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S.I. Subbotin Institute of Geophysics,
National Academy of Sciences of Ukraine, Kiev — Ukraine

Tethyan evolution and continental collision in SW Caucasus (Georgia and adjacent areas)

© S. Adamia, V. Alania, A. Gventsadze, O. Enukidze, N. Sadradze, N. Tsereteli, G. Zakariadze, 2017

Tbilisi State University, M. Nodia Institute of Geophysics, Tbilisi, Georgia

Georgia, the westernmost part of the southern Caucasus located at the junction of European and Asiatic branches of the Alpine-Himalayan orogenic belt represents an area where the Tethys Ocean was completely closed only in the late Cenozoic as a result of prolonged convergence between the Eurasian and Africa-Arabian plates.

During the Neoproterozoic—early Cenozoic, the territory of Georgia and the adjacent area of the Black Sea-Caspian Sea region were parts of the Tethys Ocean and its northern and southern margins. The Prototethys-Paleotethys-Tethys was not a single continuous oceanic plate, but rather developed in branches separating continental terranes of different sizes, which rifted and drifted away from the Gondwana margin and eventually collided with Laurasia. Prior to the final collision in the late Cenozoic, the region hosted systems of island arc, intra-arc, and back-arc basins located between the East European (Baltica) continent and Gondwana. Integrative geological and paleogeographical studies show a collage of several tectonic units (terranes) in Georgia and adjoining areas that have distinctive geological histories with Tethyan, Eurasian, or Gondwanian affinities. These include the Scythian platform, the Cavcasioni (Great Caucasus), the Transcaucasus-Pontides, and the Lesser Cavcasioni (Caucasus)—Alborz—West Iran regions. Their position between the Africa-Arabian and Eurasiatic continents provides a reason for grouping them into the Northern Tethyan (Eurasian) and Southern Tethyan (Gondwanian) domains. The Scythian platform, Caucasioni, and Transcaucasus-Pontian belts are of North Tethyan origin while Anatolia, Taurus, Iran, and the southern Lesser Caucasus belong to the South Tethys.

The Arabia-Nubian Shield, at the end of the Proterozoic, experienced basement consolidation related to the final stages of the Pan-African cycle of tectogenesis. In contrast to the southern Lesser Caucasus (Daralagöz), the Transcaucasus did not undergo this process because it broke away from the Arabia-Nubia Shield and, during Cambrian—Devonian, drifted deep into the Prototethys toward the northern (Baltica) continent.

During the early—middle Paleozoic in the wake of northward-migrating Gondwanian fragments, the Paleotethyan basin formed, and, in the Ordovician, along its border with the Transcaucasus, subduction of oceanic crust occurred, accompanied by suprasubduction volcanic eruptions. Northward migration of the Transcaucasus throughout the Paleozoic caused narrowing of the Prototethys and its transformation into an oceanic back-arc (Dizi) basin. Fragments of paleoceanic crust are found along the southern border of the Transcaucasus, within accretionary complexes of the Lesser Caucasus ophiolite suture, and in the Pontides, also in Iranian Garadagh. During the late Paleozoic—early Mesozoic, the oceanic basin separating the Africa-Arabian continent from the Taurus-Anatolian-Iranian platformal domain gradually extended. During this phase, only the Central Iranian terrain separated from Gondwana, drifted northward, and collided with the Eurasian continent in the Late Triassic.

The Taurus-Anatolian terrane separated from Gondwana later, in the Early-Middle Jurassic. During the Mesozoic—Cenozoic, Daralagöz represented the northwestern most margin of the Central Iranian platform and was separated from the North Anatolian platform by an oceanic or back-arc basin (Khoy basin), which within the modern structure is represented by Mesozoic — Cenozoic ophiolites of Urumieh-Khoy (Iran) and Van (Turkey).

The Paleozoic–Eocene evolution of the North Tethyan domain was marked by major magmatic events corresponding to the Pacific-type and Mediterranean stages of Tethyan development. The precollisional magmatic assemblages reflect a variety of paleotectonic environments. They are indicative of a west Pacific-type oceanic setting in which a mature, Andean-type continental arc developed. There were several episodes of oceanic lithospheric obduction onto the continental terranes of the region: the middle-late Paleozoic, during which basite-ultrabasite complexes were thrust over the island-arc system of the Transcaucasus and the Main Range zone of Caucasioni; pre-Late Triassic obduction in the Lesser Caucasus; and pre-Late Jurassic obduction during which ultrabasic rocks were thrust over the continental unit of the Artvin-Bolnisi Block of the Somkhet-Garabagh zone. The metabasites apparently represent Paleotethyan fragments.

During the Oligocene, marine Tethyan basins were replaced by euxinic basins, which are considered to represent the beginning of syncollisional development between Arabian and Eurasian plates in the region. Ongoing collision during Miocene—Quaternary caused inversion of topography such that fold-and-thrust mountain belts of the Cavcasioni and Lesser Cavcasioni, and the intermontane foreland basins in between were formed. In the late Miocene, coeval with molasse deposition in the foreland basins, subaerial volcanic eruptions occurred, characterized by intensively fractionated magma of suprasubduction-type calc-alkaline series from basalts to rhyolites.

In addition to volcanism, earthquakes indicate active tectonics in Georgia. Some of the

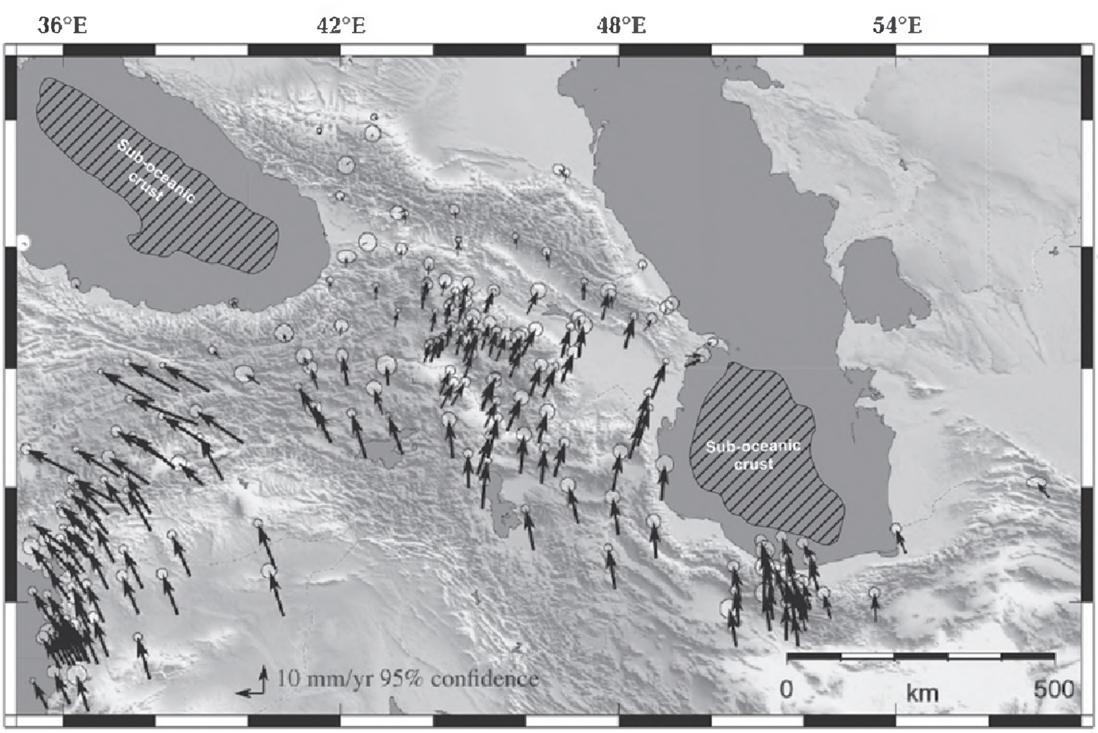

Fig. 1. Map showing global positioning system (GPS) velocities with respect to Eurasia and 95 % confidence ellipses for the eastern Black Sea—Caucasus—Caspian region [Vernant et al., 2013].

major earthquakes have proven to be devastating; i.e., the Racha earthquake of 29 April 1991, with *Ms*=6.9, was the strongest ever recorded in Georgia. The fault plane solution data for 130 earthquakes show that the territory of Georgia is currently under latitudinal compression, longitudinal extension, and an overall crustal thickening. A complex network of faults divides the region into a number of separate blocks. Three principal directions of active faults compatible with the dominant, near N-S compressional stress produced by northward displacement of the Arabian plate can be distinguished: one longitudinal, trending WNW-ESE or W-E, and two transversal, trending NE-SW and NW-SE. The first group (WNW-ESE), the so-called «Caucasian» strike, is composed of compressional structures, including reverse faults, thrusts, thrust slices, and strongly deformed fault-propagation folds. The transversal faults are also mainly compressional structures, but they contain considerable strike-slip components as well. The tensional nature of submeridional faults is associated with intensive Neogene-Quaternary volcanism in the Transcaucasus. The NE-SW left-lateral strike-slip faults are the main seismoactive structures in the western Transcaucasus, while right-lateral strike-slip faults are developed in the southeastern Transcaucasus. Considerable shortening and deformation of the crust and lithosphere of the region have taken place via compressional structures, as well as lateral tectonic escape. The geometry of the topography and tectonic features is largely determined by the wedge-shaped rigid Arabian block (indentor) and by the configuration of the oceanic-suboceanic lithosphere (buttresse) of the eastern Black Sea and south Caspian Sea, all of which cause bending of the main morphological and tectonic structures of the region around the strong lithosphere (Fig. 1).

Large-scale intraplate deformation of the lithosphere of the region as a result of the indentation of Arabian and Indian plates resulted in Late Cenozoic shortening and uplift of the mountain belts of the region, subsidence acceleration of the Black Sea—South Caspian crust, formation of submeridional, transversal megastructure of the Caspian Sea that evidence for interference of lithospheric folding patterns induced by the Arabian and Indian collision with Eurasia [Smit et al., 2013].

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Structural architecture of the eastern Achara-Trialeti fold and thrust belt, Georgia: Implications for kinematic evolution

© V. Alania[1], M. Sosson[2], O. Enukidze[1], N. Asatiani[3], T. Beridze[4], Z. Candaux[2], A. Chabukiani[1], A. Giorgadze[3], A. Gventsadze[1], N. Kvavadze[1], G. Kvintradze[3], N. Tsereteli[1], 2017

[1]Tbilisi State University, M. Nodia Institute of Geophysics, Tbilisi, Georgia
[2]Université Côte d'Azur, UMR Géoazur, CNRS, Observatoire de la Côte d'Azur, IRD, Sophia Antipolis, France
[3]Tbilisi State University, Faculty of Exact and Natural Sciences, Tbilisi, Georgia
[4]Tbilisi State University, A. Janelidze Institute of Geology, Tbilisi, Georgia

We introduce a tectonic model of the eastern Achara-Trialeti fold and thrust belt (ATFTB) based on the recent field data, interpreted seismic reflection profiles and regional balanced cross section from northern part of Lesser Caucasus orogene. Like other collision-induced Alpine-type fold-thrust belts (e.g. [Naylor, Sinclair, 2008]), the Lesser Caucasus is a typical doubly-vergent orogenic wedge represented by pro and retro wedges and ATFTB is a constituent part of retro wedge [Alania et al., 2017].

The seismic interpretation presented here is further constrained by surface geology and subsurface geology revealed by several well penetrations. Fault-related folding theories were used to constrain the seismic interpretation and of the regional balanced cross-section [Suppe, 1983; Shaw et al., 2005]. Seismic reflection data reveals presence of basement structural wedge, south-vergent backthrust, north-vergent forethrust and some structural wedges.

Stratigraphy in the ATFTB records the evolution from the extensional Achara-Trialeti Basin to Kura foreland basin of the Arabia-Eurasia collision zone. The rocks involved in the deformation range from Paleozoic basement rocks to Mesozoic-Neogene strata. The growth of eastern Achara-Trialeti thick-skinned structures at northern part of the Lesser Caucasus, formed by basement wedge that propagated along detachment horizons within the cover generating thin-skinned structures. The kinematic evolution of south-vergent backthrust zone is related to northward propagating thrust wedge. The main style of deformation within the backthrust zone is a series of fault-propagation folds and are developed in Cretaceous-Paleogene strata. Frontal part of the eastern ATFTB is represented by triangle zone [Alania et al., 2016; Sosson et al., 2013, 2016].

On base of published information about historical and recent earthquake data [Tsereteli et al., 2016; Varazanashvili et al., 2011], absolute ages of deformed volcanic rocks (Pliocene-Quaternary) from southern part of study area [Lebedev et al., 2007] and syntectonic units from frontal part of eastern ATFTB [Alania et al., 2016] we conclude that compressive deformation started in Middle Miocene and continues today.

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Evidence of volcanic eruptions witnessed by prehistoric man in Armenia and Argentina

© A. Avagyan[1], J-F. Ritz[2], P-H. Blard[3], Kh. Meliksetian[1], Ph. Munch[2], P. Valla[4], K. Tokhatyan[5], A. Caselli[6], M. Mkrtchyan[1], T. Atalyan[1], 2017

[1]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[2]Géosciences Montpellier, Montpellier, France
[3]NancyUniversité, Vandoeuvre-lès-Nancy, France
[4]Institute of Geological Sciences, University of Bern, Bern, Switzerland
[5]Institute of History, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[6]Instituto de Investigación en Paleobiología y Geología Universidad Nacional de Río Negro, Río Negro, Argentina

Prehistoric petroglyphs (rock-carvings, rock engravings) are widely spread from Europe to the Far East, Central Asia, Africa, Australia and Americas. Tens of thousands of petroglyphs have been discovered in the Armenian Highland, at elevations ranging in from 600 to 3300 m a.s.l. Strikingly, two rock-art sites, although located thousands km away from each other (Armenia in Eurasia, and Argentina in South America) exhibit well pronounced similarities in content and style. Geological evidences indicate that both areas were affected by recent volcanic eruptions. In both sites, interpretation of the pictures, as well as historical and archaeological data, strongly suggest that the engraved images may depict volcanic eruptions.

In the Armenian site, situated on the bank of a small river in Syunik volcanic upland, several petroglyphs are engraved on ca. 1.5 m diameter basalt boulders. The ancient artists have represented splashing lava fountains with volcanic bombs similar to volcanic eruption of Strombolian type. Depiction of such geological phenomenon found in Armenia, is unique for the entire region, including Eastern Turkey, Transcaucasia and Iran. This fact can be an indication, that our prehistoric ancestors witnessed volcanic eruption in Transcaucasia.

There are several direct and indirect techniques to date petroglyphs. The relative-comparative methods based on the analysis of content, style and carving technique with related archaeological monuments give approximate age estimations. The precise dating of petroglyphs is quite difficult, since the nature of the material to be dated is rarely suited to apply the whole variety of traditional physical dating methods.

In this contribution we focus on an indirect dating technique, by first dating the main lava-flow surrounding the petroglyphs site.

Geochronological dating techniques: cosmic ray exposure dating with ^{3}He and Ar/Ar were applied in parallel, along with the classical geological and geomorphological characterization. About 35 samples were collected for cosmogenic ^{3}He exposure dating, from different lava flows. The eruption of Porak volcano, situated 11 km NNW from the rock-art site, indicates an age of 28±6 Ka (1σ). Another source of lava flow in the Karkar plateau situated about 25 km to the SSE yields younger ages of 9.4±1.2 Ka and 5.2±0.4 Ka. Cosmogenic ^3He dating of boulders samples at the site where the Armenian petroglyph was discovered yield exposure ages comprised between 15 and 30 Ka. A global analysis including the geological, geomorphological and glaciological data supports the reliability of these new geochronological data and makes possible to establish a first time frame for the age of these petroglyphs: they were probably carved between 30 and 5 Ka. In order to obtain more precise age of the engraving, we will carry out further cosmogenic ^3He dating and OSL dating (surface age) of basaltic boulders at the petroglyph site.

New data on the tectonic evolution of the Khoy region, NW Iran

© A. Avagyan[1], A. Shahidi[2], M. Sosson[3], L. Sahakyan[4], G. Galoyan[1], C. Muller[4], S. Vardanyan[1, 3], K. B. Firouzi[2], D. Bosch[6], T. Danelian[5], G. Asatryan[1, 5], M. Mkrtchyan[1, 6], M. A. Shokri[2], 2017

[1]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[2]Geological Survey of Iran, Tehran, Iran
[3]Université Côte d'Azur, UMR Géoazur, CNRS, Observatoire de la Côte d'Azur, IRD, Sophia Antipolis, France
[4]Nannofossils Biostratigraphy Consulting, Santok, Poland
[5]Universite´ de Lille — Sciences et Technologies, CNRS, UMR 8198 Evo-Eco-Pale´o, Lille, France
[6]Université de Montpellier INSU-CNRS, Laboratoire Géosciences, Montpellier, France

The Khoy region (NW Iran) is important in the clarification of the structural framework of the Alpine Belt between the Taurides, the Lesser Caucasus and the NW Iran belt. This area is well known for its ophiolitic units. We present here new stratigraphic and structural data that can be used to reconstruct the tectonic evolution of this region and then to establish connections between these belts. According to new data from nannoplankton assemblages, the obducted ophiolite of the Khoy complex was thrusted over a sheared Campanian olistostrome and lenses of amphibolite included within the contact. The obduction event is also marked by erosion of the ophiolitic unit and the deposition of conglomerates, shales, sandstones and siltstones. Poorly extended Paleocene detrital deposits cover the Campanian-Maastrichtian rocks. The Eocene formations characterize a basin filled with volcanogenic and sedimentary layers. The Middle and Upper Eocene series unconformably overlie the ophiolites, their Campanian–Maastrichtian cover and Paleocene deposits. This corresponds to a syn-orogenic basin formed after the collision between Eurasia and the Taurides–Anatolides–South Armenian microplate. The Oligocene–Miocene Qom Formation with basal conglomerates unconformably covers all the earlier formations, including the Palaeozoic formations, indicating intense shortening before its deposition. Compression deformation is currently ongoing and is manifested by numerous folds, mainly west-dipping thrusts and reverse faults cutting the Qom Formation, and by recent NW–SE dextral strike-slip faults. This illustrates the continuous shortening and uplift (with intense erosion) resulting from the advanced stage of the collision between Arabia and Eurasia. The structural location of the tectonic units suggests that the Khoy

Gondwana-related basement was part of the South Armenian Block and that the Khoy allochthonous ophiolites were obducted on it from the Amasia-Stepanavan-Sevan-Hakari suture zone.

Reverse and thrust tectonic heritage in the south-east intermountain Ararat depression (Armenia)

© *A. Avagyan*[1] *M. Sosson*[2], *L. Sahakyan*[1], *S. Vardanyan*[1, 2], *Y. Sheremet*[2], *M. Martirosyan*[1], *C. Muller*[3], 2017

[1]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[2]University Côte d'Azur, UNS, CNRS, OCA, IRD Geoazur, Valbonne, France
[3]Université Côte d'Azur, UMR Géoazur, CNRS, Observatoire de la Côte d'Azur, IRD, Sophia Antipolis, France
[3]Nannofossils Biostratigraphy Consulting, Santok, Poland

The studies of the south-eastern part of the Ararat basin and neighboring mountain and intermountain depressions of the Republic of Armenia, allow reevaluating of previous researches and revealing tectonic processes developed since the Late Cretaceous continental collision according to recent geodynamic concepts. The Ararat basin structural setting and tectonic evolution investigation is perspective for hydrocarbon traps identification.

The thrust and reverse stress regime of the study area was dominant during long period from collision initiation, influencing farther tectonics, complicated by strike-slip faulting. The secondary normal faults, superimposed gravitational slopes processes and selective erosion complicate moreover the overall structure pattern. These processes continue up to date.

The thrust and reverse tectonics form and develop asymmetric, oblique, fold structures, cuestas with structural slops in back-limb and intensive weathered foreland in fore-limb. The result of these faults activity is seen in the Paleozoic substratum, newly discovered volcanic rocks (OIB type, probably associated with the ophiolites) outcropping from Ararat depression alluvial and lacustrine Quaternary cover.

Preliminary results of paleomagnetic study of flysch sequences in Eastern Crimea mountains

© V. Bakhmutov, Ye. Poliachenko, T. Yegorova, A. Murovskaya, 2017

Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine

The new dating of the Tavric flysch complex at the Eastern Crimean Mountains [Sheremet et al., 2016] requires independent age determination of Crimea flysch sequences. It has been proposed to use the paleomagnetic method taking into account that recent paleomagnetic data from Crimea had been successfully applied both for tectonics [Çinku et al., 2013] and magnetostratigraphy [Guzhikov et al., 2012; Bakhmutov et al., 2016]. The key task of our study is to distinguish the paleomagnetic zones of normal and reverse polarity and their binding to the geological time scale considering the paleontological and lithological markers. But the analysis of new data of micropaleontological complexes without additional geological information, taking into account the frequent changes in magnetic polarity in the Jurassic-Early Cretaceous time span, shows some difficulty of this approach for our study. We have proposed another approach — to distinguish the primary magnetization and calculate paleopoles that are compared with expected reference apparent polar wander path (APWP) of Eurasia. Thus, we consider the main purpose of our paleomagnetic studies is the definition of paleo-latitudes of flysch sequences in Crimean Mountains.

The second objective of our research relates with study of anisotropy of magnetic susceptibility (AMS). Due to the presence of ferromagnetic particles of non-isometric form, it is assumed that magnetic structure was formed under the influence of some factors, such as bottom currents-In structural applications, AMS have been used to examine patterns of strain. An oversimplified view is that elongate ferromagnetic grains are passively rotated during deformation of rocks.

Palaeomagnetic measurements were carried out in the laboratory of the Institute of Geophysics of the National Academy of Sciences of Ukraine in Kiev. Specimens were stepwise thermally demagnetized using an MMTD80 oven up to 600 °C. The demagnetization of specimens (thermal and alternating field (AF)) and all measurements were made inside magnetically shielded rooms to minimize the acquisition of present-day viscous magnetization. After each heating step, the magnetic susceptibility (k) at room temperature was measured by a MFK1 Kappabridge to estimate possible mineralogical changes. Duplicate specimens were subjected to AF demagnetization up to 100 mT using a LDA-3A demagnetizer. Demagnetization steps were adjusted during thermal or AF procedures from 10° to 50 °C and 10—20 mT, respectively. The natural remanent magnetization (NRM) of specimens was measured by JR-6 spin magnetometer. Demagnetization results were processed by multicomponent analysis of demagnetization path [Kirschvink, 1980] using Remasoft 3.0 software [Chadima, Hrouda, 2006]. AMS was measured by MFK-1 Kappabridge, and magnetic anisotropy parameters were calculated with the Anisoft program.

During 2015—2016 field expeditions in Crimean Mountains we have examined 15 sites, and from 10 of them have collected the sandstones and argillites from flysch sequence of Tavric(?) series for paleomagnetic analysis. Results from 7 sites (their location is shown in Fig. 1), mainly of 2015 collection, were taken for further interpretation.

In general, the samples from different sites have different magnetic parameters and stability to thermal and AF demagnetization showing no common regularities. So, during next data processing and selection of magnetization components, some samples were excluded from the data base and were taken not suitable for further interpretation due to: 1) weak NRM (<0.001 mA/m); 2) large MAD (>10°) of selection component; 3) unstable behavior during demagnetization; 4) strong inconsistency to the rest of samples in the group. Despite the number of samples from each site was enough, the *Q* index of [Van der Voo, 1990] could not be satisfied for most sites. Many samples show dramatic increase of susceptibility during thermal demagnetization in the range 300—400 °C. Some of the samples are characterized by a peak of the NRM at different temperatures, which indicates significant changes in magnetic minerals behavior during heating.

Usually two NRM components could be distinguished during demagnetization. A low unblocking temperature component, recording probably a minor viscous origin, is removed between 100—200 °C. The directions of this component are scattered, but the mean close to the present Earth's magnetic field. After removal of this weak overprint, a second component with unblocking temperatures between 300 and 400—480 °C was calculated from the vector that decays linearly close to the origin. Several samples have unblocking temperature more than 500 °C. Taken into account the high increases of susceptibility above 400 °C we can't extract the more stable component decays linearly to the origin. So the ChRM (characteristic component of remanent magnetization) direction was calculated from the vector that decays linearly to the origin of the orthogonal vector plots.

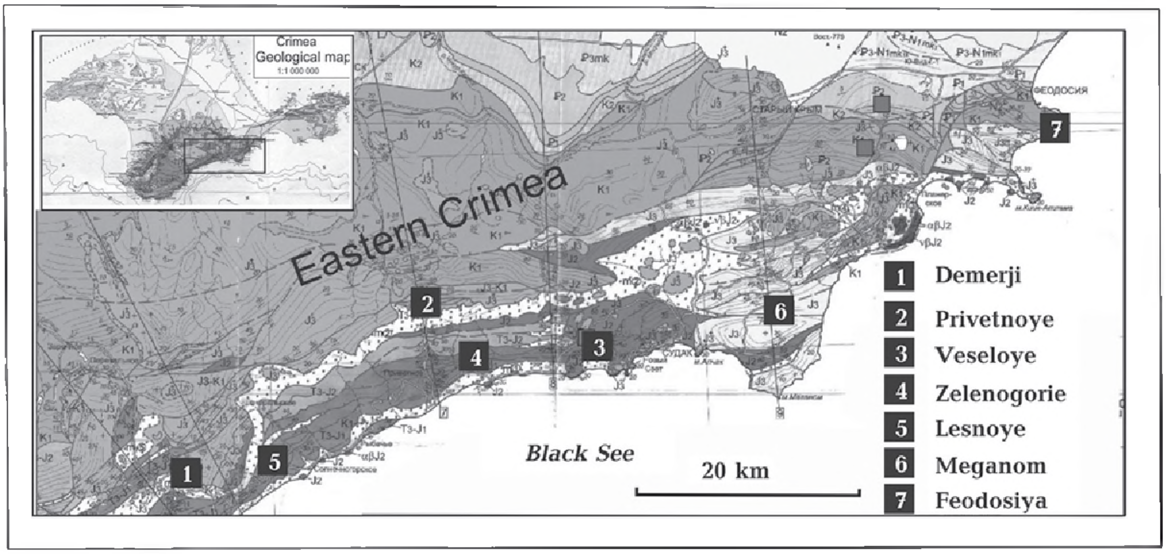

Fig. 1. Sites of sampling for paleomagnetic study in Eastern Crimea Mountains.

Five sites (numbers 1—5 in the Fig. 1) show the ChRM direction corresponding to normal polarity; after correction for fold bedding elements it becomes more scattered. Palaeomagnetic fold test show that all palaeomagnetic groups carry a post-folding remanent magnetization. This result confirms the Early Cretaceous remagnetization of sediments from other sites in Crimean Mountains reported by [Çinku et al., 2013].

The ChRM-directions of samples from sites 6 and 7, obtained from both high unblocking temperature and high coercive components, show normal and reversed polarities. The correction for folding suggests that the magnetization is primary. Site 7 was dated as

Tithonian-Berriasian boundary, the ChRM-directions have normal and reverse polarities and confirmed the result of [Guzhikov et al., 2012] about primary magnetization of Tithonian flysch near Feodosiya.

The tectonics implication of our results is not clear because of the data shortage. Meijers et al. (2010) considered the ChRM magnetization is primary and reported the Upper Jurassic palaeolatitudes in Crimea, which is inconsistent with the paleolatitudes obtained in [Çinku et al., 2013], which used age and refernece palaeolatitude curve derived from the APWP paths of Eurasia and Gondwana. Comparison of the average mean palaeomagnetic poles in the Triassic—Upper Jurassic units of Crimea with that expected for the Eurasian APWP, suggests an age as post-Berriasian. For the most cases the mean remagnetization directions are defined by a single stable component. To perform this procedure to our data we have to involve our new results on the collection of 2016 (mainly collected in western Crimean Mountains). Now this collection is laboratory measured.

The AMS data show typical sedimentary structure of sediments after bedding correction. The minimum axis of the AMS ellipsoid is normal to bedding, while the direction of the maximum axis is NE-SW for sites 1-5, N-S for site 6 and NW-SE for site 7. The directions of maximum axis of AMS tensor will be compared with structural and tectonophysical data from the area to define their possible connection.

In the case of the shape of the AMS tensor is related to tectonic deformation, the measurement of AMS in rocks of different ages will allow us to define an upper age limit for deformations.

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Mesozoic geodynamic and paleoenvironmental evolution of the Tethyan realm preserved in the Lesser Caucasus

© T. Danelian[1], M. Seyler[2], G. Galoyan[3], M. Sosson[4], G. Asatryan[1, 3], C. Witt[2], L. Sahakyan[3], A. Avagyan[3], A. Grigoryan[3], C. Crônier[1], 2017

[1]Université de Lille, CNRS, UMR 8198 Evo-Eco-Paleo, Lille, France
[2]Universite′ de Lille, CNRS, Université Littoral Côte d'Opale, Laboratoire d'Océanologie et de Géosciences, Lille, France
[3]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[4]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France

In the Lesser Caucasus (Armenia and Karabagh; Fig. 1) can be found remnants of a Tethyan oceanic realm that existed during the Mesozoic between Eurasia and the South-Armenian Block, a Gondwana-derived terrain considered as the eastern extension of the Tauride-Anatolide plate. The Tethyan remains in the Lesser Caucasus are part of

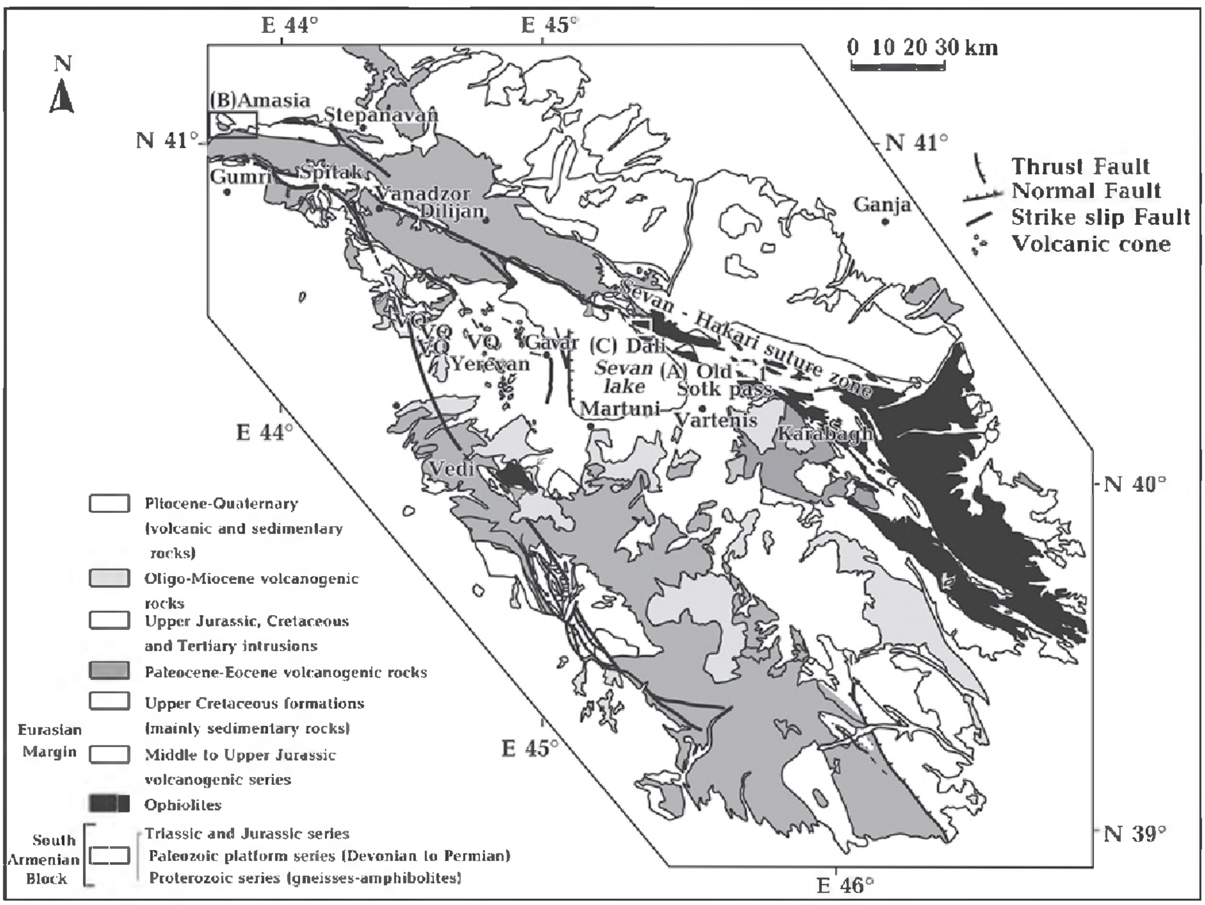

Fig. 1. Geological map of the Lesser Caucasus (after [Sosson et al., 2010], modified), including the location of the key studied areas: A — Old Sotk Pass; B — Amasia; C — Dali.

an over 2,000 km long suture zone, running through the northern part of Turkey towards Iran. As it is often the case, radiolarites are here associated with submarine lavas that are considered to be part of an ophiolitic complex. Radiolarian biochronology of radiolarites, combined with petrographic observations and geochemical analyses of ophiolitic lavas, helps us to improve our understanding of the geodynamic and paleoenvironmental evolution of this geologically complex region.

Fig. 2 synthesizes all available radiometric and biochronological data from the Lesser Caucasus. It is likely that oceanic floor spreading was taking place during the Middle/Late Triassic between the South Armenian-Tauride-Anatolide plate and Eurasia. This is suggested by upper Triassic gabbros dated in Karabagh [Bogdanovski et al., 1992] and an upper Triassic-Liassic deep-sea sedimentary sequence dated in the same area by radiolarians [Knipper et al., 1997]. Based on

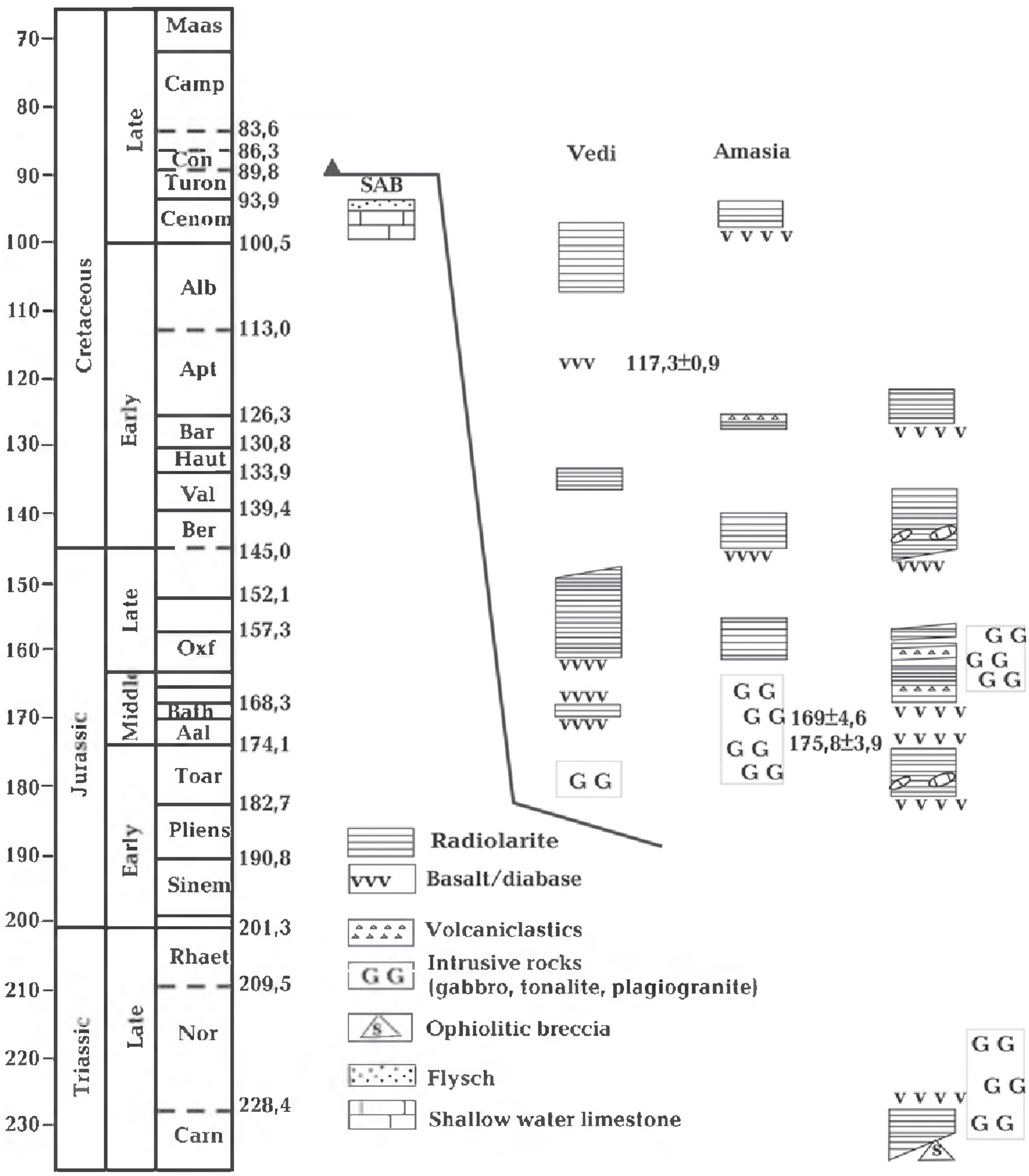

Fig. 2. Synthesis of all known ages (both biochronological and geochronological) for the ophiolitic rocks and their sedimentary cover in the Lesser Caucasus (after [Danelian et al., 2016], modified).

our own investigations along the Old Sotk Pass (Fig. 1, A) radiolarian-rich cherts or siliceous claystones occur as large blocks preserved in a mélange, together with basic igneous lithologies and carbonate blocks with Triassic conodonts. Recent results point to the presence of Bajocian radiolarian cherts and Albian siliceous claystones, both of which contain evidence of fine volcanoclastic input from subaerial volcanic activity. Based on all the radiolarian ages obtained on siliceous tuffs found in the sedimentary cover of the Amasia-Sevan-Hakari ophiolitic zone (Amasia, Sarinar, Old Sotk Pass) there is now good evidence that subaerial volcanic activity was underway for most of the Middle Jurassic to Lower Cretaceous (Bajocian/Bathonian to Albian).

Radiolarites are in general the sedimentary product of moderate levels of radiolarian productivity in a pelagic environment starved of any terrigenous or carbonate input; in the Lesser Caucasus radiolarites are either the sedimentary cover of ophiolitic lavas or intercalated in them. A synthesis of all currently available data suggests that radiolarian cherts accumulated more or less continuously during the Bajocian to Cenomanian time interval in the Tethyan oceanic realm preserved in the Caucasus.

Bajocian cherts are now discovered throughout the Lesser Caucasus (Vedi, Sevan and Hakari ophiolites); on the contrary, Cenomanian cherts are known for the moment only from Amasia (NW Armenia; Fig. 1, B).

The Dali outcrop, situated east of Lake Sevan (Fig. 1, C), bears a particular geodynamic significance. It exposes a thick basaltic sequence that overlies layered dioritic cumulates intruded by a small plagiogranite body. Based on igneous mineral chemistry and bulk rock geochemistry three major basaltic groups were identified; it is likely that they are separated by thin thrust zones. The contact between the diorites and the overlying basalts is cataclastic and underlined by hydrothermal deposits of epidote and quartz; epidotization also affects the base of the basalts. Those are aphanitic tholeiites that display a clear island arc signature. They are overlain in their turn by lavas transitional between tholeiitic and calk-alkaline, partly recrystallized into chlorite, albite, titanite and minor calcite and quartz. They show various textures and mineralogy (aphyric or with phenocrysts of plagioclase + augite ± amphibole or olivine + Cr-spinel ± augite) and coarse vesicles filled with calcite. The sequence ends with alkaline basalts, containing abundant phenocrysts of amphibole + diopside or diopside ± olivine and Cr-spinel, and rich in calcite replacing the mafic minerals and filling vesicles. The Dali volcanic sequence is characterized by a progressive enrichment in incompatible elements from the base to the top. In the tholeiitic/calk-alkaline and alkaline basalts the Nb/La ratio is very variable (amphibole-rich alkali-basalts have negative Nb anomaly), and all units show evidence supporting hydrous magmas (amphibole, coarse and abundant vesicles). Overall a subduction-related environment is suggested for the Dali magmatic rocks. The calk-alkaline lavas are overlain by radiolarites that are dated as late Tithonian-Berriasian in age [Asatryan et al., 2012]; blocks of oolitic grainstone with crinoid bioclasts integrated in the radiolarite sequence attest for the presence of shallow water carbonate sedimentation in the neighboring realm. A second interval of radiolarian cherts, intercalated between the alkaline lavas are Valanginian in age; the cherts do not contain the above mentioned limestones and are much darker in color (more Mn-rich?).

Finally, the microfossil record preserved in both the uppermost part of the shallow water carbonate sequence and overlying flysch that crop out in the Vedi area (SE of Yerevan; Fig. 1) establish that the initial stages of obduction of ophiolites onto the South-Armenian Block took place during the Cenomanian (see [Danelian et al., 2014, 2016]).

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The obduction process: What extent? What timing? What cause(s)? The study of the northern branch of Neotethys in Anatolia and the Lesser Caucasus (Turkey and Armenia)

© M. Hässig[1], M. Sosson[2], Y. Rolland[2], 2017

[1]Department of Earth Sciences, University of Geneva, Geneva, Switzerland
[2]Université Côte d'Azur, Géoazur, UNS , CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France

Worldwide within mountain ranges the presence of slivers of preserved oceanic lithosphere known as ophiolites evidence a tectonic process responsible for their emplacement on top of the continental crust called obduction. The first order anomaly inherent to this phenomenon is that dense rocks ($\rho>3$) end up on top of less dense rocks ($\rho\approx2.7$). The driving forces responsible and consequent/accompanying processes for such a tectonic oddity remain uncertain. The ophiolites of the Lesser Caucasus and NE Anatolia are prime examples of this phenomenon with tectonic transport (> 150 km) of fragments of oceanic lithosphere towards the south on top of the South Armenian Block-Tauride-Anatolide Platform along the entire continental marge (>1000 km) (Fig. 1). The multidisciplinary approach used throughout the study of these ophiolites yielded clues specifying the evolution of the Northern Neotethys Ocean before and around the time of ophiolite emplace-

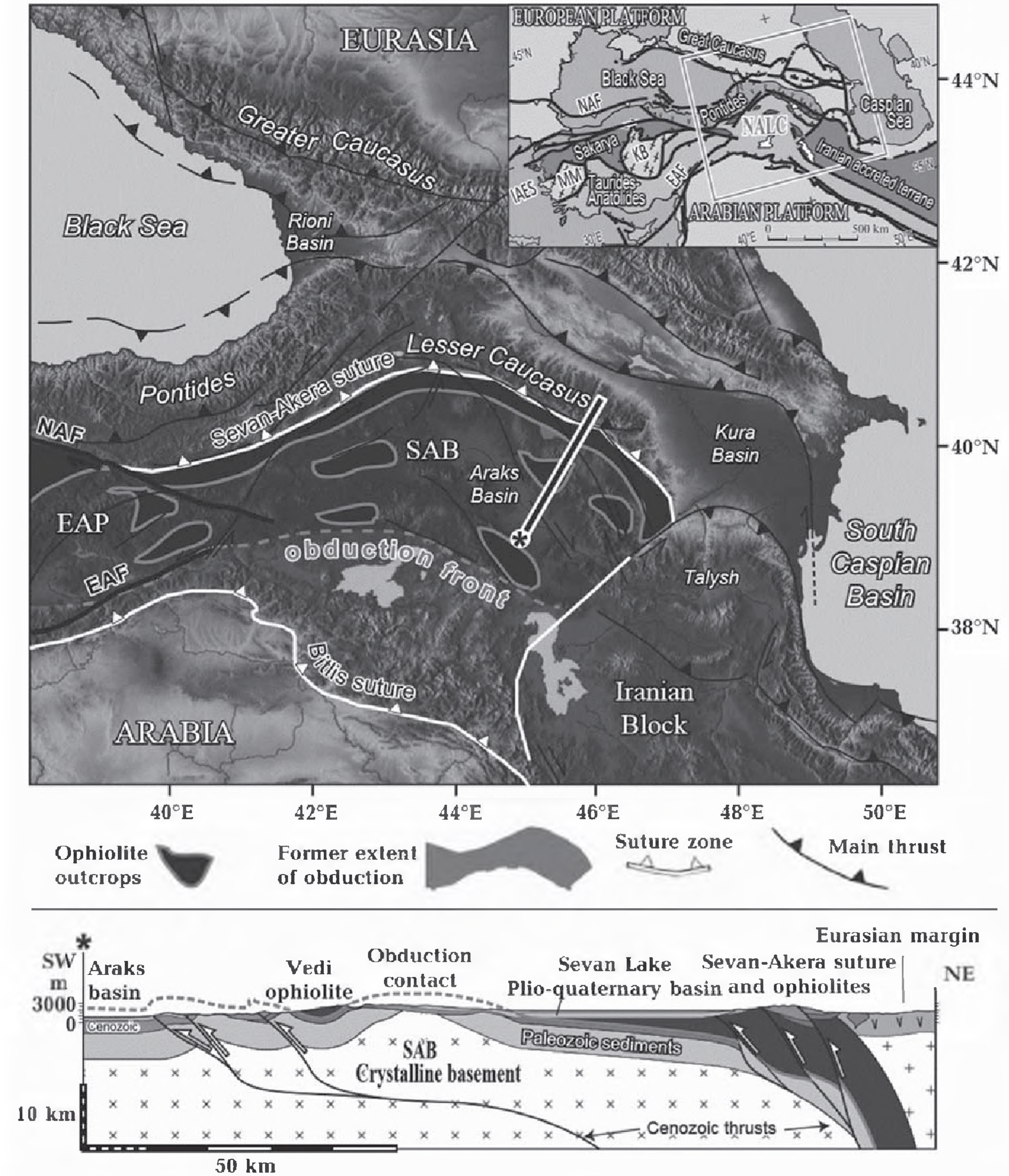

Fig. 1. Tectonic map of the Middle East-Caucasus area, showing the main blocks and suture zones, and corresponding crustal-scale section showing the obduction, after [Hässig et al., 2013]: EAF — East Anatolian Fault; IAES — Izmir—Ankara—Erzincan Suture; KB — Kirshehir Block; MM — Menderes Massif; NALC — North-East Anatolia—Lesser Caucasus domain (zone of ophiolite obduction); SAB — South Armenian Block; V — volcanic arc of Eurasian margin of Pontides. * position of cross-section (below). Lower panel: Upper-crustal-scale geological section of the NALC showing the geometry of the obduction front propagated towards the south and its rooting into the Sevan Akera suture to the north, below the Eurasian margin (see [Rolland et al., 2012]).

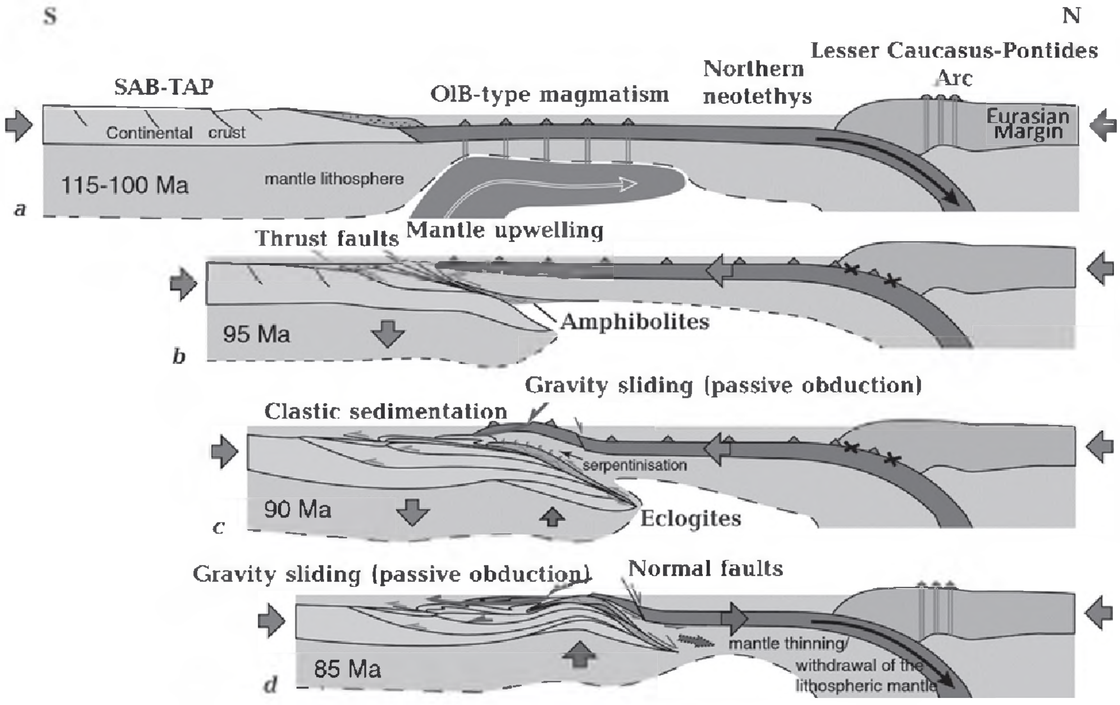

Fig. 2. Conceptual model of the obduction process in the NALC: *a* — situation in the Early Cretaceous showing the convergence of SAB—TAP (South Armenian Block—Taurides Anatolides) with the Eurasian margin, the onset of mantle upwelling and heating of the oceanic lithosphere at 115 Ma, *b* — triggering of obduction, due to the blocking of the northern subduction zone and the increase in buoyancy of the oceanic lithosphere, *c* — thickening of the continental crust below the obduction, erosion and the onset of passive obduction [Lagabrielle et al., 2013] by gravity sliding of the ophiolites on the flexural basin, *d* — transition from a contractional to an extensional regime due to renewed subduction. Mantle thinning and withdrawal leads to the exhumation of the continental crust.

ment (90 Ma), consequently the obduction event. Our findings strongly suggest common emplacement of all the ophiolites of the study area as a thrust sheet of Middle Jurassic oceanic lithosphere, ~70—80 Ma old at obduction onset. This would be one of the biggest preserved ophiolite nappe complexes in the world (outcropping in a mountain range).

Numerical modelling validated, firstly, the hypothesis that emplacement of such an ophiolitic nappe is due to particular thermal conditions. For old oceanic lithosphere to obduct it needs to be in a thermal state close to that of young oceanic lithosphere (0—40 km thick). Secondly, numerical modelling showed that the progression of obduction over a great distance and current position of the ophiolites far over the continental margin could be explained by post-compression extension. This switch in tectonic regime is responsible for the thinning of the ophiolitic nappe, underplating of underthrusted continental lithosphere and exhumation of continental crust.

Thermal rejuvenation is supposed for the ophiolites of the Caucasus s.l. argued by alkaline lavas emplaced on the sea floor prior to the obduction event during the Late Cretaceous (117 Ma). The resulting seamounts and/or oceanic plateaus of this magmatism would then have blocked the north-dipping subduction zone father north under Eurasia upon their entree and this until the end of the obduction event. The obduction event on the South Armenian Block—Tauride—Anatolide Platform is synchronous along the Eurasian margin from the Pontides to the Somkheto-Karabakh. Reactivation of the north-dipping subduction zone under Eurasia is compatible with traction on the obducted oceanic lithosphere responsible for its mantle thinning, continental lithospheric underplating and continental crust exhumation. Thus the propagation of thin obductions according to the «flake tectonics» concept over an eclogite-free underthrusted continental margin can result from a combination of reheating of the oceanic lithosphere and far-field plate kinematics (Fig. 2).

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Ore-forming processes in basite-ultrabasite complexes of ophiolites of the Lesser Caucasus

© A. Ismail-zade, T. Kangarli, 2017

Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan

The basite-ultrabasite complex of ophiolites was formed in the result of many-stage mantle-crust evolution of mantle substance. All this was stipulated by different genesis processes forming deposits of chromite, gold and mercury. Magmatic chromites are connected with mantle ultrabasite part of ophiolite profile formed in the process of oceanic crust formation accompanied with gabbro and tholeitic volcanism. Mantle differentiation of ultrabasite substance in the process of its high-temperature viscous displacement was one of the factors of chromite isolation. Gold deposits in basite-ultrabasites of ophiolites are related to autometamorphic process and lay on hydrothermal metasomatic processes. Combination of these processes caused extraction of gold out of ultrabasites at early mantle metamorphism and is reaccumulation under the hydrothermal solutions of gabbro-plagiogranite intrusive. Mercury deposits in ultrabasites complex are of hydrothermal type. Deep faults of this belt activation in postcollision period serve as leading channels of Mio-Pliocene acid volcanism and mercury-content hydrothermal solutions. Serpentinized peridotites in these processes played the role of a screen. However regeneration of early deeper deposits could also occur. Different types of ore-forming activity connected with forming of ophiolites reflect the complex spatial correlation between the processes of ore formation, evolution of ultrabasits and geodynamical regime of the region.

Petrology and geochemistry of basaltic series in Cenozoic volcanic belts of Gaucasus

© *A. Ismail-zade, T. Kangarli, 2017*

Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan

Alpine stage of tectonic-magmatic development of Caucasus is considered in sphere of complete geodynamic process caused by the correlation of Tethys oceanic crust with continental margins of ancient lithospheric plates of Eurasia and Afroarabia. As Mesozoic-Cenozoic period is characterized by the manifestation

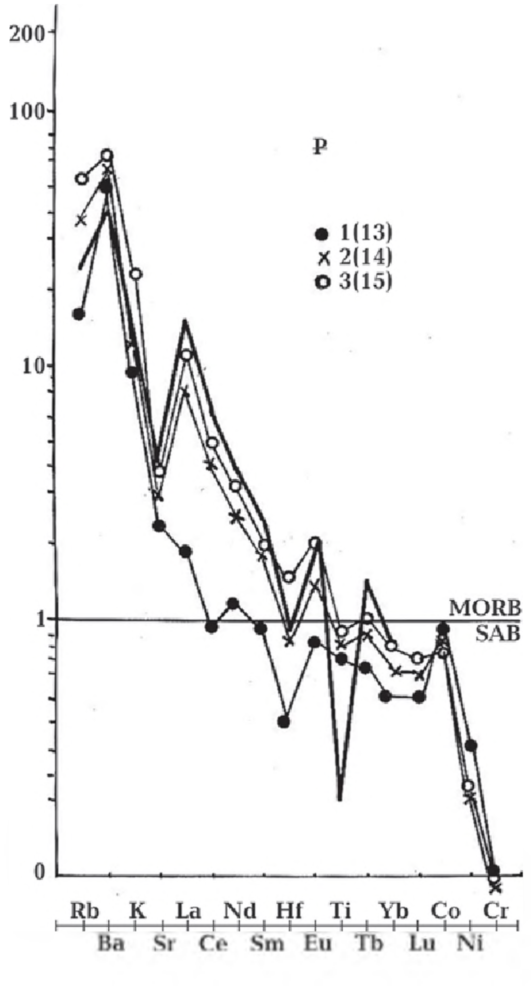

Fig. 1. Normalized multicomponent diagram of the volcanic rock complexes of the Middle Eocene (Yerevan-Ordubad zone): *1* — toleitic basalt (13); *2* — calc-alkaline basalt (14); *3* — Trakhibasalt (15).

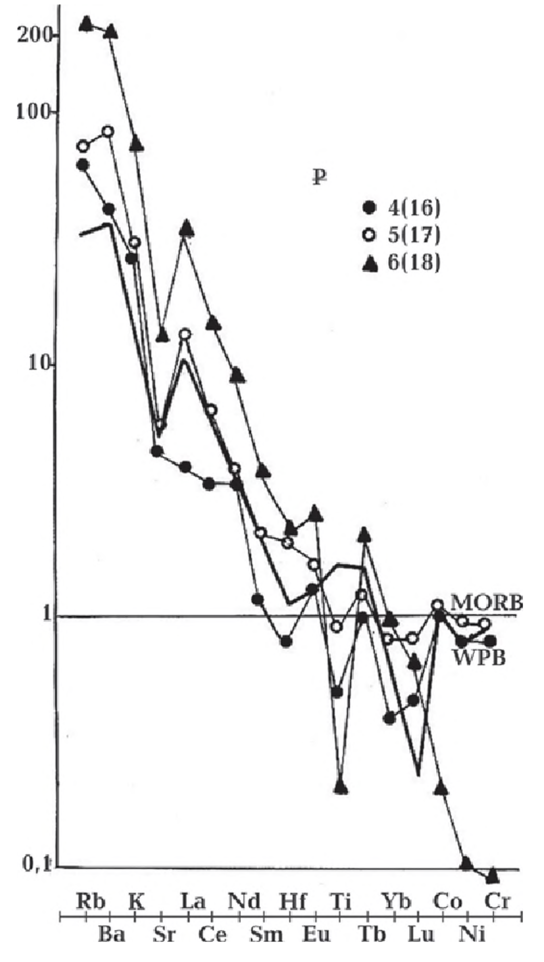

Fig. 2. Normalized multicomponent diagram of the volcanic rock complexes of the Middle Eocene (Talish, Adjara-Trialety and Geychay-Akerin zones): *1* — toleitic basalt, middle (16); *2* — sub-alkalinetrekhibasalt, middle Eocene (17); *3* — alkaline melafonolite, Oligocene—Miocene (18).

of riftogenic and island arc volcanism, so Cenozoic one is noted by the regime combination of active continental margins completed by continental rift with activation regime for area of completed folding. Three active phases can be distinguished for Cenozoic volcanism fully manifestated in Lesser Caucasus: 1) Eocene; 2) Miocene—Early Pliocene; 3) Late Pliocene—Quaternary (Fig. 1—4).

At Paleogene stage there was formation of two symmetrically situated volcanic belts on both continental margins which are close according to their content and consist of separated by Zangazur geosuture zone. Basalts of these belts with low content of K, Rb, at La/Yb = 3 and not so high of Ni, Cr correspond to tholeitic basalts of island arcs. This stage includes two regions of alkaline basaltoid volcanism corresponding to inside arc riftogenesis with basalt with La/Yb = 11÷15 and high content of K, Rb, Ni, Cr.

At Neogene stage volcanism is manifestated in two series: calcalcali, andesite-dacite-rhyolite developed in Paleogene depression of both continental margins and trachybasalt-phonolite developed within rises. Middle members of the first series (La/Yb = 30÷40) are characterized by high K, Rb, Ba, Sr, light REE, low Ni, Co, Cr and correspond to residual melting in Paleogene chambers, are subjected to differentiation in the crust. In subalkaline series the middle differentiation on high K, Rb, Ba, Sr, light REE, Co, Ni, Cr correspond to basalts of riftogenic zones.

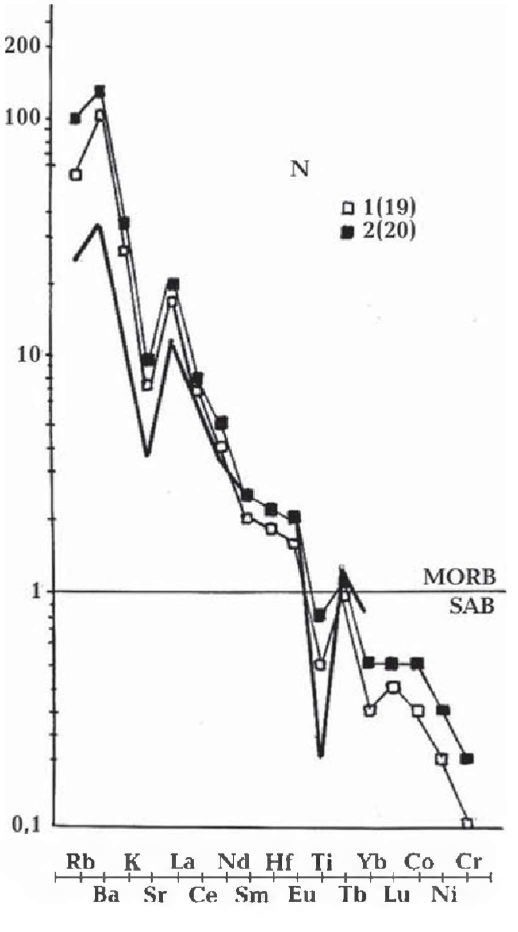

Fig. 3. Normalized multicomponent diagram of the volcanic rock complexes of the Neogene (Yerevan-Ordubad zone): *1* — andesidasite (19); *2* — andesite (20).

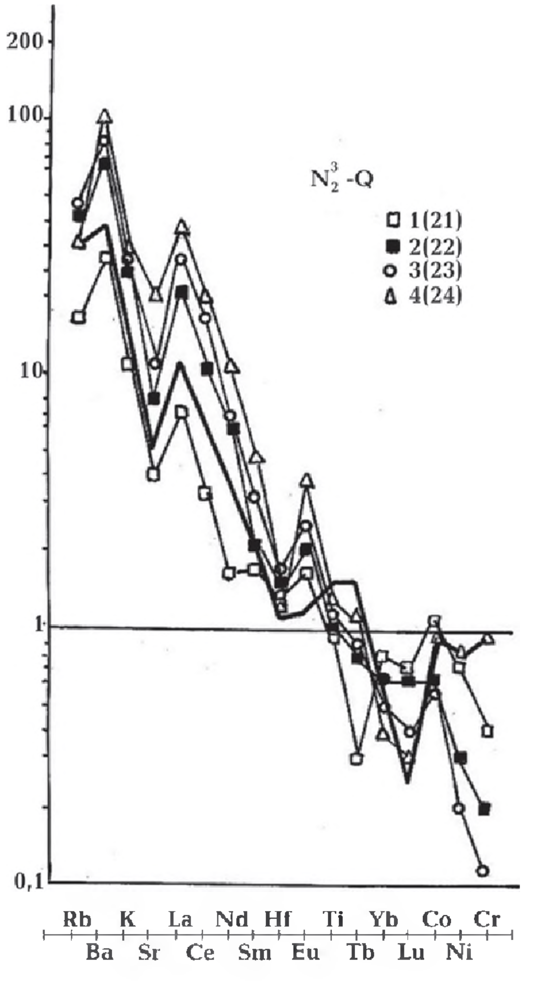

Fig. 4. Normalized multicomponent diagram of the volcanic rock complexes of the Late Pliocene – Holocene: *1* — low potassium dolerite, Trans-Caucasus rise (21); *2* — trakhiandesibasal, Gegam (22); *3* — trakhiandesibasal, Kelbajar (23); *4* — basanite, Kafan, Zangezur suture zone (24).

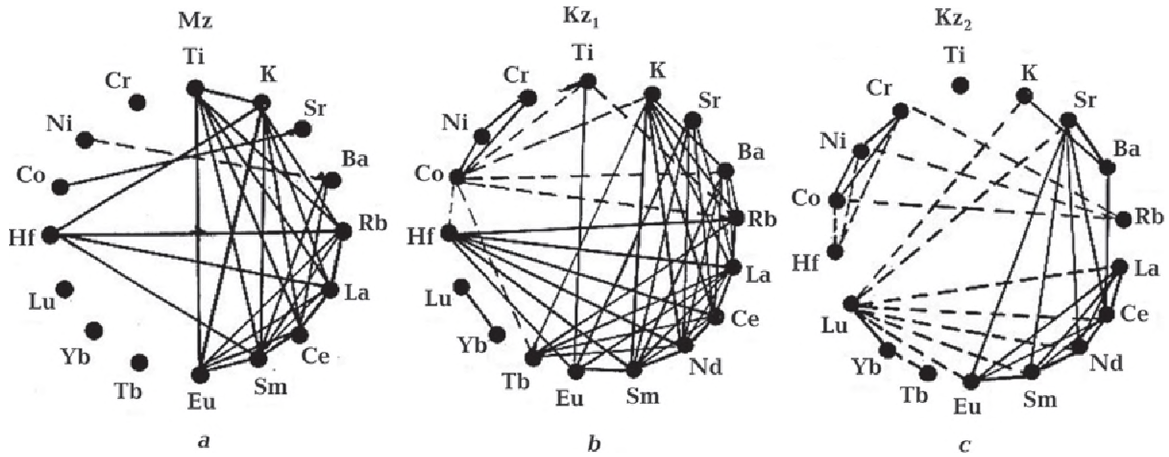

Fig. 5. Correlation of rare elements in Mz (*a*) and KZ (*b*, *c*) in basites of the Lesser Caucasus.

At Late Pliocene—Quarternary stage volcanism is presented by tholeitic (La/Yb=7.5), subalkaline (La/Yb=40.5) and alkaline (La/Yb=66÷70) basalts which are characterized by the increazing accumulation of K, Rb, Ba, Sr, light REE, Ni, Co, Cr. In formation of them one can observe the change of fusion level of magmatic melt from mantle for the first (tholeitic basalt, olivine basanites) to the mantle crustal, intermediate — trachyandesite-basalts (Fig. 5).

Change of low-potassic low-Ti, deplited by light REE of Early Cenozoic volcanites by rather enriched light REE and elements with large ionium radii of Late Cenozoic volcanites can be connected with the change of geodinamics of the region from the active continental margins to activized area of completed olding, accompanied by the rise of fusion front, transported from depleted abnormal mantle in the sphere of metasomatically overdone upper mantle in the base of lithospheric plates.

Active geodynamics of the Caucasus

© *F. Kadirov, S. Mammadov, R. Safarov, 2017*

Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan

We present GPS observations of crustal deformation in the Africa-Arabia-Eurasia zone of plate interaction, and use these observations to constrain broad-scale tectonic processes within the collision zone of the Arabian and Eurasian plates. Within this plate tectonics context, we examine deformation of the Caucasus system (Lesser and Greater Caucasus and intervening Caucasian Isthmus) and show that most crustal shortening in the collision zone is accommodated by the Greater Caucasus Fold-and-Thrust Belt (GCFTB) along the southern edge of the Greater Caucasus Mountains (Fig. 1).

The eastern GCFTB appears to bifurcate west of Baku, with one branch following the accurate geometry of the Greater Caucasus, turning towards the south and traversing the Neftchala Peninsula. A second branch (or branches) may extend directly into the Caspian Sea south of Baku,

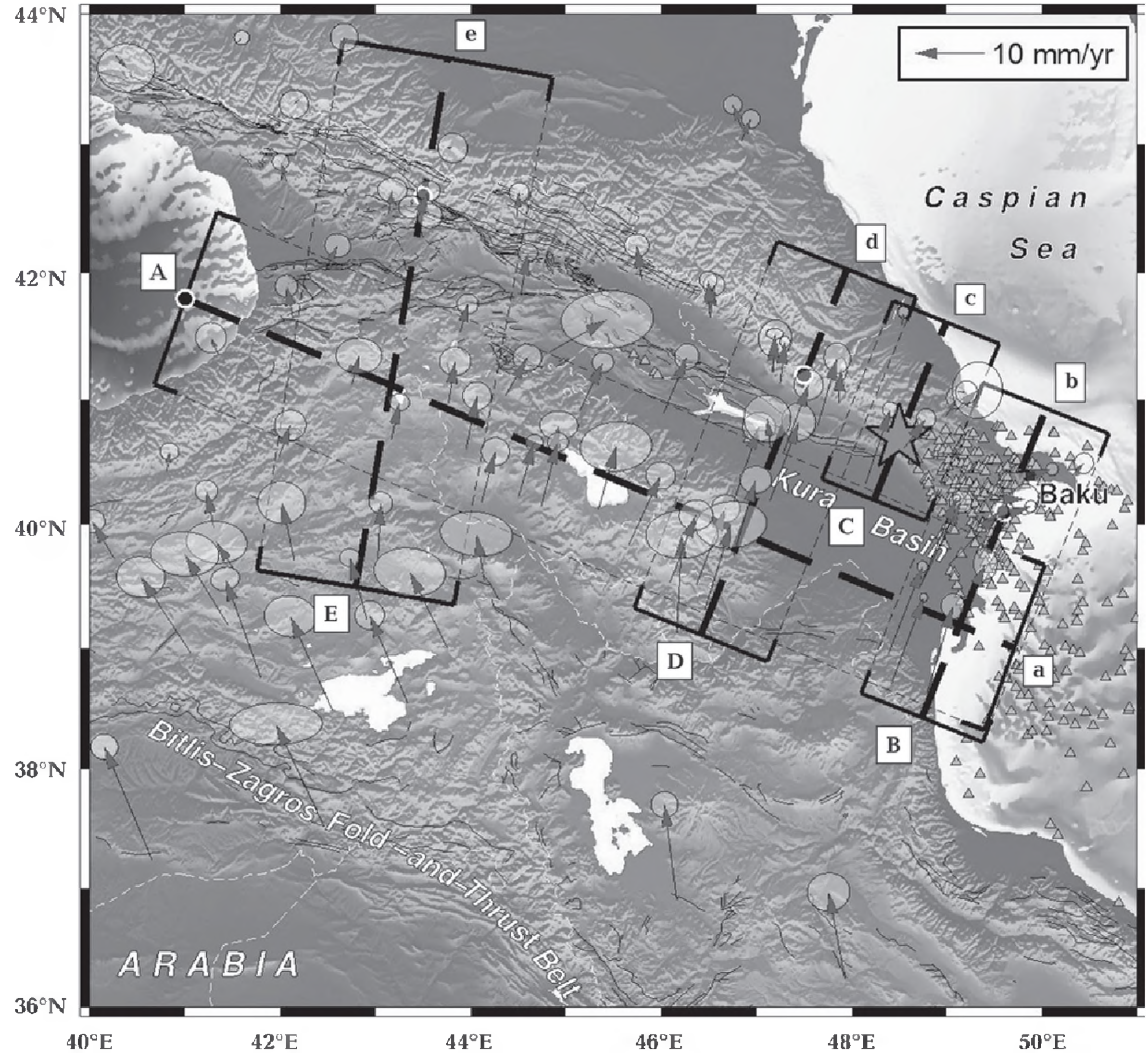

Fig. 1. GPS velocities and 95 % confidence ellipses w.r.t. (with respect to) Eurasia for the eastern AR-EU collision zone.

likely connecting to the Central Caspian Seismic Zone (CCSZ). We model deformation in terms of a locked thrust fault that coincides in general with the main surface trace of the GCFTB. We consider two end-member models, each of which tests the likelihood of one or other of the branches being the dominant cause of observed deformation (Fig. 2).

Our models indicate that strain is actively accumulating on the fault along the ~200 km segment of the fault west of Baku (approximately between longitudes 47—49°E). Parts of this segment of the fault broke in major earthquakes historically (1191, 1859, 1902) suggesting that significant future earthquakes (M~6÷7) are likely on the central and western segment of the fault. We observe a similar deformation pattern across the eastern end of the GCFTB along a profile crossing the Kur Depression and Greater Caucasus Mountains in the vicinity of Baku. Along this eastern segment, a branch of the fault changes from a NW-SE striking thrust to an N-S oriented strike-slip fault

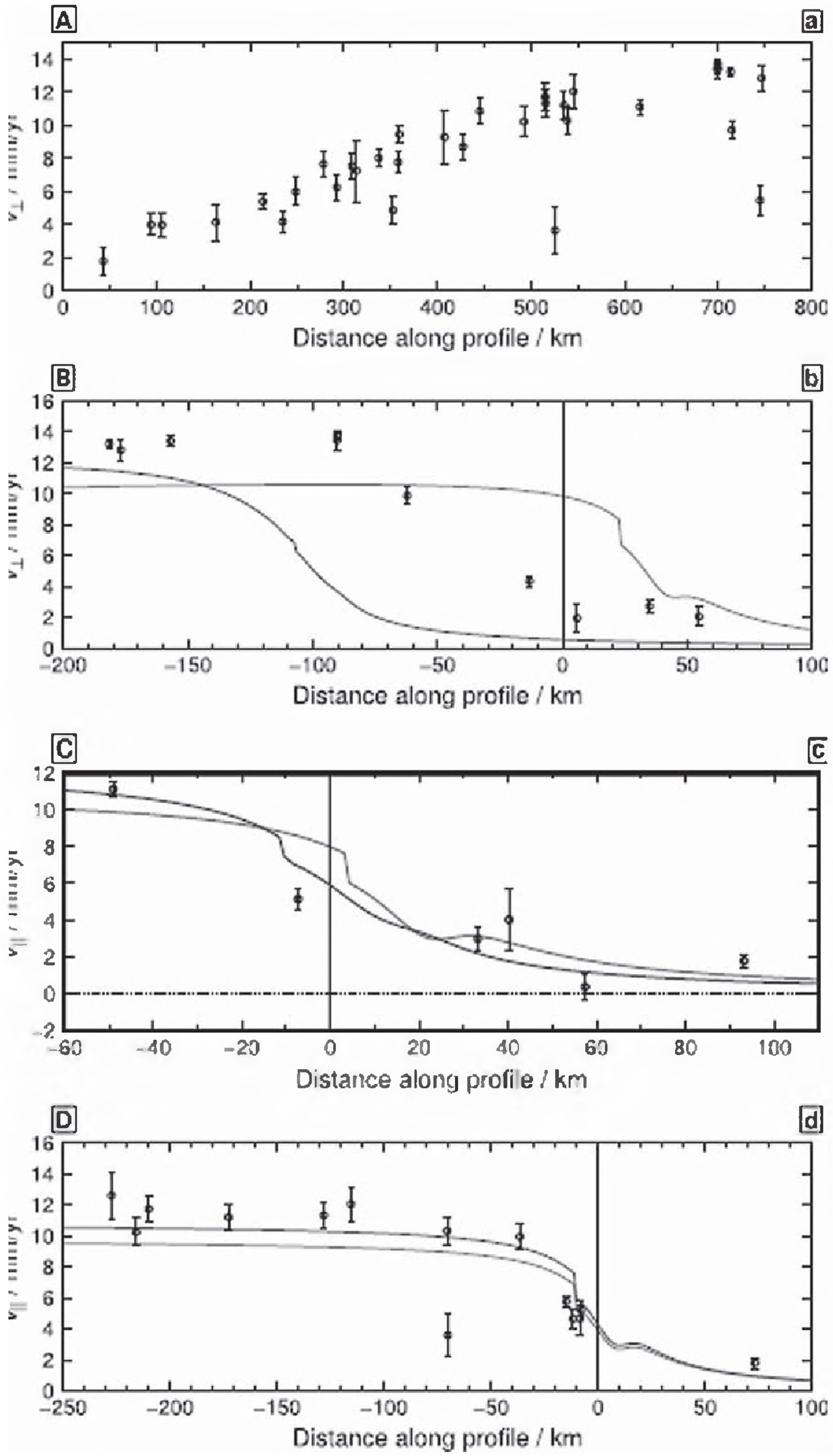

Fig. 2. Plots of transverse (A) and parallel (B-E) components of velocities versus distance along the profilesshown in Fig. 1.

(or in multiple splays). Similar deformation pattern along the eastern and central GCFTB segments raises the possibility that major earthquakes may also occur in eastern Azerbaijan. However, the eastern segment of the GCFTB has no record of large historic earthquakes, and is characterized by thick, highly saturated and over-pressured sediments within the Kur Depression and adjacent Caspian Basin that may inhibit elastic strain accumulation in favour of fault creep, and/or distributed faulting and folding.

Thus, while our analyses suggest that large earthquakes are likely in central and western Azerbaijan, it is still uncertain whether significant earthquakes are also likely along the eastern segment, and on which structure. Ongoing and future focused studies of active deformation promise to shed further light on the tectonics and earthquake hazards in this highly populated and developed part of Azerbaijan.

Active tectonics and focal mechanisms of earthquakes in the pseudosubduction active zone of the North- and South-Caucasus microplates (within Azerbaijan)

© *T. Kangarli, F. Aliyev, A. Aliyev, U. Vahabov, 2017*

Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan

The Greater Caucasus was formed during the last stage of tectogenesis in a geodynamic environment of the lateral compression, peculiar to the zone of pseudosubduction between Northern and Southern Caucasian continental microplates. Its present structure was formed as a result of horizontal movements during different phases and sub-phases of Alpine tectogenesis (from late Cimmerian to Walakhian). The Greater Caucasus is generally considered as a zone where (along Zangi deformation) the insular arc formations of the Northern edge of the South Caucasian microplate thrust under thick Mesozoic-Cenozoic complex composed of marginal sea deposits of Greater Caucasus. The last, in its turn, has been pushed beneath the North-Caucasus continental margin of the Scythian plate (Epihersinian platform) along the Main Caucasus Thrust. As a result of the underthrusting, the accretion prism compressed between the indicated faults, was formed.

Within the territory of Azerbaijan the tectonic stratification of the Greater Caucasus marginal sea alpine complex is distinguished in the structure of the Southern Slope zone (megazone). Within the megazone different-scale and different-age cover-thrust complexes — Tufan, Sarybash, Talachay-Duruja, Zagatala-Dibrar and Govdagh-Sumgayit — were identified and described. Allocated beneath accretionary prism of the Southern Slope, the autochthonous bedding is presented by Mesozoic-Cenozoic complex of the northern Vandam-Gobustan margin (megazone) of the South-Caucasus microplate, which is in its' turn crushed and lensed into southward shifted tectonic microplates gently overlapping the northern flank of Kura flexure along Ganykh-Ayrichay-Alat thrust.

Formation of folded-cover structure of the Greater Caucasus accretionary prism is studied within the geodynamic model of intracontinental C-subduction (pseudo-subduction) under pressure of the advancing northward Arabian plate. This concept for the Caspian-Caucasian-Black Sea region is justified by a number of researches of the region. The described process continues up at the present stage of alpine tectogenesis as demonstrated by real-time GPS survey. Monitoring of the distribution of horizontal shift velocity vectors, produced during 1998—2016 by GPS geodesic stations in Azerbaijan, indicates considerable (up to 29 mm/year) north-northwestward shifting velocity of the southwestern and central parts of South-Caucasus microplate, including territories of the southeastern part of Lesser Caucasus, Kura depression and Talysh. At the same time, within the microplate's northeastern flange confined to Vandam-Gobustan megazone of Greater Caucasus, velocity vectors reduce by 6—13 mm/year, while further to the north, on a hanging wall of Kbaad-Zangi deep underthrust, e.g. directly within the boundaries of accretionary prism the velocity becomes as low as 0—6 mm/year (2010—2016 data). In general, the belt's earth crust reduction is estimated as 4—10 mm/year. This phenomenon reflects consecutive accumulation of elastic deformations within pseudo-subduction interaction zones between structures of the northern flank of South-Caucasus microplate (Vandam-Gobustan megazone) and the accretionary prism of Greater Caucasus.

The ongoing pseudo-subduction is indicated by unevenly distributed seismicity by depths (seismic levels of 2—6, 8—12, 17—22 and 25—45 km): distribution analysis of the earthquake cores evidences the existence of structural-dynamic interrelation between them and the subvertical and subhorizontal contacts in the earth crust. Horizontal and vertical seismic zonality is explained from the viewpoint of block divisibility and tectonic stratification of the earth crust, within the structure of which the earthquake cores are confined mainly to an intersection knots of the ruptures with various strike, or to the platitudes of deep tectonic failures and lateral shifts along unstable contacts of the substantial complexes with different competency.

Types of focal mechanisms in general correspond to the understanding of geodynamics of the microplates convergent borders, where the entire range of focal mechanisms, from normal-fault to upthrust, is observed. At the contemporary stage of tectogenesis the maximum seismic activity is indicated in structures of the northern flank of South-Caucasus microplate controlled by Ganykh-Ayrichay-Alat deep overthrust of the «general Caucasus strike» in the west, and submeridional right-slip zone of the West-Caspian fault in the east of the Azerbaijani part of Greater Caucasus.

Under lateral compression the small-scale blocks that constitute the earth crust in this region become reason for the creation of transpressive deformations, which combine shift movements along limiting transversal deformations with compression structures to include general Caucasus strike ruptures. Such regime leads to the generation of multiple concentration areas of the elastic deformations confined to mentioned dislocations and their articulation knots. It is just the exceeded ultimate strength of the rocks that causes energy discharge and brittle destructions (according to stick-slip mechanism) in such tectonically weakened regions of the southern slope of Azerbaijani part of Greater Caucasus.

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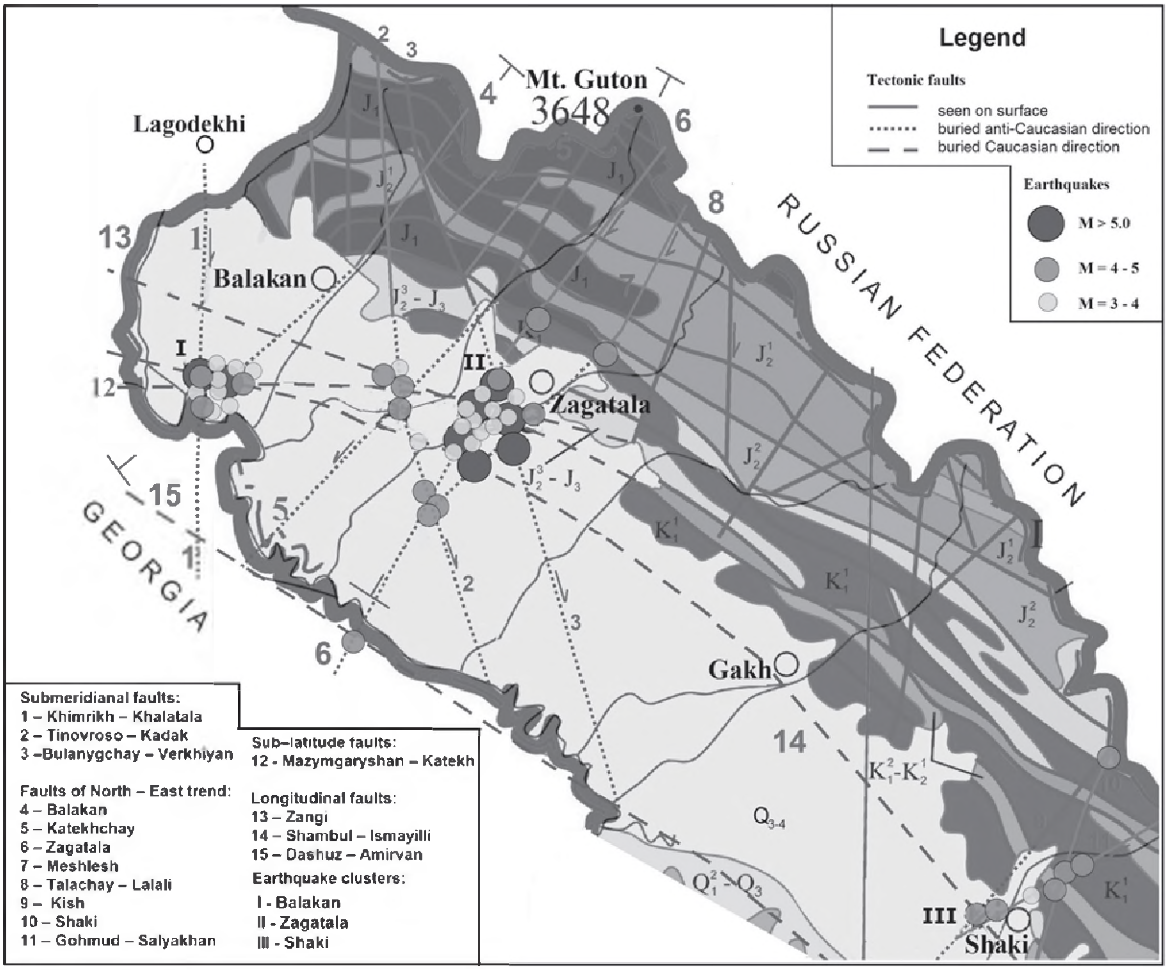

Fig. 1. Allocation of earthquake foci zones of the North-Western Azerbaijan.

«general Caucasus strike» in the west, and submeridional right-slip zone of the West-Caspian fault in the east of the Azerbaijani part of Greater Caucasus. This fact is particularly proved by earthquakes which took place in May and December, 2012 in Zagatala, Shaki and Balakan (Fig. 1).

Zagatala earthquake. Focal zone of the earthquake is confined to a complex intersection knot of different strike faults, and is located in Pre-Jurassic basement. The main shock is related with activity of Zagatala fault with northwestern strike which caused activation of connected dislocations.

Balakan earthquake. Focal zone of the earthquake is confined to a complex intersection knot of the faults with various strikes, and is located in the upper part of Pre-Jurassic basement. Seismic event is mainly related to activity of Khimrikh-Khalatala fault with submeridional strike, which in turn led to activation of connected northeastern Balakan and sublatitudinal Mazymgaryshan-Katekh dislocations. Discharge of seismic energy occurred in most granulated zones confined to the intersection knots of these dislocations with faults of the general Caucasus strike.

Shaki earthquake. The focal zone of the earthquake located in the upper part of Pre-Jurassic basement. Seismic event is connected with activity of subvertical faults with northeastern strike. Discharge of seismic energy occurred in most granulated zones confined to the intersection knots of these dislocations with faults of the general Caucasus trace.

On the basis of the spatial-temporal analysis of the earthquake foci distribution with M ≥ 3 for the instrumental period of observations (1902—2013), we established the dynamics of seismic activity on the southern slope zone of the Greater Caucasus the following are defined:

– the epicenters spatial distribution demonstrates that the above mentioned events are confined to the transverse (northwestern, northeastern, and submeridional strike) disjunctive dislocations. However, epicentral zones are of a General Caucasus strike, dislocated along and to the north of the deep upthrust. Both transverse and longitudinal dislocations are mapped by a complex of seismic and electrical reconnaissance methods. They are characterized as a natural southern extension of the fault-slip type disjunctive zones that outcrop in the mountainous area where structural-substantial complexes of an accretionary zone come to the surface;

– focal mechanisms of events in the separate groups reveal different, mainly close-to-vertical, planes of fault and fault-slip type movements in the earthquake foci. Only in four cases were strictly upthrust and upthrust-overthrust type movements established;

– hypocenters of major seismic impacts (M=4.5÷5.7) and the absolute majority of aftershocks are confined to the surface of the pre-Jurassic basement or its depths (up to 20 km);

– most of hypocenters are confined to a sloping strip which subsides in the northern azimuths, identified with the zone of Ganykh-Ayrichay-Alat deep overthrust and its flakes;

– in general, the seismic activity of a mentioned period is explained by accumulation of lateral compression stresses and their later discharge in an underthrust articulation line from the Middle Kur and Vandam tectonic zones along the Ganykh-Ayrichay-Alat deep overthrust;

– lateral compression first contributed to the creation of transpressional failures along the displacement planes of various-strike transverse dislocations, and the energy discharge in most granulated and weakened areas was confined to the intersection knots of these dislocations between each other and with the deep overthrust with its northern rear flakes.

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Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan

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This phenomenon reflects consecutive accumulation of elastic deformations within pseudo-subduction interaction zones between structures of the northern flank of the South Caucasus microplate (Vandam-Gobustan megazone) and the accretion prism of the Greater Caucasus.

The ongoing pseudo-subduction is indicated by unevenly distributed seismicity by depths (at 2—6, 8—12, 17—22 and 25—45 km depth): distribution analysis of the earthquake foci evidences the existence of structural-dynamic relation between them and the subvertical and subhorizontal contacts in the Earth's crust. Horizontal and vertical seismic zoning is explained from the viewpoint of block structure and tectonic stratification of the crust, where the earthquake foci are confined mainly to intersection nodes of faults of different strike, or to the planes of deep tectonic faults and lateral displacements along unstable contacts of substantial complexes with different competency.

Types of focal mechanisms in general correspond to the understanding of geodynamics at the convergent margins of microplates, where the whole range of focal mechanisms, from normal faults to overthrusts, is observed.

Under lateral compression the small-scale blocks that constitute the crust in this region become a reason for creation of transpressive deformations, which combine strike-slip movements along transversal faults limiting the blocks with compression structures to include general Caucasus strike faults. Such a regime leads to generation of multiple places of localization of elastic deformations confined to mentioned dislocations and their articulation nodes. It is just the exceeded ultimate strength of the rocks that causes energy discharge and brittle deformations (according to strike-slip mechanism) in such tectonically weakened regions of the southern slope of Azerbaijan part of the Greater Caucasus.

At the contemporary stage of tectogenesis the maximum seismic activity is released within the structures at the northern flank of South Caucasus microplate controlled by Ganikh-Ayrichay-Alyat deep overthrust of «general Caucasus strike» in the west, and by ~N-S right-slip zone of the West-Caspian fault in the east of the Azerbaijan part of the Greater Caucasus.

This fact is particularly proved by the earthquakes which occurred in May and December, 2012 in Zagatala, Sheki and Balakan.

Zagatala earthquake. Focal zone of the earthquake is confined to a complex intersection knot of different strike faults, and is located in the Pre-Jurassic basement. The main seismic event is related with activity of Zagatala fault of northwestern strike which caused activation of connected dislocations.

Balakan earthquake. Focal zone of the earthquake is confined to a complex intersection knot of the faults with various strikes, and is located in the upper part of the Pre-Jurassic basement. Seismic event is mainly related to activity of Khimrikh-Khalatala fault of ~N-S, strike, which, in turn led to activation of related N-E Balakan and ~ E-W Mazimgarishan-Katekh faults. Release of seismic energy occurred in most granulated zones confined to the intersection nodes of these dislocations with faults of general Caucasus strike.

Sheki earthquake. The focal zone of the earthquake is located in the upper part of the Pre-Jurassic basement. Seismic event relates with activity of subvertical faults of NE strike. Discharge of seismic energy occurred in most granulated zones confined to the intersection knots of these dislocations with faults of the general Caucasus trace.

Study of the space-time sequence of the earthquakes of different magnitudes in each seismic zone allows us to draw the following conclusions:

– the spatial distribution of foci demonstrates that the earthquakes are confined to the transverse (NW, NE and ~NS strike) faults. However, the epicentral zones have a general strike similar to that of Greater Caucasus, dislocated along and to the north of the deep overthrust. Both transverse and longitudinal dislocations are mapped by seismic and electrical surveys. They represent the southern extension of the fault zones that outcrop in the mountain area where accretion zone rock complexes come to the surface;

– focal mechanisms of events of separate groups reveal different, mainly near vertical, planes of fault in the earthquake foci. Only in four cases there were determined the overthrusts strictly directed upwards;

– the foci of major strong earthquakes ($M=4.5\div5.7$) and the majority of the aftershocks are confined to the surface of the pre-Jurassic basement at the depths down to 20 km;

– most of foci are confined to a sloping strip which subsides in the northern direction, identified with the zone of Ganikh-Ayrichay-Alyat deep overthrust and its flakes;

– in general, the seismic activity of the mentioned period is explained by accumulation of lateral compression stresses and their later discharge in the junction zone of the Middle Kura and Vandam tectonic zones along the Ganikh-Ayrichay-Alyat deep overthrust;

– lateral compression first contributed to the creation of transpressional failures along the displacement planes of various strike transverse dislocations, and the energy discharge in most granulated and weakened areas was confined to the intersection nodes of these dislocations between each other and with the deep overthrust with its' northern flakes.

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Paleo- and recent stress regimes of the Crimea Mountains based on micro- and macroscale tectonic analysis and earthquakes focal mechanisms

© *A. Murovskaya*[1], *Ye. Sheremet*[2], *M. Sosson*[2], *J.-C. Hippolyte*[3], *O. Gintov*[1], *T. Yegorova*[1], *2017*

[1]Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[2]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France
[3]Aix-Marseille Université, Aix-en-Provence, France

The Crimea Mountains (CM) belongs to the northern branch of the Alpine Belt. Being the northwestern continuation of the Greater Caucasus (GC) and a part of the inverted northern margin of the Black Sea (BS), the CM region shows the similarities in structural development of both the domains, implying the common tectonic evolution of the GC — Eastern BS area.

In the current study, we focus on the Meso-Cenozoic time-span of tectonic evolution of the CM and the adjacent BS margin in order to define paleo- and recent stress regimes alternated during its tectonic history, based on the recent geological field observations, the results of structural analysis, the microtectonic data and the analysis of focal mechanisms of the earthquakes. Thus, the main purpose of our study is to find and investigate the correlation between the stress field and the large-scale deformation structures with subsequent determination of major tectonic events.

The Cenozoic compression. The major direction of the shortening during the Cenozoic was defined in regards of main orientation (trends) of the thrusts and fold axis developed in the Eastern CM and its nearest offshore area [Sheremet et al., 2016a, b]. Thus, the westernmost part of the Eastern CM is characterized by the NW-oriented compression, while its eastern part is characterized by NNW-SSE direction of the shortening. Two stages of the shortening during the Cenozoic were defined based on the major Middle Eocene unconformity: the age-frames of the earliest compression stage is defined as the Paleocene—Middle Eocene time, whereas the youngest compression is suggested in the Oligocene—Middle Pliocene.

Reverse regime. For the majority of sites in the CM we obtained the large display of reverse regimes with σ_1 trending N-S, NNW-SSE and NW-SE. According to orientation of the thrust front defined offshore, the NW-SE orientation of the σ_1 compressional axis prevails in the CM during the formation of the main compressional structures. It also has a point for the NE-SW oriented structures of the southwestern part of the Kerch Peninsula (KP).

In the area of Sudak the N-S shortening was defined. This N-S and NNE-SSW trend of shortening can be traced in KP where the corresponding structures overthrust those, which were formed under the NW-SE compression. Moreover, the reverse regimes with σ_1 trending NNE-SSW characterize the structures of the Western CM. Thus, the first compression, which follows the Cretaceous extension stage, was the one of, mainly, NW-SE orientation.

Strike-slip regime. The analysis of the structural patterns in the Eastern CM reveals several faults of NE-SW and NNE-SSW trends with left-lateral strike-slip movements along them. These strike-slip faults cut several thrusts and displaced laterally the thrust front in several places. In other cases, there is a right-lateral displacement along NW-SE strike-slip faults. These strike-slip faults also expressed in the youngest deposits of the Miocene-Pliocene age.

For the westernmost part of CM the strike-slip regimes with NE-SW orientation of σ_1 axis were obtained. We consider their relation with the activity along the Western Crimea dextral strike-slip fault. This is confirmed by focal mechanisms of the earthquakes occurred at recent tectonic stage in the Western Crimean Seismic Zone [Gobarenko et al., 2016].

A strike-slip regime with N-S orientation of the σ_1 axis was also detected in the easternmost part of the Eastern CM. We relate some NNE-SSW-oriented left-lateral strike-slip faults during the Miocene-Pliocene, in agreement with [Saintot et al., 1999], to the latest transtensional regime with E-W orientation of σ_3 axis. Thus, the N-S trend of the compression characterizes the youngest tectonic stage of the CM evolution resulting in a numerous strike-slip faults in the Eastern CM and folding of E-W trend in KP.

Normal regime. A large variety of data related to the normal faulting type regimes were obtained in the CM. Based on the structural analysis and field observations two types of normal regimes have been defined in the area.

1. Extensional deformations **in regards to the rifting stage of the BS** during the Cretaceous. These normal faults, containing the relict slickensides, tectonic breccias and traces of attached marine organisms, confine the Early Cretaceous depressions within the CM. The corresponding stress fields are characterized by N-S and NNE-SSW trend of the σ_3 extensional axis in the Western Crimea and by the NE-SW orientation of the σ_3 axis in the Eastern CM. New stratigraphy dating and structural analysis in the Western CM indicate a later extensional stage for the Western BS (Valanginian-Barremian) [Murovskaya et al., 2014] than for its Eastern part when the latter experienced the loading of the GC basin since the Middle Jurassic.

2. The second type of extensional deformations corresponds to the NW-SE orientation of σ_3 axis perpendicular to the NE strike of the compressional structures, which is manifested in the main scarp of the slope offshore the Eastern CM. We relate it with a gravitational effect (sliding) that occurred during the uplifting of the Crimea due to the shortening, thus, some structures, formed under the compression, underwent the extension. It also finds the support in the orientation of the Eocene extensional syndepositional faults. Possibly, they relate with the formation of the piggy back basin on top of the highest allochtonous unit northwards.

Recent regime. Along the northern margin of the BS (the Crimea-Caucasus coast), the main structures of shortening are marked by an active Crimea Seismic Zone (CSZ). The analyses of the **focal mechanisms of 31 strong earthquakes** during 1927—2013 reveals the recent transpression regime in the western part of the CSZ whereas in its eastern part, according to seismicity, gravity field, modes of deformation and the velocity model, it is possible to suggest the present day compressional regime. The latter demonstrates: 1) the reactivation of basement faults that, according to [Sydorenko et al., 2016], related to the formation of the Triassic basin, and 2) indicates the underthusting of the East BS highly extended crust under the Scythian Plate continental crust.

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Magmatism and ore formation on the example of Upper Cretaceous Bertakari and Bneli Khevi Ore deposits, Bolnisi ore district, Georgia

© N. Sadradze[1], Sh. Adamia[1], T. Beridze[2], T. Gavtadze[2], R. Migineishvili[2], 2017

[1]Tbilisi State University, M. Nodia Institute of Geophysics, Tbilisi, Georgia
[2]Tbilisi State University, A. Janelidze Institute of Geology, Tbilisi, Georgia

Magmatic evolution is an important event in the formation and development of the geological structure of Southern Georgia, where several reliably dated volcanogenic and volcanogenic-sedimentary formations are established. The region represents a modern analogue of continental collision zone, where subduction-related volcanic activity lasted from Paleozoic to the end of Paleogene. After the period of dormancy in the Early-Middle Miocene, starting from the Late Miocene and up to the end of the Pleistocene, syn-postcollisional primarily subaerial volcanic eruptions followed by formation of volcanic highlands and plateaus occurred in the region.

The Artvin-Bolnisi unit forms the northwestern part of the Lesser Caucasus and represents an island arc domain of so-called the Somkheto-Karabakh Island Arc or Baiburt-Garabagh-Kapan belt. It was formed mainly during the Jurassic-Eocene time interval on the southern margin of the Eurasian plate by north-dipping subduction of the Neotethys Ocean and subsequent collision

Ma	Age	Formation	Thickness	Lithology	Description
72,1	Maastrichtian	Tetritscaro K_2t	200–300 m		Limestones, marls, interlayers of epiclastic deposits
	Senonian	Shorsholeti K_2sh	150–350 m		Extrusive, coarse-grained, medium-grained and fine-grained volcanoclastic rocks of calc-alkaline and sub-alkaline andesite-basaltic composition; interlayers of limestones, marls and epiclastic deposits
	Senonian	Gasandami K_2gs	150–600 m		Extrusive, coarse-grained, medium-grained and fine-grained volcanoclastic rocks of calc-alkaline dacite-rhyolitic composition; interlayers of limestones, marls and epiclastic deposits
	Senonian	Tandzia K_2tn	150–700 m		Extrusive, coarse-grained, medium-grained and fine-grained volcanoclastic rocks of calc-alkaline andesite-basaltic composition;f rare interlayers of limestones, marls and epiclastic deposits
89,8	Senonian	Mashavera K_2ms	250–1000 m		Extrusive, coarse-grained, medium-grained and fine-grained volcanoclastic rocks of calc-alkaline dacite-rhyolitic composition; interlayers of carbonate and epiclastic deposits
	Senomanian-Turonian	Didgverdi K_2dg	250–750 m		Extrusive, coarse-grained and fine-grained volcanoclastic rocks of andesite-basaltic composition; interlayers of limestones, marls and epiclastic deposits
	Senomanian-Turonian	Tseraqvi K_2ts	50–400 m		Extrusive, medium-grained and fine-grained volcanoclastic rocks of dacite-rhyolitic composition; interlayers of limestones and epiclastic deposits
100,5	Senomanian-Turonian	Opreti K_2op	60–70 m		Conglomerates, gritstones, sandstones, limestones and fine-grained volcanoclastic rocks

Fig. 1. Lithostratigraphic column of the Upper Cretaceous deposits of the Bolnisi ore district, modified by [Adamia et al., 2016].

of the Anatolia-Iranian continental plate.

The Artvin-Bolnisi tectonic unit, including the Bolnisi ore district, was developing as a relatively uplifted island-arc type unit with suprasubduction magmatic events. Volcanogenic complexes are characterized by variable lateral and vertical regional stratigraphic relationships and are subdivided into several formations due to their composition. Volcanics are attributed to calc-alkaline-subalkaline series. Depositional environment of the Upper Cretaceous volcanic formations varies from shallow-marine to subaerial settings. Mafic to intermediate volcanic rocks

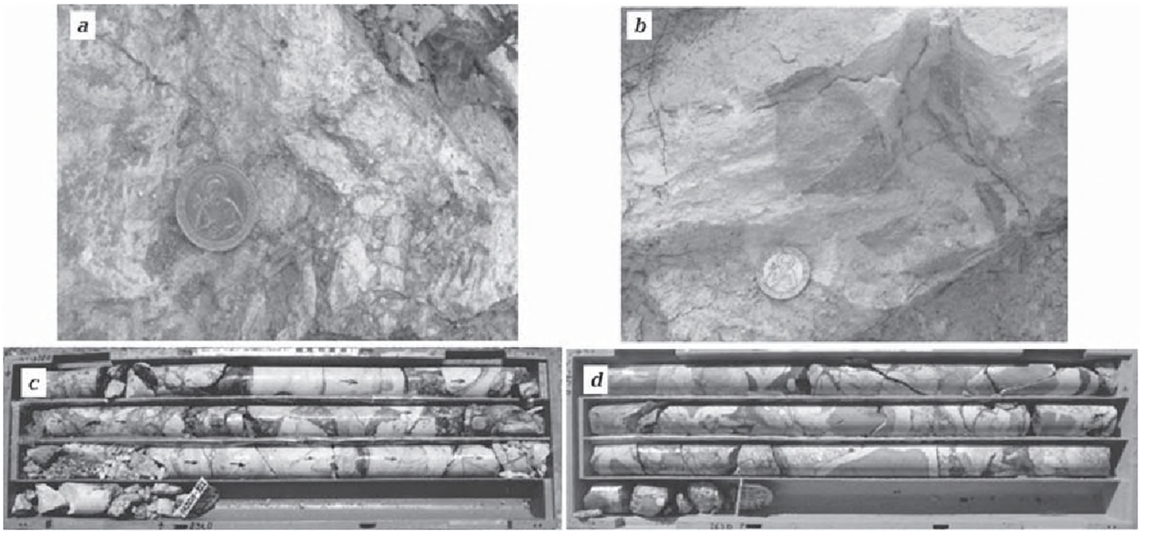

Fig. 2. Types of hydrothermal breccias: *a* — hydrothermal breccia, Bneli Khevi outcrop; *b* — pseudobreccia, Bneli Khevi outcrop; *c* — hydrothermal breccia, Bertakari, Kldovani Ubani, core image BK 822, 228—231 m; *d* — pseudobreccia, Bertakari, Kldovani Ubani, core image BK 875, 260—263 m.

are in subordinate amount. Felsic formations (Mashavera and Gasandami) are the major hosts of numerous ore deposits (Madneuli, Sakdrisi, Bertakari, Bneli Khevi etc.) within the ore field (Fig. 1).

The common consent of the researchers exists about the genetic link of the Bolnisi ore field gold-polymetallic ore-forming processes with the late Cretaceous suprasubduction magmatism. The latter is related to the north-dipping subduction zone of the Lesser Caucasus which conditioned island-arc type volcanic activity and mineralization of the late Cretaceous Tethys and its northern active margin.

Campanian nannoplankton fossils have been discovered in hydrothermally slightly altered rocks (pelitic tuffs, tuff-argillites, tuff-sandstones) of Bertakari area.

The peculiarities of magmatic activity and geodynamic development of the region stipulated synchronous formation of significant base and precious metals deposits of the Bolnisi ore district.

Within the Bolnisi ore district, Bertakari and Bneli Khevi deposits host lithofacies and spatial distribution of associated mineralization that has been studied. The outcrops and drill cores visual observations as well as thin section microscopy has revealed the link of the mineralization to various types of breccias (phreatic, phreatomagmatic and hydrothermal) within Bertakari and Bneli Khevi.

It is noteworthy the recognition of hydrothermal breccias with jigsaw-fit clast textures (Fig. 2, *a*, *b*) and pseudobreccias (Fig. 2, *c*, *d*) in the mentioned above deposits [Gelashvili et al., 2015; Lavoie, 2015]. Pseudobreccias are resulted from diffusive/selective alteration of intrusive, subvolcanic or volcaniclastic rocks. Development of jigsaw-fit clast textures in breccias is induced by hydraulic brecciation [Cas et al., 2011].

The deposits are hosted by Gasandami formation that is represented by following lithofacies types: felsic volcanic lapilli tuffs, ignimbrites, pumice tuffs and reccias and rhyodacitic dome. The existence of epigenetic hydrothermal breccia bodies is the common feature of many geodynamic setting types, especially of island-arcs, and is the substantial part of the long-lasting history of magmatic-hydrothermal activity [Howard et al., 2015].

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Paleogene sedimentary development and tectonic conditions of shagap piggyback basin (Armenia)

© L. Sahakyan[1], M. Sosson[2], A. Avagyan[1], D. Bosch[3], T. Grigoryan[1], S. Vardanyan[1], O. Bruguier[3], 2017

[1]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[2]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France
[3] Université de Montpellier II, UMR Géosciences, CNRS, Montpellier, France

Shagap syncline is elongated asymmetric basin presented by Paleogene deposition of about 1.5 km thicknesses. Sedimentation took place after collision of Eurasian plate and South Armenian Microcontinent (SAM). In Middle Eocene—Oligocene time piggyback basin by slope deposition and turbidite accumulation, controlled by gravitational processes, was formed. Lithologically different type of deposition in this partly isolated basin is the result of constant input of terrigenous material, volcanism and palaeoclimate changes.

Discocyclina-Nummulitic limestones (*packstone/grainstone*) without micrite and cement evidence shallow marine slope environment where regular flow was available. Nummulite and red algae (*Lithothamnion*) limestones show relatively low light sea environment (*oligophotic zone*). Coralline built with nummulitides were formed in-situ indicating accumulation in a shallow condition with intense light (photic zone).

Trachyandesite dikes and sills (AL10-14 — N 39° 57.296', E 44° 51.195') were injected into Lower Paleocene—Lower and Middle Eocene sedimentary rocks.

Shoshonite series trachyandesites normalised by chondrites have mobile elements enrichment (Rb, Ba and Th) with negative HFSE (Nb, Ta) anomalies. The $(La/Sm)_{CN}$ ratio yield 6.84 value but the $(La/Yb)_{CN}$ ratio is 38.17, suggesting the presence of residual material from the deep magmatic source. Neodymium and strontium isotopes yield low $\varepsilon Nd_{(14.5Ma)}$ and high $^{87}Sr/^{86}Sr_{(14.5Ma)}$ ratios, respectively –0.4 and 0.7054. Initial Pb/Pb isotopic ratios yield $^{207}Pb/^{204}Pb_{(i)}$ — 15,67; $^{208}Pb/^{204}Pb_{(i)}$ — 39.05, suggesting EM2, slab-component contribution and crustal contamination.

The obtained U-Pb zircon age for trachyandesites is 14.5±0.2 Ma, which is coincident with magmatism reactivation in the Middle-Upper Miocene, after Arabian-Eurasian plates collision in the Upper Eocene-Oligocene.

Tectonic evolution of the Crimean Mountains since the Triassic: Insight from the new dating and on-and-offshore structural data (macro- and microscale), In general tectonic context of the Greater Caucasus-Black Sea domain

© *Ye. Sheremet[1], M. Sosson[1], A. Murovskaya[2], O. Gintov[2], T. Yegorova[2], 2017*

[1]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France
[2]Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine

The Crimea, being a part of the Black Sea-Greater Caucasus system (BS-GC), owes its origin to the subduction of the Neotethys beneath the Eurasian margin which is the main geodynamical process that had a significant influence on the development of the Crimea and changed the tectonic conditions during its geological history.

Two main tectonic stages were recorded in BS-GC region concerning the subduction of the Neotethys and its closure: 1) the opening of the BS and the GC basins in a back-arc position, starting from the Early-Middle Jurassic and then after during the Early to mid-Cretaceous and in the Paleocene-Eocene times; 2) the continental collision between the Eurasian margin with the Taurides-Anatolides and the South Armenian Microplate (TASAM) and then with Arabian plate. This collision triggered the shortening of the BS Basins, thus, the inversion structures have been described all around the Black Sea (Pontides-Balkanides orogens, Romanian shelf and the area of Odessa Shelf—Crimea—Greater Caucasus).

The presence of two flysch units of different ages (Tauric Gp and Cretaceous basin deposits) that are outcropping in the CM reveals a period of subsidence. That allows the conclusion about the formation of the Triassic Trough (Basin) within the southern margin of Laurasia in the fore/back-arc position. The normal faults in the basement which have been formed during this period in consequence will be reactivated during the following BS rifting stage and the Cenozoic shortening [Sydorenko et al., 2016[).

The enigmatic Cimmerian deformations, in addition to other well-known stated versions, one can suggest a slab shallowing during the Early Jurassic that could result in compression (accretion) of basin sediments.

The extensional stage, in the Crimea region, was followed by the development of the GC back-arc Basin in the Early-Middle Jurassic and capped by back-arc magmatism of the Middle Jurassic related to the subduction ($^{40}Ar/^{39}Ar$ dating and the geochemical analysis of magmatic rocks, according to [Meijers et al., 2010]) in both future mountain systems.

The Jurassic period is characterized by wide distribution of massive carbonated platforms and reef limestones on top of the deformed basinal deposits of the Triassic-Middle Jurassic age (the carbonate build-up are known in the GC, and evidential from the seismic data on the Shatskiy Ridge). These carbonated facies, much of them are platform, continued through the entire Late Jurassic-Berriasian time span (till the Hauterivian) in the central CM. The olistoliths origin of large carbonated Plateaus in the Crimea is not confirmed during the field observations.

During the Early Cretaceous the BS basin (a back-arc basin, north of the subduction zone of Neotethys beneath Eurasia) was initiated by rifting and then, a probable spreading center produced the oceanization of this basin [Sosson et al., 2016]. Subduction of the spreading center of the north branch of Neotethys formed an asthenospheric window. It could produce heating and, as the result, the weakening of the strong lithosphere of Eurasia. This process should initiate the rifting of the Eastern BS during the Early Cretaceous, and then, as mentioned by [Stephenson, Schellart, 2010]), the roll back of the slab should favor the opening of this small oceanic basin probably during the time limit between Early and Late Cretaceous.

The inversion of the North Eastern BS margin is also the result of the evolution of the Neotethys subduction zone. During the Latest Cretaceous—Middle Eocene period (74—40 Ma), collision between a continental microplate (TASAM) with the Eurasia initiated in the Lesser Caucasus and then continued westward during the Eocene. The inversion of the CM commenced during the Paleocene [Sheremet et al., 2016a, b]. Thus, we suggest that the collisional process to the south of the Eastern BS initiated the compression in the CM by reactivation of the Late Triassic-Early Jurassic normal faults in the basement. Then, after a period of a low rate compression (Middle Eocene), the inversion since the Latest Eocene has been renewed. Probably, this second period of shortening in the Crimea could be explained by initial collision of the Arabian plate with Eurasia since they coincide in time. The very extended (sub-oceanic) crust, created during the Cretaceous by the latest period of shortening (latest Eocene-Miocene time span) have been already cold enough and, therefore, mechanically stronger in order to affect the continental margins and produce the compressional deformations. The Shatskiy Ridge plays as indenter in the underthrusting of the Eastern BC margin. Thus, the CM have been occurred as a result of a thin skin tectonic offshore and both thick- and thin-skin tectonic on land [Sheremet et al., 2016a].

In the Latest Miocene the Messinian sea level drop, recorded in the significant erosion surface offshore, against the background of continuing shortening, most likely triggered the mud volcano activity that at present is the distinctive feature of the BS topography.

The current stage of the CM is characterized by the seismicity of magnitude 4—6 located in lower crust and upper mantle at depth between 30 and 38 km showing, mainly a north dipping plan of its distribution in the Eastern CM [Gobarenko et al., 2016]. The reverse faults in the basement, as well as strike slip faults, reactivated by the inversion of the BS (Alushta-Simferopol fault, Western Crimea dextral strike-slip fault), should be responsible for the main seismic activity in Crimea.

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The highlights and the contribution of International Research Group (IRG) «South Caucasus Geosciences» (France, Armenia, Azerbaijan, Georgia and Ukraine)

© M. Sosson[1], S. Adamia[2], T. Kangarli[3], A. Karakanian[4], V. Starostenko[5], T. Danelian[6], J. F. Ritz[7], 2017

[1]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France
[2]Javakhishvili Tbilisi State University, Tbilisi, Georgia
[3]Institute of Geology and Geophysics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan
[4]Institute of Geological Sciences, National Academy of Sciences of Republic of Armenia, Yerevan, Armenia
[5]Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[6]Université de Lille, CNRS, UMR Evo-Eco-Paleo, Lille, France
[7] Université de Montpellier II, UMR Géosciences, CNRS, Montpellier, France

Initiated in collaboration within the framework of projects funded by the European programmes INTAS, Erasmus Mundus and PICs, LIA programmes of the CNRS/INSU, three French laboratories (Géosciences of Montpellier, Géoazur of Nice Sophia Antipolis and Evo-Eco-Paleo of Lille), and Institutes of Academies of Sciences and Universities of Armenia, Azerbaijan, Georgia an International Research Group (IRG: GDRI de CNRS/INSU) «South Caucasus Geosciences» were founded in 2010. Ukraine, presented by Institute of Geophysics of the Academy of Science of Ukraine, became one of the partners of IRG in 2014.

With a support of Middle East Basins Evolution and DARIUS programmes (consortium of oil companies, Univ. Pierre et Marie Curie Paris VI, and CNRS/INSU) this IRG aimed at solving the Earth Sciences questions, mainly in resources and hazard fields, in the Caucasus-Eastern Black Sea Domain (CEBSD) that has a high potential in research since this part of the Alpine belt evolved during the long-lived subduction of the Neotethys ocean due to its closure (see for a review e.g. [Sosson et al., 2010, 2016]).

The main issues to solve in the eastern Black Sea and Caucasus realm in this geodynamic context are: 1) the time-space evolution of geodynamic processes (subduction, oped in these tectonic settings; 3) the relation in time and the continuity of structures between the eastern Black Sea, the Greater Caucasus, the Lesser Caucasus and those of the Taurides-Anatolides, Pontides belt and of the NW Iran as well.

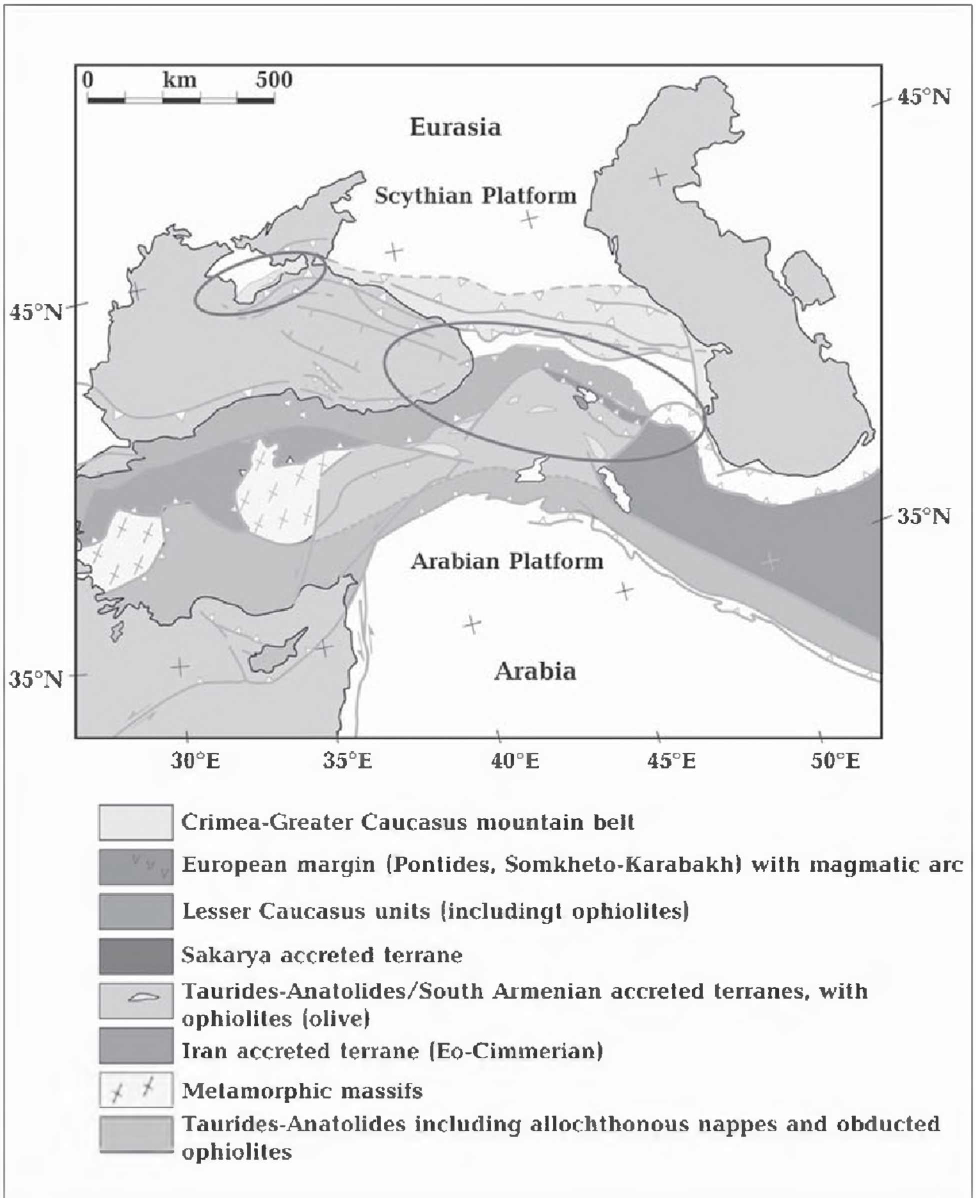

Fig. 1. Tectonic map of the Black Sea-Caucasus domain and surrounding areas, modified from [Sosson et al., 2016, 2017], showing the main field locations of IRG studies.

obduction, collision) responsible for the closure of the northern and southern branches of Neotethys; 2) the timing of deformation and the evolution of the back-arc basins devel-

An integral part of the project, exchange of scientists, apart from the important role of joint research, favored to the development of its international level, giving the birth to a new generation of scientists able to provide the research in the good tradition of French (European) geological school (Masters, PhDs, postdocs).

A significant part of these **valuabl**e **results** constitute: two volumes of Special Publications of the Geological Society of London (Vol. 340 and 428), they have been published in the international and local editions, as well as presented in Ph.D Thesis. It is a multidisciplinary study covering topics in structural geology/tectonics, passive and active source seismology and seismic profiling, deep Earth's structure (seismic images), geochemistry, palaeontology, petrography, paleomagnetism, geochronology, sedimentology and stratigraphy, reporting results obtained during the DARIUS programme and related projects in the eastern Black Sea and Caucasus realm.

During 2014—2017 our IRG group worked in the region north of the Eastern Black Sea Basin (Crimea), in the Greater Caucasus (Georgia and Azerbaijan), and in the Lesser Caucasus (Armenia, Azerbaijan and Georgia) aiming to precise the evolution of the Eastern Black Sea-Caucasus realm primarily during the Mesozoic-Cenozoic time span.

During this time the tectonic setting of the area can be characterized as one of general plate convergence as the Neotethys Ocean (or branches of a Neotethys Ocean system) was subducted and eventually closed. The geological record is essentially one of sedimentary basins being formed in an extensional back-arc setting and through to the compressional deformations (inversion) of these basins linked to the Neotethys closure and the consequences of the related deformations. The inversion of basins has roughly occurred in two main phases: 1) from Late Cretaceous to Early Eocene linked broadly to the closure of what is referred to as the northern branch of Neotethys, and 2) from Oligocene to recent, linked broadly to the closure of what is referred to as the southern branch of Neotethys, which corresponds to the eventual suturing of the Arabia with Eurasia.

The main directions of our activity within the IRG project: 1) onshore geological studies from Georgia, Azerbaijan, Armenia and Iran; 2) onshore geological studies from the Black Sea margins of Crimea and Turkey as well as geophysical data and other subsurface data from the eastern Black Sea and its northern margin.

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Deep crustal structure of the transition zone of the Scythian Plate and the East European Platform (DOBRE-5 profile): consequences of the Alpine Tectonic evolution

©V. Starostenko [1], M. Sosson [2], L. Farfulyak [1], O. Gintov [1], T. Yegorova [1], A. Murovskaya [1], Ye. Sheremet [2], O. Legostaeva [1], 2017

[1]Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[2]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France

In 2011 an international team carried out the DOBRE-5 WARR (wide-angle reflection and refraction) seismic profile [Starostenko et al., 2015]. Its major part runs in the W-E direction through the Scythian Plate in the northwestern shelf of the Black Sea (BS) and the plain Crimea. The velocity section on the profile indicates a seismic boundary inclined eastwards with a low angle. The boundary is traced at the depth of ~2 km near the Zmeinyj Island then it goes below the northwestern shelf (Karkinit Trough) and beneath the plain Crimea, and plunges to a depth of 47 km at the transition to the Kerch Peninsula. This zone is interpreted as a transition zone (TZ) between the Eastern European platform (EEP) and the SP, naimely on the seismic profile we the projection of this zone [Starostenko et al., 2015].

A geodynamic interpretation of this tectonic zone, proposed by Farfulyak [2015], considers it as the Paleozoic North Crimean suture of Yudin [2008], formed as a result of the closure of the Paleotethys ocean during the Paleozoic-Triassic time span.

New results, obtained in the framework of our IRG project in regards to the northern margin of the BS: 1) The new onshore structural data in the Crimean Mountains (CM) [Murovskaya et al., 2014; Sheremet et al., 2016b] and 2) the new structural offshore data (Sorokin Trough and Kertch Taman Trough) [Sheremet et al., 2016a; Sydorenko et al., 2016] allowed us to identify the structures developed in the CM and the northern margin of the BS in the context of two generalized phases of evolution: Mesozoic extension and Cenozoic compression.

In the current presentation we propose an interpretation of the DOBRE-5 seismic model and show the development of the TZ between the EEP and SP during the Alpine orogenesis in the frames of the Crimean-BS evolution.

Mesozoic extension. The red dashed line on Fig. 1 shows the projection of the transitional zone (TZ) between EEP and SP on the DOBRE-5 profile; the zone itself is located to the north and has a ~W-E strike. According to the interpretation, the Paleozoic-Mesozoic basement of the SP is displaced by the gently dipping normal fault, reaching the Moho boundary: the thickness of the Paleozoic-Mesozoic deposits is twice thicker on the footwall than on the hanging wall of this fault.

We suppose, that this listric fault (outlined by 1 in Fig. 1) plays an active role (also?) during the Cretaceous rifting. It is found the support in presence of a high-velocity body (HVLC in Fig. 1) detected in the lower crust in the area of Karkinit Trough. Such HVLC bodies are very typical for the rift zones.

Cenozoic compression. The Paleozoic-Mesozoic basement of the SP (the Central Crimean uplift) includes the layers of increased velocities (V_P=6.22÷6.3 km/s) at the depth of 4—15 km (See Fig. 1), which we interpret as the parts (blocks) of the pre-Riphean basement, involved in the thrusting. The age of the compression postdates the Mesozoic, since the Mesozoic strata is affected by thrusts.

Several detachments of gentle dipping at the depths of 15 and 7 km (denoted by 2

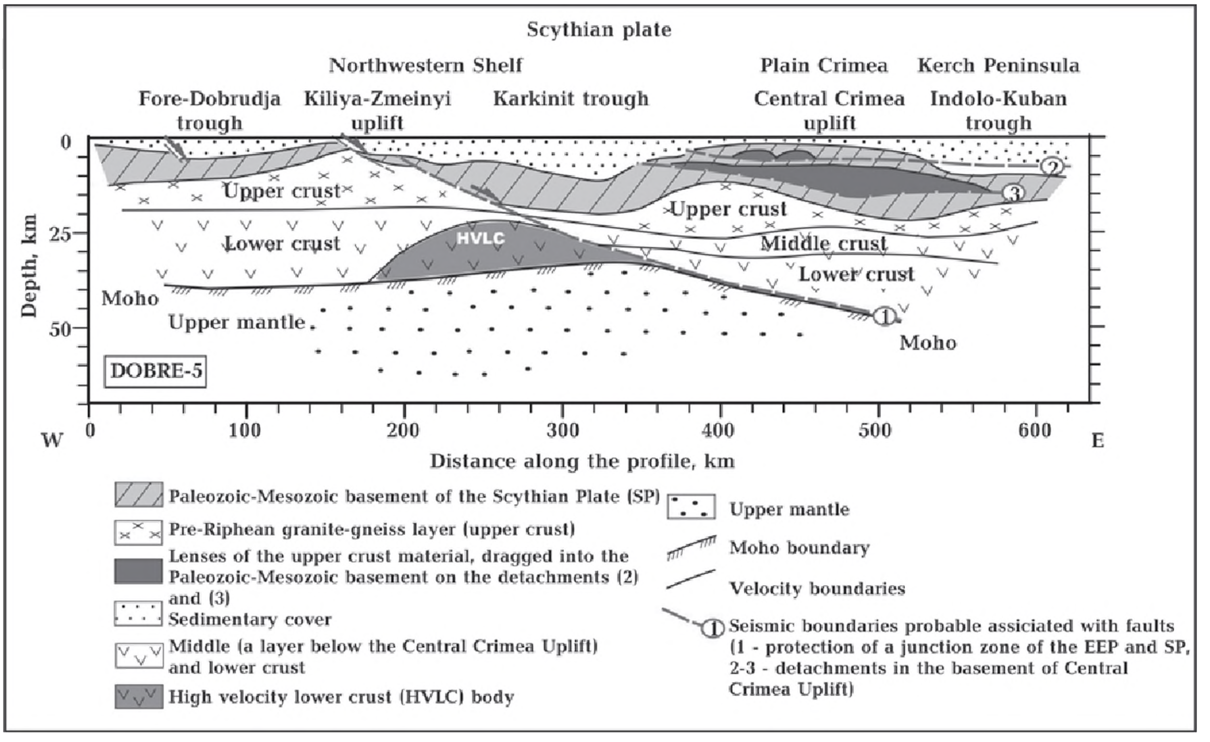

Fig. 1. Interpreted seismic model on the DOBRE-5 profile.

and 3 in Fig. 1) we relate with the Cenozoic compression that most likely was released in two-stages:1) during the Paleocene-Early Eocene, revealed by the recent structural and geological studies, onshore and offshore [Sheremet et al., 2016a, b; Sydorenko et al., 2016] and 2) in the latest Eocene — Pliocene which is also evident on many seismic profiles from the western and northwestern shelf of the BS [Khriachtchevskaia et al., 2010; Morosanu, 2012; Dinu et al., 2005; Munteanu et al., 2013; Sheremet et al., 2016a; Sydorenko et al., 2016].

In the upper part of the interpreted cross-section (See Fig. 1) we distinguished several normal faults that affected the middle Miocene-Quaternary sediments, which we associate with the continuing loading of the western BS. In regards to the Eastern BS, here we observe the uplifting of the CM due to the collisional processes [Murovskaya et al., 2014; Gobarenko et al., 2016].

Detailed interpretation of the DOBRE-5 profile allowed clearing up the long tectonic evolution of the EEP with the formation of the TZ to the SP during the closure of the Paleotethys Ocean that imprints the Cretaceous extension and the Cenozoic compression.

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Intraplate orogenesis

© *R. Stephenson, 2017*

School of Geosciences, Geology and Petroleum Geology, Meston Building, King's College, University of Aberdeen, Aberdeen, UK

Plate tectonics has it that major orogens form at plate boundaries, specifically in response to collision of continental lithospheric plates with other continental lithospheric plates or island arc terranes and so on. A multitude of schematic diagrams have been published in the last 50 years showing black-coloured oceanic crust being subducted under white-coloured continents, continental fragments, other pieces of oceanic crust, often with subduction polarity flipped from one panel to another. Lately, abundant evidence, and a theoretical basis for it, has been published showing that many orogenic belts involve extreme shortening of previously severely thinned and often significantly intruded and infiltrated continental lithosphere but, nevertheless, continental lithosphere that was not breached or broken in a plate tectonic sense to produce a new lithospheric plate boundary at which new oceanic lithosphere is accreted. Although there are semantics involved, this cannot count as orogenesis at a plate boundary: it is, accordingly, «intraplate orogenesis». It seems likely to me that much of the large-scale compressional deformation recorded in the Alpine-Tethys belt might qualify as «intraplate orogenesis» in this regard and that many (if not all?) ophiolite complexes ubiquitous in this belt do not represent obducted crust of oceanic lithospheric affinity but rather remnants of highly deformed, infiltrated and magmatised crust of continental lithospheric affinity. I'll review the literature published during the last years that supports this model and try to demonstrate some of the as yet not fully explored implications of such a model for the geodynamics of «intraplate orogenesis».

Seismicity and crustal structure of the Southern Crimea and adjacent Northern Black Sea from local seismic tomography

© *T. Yegorova*[1], *V. Gobarenko*[1], *R. Stephenson*[2], *M. Sosson*[3], *2017*

[1]Institute of Geophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[2]School of Geosciences, Geology and Petroleum Geology, Meston Building, King's College, University of Aberdeen, Aberdeen, UK
[3]Université Côte d'Azur, UMR Géoazur, CNRS, Sophia Antipolis, France

The Greater Caucasus and the Crimea Mountains constitute a fold-and-thrust belt that formed near the southern margin of Eurasia as a result of Cenozoic collision between Eurasia and the Africa—Arabian Plate. The Main Caucasus Thrust (MCT), which marks the southern boundary of the Greater Caucasus orogen, can be traced westward along the northern margin of the Black Sea and coincides at depth with a zone of seismicity called the Crimea Seismic Zone (CSZ).

The CSZ is characterized by earthquakes of M=3÷5 with foci in the crust and uppermost mantle with abundant weak seismicity (M≤3). The latter was used to recover the velocity structure of the crust of southern Crimea Peninsula and adjacent northern Black Sea employing local seismic tomographic techniques. Events were recorded during 1970—2013 by nine stations on the Crimea peninsula (Crimea Seismic Network; CSN) and by one station (Anapa) on the Caucasus coast of the eastern Black Sea. Data for the tomographic modelling, earthquake hypocentres, were relocated for the *P*- and *S*-wave arrivals at all permanent stations of CSN. Earthquake relocation was done via error minimisation starting with a 1D reference velocity model based on seismic surveys (active and passive) in the study area.

The distribution of determined hypocentres indicates three main seismicity subzones: 1) the Kerch-Taman subzone, which dips northward at an angle of ~30° to a depth of 90 km; 2) the South Coast (or Yalta-Alushta) subzone, which dips to the southeast at an angle of ~18° with earthquake foci dominantly at depths of 10—25 km; 3) the Sevastopol subzone, which is orthogonal to the South Coast subzone and confines it from the west, characterised by diffuse seismicity to a depth of ~40 km.

The new local tomographic results document significant *P*- and *S*-wave velocity heterogeneities in the depth range 10—30 km. Stable solutions have been obtained for depths of 15, 20 and 25 km. A distinctive feature of the crust of Crimea Mountains (western Crimea) is the presence of a high-velocity (6.7—6.8 km/s) domain of complex configuration, comprising a number of separate bodies. It is separated from the more eastern Crimea and Kerch peninsula by a linear low-velocity zone of ~N-S strike (in the Sudak area) interpreted as a manifestation of a weakened crustal zone, possibly associated with the Feodosiya Fault expressed at the surface, which, in turn, could be linked to a collinear Proterozoic N-S trending fault zone in the Ukrainian Shield. From other side, it could be indication of a normal fault zone related to the Early Cretaceous rifting and opening of the East Black Sea Basin. To the east of this low-velocity zone the crustal structure lacks notable velocity anomalies.

Preliminary interpretation of velocity anomalies suggests that complex 3D crustal geometries are involved. The relocated hypocentres in combination with the tomography models show that there is a change of underthrusting polarity in the western Crimea Mountains crust compared to eastern Crimea. This may be a reflection of structural inheritance and reactivation during compression of the same deeper structures that earlier controlled formation of the mid-Black Sea Rise during Black Sea extension.