Geodynamic Situation in Central Caucasus and Structural Complexes on Depth Section of Genaldon Profile

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***Abstract*—The article considers the possibility of identifying of an inheritable character of the geodynamic situation and elements of structural and compositional complexes involved in the geological development of the Caucasus on geoelectrical and seismological depth sections in order to create a geological and geophysical model of the Earth's crust along regional profiles. Modern structural-tectonic, structural and compositional complexes of the eastern part of the Central Caucasus are interpolated with the main structures of the consolidated crust and lower crust. The correlation of deep crustal and mantle structures with deposits of solid minerals and hydrocarbons and the role of Moho discontinuity in the localization of deposits are of scientific and practical interest.**

Keywords—geodynamics; depth structures; Central Caucasus; gravitational field; magnetic field

I. Geodynamic Development Cycles and Components of the Structure of the Greater Caucasus

During deep penetration survey of the Earth's crust and the upper mantle, understanding of the historical cycles of activation facilitates the correct interpretation of the geophysical model. Such geodynamic situations (intraplate, convergent, divergent, transform) take place under the conditions of a certain complex of elements of the geological structure (island volcanic arcs, back-arc land-locked seas, types of plates and zones). Good interpretation of geophysical data largely depends on the understanding of these situations, which is the reason for a brief excursion into the explanation of geological development of the structure of the Greater Caucasus.

Features of the dynamic interaction of lithosphere plates involved in the development of the Caucasus as a geological unit are considered as geodynamic environments. Dislocation and morphological features of the elements of the complexes that are subjected to the influence of geodynamic forces are considered as structural characteristics, and formation composition of stratified, metamorphic and plutonic complexes – as compositional complexes.

The modern view of the history of geological development of the orogen of the Greater Caucasus is formed on the basis of the mosaic of the Earth's crust plates and the concept of their mobility in the viscous asthenosphere due to convective currents in the upper mantle due to various pressure-temperature conditions and plume jets. According to this concept, the geodynamic situation and elements of the geological structure relating to the Greater Caucasus originated at the end of the Paleozoic. In the subduction zone of the northern frames of the oceanic crust and southern edges of the Russian (East European) platform (mobile belt formerly) a mountain structure formed, which later transformed into the Scythian platform as a result of the collapse.

The further spreading-subduction interactions of the oceanic crust (and then the Greater Caucasus basin or rift-induced deflection of the Cimmerian time according to a different model [1], separated from the main ocean by an island volcanic arc [2, 3]**)** and continental plates of Gondwana from the south and Eurasia from the north led to the formation of the back-arc basin of the West Black Sea and South Caspian depressions in the west and east [4]. Herewith the Scythian plate was immersed in the shelf of the shallow sea to the south of the Eurasian continent, where the conditions for the accumulation of carbonate and clay-carbonate sediments of foraminiferal series appeared.

The reduction of the Tethys Ocean due to the approach of Africa and Eurasia led to the subduction of the oceanic crust of the Greater Caucasus back-arc basin under the southern margin of the Eurasian continent. The approach of the Arabian Plate to the strip of island arcs and its further northward movement accelerated the termination of the contraction of the Greater Caucasus basin and the subsequent transformation of marine sediments into mountainous terrain.

The lasting collision of the Eurasian and Afro-Arabian continental plates led to the intensive mountain folding and the genesis of a new volcanic zone along the southern edge of the Scythian plate (Kazbek, Elbrus, Chegem caldera) [5].

In the formed mountain structure of the Greater Caucasus, the Scythian plate forms its northern slope and extends to the north in the form of the modern Ciscaucasian plain. The marine sediments of the Greater Caucasus back-arc basin form the southern slope of mega-anticlinorium, and the island volcanic arc became the basis of the Transcaucasian massif, the southern part of which is represented by the Lesser Caucasus.

This is in general terms the explanation of the geological development of the Caucasian orogen zone for more than 400 million years, based on the concept of mobility of lithosphere plates.

Each of these events made changes in the development of the crust and the spatial position of the main marking boundaries, in the lithologic-stratigraphic content of the sedimentary cover, in the structural-tectonic zoning scheme, in the formation of minerogenic belts, in the occurrence of the zones of volcanic manifestations and magmatism, in seismic activity, although the subsequent event could both overlap and mitigate the previous transformations.

II. Conditionality of Deep Investigations

Modern level of scientific-and-technological advance is limited by single possibilities of penetration by direct methods of investigations into the earth interior to a depth of just over 10 km, the results of which can only be considered a priori in a sequential chain of genetic links between interdependent geological processes. Such consideration is possible either on the basis of theoretical ideas of geological development or on the basis of data from indirect research methods, among which the main role belongs to a geophysical investigation.

Hidden ore occurrences within even well-known ore provinces have been studied (also with the help of geophysical methods), as a rule, up to the depths of the order of 100 m. Underlying deposits remain undetected, on the one hand, due to the low resolution of traditionally used geophysical methods at such depths, and on the other hand, due to the insufficient understanding of the genesis of ores, geological conditions of their formation, characteristic structural and tectonic, magmatic, geomorphological, physical and chemical concomitant signs associated with the localization of a deposit of one or another type. Meanwhile, polymetallic deposits, for example, can be localized up to the depths of 5 km or deeper.

Having studied a separate deposit in detail, it is impossible to create an algorithm to search for its analog according to its own characteristic features (structural and tectonic, lithological, geochemical, magmatic or some other characteristic of this field). In order to create such an algorithm, it is necessary to know the regional feature of geological development of the territory and fluid-controlled structures. Deep sources of fluid-income are referred to such features. The main role is assigned to depth geomorphological structures and tectonic deformations (with ore-bearing and ore-controlling structures) as well as to the qualitative and quantitative characteristics of geophysical fields.

Scientific interest of deep investigations consists in understanding general directions of the formation and development of the main structures of the Greater Caucasus, in reconstruction of the geodynamic situation in the collision zone, in determination of the morphology of the roof and the bottom of the consolidated crust, in creation of a modern depth model of the Central Caucasus [6-8].

The possibility of establishing an inherited space-time relationship between the features of deep geodynamics and the crust-mantle structures and near-surface mineral deposits and host structures of higher orders determines the applied significance.

According to the results of the deep seismic studies, linear positive and negative structures, low velocity zones and gradient zones in the tops of the mantle and, as a rule, in the topography of the Moho discontinuity, correspond to minerogenetic zones that may indicate the influence of deep processes on the formation of deposits and mantle sources of ore material and hydrocarbons [9]. According to the telluric sounding (MTS) data, linear subvertical and areal conductive zones in the crustal layers correspond in the first case to carbonaceous rocks and ore mineralization, and in the second case – to hydrocarbon deposits [10]. The conductive zones along the TS and the zones of low velocities of the deep seismic sounding (DSS), traced to depth, including the tops of the mantle, often coincide with fault zones, which, apparently, are the canals of approach for fluids from the mantle.

Being a marker horizon for seismic waves during deep seismic sounding (DSS), morphological features of the Moho discontinuity represent the main structural and tectonic units of the Earth's crust. The region covering Ciscaucasia is distinguished on the Moho discontinuity by a series of positive and negative linearly elongated structures of northwestern striking. On the eastern segment of the orogen, the structure with a convex shape with a difference in depth from 30 km in the central part to 40 km to the periphery of the depression corresponds to the Caspian depression on the Moho discontinuity [11].

Similar behavior of the Moho boundary is also observed in the Black Sea Basin, where the border from the center subsidies to the margins from 18–22 km to 35–40 km. Based on these studies for the Black Sea basin, an important conclusion about the values and dependences of average and boundary velocities on depth was made. For the "granite-less" deep-water part, the dependence of the average speed on depth can be represented by the expression V_g=1.8+h*tag22°, for the transition zone up to depths of 17-18 km – V_g=2.3+h*tag7.5° and below the depths of 17 -18 km the expression is V_g=3.4+h*tag4°.

The dependence of average velocity on the depth in the shelf area may vary within V_g=(2.5÷4.8)+h*tag4°. At the same time the boundary velocities both in sedimentary rocks and in the "granite" and "basalt" layers and at the Moho boundary, are practically independent on depth, that indicates the dependence of this parameter on the lithological composition of rocks, and not on the value of the static pressure [12].

The deep section of the eastern flank of the Central Caucasus is confidently differentiated by three distinct boundaries interpreted as boundaries between the bottom of the Paleozoic foundation and the "granite" layer, the bottom of the consolidated crust and the Moho boundary and the boundary into the asthenosphere in the upper mantle [13].

In point of the geology of oil and gas with respect to the traditional organic origin, it has always been deep and, as a rule, stratified. Oil and gas traps are confined to regional structures of flat-platform type and are obviously remaining stratified due to the corresponding geodynamic situation in a particular mobile zone, although such an assumption can already be interpreted in favor of the mantle source of oil.

If we consider the mantle nature of oil (and we should already take it into consideration), then along with deep tectonic dislocations going into the mantle, continental rifts (aulacogens) that were not developed and cured by thick sedimentary rocks can be used as the connecting channels of traditional oil traps with the tops of the mantle.

Consideration of trap structures for ore and hydrocarbon mineral resources as derivatives of a single chain of geological development makes it possible to expand the complex of main features of deposits localization, which allows us to develop an algorithm for their extraction; it certainly represents a great practical interest to the carried out fundamental deep investigations.

III. Deep Geophysical Investigations of the Central Caucasus

In the framework of the "Federal Target Programme (FTP) for the Development of the Mineral Resources Base of the Russian Federation", the territory of Ciscaucasia and the Russian territory of orogen of the Greater Caucasus are covered by a network of regional profiles of deep geophysical investigations in order to obtain valid global models of geotectonics, oil and gas bearing capacity and metallogeny as well as for solving the problems of detailed seismic zoning.

The analysis of the results of these works is emphasized on the separation of inheritable occurrence of geodynamic processes and elements of structural and compositional complexes in the sections of regional deep geophysical profiles.

Investigation results are of particular interest in two aspects: the prospects for identifying deep oil and gas bearing structures in the consolidated basement of the Ciscaucasia (possibly with time), and prediction of the mantle sources of migration of hydrocarbon-containing fluids; determination of regularities of the spatial distribution of the main lithologic and stratigraphic and structural and tectonic elements of the Scythian plate within the folded-block mobile zone of the northern slope of the Greater Caucasus as a consequence of geodynamic processes in the zone of collision of lithosphere plates and the position and morphology of the main intercore marking boundaries, the Moho boundary. The second aspect is the subject of a multifaceted stepped analysis of the deep sections of the Greater Caucasus structure (one of which is situated along the Genaldon profile) are considered in this article.

The main complex of geophysical research methods includes earthquake converted-wave method (ECWM), telluric sounding (MTS), gravity and magnetic survey. The Genaldon profile has been worked out in two stages: in 2003 in the Ossetian sector of the Central Caucasus, at the level of the meridian of Vladikavkaz, from the northern slope of Kazbek, 55 km to the river Kambileevka on the latitude of Beslan in connection with the glacier Kolka surge. Investigations in this section of the profile were supposed to find an answer to the question of volcanic nature of the impact of the Kazbek volcano on the Kolka glacier, once again descending from its bed with disastrous consequences.

Further investigations of the Genaldon profile northward to the settlement of Levokumskoe was completed in 2013 in the framework of the programme for obtaining valid global models of geotectonics, oil and gas bearing capacity and metallogeny along regional profiles.

The section on the southern flank of the profile (Fig. 1) represents the Greater Caucasus folded-block elevation and the Ossetian Basin, composing a structure of the Tersk-Caspian foredeep laid in the marginal part of the Scythian platform. The North wing without clear boundaries in the physical fields passes into the Main Ridge zone, which is characterized by relatively positive values of the gravity field. Gravitational maxima here are determined by the near-surface layer with an excess density of 0.15 g/cm^3, the upper and the lower boundaries of which are located at depths of 0.5 and 4.5 km. This may correspond to the thickness of deep-water Lower Jurassic sediments with products of basic magmatism (dikes, intrusions, sills of the Kazbek diabasic belt), which lies on the crystalline basement.

The folded-block elevation includes three structural and compositional complexes: the zones of the Main Range, the Northern Monocline and the Skalisty Range. The main structural and compositional complexes of the Main Range, crossed by the Genaldon profile, are the following: the zone of Cimmerian folding, the narrow strip of Shaukhokh-Daryal elevation and the Mamison-Kazbek relic scar, bounded from the south by the Adaykom-Kazbek fault and from the north by flat underthrust, passing the base of the escarp of the Skalisty Range.

The Cimmerian folding zone is limited from the south by the Tsariit-Tsatadon and Belorechensky faults separating it from the Shaukhokh-Daryal elevation. According to the composition of the base of the Jurassic strata in the Cimmerian folding zone, lithology is represented by siltstones and sandstones separated into the marine terrigenous formation of the Middle Lias.

Shaukhokh-Daryal elevation is located in the south-eastern part of the Mountain Ossetia, where it occupies the ridge and the slopes of the Bokovoy Range. It consists of relatively large Shaukhokh and Daryal massifs separated by the Chachskiy cover. The Shaukhokh massif is located between the rivers Fiagdon and Gizeldon. The massif is restricted from the north by the southwestern part of the Dzhimara-Godtanadag fault and Tsariit-Tsatadon uplift. Its southern border is represented by the Syrkhubarzond uplift, restricting the Mamison-Kazbek relic scar from the north (as well as the Main thrust in the west). A core part of the block is composed by sediments of late-carbonic grey-colored molasses and Late-Carbonic – Early-Permian tuffite - sand and Late-Permian Carbonate metamorphosed formations which are overlapped by formations of Early Lias metasandstones, quartzite, nodular and spotted schist as well as by sediments of Middle- Lias slate formation. The mentioned rocks are split by numerous dikes of the Middle Jurassic gabbro- diabasic formation of the Kazbek complex. The foundation of the massif, represented by Paleozoic deposits, is exposed in tectonic wedge-shaped blocks and in the core of the Genaldon anticline.

Mamison-Kazbek relic scar or geosuture is represented by tectonized terrigenous material containing blocks of different size and blocks of volcanic-sedimentary rocks and remobilized olistostrome of the ophiolitic complex. At the same time, serpentinous to various extents picrites which are nowhere to be found without andesite-basalt or diabasic membrane, fit well into the scheme of the process of diapirism, which occurred at the first stage of tectonic mobilization of ophiolites. A minor role in the structure of the Mamison-Kazbek zone belongs to the sub-intrusive formations of the Pliocene diorite formation.

The zone of the Northern monocline covers the Pastbischny and Skalisty Ranges. Its main tectonic element is fault tectonics, the intensity of which increases significantly from north to south, i.e. downwards the stratigraphic section, reaching the maximum at the southern boundary of the zone (at the underthrust of the Skalisty Range).

From the south the Northern monocline restricts the Ossetian depression, which is a deep downfold, turning into the north wing of the Caucasian anticlinorium in the south. The formation of the downfold refers to the Upper Sarmatian period of establishing a regime of sustainable deflection. A depression is formed by the thick strata of continental formations of the Neogene and Quaternary periods [14], forming the upper molasse, at the base of which conglomerates and pebbles of the Lysogorsk suite are. Tuff-conglomerate deposits of the Rukhsdzuar suite are located on the conglomerates of the Lysogorsk suite. These rocks perform a significant hollow area. Their thickness reaches 1450 m. The upper molasse section culminates in Quaternary Pleistocene-Holocene alluvial and fluvioglacial formations with a thickness from 0 to 750 m. The total thickness of its sedimentary cover in the central part is (without subsalt complex) about 9 km.

The folded-block elevation of the Greater Caucasus and the Ossetian Basin are separated by a fault zone located between the 17 and 28 kilometers of the profile. It is characterized by sharp displacements of the axes of electrical conductivity and the boundaries of PS waves exchange, increased gradients of the gravitational field. The zone of the deep fault (with a thickness of 10 km) is a regional Ciscaucasian fault and characterizes the junction zone of the Alpine folded area and the Scythian platform. The zone is largely covered by a complex of the monocline of the Skalisty Range, which represents the boundary structure between the Greater Caucasus orogen and the Tersk-Caspian downfold. Quantitative calculations for the gravity step, observed at 28-29 km of the profile, give the northern incidence of the division plane at angles of 65-70° with an effective density of about -0.1 g/cm^3. The anomaly reflects the flexure bend of Vladikavkaz fault in recent deposits [15]. At depths of 5–10 km of the section, the fault zone is distinguished at the 26–27 km of the profile by the maximum gradients of the electric resistance field and the misphasing of the waveforms. Dislocations of the Ciscaucasian fault are also fixed to the west within the 17–23 km of the profile (between the points of location of ECWM stations No. 3–5), which continue into the mantle.

A low-resistance layer with electrical resistance values below 10 Ohm is distinguished under the Ossetian Basin, composed of the Paleogene – Quaternary formations at a depth of 6–13 km. Taking into account the presence of local anomalies with resistance values less than 1 Ohm within the layer, sediments can be represented by the alternation of anhydrides, halites and gypsums (Gandalbos suite).

The surface of the assumed subsalt deposits, characterized by electrical resistance over 100 Ohm, is located at depths of 12–13 km. The carbonate-sulphate-salt-bearing thickness may indicate the existence of paleo-deflection. Data of geophysical investigations emphasize its graben character. Thus, the near-vertical southern interface of the paleo-deflection lies on the 25–27 km of the Genaldon profile, that is, slightly southward the Vladikavkaz flexure bend. It was determined that reef structures, which were subsequently dolomitized [16], were widely developed along the southern border of the Ossetian Basin in the Early-Tithonian time. In the section, they are distinguished by increased values of electrical resistances to the south of highly conducting salt-bearing thickness in the range of 18–25 km of the profile. Seismic work reef formations are among the promising structures for oil and gas potential.

From the north the Ossetian depression is restricted by Sunzha and Tersk anticlinal neotectonic structures (separated by the Alkhanchurt synclinal) which are a zone of injection folding caused by high activity of the deep mantle faults, leading to high tectonic stratification of the upper horizons of the sedimentary cover.

Correlation pattern of the wave exchange in combination with the data of telluric observations makes it possible to single out the deep structures and interfaces, interpreted as reef and two borders of the consolidated crust (K1 and K2) due to the conceivably doubling of the thickness of the conventional basalt layer. The Moho boundary is determined as a marking boundary. The crystalline basement is noted at depths of the order of 5 km.

The model of the deep structure along the entire profile line was constructed primarily according to the data of the ECWM and on the basis of density section selection (Fig. 2). The data of MTS was used for the southern fragment of the section.

Gravitational field throughout the profile is negative (from -25 to -50 mGal). In the area of the folded-block uplift of the eastern part of the Central Caucasus, the field of gravity is calm, practically non-differentiable (from -25 to -30 mGal), in general, it has a latitudinal orientation. When moving to the zone of the Ciscaucasian troughs, the drawing of gravitational field's isanomals acquires a north-western orientation, which is most likely associated with the junction area of the Chernolessk-Kabardian and Tersk-Caspian regional foredeeps. The field values in this area are reduced to -40 – -50 mGal. The border of the folded-block uplift of the Central Caucasus with the zone of the Ciscaucasian foredeeps and uplifts is accompanied by a high gradient of the gravitational field of a straight latitudinal direction identified with the zone of the deep Vladikavkaz fault. Less contrasting gradients indicate the contact of the Ciscaucasian foredeeps and elevations with the Tersk-Sunzhensk anticlinal zone.

The magnetic field is weakly positive, and only on the southern segment of the high-mountain part of the profile it has negative values (up to -20 nT). The change of the sign of the magnetic field occurs during the transition from the zone of the Cimmerian folding to the Shauhokh-Daryal uplift and into the zone of the Mamison-Kazbek suture. The negative magnetic field is associated with the near-surface location of the pre-Mesozoic basement, which is consistent with the general negative field that is characteristic for the folded-block uplift of the Main Range along its entire length. As well as in the gravitational field, in the junction part of the mountain structure with the system of Ciscaucasian foredeeps the field is reoriented from the latitudinal to the north-western direction.

According to seismic data, two almost continuous wave exchange boundaries are traced. The upper boundary is identified with the roof of the (crystalline) basement. In the region of the North Caucasus folded-block system, this boundary is located in a general form conformally with the surface of the pre-Mesozoic basement and it is registered at depths of 8-10 km. Within the Scythian plate of the Ciscaucasia, the position of the seismic boundary of the basement is not consistent with the position of the bottom of the Mesozoic sediments. Here, along with the Mesozoic base, the positive structure of the Prikumsk-Neftekumsk arched uplift stands out. Its base smoothly rises from south to north from a depth of 8 to a depth of 3 km, while horst and graben structures of the Nogai phase and the Prikumsk elevation system are clearly traced along the roof of the crystalline basement.

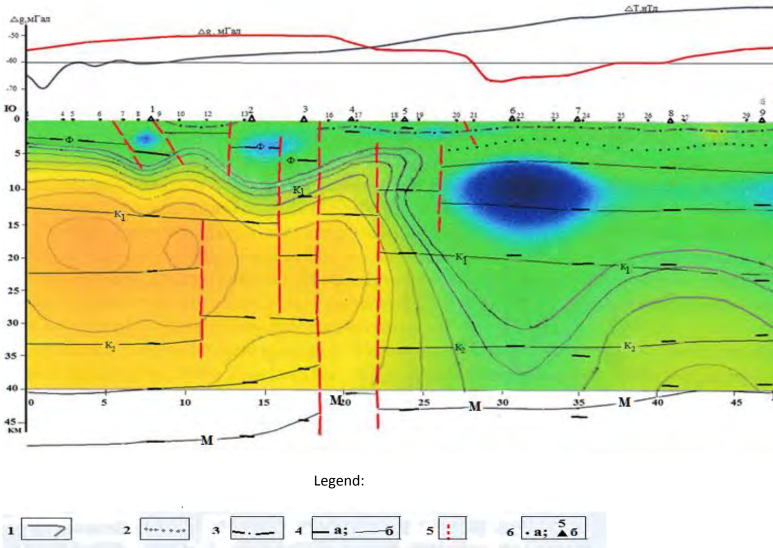

Fig.1. Deep geological and geophysical model of the southern flank of the Genaldon profile: 1 - isolines of electrical resistance (lgρ); 2 - horizon axis of increased electrical resistance; 3 - axis of the conducting horizon; 4 - points (a) and assumed surfaces (b) of PS-wave exchange (M - Moho, K - Conrad, F - basement); 5 - subvertical violation zone of the waveform correlation; 6 - MTS (a) and ECWM (b) stations and their numbers.

The lower boundary of the wave exchange is taken as the marking for Moho boundary. In the folded-block system, the Moho boundary plunges southwards from the region of the Tersk-Sunzhensk uplift system under the folded zones of the Central Caucasus uplift from -45 to -55 km. Within the boundaries of the Scythian Plate of the Ciscaucasia, the Moho boundary is located almost horizontally at -44 – -45 km. The jump in the position of the Moho boundary occurs on the northern slope of the Mozdok crystalline protrusion. The total crustal thickness in the southern part of the Genaldon profile increases to 49 km. The correlation pattern of the wave exchange in combination with the data of telluric observations makes it possible to isolate the deep structures and surfaces of discontinuity, interpreted as reef and two borders of the consolidated crust (K1 and K2) due to the supposedly doubling of the thickness of the conventional basalt layer. The Moho border is identified as a marker horizon. The crystalline basement is noted at depths of the order of 5 km. The total crustal thickness in the southern part of the Genaldon profile increases to 49 km.

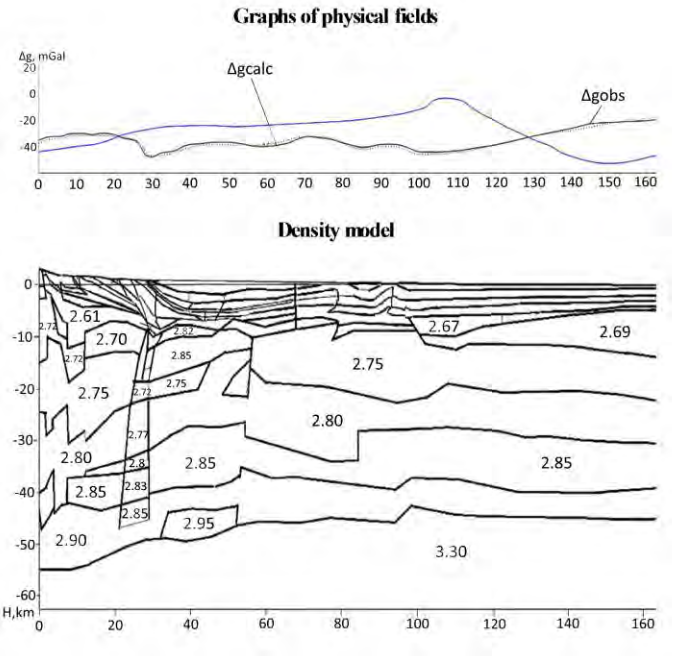

Fig. 2. Graphs of physical fields and density model along the Genaldon profile

The investigated area is located in a zone with a high level of seismic hazard [17]. At the same time, this zone is located within the mountain range with the Kolka glacier, which collapsed in 2002 [18]. It is precisely geodynamic activity, according to a number of authors, that was one of the reasons for this collapse. It should be added that considered area is located almost in the center of a mountainous region with a powerful mining industry active in the past [19, 20]. Finally, there are located areas saturated with geothermal waters that are promising for economic use [21]. And many of their features can also be significantly influenced by the geodynamic situation at the mining sites.

IV. Conclusion

One of the main features of the geodynamic setting of the subduction zone is the "doubling" of the thickness of the basalt layer, which occurs on the basis of two distinguished boundaries K1 and K2, which probably separate the granite and basalt layers of the continental crust and the basalt layers of the continental and oceanic crusts. The increase in the total thickness of the crust in the direction to the folded-block structure due to the basalt component confirms the subduction nature of the collision of lithospheric plates.

The sublatitudinal structure of the Mamison-Kazbek relic scar (geosuture), confidently distinguished by the tension minima of the full magnetic field vector and traced for 550 km, by structural and compositional elements (olistostromes, ophiolites, mixtites) is a convincing inheritable character of subduction. Mamison-Kazbek relic scar or geosuture is represented by tectonized terrigenous material containing blocks of different size and blocks of volcanic-sedimentary rocks and remobilized olistostrome of the ophiolitic complex.

The intensification of the advancement of the Arabian plate deep into the Eurasian continent leads to an intensive reduction of the Caucasus area in the meridional direction due to the huddling of material, that is characterized by the elevation of the "rejuvenated" mountains, in which the mountain ranges are the bodies of thrusts, which have a complex internal structure and are characterized by a combination of multi-stage deformations (Bokovoy, Skalisty, Pastbischny, and Lesisty Ranges). Movement here took place in the form of underthrust from south to north. Vivid illustrations of this are the Bokovoy Range, under which the structural formations of the relic scar move along the "Main thrust", and the Skalisty Range, under which all the more old rocks and structures formed by them advance to south along the " Skalisty Range" subduct. The formation of "rejuvenated" mountains is accompanied by intense volcanic activity of Quaternary volcanics (Kazbek-Kabardzhinsk group). Accumulation of the upper molasse material, which builds up the Vladikavkaz basin (the Rukhsdzuar suite and Quaternary alluvial fluvioglacial deposits), continues.

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