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3D non-stationary Thermo-geodynamics of the Caucasus and the Black and the Caspian seas water areas

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Keywords: Thermo-geodynamics, Thermo-density, vertical displacements, thermoelastic, Mohorovichich, Paleoreconstruction, non-stationary.

Abstract. Tree-dimensional non-stationary geothermal and thermoelastic models of the Caucasus and the Black and the Caspian seas is developed and their geological-geophysical interpretation is given. Till 410 Ma temperature field was defined on the basis of the stationary model of the investigated region. Afterwards, from the period of formation of the most part of the sedimentary cover, computations were carried out on the basis of non-stationary thermal model. On the basis of thermal field the thermoelastic equations are solved and charts of vertical thermo-displacements have been calculated.

Earlier M. Alexidze et al. (1969, 1989, 1991) a three-dimensional stationary geothermal and thermoelastic models of the Caucasus and Black and the Caspian seas water areas have been produced. Besides charts of temperature and thermoelastic displacement were plotted for the “granitic”, Conrad and Mohorovicic discontinuities. These models revealed a number of interesting features in the geodynamic of the region. Nevertheless, they did not give an opportunity to consider the models in dynamics, taking into account process of sedimentation in time. Such a possibility gives the construction of three-dimensional non-stationary geothermal and thermoelastic models of the Caucasus and the Black and the Caspian seas water areas offered by authors of this paper. For the construction of three-dimensional non-stationary models of investigated region paleoreconstruction schemes of development of sedimentary cover of the Caucasus (Sholpo, 1978), of the Black sea area (Kasmin at al. 2000) and many different data about the Caspian sea area have been used. Numerical modelling of thermal and thermoelastic processes allows revealing temporal distribution of a number of thermogeodynamic events including formation of deep faults, thermoearthquakes and so on.

Before the origin of sedimentary complex thermal situation was considered as stationary: according to (V.N. Tikhonov, 1937) thermal flow of the whole Earth without sedimentary complex differs from stationary one by only 3%).

Reconstruction of 3D geothermal model

On the basis of seismic and gravimetric data the structure of the Earth’s crust is received for the region. It consist of sedimentary, granite and basaltic layers. According to geological age and physical property of the sedimentary layer, in its turn, is divided into seven layers (see below). On the surface the geographic relief is taken into account.

Data base is compiled for all these data. Thermal conductivity, heat capacity, density and magnitude of heat were determined for each layer. A three-dimensional non-stationary geothermic problem is formulated.

In order to realize this problem an algorithm has been developed.

Let’s consider non-stationary thermal conductivity equation

$$\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(a\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(a\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(a\frac{\partial T}{\partial z}\right)+\frac{W}{c\rho} \quad (1)$$

Were T is temperature, t is time, x, y, z are spatial coefficients, λ is thermal conductivity, c is heat capacity, ρ is density, w - magnitude of radioactive heat, given off by sedimentary complex. If we assume that thermal conductivity a is constant for each layer, then we receive:

$$\frac{\partial T}{\partial t}=a_p\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{W_p}{c_p\,\rho_p} \qquad (2)$$

were λ_p, c_p, ρ_p and w_p are corresponding coefficients of p layer.

$$a=\frac{\lambda}{c\rho}$$

In order to solve the equation boundary and initial conditions are necessary: let’s take for initial conditions

$$\left.\frac{\partial T}{\partial x}\right|_{x=0,X}=0 \quad , \qquad \left.\frac{\partial T}{\partial y}\right|_{y=0,Y}=0 \ ; \qquad (3a)$$

$$T\big|_{z=0}=T_0 \quad , \qquad T\big|_{z=H}=T_H ; \qquad (3b)$$

$$\lambda_p\frac{\partial T}{\partial n}=\lambda_{p+1}\frac{\partial T}{\partial n} \quad . \qquad (3c)$$

were λ_p is thermal conductivity coefficient and for the initial condition

$$T_{t=0}=T_0 \quad . \qquad (3d)$$

Boundary problem (1-3d) is solved for corresponding values and temperature distribution for discussed area is received.

Reconstruction of 3D thermoelastic model.

Warming up of non homogenous geological structure may yield considerable gradients of thermal stresses vertically, as well as laterally, because of differences in coefficients of thermal expansion of various formations.

These gradients may be very big in geosynclinicareas, such as Alpine orogenic belt and the Caucasus. We have undertaken the task of revealing these mechanisms on the basis of investigations of thermoelastic stresses. Heterogenous geological structure’s heating up can result in significant gradients of thermal stresses $\Delta\sigma_T$ on vertical line $\Delta\sigma_Z$, as well as on lateral line $\Delta\sigma_L$, because of differences in coefficients of thermal expansion of various parts of the Earth’s crust. These gradients may be particularly steep in folded areas, such as Alps, the Caucasus, etc., in view of deviations from horizontally – foliated structure. Because of complexity of surface and depth relief, due regard for thermal field’s three – dimensionality in construction of thermal models of folded areas and in estimation of various geothermal effects becomes particularly important.

In the work (G.Gugunava, V. Sholpo et all.2003) a three-dimensional non-stationary thermal model of the Caucasus and Black Sea and Caspian Sea water areas was considered and its geologicgeophysical interpretation was given. Earlier, on the basis of the same data, a three-dimensional boundary problem of thermoelasticity theory was solved numerically (N. Muskhelishvili 1966).

In consequence of thermal field covering, in each point of medium shift vector U appears, with components U_1, U_2, U_3 (correspondingly 1-x, 2-y, 3-z) directed towards surface on the normal.

With that end in view, computations of non-stationary thermal condition of entrails of the Caucasian region and the Black Sea and the Caspian Sea water areas were used (G.Gugunava, V. Sholpo et all.2003).

Thermoelastic stresses of the investigated region were determined by numerical solution of the thermoelastic problem.

$$\mu\left(\frac{\partial^2 U_1}{\partial x^2}+\frac{\partial^2 U_1}{\partial y^2}+\frac{\partial^2 U_1}{\partial z^2}\right)+(\lambda*+\mu)\left(\frac{\partial^2 U_1}{\partial x^2}+\frac{\partial^2 U_2}{\partial x\partial y}+\frac{\partial^2 U_3}{\partial x\partial z}\right)=\frac{\partial(\beta T)}{\partial x} \quad (4)$$

$$\mu\left(\frac{\partial^2 U_2}{\partial x^2}+\frac{\partial^2 U_2}{\partial y^2}+\frac{\partial^2 U_2}{\partial z^2}\right)+(\lambda*+\mu)\left(\frac{\partial^2 U_1}{\partial x\partial y}+\frac{\partial^2 U_2}{\partial y^2}+\frac{\partial^2 U_3}{\partial y\partial z}\right)=\frac{\partial(\beta T)}{\partial y} \quad (5)$$

$$\mu\left(\frac{\partial^2 U_3}{\partial x^2}+\frac{\partial^2 U_3}{\partial y^2}+\frac{\partial^2 U_3}{\partial z^2}\right)+(\lambda*+\mu)\left(\frac{\partial^2 U_1}{\partial x\partial z}+\frac{\partial^2 U_2}{\partial z\partial y}+\frac{\partial^2 U_3}{\partial z^2}\right)=\frac{\partial(\beta T)}{\partial z} \quad (6)$$

$$U_1=U_2=U_3=0 \quad (7)$$

$$\mu\left(\frac{\partial U_1}{\partial z}+\frac{\partial U_3}{\partial x}\right)=0 \quad (8)$$

$$\mu\left(\frac{\partial U_2}{\partial z}+\frac{\partial U_3}{\partial y}\right)=0 \quad (9)$$

$$\left(\lambda*\left(\frac{\partial U_1}{\partial x}+\frac{\partial U_2}{\partial y}+\frac{\partial U_3}{\partial z}\right)+2\mu\frac{\partial U_3}{\partial z}\right)=0 \quad (10)$$

$$\mu_n\left(\frac{\partial U_1}{\partial z}+\frac{\partial U_3}{\partial x}\right)=\mu_{n+1}\left(\frac{\partial U_1}{\partial z}+\frac{\partial U_3}{\partial x}\right) \quad (11)$$

$$\mu_n\left(\frac{\partial U_2}{\partial z}+\frac{\partial U_3}{\partial x}\right)=\mu_{n+1}\left(\frac{\partial U_2}{\partial z}+\frac{\partial U_3}{\partial x}\right) \quad (12)$$

$$\lambda*_n\left(\frac{\partial U_1}{\partial x}+\frac{\partial U_2}{\partial y}+\frac{\partial U_3}{\partial z}\right)+2\mu\frac{\partial U_3}{\partial z}=\lambda*_{n+1}\left(\frac{\partial U_1}{\partial x}+\frac{\partial U_2}{\partial y}+\frac{\partial U_3}{\partial z}\right)+2\mu_{n+1}\frac{\partial U_3}{\partial z} \quad (13)$$

Equations (4-6) are the well-known equations of the elasticity theory (N. Muskhelishvili 1966). Boundary conditions (7-9) indicate that surfaces of the area under review are free from stresses.

Formulae (10-13) are ordinary adjoint equations in the elasticity theory, equality of normal and tangential stresses. Values of Lame coefficients λ* and μ are given in table 1.

Table 1.

Parameter 10^9 N/m^2	Sediments	Granite	Basalt	Mantle
λ*	24.832	26.75	41.295	76.108
μ	16.224	32.375	41.063	70.587

For numerical solution of the formulated problem the method of finite differences was used, where U_1, U_2, U_3 - are displacement components, λ*, μ are Lame constants, β is pressure=3Kα, T is temperature, K is delitation modulus,

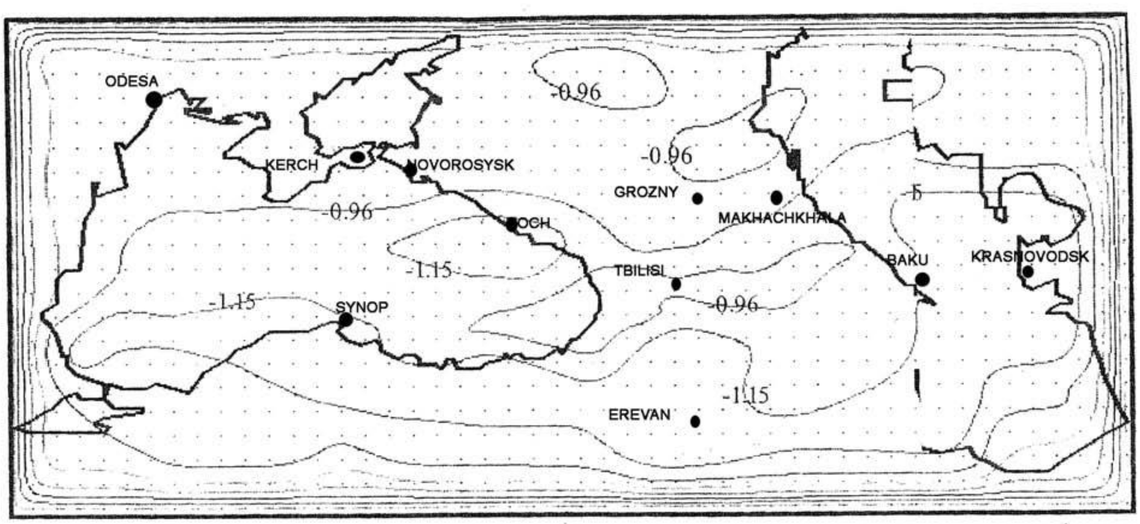
$$K = \frac{3\lambda^* + 2\mu}{3}$$

$$\alpha = (4 - 1{,}3 \cdot 10^{-3} \cdot T) \cdot 10^{-5}$$

While solving boundary problem (4-13), we receive components U_1, U_2, U_3 of displacement vector $\vec{U}$, and by its help we define stress components.

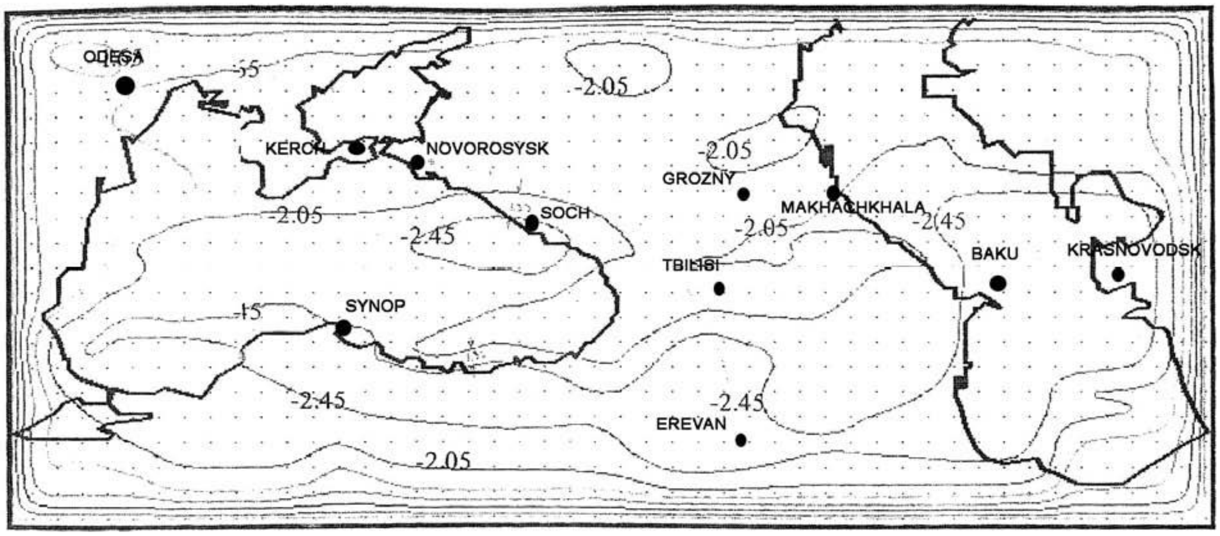
Analys and interpretation of the thermoelastic 3D model

The analysis of calculation maps of vertical thermodisplacements at 140 and 70 km depts. (410 million years) shows that already from these depths contours of Black and Caspian Seas and fault of the Caucasus are being formed. Already from these depths contours of the Black and the Caspian Seas and faults of the Caucasus are observed.



Pic.1. Thermo-vertical displacements (km) 140 km depth (410 million years)

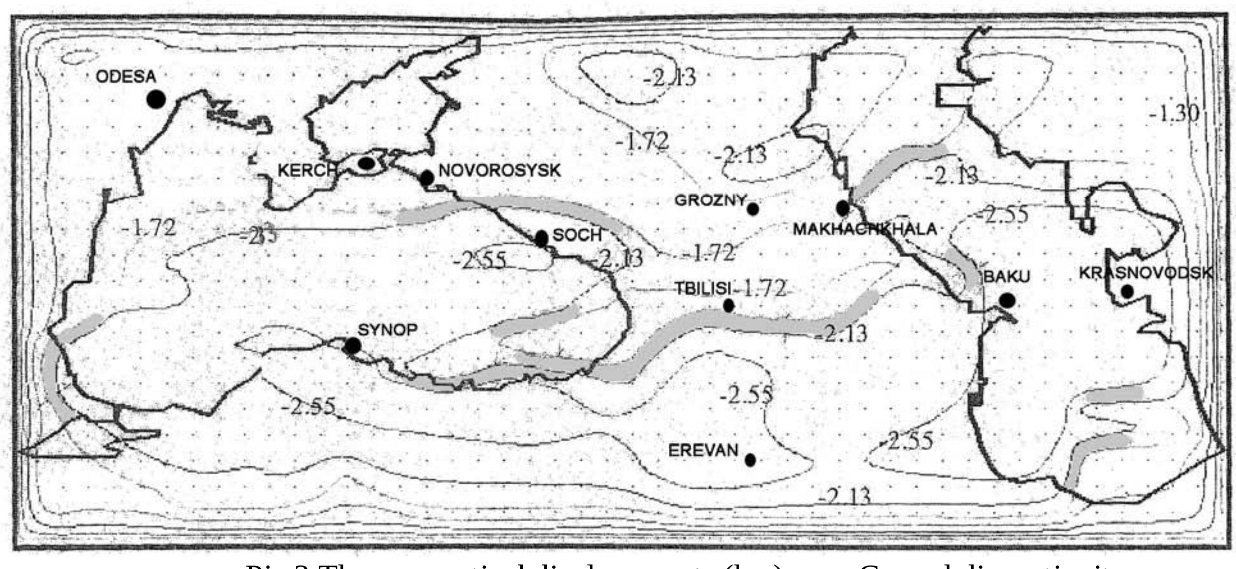
Already over Moho discontinuity outlines of Black Sea depression and deep-sea part of Caspian depression occur on maps of vertical displacements, as well as on maps of thermodense anomalies (Pic.2).



Pic.2. Thermo-vertical displacements (km) over Moho discontinoity

Isolines over Moho discontinuity (Pic. 2) represent elongated structure which is stretched from the Black Sea to the Caspian Sea, and they can not condition origin of discontinuity dislocations, i.e. deep faults, for which horizontal gradient of vertical displacements in 16 m/km is necessary.

Over Conrad discontinuity there are areas of thermodisplacements, which are forming deep thermo faults (Pic.3)

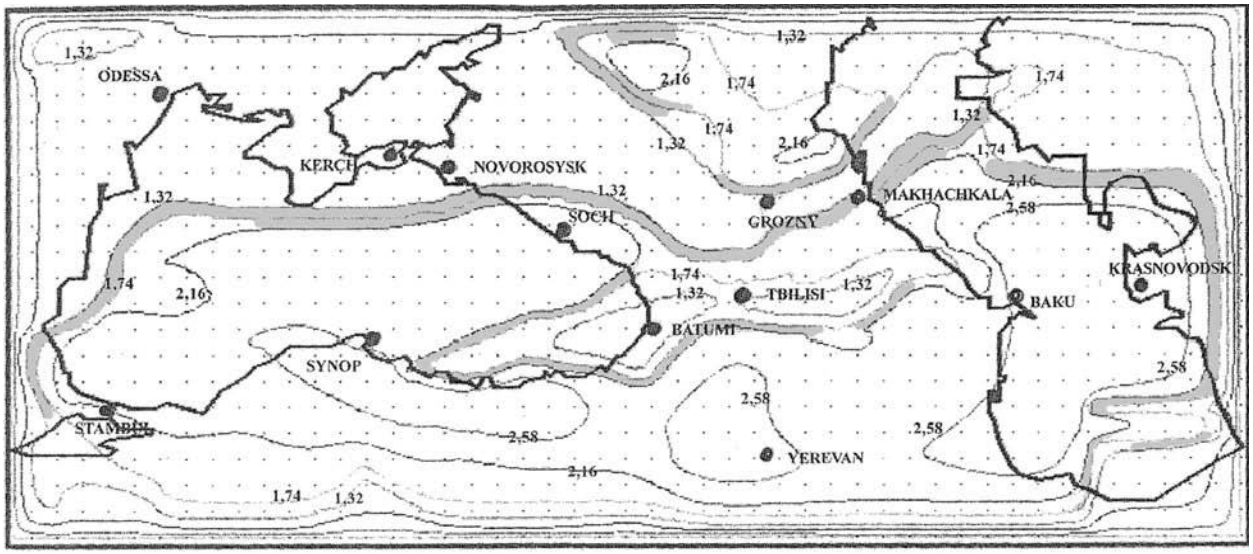


Pic.3 Thermo-vertical displacements (km) over Conrad discontinuity

Beginning from Granite layer surface, vertical displacements reach spatial critical values, at the same time isolines in some regions draw together so much that large areas of discontinuity dislocations occur (see Pic.4), crossing the whole Caucasus from sea to sea and almost utterly bordering the Black Sea and deep-sea part of the Caspian Sea.

In Transcaucasus in Devon, Carbon, Trias situation of vertical displacements is analogous of situation on granite layer surface.

In Lower Jurassic the system of discontinuity dislocations is branching even more, staying unchanged almost up to the Earth’s surface.



Pic. 4. Thermo-vertical displacements (km) over Granite layer surface

Areas of maximum approchement of isolines are shaded, which is indicative of possibility of deep faults occurrence.

West part of Achara-Trialeti zone and its prolongation to the South-West in the Black Sea are very interesting. In Achara region, on geological data basis, some deep faults are identified, which, according to our data, are clearly observed in water area of the sea.

Examination of the diagram of deep thermoelastic faults shows good correlation with geological observations in Achara. In this diagrams (Pic.4-5) faults have spindle-shaped prolongations in the South-East part of the Black Sea water area, which makes it possible to suppose sinking of Achara system faults in the Black Sea.

As model calculations of thermovertical displacements show, emersion of the territory of the Caucasus is observed, which manifests itself in uplift of crystalline substrate from 0,96 to 2,5 km before the origin of sedimentary complex. It seems that "chalk-forming" of the ocean "Tethys" in the Caucasus may be conditioned by thermoelastic vertical displacements in the mantle and the crust.

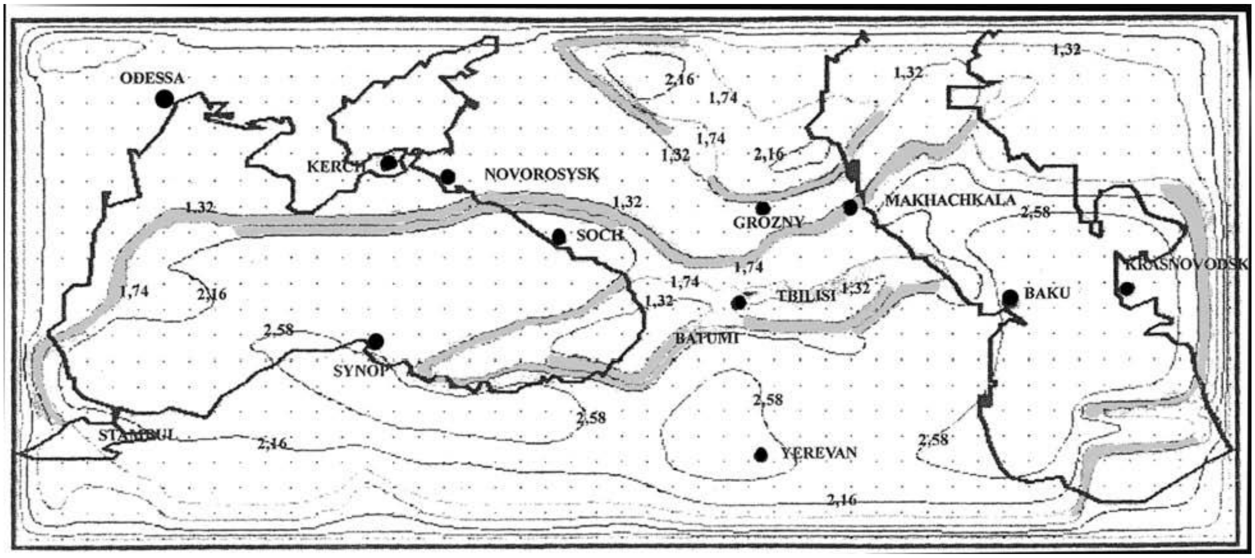
In the period of intensive uplift of central part of Black Sea and deep-water part of Caspian Sea water areas the fault of granite layer supposedly took place, which could explain the absence of this layer in the water areas.

Beginning from the surface of granite layer, along the contour of the Black Sea and deep-water part of the Caspian Sea (in the period of uplifting) ultimate strength of rocks was overcome (see Pic.4,5) which was manifested by discontinuity dislocations with deep fault formations.

When analyzing maps of distribution U_3 of vertical thermoelastic displacements of vector U , it is easy to notice that zones of anomalously high values of lateral derivatives U_3 (reaching 16 m/km and even more, considerably exceeding ultimate strength of rocks) agree well enough with data of majority of deep faults of the Caucasus and Black and Caspian Seas water areas. Faults of the Greater and the Lesser Caucasus, Black and Caspian Seas water areas, etc., are well observed on the maps.

Faults in anatolia region, conditioned by displacements of continental blocks, are transform and cannot be represented on the maps of vertical thermoelastic displacements.

Maps of thermal models, based on paleoreconstruction diagrams, show that within the Black Sea, beginning from Trias (shallow sea) till Upper Cretaceouse-Quaternary period, cristalline substrate comes to surface and only afterwards intensive deflection and accumulation of sediments begin.



Pic.5. Thermo-vertical displacements (km) on the surface of Devonian, Carbonic, Triassic period

Before Upper Cretaceous mechanical connection between blocks of the Black Sea (and earlier, deep-water part of the Caspian Sea) and the whole surrounding lithosphere plate was utterly broken, after which sinking (a bit earlier) of Caspian block and in K_2 – Black Sea block, took place, which favoured sharp accumulation of sediments in them and further sinking also at the expense of accumulated sediments.

As for Stavropol and South Caucasus, here ultimate strength of rocks was not overcome (horizontal gradient is considerably lesser than 16 m/km); see Pic.2-5.

Problem of formation of Black Sea and Caspian Sea depression is of considerable interest. Most probably their nature is similar. There exist lots of hypotheses about origin of these structures. One more is offeres in the present investigation.

The Black Sea depression and Caspian depression are almost utterly bordered with deep faults, which penetrate into 70 km and deeper depths and also cross all formations of sedimentary complex, along which gradual accretion of faults towards surface took place owing to sinking heavy and cold foundation and growth of sediments weight which were accumulating in depressions. At the some time it should be taken into account that Black Sea and Caspian Sea "plates", float on half-melt of elastico-viscous medium of upper mantle (astenosphere) and, owing to surrounding deep faults, begin to "sinking" deeper and deeper as sediments accumulate in depressions, untill all plates and buoyancy force get balanced.

In Upper Cretaceous, substrate, which is sunk under thick sediments and is not yet warmed up, represents low-temperature anomaly (at depth too); it follows that, irrespective of "screening" effect of sediments (as it is considered), this low-temperature body can not give surface high thermal flows at all.

Thus, at the first stage, against a background of general uplift, due to thermodisplacements along the whole plotting board, areas of Black Sea and deep-water part of Caspian Sea (see pic.2-5) experiance sharp uplift, which results deep faults along the whole contour of the seas. At second stage areas which are fringed with deep faults begin to come down.

Interesting picture, corroborating our model, is observed in the south of the Crimea peninsula, where, according to data of thermoelastic model, sublatitude structure of deep fault is observed, which coincides with geological data; "in the south submarine part of the Crimea structure is separated from deep-water hollow of the Black Sea by the fault which crosses the foot of continental slope (V.N. Hain, 1984, p.145). According to our data analogous picture is observed in the south of the Black Sea, in

Anatolia region.

As to absence of deep thermoelastic faults inside the Black Sea, it may be explained by tectonic (purely mechanical) crushing of oblong plate of the Black Sea, which could not reflected on thermoelastic model.

It is to be supposed that analogous picture is observed in deep-water part of the Caspian Sea water area, which is of earlier genessis, but nevertheless, proceeding from the fact that calculations for coming to surface crystalline substrate give here too isotherm sinking, i.e. upper layeres of “granite” (where they do exist) and basalt as well, are considerably cooled. “Cold” sediments are being deposited on them again. That’s why they can not be warmed up thus much as to give considerable heat flows on sea ground.

Undoubtedly initial origin impulse (in the period of 410 million years) of both depressions is of mantle origin. That fact that in the Caucasus contours of Black and Caspian Seas appear at Moho discontinuity testify to above said.

Conclusions:

1 large vertical displacements occur in the mantle; as for sedimentary complex, vertical displacements are insignificant;

2 we think that chalk-forming of ocean “Tetis” is connected with vertical thermodisplacement processes in the mantle and the crust;

3 it is possible that absence of granite layer in the Black Sea and deep-water part of the Caspian Sea is due to transgression in this period;

4 fractures arise at Moho discontinuity, continue in “basalt”, develop intensively in “granite” and exist in sedimentary complex till these days, thus conditioning occurrence of contemporary earthquakes in the region;

5 along discontinuity dislocations around the Black Sea sedimentation begins only after Upper Cretaceous, and in the Caspian Sea a bit earlier and also with sharp accumulation of sedimentary rocks.

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კავკასიის და შავი და კასპიის ზღვების აკვატორიის სამგანზომილებიანი არასტაციონალური თერმო–გეოდინამიკური მოდელი

გუგუნავა გ., ქირია ჯ., ქირია თ., ზერაკიძე ზ.

რეზიუმე

აგებულია კავკასიის და შავი და კასპიის ზღვების აკვატორიის სამგანზომილებიანი არასტაციონალური თერმო–გეოდინამიკური მოდელი, რომლის საფუძველზე ჩატარებულია რეგიონის გეოლოგო–გეოფიზიკური ინტერპრეტაცია. აგებულია წანაცვლების ვერტიკალური მდგენელის რუკები. დადგენილია ზოგიერთი რღვევის წარმოშობის თერმული ბუნება.