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VRANCEA AND HINDU KUSH AREAS OF MANTLE EARTHQUAKES: COMPARATIVE TECTONIC ANALYSIS

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Abstract: The Late Cenozoic tectonics in the Eastern Carpathians and the Pamir-Hindu Kush region are compared to ascertain structural position and origin of strong mantle earthquakes in the Vrancea and Hundu Kush megasources. Intensive Oligocene–Quaternary deformation took place in the Pamir-Hindu Kush region. Under compressive regime, large upper crust blocks were detached and displaced up to several hundred kilometers. Relics of the oceanic crust of the Precambrian, Hercynian Paleo-Tethys and Early Meso-Tethys were overthrusted by the upper crust blocks and subsided to the depth of 40–70 km, where they were metamorphosed into higher density metabasites of the granulite-eclogite type. In the Pliocene–Quaternary, the region was quickly elevated, mainly because of decrease of density of the upper mantle. As a result, the detached dense metabasite slab began to move down to the depths of 270–300 km. The same processes took place in the Vrancea area. The basic rocks of the Inner Carpathian zones were moved and underthrusted the Moesian Platform with simultaneous overthrusting by the Outer Carpathian zone. Under the load of the Outer zone nappes and the Focsani basin sediments, the basic rocks were metamorphosed into the dense metabasite slab. After decrease of the upper mantle density because of asthenospheric convection beneath the Carpathians, the slab began to move downwards. Destruction of the moving slabs produced the mantle earthquakes.

Keywords: mantle earthquakes, metabasites, change of rock density.

1. Introduction

To study mantle seismicity in the Alpine-Himalayan orogenic belt, the authors extracted from the catalogs (Karnik 1968; Shebalin et al. 1974; Kondorskaya and Shebalin 1982; Moinfar et al. 1994; Papazachos and Papazachou 1997; Kondorskaya and Ulomov 1999; Trifonov and Karakhanian 2004; National Earthquake Information Center 2007) and merged parameters from earthquakes between 1850–2007 with magnitudes Ms$\geq$5.0 and focal depths $\geq$40 km ($\geq$50 km in areas with high topograhic felief and the thickened Earth's crust). Overwhelming majority of such earthquakes is concentrated along the Hellenic and Cyprus arcs, Aegean region, Zagros, Middle Caspian, Vrancea megasource of the Carpathians and Hindu Kush megasource of the Pamir-Hindu Kush zone (Fig. 1). The Hellenic and Cyprus seismicity is related to active subduction. Seismicity in the other areas does not demonstrate association with such processes. The Vrancea and Hindu Kush megasources are the most active among them. Comparative analysis of the megasource tectonics is carried out in the paper.

2. Hindu Kush megasource

In the Pamir–Hindu Kush area, the epicenters of mantle earthquakes follow a convex distribution, extending from the Western Hindu Kush margin up to the eastern margins of the Pamirs and Kara-

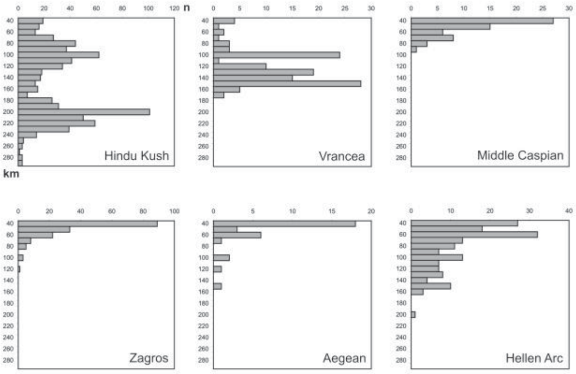

Fig. 1. Histograms of the number (n) of earthquakes with Ms$\geq$5 in different depths (km) of the mantle seismic focal zones.

korum (Fig. 2). 90% of the mantle earthquakes and 95% of the released seismic energy are concentrated within the Hindu Kush megasource that is an 1.5x1.5º area in the Western Hindu Kush. In this area, the hypocenters reach depths of ~270 km and rarely 300 km, while to the east, the maximum hypocenter depths decrease to 200km and earthquakes with Ms≥5.7 are absent deeper than 150km.

Some researchers associate this seismic activity with recent subduction processes. Vinnik et al. (1977), Tapponnier et al. (1981) and Burtman and Molnar (1993) based their models on the fact that the hypocentral area dips to the north in the western part of the Pamir–Hindu Kush zone (the Hindu Kush megasource) and to the south in its eastern part. So, they proposed the northern subduction of the Indian plate beneath the Hercynian Northern Pamir–Western Hindu Kush zone in the west and the southern subduction of the Afghano-Tadjik basin basement beneath the Pamirs in the east. Negredo et al. (2007) assumed that west India continued moving north after the early collision, reached Hindu Kush in ~8 Ma and began to subduct beneath it. They represented results of the numerical modeling of slab subsidence.

The subduction models meet the following objections (Ivanova and Trifonov, 2005). First, they do not explain why the subduction of the Indian plate takes place only in the northwestern flank of this indentor (Hindu Kush), but not in front of it (Pamirs), and why the subduction of the Afghano-Tadjik basin is absent just to the south of it and

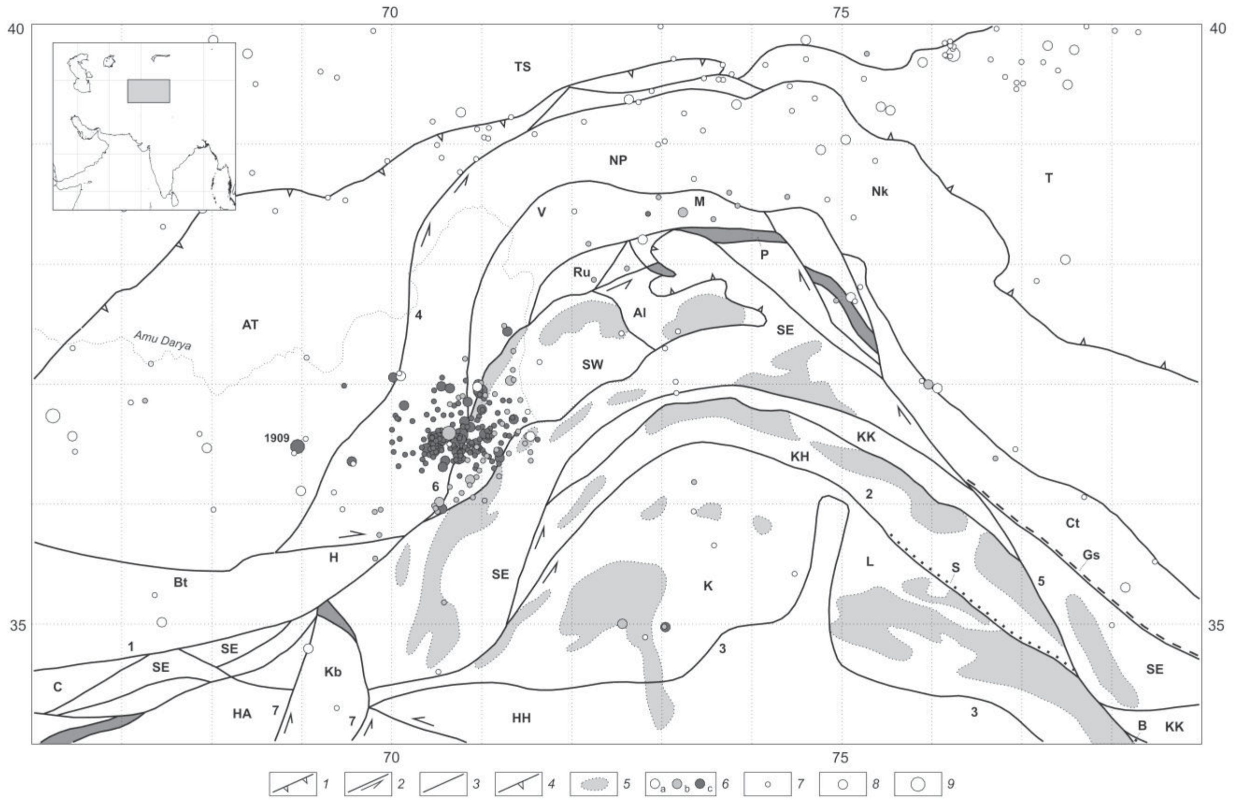

Fig. 2. Tectonic zones, granites and epicenters of earthquakes with *Ms*≥5.7 in the Pamir-Hindu Kush-Karakorum region, after (Ivanova, Trifonov, 2005) with changes. *1* – nappes and thrusts; *2* – strike-slip faults; *3* – other major faults; *4* – boundaries of basins; *5* – granite batholiths, continued to develop in Miocene; *6* – epicenters of earthquakes with depths of hypocenters h≤70 km (a), 70>h>150 km (b) and h≥150 km (c); *7–9* – magnitudes of earthquakes: *7* – *Ms* =5.7–6.5; *8* – *Ms* =6.6–7.4; *9* – *Ms* =7.5–8.3. TS – Tien Shan; AT – Afghano-Tadjik basin; T – Tarim basin; NP – Northern Pamir and its continuations (Bt, H, Nk); Al, V, Kb, M, Ru, C, Ct – zones of the Central Pamir type, including SW – South-Western Pamir and Badakhshan; P – Pshart suture and its continuations, shown as grey; Gs – supposed continuation of the Pshart suture in Tibet; SE – South-Eastern Pamir–Nuristan and its continuations in Tibet and Afghanistan; KK – Northern Karakorum and its continuation in Tibet; HA – Hilmend-Argandab block; KH – Southern Karakorum and Eastern Hindu Kush; S – Shiok suture; B – Bangun suture; K – Kohistan; L – Ladakh; HH – Hazar block of the Himalayas. 1 – Herat (Main Herirud) fault, 2 – Main Karakorum thrust, 3 – Main Mantle thrust, 4 – Darvaz reverse-sinistral fault, 5 – Pamir-Karakorum dextral fault, 6 – Central Pamir fault, 7 – Chaman sinistral fault.

takes place in the east, where the basin is reduced. Second, the detailed location of hypocenters of earthquakes with magnitudes Ms≥5.7 within the Hindu Kush megasource showed that the hypocentral area is almost vertical, thus dips neither to the north nor to the northwest (Ivanova and Trifonov 2005, fig. 5). Third, the Indian plate could not reach Hindu Kush in the Late Cenozoic, because by that time there already existed the lithosphere slab along the Main Karakorum thrust. Thus, the subduction models do not correspond to the geological and seismological data.

In Oligocene–Miocene, the upper crust tectonic zones of the Pamir arc were detached and displaced laterally, therefore the arc curvature increased because of lateral shortening (Ivanova and Trifonov 2005). The Archaean granite-gneiss block of the South-Western Pamir and Badakhshan was primarily a part of the continental crust of the Central Pamir zone, which was situated above the Early Meso-Tethys subduction zone between suboceanic basin in the south and volcanic arc, formed on the Hercynian Northern Pamir and Western Hindu Kush. Relics of the basin are represented by the Pshart suture and are manifested in the seismic cross-section of the adjacent Vanch-Yasgulem part of the Central Pamir by the ~15-km thick layer of the high-velocity “crust-mantle mixture” (Khamrabaev, 1980). Until the end of Miocene, the Archaean block was displaced to the east, at minimum, 150 km. A major part of the oceanic crust beneath the former position of the Archaean block was overthrusted by the Hercynian zone. This oceanic crust (slab) could be supplemented by relics of the Hercynian and Archaean oceanic basites, converged with the slab contributing to the Cenozoic orogenesis. Analogous rocks to the Hercynian basites are exposed in the Northern Pamir sutures and analogs to the Archaean ones are represented by amphibole gneisses and garnet amphibolites with eclogite boudines in the allochtone units of the South-Western Pamir.

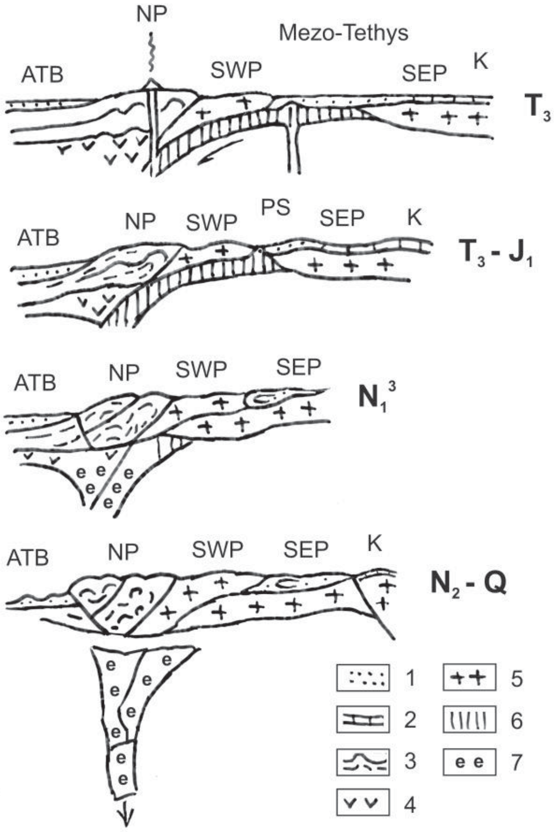

Fig. 3. Schemes of development of the Pamirs crust: (T_3) Late Triassic till Norian, (T_3–J_1) end of Triassic and Early Jurassic, (N_1^3) Late Miocene, and (N_2–Q) Pliocene–Quaternary, and formation of the Hindu Kush megasource of mantle earthquakes. 1–sedimentary cover; 2–platform carbonates; 3–Paleozoic continental crust; 4–Paleozoic oceanic crust; 5–continental crust of the Central and Southern Pamirs; 6–Mesozoic oceanic crust; 7–metabasites. ATB–Afghano-Tadjik basin, NP–Northern Pamir, SWP–South-Western Pamir, PS–Pshart suture, SEP–South-Eastern Pamir, K – Karakorum.

According to seismic profiling data, the 25-km thick Archaean block overthrusted the South-Eastern Pamir zone. As a result, the total thickness of the South-Western Pamir crust reached 60 km (Kuhtikov 1981). The thickness of the Northern Pamir and Western Hindu Kush crust is similar (Khamrabaev, 1980). Covered by the continental crust, relics of the oceanic crust were subsided down to 50–70-km depths, where they could be metamorphosed into garnet granulites and eclogites, similar with the mantle in term of their density. Studies of the Late Cenozoic magmatic rocks showed abundance of eclogite xenoliths (Kuhtikov, 1981). Velocities of the longitudinal waves are increased to 0.3–0.4 km/s in the Hindu Kush megasource and are decreased to 0.1–0.2 km/s in the surrounding mantle with respect to average ones for the Globe (Vinnik et al., 1977). The seismic focal zone is probably enriched with the dense metabasites that began to move downwards after decrease of upper mantle density in Pliocene–Quaternary and produced the mantle earthquakes (Fig. 3).

3. Vrancea megasource

113 mantle earthquakes have been registered in the Vrancea area since 1862. Except two the earliest

events that are possibly inaccurately located, all earthquakes occurred in the area 45.2–45.9º N / 26.2–27.3º E. Hence, in the first approximation, the seismic focal volume has a form of the vertical column with diameter ~80 km and depth up to 170 km. The epicentral area is situated in the junction of the eastern and southern segments of the Carpathian arc, in its Outer zone and the Focsani basin of the Foredeep (Fig. 4). The Outer zone is the accretion prism of the Mesozoic and Paleogene flysh that was detached and overthrusted onto the shallow-water Middle Miocene deposits of the Focsani basin at the end of the Middle Miocene and the beginning of the Late Miocene (Artyushkov et al., 1996). The basin had begun to sink earlier and 3 km of deposits had been accumulated there before the main thrusting. Thickness of the thrusted complex is 8–12 km and could reach primarily 10–14 km, when later erosion is taken into account. However, according to the quoted authors, this increase of the sedimentary layer thickness did not produce an isostatic uplift of the topographic relief that could reach 1.5–2.4 km according to the calculations and it remained at ~0.5 km. Thus, the 1–2-km uplift was compensated by densification at depth. The 9-km thick Neogene–Quaternary sedimentary cover was accumulated in the Focsani basin to the southeast of the Outer zone; it was deformed and thrusted in front of it (Sandulescu, 1984; Artyushkov et al., 1996).

The Focsani basin covers the Precambrian Moesian platform (Sandulescu 1984). The Intramoesian and Peceneaga-Camena faults strike correspondingly along the south-western and north-eastern basin flanks. The latter fault is a thrust that dips to the SW and separates the Moesian and epipaleozoic Scythian platforms (Sandulescu, 1984). The narrow North Dobrudja Cimmerian orogenic zone follows along the northeastern side of the fault. The zone is formed by a system of nappes, thrusted onto the Scythian platform. Two nappe units with the Triassic basites between them are differentiated (Khain, 2001). In recent structure, the North Dobrudja zone is associated with the Peceneaga-Camena thrust and possibly converge along it at depth with the Vrancea megasource.

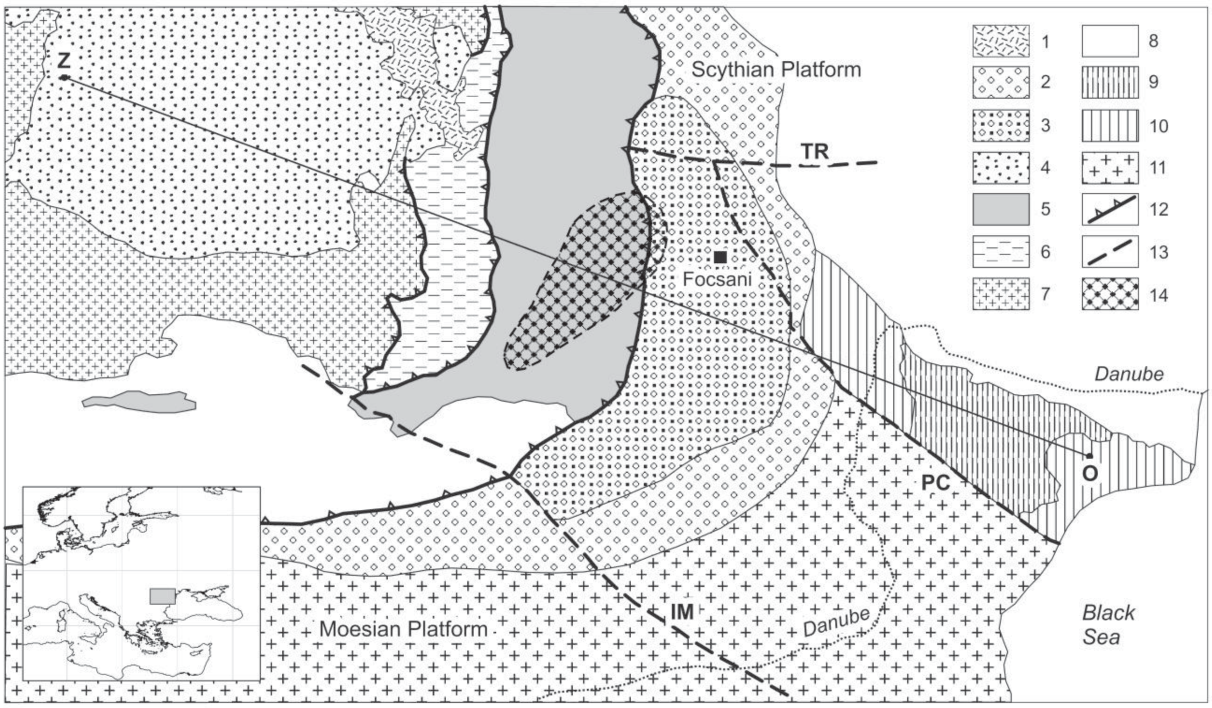

Fig. 4. Tectonics of the Carpathians around the Vrancea area (after Hauser et al., 2007, modified). 1–Neogene–Quaternary volcanic rocks; 2–Neogene–Quaternary sediments of the Foredeep; 3–Focsani basin; 4–Neogene sediments of the Transylvanian basin; 5–nappes of the Outer zone (Moldavides); 6–Outer Dacide nappes with the Cretaceous posttectonic cover; 7–Median Dacide and Transylvanide nappes with the Cretaceous posttectonic cover; 8–Carpathian tectonic zones under the Pliocene–Quaternary sedimentary cover; 9–Cimmerian orogen of the Northern Dobrudja, exposed or under thin sediments; 10–the same orogen under thick sediments; 11–sedimentary cover of the Moesian Platform; 12–main thrusts; 13–faults: IM–Intramoesian, PC–Peceneaga-Camena, TR–Trotus; 14–Vrancea epicenter area. ZO–seismic profile line.

In the seismic profile O–Z, the Moho surface is situated at 35–40 km depth beneath the inner Carpathian zones, 45–47 km beneath the Outer zone and the Focsani basin and ~44 km beneath the Moesian Platform (Hauser et al., 2007). Similar changes are seen northernmore, in the seismic profile across the Ukrainian Carpathians, where the crustal thickness reaches ~60 km beneath the Outer zone and the foredeep (Chekunov, 1993). At the lower crust, a layer at depths ~40–60 km exhibits longitudinal waves velocity 7.4–7.6 km/s. Along the profile O–Z, the longitudinal wave velocity is 7.0–7.1 km/s within the lowest crust. Probably, the high-velocity layer of the Ukrainian profile can not be distinguished there from the upper mantle.

According to Artyushkov et al. (1996), the high-velocity layer in the lowest crust manifests the metamorphic densification of basites that kept a surface of the Focsani basin in the low level after its filling by the Outer zone nappes and the Neogene–Quaternary sediments. The basites probably migrated from the inner Carpathians, where ophiolites are exposed in several zones. Their underthrusting resulted the detachment of the lower crust and took place simultaneously with overthrusting of the Outer zone.

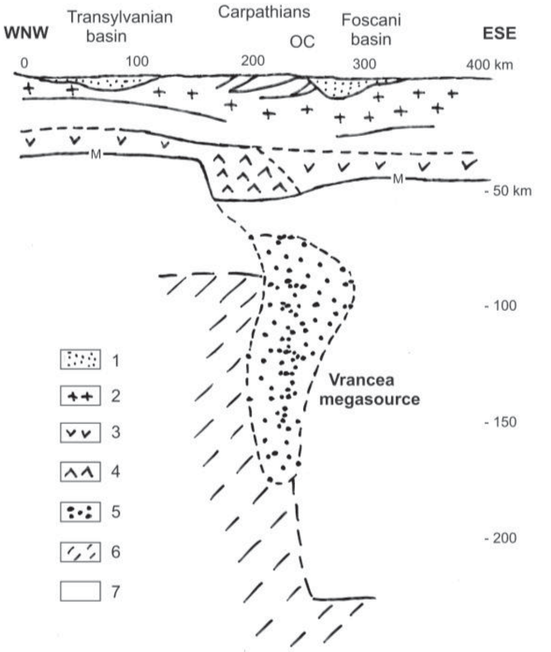

Fig. 5. Scheme of the Vrancea megasource formation (after Artyushkov et al., 1996; Hauser et al., 2007, modified). 1-sedimentary cover; 2-Upper crust; 3-Lower crust; 4-Lower crust layer, enriched by dense metabasites; 5-slab of dense metabasites (zone of mantle earthquake; their hypocenters are shown); 6-astenosphere; 7-lithosphere mantle. OC-the Outer Carpathians.

We assume that the metabasites were not restricted in the lower crust, but forming a slab they subducted into the lithospheric mantle. They were possibly supplemented by the basic rocks of the North Dobrudja, underthrusted along the Peceneaga-Camena fault zone. In the upper mantle level, the basites were moreover metamorphosed to garnet granulites and eclogites, reaching the density of lithospheric mantle rocks. After the later elevation of the asthenosphere under the Carpathians up to ~80 km depth, 120–170 km higher when compared to the adjacent platform (Artyushkov et al., 1996), the slab was at the boundary of the mantle area characterized by the decreased densities and began to move downwards, producing the mantle earthquakes (Fig. 5).

4. Conclusions

In both areas under discussion, the mantle earthquake sources are related to metabasites associated with the paleooceanic crust. Decrease of the upper mantle density in the Pliocene–Quaternary initiated motion of the dense and relatively cold metabasite slabs downwards. Because of this motion seismic stress increased and phase transformations of the slab rocks took place, like deserpentinization and (in the larger depths) eclogitization and transition of quartz into coesite and possibly stishovite. The seismic displacements were caused by decrease of strength of rocks in milonite zones rather than increase of stress (Rodkin et al., 2009). The decrease of strength was intensified by fluids that were produced by dehydration of serpentine and amphiboles and possibly were evolved by the asthenosphere.

Like the other areas of the mantle seismicity within the orogenic belt, the Vrancea and Hindu Kush areas are situated in structures, formed in the former northern margin of the Tethys. It demonstrates signs of the successive joining of more or less large fragments of Gondwana and the Eurasian plates and corresponding migration of subduction zones to the southern sides of the joining fragments. These signs are represented by sutures, obducted oceanic rocks and volcanic arc formations of different stages of the Paleo-, Meso- and Neo-Tethys and indicate presence of the paleooceanic slabs within the recent lithosphere. In Oligocene and Miocene, intensive tectonic deformation and displacement of large volumes of the Earth's crust were associated with magmatic and metamorphic processes. They consolidated the Earth's crust until Pliocene. Under this cover, the active asthenosphere replaced partly the lithosphere mantle and provoked the retro-metamorphism of the paleooceanic metabasites. These processes caused the intensive Pliocene-Quaternary uplift of mountains.

Therefore, motion of the lithospheric slabs down and intensive rise of mountains took place simultaneously. Their common source was the decrease of the upper mantle density, caused by influence of the asthenosphere. However, formation of mountains occupied the larger territories of the Alpine-Himalayan belt, than the mantle earthquakes. Obviously, there were some local geodynamic factors, controlled the mantle seismicity. They could be: firstly, big primary volume of a slab, causing preservation of its properties for a long time; secondly, presence of a major trans-lithosphere fault zone, controlling mechanically weakened zones of seismic displacement within the slab. These large zones are the Chaman-Darvaz reverse-sinistral fault zone in the Hindu Kush area (Ivanova and Trifonov, 2005) and the boundary zone between the Carpathians and the Moesian plate in the Vrancea area (Sandulescu, 1984).

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