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Structure and evolution of the Pamir–Hindu Kush region lithosphere *

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The deep structure of the Pamirs–Hindu Kush region is considered. Using the geological and tectonic data a conclusion is reached on the sliding of the 30 km uppercrustal layer and its disharmony relative to the upper crust.

On the basis of the methods of the three dimensional wave velocity model of the lithosphere, obtained by the seismic tomography algorithm, and of the investigations of the recurrency law of the earthquakes in the Pamirs–Hindu Kush mantle focal zone, developed by the author's, a considerable horizontal inhomogeneity is recognized in the structure of the region up to a depth of 300 km.

All these data indicate that the movement of the lithosphere plates is brought about not by simple subduction, but by their twisting, differentiated at various levels, occurring in the upper mantle notless but perhaps even more intensively than in the Earth's crust. The mixing of the crustal and mantle materials accompanying this process can account for the decrease in the upper mantle average density in certain parts of the region.

The Pamir region is a genotype of intracontinental areas of recent intensive lithosphere compression under conditions of plate convergence. Our knowledge of modern and recent tectonic processes in the Earth's crust and upper mantle accounts for our understanding of the geodynamics of the region. The coherence of these processes, on the basis of geologic and seismological data, is considered in this paper.

The Pamir region is located on the northern flange of the Indian, or, more precisely, Hindustan-Pamir plate. Its modern margins meet a system of large faults, active in Late Pleistocene and Holocene (Trifonov, 1983). The system begins near the town of Karachi with an imbricate series of N-trending faults extending through the continent from the Indian Ocean floor (Fig. 1). The northern Chaman fault can be traced for almost 1000 km and, to the north of Kabul, is imbricately underlain by the Darvas–Alay zone of young ruptures. It extends from south to north, crossing the Piandzh river and then deflects towards NE and ENE approaching the southern slope of the Alai valley. To the east this zone joins with the butt-end of the zone of the Pamir–Karakorum fault, which extends towards the southeast where the Main Boundary fault of the Himalayas substitutes for it. The directions of young displacements, determined over all the above faults, evidence the movement of the Indian-Pamir plate northwards with respect to the neighbouring areas of the Alpine–Asian orogenic belt and Eurasian plate located to the north of it (Trifonov, 1983).

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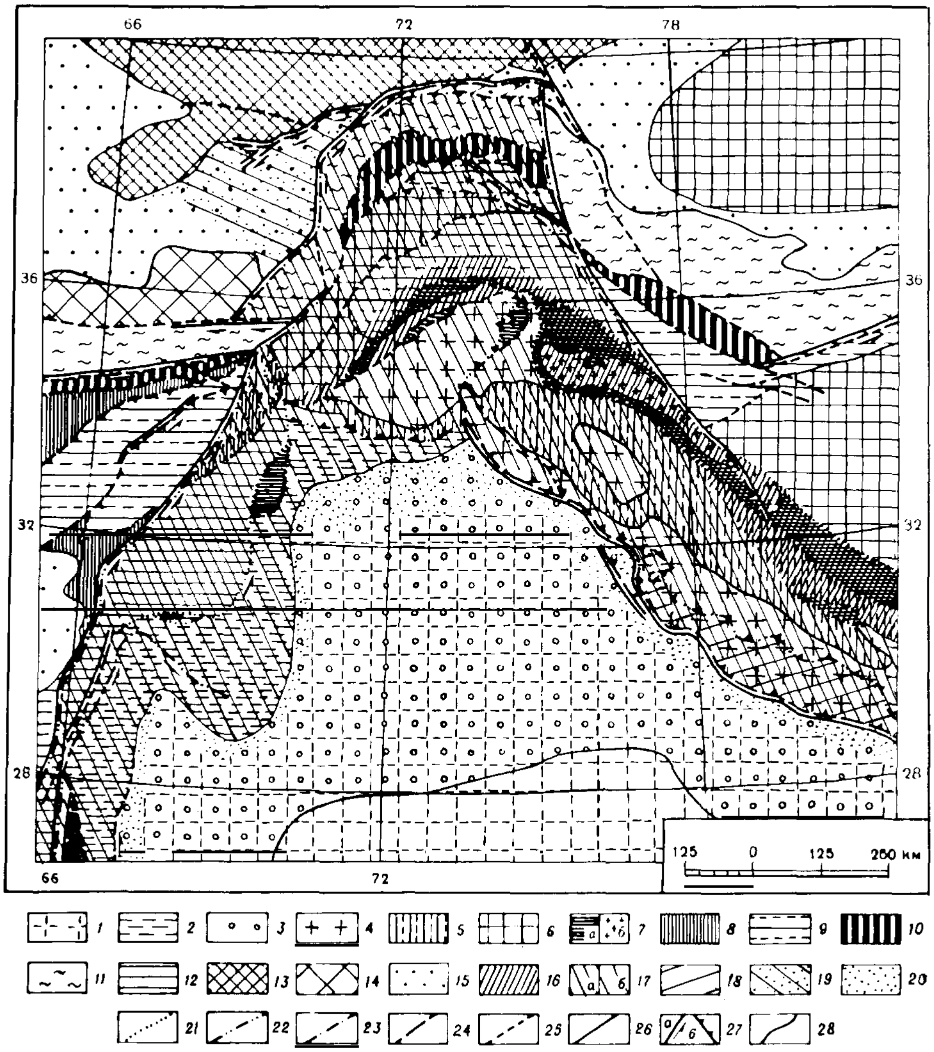

Fig. 1. Tectonic zoning of the northern part of the Indian-Pamir plate and adjacent territories. Indian platform: 1– part, inactive in the Cenozoic time; 2– Mesozoic and Cenozoic miogeosyncline basin; 3– Late Cenozoic foredeep; 4– the Himalayas; 5– the Tibetan Himalayas and their equivalents. Inner part of the orogenic belt: 6– old massif; 7– the Indus and the Quetta ophiolite zones (a) and granitic batholith in the Indus zone (b); 8– the Farahrud ophiolite zone and its equivalents; 9– the Karakorum and south-eastern Pamir zone and its equivalents; 10– the central Pamir zone and its equivalents; 11– the western Hindu Kush, northern Pamir and Kun Lun zone; 12– the Beludjistan flish zone. Southern part of the Eurasian plate: 13– the Tien Shan; 14– Palaeozoic basement of the Turanian plate; 15– Cenozoic and Mesozoic basins on the consolidated continental crust. Age of the most intense Late Cenozoic lateral movements: 16– Late Eocene and Oligocene; 17– Late Oligocene and Miocene (a), Miocene and probably Pliocene (b); 18– Late Miocene and Pliocene; 19– Late Miocene, Pliocene and Quaternary; 20– Quaternary. Beginning of intense lateral movements on faults: 21– Oligocene and earlier; 22– Late Oligocene and Miocene; 23– Late Miocene and Pliocene; 24– Quaternary; 25– unknown. Other symbols: 26– active faults; 27– wrench (a) and thrust (b) faults; 28– zone boundary.

The Hindustan–Pamir plate dimensions were smaller before Oligocene times, it was then limited in the north with the Indus zone in the Himalayas mountains (see Fig. 1). The geologic data analysis provided the reconstruction of the plate dimensions evolution. In the process of its relative movement northwards the orogenic belt fragment, located before the plate front, was affected by the intensive fold-overthrust deformations. These deformations produced its separation by growing northwards zones of strike-slip faults on the western and northeastern plate boundaries and slip of deformed and ruptured formations relative to the deeper crust. Finally they gave up their ability for intensive deformations, adjoined the marginal part of the plate and started moving northwards together with it, and the zone of the greatest displacements, fixing the location of the plate front, jumped northwards. Studies of the age of the most intensive overthrusting and folding processes in different parts of the Pamir–Himalaya region, as well as of displacements over different sections of strike-slip zones framing the plate, showed the plate from jumps to be repeated. The front was located in the Indus zone up to the Oligocene, in central Pamir zone in the Miocene, in the Karakul overthrust zone in the Late Miocene and Pliocene, and on the southern slope of the Alay valley in the Pleistocene (Trifonov, 1983).

The discovered sequence of tectonic events implies the sliding of the uppercrustal layer of the whole marginal Pamirs part of the plate as well as its structural disharmony with respect to the deeper layers of the lithosphere of the region (Fig. 2a). In the outer zone of the Pamir, Peter the First and Transalay ridges, it is evidenced by the immediate observations of Neogene–Quaternary overthrusts and torn folds (Gubin, 1960; Skobelev, 1977). In central Pamir four thrusted complexes are recognized, associated with four levels of sliding in the upper part of the crystalline basement and the sedimentary cover up to Paleogene inclusive (Peive et al., 1983). The zone of the overthrust sheet outcrops in southwestern Pamir has coupled the granite metamorphic layer. The inner structure of the plates that have isolated themselves in the

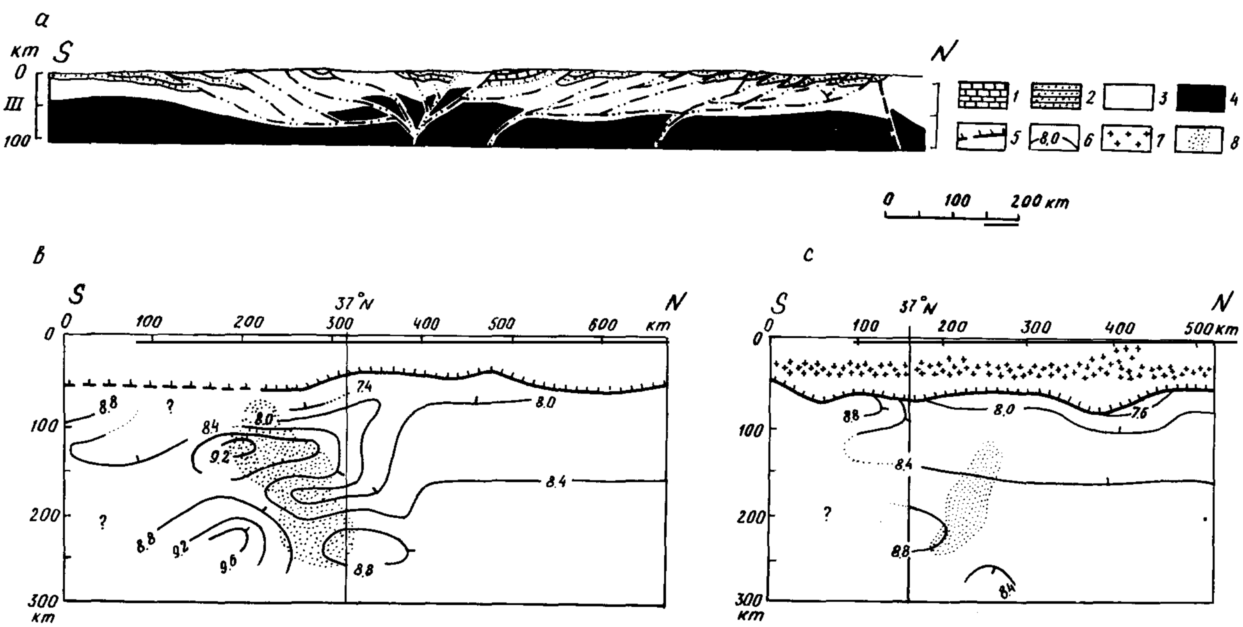

Fig. 2. Lithosphere cross-sections of the Pamirs–Hindu Kush region: (a) geological cross-section through the Pamirs and the Himalayas and (b,c) seismological cross-section through the Hindu Kush and the Tadjik basin. 1–ophiolites; 2–sedimentary cover; 3–the consolidated Earth's crust; 4–upper mantle; 5–Moho discontinuity; 6–isolines of the P-wave velocity in the upper mantle according to Fig. 5; 7–crust seismofocal zones; 8–Pamirs–Hindu Kush mantle zone.

course of the sliding process is characterized by the gigantic rootless lying folds, and the compositions of the rocks of the upper plate basal horizons (eclogite-like inclusions in plagiogneises, acid granulites, metagabbroides, ultrabasites with garnet and spinel) evidence that the slip occurred in the lower part of the Earth's crust (Peive et al., 1983).

The existence of structural-dynamic disharmony between certain horizons of the Earth's crust, and between the crust and the mantle, as well as the possibility of their differential recent displacements along subhorizontal zones, are supposed by different seismological data. Along with the general increase of the Earth's crustal thickness the low velocity layers are recognized inside and at the foot of the granite–metamorphic layer (Belousov et al., 1979; Khamrabaev, 1980). The crustal and mantle seismicity sources do not fit spatially (Belousov et al., 1979). Up to depths of 30–40 km the seismofocal zone of the northern flank of the Indian-Pamir plate dips southwards and is associated with the zones of big overthrusts of the most recent origin (see Fig. 2c). The concentration of the subhorizontal zone of hypocentres is located lower. This zone is likely to correspond to the zone of recent sliding of the uppercrustal masses, and below it there is the area where the amount of hypocentres reduces dramatically. Still lower, at the depths of 70–270 km, the Pamirs ($\varphi =$ 37–38°N, $\lambda =$ 71–71.5°E) and Hindu Kush ($\varphi =$ 36–37°N, $\lambda =$ 69–71.5°E) branches of the mantle seismofocal zone are located. They are characterized by a steep slope, the Pamirs branch being located 150 km southwards from the crustal seismofocal zone.

Vertical structural-dynamical inhomogeneity is also observed in the upper mantle. This is evidenced by the estimates of the values of relative strike-slip stresses σ acting at different levels of the mantle seismofocal zone, as well as of velocities of rupturing $\dot{\varepsilon}$ and seismic viscosity (Riznichenko, 1965). They are performed over recurrence graphs (RG) of seismic moments M of the earthquakes

$$lg\, n = \overline{lg\, n} - b\left(lg\, M_0 - \overline{lg\, M_0}\right) \quad M_0^2 \leqslant M_0 \leqslant M_0^R \quad (1)$$

were $\overline{lg\, M_0}$ is the middle point of the range $\Delta\, lg\, M_0 = lg\, M_0^R - lg\, M_0^2$ (usually $\Delta\, lg\, M_0 \leqslant 4$), $n(\overline{lg\, M_0})$ is the recurrence at this point normalized by the units of volume and time, b is the angular coefficient (slope). The coefficients (1) can be approximately calculated from magnitudinal RG $lg\, n$ using the correlation relationship $lg\, M_0 =$ const + $M \cdot$ const. RG of crustal earthquakes in wider range $\Delta\, lg\, M_0$ obey the universal recurrency law (Vostrikov, 1980)

$$lg\, n = lg\, n_0 - \beta\, lg(M_0/M_{01}) - (1/ln\, 10) \cdot (M_0/\theta)^{\alpha} \quad (2)$$

where M_{01}, α, β, n_0 are the constant coefficients and θ is a parameter (see for example curves 1, 2) Fig. 3a, for which α, β, n_0 are the same, and θ differ). The value θ can be calculated (Vostrikov, 1980) using the coefficients $\overline{lg\, M_0}$, $lg\, n$, b of the associated RG (1)

$$lg\, \theta = \overline{lg\, M_0} - 1/\alpha \cdot lg\, 2{,}3\left(lg\, n_0 - \overline{lg\, n} - \beta\left(\overline{lg\, M_0} - lg\, M_{01}\right)\right) \quad (3)$$

$$lg\, \theta = \overline{lg\, M_0} - 1/\alpha \cdot lg((b - \beta)/\alpha) \quad (4)$$

These coefficients appear to be mutually dependent (Vostrikov, 1980). The straight line in Fig. 3b corresponds to the relationship $b(lg\, N_0)$ at $lg\, M_0 = 22.7$ dyn · cm. The uppercrustal Pamirs–Hindu Kush earthquakes data (Fig. 3b) do not agree with it.

We have supposed that the line in Fig. 3b corresponds to the constant seismic viscosity η, to its average value in the Earth's crust and that Fig. 3b evidences the different η for the crust and the mantle. This was supported by the reprocessing of Sholtz's (1968a, b) experimental results concerning the uniaxial compression of rock samples. In these experiments the amplitudes A of elastic pulses occurring at microfracturing were registered simultaneously with slopes b $RG\, ln\, n_A$, stresses σ and the velocity of nonelastic deformation of volume increase $\dot{\varepsilon}_v$ that is proportional to recurrence n_A (Scholz, 1968a, b). With increase of σ the viscosity $\eta = \sigma/\dot{\varepsilon}_v$ reduces, the value of n_A increases, and b reduces (Fig. 3c). The conventional line qualitatively corresponds to the curve I of Fig. 3. The increase of η at $\dot{\varepsilon}_v =$ const is manifested by increase of b etc.

In the terms of (2) that implies the dependence of factors α, β, H_0 upon η. Meanwhile they are associated with the relationships (Trifonov et al., 1984)

$$\beta = tg(\pi/4 - arctg\ 2.3\alpha)\ 0 \leqslant \alpha \quad \beta \leqslant 1$$

$$lg\, n_0 - 227\beta = 6.56\ lg\, \beta - 2.3 \qquad lg\, M_{01} = 0$$

$$0.3 \leqslant \beta \leqslant 0.6$$

which together with (3) and (4) form a set of equations valid for variables α, β, n_0 and θ determination from factors of (I). With reduction of η factors n_0 and β increase, and α decreases. The examples of observation data approximations by the curves of (2) with α, β, n_0, θ = var are represented in Fig. 3a.

From (2) one can obtain the following expression for the seismic moments sum

$$\sum M_0 = \int_0^{\infty} M_0 \cdot n(M_0)\, dM_0$$

$$= n_0 M_{01}^{\beta}/2.3\alpha \cdot \Gamma((1-\beta)/\alpha) \cdot \theta^{1-\beta} \qquad (5)$$

where Γ is a gamma-function. The sum (5) normalized over the volume and time is an estimate of the value $\dot{\varepsilon}$ (Kostrov, 1975).

Under conditions of stationary seismic process from the (5) and Maxwell equation, satisfied by the seismic leaking of the rock masses (Kuznetsova, 1969), we obtain the following formulae

$$(M_{01}^{\beta}\theta^{1-\beta}/V) : (2.3\alpha/Vn_0\Gamma((1-\beta)/\alpha)) = \sigma/\tau$$

the numeration on the left hand side is of stress measure, the denominator of time measure, τ is relaxation time and the value V is of volume measure (in the first approximation V = const.).

Figure 4 plots the relationships of the parameters obtained in the above way from the depth in the Hindu Kush and South Pamirs branches of mantle seismoactive zone. Below the base of the Earth's crust the seismic deformation velocity in both branches, calculated using (5), dramatically in creases (Fig. 4a). Note that the calculated values of ΣM_0 are in good agreement with the observed ones.

The values σ and τ are plotted in Fig. 4b,c versus depth (the numerator and denominator in

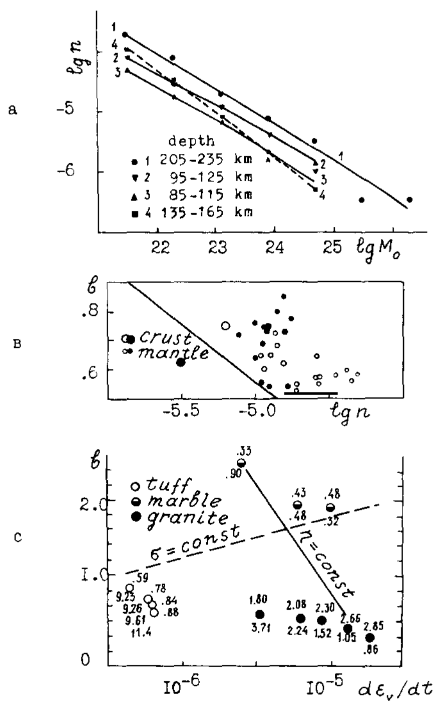

Fig. 3. Recurrency graphs (a) their slopes versus recurrency $\bar{n}(lg\, M_0)$ at $lg\, M_0 = 22.7$ dyn·cm (b) and versus features of the rocks and velocity of their unelastic deformation (c). a–the examples of the observation data approximation in Pamirs–Hindu Kush area (1, 2); b–data on b obtained by the seismological observations in the regions of Hindu Kush (light symbols) and southern Pamirs (dark symbols) straight line—average crustal relationship; c–data by Scholtz experiments, σ values (in kbars) and $\eta = \sigma/\varepsilon_v$ (in conventional units) are plotted above the experimental points and below them.

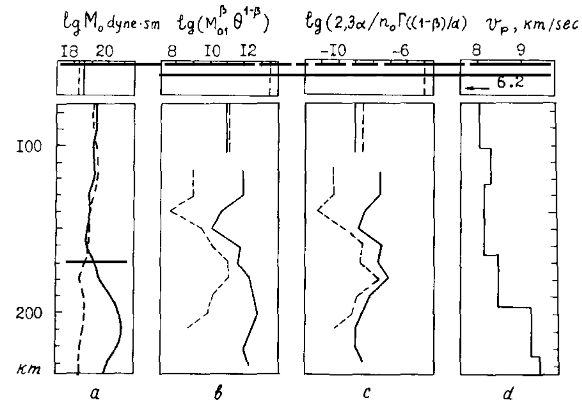

Fig. 4. Depth relationships in Hindu Kush (solid lines) and southern Pamirs (broken lines) (a) branches of the seismic active area of the seismic deformation velocity, (b) parameters $M_{01}^{\beta}\theta^{1-\beta}$, (c) 2,3 $\alpha/n_0\Gamma((1-\beta)/\alpha)$ and (d) characterizing the tensive state and seismic viscosity as well as velocities v_p.

the left part of (6) are not monotonous at both branches). At the depths of 130–160 km the areas of their reduced values are recognized. These areas are also characterized by reduced velocities v_p (Fig. 4d). However, in the area of reduced seismic viscosity, located in the Hindu Kush branch at depths of 190–240 km, both stresses and velocities are great. The areas of reduced viscosities and stresses can be recognized in both branches below the base of the Earth's crust. In general, the stresses in the upper mantle appear to be lower than in the Earth's crust and the deformation velocity is increased here due to reduced seismic viscosity.

The velocity section of the Pamirs–Hindu Kush zone lithosphere was studied applying the seismic tomography method by longitudinal waves from remote earthquakes. The layer-block model of the media is accepted, block dimensions are taken as 75×75 km in plan and 50 km in thickness. These parameters are needed to satisfy the required stability of a result on the experimental data basis available: 26 seismic stations, installed in the territories of the U.S.S.R. and Afghanistan, 15 azimuths to earthquakes sources groups (Fig. 4). For each

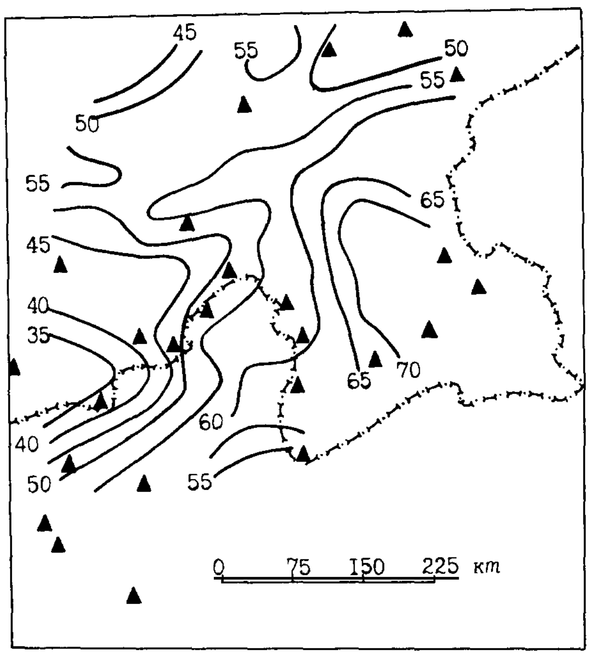

Fig. 5. Map of Mocho discontinuity relief and location of seismic stations.

particular band of azimuths, mean values of anomalies of seismic waves arrival times, with respect to the standard travel-time curve, are determined.

The inversion of seismic arrival times anomalies into velocity anomalies is performed by applying iteration technique with subsequent subtracting of time anomalies corresponding to the most contrasting inhomogeneities (PVA) (Nikolaev and Sanina, 1982). This technique is characterized by relatively high signal-to-noise ratio at a given resolution and its application is especially reasonable in the case of a relatively low density observational network.

The result of the re-establishment of velocity anomalies in the blocks of the media is shown in Fig. 5. The characteristic of the section obtained is the separation of the bulk of the media into two main parts: a homogeneous northern one and inhomogeneous SSW one.

Rather striking is the dramatic contrast in some blocks (11–12%) that provides a range of 7–9.5 km s^{-1}, average velocity being 8.2 km s^{-1}. The low velocities are associated with lower crustal material and the values of about 9.0 km s^{-1} were repeatedly obtained by DSS studies of the upper mantle (Ryaboi, 1979). The presence of considerable anomalies is also supported (Matveeva and Lukk, 1968).

Note the isometrical pattern of anomalies, their relatively small dimensions and mutual association of the anomalies of different sign: the positive ones neighbouring the negative ones.

The obtained result is in good agreement with the factual absence of a gravitational anomaly associated with the seismofocal zone. If we consider that velocity anomalies of different sign correspond to the density anomalies of different sign —this supposition is based upon the well known correlation relationships (Krasovski, 1979)—the above association can account for the lack of pronounced gravitational anomalies, hence the gravitational effects of close anomalous masses of different sign compensate for each other.

Different points of view exist concerning the problem of the structure of the zone of Pamirs–Hindu Kush deep-foci earthquakes. Lukk (1971) showed in his studies that this area is characterized by the increased absorption of seismic waves. The increased absorption is usually associated with seismic waves of low velocities. According to Vinnik (1976) the high-velocity block here is recognized surrounded by the low-velocity mantle, the velocity anomalies contrast being about 5%, the focal zone of the earthquakes is characterized by relatively high Q values.

The studies of seismic velocities definition errors yield a value of 4%, which should be taken as a cross-section when differentiating the medium into homogeneous blocks.

As a result of the studies of velocity anomalies correlation between the neighbouring adjacent layers accounting for the depth association of anomalies, the following values were obtained: layers I–II: $K_{12} = -0.05$; II–III: $K_{23} = 0.338$; III–IV: $K_{34} = 0.18$; IV–V: $K = 0.025$. Thus, the inhomogeneities are in fact not associated over depth, which can be due to strong differentiation due to mixing of big rock bulks. The processes of mixing is a deterministic one, it dominates over the processes of equalization of densities and thus seismic velocities; deep-foci earthquakes of the Pamirs–Hindu Kush zone are likely to be associated with both processes. Strong differentiation of wave velocities and thus of matter densities provides dramatically great local strike-slip and compressional (tensional) stresses, thus bringing about the idea, that local processes controlling equilibrium can be more active and thus are the very reason for the main part of the seismic activity of the Pamirs–Hindu Kush deep-foci zone, as is clearly seen in the cross-section (Fig. 6).

Note that Baltic shield surveys yielded that the most contrasting inhomogeneities are concentrated in the Earth's crust, the mantle part of the lithosphere being strongly homogeneous; the medium equilibrium is likely to be re-established here, the mantle is seismically passive, and the rigid Earth's crust is of low seismic activity.

The calculations transforming the data presented into the absolute values, of longitudinal velocities (Fig. 2b,c) show that within the Pamirs–Hindu Kush mantle seismofocal zone and to the south of it at a depth of up to 300 km, high- and low-velocity bulks of mantle matter are altering both laterally and vertically in a complicated manner.

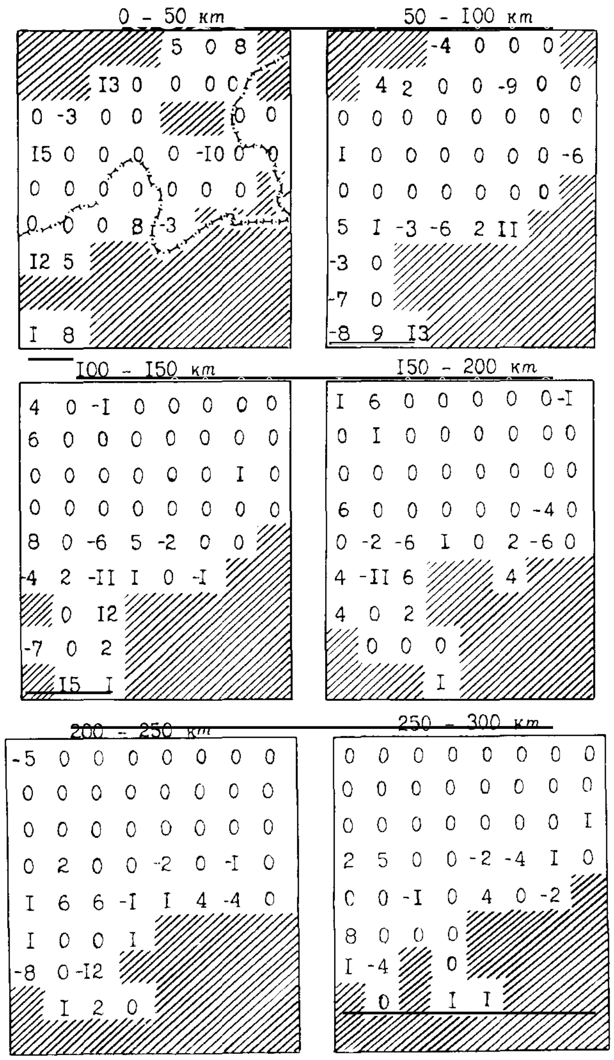

Fig. 6. P-wave velocity anomalies distribution in the Pamirs–Himalayas region.

The sharp slope of the seismofocal zone, the complicated distribution of the mantle masses with different physical properties do not agree with the model of simple subduction on the Hindustan–Pamirs and Eurasian plates boundary. Their convergence is provided by the lithospheric masses concentration, differentiated at different levels, the accumulation being not less, but perhaps even more intensive in the upper mantle than in the Earth's crust. The accompanying partial mixing of crustal and mantle matter can provide the reduction of the total density of uppermost mantle in certain parts of the region. Besides, the rock masses squeeze to both sides from the area of closest plates convergence.

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