansion (factor 3), which complicates the structure of the boundary and inner zones by thrust-fault and pull-apart structural elements. The Tien Shan is an obstacle that deviates the tectonic flow of the crustal masses of the Pamirs to the west.

CONCLUSIONS

The convergence of the Pamirs and the Tien Shan. To estimate the convergence of the Pamirs and the Tien Shan, the paleomagnetic data on Cretaceous, Paleogene, and Miocene rocks were considered, as well as the facies of Cretaceous and Paleogene sedimentary rocks in the boundary zone and the structure of the Tajik Depression and the Pamir–Alay area. Each of these phenomena can be used to estimate the recent convergence of the Pamirs and the Tien Shan.

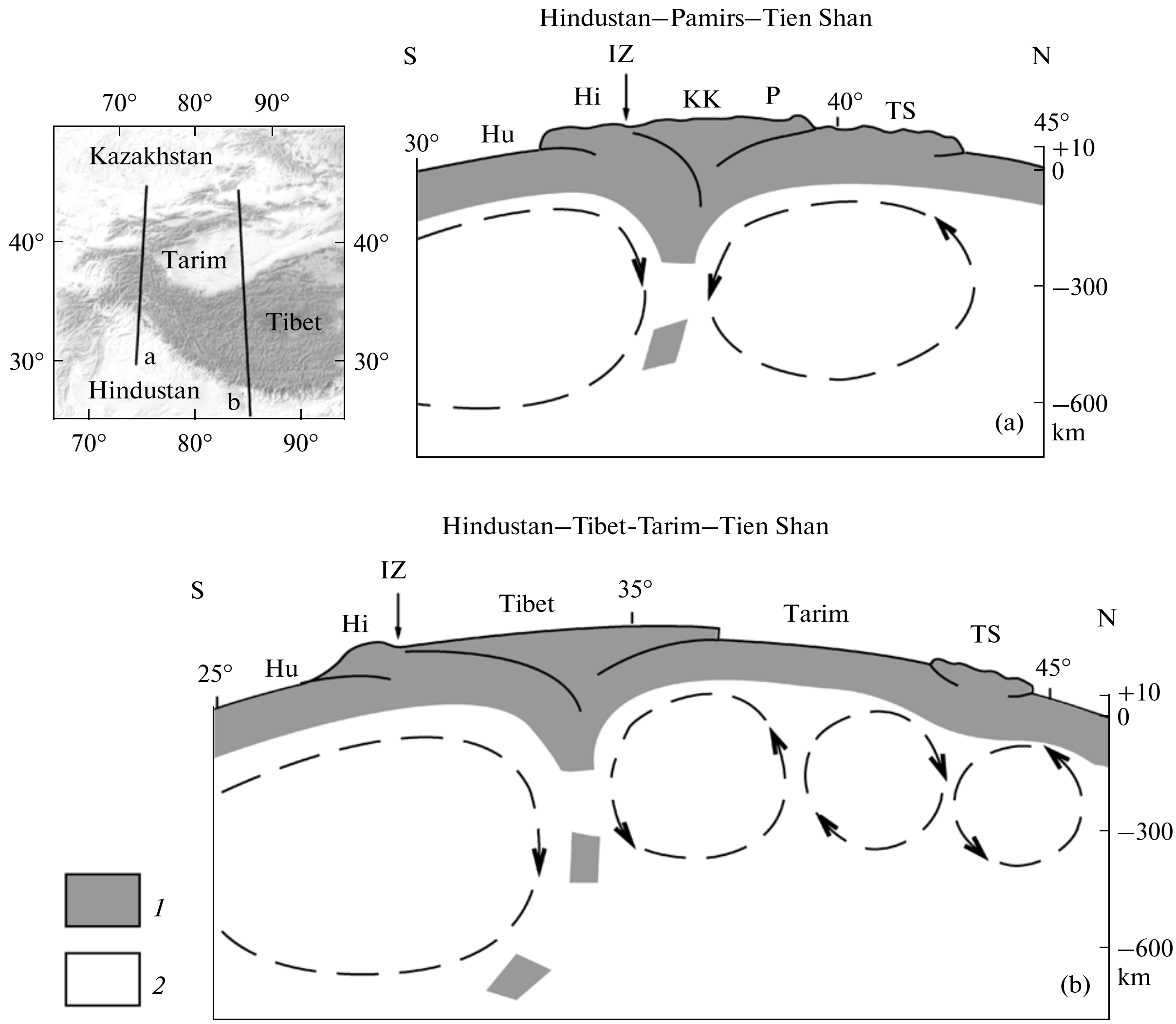

Fig. 16. A scheme of the convection in the upper mantle in the Late Cenozoic (late Miocene–Quaternary): (a) model section across the Pamir–Punjab syntaxis and the western Tien Shan along 74° E meridian; (b) model section [10] across Tibet, Tarim, and the eastern Tien Shan along 85° E meridian. (*1*) Continental lithosphere; (*2*) asthenosphere and layer C of the upper mantle; Hi, Himalayas; Hu, Hindustan; IZ, Indus–Zangpo oceanic suture; KK, Karakoram; P, Pamirs, TS, Tien Shan.

The optimal reconstruction based on paleomagnetic data assumes the convergence of the northern Pamirs and the Tien Shan for 600 km. The facies maps and the structural data on the Tajik Depression constrain the convergence by 300 km. This value corresponds to an average subduction rate of 10 or ~3 cm/yr, if the process started in the late Pliocene or late Miocene, respectively. The recent offsets along the faults and convergence rate of the Pamirs and the Tien Shan, which were determined with geological and geodetic methods, are consistent with these conclusions.

The subducted lithosphere of the Tien Shan is accommodated beneath the Pamirs. This is supported by the great thickness of its crust and the anomalous structure of the upper mantle. The lower crust and subsalt basement are involved in the process of subduction. In the northeastern Tajik Depression and in the Pamir–Alay area, the suprasalt sedimentary cover was probably involved in subduction as well. This is indicated by the tectonic gap that arises between the Pamirs and the Tien Shan in the palinspastic reconstruction for the Pliocene (Fig. 10).

Geodynamics of syntaxis. The formation of the Pamir–Punjab syntaxis is a result of the collision of the Hindustan continent with Eurasia, which started, most probably, in the late Oligocene [10]. In the late Oligocene–Early Miocene, the convective system in the upper mantle at the Pamir–Karakoram margin of the Eurasian Plate was rearranged with the subduction of the Hindustan continental lithosphere. The Pamirs also began to rise in the late Oligocene.

The Pamir–Punjab syntaxis was formed in the Miocene as a giant horizontal extrusion (protrusion) made up of the rocks that are related to Hindustan and the margin of the Eurasian Plate. The vast nappes that formed in the southern and central Pamirs then were folded with significant shortening of this territory in the meridional direction. The ongoing rise of the Pamirs led to the formation of contrasting topography. The rocks of the outer zone of the Pamirs were involved in deformation. Granite–gneiss domes were exhumed in the early Miocene in the central Pamirs and in the late Miocene in the northern Pamirs.

In the Pliocene and Quaternary, the Pamir–Punjab syntaxis developed further. In the course of this process, the deformed Pamirs, propagating northward, were transformed into a giant allochthon. A fold–nappe system was formed at the front of this allochthon in the outer zone of the Pamirs. The continental subduction was accompanied by delamination of the upper crust at the level of Jurassic evaporites and by intense folding and thrusting.

The transverse shortening of the outer zone of the Pamirs as a result of internal deformation reached 100 km. The total transverse shortening of all Pamir zones and the subducted margin of the Tien Shan could have exceeded 700 km. With allowance for the shortening of the tectonic zones of the western Himalayas (470 km), the shrinkage of the surface during formation of the Pamir–Punjab syntaxis is close to 1200 km.

The model of the mantle convection in the Pamir–Punjab syntaxis as the main process that allowed the transfer of the pulse from the zone of Hindustan–Eurasia convergence to the Pamirs and Tien Shan, is illustrated by the Hindustan–Pamir–Tien Shan section (Fig. 16a). This model section is based on the aforementioned data and their interpretation. The results of seismological, seismic tomographic, and seismic investigations confirm the existence of a convective cell in the upper mantle beneath the Tien Shan [67]. They also bear information on the scale and boundaries of thrusting of the Hindustan continental lithosphere under the Karokaram–Pamir mountains and the subduction of the western Tien Shan lithosphere beneath the Pamirs.

The Hindustan–Tibet–Tarim–Tien Shan section (Fig. 16b) was discussed in [10]. The geodynamics of the mantle in both transects of High Asia and the Tien Shan were probably similar. The difference between the model sections shown in Figs. 16a and 16b is caused by the specific kinematics of the deformation of the crust, which are reflected in the geological structure of the compared regions. In the Pamirs, which are bounded by rigid blocks, a nappe–structure system has been formed. Tibet availed itself of the refuge in the east, where its crust shortening was accommodated. As a result, in contrast to Tibet, which was only slightly deformed in the Cenozoic and to the almost undeformed Tarim, the upper crust of the Pamir–Punjab syntaxis is tectonically delaminated; the rocks underwent intense folding and thrusting and were partially metamorphosed in the Late Cenozoic. The rearrangement of the mantle convection systems, which correspond to the sections shown in Figs. 16a and 16b, probably takes place beneath the Eastern Pamirs and the northwestern Kunlun.

ACKNOWLEDGMENTS

This study was supported by the Division of Earth Sciences, Russian Academy of Sciences (program no. 9).

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