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Neotectonics and Mantle Earthquakes in the Pamir–Hindu Kush Region

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Abstract—Tectonic aspects of the formation of the Pamirs–Hindu Kush zone of intermediate earthquakes are discussed. A model of the regional late-collision (neotectonic) evolution is developed based on the analysis of geologic data. The first stage of this evolution spans from the late Eocene to the beginning of the late Miocene; the second stage, from the late Miocene to the Holocene. These stages are characterized by different thermodynamic conditions and, correspondingly, by different geodynamic settings that determined a specific style of tectonic deformation. The early stage was marked by differentiated lateral displacements of the Earth's tectonically delaminated crust. The heating of the crust that is reflected in intense granitic magmatism promoted delamination. At the late stage, the heating and delamination probably waned and were replaced by more homogeneous lateral motion of blocks and by regional uplift. Because of lateral displacements, the oceanic crust fragments of different age were overridden by blocks of the continental crust and submerged to a depth of 40–70 km. Their eclogitization might have lead to further submergence into the mantle. Mantle earthquakes in the Pamir–Hindu Kush zone are induced by relaxation of the stress that accumulates in submerging fragments.

INTRODUCTION

Analyzing the catalog of strong ($M_s \geq 5.7$) earthquakes in the central Alpine–Himalayan belt [35], one may point out a small (100 × 150 km) area in northeastern Afghanistan with coordinates of 36–37° N and 69–71.5° E that is characterized by an anomalously great amount of released seismic energy. About 20% of the energy released in the 20th century from all the earthquakes in the Alpine–Himalayan belt extending from the Dinarides to the Himalayas and Central Asia fell on this area. The overwhelming majority of earthquake hypocenters in this Hindu Kush seismic megacluster are concentrated in the upper mantle at depths of 110 ± 20 and 190–240 (down to 270–300) km. East of the meridional bend of the Pyandzh River, the epicenters of strong mantle earthquakes are shifted farther to the north (up to 38° N) and are traceable as isolated clusters up to the southeastern termination of the Tashkurgan Depression. There, together with the Hindu Kush megacluster, they form the Pamir–Hindu Kush seismic focal zone. In the Pamirs, strong earthquakes are rare, their released energy is hundreds of times less than in the Hindu Kush, and their sources are concentrated at a depth of 110 ± 20 km.

The Pamir–Hindu Kush focal zone is located in areas of intense tectonic deformation related to the Neotethys closure. Collision at its northern flank was accompanied by volcanic activity and large-scale granite formation that testifies to heating of the Earth's crust. This heating could promote delamination of the crust along surfaces with the highest gradient of mechanical properties. Such delamination provides differentiated displacements of crustal sheets and blocks under variously oriented horizontal compression. By the end of Miocene, this resulted in substantial disturbance of isostatic equilibrium, which, combined with ongoing stacking of rocks, stimulated intense and contrasting vertical movements.

In this paper, based on the analysis and generalization of geologic data obtained by V.I. Budanova, V.S. Burtman, M. Gaetani, V.I. Dronov, B.P. Pashkov, S.V. Ruzhentsev, I.M. Sborshchikov, P. Tapponnier, V.A. Shvolman, and other researchers, we made an attempt to explain the extremely high seismicity of the Pamir–Hindu Kush focal zone by specific neotectonic evolution of this region.

1. NEOTECTONIC DEFORMATION AND OFFSETS OF TECTONIC ZONES

The present-day tectonic zoning of the Pamir–Hindu Kush region [5, 9, 12, 25, 28, 40, 41, 45, 49] (Figs. 1, 2) reflects its crustal structure, which was formed as a result of multifold deformational events during the stage-by-stage closure of the Tethys. The existing structural grain was eventually formed at the postcollision stage following the closure of the Neotethys. This span of time corresponds to the neotectonic period in its traditional limits, that is, from the late Eocene to the Recent [34]. This period is subdivided into the early stage (late Eocene–Miocene), when heating and tectonic delamination of the crust were the most important factors of tectogenesis; the late stage commenced in the late Miocene, when the role of these processes decreased and intense vertical movements were occurring.

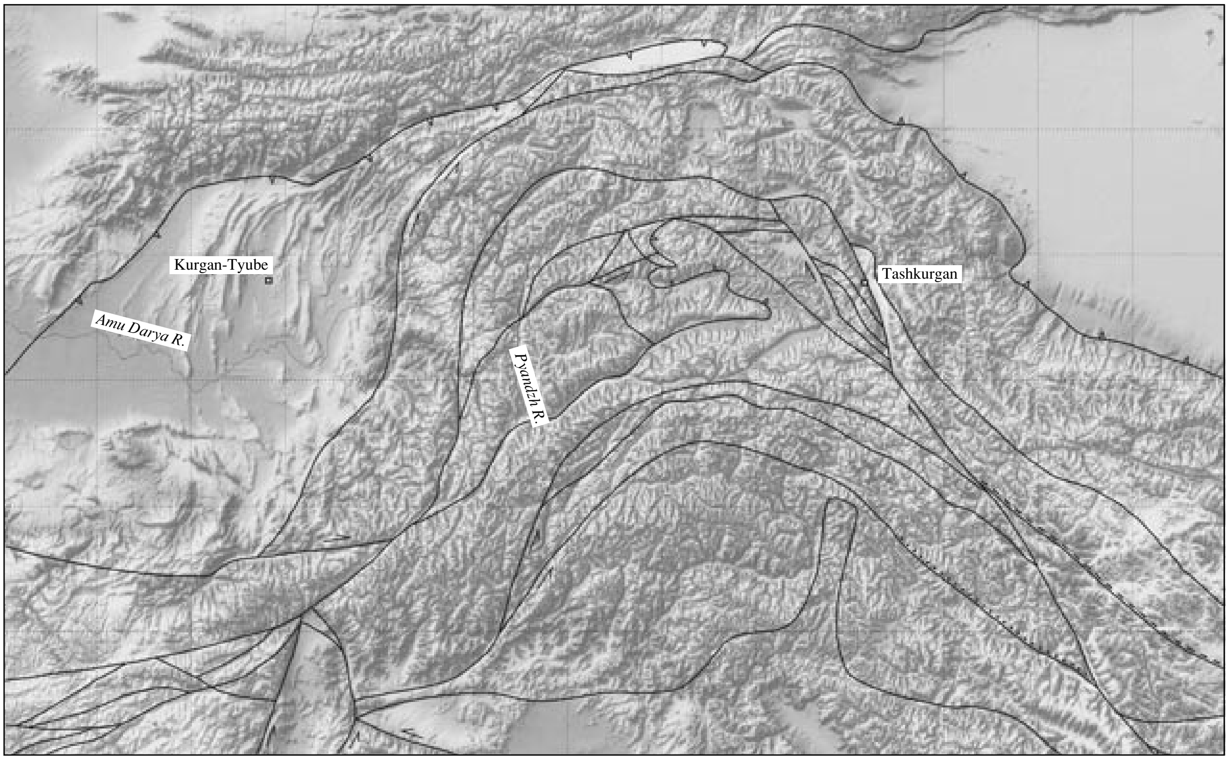

Fig. 1. Orographic map of the Pamir–Karakorum region and adjacent areas with contours of tectonic zones designated in Fig. 2.

1.1. Mesozoic Zoning and Its Distortion due to Recent Tectogenesis

In the present-day structure of the eastern Pamirs, the consecutive series of tectonic zones exhibits the evolution of the early Mesotethys. ***The Hercynides of the northern Pamirs***, where the main structure-forming processes ceased by the end of the Paleozoic, developed in the Triassic as a volcanic arc at the active northern flank of the basin underlain by oceanic crust. The arc is marked by Triassic subduction-related granites and calc-alkaline volcanics. The nonvolcanic part of the arc that comprised continental blocks of the ***central Pamirs***, heterogeneous in their geologic history and structure, was accreted to the Hercynides during the Permian after the closure of the Paleotethys. In the considered part of the region, the central Pamirs, represented by the Muzkol Zone [28], is underlain by crust 60–65 km thick; its lower part (approximately 35 km) is seismically homogeneous [23, 30]. The basin itself is designated by the ***Pshart Suture***, where the Upper Permian–Triassic sequence is largely composed of clayey and cherty shales, basalts, and basaltic andesites; volcanics prevail in its Upper Triassic portion [25]. This sequence is unconformably overlain by Norian (?) volcanogenic and terrigenous rocks with olistoliths of Paleozoic limestones. Northward, in the western Pshart and the northern Dunkel'din blocks, the Permian–Triassic calcareous–terrigenous sequences with sporadic volcanics mark the northern periphery of the basin [25]. Its southern periphery is made up of an allochthon of the ***southeastern Pamirs***, where relatively deep-water flyschoid facies of the passive slope give way to the carbonate platform facies [26, 28]. Both of these facies extends toward Nuristan [10]. The similarity in the early collision evolution of the Pshart and southeastern Pamir–Nuristan regions is expressed in the pre-Jurassic unconformity [25] and in the occurrence of Cretaceous orogenic complex [39].

Farther southward, there is a succession of tectonic zones related to the late Mesotethys and Neotethys: (1) the ***northern Karakorum*** is underlain by the Proterozoic–Cambrian continental basement overlapped by the polycyclic Ordovician–Jurassic cover, with carbonate rocks prevailing over terrigenous sediments and with signatures of the mid-Cretaceous orogeny [45]; (2) the ***southern Karakorum and the eastern Hindu Kush*** that reveal intense regional metamorphism, enclose an axial batholith in the north, and are bordered by the Main Karakorum Thrust Fault in the south [45]; (3) the eastern part of this fault controls the ***Shyok Suture***, a relict of the backarc (?) basin of the late Mesotethys that closed in the mid-Cretaceous, which is represented now by ophiolitic melange [49]; and (4) ***the Kohistan and Ladakh*** volcanic arc of the Neotethys with large granitic batholiths; the base of this section (ultramafics and garnet granulites overlain by amphib-

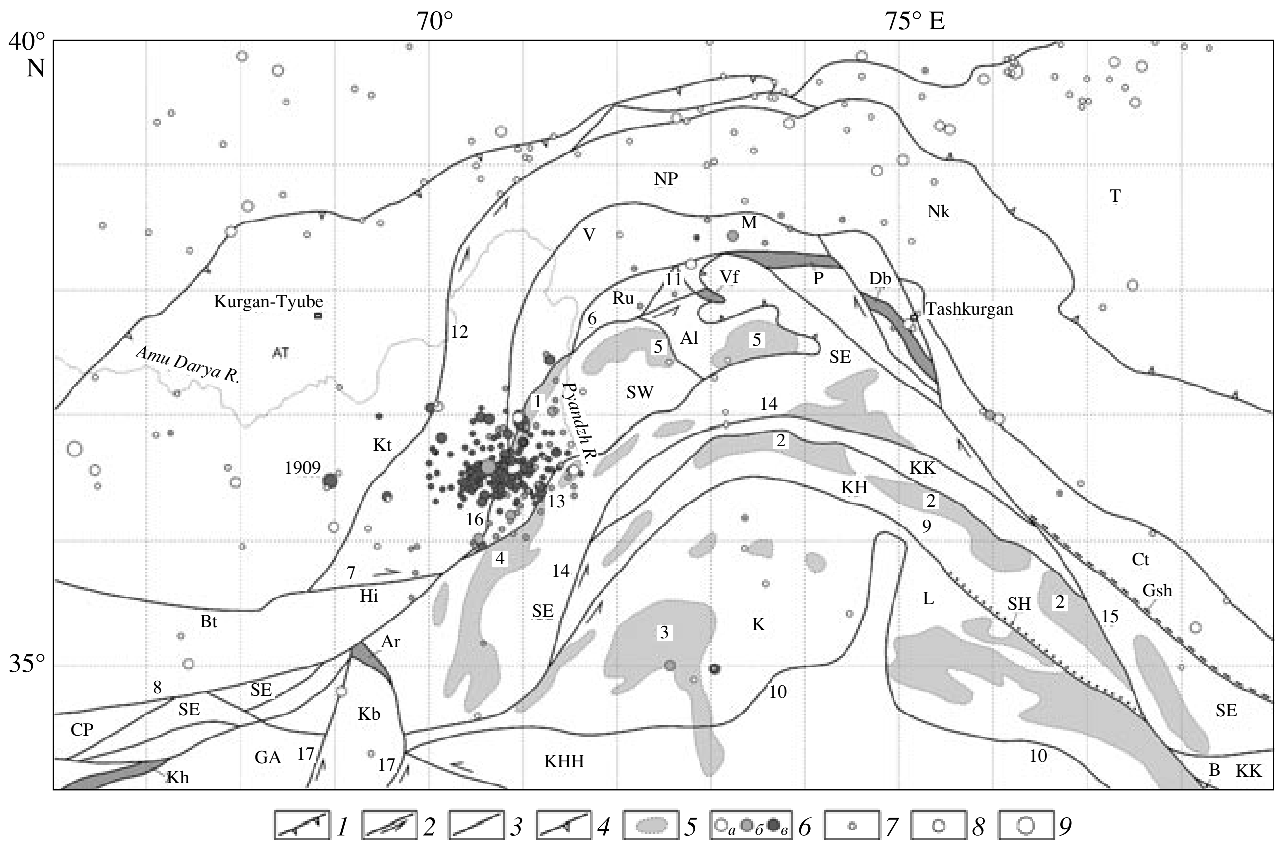

Fig. 2. Schematic tectonic zoning [5, 12, 25, 28, 40, 45, 49] and distribution of granitic magmatism [9, 43] and epicenters of strong ($M_s \geq 5.7$) earthquakes [35] in the Pamir–Karakorum region. (*1*) tectonic nappes and thrust faults; (*2*) strike-slip faults; (*3*) other major faults; (*4*) boundaries of depressions; (*5*) granitic batholiths, as young as Miocene in age; (*6*) epicenters of earthquakes with sources located at a depth of (*a*) <70 km, (*b*) 70–150 km, and (*c*) >150 km; (*7–9*) earthquake magnitudes: (*7*) M_s = 5.7–6.5, (*8*) M_s = 6.6–7.4, (*9*) M_s = 7.5–8.3. ***Tectonic zones***: (AT) Afghan–Tajik Depression including the Kulyab Trough (Kt), (T) Tarim Depression, (NP) North Pamir Zone and its extensions including (Nk) northwestern Kunlun Shan, (Hi) western Hindu Kush, and (Bt) Bandi–Turkestan; zones of the central-Pamir type including (M) Muzkol, (V) Vanch, (SW) southwestern Pamir–Badakhshan, (Al) Alichur Block, (Ru) Rushan Zone, (Kb) Kabul Block, (Ct) extension of zones of the central-Pamir type in Tibet, and (CP) fragments of the central-Pamir type in the Gerat Fault Zone in Afghanistan; (P) Pshart Suture and its extensions (dark gray) including (Db) Dunkel'din block, (Gsh) inferred extension in Tibet easterly grading into the Ganmats–Shaunkhu Suture, (Vf) Vatasaif fragment, (Ar) Altimur ophiolites, and (Kh) Kharshud Zone; (SE) southeastern Pamir–Nuristan Zone and its extensions in Tibet and Afghanistan including (KK) North Karakorum Zone and its extension in Tibet, (GA) Helmand–Argandab Massif; (KH) South Karakorum–East Hindu Kush Zone; (SH) Shyok Suture; (B) Bangun Suture; (K) Kohistan, (L) Ladakh, (KHH) Khazar Massif of the Himalayas. ***Batholiths***: (1) Bagarak, (2) Karakorum, (3) Kohistan, (4) Lagman, (5) Shugnan. ***Faults***: (6) Alichur Thrust Fault, (7) Andarab Strike-slip Fault, (8) zone of the Gerat (Main Gerirud) Fault, (9) Main Karakorum Thrust Fault, (10) Main Mantle Thrust Fault, (11) Gunt, (12) Darvaz Reverse–Strike-slip Fault, (13) Zebak, (14) Kunar–Tashkupur Zone, (15) Pamir–Karakorum Strike-slip Fault, (16) Central Pamirs, (17) Chaman Strike-slip Fault.

olites and gabbronorites) is exposed in the southern part of the zone, where it is bordered by the Main Mantle Thrust Fault [37].

This zonal pattern of the Pamir–Karakorum region likely indicates that the relative location of zones has remained principally unchanged since the late Mesozoic (the neotectonic period included). The following tectonic units among the Afghan zones serve as the most definite analogs of the Pamirs–Karakorum zones: the volcanic arc of the early Mesotethys inheriting the Hercynides in the Hindu Kush and Bandi-Turkestan and the Quetta ophiolitic zone (the Neotethys suture). Both soundly correlated with ophiolites of the Indus–Zangbo Zone as the southeastern extension of the Ladakh Zone [46]. The Altimur allochthonous ophiolitic melange in the northern Kabul Block composed of peridotites, pillow lavas, tuffs, and cherts that are overlain by limestone with poorly preserved Jurassic (?) fauna [50] is probably an analog of the Pshart Suture.

Westward, in central Afghanistan, the SW-trending ophiolitic Khashrud Zone offsets from the Gerat (Main Gerirud) Fault. The Upper Jurassic–Hauterivian sequence of this zone is composed of basic and intermediate volcanics replaced upward by sandy–shaly sediments; ultramafics and gabbrodiorite intrusions are widespread [10]. It is assumed that this section accumulated in a trough underlain by oceanic crust [29]. The fact that, at the northwestern periphery of the trough, the Upper Jurassic volcanics are underlain by Rhaetian–Liassic sandstones and shales, as well as by Upper Permian–Norian calcareous–terrigenous rocks alternating with basic and intermediate volcanics [10], points to almost coeval origination of the Khashrud and Pshart basins. It can be assumed that the Khashrud ophiolites are a fragment of the Pshart Basin extension, which continued to evolve, in contrast to the Pamirs, in the Jurassic and Early Cretaceous. Its evolution terminated by the mid-Cretaceous, as is evident from the unconformity at the base of calcareous–terrigenous partly variegated Aptian–Upper Cretaceous sequence.

Tectonic blocks with structural features similar to those of the southeastern Pamirs and Nuristan are indicated in the zone of the Gerat (Main Gerirud) Fault. Gaetani [45] notes the similarity in sedimentary covers of the northern Karakorum and the Helmand–Argandab continental massif bordered by the Khashrud ophiolites in the northwest. The Shyok Suture appears to be coeval with the Tarnak Suture at the southeastern flank of this massif [29].

Thus, the systems of the Mesozoic tectonic zones in the Pamirs and Afghanistan are similar, although there is no complete identity between them. However, most of the zones, which can be regarded as analogs, are tectonically separated by faults that extend along the western flank of the Pamirs and Badakhshan [9, 10]. Here, in the Vanch Zone of the central Pamirs and tectonic slices of the Rushan Zone corresponding to the northern margin of the Pshart Basin, the Earth's crust is thinned to 50–55 km and its granitic–gneissic portion (approximately 35 km) rests upon the layer defined by seismic velocities like a mantle–crust mixture [38]. This layer can be a relict of the early Mesotethys oceanic crust. The Vanch and Rushan zones pinch out southeastward, and the extension of the northern Pamirs borders along the steep Central Pamir Fault on the Archean metamorphic massif of the West Pamir–Badakhshan Block. Thrusting of the Shakhdara Group over the Goran Group in the Precambrian resulted in a doubled section of the massif. Tectonic sheets at the contact are composed of the rocks pertaining to the Khorog Formation and are formed in the lower crust close to the Moho discontinuity [3, 14, 28]. Contacts of the massif with neighboring zones are either tectonic or sealed by Cenozoic granites. Its margins experienced maximal Cenozoic tectono-metamorphic reworking [3]. The Kabul Block separates the northern Karakorum and the Helmand–Argandab Massif, as well as Nuristan and its probable extension in the Gerat Fault Zone. Its Precambrian basement is overlain by the Upper Precambrian–Lower Paleozoic metaterrigenous complex and by the Upper Paleozoic complex, including the Upper Permian–Norian carbonate rocks. The Kabul Block is similar in this respect to the Muzkol Zone of the central Pamirs [10, 25].

The southwestern Pamir–Badakhshan Block has been studied better as compared with the poorly explored Kabul Block. Its southeastern tectonic boundary with Nuristan is marked by the Lagman Batholith (16.5 Ma) that dates back to the Oligocene–Miocene [10]. Northward, the Bagarak Batholith, 32–19.5 Ma in age [10], extends along the boundary with the central Pamirs. Its contacts, sharp intrusive in the northwest and complicated by numerous local injections in the southeast, suggest that the batholith plunges beneath the Archean complexes [14]. To the east, at the boundary of Precambrian rocks with the Rushan Zone, a similar plunge of the Alichur Thrust Fault is confirmed by geologic observations [26]. South of this thrust fault, the Precambrian–Paleozoic Alichur Group of metamorphic rocks crops out between Archean autochthon and allochthon of the southeastern Pamirs. The Vatasaif fragment of the Pshart Suture, where Triassic volcanogenic rocks are unconformably overlain by Jurassic strata, is retained farther to the east [24, 25]. Boundaries between all these complexes are either tectonic or concealed by granites. The isotopic age of the Shugnan Batholith is estimated as 32–21 Ma; the recurrent metamorphism of older sequences took place approximately at the same time, 32–9 Ma ago [39].

The relationships described above suggest that the block of the southeastern Pamirs has occupied its present-day location only recently, and the age of the boundary batholith emplacement corresponds to tectonic convergence of the southwestern and southeastern Pamirs. We suggest that during this convergence the Triassic–Jurassic facies zones of the southeastern Pamirs that initially extend parallel to the Pshart Suture were curved and formed an arc with the western margin that trends parallel to the boundary of the southwestern Pamirs. Judging from the bend configuration, the amplitude of the eastward or northeastward offset of the southwestern Pamirs could exceed 150 km. Thereby, the sedimentary sequences of the southeastern Pamirs were involved in the thrusting, and later, in the Pliocene and Quaternary, they were subjected to strike-slip movements [26]. The Pshart Suture was also involved in bending, as is evident from the localization of its Vatasaif fragment. The area with the exposed Alichur Group, which is probably a subsided continuation of the southwestern Pamirs, also changed its location and was deformed.

According to the geophysical data, the granitic–gneissic complex of the southwestern Pamirs is 25 km thick, while the total thickness of the crust reaches approximately 60 km [14]. A part of the displaced complex likely overlapped the crystalline basement of the southeastern Pamirs that reaches a thickness of 30 km. To determine the initial structural setting of the complex, it is important to note that it could not be an element of the northern Pamirs, because no indications of Paleozoic and Early Mesozoic magmatism characteristic of this zone are known. Thus, it was probably an element of the central Pamirs.

The Precambrian clastic material derived from the southwestern Pamirs is missing in the Upper Mesozoic and Lower Cenozoic sequences of adjacent zones and first appears in the immediate vicinity of the massif only in Oligocene sediments [39]. This implies that the Precambrian complex was initially covered by sediments, fragments of which are represented by the Permian–Triassic sequence of the central-Pamir type in the Zebak Fault Zone at the southern flank of the massif [10]. This might be responsible for the formation of the allochthonous Vanch–Muzkol segment of the central Pamirs, the nappe structure of which is a result of neotectonic movements because it involves Upper Cretaceous and Paleogene strata [28]. In the opinion of Ruzhentsev [27], the recumbent folds characteristic of the early deformation stage began to form in the mid-Cretaceous or in the Paleogene and continued to develop until the Neogene, because they involve Paleogene sediments. Later, already in more recent times, structures of sedimentary cover in the Vanch Zone, where the root belts of nappes have been formed, were thrust over southerly and easterly areas of the central Pamirs, the Muzkol Zone inclusive. Other authors [16, 17, 31] provided persuasive structural arguments in favor of thrusting from the south. Pashkov and Budanov [25] assumed that the thrust faults originated in the Kunar–Tashkupruk Zone between the southeastern Pamirs and the Karakorum. We suppose that they originated nearer to their present-day location and are a detached cover of the displaced Southwest Pamir–Badakhshan Zone. The detachment was stimulated by heating and delamination of the massif that is reflected in intense generation of Cenozoic granites (the Shugnan Batholith) and by the uplift that followed the crust thickening.

Thus, the most evident distortions of the Mesozoic tectonic zoning caused by neotectonic deformation and offsets are confined to the transition between the Pamirs and Afghanistan; they are primarily related to the displacement of the massif of the southwestern Pamirs and Badakhshan. The Hindu Kush megacluster of mantle earthquakes is located precisely within the zone of this distortion at the junction of the North Pamir Hercynides and Archean sequences.

1.2. The Pamirs and Afghan–Tajik Depression

The Afghan–Tajik and Tarim depressions filled with Upper Cenozoic molasse are located on both sides of the northward-convex zone of the northern Pamirs. The Tarim Depression rests largely upon the Precambrian basement. The Afghan–Tajik Depression is a sedimentary basin with a heterogeneous basement that was consolidated by the end of the Paleozoic and probably inherited an ancient crystalline massif. The depression is filled with a thick (up to 18 km) sequence of alternating shallow-water and continental or strictly continental (since the Oligocene) sediments. Compositionally similar Cretaceous and Cenozoic sequences extend along the northern periphery of the Pamirs and form its outer zone. In the northeast, the northern Pamirs is thrust over molasse of the Tarim Depression [44], and this probably resulted in crust thickening to 75–80 km [23, 30]. To the west, the northern Pamirs is thrust over the outer zone that determined its present-day structure [21]. A waveguide with V_p of 6.0–6.3 km/s [23, 33, 38] at a depth of 5–10 km under crystalline rocks of the northern Pamirs favored this process.

The thrusting was accompanied by development of the fold structure in the Afghan–Tajik Depression, the formation of which was strongly influenced by the detachment of the 5–6-km-thick Cretaceous–Miocene cover along the Malm salt-bearing sequence [2, 13]. This growth of folds fell mainly in the late neotectonic stage, and the first regional unconformity in the molasse complex that reflects this event is dated as late Miocene. During the folding, the sedimentation basin experienced differentiation, and the Kulyab Trough located in its eastern part accumulated 11 km of Pliocene–Quaternary sediments of the 17-km total of sedimentary cover. The folding and accumulation of young molasse transformed the crust beneath the depression. Its Cretaceous and Paleogene structure can be judged from the least deformed section in the Kurgan-Tyube area. The crust is approximately 35 km thick there, and the thickness of its crystalline part is less than 20 km [14].

The amplitude of the northern Pamirs thrusting over the neighboring depressions is critical for estimating neotectonic deformations. Based on paleomagnetic studies of Cretaceous–Paleogene sediments in the Afghan–Tajik Depression [1] and on facies distribution, Burtman [4] arrived at the conclusion that the northern Pamirs was thrust over the eastern part of the Cretaceous–Paleogene trough approximately for 300 km. The sedimentary cover was detached and folded in the retained part of the depression [2, 4]. We assume that the amplitude of overthrusting could have been less, particularly in the eastern part of the Pamirs; there are two reasons for this: first, the Cretaceous–Paleogene trough might have become narrower eastward prior to the neotectonic stage due to framing of ancient massifs by the Hercynides; second, in the western Pamirs, conditions of the Hercynian complex thrusting over the thinned crust of the central part of the depression were more favorable than in the east, where the crust was normal. As concerns the folding controlled by the general detachment and displacement of sedimentary cover, this mechanism is acceptable only for the northern part of the depression and becomes doubtful in its southern part, where the detached anticlinal zones are separated by sizeable depressions that remain almost undeformed. That is why a more complex mechanism of folding has been proposed. This mechanism takes into account the change of sedimentary rock volume in response to its chemical alteration [13].

Thus, the fact that the northern Pamirs is thrust over the Afghan–Tajik Depression and partially overlaps its eastern part is beyond doubt, although the amplitude of overthrusting remains debatable. In any event, it is at least 100 km large, and this estimate is important for determining the source of mantle earthquakes in the Pamirs.

1.3. Recent Geodynamics of the Pamir–Hindu Kush Region

The most recent structure of the Pamirs was formed under horizontal compression commonly interpreted as a result of the pressure from the Punjab indentor of the Indian Plate. This assumption is consistent with the arcuate bend of the Pamir Zone: in particular, a bend of the northern Pamirs for 350–400 km with indications of meridional compression and shortening due to the latitudinal thrust faults and folds, the conjugated left-lateral slip along the Darvaz Fault, and right-lateral displacements in the southeastern Pamirs. However, amplitude of the arcuate bend in the southerly located Karakorum and Kohistan–Ladakh tectonic zones is only 200 km. This bend is conformable to the northern margin of the Indian Plate, and probably was formed immediately after the Neotethys closure, that is, preceding, at least partly, the neotectonic stage.

At the same time, the western and eastern flanks of the Pamirs bear indications of nearly latitudinal recent compression and shortening. In the west, where the Hindu Kush and the North Afghan Hercynides join the Southwest Pamir–Badakhshan and Central Pamir zones, this deformation is expressed in submeridional steep wedges, slices, and compressed folds with signs of transverse rock flattening, while the northwestern Kunlun Shan demonstrates signs of the Hercynides thrusting over the Tarim Depression. Thus, the neotectonic structure of the Pamirs was formed under differently oriented compression.

Such an intricate structure of the Pamirs could result from variation of geodynamic settings during the neotectonic period. Its early stage (late Eocene, Oligocene, and early Miocene) was characterized by significant, although irregular, heating of the Earth's crust that gave rise to the emplacement of numerous large batholiths both along the fault-related boundaries and in axial zones of tectonic uplifts. These batholiths (Kohistan, Ladakh, Karakorum, Shugnan, and others) began forming in the Cretaceous or Paleogene at the onset of collision in the respective tectonic zones and continued to rise until the Miocene. In some batholiths, the main phases of granite formation are related to the late collision (neotectonic) stage. Heating stimulated delamination of crustal rocks along the surfaces with the highest gradients of mechanical properties and differentiated lateral displacements. The heating of the thinned crust of the Afghan–Tajik Depression likely resulted in extension and volcanic activity at its southern flank, which was intense at the early stage of the neotectonic period and lasted until the mid-Pleistocene [10]. Since the late Miocene, the heating of the Earth's crust waned, and the crust became more homogeneous in its physical properties and less favorable for tectonic delamination. This background is complicated by changes in direction of maximal lateral compression in the orogenic belt (Fig. 3) that are similar to the changes in the region of Arabia–Eurasia collision [34]. Since the late Eocene and until the early Miocene (approximately 40–20 Ma ago), the axis of maximal compression at the northern and western flanks of the Indian plate was probably oriented in the NW–SE direction. Intense transverse shortening was also recorded in the northern Quetta Zone, where the Eocene Katavaz Trough was deformed and the NE-trending tectonic nappes and thrust sheets were formed in the Khost, Tarnak, and Khashrud ophiolitic zones [10, 29, 50]. They were conjugated with right-lateral movements along the nearly latitudinal Gerat Fault Zone, along which the Khashrud Zone was displaced for 150 km relative to the Altimur ophiolites. This dextral displacement could also result from extension in the Afghan–Tajik Depression that was brought about by movement for 40 km along the latitudinal Andarab Fault [10].

Intense heating of the crust and its rheological delamination in the narrowest tract of the orogenic belt between the western Khazar Massif of the Himalayas and the salient southeastern margin of the Turan Plate could result in destruction and extrusion of crustal blocks away from this area. The Southwest Pamir–Badakhshan Block, which was formerly a tectonic unit of the central Pamirs, moved eastward; this led to the detachment and sigmoid bend of the Pshart Suture and lithotectonic zones of the southeastern Pamirs, where tectonic nappes began forming. The sedimentary cover of the southwestern Pamirs became detached and formed the Vanch–Muzkol nappes of the central Pamirs. It appears likely that the Kabul Block moved southward at that time dividing Nuristan from its western extension and separating the Karakorum and Helmand–Argandab massifs.

Since the early Miocene and until the late Miocene (20–8 Ma ago), the Indian Plate moved to the northeast, and, correspondingly, the maximal compression and belt shortening were oriented in the same direction. This was expressed in thrusting, granitization, and metamorphism in the Himalaya and the Karakorum [8, 12, 48] and volcanism in Tibet. Involved in intense deformations, Tibet and Qaidam might have, in turn, exerted influence upon the Tarim Massif. The left-lateral Altyn Tag Strike-slip Zone arose along its southeastern boundary; as a result, the Tarim drift acquired a substantial western component and compressed the Pamirs. Central Afghanistan was also involved in the northeastward drift. The left-lateral slip also occurred along the Gerat Fault and continued with the Gunt Fault as its extension. These movements enhanced the displacement of the Southwest Pamir–Badakhshan Block and reinforced deformation of neighboring zones. In

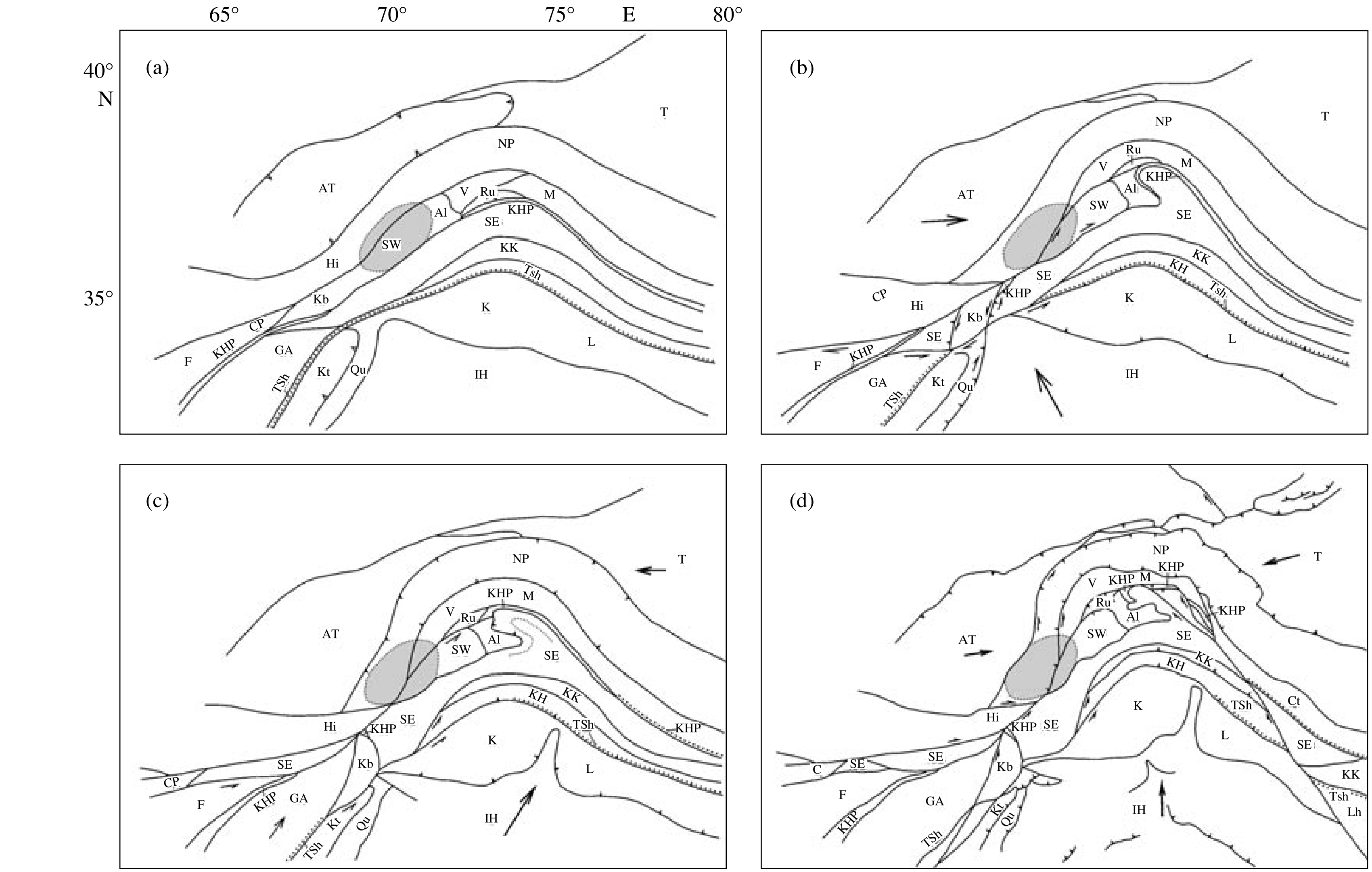

Fig. 3. Conceptual schemes of the geodynamic setting and tectonic zoning of the Pamir–Karakorum region at sequential stages of recent tectogenesis: (a) tectonic zoning in the late Eocene; (b) geodynamic setting in the late Eocene–early Miocene and tectonic zoning by the end of the early Miocene; (c) geodynamic setting in the terminal early Miocene–late Miocene and tectonic zoning by the end of the Miocene; (d) geodynamic setting in the late Miocene–Recent and present-day tectonic zoning. (IH) Indian Plate and Himalayas; (Kt) Katavaz Trough; (Qu) Quetta Zone, Khost ophiolites included; (Lh) Lhasa Block; (TSh) Tarnak–Shyok–Bangun Suture; (F) Farakhrud Zone; (KHP) Khashrud–Altimur–Pshart Suture. Arrows indicate direction of compression. The area of the Hindu Kush seismic megacluster is shaded. See Fig. 2 for other symbols.

particular, the nappe structure of the southeastern Pamirs was eventually formed, and the northward-bent North Pamir Zone started to thrust over the Afghan–Tajik Depression.

At the late stage of the neotectonic period, when the Earth's crust was homogenized in its physical properties, direction of the Indian Plate pressure in the Pamir segment of the orogenic belt became close to meridional, giving rise to latitudinal compression and related strike-slip fault zones at the eastern and western flanks of the region. These zones have remained active to date [36]. Simultaneously, latitudinal compression of the Pamirs continued. In the east, it experienced pressure from the Tarim Block, the drift of which had a western component due to the left-lateral movements along the Altyn Tag Fault with a rate that reached 1 cm/yr in the Quaternary. The Tajik–Karakorum Block of the Turan Plate could move in the opposite direction because of the right-lateral displacement along the Main Kopet Dagh Fault (>2 mm/year in the Quaternary). The countermovement of flanks shortened the Pamirs in the latitudinal direction and stretched it in the meridional direction, so that the North Pamir Zone was thrusted over the Afghan-Tajik Depression.

The convergence of the Pamirs and Tien Shan was caused by this process, and the westward removal of sedimentary sequences from the area of maximal shortening has been occurring until now, as follows from geodetic and geologic evidence [11, 36].

Intense vertical movements, the amplitude of which during only the Quaternary exceeded 6 km, were the most important process at the late stage of neotectonic period. Uplifting was driven by ongoing stacking of crustal blocks and by isostatic leveling of gravity heterogeneities that arose during the early stage. These processes were most large-scale in the western Pamirs; therefore, its uplift rate in the Pliocene–Quaternary was higher than in the eastern Pamirs [15]. The Quaternary rise was accompanied by gravity-driven overthrusting at the northern, western, and eastern flanks of the Pamirs and by extension in its axial zone (depression of Lake Karakul). Tectonic stacking, along with vertical movements, led to compositional and structural transformations deep in the Earth's crust; in our opinion, this was the main cause responsible for the formation of the Pamir–Hindu Kush zone of mantle earthquakes.

2. THE PAMIR–HINDU KUSH MANTLE FOCAL ZONE

2.1. Geophysical Characteristic of the Zone

According to the seismological data, including low-magnitude events, the Pamir–Hindu Kush focal zone of intermediate earthquakes is a steep lens with variable thickness and changing density of hypocenters (Figs. 2, 4) [19]. In both the Hindu Kush and Pamir segments of the zone, strong earthquakes occur at a depth of 110 ± 20 km. Deeper, at a depth of 130–170 km, the thickness of the

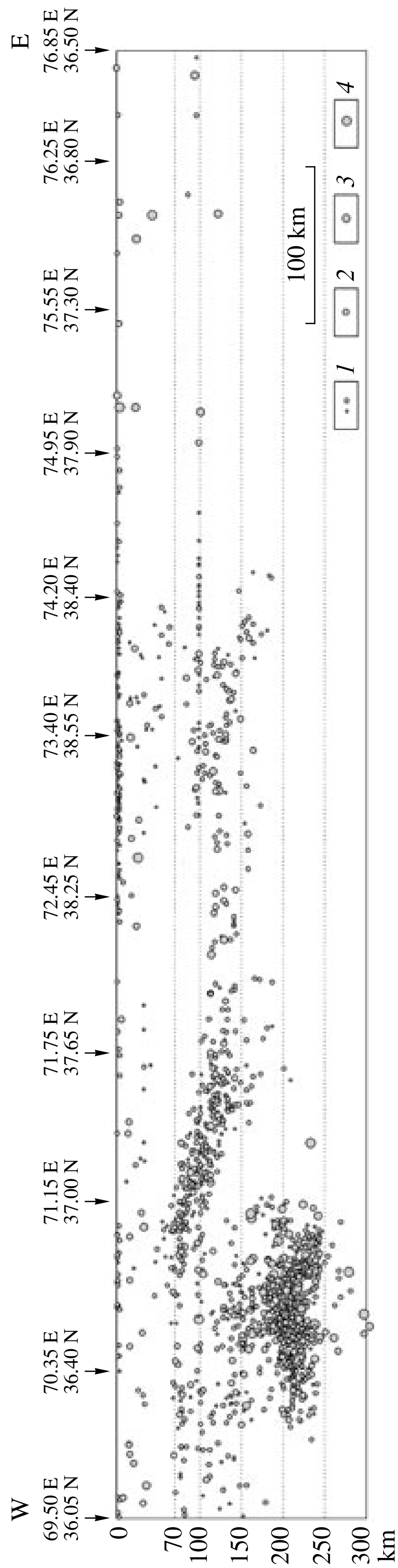

Fig. 4. Location of earthquake hypocenters along the longitudinal profile of the Pamir–Hindu Kush seismic focal zone. Compiled by D. M. Bachmanov using data from the catalog [32]. (*1–4*) earthquake magnitudes: (*1*) $M_s < 5.7$, (*2*) $M_s = 5.7–6.5$, (*3*) $M_s = 6.6–7.4$, (*4*) $M_s = 7.5–8.3$.

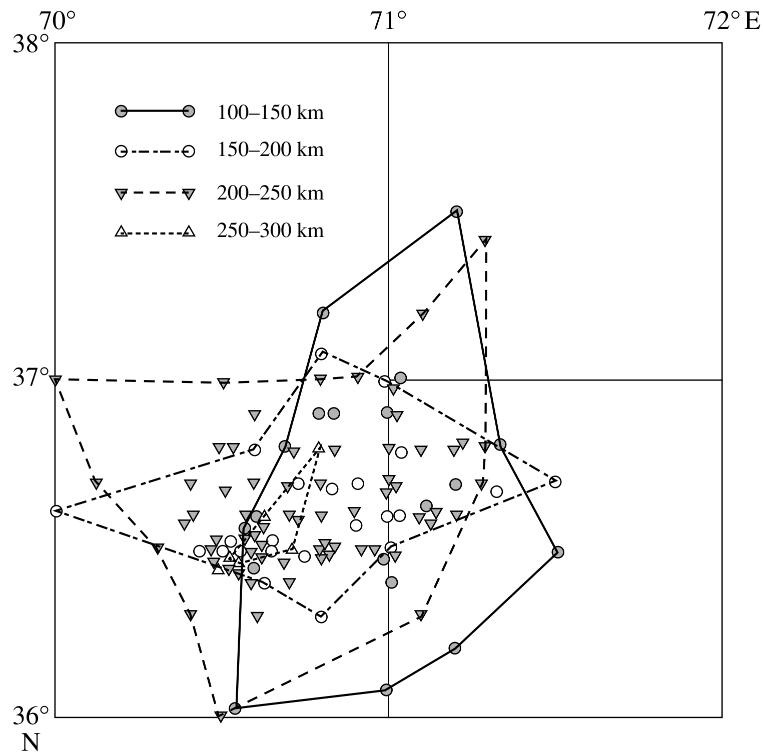

Fig. 5. Correlation between location of earthquake hypocenters with magnitudes $M_s \geq 5.7$ [35] and contours of their distribution at a different depths within the Hindu Kush seismic megacluster.

focal lens decreases. Strong earthquakes never occur in the Pamirs and are extremely rare in the Hindu Kush. Deeper, at 190–240 km, the thickness of the lens beneath the Hindu Kush abruptly increases, the number of hypocenters also increases, and the amount of released energy becomes greater than in the upper part of the lens. Seismic activity attenuates with depth, although it remains traceable to a depth of 270–300 km. In the Pamir segment of the zone at a depth of approximately 200 km, the thickness of the lens is also noted, but strong earthquakes never occur here, and the amount of released seismic energy is less than in the upper part of the lens.

The Hindu Kush segment of the focal zone is very compact. If the extremely strong earthquake of July 7, 1909 ($M_s = 8$; 36.5° N, 69° E), is ruled out because of inaccurately determined coordinates, almost 95% of strong earthquake epicenters fall within an isometric area $1.5 \times 1.5°$ with the maximum concentration located near 36.5° N and 70.8° E. Over 90% of strong earthquakes in the Pamir–Hindu Kush zone and over 95% of the released seismic energy are concentrated in this area. In the east, near the meridional bend of the Pyandzh River (71.5° E), the mantle seismicity abruptly drops, earthquakes with $M_s \geq 5.7$ are absent, and the maximal depth of hypocenters is reduced to 150 km [18]. Thereby, the area with maximal seismic activity shifts northward up to 37–38° N. To the east, in the Pamirs, mantle seismicity rises, although it remains substantially lower in comparison with the Hindu Kush. Earthquakes are scattered irregularly, particularly as it concerns strong events that are clustered into four compact groups. The depth of hypocenters reaches 240–250 km, but the amount of released seismic energy is at least three orders of magnitude lower than in the Hindu Kush region [7].

Lukk and Vinnik [18] have analyzed all the available data set on mantle earthquakes in the Hindu Kush and Pamir segments of the zone and showed that their hypocenters steeply dip northwestward and southward, respectively. The distribution of only strong earthquake hypocenters reveals an almost vertical orientation of the Hindu Kush segment (Fig. 5); data on the Pamirs turned out to be insufficient for such a suggestion.

The velocity section of the upper mantle in the Pamir–Hindu Kush region is known from deep-sounding data [23, 30, 38] and from the processed kinematic parameters of intermediate earthquake records [6]. Both of these sources point to elevated stratified P-wave velocities V_p and V_p/V_s ratios at a depth of 90–120 km and to the drop of these parameters at a depth of 120–150 km, which are consistent with the seismicity distribution at these levels of the focal zone. Values of V_p/V_s increase within a depth interval of 150–200 km, and stratified velocities V_p also rise at these depths and reach higher values at deeper levels.

Lateral heterogeneities of the upper mantle in the region are of particular importance for understanding the structure of the focal zone, which has been studied with various modifications of two methods. The first method is based on measurements of spectral characteristics of waves recorded at different distances and in different directions from sources of local intermediate earthquakes. This method helped to determine a large domain of the upper mantle, including the Pamir–Hindu Kush zone, which is distinguished by the anomalously high mechanical Q-factor [20].

The second method of seismic tomography based on the measurement of P-wave travel times from remote earthquakes to the network of local stations allows this domain to be specified. This method makes it possible to define a smaller mantle domain comprising the entire Hindu Kush part and to a great extent the Pamir part of the focal zone, where P-wave velocities down to a depth of 300 km are 0.3–0.4 km/s higher than in comparison with their average worldwide values [6, 18]. According to the calculations by Vostrikov [7] and based on his method of interpretation of earthquake-recurrence plots and his investigation of spatial variations in the seismic flow, the high-velocity domain is characterized by the elevated effective viscosity of rocks. This domain is restrained by the upper mantle masses with an average P-wave velocity 0.1–0.2 km/s lower than against their average worldwide background.

Using seismic tomography, Nikolaev and Sanina [22] constructed a three-dimensional velocity model of the focal zone and its vicinity that demonstrates the distribution of mantle domains with P-wave velocities distinguished from, to a variable extent, the average worldwide values at the same depth. Subsequently, these anomalies were recalculated into absolute velocity values [47]. The obtained velocity field within the focal zone and south of it is characterized by complexly alternating high- and low-velocity domains. This contrast is the most significant (up to 11–12%) in the Hindu Kush segment of the zone. North of the seismic focal zone, no similar anomalies are observable.

2.2. The seismic Focal Zone As a Result of Neotectonic Evolution

It is evident that the horizontal shortening of the upper crust, which has been convincingly deduced for neotectonic regional evolution both from the relationships between geologic zones and bodies and from modern geodynamics, must be accompanied by a similar or greater shortening of the lithospheric mantle. The origin of the Pamir–Hindu Kush focal zone is commonly interpreted exactly in this way.

The geophysical and, first and foremost, seismological study of the zone revealed an elevated strength of rocks from this zone relative to the surrounding mantle. In combination with modern high-rate strain, this gives rises to the rock failure accompanied by earthquakes [6, 7]. Assuming a similar rate of transverse shortening of the orogenic belt at the crustal and mantle levels, the elevated rate of mantle strain calculated from seismological parameters was ascribed to their concentration in a smaller rock body in comparison with the Earth's crust as follows from the spatial distribution of crustal and mantle earthquakes [21]. The elevated strength of rocks in the seismic focal zone was attributed to subduction of lithospheric masses deep into the mantle; this was argued on the basis of the northwestward dip of the Hindu Kush focal zone and the southward dip of the Pamir focal zone [18, 42, 50]. It was also assumed that the oceanic lithosphere of the Hindu Kush segment is compositionally similar to rocks of the Indus–Zangbo Suture subducted beneath the Hindu Kush, whereas the lithosphere of the extending Afghan–Tajik Depression enriched in mafic components is subducted beneath the Pamirs and Karakorum in the Pamir segment [50].

However, a subduction-related model of the focal zone provokes some objections. First, the distribution of strong earthquake hypocenters indicates a vertical rather than a tilted Hindu Kush focal zone. Second, the assumed localization of subduction zones nowise follow from structural relationships between tectonic zones and neotectonic displacements. It is unclear why the seismic focal zone is situated in its present-day position and is not traceable at the extension of the same structures. For instance, assuming the modern lithospheric subduction of the Indus–Zangbo type, there are no geologic reasons to constrain it by the Hindu Kush area and not extend it farther eastward, where geologic conditions are more favorable but the focal zone is missing. Similarly, a question arises as to why underthrusting of the Afghan–Tajik Depression beneath the Pamirs is expressed only in the east and not observable in the Hindu Kush, where it is geologically more suitable. Aditionally, the question arises as to why the rate of recent strain in the focal zone is higher than in other active structures of the region.

At the same time, the above hypotheses contain a sound point concerning the relationship between mantle earthquakes and mafic elements of the lithosphere. We also impart the decisive role to this aspect, although from a distinct standpoint.

With maximal clustering of mantle earthquakes, the highest release of seismic energy, and a depth of hypocenters as low as 270 km, the Hindu Kush zone corresponds on the Earth's surface to the adjacent areas of the Hindu Kush Hercynides with prevalent exposures of the Proterozoic basement and, to a lesser extent, the Archean massif of the Southwest Pamir–Badakhshan Zone (Fig. 2). If we assume that prior to the neotectonic period this massif was located at least 150 km to the west and was a crustal element of the central Pamirs between the volcanic arc and the oceanic trough of the early Mesotethys, then in the depths of the area of its initial location there might have been preserved deep-seated relicts of the overridden oceanic crust; these relicts are presented in the seismic velocity section of the neighboring Vanch–Yazgulem part of the central Pamirs by the approximately 15-km-thick crustal–mantle mixture.

Deep-seated analogs of the Khorog Formation exposed now in the zone of the tectonic contact between the Archean Shakhdara and Goran groups of the southwestern Pamirs could be another source of mafic material. The Khorog Formation is 0.5–2.0 km thick and mainly composed of amphibole gneisses and garnet amphibolites with boudines of eclogites and eclogitized rocks. Ruzhentsev [28] considered the Khorog Formation to be the basement of the continental crust of the overthrust Shakhdara Group. Budanova and Budanov [3] view it as a relict of the mafic riftogenic complex crushed between the converged Goran and Shakhdara continental massifs. In the last case, volumes of metabasic rocks beneath the initial location of this complex may be especially great.

Finally, the deep extensions of the Hercynian sutures overridden by nappes of the continental crust might have occurred immediately near these areas.

The Hindu Kush field of mantle earthquake epicenters fits the area of initial location of the above-mentioned metabasic complexes (Fig. 3). The area stands out as a depression of the Earth's surface occupied by valleys of the left tributaries of the Pyandzh River filled with Quaternary sediments. In the course of recent tectogenesis, the metabasic rocks were overthrust by thick sheets of the continental crust and pressed into the mantle to a depth of 40–70 km, where a moderately elevated temperature and a high pressure induced by intense lateral compression and the load of the overlying continental masses were favorable for eclogitization as indicated by petrologic studies and deep-sourced xenoliths [14]. The crust that got heavier by eclogitization submerged into a relatively low-velocity and hotter mantle that retained its high viscosity and strength, that is, the ability to accumulate the elastic strain that gives rise to the brittle failure responsible for mantle earthquakes.

In the easterly areas of the Pamir–Hindu Kush zone, epicenters of mantle earthquakes are confined to the central Pamirs and to its boundaries with neighboring zones. If detachment and northward displacement of the upper-crustal tectonic zones during recent tectogenesis are taken into consideration, the roots of Hercynian sutures, as well as Mesotethyan relicts buried beneath the continental crust of the central Pamirs, might have become sources of deep-seated metabasic rocks. Inasmuch as neotectonic lateral compression in this area was weaker than in the Hindu Kush, large sialic massifs are not typical. Thus, the lithostatic load of the overlying continental masses was lower, and eclogitization was less intense and occurred here only locally. Therefore, mantle earthquakes are much weaker in this area and strong events are recorded only at a depth of about 110 km being irregularly distributed.

Tectonic zones located on either side of the Pamir arc (to the east in Tibet and to the west in Afghanistan) widen, indicating a decreased intensity of their recent stacking and the above-mentioned consequences of this process. This is probably why mantle seismicity is almost completely lacking west of the Hindu Kush and east of Tashkurgan.

CONCLUSIONS

The proposed model of the Pamir–Hindu Kush tectonic evolution supposes a change in geodynamic settings during the late collision (neotectonic) period following the closure of Neotethyan relict basins.

The first stage of recent tectogenesis lasted from the late Eocene to the late Miocene and was characterized by heating of the continental lithosphere north of the Neotethyan suture that is expressed by intense granitic magmatism, metamorphism, local volcanic activity, and delamination of the heated lithosphere along surfaces with the highest gradient of rock mechanical properties. Under variously oriented compression controlled by lateral pressure from the Indian Plate and, probably, by longitudinal strain related to the convergence of the Tarim and Tajik–Karakorum blocks, the detached slices experienced horizontal movements. The structure of the Southwest Pamir–Badakhshan Block and its framework suggests that this ancient crystalline massif and Proterozoic block of the Afghan Hercynides were detached from their roots and thrust over relicts of the late Paleotethyan sutures and fragments of the early Mesotethyan oceanic crust.

At the late stage of recent tectogenesis spanning the late Miocene–early Pliocene, magmatic activity practically ceased and movements of delaminated slices in the cooling crust gave way to displacements and stacking of crustal blocks under the ongoing confining pressure. In combination with isostatic compensation of arising gravity inhomogeneities, this resulted in the rapid regional uplift.

Due to the motion of delaminated slices and stacking of crustal masses, fragments of the oceanic crust overlain by these masses and separated from their obducted counterparts were shown to be pressed-in to a depth of 40–70 km, where *P–T* conditions allow the eclogitization of basic rocks that leads to an increase in their specific weight. This likely resulted in the subsidence of eclogitized bodies into the upper mantle, which is characterized by a lower density in comparison with world-averaged values. Sources of mantle earthquakes in the Pamir–Hindu Kush focal zone arise from the release of stress accumulated in these submerging blocks. The maximal concentration of the pressed-in mafic blocks was confined to the Hindu Kush seismic megacluster. Therefore, their eclogitization and submergence proceeded here with a particular intensity such that the frequency and the energy of mantle earthquakes were maximal here, respectively.

To summarize, it should be noted that the proposed model of neotectonic events and their consequence in the form of the Pamir–Hindu Kush focal zone is internally consistent, and its most important statements are based on reliable facts. For instance, the suggestion of significant heating of the Earth's crust and its role in tectonic delamination at the early stage is substantiated by isotopic ages available for many granitic batholiths. Paths of crustal slices and blocks detached along delamination surfaces are reconstructed by analyzing alpine structures. Occurrence of eclogites at the base of the crust is deduced from petrologic data. At the same time, the model remains hypothetical in many respects because of insufficient geologic and geophysical data, particularly those for Afghanistan. Only further research can eliminate these uncertainties.

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