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Features of Caucasian Segment of the Alpine-Himalayan Convergence Zone: Geological, Volcanological, Neotectonical, and Geophysical Data

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1. Introduction

The Caucasus Mountain System (Fig. 1) is the part of the largest Alpine-Himalayan collision zone, stretching out for 16,000 kilometers across Eurasia from the Western Mediterranean to the Western Pacific. In geological terms, it is represented by huge area of the Trans-Eurasian Belt (TEB) of Late Cenozoic activation, which was formed after the closure of the Mesozoic-Early Cenozoic ocean Neotetis (Sharkov, 2011). TEB is characterized by powerful modern processes of mountain building, appearance of rift structures, numerous intraplate basaltic lava plateaus and chains of intracontinental andesite-latite volcanic arcs that trace suture zone of continental plates collision. In that both types of magmatism developed almost simultaneously with each other and with the tectonic processes of the entire length of the belt. Large amagmatic blocks (North-Eurasian and Indian) are located on its both sides.

Despite of long-standing geological and geophysical investigations, the Caucasus is still insufficiently studied region, especially in terms of interrelation of its deep-seated structure with neotectonics and manifestations of late Cenozoic volcanism. However, numerous diverse data obtained during the recent years, allow us to consider this region as a testing place for a comprehensive study of modern geodynamic and petrologic processes in zone of continental plates collision.

The aim of this chapter is synthesis of geological, petrological and geophysical information about the deep-seated processes in the Caucasian parts of the collision zone and their expression in the geological processes in the crust.

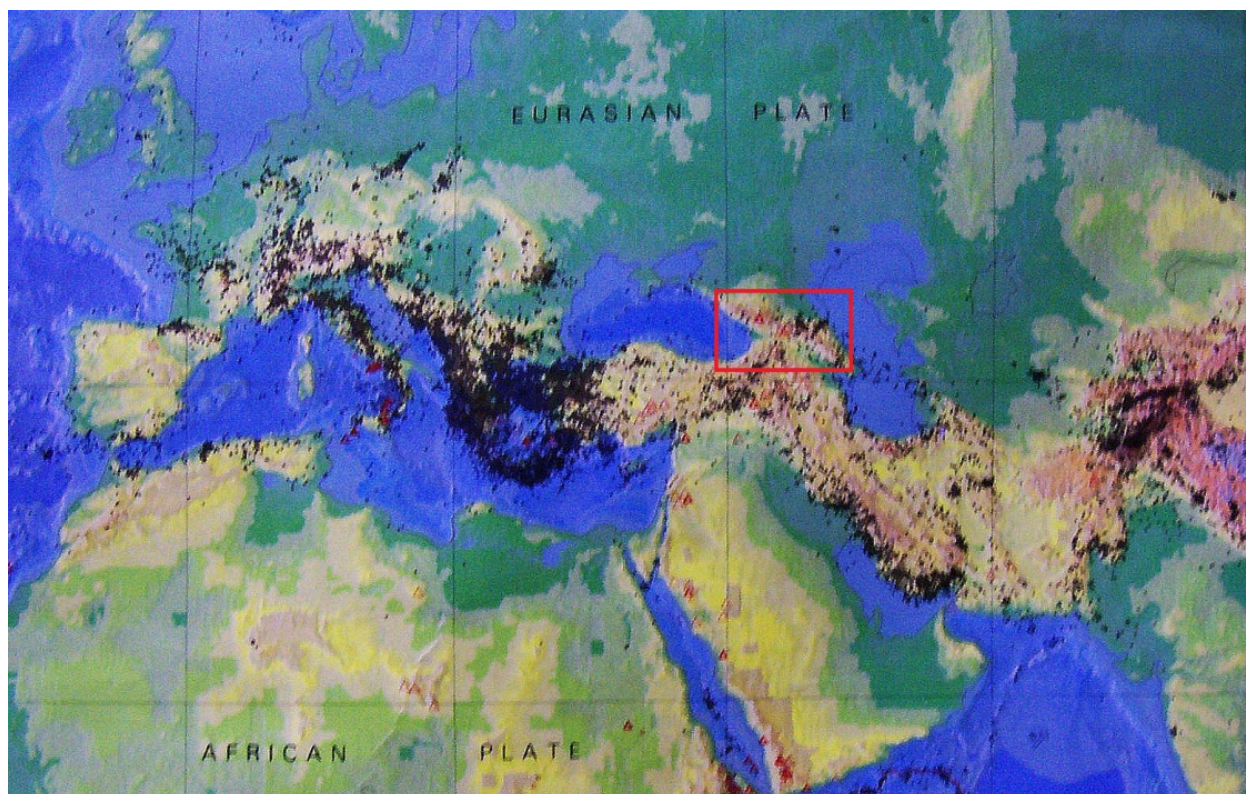


Figure 1. Location of the Caucasus Mountain System in World map of volcanoes, earthquakes and plate tectonics (World map of volcanoes, earthquakes and plate tectonics; Compiled by T. Simkin, R.L. Till- ing, J.N. Taggart, W.J. Jones and H. Spall. Smithsonian Institution and US Geological Survey, 1989).

2. Alpine-Caucasian part of the convergence zone

The most complicated structure within of the Trans-Eurasian Belt of the late Cenozoic activization has Alpine-Caucasian segment, where systems of andesite-latite volcanic arcs and back-arc basins (Alboran, Tyrrhenian, and Aegean seas as well as Pannonian depression) occur (Fig. 2). Despite the differences in the morphology of these structures, they have several common features. Along their periphery developed fold-thrust zone, a kind of "accretionary prism" that form the ridges of the Alps, Carpathians, Apennines, Gibraltar arc, etc. Among tectonic slices are often observed deep-water sedimentary rocks of the Tethys, ophiolite complexes, and sometimes blocks of the lower crust and upper mantle rocks like Ivrea-Verbano, Ronda, Beni Bousera and others (Magmatic ..., 1988).

In the rear of these structures, repeating their configuration, andesite-latite volcanic arc of three types occur: (i) island (Aegean), (ii) "semicontinental", located partly on the continent and in part - directly adjacent to it (Alboranian, South-Italian, etc.), and (iii) "intracontinental" (Carpathian, Anatolian-Caucasian-Elburssian, etc.). Behind these arcs newly-formed depressions occur with thinned at the expense of lower high-velocity layers (Gize, Pavlenkova, 1988) crust of intermediate or even oceanic type, within which basaltic volcanism develops. Oceanic crust in the Western Mediterranean has evolved in the Late Cenozoic due

to continental crust the African plate (Ricou et al., 1986; Ziegler et al., 2006) as a result of back-arc spreading (Sharkov, Svalova, 2011).



Figure 2. Distribution of the late Cenozoic igneous rocks within the Alpine Belt

1 – back-arc seas (A – Alboran, T – Tyrrhenian; Ae – Aegian) and “downfall” seas (B – Black, C – Caspian);
2 – back-arc sedimentary basins (P – Pannonian, Po – Po valley); 3 – late Cenozoic andesite-latite volcanic arcs (in circles): 1 – Alboran, 2 – Cabil-Tell, 3 – Sardinian, 4 – South-Italian, 5 – Drava-Insubrian, 6 – Evganey, 7 – Carpatian, 8 – Balkanian, 9 – Aegian, 10 – 12 – Anatolian-Caucasian-Elburssian (10 – Anatolia-Caucasian, 11 – zone of the Modern Caucasus volcanism, 12 – Caucasus-Elburssian);
4 – areas of flood basaltic volcanism (in square): 1 – South Spain and Portugal, 2 – Atlas, 3 – Eastern Spain, 4 – Central France massif, 5 – Rhine graben, 6 – Czech-Silesian, 7 – Pannonian, 8 – Western Turkey, 10 – northern Arabia; 5 – suture zones of major thrust structures

According to geophysical data, lithosphere of the Alpine Belt has very complicated structure and rather different beneath ridges and basins (Hearn, 1999; Artemieva et al., 2006, Kissling et al., 2006). M. Artemiev (1971) firstly showed that two types of basins exist here (Fig. 3). The first type (Tyrrhenian, Aegian, and Alboran seas as well as Pannonian depression) is characterized by large positive isostatic anomalies, which evidence about excess of mass beneath them, and presence of basaltic volcanism. Very likely, they represent occurrence of the present-day extended mantle plume heads, which continues to receive fresh material resulting in onwads displacement of volcanic arcs in time. Judging by the magnitude of the anomalies, the most intense it arrives in the areas beneath the youngest back-arc sea of the Mediterranean - Aegean, as well as under the Pannonian basin.

Propagation of the plume heads, judging on geological data, had diversy-oriented character - under the Carpathians material moved to the east (Royden, 1989; Harangi et al., 2006), under the Tyrrhenian Sea - in the south-east (Rehault et al., 1987; Harangi et al., 2006), under the Aegean Sea - to the south (Harangi et al., 2006), under the Alboranian Sea – to west (Lonengran, White, 1997). At that crustal material above extended plume heads was trans-

ported to their front, where involved into descending mantle flows with the formation of subduction zones with the corresponding magmatism; back-arc basins with transitional and oceanic crust were formed in their rear (Bogatikov et al, 2009).

Simultaneously with formation of depressions in the collision zone rift systems formed and basaltic volcanism develops, represented mainly Fe-Ti subalkaline basalts typical for intraplate (plume) magmatism (rifts in Central and Western Europe, Atlas, basalt plateaus of North Africa and Western Arabia, etc.), emerging in front of the mountain ranges (Grachev, 2003; Wilson, Downes, 2006). Based on isotopic and geochemical data, this anorogenic Circum-Mediterranean magmatism has a common source - the so-called Common Mantle Reservoir (Common Mantle Reservoir, Hofmann, 1997; Lustrino, Wilson, 2007). This obviously indicates presence of the modern mantle superplume beneath the whole region; Alpine orogen with its complex system of ridges and basins located over the central part of this superplume. It is in a good agreement with geophysical data: according to (Hearn, 1999; Smewing et al., 1991, etc.), these plumes are merged into a single asthenospheric uplift at a depth of 200-250 km.

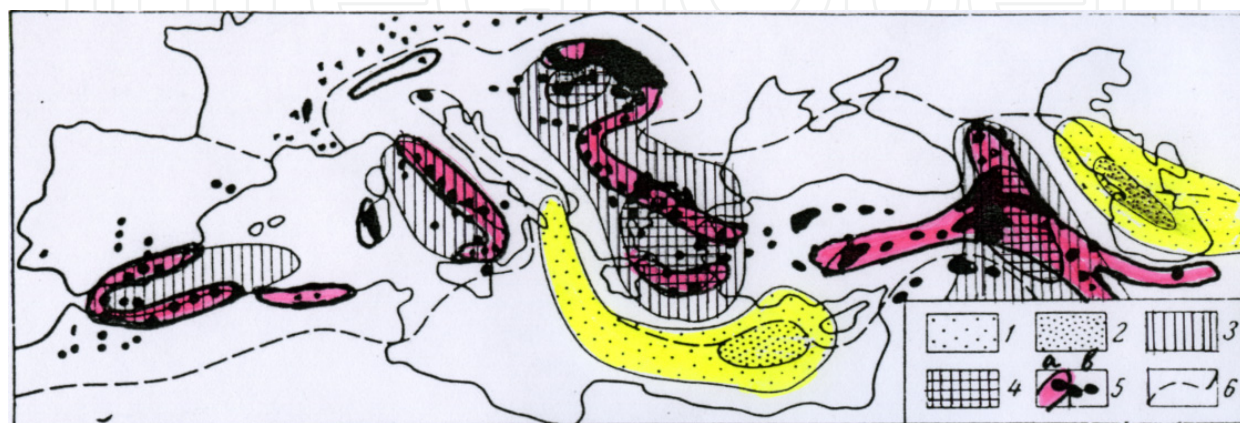
The second type of depressions presented by the Eastern Mediterranean, including the Ionian Sea, and the Black and Caspian seas. In contrast to the aforementioned first type of depressions, there are large isostatic minimums occurred beneath them, indicating a deficit of mass, probably due to the downward currents in the mantle ("cold plumes") between extended heads of "hot" plumes. For these seas are typical passive margins, thick (up to 16-20 km) covers of Meso-Cenozoic sediments and oceanic crust; magmatic activity absent in connection with them. One of the main minima located in the eastern Mediterranean (Levantine basin), where approximately 3-3.5 Ma rapid subsidence area below sea level occurred (Emels et al., 1995). Substantial isostatic anomalies are absent in connection with the Black Sea, which, probably, indicates a reduced rate of downward movement.

Basins of the Black and Caspian seas look like a large "downfalls" which cutoff pre-Pliocene structures of the Caucasus and the Kopetdag. The formation of these seas began, apparently, in the early Cretaceous, but a significant deepening of the basins occurred in the late Oligocene-early Miocene, and in Miocene gradual shallowing of the basins took place (Zonenshain, Le Pichon, 1986). New deepening of the Black Sea and South Caspian basins occurred in Pliocene-Quaternary, which happened almost simultaneously with the uplift of the Caucasus and the Crimea, which in the Oligocene-early Miocene were not expressed in the relief (Grachev, 2000).

Judging on geophysical data, along the sides of "downfall" basins (for example, under the northern parts of the Black Sea and Eastern Mediterranean), steeply-dipping seismically active zones occur, which stretching in the mantle to depths of 60-70 km (Zverev, 2002; Shempelev et al, 2001).

An exception to the general rule, a large positive isostatic anomaly is, situated beneath the Trans-Caucasian Transverse Uplift on the Great and Lesser Caucasus (see Fig. 3). It is located between the "downfalls" of the Black and Caspian Seas, and continues to south to eastern Anatolia and north of the Arabian Peninsula. Obviously, this anomaly is also

associated with ascending of a mantle plume. There is no depression here, but the front of the Anatolian-Caucasian-Elburssian andesite-latite arc shifted sharply to the north, forming a zone of young volcanism of the Caucasus.



1 - regional lows of average intensity; 2 - of high intensity; 3 - regional highs of average intensity; 4 - intense;
5 - volcanic rocks: a - calc-alkaline series, b - basalt series; 6 – boundaries of the Alpine Belt

Figure 3. Distribution of regional isostatic anomalies and areas of Cenozoic volcanism in Alpine Belt.
After M.Artemiev.

3. Features of structure of Caucasian segment

The Caucasus Mountains are located in the eastern part of the actual Alpine zone itself in the Arabian-Eurasian syntaxis, between the "downfalls" of Black and Caspian seas (Fig. 1). As it was mentioned above, these seas, very likely, represent small relics of the Neotethys Ocean, which gradually shallowed in the Miocene; their new significant deepening began in the Pliocene-Quaternary, along with the rise of the Caucasus and the Crimea.

Main Caucasian Ridge (Greater Caucasus, GC), in essence, is the southern edge of the Eurasian plate, raised along the Main Caucasus Fault (MCF). The latter is a part of a super-large deep-seated fault, traceable from the Kopetdag across the Caspian Sea, the Caucasus and the Crimea. Very likely, that its further continuation is the Trans-European Suture Zone (Tornquist-Teisseyre Fault Zone), which separates the East European craton from European Variscides and Alpides (Artemieva et al., 2006). In essence, this Kopetdag-Caucasus-Trans-European super-fault divides the Alpine orogen and stable Eurasian plate *sensu stricto* (Fig. 4).

There is a consensus now that formation of the Alpine tectonic structure of the Caucasus occurred under leadership of submeridional horizontal compression. It is generated by a counter movement of two plates: the Arabian ledge (the indenter) and the East European

Craton. Pressure is transmitted from the Arabian to the area of the Greater Caucasus (Arabi- (Arabian-Caucasian syntaxis). The current "invasion" of the Arabian wedge into the Eurasian plate occurs along the Bitlis-Zagros toward the Greater Caucasus, and its displacement relative to Eurasia takes place at a rate of several centimeters per year (Saintot et al., 2006). Reducing the space between Arabian indenter and Eurasian plate in the Late-Alpian time reaches a total of 400 km, but it is unevenly distributed over the area (Leonov, 2007). The bulk of it falls on the territory lying south of the Main Caucasian Fault. To the north of it, within the Greater Caucasus, some reduction also takes place, but it is small and, apparently, does not exceed a few tens of kilometers.



TESZ – Trans-European Suture Zone; MCF – Main Caucasian Fault; KDF – Kopetdag Fault

Figure 4. Kopetdag-Caucasian-Trans-European superfault.

In this context, great importance is the structure of the MCF. According to popular opinion, it is a large overthrust or underthrust Transcaucasian massif under the Great

Caucasus (Khain, 1984; Saintot et al., 2006 and references therein). However, the direct and indirect observations of geological data, as well as the most straightforward form of the fault suggests that the leading role play here steep imbricate structures and reverse faults; a steep or vertical inclination of the MCF observed from geophysical data to depths of 70-80 km (Shempelev et al, 2005). From this position the MCF is a reverse fault with a large value of vertical displacement, but without a large horizontal component (Leonov, 2007). In this case, the reduction of space to the south of the GC may be due to lateral "diffuence" of the matter to both sides before the hard "stop" of the East European Craton under the pressure of the Arabian indenter, as it can follows from the results of the study of modern GPS-deformation in the zone of Africa-Arabia-Eurasia continental collision (Reilinger et al., 2006). In other words, judging on geological and geophysical data, convergence of Arabia with Eurasia is substantially accommodated by lateral transport of material within the interior part of the collision zone and lithospheric shortening between the Caucasus and Zagros mountains.

4. Late Cenozoic volcanism of the Caucasus

An important feature of the area of syntaxis is a large belt of Late Cenozoic (up to practically present-day) volcanism, which extends in submeridional (Transcaucasian) direction from the eastern Anatolia via the Lesser to the Greater Caucasus, where large Elbrus and Kazbek volcanoes occur. Volcanics of this belt on their petrological and geochemical features are often close to the suprasubduction calc-alkaline magmas, and represented mostly by basaltic andesites, andesites and dacites under subordinate role of low-Ti basalts and rhyolites (Koronovsky, Demina, 2007; Keskin et al., 2007). Volcanic structures themselves with a lot of calderas and acid pyroclastics are also very close to the volcanoes of island arcs and active continental margins. Along with this type of magmatism, extensive lava plateaus, formed by eruptions (often fissured) of moderately alkaline basalts of within-plate type, such as Javakheti, Geghama, Syunik, Kars, and others, are also observed in the region.

Volcanics of the calc-alkaline series ("suprasubduction type") is of a prime interest. In contrast to the island arcs and active continental margins, Eastanatolian-Caucasus volcanic belt stretches across the overall structure of the Greater Caucasus, following the direction of positive Transcaucasian isostatic anomaly. Just south of the Van Lake, this belt is divided into two branches: one of them can be traced to the west, to Central Anatolia, and the other - to the east, toward the Elburs and the Zagros. Moreover, although the Arabian-Caucasian syntaxis is characterized by high seismicity, the earthquake hypocenters with depth not more than 50-60 km dominated, and deep-focus earthquakes (up to 120 km) are extremely rare and occurred only in the eastern part of the GC at its border with the Caspian Sea (Fig. 5 and 6). From this it follows that there is no any subduction beneath the eastern Anatolia (Sandvol et al., 2003) and Caucasus at present.

Isotopic and geochemical data suggest that origin of magmatism of "suprasubduction type" associated with interaction between a mantle plume head and continental crust material (Lebedev et al, 2006; 2011; Chugaev et al., 2012). Judging by the fact that the orientation of

East-Anatolian-Caucasian zone, where joined Anatolian-Caucasian and Caucasian-Elburssian arcs, practically coincides with the zone of syntaxis, i.e. with the area of maximum stress, we think that melting of crustal material in processes of deformations at high pressures played an important role in generation of these magmas. As shown earlier, crystal lattice of minerals under such conditions is at the stress state, which making them easier to disintegrate, and the conversion to the liquid phase requires much less heat (Sharkov, 2004 and references herein).

An essential role in this process of melting can play frictional heat generated during deformation (Frischbutter, Hanisch, 1991; Molnar, England, 1995) and mantle fluids from degassing due to decompression of the plume head, which penetrated a deformable crust, introducing some warmth and some components, how it is determined by isotopic and geochemical methods. From this standpoint the emergence of the Anatolian-Caucasian and Caucasian-Elburssian arcs may be due to the diffidence of deep-seated crustal material to both sides from the Arabian indenter, fixing appearance of foci of melting related to the tectonic flowage of material. In other words, these volcanic arc trace suture zone, on which outflow of crustal matter from the “stop” of the Eurasian plate occurred in the process of continental collision. Likely, the location of these sutures zones was determined by configuration of the plume head which extends to the north and oncoming “streamlined” from the both sides by tectonized material of shallow lithosphere.

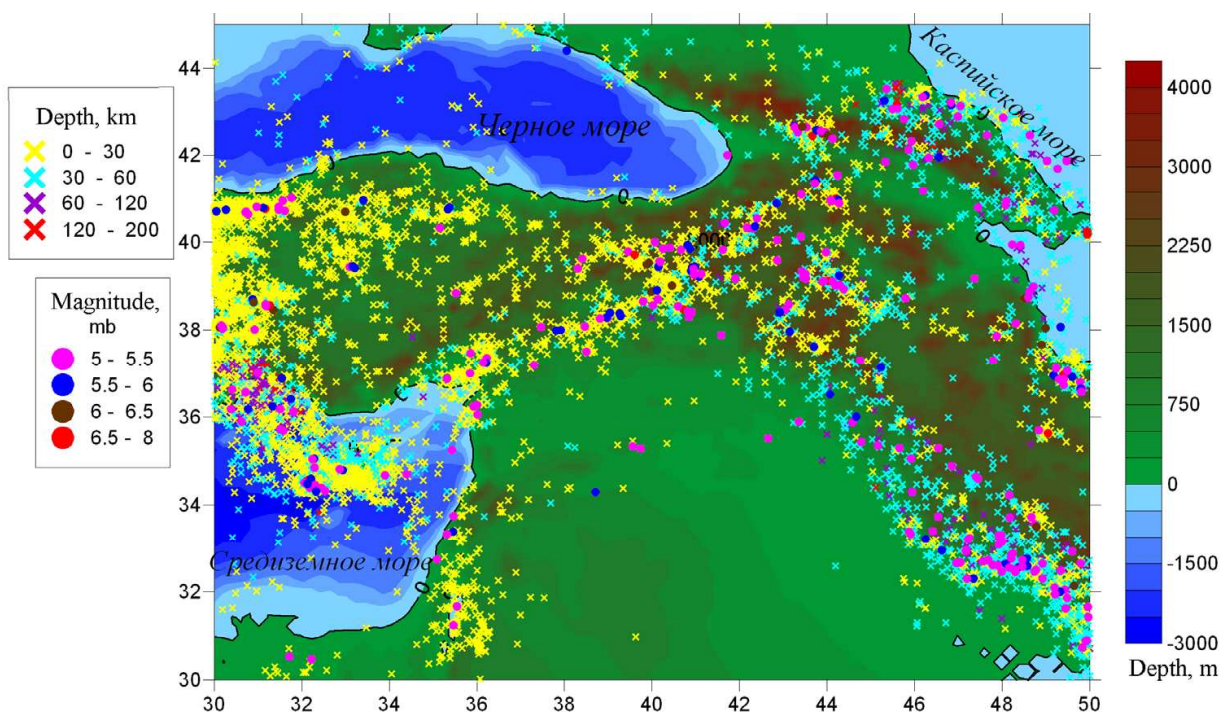


Figure 5. Distribution of the earthquakes in the region. Shallow focuses sharply predominate.

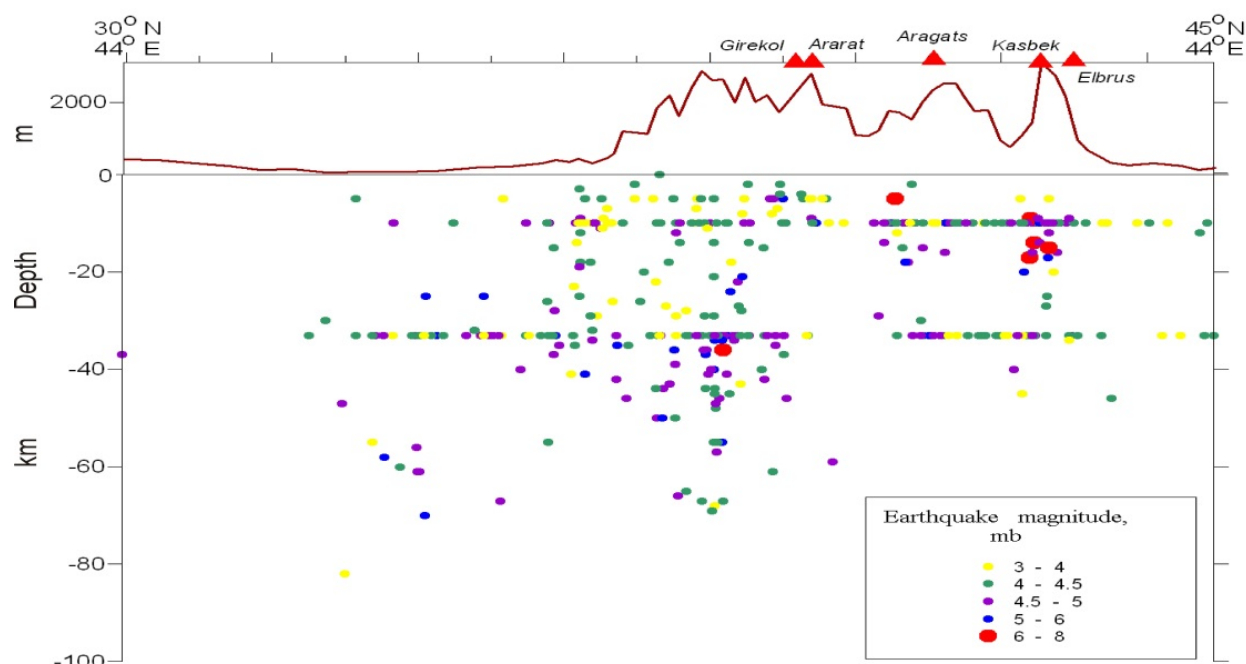


Figure 6. Distribution of earthquake focuses beneath the volcanic area Eastern Turkey – Caucasus

Similar isotopic and geochemical characteristics were established for the late Cenozoic calc-alkaline volcanic rocks in the zone of continental collision in the Alpine-Mediterranean region, where these features of magmas are usually explained by the complex composition of the mantle sources, strongly contaminated by crustal material (Harangi et al., 2006 and references herein).

5. Discordance between deep-seated situation and geological structure of the region

Attention is drawn to discordance of deep-seated processes and geological situation on the surface: the Kopetdag-Caucasian-Trans-European superfault sinking beneath level of the Caspian Sea, where it can be traced only by a strip of earthquakes. This fault is distorted in the north of the Black Sea, which may be indicative of the continued deepening of the sea which disturb the subsurface geological structures (Fig. 7). In addition, geophysical and geological data indicate that the head of the mantle plume from the late Miocene has extended to the north, crossing at the depth the MCF and resulting in the appearance of the modern volcanism including the late Quaternary volcanoes Kazbek and Elbrus with its present-day shallow magmatic chambers (Masurenkov, Sobisevich, 2010; Gurbanov et al., 2011). It is possible that "diving" of the plume head under the edge of the Eurasian plate, which occurred in the Miocene and continued at present, caused a regeneration of an older suture zone, leading to the rise of the Greater Caucasus. Thus, the geological situation in the region continues to develop, mainly due to large-scale deep-seated processes.

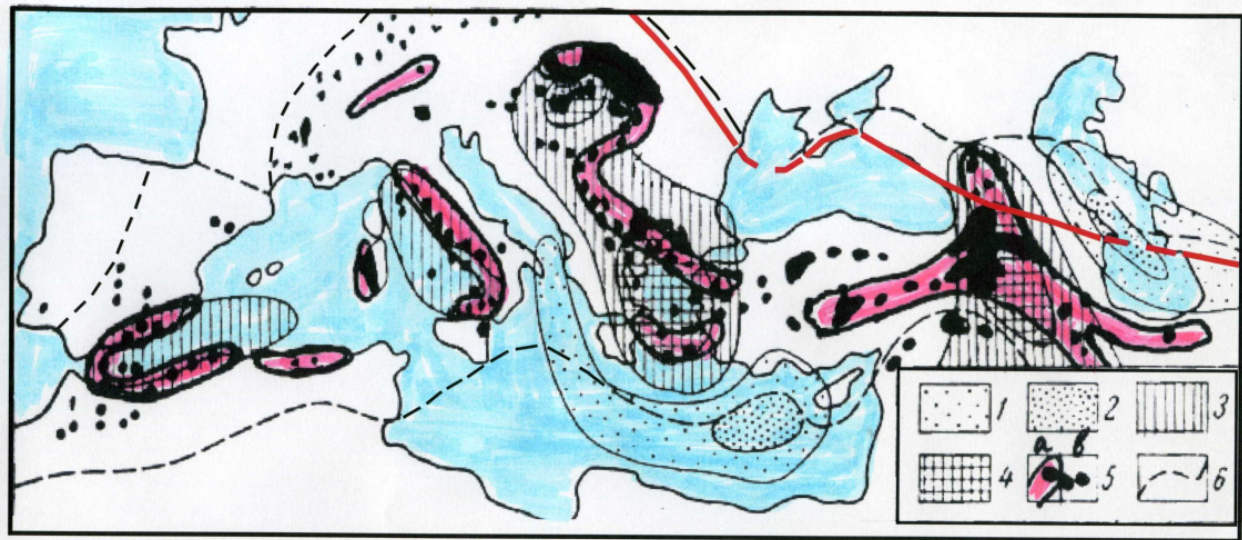


Figure 7. Discordances of the Kopetdag-Caucasian-Trans-European superfault in the region

It is pay attention that orientation of the Anatolian-Caucasian volcanic arc does not coincide with the largest neotectonic structures on the Turkish territory – North-Anatolian and East-Anatolian fractures zones: it is located between them. There is no clear correlation also between volcanism and the present-day motions of crustal material which established in the zone of Africa-Arabia-Eurasia continental collision by GPS constraints (Reilinger et al., 2006). All of these also evidence that deep-seated processes in the mantle not always found their reflection on the relatively shallow crustal level.

What could be further scenario? Most likely, this process of propagation of the mantle plume head to the north could lead to "cut open" of the lithosphere of the Eurasian plate, the separation of the Caucasian mountain system into two parts and the formation here continental rift zone like the Rhine Graben.

6. Conclusions

1. The Caucasus is a part of huge Late Cenozoic Alpine-Himalayan convergence zone. The Greater Caucasus is an edge of the Eurasian plate, raised along the large reverse fault - the Main Caucasian Fault. This fault, in turn, is a part of the super-fault, stretching from the Kopetdag to the Trans-European Suture Zone (zone Tornquist-Teisseyre).
2. The Caucasus is limited from both sides by large depressions modern Black and Caspian seas of "downfall" type, which "cut" pre-Pliocene structures both the Caucasus and the Kopetdag; origin of these seas is associated with downward currents in the mantle ("cold plumes").
3. The peculiar structure of the region is north-south Transcaucasian Rise, which is located in the northern part of Caucasian-Arabian syntaxis. Large positive isostatic anomaly is confined with it, apparently indicating presence here of the mantle plume head.
4. Along the zone of syntaxis the belt of Neogene-Quaternary volcanism occurs which begins in Eastern Anatolia and traced through the Lesser and Greater Caucasus. Two

types of volcanic rocks are represented here: (1) prevailing volcanics of calc-alkaline series, very close in petrological and geochemical characteristics to suprasubduction type, and (2) extensive lava plateaus formed by basalts of intraplate (plume related) type.

5. However, subduction zone under the Caucasus region, as well as throughout the Caucasian-Arabian syntaxis is absent and shallow earthquakes (50-60 km) are dominated here. We considered that origin of calc-alkaline magmas is associated with interaction between the mantle plume head and crustal material at relatively shallow depths under conditions of deformation at high pressures, leading to melting of the material in the zone of collision. In other words, appearance here of such magmas has not considered to any subduction zone.
6. Reduction of space in the area of Caucasian-Arabian syntaxis, which occurred during the Late Cenozoic, reached 400 km; such shortening in absence of subduction was apparently achieved mainly due to "difffluence" of the crustal material to both sides before hard "stop" of the East European Craton under the pressure of the Arabian indenter.
7. Situation in the region continues to develop now mainly due to deep-seated mantle processes, destroying the structure of the pre-Pliocene collision zone, while the development of the underlying processes occurs independent of the processes in the earth's crust.

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