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Geodynamics of Alpine Belt and Caribbean Region: Plate - Tectonics and Plume - Tectonics

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Abstract:

The origin and evolution of geological structures reflect lithosphere-asthenosphere interaction in the process of lithospheric plate movement. Mantle diapirs contribute significantly to the sedimentary basins formation in Alpine belt and Caribbean region. Mantle diapirs are the result of density inversion in the asthenosphere–lithosphere system in the periods of tectonomagmatic activations. Increasing heat flow and mantle diapirs on the phone of convergence of Africa and Eurasia in Alpine belt and North and South Americas in Caribbean region produce intercontinental seas in the Cenozoic. The analytical solution of the problem give possibility to find the critical parameters connecting the mantle flow dynamics with surface relief evolution. In Alpine belt, the mantle diapirs form new basins at the final stage of Africa–Eurasia collision in the Cenozoic. In the Caribbean region, great mantle diapir separates the North and South Americas in the Mesozoic, and then the diapir is the source for different smaller diapirs during the convergence of these continents in the Cenozoic. The Gulf of Mexico and Pre-Caspian Depression are connected with mantle diapirs upwelling and have common geological-geophysical features as very rich oil-gas and salt bearing structures. Geodynamics of Alpine belt and the Caribbean region is determined by plume - tectonics on background of plate - tectonics in these regions.

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1. INTRODUCTION

Geological structures formation and evolution, the connection of surface structures with deep movements in the lithosphere and asthenosphere are the most important and complicated problems in tectonics and geodynamics.

The movement of the asthenosphere is reflected in the surface geophysical fields - geothermal, gravitational, electromagnetic. The presence of molten asthenospheric masses is confirmed by seismic data, including seismic tomography.

The movement of the upper surface above the rising mantle diapir is fixed by a change in the sedimentation regimes. The rise of the diapir is reflected in the surface topography, the structure of the basement, and the shape of the Moho and Conrad boundaries.

The collision of lithospheric plates is determined by the collision of deep flows in asthenosphere. The geodynamics of collision zones is determined by relationship between density, viscosity and temperature of the layers of the lithosphere and asthenosphere. A complex geodynamics is determined by the relations between geological and geophysical parameters and external limiting factors for movements on the spherical surface of the Earth.

The stress-strain state of the lithosphere is expressed in the presence of faults, fractures, magmatism, volcanism, high seismicity, increased heat flow, hydrothermal activity, and is confirmed by geophysical and seismic tomography data (Figure 1).

Geophysics and seismic tomography provide a deep section at the present time, while mechanical - mathematical modeling gives possibility to study the evolution of the structures in dynamics.

2. ALPINE BELT GEOLOGICAL-GEOPHYSICAL DATA

Alpine belt is determined by collision of Arabian-African and Euroasian plates [1-13]. Structures of Alpine belt include sedimentary basins, back-arc basins, seas and orogens (Figures 2-6) [9]. Depressions are characterized by thin crust and high heat flow (Table 1) [1, 4, 6, 11, 12, 14-18]. Region is characterized by active magmatism and basalt volcanism with xenoliths of asthenospheric matter. Geological-geophysical data give possibility to link these structures with upwelling of mantle diapirs (Figures 4-6) [1, 3-5, 9, 13-15, 19-23]. Above rising mantle diapirs on the upper surface the structures of swell, deep basin or basalt intrusion can arise depending on energy and upwelling stage of the diapirs (Figure 5). The structures of orogens and thickening of the crust can arise between diapirs. The Caucasus is connected with collision zone of the lithosphere plates and with collision of asthenosphere fluxes from mantle diapirs under Black and Caspian seas. It is possible to explain origin and evolution of these structures on the base of mechanical-mathematical modeling.

The Mediterranean Sea opened and closed repeatedly due to tectonic-magmatic activation, the rise of a

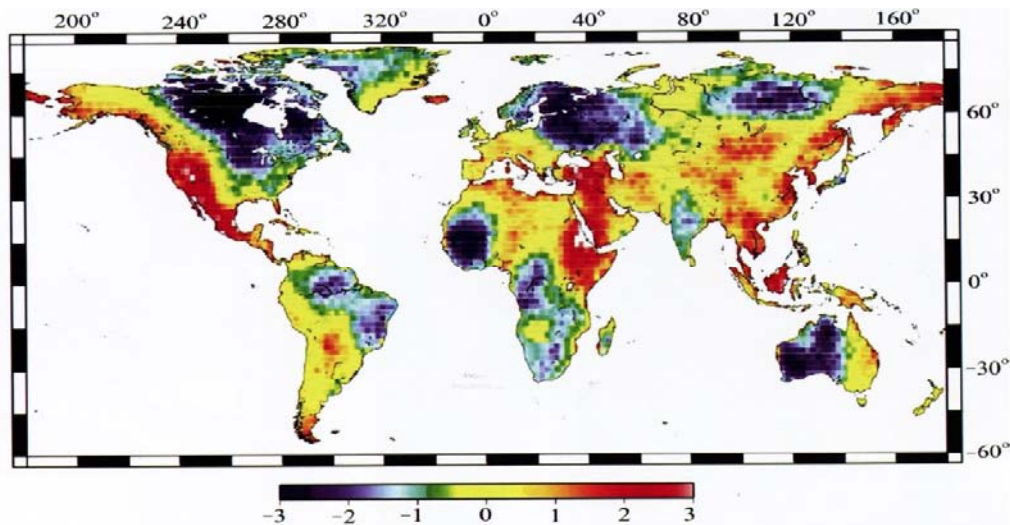


Figure 1: Seismic tomography of lateral inhomogeneities of the lithospheric mantle under the continents. Positive and negative deviations of the shear wave velocity are shown. (J. Poupine). The maximum speeds are confined to the ancient cores of cratons. The Alpine belt and the Caribbean-Mexican region correspond to the minimum speeds [15].

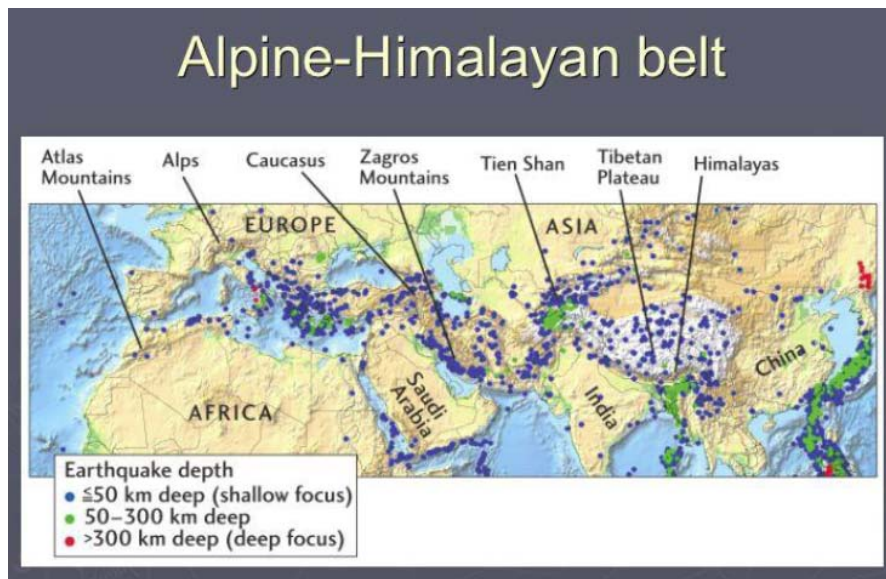


Figure 2: Alpine-Himalayan belt. (NASA).

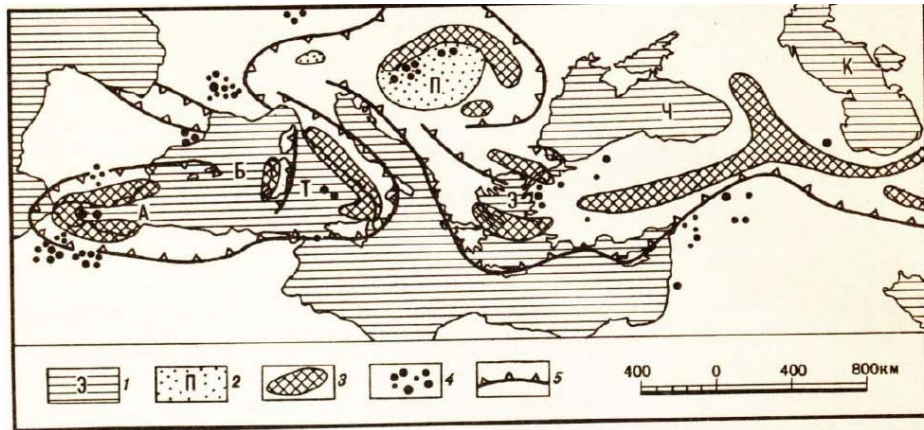


Figure 3: Structure of Western sector of Alpine-Himalayan belt. 1 – seas (A – Alboran sea, Б – Balearic sea, К – Caspian sea, Т – Tyrrhenian sea, Ч – Black sea, Э – Aegean sea). 2 – Pannonian Depression. 3 – volcanic arcs. 4 – areals of basalt volcanism. 5 – frontal zones of napping structures [9].

Table 1: Geological-Geophysical Data for Alpine Belt

Structure	thickness of sedimentary cover (km)	Thickness of crystal crust (km) in depression (numerator) in frame (denominator)	Heat flow (mW/m ²)
1. Tyrrhenian sea	6	16/45	30-160
2. Aegean sea	3	15/23	100
3. Black sea	16	15/45	30-35
4. Pre-Caspian depression	24	12/40	50
5. South-Caspian depression	20	12/45	40-50
6. Ionian sea (South)	12	10/35	30-40
7. Ionian sea (North)	8	10/30	50-70
8. Balearic sea	8	10/40	50
9. Levant sea	6	8/30	30
10. Pannonian depression	9	18/27	90

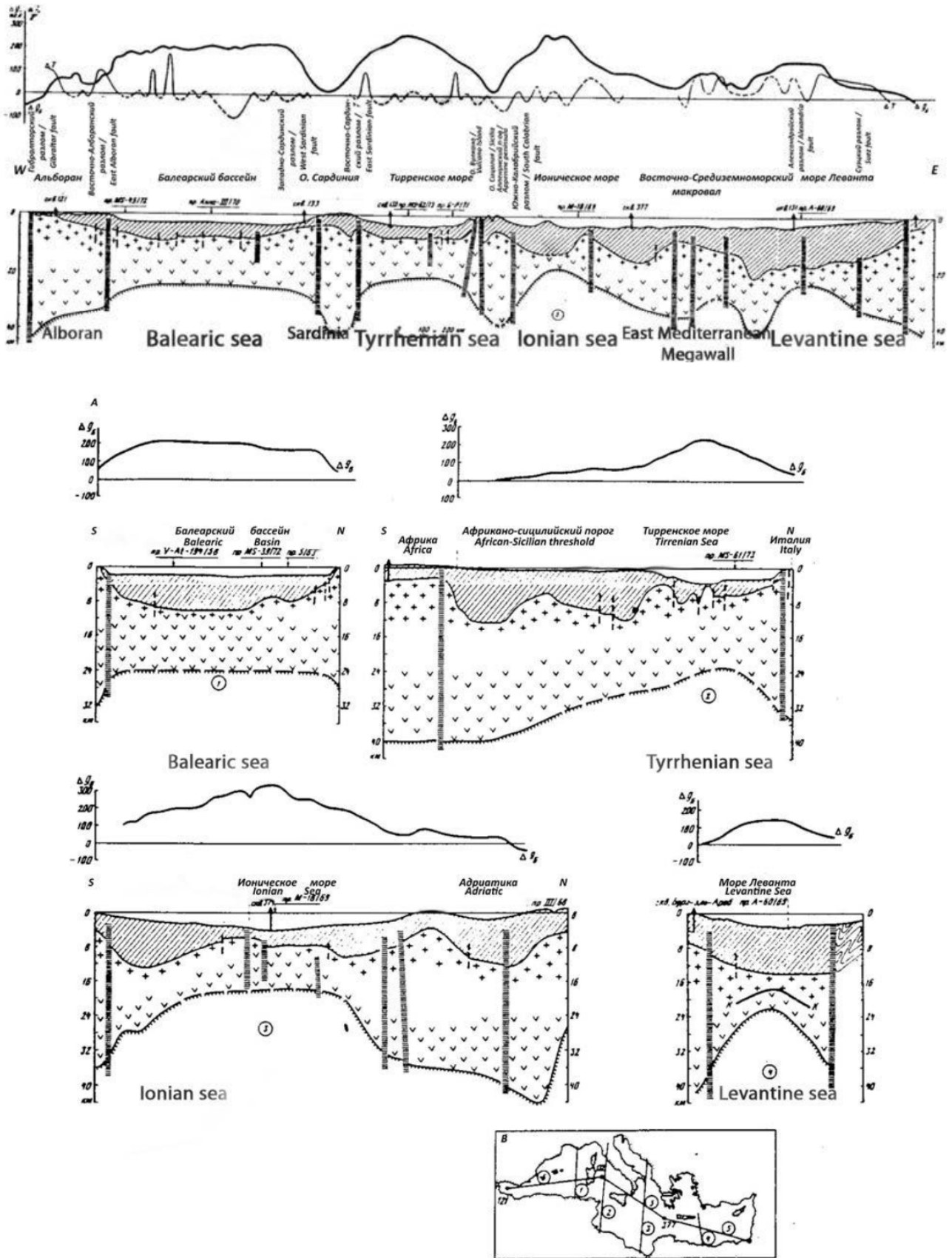


Figure 4: Results of geological and geophysical studies of tectonic structures of the Mediterranean (Sulidi-Kondratyev, Kozlov, 1980, in [11]).

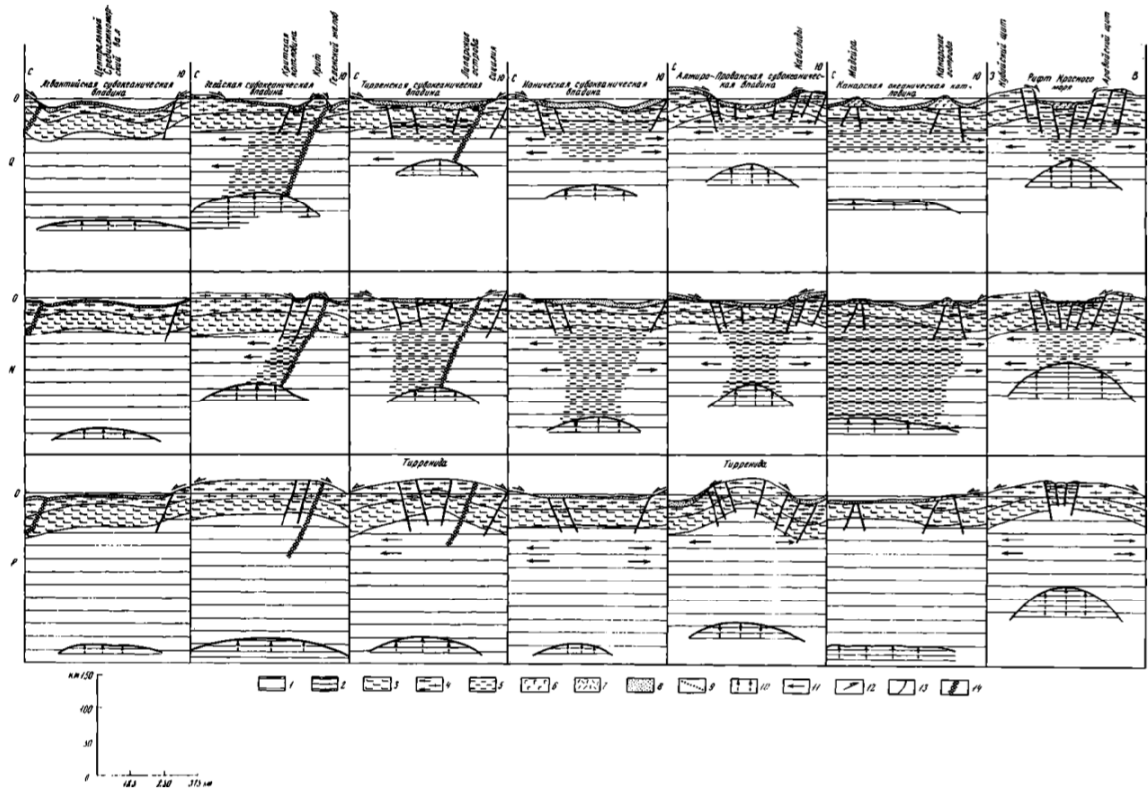


Figure 5: Map of the main structures of the joint zone of the Arabian-Himalayan fold belt with the African-Arabian continent (Sulidi-Kondratyev, Kozlov, 1980, in [11]).

1 - exits of the granite layer to the surface within the continents; 2 - areas of platform slabs on the Pre-Cambrian basement within the continents; 3 - orogenic active margins of the continents (a), the corresponding tectonic zones of the submerged parts of the continents with a crust of suboceanic and subcontinental types (b); 4 - zones of covers and large thrusts; 5-9 - suboceanic and subcontinental deep-sea basins at different stages of transformation of the earth's crust: 5 - stage of thinning of the continental crust, 6 - stage of differentiated destruction of the continental crust, 7 - stage of general destruction of the continental crust, 8 - stage of completion of the destruction of the continental crust, 9 - stage of stabilization of the suboceanic crust; 10 - slotted rifts; 11 - Alpine eugeosynclinalis with continental type crust; 12 - contours of deep-water depressions; 13 - deep faults; 14 - Gibraltar-Omani ophiolite suture. Deep water depressions: I - Alboran, II - North Balearic, III - Tunisian-Sicilian, IV - Levantine, V - Aegean, VI - Tyrrhenian, VII - Ionian, VIII - Algerian-Provençal, IX - Canary, X - Oman, XI - Rift of the Red Sea.

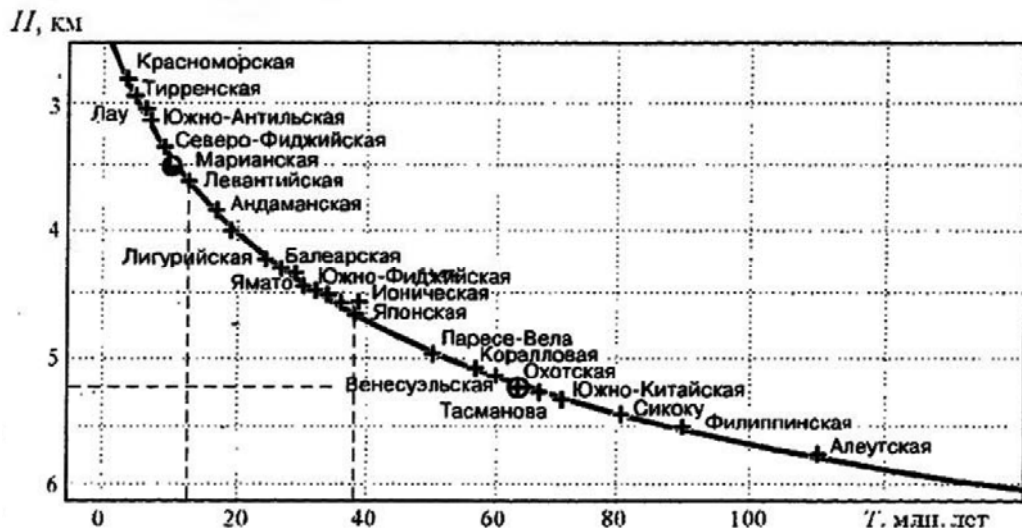


Figure 6: Graph of the dependence of depths and age of deep-sea basins. (Parsons and Sclater, 1977, in [1]).

From left to the right: Red Sea, Tyrrhenian, Lau, South Antilles, North Fijian, Mariana, Levantine, Andaman, Ligurian, Balearic, Yamato, South Fijian, Ionian, Japanese, Parese Vela, Coral, Venezuelan, Okhotsk, Tasmanova, South China, Shikoku, Philippine, Aleutian.

large-scale mantle plume and the spreading of plates above it, and then, after the exhaustion of the plume energy, the closure of the Tethys Ocean and the convergence of lithospheric plates in the Alpine-Himalayan belt. The phenomenon of gravitational instability on the surface of the global mantle plume manifests itself in the form of the rise of individual mantle diapirs of a smaller scale, which are responsible for the formation of sea depressions in the western sector of the Alpine-Himalayan belt. These depressions are characterized by a sequence and stages of development, and it is possible to trace how the energy of the rising plume is concentrated in individual depressions and migrates from the periphery to the center, where the activation maximum is realized in the Aegean Sea. And Corsica and Sardinia move away from the Apennines due to the rise of the diapir under the Tyrrhenian Sea.

In the Aegean Sea, in the area of Santorini volcano, there is the largest positive gravity anomaly in the Mediterranean Sea, which indicates the proximity to the surface of a molten lighter asthenosphere. Also an important indicator of the activity of processes at the bottom of the Aegean Sea are the earthquakes that constantly occur there. An analysis of earthquake epicenters indicates a particularly high seismic activity in the zone passing through the Peloponnesian Peninsula and the islands of Crete and Rhodes, where earthquakes with a magnitude of 9 balls were repeatedly recorded. This is well explained by the presence of a subduction zone here [15].

In the Mediterranean, geological processes are actively taking place, leading to the transformation of the earth's crust. Geological processes are manifested in the emergence of high mountain ranges, such as the Alps and the Caucasus, and at the same time in the formation of deep-water depressions. The Mediterranean is characterized by unusually high seismic activity and a variety of volcanic activity. Many areas of the Mediterranean and the mountain structures surrounding it are characterized by an increased heat flow from the bowels of the Earth, which indicates a high degree of heating of the earth's crust. The rate of vertical movements of the earth's crust is also maximum here (up to 10 mm per year).

35 million years ago at the site of the Greater Caucasus there was a deep-sea basin about 200 km wide. Its sides approached until a full collision about 11 million years ago. Then the region began constant uplift. During compression, a mountain belt with a

crustal thickness of 45–50 km and a thickness of the lithosphere up to 250 km was formed. 5-10 million years ago, the Greater Caucasus began to rise rapidly. Volcanoes Elbrus, Kazbek, and others arose on its axis [11].

The Caspian basin and the eastern segment of the Caucasus region, including the Caspian Sea, can be considered as regions in the vicinity of the eastern part of the Alpine belt, which in turn is the western part of the Alpine-Himalayan belt, stretching from the western side of the Mediterranean Sea to the Pacific coast. The Caspian Sea crosses from north to south a series of latitudinal structural zones of the southeastern margin of the ancient Precambrian East European platform, the young epi-Hercynian Scythian-Turanian platform and the modern Alpine-Himalayan orogenic belt (Figure 7, 8).

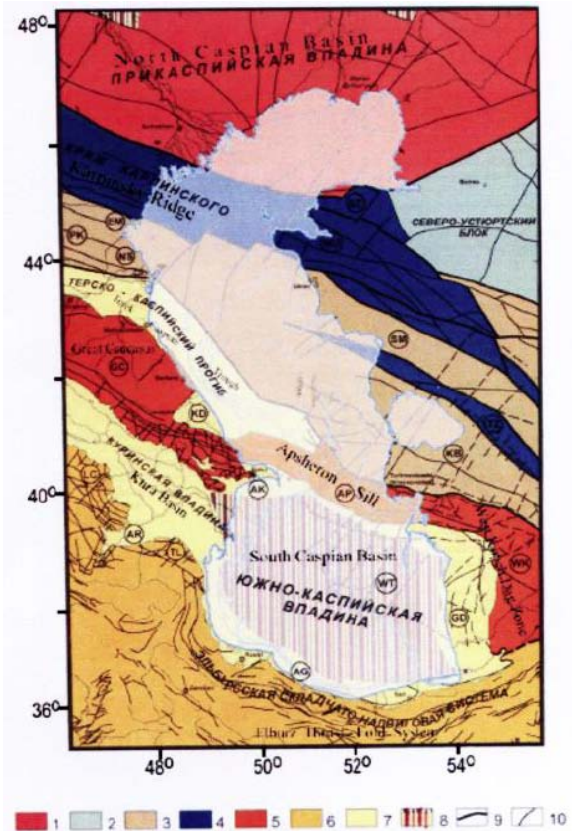


Figure 7: Tectonic map of the Caspian Sea. (International tectonic map, 2003).
 Foundation of platform areas (1-4):
 1 - Early Precambrian, 2 - Baikal, 3 - Hercynian, 4 - Early Cimmerian.
 Alpine fold-cover systems (5, 6):
 5 - Greater Caucasus and Kopetdag, 6 - Lesser Caucasus, Talysh, Elburz.
 7 - forward troughs and troughs, 8 - troughs with oceanic-type crust,
 9 - discontinuous faults at the boundaries of large structures,
 10 - important gaps.

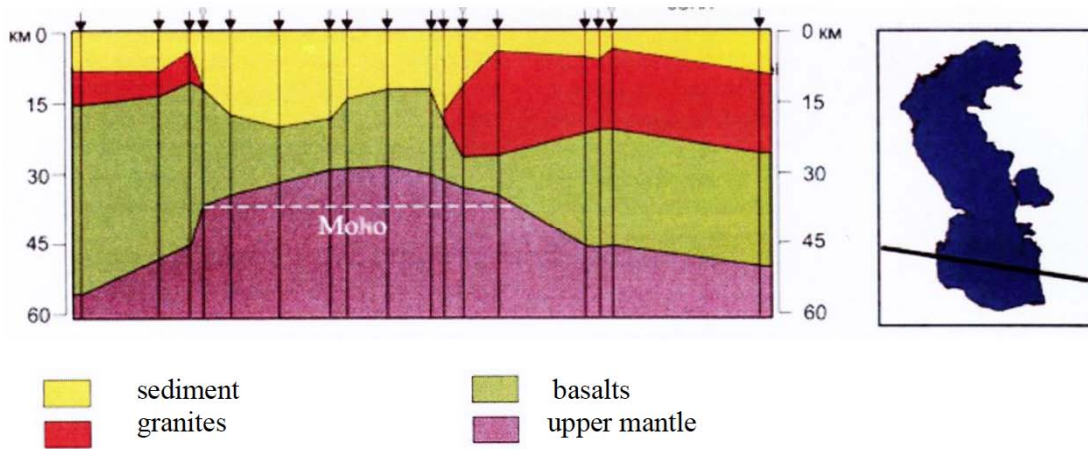


Figure 8: Geophysical section of the lithosphere of the South Caspian Basin (Jackson *et al.*, 2002).

The Pre-Caspian and South Caspian depressions are deep sedimentary basins with a sedimentary cover thickness of more than 20 km, which have a high oil and gas potential and are of great national economic importance (Figures 9-11).

The deep gravitational instability of the asthenosphere manifests itself in the form of the rise of a large-scale mantle plume, which forms the structure of the Alpine belt as a whole. Against the background of the general rise of the plume, individual diapirs rise, forming deep-water basins of sedimentary basins. The manifestation of gravitational instability has a characteristic scale of distances between depressions, determined by the thickness of the layers of the sedimentary cover, consolidated crust, mantle lithosphere and asthenosphere, as well as the mechanical properties of the forming rocks, in particular, density and effective viscosity. The stages of uplift of diapirs determine the heat flux of the structure, as well as magmatism, volcanism, and seismicity; geodynamic activity or tectono-magmatic activation.

The successive activation and rise of diapirs under the conditions of collision of lithospheric plates and the closure of the Alpine paleocean could first form the Pre-Caspian depression, then the Middle Caspian, and then the South Caspian depression. The heat from the rising mantle diapirus could reach the earth's surface in the Caspian basin, but not yet in the South Caspian. And this determines the different thermal background in the basins, making it higher in the Caspian than in the South Caspian.

Seismic tomography data confirm the presence of subduction of the South Caspian Basin under the Elburz, which also emphasizes the similarity of the

formation of the back-arc seas of the Alpine Belt and the South Caspian Basin.

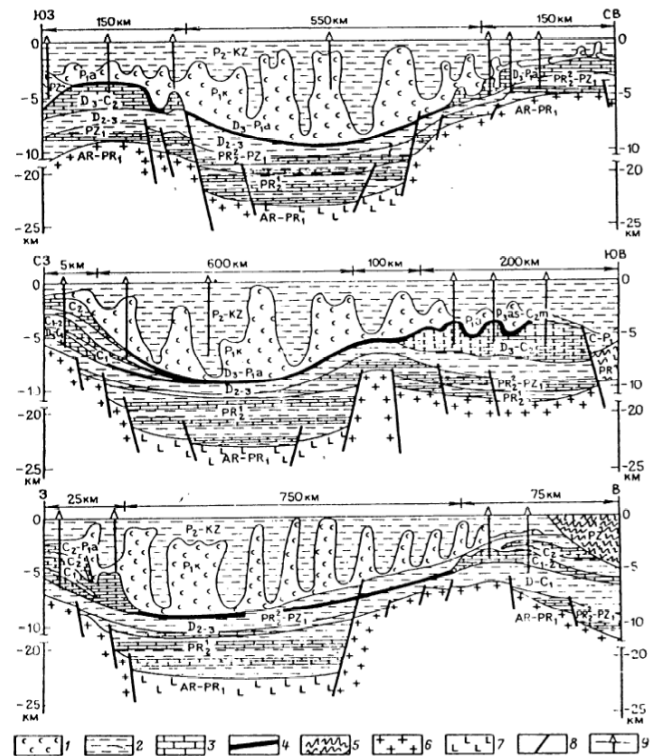


Figure 9: Geological section of the Pre-Caspian depression. (Maksimov *et al.*, 1990).

Rocks: 1 – salt, 2 – terrigenous, 3 – carbonates, 4 – clays, 5 – condensates.

Complexes: 6 - granites, 7 - basalts. 8 - folds, 9 - deep wells.

3. THE CARIBBEAN REGION GEODYNAMICS.

There are many models of the Caribbean region's structure and evolution. It is located between North and South America and consists of continental, subcontinental, and oceanic elements.

The Caribbean Sea is a typical intracontinental sea [1, 2] (Figure 12-14). It concentrates multiple hydrocarbon fields (Cuba, Venezuela, Columbia, Nicaragua, Trinidad).

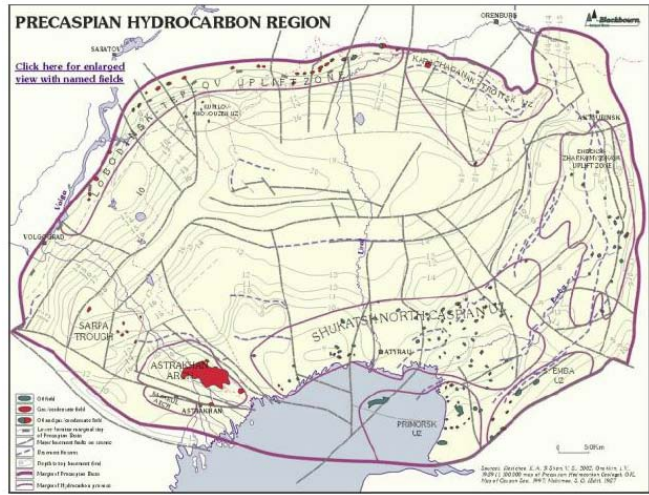


Figure 10: Isohypses of the basement surface and the main deposits of the Pre-Caspian depression. (Kleshchev, 2002).

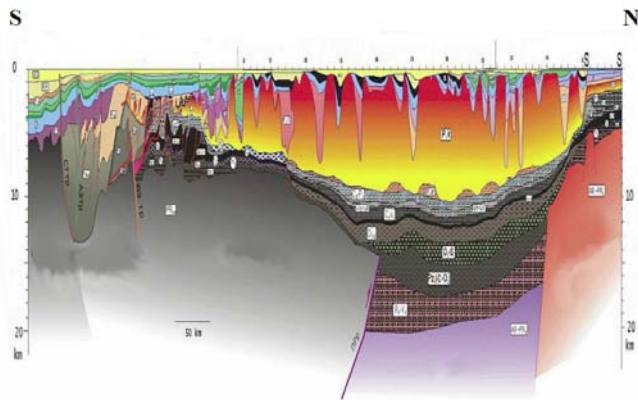


Figure 11: Geological section of the Pre-Caspian depression. <http://educationally.narod.ru/kaspivolgaphotoalbum.html>

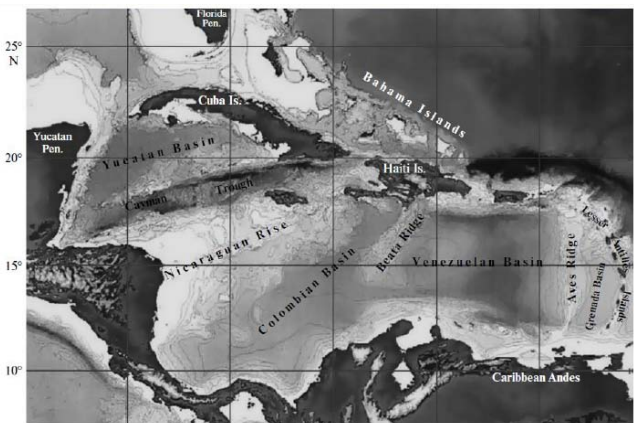


Figure 12: Map of the Caribbean region (based on the GEBCO, General Bathymetric Chart of the Oceans).

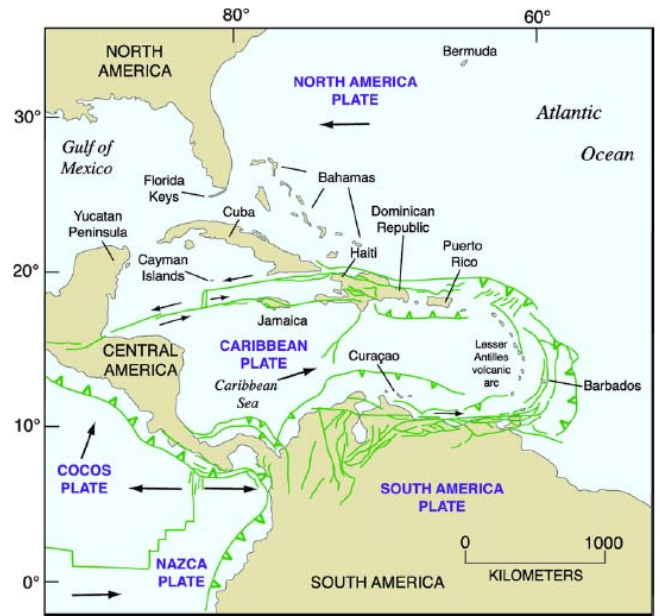


Figure 13: Caribbean plate with movement directions. (Wikipedia).

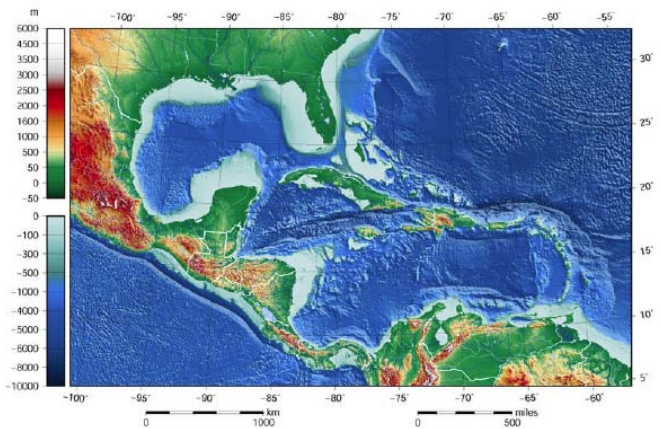


Figure 14: Caribbean Sea and Gulf of Mexico shaded relief bathymetry land map. https://en.m.wikipedia.org/wiki/File:Caribbean_Sea_Gulf_of_Mexico_shaded_relief_bathymetry_land_map.png

The largest island in the region Cuba is incorporated into the Caribbean island arc including the Greater and Lesser Antilles. It is located in the periphery of the North American continent. Formation and evolution of the Yucatan Basin and the tectonic origin of the Cuban accretionary structures can be described by the next stages [1, 2].

The initial opening of the basin started in the pre Late Jurassic age. Large mantle diapir penetrated into Caribbean Sea during lithosphere extension. It caused the rifting of the united continent, which included both Americas and the African continent. By the beginning of the Cretaceous, the rates of divergence between (a)

North and South America and (b) North America and Africa were the same, whereas by the present day Africa is distant from both Americas owing to spreading of the Atlantic. The divergence between Americas ended in the Cretaceous and became convergence in the Cenozoic. Data from the GPS network reveal a convergence between South and North America, leading to the meridional shortening of the Caribbean Plate between them. Despite the convergence of the two Americas, the mantle diapir between them is clearly manifested in the velocity structure of the mantle beneath the Caribbean Basin, based on *P*-wave seismic tomography data [2] (Figure 15). It makes the Caribbean region similar to the Mediterranean.

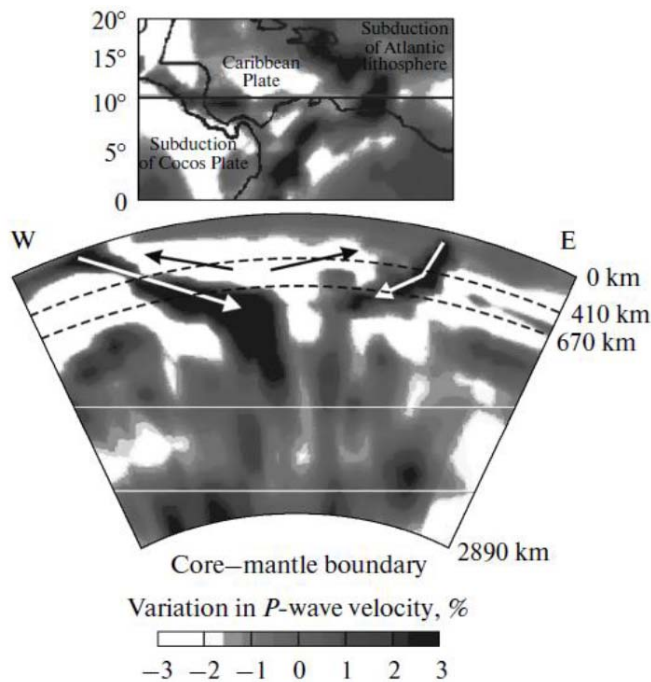


Figure 15: *P*-wave velocities in the mantle beneath the Caribbean region (Van der Hilst, in [2]). Mantle diapir beneath the Caribbean region. White arrows - directions of the cold material from the Atlantic lithosphere (east) and the Cocos Plate (west) beneath the hot mantle diapir in subduction zones. Black arrows - directions of the hot material flow.

The diffuse spreading replaced rifting in the Late Jurassic–Neocomian in the oceanic crust formation. The basin began the next phase of its opening and evolution by the end of Aptian.

Another zone of diffuse spreading was formed to the south of the Yucatan Basin and north of the Columbian and Caribbean Andes in the Late Jurassic–Early Cretaceous. In addition to the Yucatan Basin, the Columbian and Venezuelan basins were formed in this epoch. There are the anomalously thick oceanic crust

20 and 15 km, respectively in these basins. A sedimentary cover is 3–4 km thick in both basins. The acoustic basement revealed by deep drilling.

The cause of the considered tectonic processes was the penetration of a large mantle diapir into the zone beneath the region in the Early Mesozoic. The diapir led to diffuse spreading concentrated simultaneously in three tension centers the Yucatan, Colombian, and Venezuelan deep basins.

Mantle diapirs occurred due to density inversion in the asthenosphere–lithosphere system in the background of increasing heat flow and produced depressions in the Mediterranean and Caribbean regions and the surrounding thrust orogens.

Subduction and collision in the approach of Africa and Eurasia in the Mediterranean region or North and South America in the Caribbean region are closely connected with mantle diapirism and produce different geological constructions depending on geophysical properties of rocks and the lithosphere geodynamics.

The Caribbean region is connected very close with the Gulf of Mexico, a very rich oil-bearing basin (Figures 16-18). The peculiarity of the tectonic evolution of the Gulf of Mexico was given by R. Baffler, who suggested that the formation of the Gulf occurred in the interval of 170-150 million years ago in connection with the development of the passive margin of the Atlantic Ocean, i.e. in the Bathonian-Titonian time, in the process of pushing the Yucatan continental block away from the southern edge of North America.

It is possible to compare evolution of the Gulf of Mexico with Pre-Caspian Depression in connection with Mediterranean and Alpine belt, when different impulses of mantle activity produced consequently new sedimentary basins. As depression of the Gulf of Mexico is older than depressions of the Caribbean sea, as the Pre-Caspian Depression is older than South Caspian Depression and basins of Mediterranean.

4. MECHANICAL-MATHEMATICAL MODELING

An adequate mechanical-mathematical model construction for the geological structures formation and evolution analysis is an important technique for the studies of velocity fields, stresses and temperatures in the sedimentary cover, crust and upper mantle at different tectonic conditions [8, 9, 24-30].

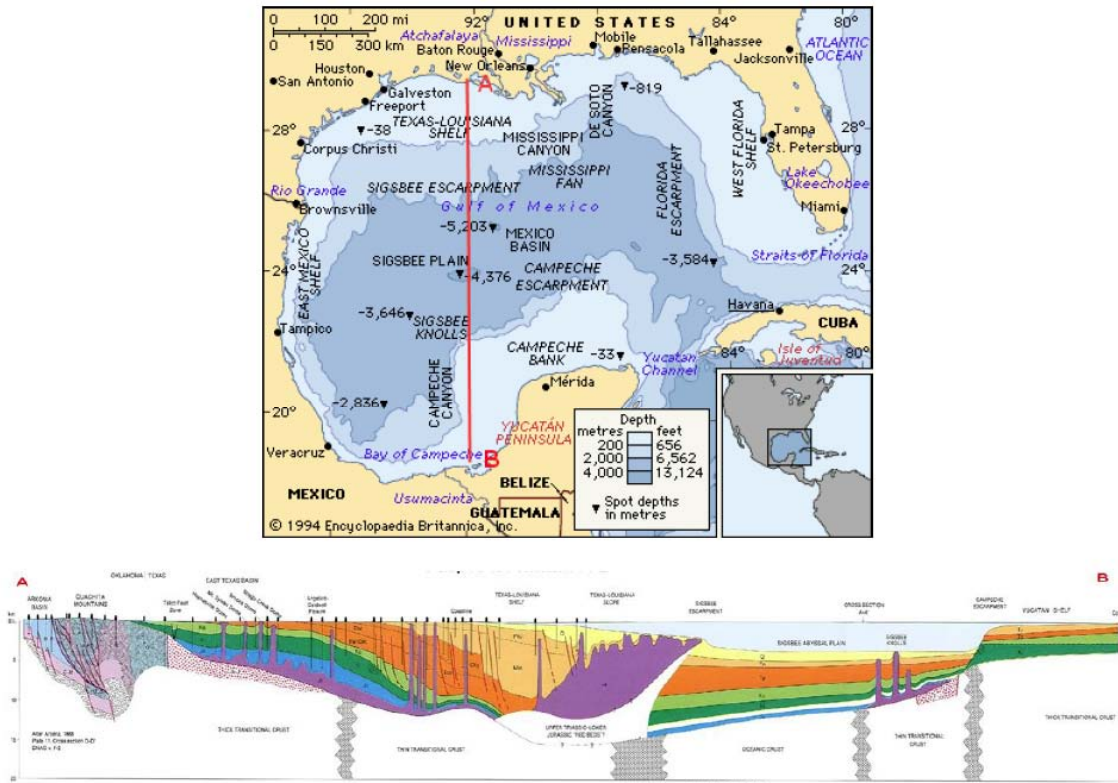


Figure 16: Schematic geological section of the Gulf of Mexico (RV METEOR cruise M67, 2005).

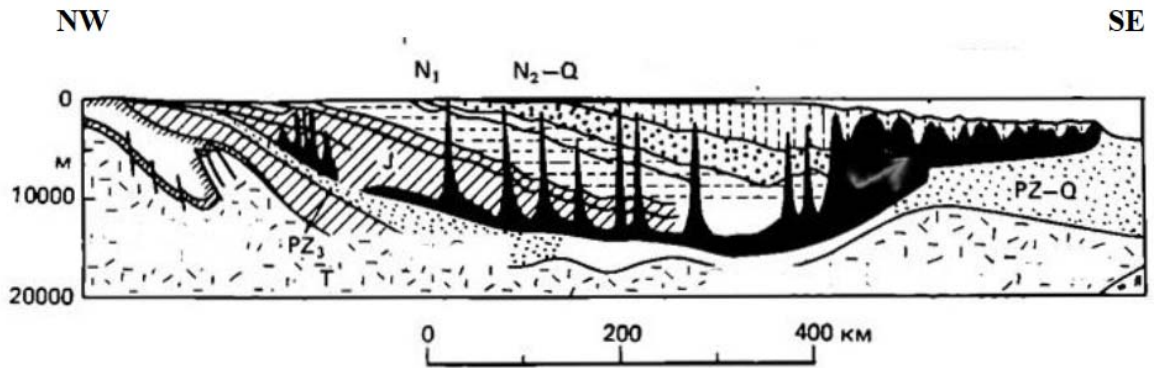


Figure 17: Geological section of the southern part of the North American continent with the Gulf of Mexico. (King, 1977).

It is possible to use two different approaches to mathematical modeling of geological structures and processes. The first one is to use complete system of mechanical- mathematical equations and then to calculate the obtained equations under required boundary and initial conditions with high-capacity computers.

The second one is to simplify the obtained equations for analytical decision of the problem with semi quantitative conclusions comparable with geological-geophysical data. Optimal variant is to combines the advantages of both methods.

For description of geological structures evolution above upwelling mantle diapir the mechanical-mathematical model of high viscous fluid is used. The models are investigated on the base of geological structures of Alpine belt and the Caribbeans.

For approximate equations construction it is necessary to get small parameters of the problem which can be used for the decomposition.

Numerous geological structures are characterized by significant elevation of horizontal regional scale L over vertical scale h of typical layer thicknesses. This allows

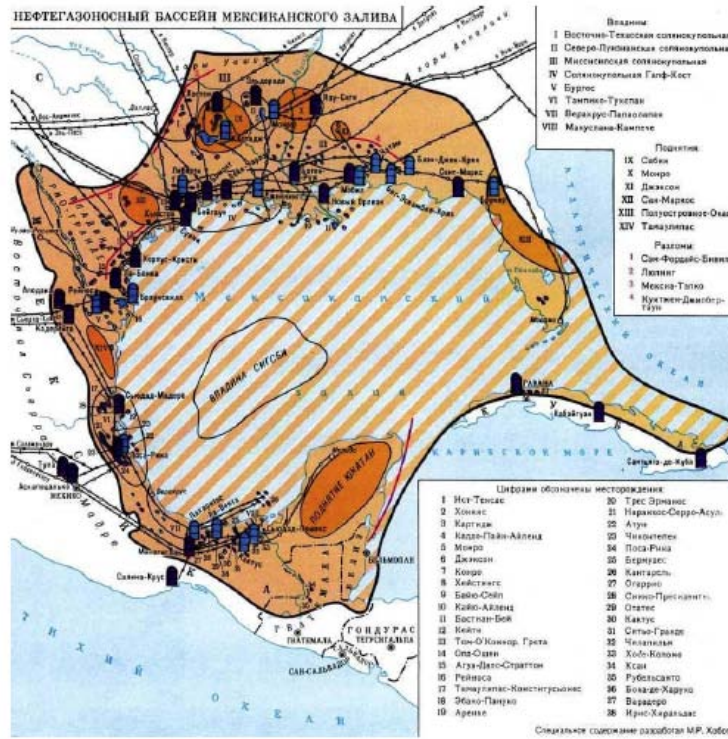


Figure 18: Oil and gas basin of the Gulf of Mexico. (Khobot M.R.).

to get small parameter h/L for analysis of the problem. The second small parameter of the problem F/R arises during analysis of rheological behavior of matter in the layers. F – Froude number, R – Reynolds number [25, 26, 28, 30].

It is possible to simulate the slow lithosphere movements by model of viscous flow in multi-layered, incompressible, high-viscosity Newtonian fluid, using Navier-Stocks equation (1) and discontinuity equation (2):

$$d\mathbf{v}/dt = \mathbf{F} - (1/\rho)\text{grad } p + (\mu / \rho)\Delta\mathbf{v} \quad (1)$$

$$\text{div } \mathbf{v} = 0 \quad (2)$$

\mathbf{v} – velocity vector, \mathbf{F} – force of gravity, p – pressure, ρ – density, μ - viscosity, t - time.

Here are the dimensionless values for coordinates, velocities and pressure X, Y, Z, U, V, W, P :

$$x=LX, \quad y=LY, \quad z=hZ, \quad u=u_0U, \quad v=u_0V, \quad w=u_0(h/L)W, \quad p=\rho_0ghP. \quad (3)$$

ρ_0, u_0 - characteristic scales of density and velocity.

Then here is the dimensionless form of Navier-Stocks equation and discontinuity equation for slow movements in thin layers for 2-dimension case:

$$\begin{cases} \frac{\partial P}{\partial X} = \alpha\mu \frac{\partial^2 U}{\partial Z^2} \\ \frac{\partial P}{\partial Z} = -\rho \end{cases} \quad (4)$$

$$\frac{\partial U}{\partial X} + \frac{\partial W}{\partial Z} = 0 \quad (5)$$

$$\alpha = \frac{F}{R\left(\frac{h}{L}\right)^3}, \quad F = \frac{u_0^2}{gL}, \quad R = \frac{u_0 L \rho_0}{\mu_0} \quad (6)$$

F – Froude number, R – Reynolds number, ρ_0, μ_0, u_0 - characteristic scales of density, viscosity and velocity.

At the upper boundary the condition of free surface is fulfilled. It means that the forces are equal to zero. It gives pressure and velocities in the layers [28, 30].

On the upper boundary ζ^* , the kinematic condition of a free surface also is executed (7). That is the points of a surface will not escape it during motion:

$$S \frac{\partial \zeta^*}{\partial t} + U^* \frac{\partial \zeta^*}{\partial X} - W^* = 0 \quad (7)$$

$$S = \frac{L}{u_0 t_0} \quad (8)$$

S is the Strukhal number. t_0 is the scale of time.

Moho boundary as the other matter boundaries also can be considered as a surface where the condition of non-penetration is fulfilled. So, substituting velocities, it is possible to get an equation of movement for any non-penetrated boundary.

Surface of asthenosphere under Alpine belt changes from 30 km in the centre of Tyrrhenian sea up to 70-100 km in depressions of East Mediterranean. The characteristic lateral size of depressions is 500-1000 km, distance between them is of 1000-1500 km.

Hence the characteristic parameters of a problem: $h_3 \sim 10$ km thickness of crust, $h_2 \sim 100$ km - thickness of mantle lithosphere, $L \sim 1000$ km - horizontal scale, $\varepsilon = h_3/L = 10^{-2}$ -small parameter.

Then it is possible to receive in zero approximation the equation of upper surface ζ_3 and Moho surface ζ_2 dynamics depending on velocities of the mantle diapir surface ζ_1 $U_0, W_0|_{\zeta_1}$ by decomposition of velocities and pressure on $\sqrt{\varepsilon}$:

$$\begin{cases} \frac{\partial^2 \zeta_3}{\partial X^2} = \beta \left[h_2 \frac{\partial U_0}{\partial X} - W_0 \right] \\ S \frac{\partial \zeta_2}{\partial t} + U_0 \frac{\partial \zeta_2}{\partial X} + \alpha \left[h_2 \frac{\partial U_0}{\partial X} - W_0 \right] = 0 \end{cases} \quad (9)$$

$$\alpha = \frac{(h_3)^3}{(h_3)^3 + \frac{\mu_3}{\mu_2} (h_2)^3}, \quad \beta = \frac{I}{\frac{\rho_3}{3} \left[\frac{(h_3)^3}{\mu_3} + \frac{(h_2)^3}{\mu_2} \right]}$$

$S = \frac{L}{u_0 t_0}$ - Strukhal number, u_0 - characteristic velocity

of the lithosphere matter, t_0 - characteristic time of considered processes, μ_i - viscosity, ρ_i - density in layers.

Let us consider a field of velocities and morphology of boundary ζ_1 as:

$$U_0 = a th kX, \quad \zeta_1(X,t) = -\gamma sh^2 kX - (h_2 + h_3) + \frac{D}{S}t \quad (10)$$

Here k and a characterize intensity of spreading: k -in the centre of structure, a - far from the centre; γ - gives possibility to vary the form of rising diapir; $D = S \frac{\partial \zeta_1}{\partial t}$ - velocity of rising diapir (Figure 19).

This field of velocities reflects the main features of a considered class of movements: the diapir upwelling,

spreading and lowering of substance far from the centre. Quantitative conformity is reached by variation of factors under preservation of the general structure of movements.

The decision of system (4, 5, 7) gives for big t :

$$\begin{cases} \zeta_2 = -h_3 - \alpha \gamma sh^2 kX + \alpha h_2 \ln(ch kX) + \alpha (D - h_2 ak) \frac{t}{S} \\ \zeta_3 = \beta \left[\frac{h_2 a}{k} \ln(ch kX) + \frac{\gamma a}{(2k)^2} ch 2kX - \left(\frac{\gamma a + D}{2} \right) X^2 \right] + C_1(t) \end{cases} \quad (11)$$

$C_1(t)$ is defined from the mass balance.

The analysis of these expressions gives critical parameters of the problem: depth of upwelling of mantle diapir $h_2 = 2\gamma$ when the characteristic form of the lithosphere layers is changed. If $h_2 > 2\gamma$ there is a deflection of a surface of the base in the centre of spreading, that really takes place in back-arc seas. If $h_2 < 2\gamma$, that is the depth of diapir is small, or speed of its rise is essential ($D > h_2 ak$), the diapir surface corresponds to rise of Moho surface (Figure 19).

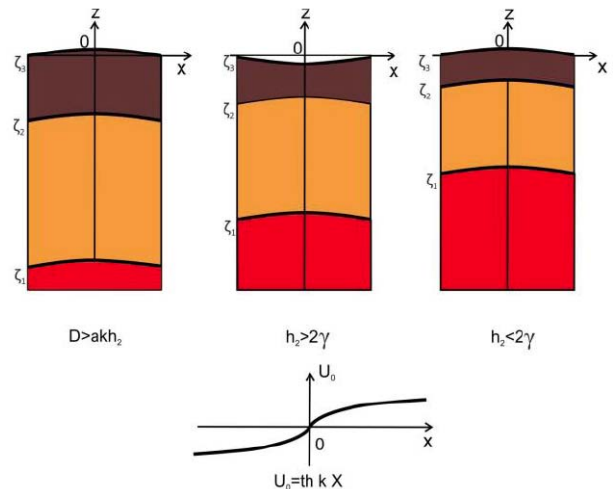


Figure 19: Characteristic section of layers of crust and mantle lithosphere above asthenosphere diapir upwelling without lateral restriction of movement. $U_0 = a th kX$.

When on periphery of basin there are the conditions interfering free spreading of the lithosphere of region, for example, caused by collision of the Arabian-African and Euroasian plates, the field of velocities on the bottom border of layers can be modelled as:

$$U_0 = \frac{th X}{ch^2 X}, \quad \zeta_1 = -sh^2 X - (h_2 + h_3) \quad (12)$$

For better presentation of result the coefficients in a modeling problem are omitted. Then:

$$\left\{ \begin{aligned} \zeta_3 &= -\frac{\beta h_2}{2} \frac{1}{ch^2 X} + \frac{\beta}{2} X^2 - \beta \ln(ch X) + C(t) \\ \zeta_2 &\equiv -h_3 - \frac{\alpha h_2}{S} t - \alpha(1-2h_2)sh^2 X + \\ &\alpha(1-2h_2)(sh X)^{\frac{2(h_2-1)}{1-2h_2}} \exp\left[\frac{2-3h_2}{1-2h_2}\left(\frac{t}{S} - sh^2 X\right)\right] \end{aligned} \right. \quad (13)$$

C (t) is defined from the mass balance.

In this case there are two critical depths of a roof of the asthenosphere diapir at which the section of layers qualitatively changes the structure. At $h_2 > 2/3$ in the centre of structure the deflection is formed. At $1/2 < h_2 < 2/3$ Moho surface uprise in the center of structure, and at $h_2 < 1/2$ reflects morphology of diapir in the centre of spreading and forms concavity of the base on periphery of basin (Figure 20).

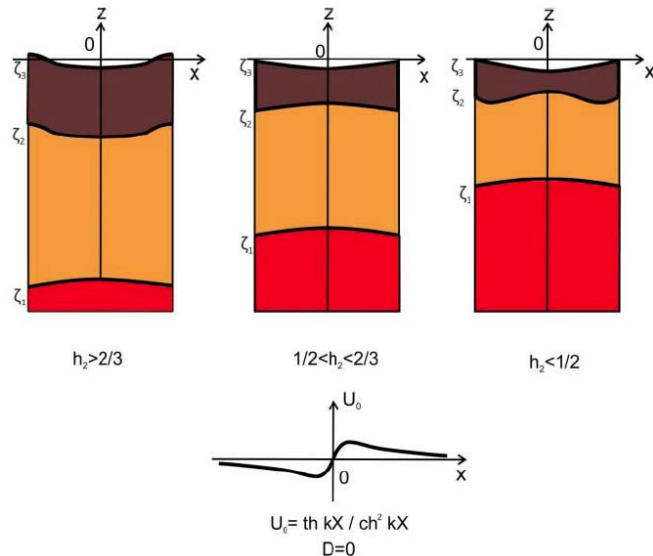


Figure 20: Characteristic section of layers of crust and mantle lithosphere above asthenosphere diapir upwelling with lateral restriction of movement.

The first type of velocities (10) can describe the initial stage of the structures development. The second type (12) describes the internal basins and seas structures.

The solutions obtained are quite natural and well explain the behavior of the lithosphere during tectonomagmatic activation. Indeed, a domed uplift on the Earth's surface is formed if an asthenospheric diapir has risen close to the surface. Or if a deep diapir has a high energy and uplift rate, which gives a strong impetus to the uplift of the lithosphere and it does not have time to spread away from the activation center. At the same time, at the next stages of the development of the process, a breakthrough of the lithosphere and

an outpouring of basalt magmas to the surface with the formation of basalt plateaus are possible. If a depression forms on the surface, then this can be explained by the fact that the rise of the diapir occurred slowly and for a long time from great depths, and the lithosphere has time to spread over it through the mechanism of scattered spreading. The process depends on the rheology of the layers and the relationship between the physical parameters of the substance - densities, viscosity, thermal characteristics, layer thicknesses, as well as on the boundary conditions of the problem. The choice of model is determined by the detail of research and the tectonic layering of the lithosphere - which layers to consider and model.

5. CONCLUSIONS

Mechanical-mathematical modeling of the lithosphere evolution above rising asthenosphere diapirs shows that the swell structure is formed on the upper surface and then deep depression arises. The deep depression formation does not demand big stretching in the layers of the lithosphere. The depth of depression is determined by velocity, depth and form of uprising diapir. The changing of swell structure by deep depression structure is confirmed by many geological factors: sedimentation regime characteristics, paleorivers direction change, evolution of paleodepthes of basins.

The results of mechanical - mathematical modeling are in good agreement with geological - geophysical data on the formation and evolution of geological structures and explain many observed processes and phenomena.

Cenozoic basins in the Mediterranean region and developed since the Mesozoic in the Caribbean region are produced by mantle diapirs, which take place due to density inversion in the astenosphere-lithosphere system in the background of increasing heat flow.

Geodynamics of Alpine belt and the Caribbean-Mexican region is determined by complicated plate - tectonics and plume - tectonics in these regions which have common and specific features in different geological structures and conditions.

There is no conflict of interest in the paper.

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REFERENCES

- [1] Bogdanov NA. Geology of deep depressions of back-arc seas. Moscow, Nedra 1989; p. 221.
- [2] Goncharov MA, Koronovskii NV, Raznitsin YuN, Svalova VB. The contribution of mantle diapirism to the formation of newly formed basins of the Mediterranean and the Caribbean and the surrounding centrifugal-vergent folded-overlapped orogens. *Geotectonics* 2015; 6: 80-93.
- [3] Karig DS. Evolution of arc systems in the Western Pacific. *An Rev Earth and Planet Sci* 1974; 2: 51-75.
<https://doi.org/10.1146/annurev.ea.02.050174.000411>
- [4] Malovitsky YaP, Senin BV. Pelagogenic depressions on modern and ancient continental margins. *Geotectonics* 1988; 1: 11-23.
- [5] Milyukov VK, Mironov AP, Rogozhin EA, Steblou GM. Estimates of the speeds of modern movements of the North Caucasus from GPS observations. *Geotectonics* 2015; 3: 56-65.
<https://doi.org/10.1134/S0016852115030036>
- [6] Nikolaev VG. Pannonian basin. Moscow, Science 1986; p. 120.
- [7] Rogozhin EA, Gorbatiy AV, Stepanova MYu, Ovsyuchenko AN, Andreeva NV, Kharazova YuV. The structure and modern geodynamics of the megantyclorium of the Greater Caucasus in the light of new data on the deep structure. *Geotectonics* 2015; 2: 36-49.
<https://doi.org/10.1134/S0016852115020053>
- [8] Sharkov E, Svalova V. Geological-geomechanical simulation of the Late Cenozoic geodynamics in the Alpine-Mediterranean mobile belt. *New Frontiers in Tectonic Research – General Problems, Sedimentary Basins and Island Arcs*. INTECH, Croatia 2011; pp. 18-38.
<https://doi.org/10.5772/25250>
- [9] Sharkov EV, Svalova VB. Intracontinental seas as a result of back-arc spreading with a collision of continental plates. *Reports of the USSR Academy of Sciences* 1989; 308(3): 685-688.
- [10] Svalova VB, Sharkov EV. Formation and evolution of back-arc basins of the Alpine and Pacific belts (comparative analysis). *Pacific Geology* 1991; 5: 49-63.
- [11] *Tectonics of Mediterranean belt*. Moscow, Science 1980; p. 244.
- [12] Tamaki K. Geological structure of the Sea of Japan and its tectonic implications. *Bull Geol Surv Japan* 1988; 39(3): 269-365.
- [13] Ulomov VI, Danilova TI, Medvedeva NS, Polyakova TP, Shumilina LS. To the assessment of seismic hazard in the North Caucasus. *Physics of the Earth* 2007; 7: 31-45.
<https://doi.org/10.1134/S1069351307070051>
- [14] Anderson DL, Dzevonsky AM. Seismic tomography. In *The World of Science* 1984; 12: 16-26.
- [15] Khain VE, Lomize MG. *Geotectonics with the basics of geodynamics*. M.: KDU, 2005; p. 560.
- [16] Koulakov I, Zabelina I, Amanatashvili I, Meskhia V. Nature of orogenesis and volcanism in the Caucasus region based on results of regional tomography. *Solid Earth* 2012; 3: 327-337.
<https://doi.org/10.5194/se-3-327-2012>
- [17] Moiseenko UI, Negrov OB. Geothermal conditions of the North Caucasian seismic hazard zone. In: *Geothermy of seismic and non-seismic zones*. Moscow, Science 1993; pp. 32-40.
- [18] The Global Heat Flow Database of the International Heat Flow Commission. <http://www.heatflow.und.edu/>
- [19] Condie KC. *Mantle plumes and their record in Earth history*. Cambridge University Press 2001; p. 306.
<https://doi.org/10.1017/CBO9780511810589>
- [20] Davies GF. *Dynamic Earth. Plates, Plums and Mantle Convection*. Cambridge University Press 1999; p. 458.
<https://doi.org/10.1017/CBO9780511605802>
- [21] Gee DG, Zeyen HJ, (Eds). *EUROPROBE 1996 - Lithosphere Dynamics: Origin and Evolution of Continents*. Uppsala University 1996; p. 138.
- [22] Ringwood AE, Irifune T. Nature of 650 km seismic discontinuity: implication for mantle dynamics and differentiation. *Nature* 1988; 331(6152): 131-134.
<https://doi.org/10.1038/331131a0>
- [23] Svalova VB, Zaalishvili VB, Ganapathy GP, Nikolaev AV, Melkov D. A Landslide risk in mountain areas. *Geology of the South of Russia* 2019; 9(2): 109-127.
- [24] Sharkov EV, Svalova VB. On the possibility of involving the continental lithosphere in the subduction process during back-arc spreading. *Izv. AN USSR, ser.geol* 1991; 12: 118-131.
<https://doi.org/10.1080/00206819109465745>
- [25] Svalova VB. Mechanical-mathematical models of the formation and evolution of sedimentary basins. *Sciences de la Terre, Ser Inf* 1992; 31: 201-208.
https://doi.org/10.6010/geoinformatics1990.4.3_153
- [26] Svalova VB. Mechanical-mathematical simulation of geological structures evolution. *Geoinformatics* 1993; 4(3): 153-160.
- [27] Svalova VB. Thermomechanical modeling of geological structures formation and evolution on the base of geological-geophysical data. *Proceedings of the Third Annual Conference of the International Association for Mathematical Geology IAMG'97, Barcelona, Spain. 1997; Part 2: pp. 1049-1055.*
- [28] Svalova VB. Mechano-mathematical modeling of the formation and evolution of geological structures in connection with deep mantle diapirism. *Monitoring. Science and Technology* 2014; 3(20): 38-42.
- [29] Svalova VB, Sharkov EV. Geodynamics of the Baikal rift zone (petrological and geomechanical aspects). *Geology and Geophysics* 1992; 5: 21-30.
- [30] Zhanomonetz (Svalova) VB, Kotelkin VD, Miasnikov VP. On the dynamics of lithospheric movements. *Izvestia of the USSR Ac Sci Ser Physics of the Earth* 1974; 5: 43-54.