沉积盆地演化的沉积学模式和模拟：前里海凹陷实例研究

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前里海凹陷的热流密度从北向南、从东向西增加，区域热背景值正常。诸多因素均可解释热流密度的侧向和垂向变化。前里海凹陷最重要的特征之一是盐层的存在。本文利用多层高粘滞流体的热机模式对热流密度的分布进行了模拟，并根据地幔底辟的上升解释了前里海凹陷的形成和演化。地球物理资料已证实底辟的存在。热机模拟表明，盐层和盐底辟是油气生成带形成和保存的确定性因素。热机模拟指出了沉积盆地演化过程中确定油窗迁移位置的可能性。本文还根据盐层的特征和盆地演化的历史解释了热流密度的变化。

SEDIMENTOLOGICAL MODELS AND SIMULATION OF SEDIMENTARY BASIN EVOLUTION: CASE STUDY OF THE PRECASPIAN DEPRESSION

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ABSTRACT

Heat-flow density of the Precaspian Depression increases from north to south and from east to west. The regional thermal background is normal. Lateral and vertical variations of heat-flow density are explained by many factors. One of the most important characteristic features of the Precaspian Depression is the existance of a salt layer. For simulation of the heat-flow density distribution, the thermomechanical model of a multilayer, highly viscous fluid was used. Formation and evolution of the Precaspian Depression are explained by upwelling of a mantle diapir. The existance of a diapir is confirmed by geophysical data. Thermomechanical modelling shows that the salt layer and the salt diapirs are the positive factors of the formation and preservation of oil and gas generation zones. Thermomechanical modelling gives the possibility to locate the migration of the oil window during the process of sedimentary basin evolution. Variations of heat-flow density are explained by the characteristics of layers and the history of the basin evolution.

DESCRIPTION OF THE MODEL AND MAIN EQUATIONS

Detailed description of the model and main equations should be referred to Svalova (1993).

The surface elevation above the diapir depends on its velocity and depth. The regional geodynamics is controlled by the rheology of layers and depends on whether the layers have time for diffluence above the mantle or the velocity of the uprise prevails over the diffluence. This analysis of the dynamics of a layered lithosphere above a rising mantle diapir shows that if the diapir is deep and its velocity is low, a depression is formed on the earth surface. If the velocity of rising diapir is high or the diapir is not deep a sufrace bulge can be formed. The comparison of the theoretical sections with geological reconstruction for Alpine belt sedimentary basins shows good conformity(Svalova, 1993).

It is possible to connect all stages of evolution of the Precaspian Depression with upwelling of mantle diapir (Solovjev *et al.*, 1991).

The Precaspian Depression is the unique structure of ancient platforms with sedimentary cover near 24 km(Fig. 1). The existance of mantle diapir could be confirmed by geophysical data, that fix two gravity maximum(Hobdinsky and Aralsorsky), the oomplex of higher electroconductivity on the depth of 70—100 km(Intelegator *et al.*, 1979)and higher deep heat flow in the center of structure (oil-gas potential of subsalt deposits, 1985. Moscow, Entrails) (Fig. 2). The morphology of basement and Moho is characteristic for upwelling movements from deep mantle(Zanemonetz *et al.*, 1974).

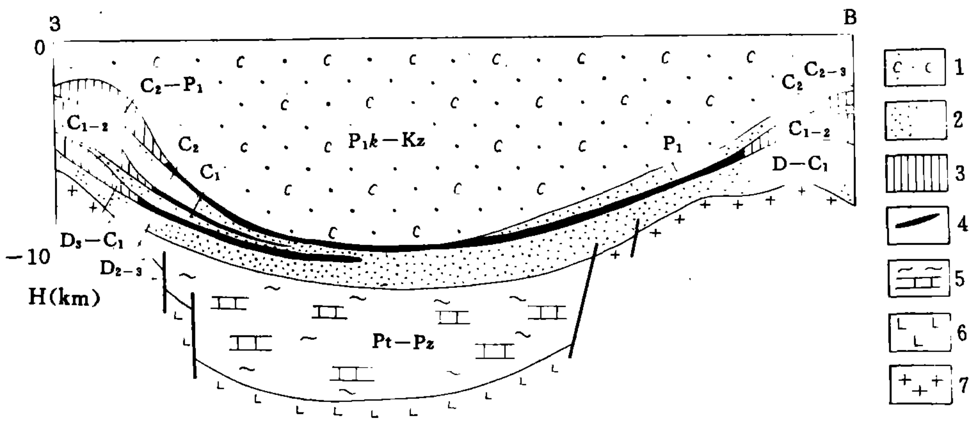

Fig. 1 Principal scheme of the Precaspian Depression structure(oil-gas potential of subsalt deposits, 1985. Moscow, Entrails)

Rocks: 1. salt and terrigeneous; 2. terrigeneous; 3. carbonate; 4. clay-carbonate;

5. terrigeneous and carbonane-terrigeneous of the befope-plate complex;

Geophysical layers of the basement: 6. basalt; 7. granite

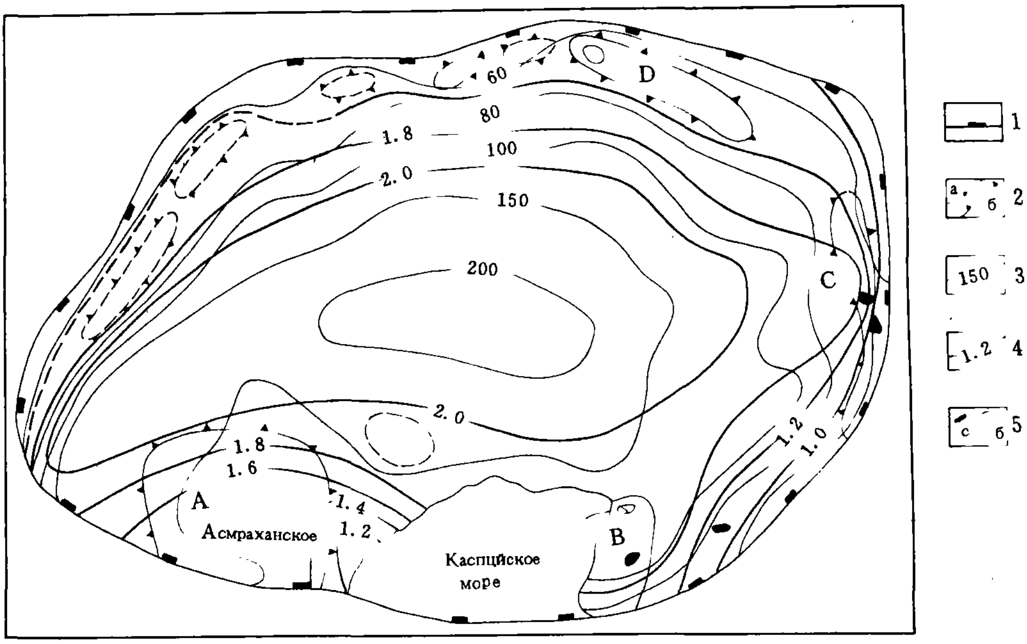

Fig. 2 Scheme of the thermal-pressure conditions of subsalt deposits of the Precaspian Depression by Egorova R. I. and Nijazgaliev T. K. (Oil-gas potential of subsalt deposits, 1985. Moscow, Entralis)

Boundaries: 1, of the Precaspian oil-gas potential province; 2, of the oil-gas potential zones (a, known; b, forecasted); 3, the geoisotherms on the subsalt deposits surface, ℃; 4, the isolines of abnormal layer pressure coefficients; 5, oil (a) and gas (b) deposits

Main oil-gas deposits: A, Astrahan; B, Tengiz; C, Kenkijak; D, Karachaganak

The upwelling of mantle diapir in early riphej could be the reason of triangle rift in basement—Pachelmsky, Novoalekseevsky and Safpinsky—in the stage of swell formation, Fig. 1, left. The stage of deep sineclyse formation in Precaspian Depression is connected with regime on Fig. 1, middle. More detailed information about sedimentary cover structure gives possibility to reconstruct more complicated picture of the structure evolution (Solovjev *et al.*, 1991, Svalova *et al.*, 1993.)

GEOTHERMY OF SEDIMENTARY BASINS

Detalied discussion on the geothermy of sedimentary basins should be referred to Svalova (1993).

Convective movements help to temperature changing in the lithosphere. Sinking of the matter above the rising diapir on the stage of the deep depression formation can explain the low surface heat flow in Black Sea and South Caspian Depression at the same time with high thickness of sedimentary cover.

Convective movements can explain the equality of the surface heat flows for oceans and continents.

It is necessary to take into consideration that heat generation for every layer of sedimentary cover, crust and mantle is rather complicated. And hence all these approaches are very rough. But for practical purposes it is not very difficult to take into account all geothermal data. In any case it is interesting to understand the main features of the geothermal field evolution.

Let us analyse some features of the geothermal field of the Precaspian Depression. The regional geothermal background is normal. Heat-flow density increases from north to south and from east to west. Surface heat flow is 25—33mw/m^2 in the North—East part and 50 mw/m^2 near the Caspian Sea. Reconstruction of paleotemperatures by vitrinite reflectance for easten part of depression shows that the temperatures was 110—125° at the depth of 3.7—4.5 km, that is 40—50℃ higher than modern temperatures (oil-gas potential of subsalt deposits, 1985. Moscow, Entrails). The main geothermal zones of the Precaspian Depression are shown in Table 1.

Table 1　The main geothermal zones of the Precaspian Depression

ZONE		T℃		T
	4km	5km	7km	℃/100m
Kenkijak	65—74°	76—90°	98—120°	1.7—2.0
Caspian	—	162—186°	218—252°	2.8—3.1
Tengiz	128—133°	160—167°	—	2.8—3.2
Astrahan	102—128°	124—156°	165—216°	3.0—3.6

For the analysis of the geothermal field changings let us consider temperature distribution for stable stage of evolution.

Let us consider the geothermy of multilayer sedimentary cover, crust and mantle lithosphere. For this case $\zeta n(x,y,t)$ is the earth's surface equation, ζ_i is the boundaries in sedimentary cover, ζ_3 is the basement, ζ_2 is the Moho, ζ_1 is the lithosphere/asthenosphere boundary, which could be associated with the isotherm 1200℃ of basalt melting temperature. $h_i/L=\varepsilon$ for every layer here.

Then heat conductivity equation will be:

$$\frac{\partial^2 T_i}{\partial Z^2}=-\frac{Q_i}{æ_i}$$

$æ_i$ is the coefficients of heat conductivity, Q_i characterizes the heat generation in layers.

Let $n=4, Q_4=Q_2=0$, i. e. we take into account the heat generation in the crust only. Then:

$$q^*=-\frac{T_*+\frac{Q_3}{2æ_3}\left(h_3^2+2h_3h_2\frac{æ_3}{æ_2}\right)}{h_2/æ_2+h_3|æ_3+h_4|æ_4}$$

$h_4(x,y,t)$ is the thickness of sedimentary cover, h_3 is the crust thickness, h_2 is the mantle lithosphere thickness.

Analysis of q^* shows that the smaller lithosphere thickness the larger surface heat flow. Maximum surface heat flow will be in the centre of depression above the mantle diapir. The geothermal data confirm it very well. Increase of the sedimentary cover thickness h_4 influences on decrease of surface heat flow q^* very much. It explains again the low heat flow of the Black Sea and South Caspian Depression.

Every new stage of the diapir upwelling is characterized by smaller lithosphere thickness, but larger sedimentary cover thickness. It means that temperatures of oil-gas generation are achieved on smaller depth. The migration of oil window up the section takes place with any new episode of sink and sedimentation. New layers of sedimentary cover are involved to the process of oil-gas generation.

Very important factor of temperature calculating for many sedimentary basins is the existence of salt layer. Investigation of subsalt complex for Precaspian Depression is especially important as for gigantic oil and gas deposits there (Fig . 3)

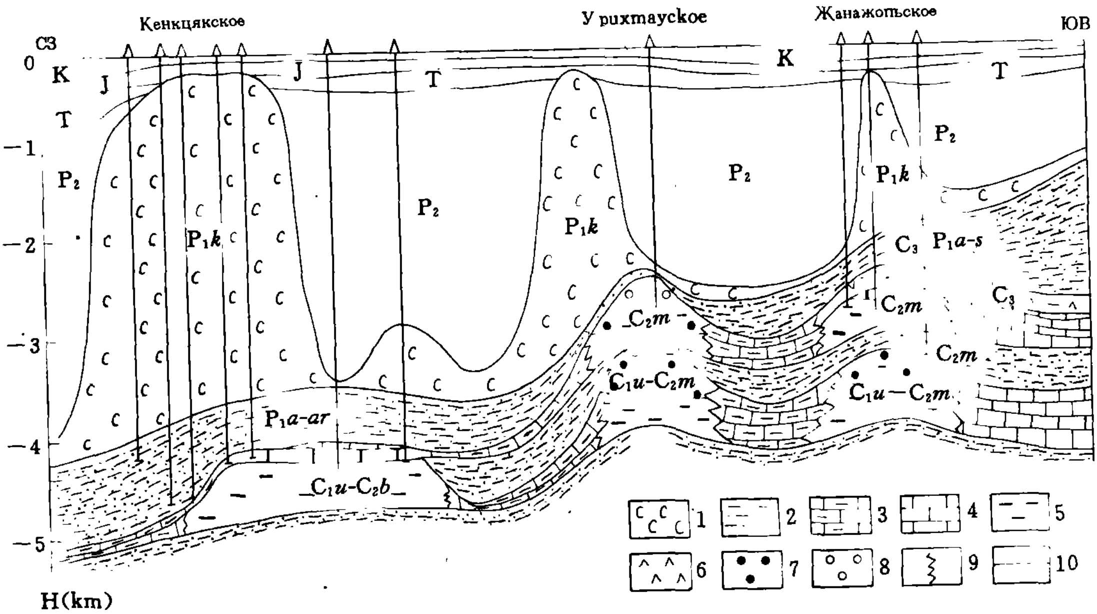

Fig. 3 Geological profile through Kenkijak-Zhanazhol oil-gas potential zone (along the Zhanazhol-Kenkijak line) by Obrjadchikov O. S. and Konstantinov A. A. (Oil-gas potential of subsalt deposits, 1985. Moscow, Entrails)

Rocks: 1, salt; 2, terrigenous; 3, clay-carbonate; 4, carbonate shelf type; 5, carbonate reef type; 6, sulfate-clay. Deposits: 7, oil; 8, gas; 9, the zones of lithological changing of rocks; 10. oil-water contact

Let us consider three-layer sedimentary cover consisting of above-salt complex (layer 4), salt complex (layer 3) and sub-salt complex (layer 2) with basement temperature $T_F(x, y, t)$. Then we can find the relationships between grad T in layers:

$$\frac{\partial T_4}{\partial Z}=-\frac{T_F}{\frac{æ_4}{æ_2}h_2+\frac{æ_4}{æ_3}h_3+h_4} \qquad \frac{\partial T_3}{\partial Z}=\frac{æ_4}{æ_3}\frac{\partial T_4}{\partial Z},\ \frac{\partial T_2}{\partial Z}=\frac{æ_4}{æ_2}\frac{\partial T_4}{\partial Z}$$

$$æ_3>æ_2>æ_4\Rightarrow\frac{\partial T_4}{\partial Z}>\frac{\partial T_2}{\partial Z}>\frac{\partial T_3}{\partial Z}$$

Larger grad T will be in above-salt layer and sub-salt layer. There is low grad T in salt layer(Fig. 4a). Hence higher temperatures are achieved on smaller depth in above-salt layer when salt layer exists. It means that in such basins the main phase of oil generation is on smaller depth. And in sub-salt layer the temperature decreases quicker up the section, that preserves the deposits in upper part of sub-salt complex. Hence the salt layer is the important positive factor of oil and gas generation and preservation zones.

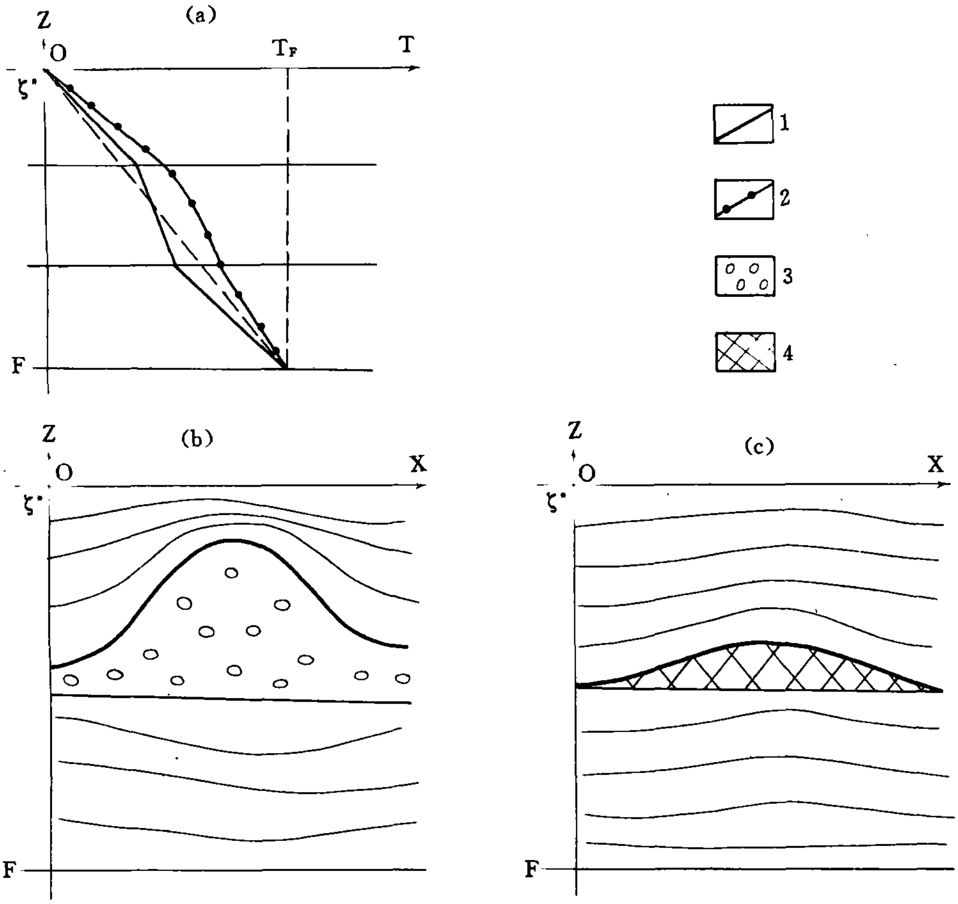

Fig. 4 a, temperature in sedimentary cover with salt layer(1)and high heat generation layer(2); b, isotherms in sedimentary cover around salt diapir; c, isotherms in sedimentary cover around the layer of high heat generation

ζ* , day-surface; F, basement; 3, salt layer; 4, the layer of high heat generation

The salt diapirs change the surface heat flow in lateral. If the salt layer has thickening Δh up the section, then the heat flow increases above the diapir:

$$|æ_4\frac{\partial T_4}{\partial Z}|=|-\frac{T_F}{\frac{h_2}{æ_2}+\frac{h_3}{æ_3}+\frac{h_4}{æ_4}+\triangle h(\frac{1}{æ_3}-\frac{1}{æ_4})}|>|-\frac{T_F}{\frac{h_2}{æ_2}+\frac{h_3}{æ_3}+\frac{h_4}{æ_4}}|$$

And heat flow increases in sub-salt layer under the salt diapir too. Hence the salt diapirs are the local positive factors for deposits formation(Figs. 4a and b)

If at any stage of basin evolution the heat generation begins in the layer it changes the temperatures in the sedimentary cover. Let there is the heat generation in middle layer(3) and there is no heat generation in layer 2 and 4. Then:

$$æ_4\frac{\partial T_4}{\partial Z}=-\frac{T_F+\frac{Q_3}{2æ_3}(h_3^2+2h_3h_2\frac{æ_3}{æ_2})}{h_2|æ_2+h_3|æ_3+h_4|æ_4}$$

$$æ_3\frac{\partial T_3}{\partial Z}=æ_4\frac{\partial T_4}{\partial Z}+Q_3(\zeta_3-Z),æ_2\frac{\partial T_2}{\partial Z}=æ_2\frac{\partial T_4}{\partial Z}+Q_3h_3$$

The analysis shows that existing of the layer with heat generation increases the heat flow above the layer and decreases the heat flow under the layer. Temperature changing in the layer has the parabolic character(Figs. 4a and c).

Hence the local increase of the surface heat flow is possible as due to layer of higher heat conductivity as due to heat generation in the layer. But influence of these two factors on underlying layers will be different.

CONCLUSIONS

1. Mechanical-mathematical modelling shows that structure of depression is formed on the earth's surface above rising mantle diapir if diapir is deep and its velocity is low. Streching in layers can not be large.

2. If the velocity of rising diapir is high or the diapir is not deep the structure of superficial swell can be formed.

3. For every case it is possible to find critical parameters of the problem connecting form of the diapir,its depth and velocity with structure of the earth's surface.

4. Thermomechanical modelling shows that surface grad T depends on the basin evolution history and thickness of sedimentary cover.

5. During the basin evolution the oil-gas generation zones arise in the central part, spread to the boundaries,are destroyed in the center and stay in the peritherical parts of the basin only. It gives good agreement with geological data.

6. Low heat flow of the Black Sea and South Caspian Depression can be explain by high thickness of the sedimentary cover and by sinking of the lithosphere matter above upwelling mantle diapir.

7. The layer of higher heat generation in the sedimentar cover increases the heat flow above and decreases under the layer.

8. The layer of higher heat conductivity in the sedimentary cover increases the heat flow above and under the layer. The salt layer and the salt diapirs are the positive factors

of the formation and preservation of oil and gas generation zones.

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