Neotectonic uplift and mountain building in the Alpine-Himalayan Belt

V.G. Trifonov, S.Yu. Sokolov and D.M. Bachmanov

The book describes neotectonic uplifts producing mountain building in the Alpine-Himalayan Belt. This process began in the Oligocene as formation of local uplifts in zones of concentration of collision compression and accelerated in the Pliocene and Quaternary as the isostatic effect of decrease of density of the uppermost mantle and the lower crust by partial replacing of the lithospheric mantle by the asthenosphere material and retrograde metamorphism of high-metamorphosed rocks by asthenosphere fluids. These changes were initiated and kept up by the sub-lithosphere upper mantle flows that spread, according to the seismic tomography data, from the Ethiopian-Afar superplume and were enriched by fluids, reworking the transitional mantle layer beneath the future mountain belt. The upper mantle flows not only move lithosphere plates with all plate-tectonic consequences of this process, but also initiate transformations of the lithosphere that results in vertical movements producing mountain building. The book is intended for wide circle of geoscientists.

Keywods: Oligocene to Quaternary, neotectonics, uplift, mountain building, molasses, seismic tomography, lithosphere, asthenosphere, mantle flows

Content

Introduction

Obruchev (1948), introducing the terms *neotectonics* and *neotectonic* epoch, applied them to the process leading to the formation of the present-day topography that is distinguished by high-mountain systems, which did not exist earlier in the Mesozoic and Cenozoic geological history. In this book, we consider the tectonic movements, which gave rise to the contemporary topography of the central Alpine–Himalayan Orogenic Belt between the Carpathians and Balkan–Aegean region in the west and the Tien Shan, Kunlun, Tibet, and Himalayas in the east (Fig. 1)[1].

In the first part of the book, we describe the history of neotectonic (Oligocene–Quaternary) movements that produced uplift of orogenic structures of the belt. Analyzing neotectonic evolution of the Central Tien Shan, Pamirs, Great Caucasus, and finally the orogenic belt as a whole, we show that their evolution includes two main stages. During the first long-time stage that lasted from Oligocene till the end of Miocene and even Pliocene in some regions, local uplifts formed. They were usually not higher than middle-level mountains (< 1500 m) and formed under collision compression as the results of isostatic compensation of thickening of the Earth's crust in zones of concentrated deformation. During the second Pliocene–Quaternary stage, the height of the mountains increased 2–3 times. This intensification of tectonic uplift producing mountain building can not be explained by effects of the collision compression. It was caused by a decrease in the density of the crust and upper mantle under the effect of the asthenosphere, which was activated by fluids.

The second part of the book is devoted to deep-seated sources of the neotectonic processes mentioned above. The analyzing seismic tomography data demonstrate two important features of the mantle. First, in the eastern (Indonesian) part of the Alpine-Himalayan Belt, where subduction has continued till now, the higher-velocity subducted slabs became approximately horizontal at the depths of about 400–700 km and these sub-horizontal lenses spread beneath the adjacent continental upper mantle. The same continuations of the subducted slabs are known in the North-Western Pacific, where they were termed as stagnant slabs (Fukao et al., 2001), or big mantle wedges (BMW) (Zhao, 2009; Zhao et al., 2010). Second, in the more western mountain part of the Alpine-Himalayan Belt, sub-lithosphere low-velocity (hot and lower-dense) mantle flows were identified. They begin in the Ethiopian–Afar superplume rising from the lower mantle and spread beneath the orogenic belt.

[1] For the sake of brevity, these segments will be called further merely the Alpine–Himalayan Belt.

Thermo-dynamic calculations based on the results of geochemical and petrological studies showed that magmas in the south of the Armenian Highland were generated under the pressure P=1.1–1.2 Gpa characteristic for the upper mantle, while in the north of the Highland and in the Greater Caucasus, the level of the magma generation is characterized by P=0.95–1.05 Gpa and T=850–1100° that corresponds to the depths of 35–40 km, i.e. the bottom of the Earth's crust in the Highland and the lower crust in the Greater Caucasus (Koronovsky, Demina, 1999, 2007). In the Elbrus area, a depth of the acid magma generation is characterized by P=0.5–0.7 Gpa, corresponding to the depths of 17–25 km. At a depth of 35 to 50 km beneath Elbrus there have been found a rock body with decreased velocities of seismic waves and increased electrical conductivity that may be identified with the magmatic source (Modern and Recent Volcanism…, 2005). So, the sources of the Late Cenozoic volcanism of the region were situated mainly in the lower crust and near the crust–mantle boundary.

Data of the Sr–Nd–O isotopic analysis of the volcanic rocks in the region, as well as high $^{3}He/^{4}He$ ratios in water springs of Elbrus and Kazbek strongly suggest the mantle material to have penetrated to the magmatic sources (Ivanov et al., 1993; Bubnov et al., 1995; Polyak et al., 1998). Karyakin (1989) noted a similarity between the Armenian Highland basalts and basalts from ensialic island arcs and active continental margins. The decrease of the seismic wave velocities by 1.5% was found in the uppermost mantle beneath the Elbrus area (Milanovsky et al., 1989). Based on these data, Koronovsky and Demina (1996, 2004, 2007) proposed a model of the Late Cenozoic magma generation in the region. According to the model, the magma sources in the lower crust and the uppermost mantle formed under influence of heat and oxidation of fluids, transported from the deeper levels in the mantle. One of sources of the fluids could be deformational heating of the Mesotethys suboceanic slabs persisting within the lithosphere. At the same time, we agree with the idea of Ershov and Nikishin (2004) that the sublithosphere flow from the Ethiopia–Afar superplume could be another, and essential, source of the magma generation. The flow penetrated beneath the inner zones of the Alpine–Himalayan collision belt in the Miocene and reached the Greater Caucasus to the Upper Miocene. The Armenian Highland was subjected to both sources of the magma generation, which may account for the most intensive volcanism in the region (Trifonov et al., 2011).

2.2.3. Intracontinental mantle seismic-focal zones in the Alpine-Himalayan Belt

To contradict the study, we summarized catalog data (Kárník, 1968; Kondorskaya, Shebalin, 1982; Kondorskaya, Ulomov, 1995; Moinfar et al., 1994; National…, 2007; Papazachos, Papazachou, 1997; Trifonov, Karakhanian, 2004) on the earthquakes, which took place in 1850–2007 and had $M_S \geq 5$ and hypocenters at depths of $\geq$40 km ($\geq$50 km in thick-crust areas). Almost all such earthquakes are concentrated in the Hellenic and Cyprus arcs, Aegean region, Zagros Mountains, Vrancea megafocus, Middle Caspian, and Pamir–Hindu Kush zone with the Hindu Kush megafocus. The earthquakes in the Hellenic and Cyprus arcs are related to recent subduction zones. The other areas do not show such a relationship. The most active ones are Hindu Kush and Vrancea.

2.2.3.1. The Pamir–Hindu Kush mantle seismic zone

Analyzing the catalog of strong ($M_S \geq 5.7$) earthquakes in the central Alpine–Himalayan belt (Trifonov, Karakhanian, 2004), one may point out a small (100 x 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 (Fig. 12). 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 $\pm$ 20 and 190–240 (down to 270–300) km. East of the N-S-trending bend of the Pyandzh River (Fig. 11), 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 Afghan-Tajik Basin. 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 $\pm$ 20 km.

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 (Lukk, Nersesov, 1970). In both the Hindu Kush and Pamir segments of the zone, strong earthquakes occur at depths of 110 $\pm$ 20 km (Fig. 36). Deeper, at depths of 130–170 km, the thickness of the focal lens decreases. Strong earthquakes are not recorded 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 depths 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 did not occur here, and the amount of released seismic energy is less than in the upper part of the lens.

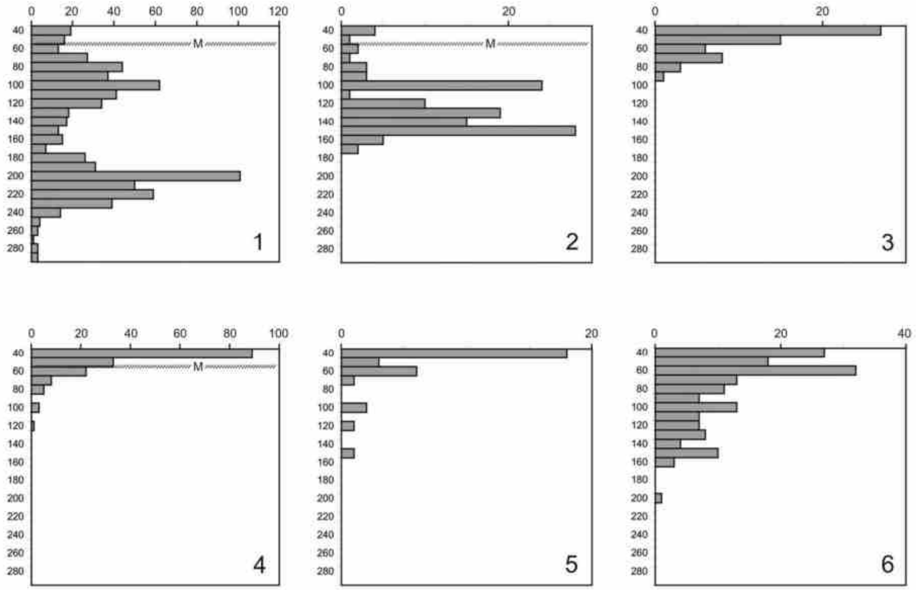

Fig. 36. Histograms showing the distribution of $M_S \geq 5$ earthquakes (N) over depth (h) in mantle seismic focal zones, modified after (Trifonov et al., 2012_1): 1, Pamir – Hindu Kush; 2, Vrancea; 3, Middle Caspian; 4, Zagros; 5, Aegean region; 6, Hellenic arc. Cross ruling shows the approximate position of the crustal bottom (Moho discontinuity) if it is localized at a depth lower than 40 km

The Hindu Kush segment of the focal zone is very compact. If the extremely strong earthquake of July 7, 1909 (*Ms* = 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 × 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 N-trending bend of the Pyandzh River (71.5° E), the mantle seismicity

abruptly drops, earthquakes with $Ms \geq 5.7$ are absent, and the maximal depth of hypocenters is reduced to 150 km (Lukk, Vinnik, 1975). 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 (Vostrikov, 1994).

Lukk and Vinnik (1975) 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. 37); data on the Pamirs turned out to be insufficient for such a suggestion.

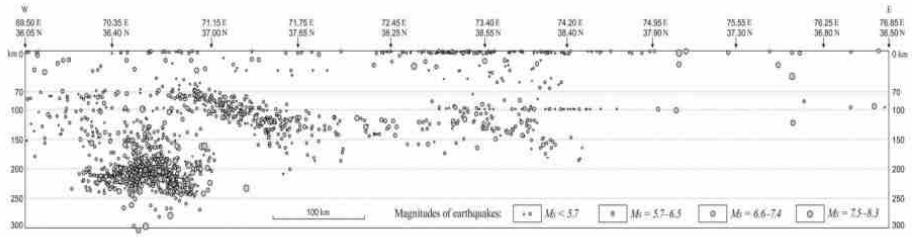

Fig. 37. Location of hypocenters of earthquakes along the Pamir – Hindu Kush seismic focal zone; compiled by D.M. Bachmanov with using the catalog (Kondorskaya, Ulomov, 1999)

The velocity section of the upper mantle in the Pamir–Hindu Kush region is known from deep-sounding data (Khamrabaev, 1980; Seismic models…, 1980; Pamirs–Himalayas…, 1982) and from the processed kinematic parameters of intermediate earthquake records (Vinnik, Lukk, 1974). Both of these sources point to increased P-wave interval velocities and *Vp*/*Vs* ratios at depths of 90–120 km and to the drop of these parameters at depths of 120–150 km, which are consistent with the seismicity distribution at these levels of the focal zone. Values of *Vp*/*Vs* increase within a depth interval of 150–200 km, and P-wave interval velocities 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 (Molnar et al., 1976).

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 (Vinnik, Lukk, 1974; Lukk, Vinnik, 1975). According to the calculations by Vostrikov (1994) 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 increased 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 (1982) 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 (Nikolaev et al., 1985). 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.

<u>The seismic focal zone as a result of neotectonic evolution</u>. 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 recent 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 increased strength of rocks from this zone relative to the surrounding mantle. In combination with recent high-rate strain, this gives rises to the rock failure accompanied by earthquakes (Vinnik, Lukk, 1974; Vostrikov, 1994). Assuming a

similar rate of transverse shortening of the orogenic belt at the crustal and mantle levels, the increased 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 (Neotectonics and recent geodynamics of mobile belts, 1988). The increased 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 (Lukk, Vinnik, 1975; Tapponnier et al., 1981; Burtman, Molnar, 1990). 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 Basin enriched in mafic components is subducted beneath the Pamirs and Karakorum in the Pamir segment (Tapponnier et al., 1981).

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 (Fig. 37). Second, the assumed localization of subduction zones nowise follows 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 recent lithosphere 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 Basin beneath the Pamirs is expressed only in the east and not observable in the Hindu Kush, where it is geologically more suitable. Additionally, 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 Archaean massif of the South-Western Pamir–Badakhshan Zone (Fig. 12).

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 relics of the overridden oceanic crust; these relics 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. The deep extensions of the Hercynian sutures overridden by nappes of the continental crust might have occurred immediately near these areas.

Deep-seated analogs of the Khorog Formation exposed now in the zone of the tectonic contact between the Archaean Shakhdara and Goran groups of the South-Western Pamirs could be also a 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 (1990) considered the Khorog Formation to be the basement of the continental crust of the overthrust Shakhdara Group. Budanova and Budanov (1983) view it as a relic of the mafic riftogenic formation 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.

The Hindu Kush field of mantle earthquake epicenters fits the area of initial location of the above-mentioned metabasic complexes (Fig. 14). 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 neotectonic deformation, 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 intensive lateral compression and the load of the overlying continental masses were favorable for eclogitization. It is indicated by petrologic studies and deep-sourced xenoliths (The Earth's crust and upper mantle of Tadjikistan, 1981). The crust that got heavier by eclogitization submerged into a relatively low-velocity and hotter mantle (Fig. 12, profile) that retained its high viscosity and strength, that is, the ability to accumulate the elastic strain that gives rise to the brittle failure producing 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 the neotectonic epoch are taken into consideration, the roots of Hercynian

sutures, as well as Mesotethyan relics 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 intensive 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 the town of Tashkurgan.

This model 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.

2.2.3.2. The Vrancea mantle seismic megafocus

Since 1862, 113 earthquakes have been recorded in the Vrancea area at depths of 60–170 km (Fig. 38). Except two early events whose coordinates might be imprecise, all the earthquakes occurred at N45.2–45.9º and E26.2–27.3º. In the first approximation, the seismic focal zone is a near-vertical column ~80 km in diameter and up to 170 km deep.

Mantle earthquakes are confined to the bend between the Eastern and Southern Carpathians and their hypocenters are located under the Outer Carpathians and the Focsani Foredeep (Fig. 39). The Outer zone is the accretionary wedge of the Mesozoic-Paleogene flysch detached and overthrust in the Late Miocene upon the Middle Miocene sediments of the Focsani Basin, in which up to 3 km sediments had accumulated by the time of the overthrusting (Artyushkov et al., 1996). The thickness of the nappe complex was 8–12 km (with regard to erosion, it might have reached 10–14 km). However, the thickening of the cover did not cause an isostatic crustal uplift to the calculated value of 1.5–2.4 km. According to the authors cited, the land surface remained at a height of ~0.5 km, i.e., an uplift of 1–2 km was compensated for by bedrock compaction. The Neogene-Quaternary sediments up to 9 km thick accumulated in the Focsani Basin southeast of the nappes; near their front, the sediments are folded and thrust (Sandulescu, 1984; Artyushkov et al., 1996). The Focsani Basin is superimposed on the Precambrian Moesian Plate (Sandulescu, 1984). The north-eastern edge of the basin is lined by the Pechenyaga-Kamena Thrust, which is inclined beneath the basin and the Outer Carpathians and separates the Moesian Plate from the post-Paleozoic Scythian Plate. The north-eastern side of the fault is composed of the Cymmerian Northern Dobruja – a nappe system overthrust upon the Scythian Plate. Two nappes are separated by the Triassic mafic volcanics (Khain, 2001). Now they belong to the Pechenyaga-Kamena thrust zone and might extend along it at depth towards the Carpathians.

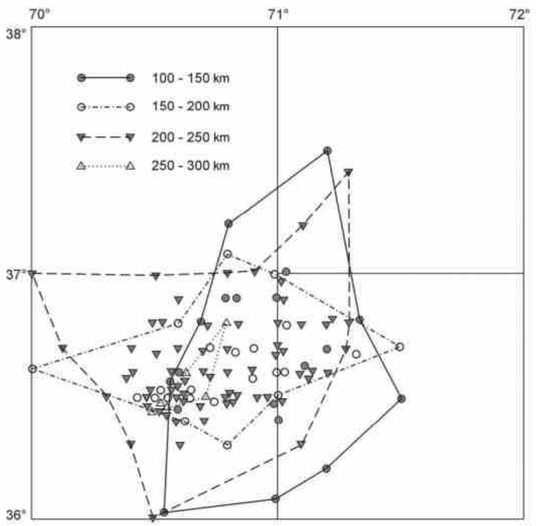

Fig. 38. Comparison of location of hypocenters and contours of their distribution in different depths of the Hindu Kush seismic mega-source (Ivanova, Trifonov, 2005)

On seismic profile O–Z, the Moho is located at depths of 35–40 km under the Inner Carpathians, at depths of 45–47 km under the Outer Carpathians and the Focsani Basin, and at a depth of ~44 km under the Moesian Plate (Hauser et al., 2007). Similar changes were observed on a more northern seismic profile crossing the Ukrainian Carpathians. The crust is ~60 km thick here beneath the Outer Carpathians and the foredeep; in the lower crust, a layer was detected with *Vp* velocities of 7.4–7.6 km/s, with a thickness increasing to ~20 km from the Inner to the Outer Carpathians and the foredeep (Chekunov, 1993). On the profile O–Z, the *Vp* velocities are 7.0–7.1 km/s in the lowest part of the crust.

The high-velocity lower-crust layer of the Ukrainian section might be indistinguishable there from the uppermost mantle. Artyushkov (1993; Artyushkov et al., 1996) considers that the high-velocity layer in the lower crust indicates metamorphic compaction of mafic rocks, which kept the Focsani Basin, filled with the nappes of the Outer Carpathians and the Neogene-Quaternary sediments, at a low hight. The mafic rocks might have originated from the Inner Carpathians, where ophiolite outcrops, for example, in the Mureş zone. Their underthrusting resulted from the detachment of the lower crust and was simultaneous with the thrusting of the Outer Carpathians.

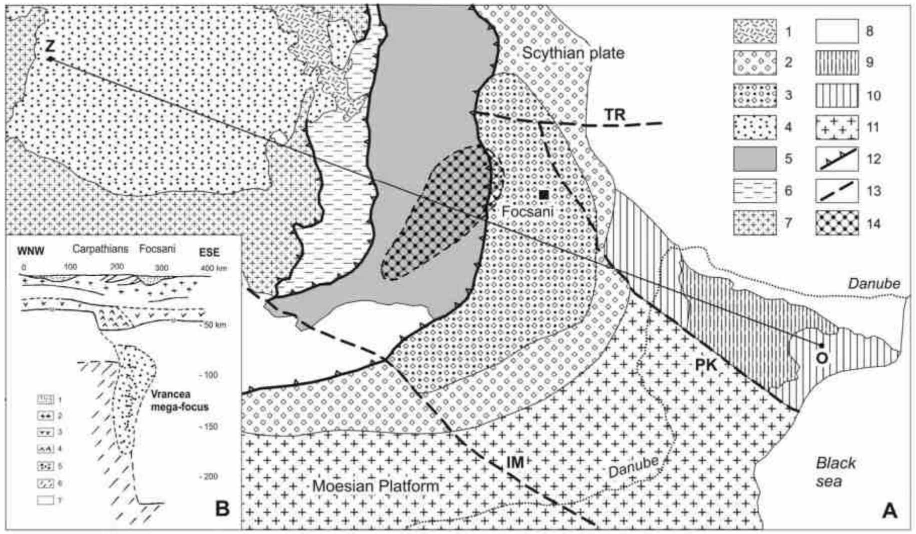

Fig. 39. Tectonic sketch map of the Carpathians around the Vrancea seismic region (A) and a sketch profile of the formation of the Vrancea mega-source of mantle earthquakes, modified and supplemented after (Arthyushkov et al., 1996; Hauser et al., 2007; Trifonov et al., 2010, 2012_1).

A: *1*, Neogene-Quaternary volcanics; *2*, Neogene-Quaternary sediments of the Carpathian Foredeep; *3*, Focsani Basin; *4*, Neogene sediments of the Transylvanian Basin; *5*, nappe complex of the Outer Carpathians (Moldavides); *6*, External Dacides with the Cretaceous parautochthon; *7*, Median Dacides and Transylvanides with the Cretaceous parautochthon; *8*, Carpathian tectonic zones under the Pliocene-Quaternary cover; *9*, *10*, Cymmerian orogen of Northern Dobruja: exposed or overlain by thin sediments (*9*), under a sedimentary cover (*10*); 11, Moesian Platform cover; *12*, major thrusts; *13*, faults: IM, Intramoesian, PK, Pechenyaga-Kamena, TR, Trotus River; *14*, Vrancea epicentral area; ZO, seismic-profile line. *B*: *1*, sedimentary cover; *2*, upper crust; *3*, lower crust; *4*, lower crust saturated with dense metamafic rocks; *5*, dense metamafic slab (zone of mantle earthquakes); *6*, asthenosphere; *7*, lithospheric mantle

We think that the metamafic rocks extended as a slab into the lithospheric mantle and their additional source might have been the mafic rocks of Northern Dobrudja, which underthrust beneath the Focsani Basin along the Pechenyaga-Kamena Thrust

(Fig. 39). In the upper mantle, the mafic rocks underwent additional metamorphism with the formation of garnet granulites and eclogites, close in density to the lithospheric mantle. During the rise of the asthenosphere beneath the Carpathians to a level of about –80 km (Artyushkov et al., 1996), the slab found itself between the lower-density mantle of the Carpathians and the dense lithosphere of the Moesian Plate. This led to its subsidence, accompanied by earthquakes.

2.2.3.3. Origin of mantle seismicity

In the both examples, the mantle earthquakes are related to the paleo-oceanic metabasic rocks. The upper-mantle decrease of density in the Pliocene–Quaternary led to the breakoff and subsidence of dense cold metamafic slabs. Along with the subsidence, the earthquakes were powered by the phase transformations of the slab rocks: deserpentinization and, at greater depths, the eclogitization of the remnants of less metamorphosed mafic rocks and the transformation of quartz into coesite. The seismic shifts might have resulted not so much from high deviator stress as from rock weakening in mylonitized zones, intensified by fluids (Rodkin et al., 2009). The latter originated from the products of dehydration of serpentine and amphibole as well as from the asthenosphere.

Thus, the subsidence of the earthquake-inducing slabs and the intense uplift of the mountains were simultaneous and both resulted from the upper-mantle decrease of density under the effect of the asthenosphere. However, the tectonic uplift took place in a larger territory of the Alpine-Himalayan Belt. Evidently, the local geodynamic factors of seismicity played a role. First, this might have been the large initial size of the slab, which permitted its long-lasting isolation. Second, this might have been the presence of a large trans-lithospheric fault zone related to within-slab slip zones. These are the Pamir-Afghan (Chaman-Darvaz) zone of sinistral strike-slip faults in Hindu Kush (Ivanova, Trifonov, 2005) and the Carpathians–Moesian Plate boundary in the Eastern Carpathians (Sandulescu, 1984).

Three other regions of mantle earthquakes within the orogenic belt (Aegean, Zagros, and Middle Caspian) show the same, but weaker, factors of seismicity, and the number of hypocenters decreases quickly with depth (Fig. 38). This might be because the slab subsidence is only incipient or is slow owing to the slight density difference between the slab and neighboring mantle.

2.3. Plate tectonics and tectonics of mantle flows

The principles of the tectonics of lithosphere plates, or plate tectonics, were formulated first about a half of century ago. Since that time the theory has been essentially complicated. At the same time, it has been found that some tectonic processes can not be satisfactory explained by the plate-tectonic theory. This is related to some sources of vertical movements and first of all neotectonic uplifts producing formation of recent mountain systems. Comparison of the geological data, which can and cannot be explained by the plate-tectonic theory, with the results of seismic tomography of the mantle give a possibility to propose the new tectonic model. According to it, the sources of tectonic processes are the upper mantle lateral flows spreading away from the superplumes that are the flows of matter and energy rising from the lower mantle. These lateral flows not only move the lithosphere plates with all consequences of the movement, but also cause structural and mineral transformations in the lithosphere and sublithosphere upper mantle, which lead to additional vertical movements and mountain building.

2.3.1. Development of plate tectonic theory

Plate tectonics was created as a kinematic model. According to it, the ~50-km thick under oceans and ~100-km thick under continents lithosphere plates occupying the Earth's crust and the uppermost part of the mantle move from spreading zones along transform faults to zones of subduction and collision. The deep mantle material builds up the lithosphere in the spreading zones. In the zones of subduction and collision, the accretion of the lithosphere is compensated by its sinking into the lower mantle. The plate movement is described by their rotation around the Euler's poles (Vine, Matthews, 1963; Wilson, 1965; Dickinson, Hatherton, 1967; Isacks et al., 1968).

The researchers tried to find the sources of plate motion in the plate-tectonic mechanism itself, for instance, in moving apart effect of magmatic intrusion into the spreading zones or sucking in by the subducted parts of the plates. However, Sorokhtin (1974, 2007) showed that these processes influence locally and can not produce the plate motion as a whole. Forsyth and Uyeda (1975) proposed the mantle thermal convection as the general mechanism of the plate motion, but Artyushkov (1968) and Sorokhtin (1974) argued the higher efficiency of the convection caused by the transformations of chemistry and density of rocks and related to the mantle differentiation and enriching of the outer core of its ferriferous components.

The main achievement of the plate tectonics was that it consolidated affords of geologists, geophysicists and geochemists for solution of common tasks. This essentially improved their mutual understanding and cognition of tectonic processes. At the same time, accumulation of new knowledge required complication of the initial plate-tectonic model. The important subjects of discussion were parameters of the mantle convection as a source of the plate motion. The transition layer between the upper and lover mantle was distinguished by the seismological data. The jumps of seismic wave velocities in its upper (~410 km) and lower (~670–680 km) boundaries are so high that they can occur only with mineral transformations of the mantle matter. With some parameters of the system, these exothermic and endothermic transformations make the all-mantle convection impossible. The reasons for absence of essential exchange of the matter between the lower and upper mantle (Hamilton, 2003; Ivanov, 2011) conform to this idea. However Sorokhtin (2007) produced convincing reasons for the chemical-thermal density all-mantle convection. Proceeding from the assumption of full circulation of the mantle matter during the tectonic cycle, he came to the conclusion on sufficiently high rates of the mantle flows, with which the mineral transformations do not interrupt the flow and manifest themselves only in rise or subsidence of the transitional layer at a magnitude up to ~20 km. The reasons for combined influence of the all-mantle and upper mantle convection onto the lithosphere seem now to be the most ponderable (Dobretsov et al., 2001; Kovalenko et al., 2009).

The initial variant of the plate-tectonic theory assumed that the spreading zones represent the rising strands of the mantle convection and the subduction zones correspond to its sinking strands that are expressed at the depths up to ~650 km by the mantle seismic focal zones. Tracing of the subducted slabs down to ~900 km (Creager, Jordan, 1984) strengthened this view. The seismic tomography studies corroborate that some slabs continue to the lower mantle, but show that this is not universal rule (Grand et al., 1997; Van der Hilst et al., 1997). At the same time, it has become evident that the spreading zones can not directly correspond to the rising strands of the mantle convection. The surrounding of the African Plate clearly demonstrates this. Some segments of the spreading zones bounding the plate by the west and east are parallel to each other. Because the plate widens in time, a distance between the spreading zones increases. This means that one or both the spreading zones change their position relative to the upwelling strands of the convection. As a result, it was admitted that the zones of spreading and subduction correspond to the rising and sinking strands of the convection only in general.

Two other discrepancies with the initial plate-tectonic model were grounded by new geological data. They are the tectonic layering of the lithosphere and the diffuse plate boundaries. The Russian term of tectonic layering approximately corresponds to the English-language term of detachment tectonics, but includes also some tectonophysical effects of this phenomenon. The tectonic layering is the difference of stress and/or strain conditions in different layers of the lithosphere that leads to their detachment and movement relative to each other. Peive (1967) was the first who stated this idea. Developing it, he wrote: "The matter in different layers of the lithosphere moves laterally with different rates. If we consider that the asthenosphere is the main zone of tectonic flow, we can consider also the important role of relative lateral movements on the bottom of the crust and within it" (Peive, 1977, p. 7). Later the Russian scientists grounded this idea in detailed studies of paleotectonics and neotectonics in different regions (Tectonic layering…, 1990). Trifonov (1987) showed that the lower crust plays the same role for the upper crust in some regions that the asthenosphere plays for the lithosphere as a whole. Lobkovsky (1988) proposed the model of the two-level plate tectonics. According to it, the plate-tectonic mechanism works in the mobile belts more or less independently in the crustal and mantle levels.

The diffuse plate boundary within more or less wide belt is characteristic of the zones of subduction and collision (Gordon, 1998). The arc-type structural belt around the northern Pacific is shown in fig. 40. The northern and northwestern parts of this belt are characterized by subduction of the Pacific plate beneath the North-American and Eurasian plates (the Aleutian, Kurile-Kamchatka and Japanese arcs). The system of oceanic trenches in front of the island arcs is considered to be the boundary of the Pacific. However, there is uncertainty in location of the Eurasian–North American plate boundary within the backarc basin and the island arc. Some researchers outline the Okhotsk Sea lesser plate here. Other researchers include the Okhotsk Sea into the North American plate. Kozhurin (2004) showed that both these solutions contradict geological data. He argued that all the belt of deformation including the trench, island arc and backarc basin with surrounding structures is the diffuse plate boundary.

The diffuse character of plate boundaries is more evident in the regions of collision interaction of the plates, where structural records of the collision diffuse within the belts up to several hundreds of kilometers wide (Fig. 41). The belt consists of series of weakly deformed blocks (microplates) that are separated and bounded by zones of concentration of deformation. In the recent structure of the Himalayan-Tibetan segment of the Alpine-Himalayan Belt, such zones were identified in the

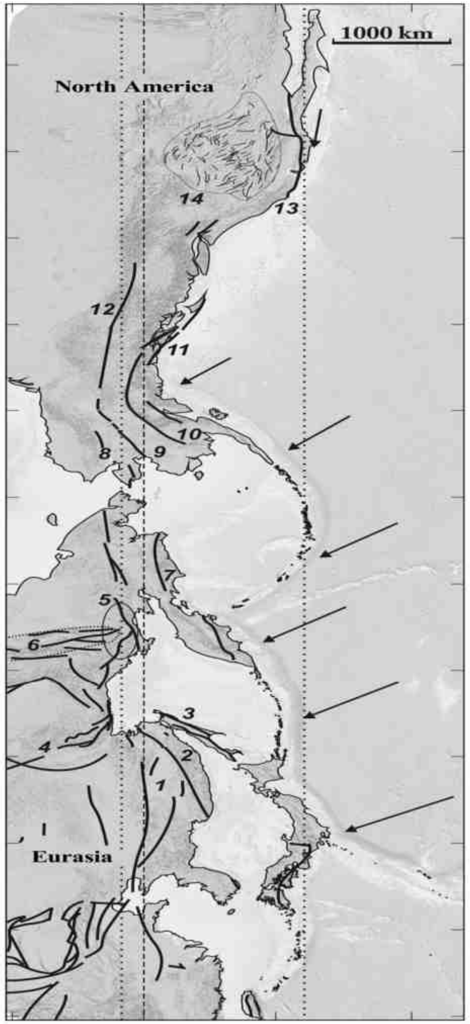

Fig. 40. The mobil belt of the northern surrounding of the Pacific, modified after (Kozhurin, 2004)

Points draw the belt boundaries. Dotted line corresponds to the major circle arc. Active mainly strike-slip faults are shown by solid lines. The main fault zones and systems: 1, Tanlu; 2, Central Sikhote-Alin; 3, East Sakhalin; 4, of the Stanovoy Highland; 5, Lankovo-Omolon; 6, Moma-Chersky; 7, Khatyrka-Vyven; 8, Kobuk; 9, Kaltag, 10, Totchunda; 11, Fairweather and Queen Charlotte Islands; 12, Denali; 13, San Andreas; 14, Basin and Range Province

southern flank of the Himalayas, in the boundary of the Southern and Central Tibet, the northern flank of Tibet and Qaidam (the Altyn Tagh Fault) and the southern flank of the Tien Shan (Fig. 1 & 31). The rate of the Late Quaternary movements on each of the zones mentioned above reaches ~1–1.5 cm/a (Trifonov et al., 2002), and it is impossible to give a preference to any of them as the boundary of Indian and Eurasian plates. The all belt became deformed as the diffuse boundary of these plates.

The aforecited geological peculiarities complicate the plate-tectonic theory and induce to refuse some postulates of its initial version, but do not change the sense of the theory. The main its principle that the structural manifestations of tectonic processes are the results of plate interaction remains immutable.

2.3.2. Tectonics of mantle flows

The data represented in this book give a possibility to propose the following model in the tectonic development of the Tethys Ocean and the Alpine-Himalayan Belt in the Mesozoic and Cenozoic. The main sources of tectonic processes were the sublithosphere upper mantle lateral flows that spread away from the Ethiopian-Afar superplume. In the

Mesozoic and Paleogene, the flows moved the oceanic lithosphere formed above the superplume, together with the torn off Gondwanan fragments towards the Eurasian Plate. The oceanic lithosphere subducted there and the Gondwanan fragments joined the Eurasia. A closure of the Tethys decelerated the convergence of the southern plates and Eurasia, but the upper mantle flows continued the former motion and spread beneath the all future orogenic belt. On moving, the flows were enriched in aqueous fluids that could derive from the former BMW lenses related to subduction zones. The asthenosphere activated by this way produced structural and mineral transformations in the uppermost mantle and the lower crust that resulted in decrease of their density and correspondingly intensive tectonic uplift and mountain building in the Pliocene–Quaternary.

Fig. 41. Mobil belts in Eurasia with diffuse plate boundaries (grey color): I, around the Pacific; II, Alpine-Himalayan; III, Altai-Stanovoy; IV, Moma-Chersky. The largest active faults are shown

Records of intensive Pliocene–Quaternary tectonic uplifts were found in other mountain belts of the World. The neotectonic development of the Gorny Altai forming the western part of the Altai-Stanovoy Belt (Fig. 41) demonstrates some features similar to the Tien Shan development. In the Chuya Basin of the Gorny Altai, the Lower Paleogene continental silty–clayey sequence up to 30 m thick is known (Zykin, Kazansky, 1995). The Oligocene and early Miocene are composed of lacustrine and swamp sand-shale sediments with interbeds of brown coal. The alluvial sandy–gravely–pebble sediments in the marginal parts of the basin provide evidence for origination of neighboring uplifts (Devyatkin, 1965; Zykin, Kazansky, 1995, 1996). From the Middle Miocene to the Early Pliocene, the lacustrine fine clastic sand-shale sediments were deposited in the center of the basin and they were replaced with coarser clastic alluvial–deltaic deposits varying from fine-grained sand to pebbles at the basin margins (Bogachkin, 1981). In the Upper Miocene, the content of coarse clastic deposits increases in the fill of the basin (Zykin, Kazansky, 1995, 1996). The accelerated uplift of Altai over the last ~3.5 Ma has been revealed from the fission track dating (De Grave et al., 2007). At the same time, the topography of the East Baikal region became more contrasting. The molasses in the Tunka, South Baikal, and other basins became coarser, owing not only to activation of rifting, but also to growth of high mountain ridges on the place of former low mountains.

The significant rise of mountain systems in the NE Asia occurred during the last several million years (Map of neotectonics of the USSR…, 1977). Ollier (2006) summarized the data on recent tectonic uplift in different mountain system of the World and reported the Pliocene–Quaternary and rarely the Upper Miocene–Quaternary age of the dominant uplift in the western North America (the Rocky Mountains, Coast Ranges, Cascades, and adjacent areas like Basins and Ranges and Colorado Plateau), the Andes, and the western surrounding of the South Pacific. The Pliocene–Quaternary tectonic rise, sometimes reaching and even exceeding 1 km occurred in the surrounding of the East African Rift System and in some territories of the African, Arabian and Siberian platforms (Artyushkov, 1993, 2003; Partridge, 1997; Artyushkov, Hofmann, 1998). These data show that the regularities, found in the Alpine-Himalayan Belt can be global. To estimate a possibility to apply the Alpine-Himalayan model to other regions of the World, let us discuss the data on the rising, lateral and sinking strands of the global mantle convection.

Morgan (1971) introduced the term of mantle plumes. He understood them as the streams of matter and heat upwelling from the lower mantle, burning through the lithosphere and manifesting in the land surface by volcanism (hot spots). This idea

was criticized (Hamilton, 2003; Sorokhtin, 2007). Sorokhtin (2007) considered that it is incompatible with the concept of mantle convection as the source of plate motion. Nevertheless, the idea of plumes as the sources of intraplate volcanism was recognized by geologists (Kovalenko et al., 2009).

The existing geochemical data do not contain records of magma formation deeper 700 km (Ivanov, 2011). This does not prove that the material can not come to the upper mantle and the Earth's crust from the larger depths and means only that, if it comes, it loses marks of the former depth because of rebuilding. Thus, the only source of information about the lower mantle flows is the data on seismic tomography. They have helped to find not only the Ethiopian-Afar, but several other superplumes rising from the lower mantle. The largest of them is the N-trending Pacific superplume dividing in the upper part into several strands (Fig. 30). It does not reach the lithosphere, being transformed to the upper mantle lateral flows. The eastern flow extends up to the East Pacific spreading zone. The smaller superplume is identified under the Islands of Green Cape westwards of Africa (Fig. 42). It is also transformed in the upper mantle to the lateral flow that extended to the west and reaches the Mid-Atlantic spreading zone.

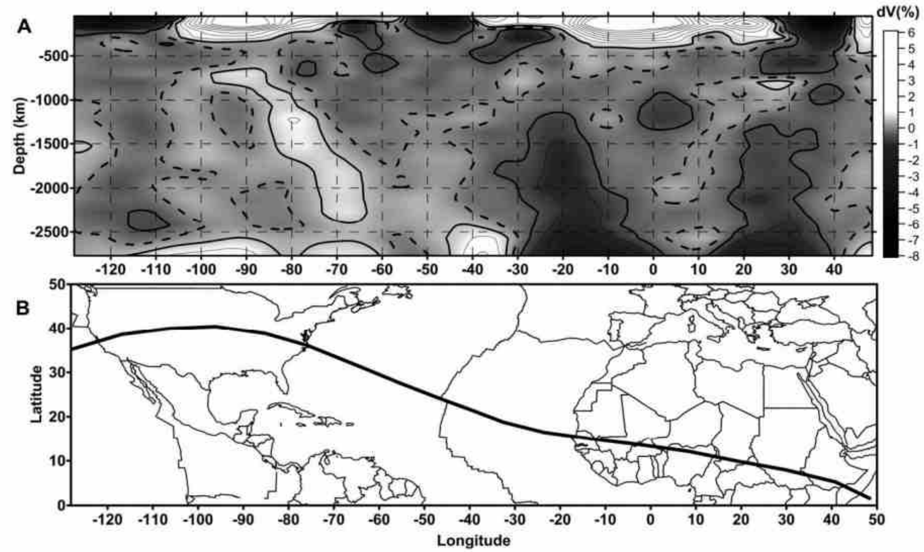

Fig. 42. Seismic tomography section (A) of dV_S through Central Africa, Atlantic Ocean and North America. The Ethiopian-Afar superplume is at the right part of the section. The plume under Cape Verde Islands is at the center; the sub-lateral flow in upper mantle propagates into Atlantic from it. The upper mantle flow beneath western part of North America propagating from Pacific superplume is at the left part of the section. The profile position is shown in (B). Compiled after the data in (Becker, Boschi, 2002; Grand et al., 1997). Contour lines are spaced at 0.5%; the dashed line corresponds to zero value

In Northern Atlantic, the similar superplume is dipped to the east and reaches the Earth's crust in the Icelandic region (Fig. 43). There have not been found some records of the through-mantle upwelling structures, except the superplumes mentioned above and several other that are expressed not so clearly in the lowered velocities of seismic waves. We consider that just the found superplumes correspond to the upwelling strands of the all-mantle convection.

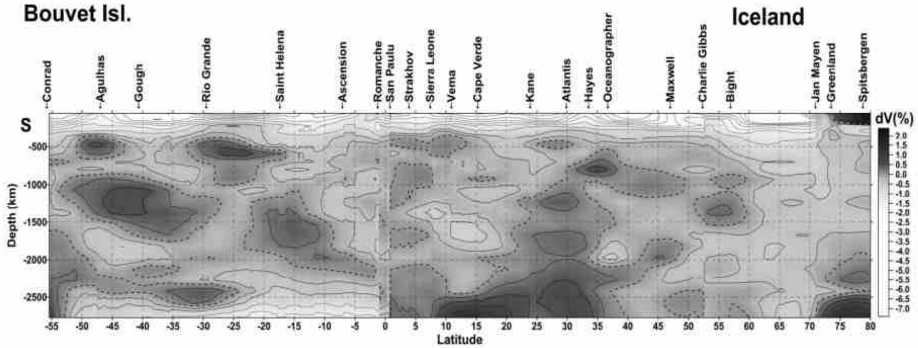

Fig. 43. Seismic tomography section of dV_S along Mid Atlantic Ridge (MAR). The Icelandic superplume is at the right part of the section. Other parts of MAR are featured by low-velocity lenses in the lower parts of lithosphere and the upper mantle. This low-velocity zone of MAR decays to the depths of 200–300 km. Compiled after the data in (Becker, Boschi, 2002; Grand et al., 1997). Contour lines are spaced at 0.5% (0.25% at values lower 1%); the dashed line corresponds to zero value

According to the seismic tomography data, the lateral upper mantle flows spread away from the superplumes. Because of viscous friction between the asthenosphere and the lithosphere, the flows move the lithosphere plates. A location of the spreading zone just above the superplume is rather an exception than a rule. Only the Icelandic superplume is identified in the profile along the Mid-Atlantic Ridge, while the "hot" areas under the other parts of the spreading system that are evident in the levels of the lithosphere and the uppermost asthenosphere, disappear at the depths lower than 200–300 km (Fig. 43). So, the spreading zones are not related exactly to the superplumes and their origin is due to the weakened zones in the heterogeneous lithosphere and to the extension of the lithosphere because of interactions of the sublithosphere flows. Formation of magmatic sources erupting the MORB in the spreading zones is the forced reaction to the uneven plate divergence and is caused by the adiabatic melting of the lithosphere and the uppermost sublithosphere mantle in the zones of the divergence concentration. So, these magmatic sources are not deep.

The majority of the studied subduction zones are completely or partly transformed into the sub-horizontal BMW. Their influence on tectonic processes can be different. The studies of BMW in the NE Asia led to the conclusion about the related upper mantle convection resulting in the mantle diapirism and intraplate volcanism (Dobretsov et al., 2001; Zhao et al., 2010; Ivanov, 2011). The convective movements of the upper mantle could produce the deformational thickening of the Earth's crust, which combined with decrease of its density by fluids from the BMW and resulted in recent uplift of mountains (Artyushkov, 2012). In the Alpine-Himalayan Belt, as it was shown in the chapter 2.2, the reworking of the fluid-enriched BMW by the upper mantle flows from the Ethiopian-Afar superplume activated the flows. Their influence decreased the density of the uppermost mantle and the lower crust that resulted in the acceleration of tectonic uplift and formation of high mountain systems. This process was the most effective in the Central Asian segment of the belt, where the lithosphere was significantly thickened by the collision deformation and enriched by relics of the former Tethyan oceanic lithosphere. In the Mediterranean part of the belt, the rise of mountain ridges combined with the subsidence of basins under influence of the mantle diapirism due to the activated upper-mantle flows. Some details in tectonics of the Alpine-Himalayan Belt can be also caused by the sublithosphere upper-mantle flows. They are the abnormal motion of the Anatolian Plate and the high volcanism in the Armenian Highland (see section 2.2.2) as well as the intracontinental mantle seismic focal zones like the Hindu Kush and Vrancea megafoci (see section 2.2.3).

Because the majority of subduction zones are transformed into the BMW, the sinking of the rest of subducted slabs into the lower mantle can hardly compensate the lithosphere accretion in the spreading zones. Probably, the sinking strands of the mantle convection are formed not only by the subducted slabs, but also by the delaminated and condensed by high metamorphism lithosphere fragments under the collision zones and old cratons. Volumes of rocks with weakly increased velocities of seismic waves under the collision zones and cratons below the transitional layer of the mantle justify a possibility of such deep subsidence (Fig. 27, 28, & 30).

Thus, we propose the global model of tectonics of mantle flows that includes completely the plate-tectonic theory and, at the same time, explains some geological phenomena that can not be satisfactory explained by the plate tectonics. According to this model, the plate moved by the upper mantle flows because of the viscous friction between them and the lithosphere. These lateral flows are parts of the all-mantle convection. Its upwelling strands correspond to the superplumes and the sinking strands are formed not only by a part of subducted slabs, but also by some delaminated dense fragments of the lithosphere under the collision zones and old cratons. The plate tectonics are the main, but not single results of the upper mantle flows. They produce also tectonic processes that are caused by phase and mineral transformations of the crustal and mantle rocks, by formation of the BMW and related potential enrichment of the transitional layer of the mantle in aqueous fluids. The Pliocene–Quaternary intensification of tectonic uplift producing the recent mountain building is one of these processes.

The global intensive tectonic uplifts and mountain building in the Late Cenozoic might be partly due to the closure of the Tethys Ocean. At all the stages of its development, its northern (in present-day coordinates) flank had subduction zones, which compensated for spreading. The Indian Ocean, which partly took up the role of the Tethys Ocean, had no such zones all the way from Cyprus to the Andaman arc. This changed the kinematics of sublithosphere flows and the global plate balance, thus causing large-scale tectonic uplifting.

Shultz (1948, 1979) distinguished the neotectonic epoch as the specific orogenic period (period of mountain building) in the Earth's tectonic evolution. Such periods that lasted 20–40 Myrs repeated several times during the Phanarozoic (Leonov, 1976, 1980; Shultz, 1979). They took place in the Late Vendian, Early Devonian and Early Permian and occupied the regions with different previous tectonic history, overlaying the regional expressions of plate interaction.

Conclusions

The neotectonic epoch, which is characterized by tectonic uplift producing mountain building in the Alpine-Himalayan Belt, has lasted from the Oligocene to Quaternary. Detailed studies in the Central Tien Shan, the Pamirs and the Greater Caucasus and their comparison with other mountain systems of the belt show that this epoch includes two main stages. During the first stage that lasted from Oligocene till the end of Miocene and even Pliocene in some regions, local uplifts formed. They were usually not higher than the middle-level mountains (< 1500 m) and formed under collision compression as a result of isostatic compensation of thickening of the Earth's crust in zones of concentrated deformation. Because of changes in direction of maximum compression at different sub-stages of the first stage, the local uplifts formed in different tectonic zones and, as a result, occupied large territories. During the second Pliocene–Quaternary stage, the height of the mountains increased 2–3 times. This intensification of tectonic uplift producing mountain building can not be explained by effects of the collision compression. The rates of transverse shortening decrease in some regions. Even in the regions, where they increase (the Himalayas, Pamirs, Tien Shan, and some others), the increased rates could yield 20–50% of the real uplift. The remainder was provided by isostatic compensation of the decrease in the density of the lower crust and the upper mantle under two effect of the asthenosphere, which was activated by fluids. First, the tectonically delaminated lithospheric mantle including the high-metamorphosed fragments of the lower crust was partly replaced by the lower-dense asthenosphere. Second, a part of the high-metamorphosed rocks in the lower crust and near the crust-mantle boundary underwent the retrograde metamorphism under the effect of cooled asthenosphere fluids.

The analyzed seismic tomography data demonstrated two important features of the mantle under the Alpine-Himalayan Belt. First, in the eastern (Indonesian) segment of the belt, where subduction has continued till now, the higher-velocity subducted slabs become approximately horizontal at the depths of about 400–700 km and these sub-horizontal lenses spread beneath the adjacent continental upper mantle. The same continuations of the subducted slabs (stagnant slabs, or big mantle wedges, BMW) are known in the North-Western Pacific. Second, in the more western mountain part of the Alpine-Himalayan Belt, sublithoshere low-velocity (hot and lower-dense) mantle flows are identified. They begin in the Ethiopian–Afar superplume rising from the lower mantle and spread beneath the orogenic belt.

We suppose that the elongated Ethiopian-Afar superplume developed as a more or less stationary structure at least from the end of the Paleozoic. The portions of moving Gondwana, which turned out to lie above the superplume, underwent rifting that developed into spreading that formed the Tethys Ocean. Flows of heated asthenosphere material from the superplume caused the moving of torn-off fragments of Gondwana to the north-east toward Eurasia. The oceanic Tethyan lithosphere subducted there, and the Gondwanan fragments accreted to Eurasia. As a result, series of microplates, separated by sutures, accretionary wedges, and magmatic bodies related to different stages of the Tethyan evolution, formed on the place of the future mountain belt. Probably, the mountain segments of the belt had previously the same structure as the south-eastern Indonesian segment, i.e., the subducted slabs transformed there at the depths of 400–700 km into the BMW that extended beneath the future mountain belt.

Closure of the Tethys and collision of the Eurasian and Gondwanan lithosphere plates decelerated their convergence, but the hot asthenosphere flows from the Ethiopian-Afar superplume probably prolonged the former movement and gradually spread under the entire orogenic belt. On moving, the sublithosphere flows were enriched in aqueous fluids that could derive from the former BMW lenses related to subduction zones. The asthenosphere, activated in this manner or its fluids penetrated into the lithosphere and produced its softening and detachment that facilitated deformational thickening of the Earth's crust and, correspondingly, the tectonic uplift in areas of maximum compression. During the first stage, it was the single or, at least, main source of the rise. During the second stage (the last 5–2 Ma), the deformational effect was supplemented by two other processes that were initiated by the sublithosphere flows and their fluids. The first process was the partial replacing of the lithosphere mantle by the lower-dense asthenosphere material and, as a result, decrease of density of the uppermost mantle. The second process was the retrograde metamorphism and, correspondingly, decrease of density of metamorphosed rocks of the crustal origin within the lower crust and near the crust-mantle boundary with participation of the asthenosphere fluids. The both processes produced additional rise of the land surface and caused the acceleration of total uplift of the belt during the Pliocene–Quaternary.

The determining role in this model of the Alpine-Himalayan Belt evolution belongs to the sublithosphere upper mantle flows that spread away from the Ethiopian-Afar superplume. We have analyzed the neotectonic and seismic tomography data on other territories and have found similar features. Some other

orogenic belts, as the Altai-Stanovoy Belt, North-East Asia, the western North America and the western South America demonstrate acceleration of tectonic uplift in the Pliocene–Quaternary. Several superplumes and upper mantle flows, which spread away from them, were found by the analysis of seismic tomography data.

Basing on the data represented above, we propose the global model of tectonics of mantle flows. Lithosphere plates move by the sublithosphere upper mantle flows because of viscous friction in the lithosphere-asthenosphere boundary. The flows spread away from the superplumes that represent the upwelling strands of the mantle convection. As a rule, zones of the lithosphere spreading do not correspond to the superplumes. The MORB volcanism does not related to the superplumes and is a result of adiabatic melting of the uppermost asthenosphere and the lithosphere due to the extension. Because majority of the subducted slabs transforms into the BMW in the depths about 400–700 km, only a part of the subducted material penetrates into the lower mantle and is not enough to compensate a grow of the lithosphere in the spreading zones. The sinking strands of the mantle convection are represented not only by such material, but also by volumes of dense and depleted upper mantle as well as high-metamorphosed basic rocks beneath cratons and collision zones. The plate tectonic mechanism is not the only result of the upper mantle flows. It is supplemented by tectonic processes that are caused by phase and mineral transformations of the mantle and lower crustal rocks, by formation of the BMW and their fluid potential. The tectonic uplift producing mountain building is one of such processes.

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