
G E O P H Y S I C S

One of the Possible Mechanisms of the Replenishment of Hydrocarbon Reserves

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1. An unusual phenomenon, the appearance of oil inflow in old oilfields and wells worked out long ago, has long been known to many researchers. At present, it is more expedient to obtain the increment of mineral reserves through revision of geological–geophysical materials on old oilfields than to carry out expensive geological exploration. This work presents one of the possible concepts pertaining to the phenomenon mentioned above.

New materials on the structure of the Earth's crust and upper mantle were acquired due to geophysical investigations at the end of the last century and at the beginning of the current century. At present, tectonic delamination of the Earth's crust (especially, its upper part) can be considered a proved and sufficiently substantiated fact [1, 2, 4, 5]. The results of the study of the deep structure of the crust based on seismic, magnetotelluric, and superdeep drilling methods show that the crust has a complicated layered structure representing a “layered pie” composed of alternating rigid (seismically transparent and opaque) soft layers. Based on the complex of geophysical data, opaque soft layers (waveguides) are identified with fissured, porous, and fluid-saturated layers. Unique materials on the fluid dynamics were obtained in oilfields of the Northern Caucasus, Ukraine, West Siberia, and Volga–Ural region [4, 5]. The authors believe that the phenomenon of oilfield replenishment can be explained reasonably at present based on modern ideas about the fluid-dynamic regime of the upper crust and the mechanism of hydrocarbon deposit formation.

Let us analyze the fluid regime of oilfields with the unique Romashkino oilfield as example. Devonian and Carboniferous rocks of the oilfield section incorporate 22 horizons, including 18 commercial oil-bearing horizons. At present, more than 400 oil pools have been established at the oilfield. Oil pools of the Devonian terrigenous complex (Pashii and Kynov horizons) are characterized by considerable oil reserves, which

account for ~70% of proved reserves. Lower Carboniferous terrigenous deposits comprise more than 15% of proved oil reserves of the oilfield.

Among 209 wells drilled down to the basement in the Romashkino oilfield, three wells have penetrated more than 100 m of the basement. The dynamics of initial and residual recoverable reserves, as well as data on cumulative oil production, make it possible to control the process of variations in the reserve structure related to variations in relationships between rates of the replenishment of reserves and their exhaustion.

It has been established that the cumulative oil production in some areas of this oilfield exceeds reserves approved previously. Application of a progressive technique of supplementary exploration at well-known oilfields made it possible to increase the proved oil reserves in Tatarstan over the past 25 years by 1.5 times, relative to the probable resources calculated earlier [4, 6]. According to materials of the Tatneft Open Joint-Stock Association, more than 65% of total oil production in Tatarstan was obtained in old oilfields, which had been worked out for 80%. To date, 85% of initial recoverable reserves have already been recovered in the Romashkino oilfield. Since 1975, within the framework of the program of study of the Earth's interior in Tatarstan, two superdeep wells have been drilled in this republic: well 20000-Minnibaevo (hole bottom at 5099 m, penetration into the basement of 3215 m) and well 20009-Novoelekhovo (hole bottom at 5881 m, penetration into the basement of 4077 m). In addition, 24 wells have penetrated the basement to a depth ranging from 100 to 2432 m.

2. The available materials have made it possible to distinguish old worked out wells with renewed inflows of oil and oil plus water—wells of the Pavlovsk (nos. 19413, 19417, 19418, 19534), Zelenogorsk (nos. 8665, 8670), Minnibaevo (no. 14917), Al'met'evsk (no. 1991-d), Abdrakhmanovo (no. 23730), and other oilfields in oil-bearing beds D_{III} and D_{IV} . These beds are characterized by the confinement of their oil pools to faults, tectonic dislocations, and their junctions [4, 6]. It has been established that the area of oil pools, their reserves, and yield show direct correlation with the

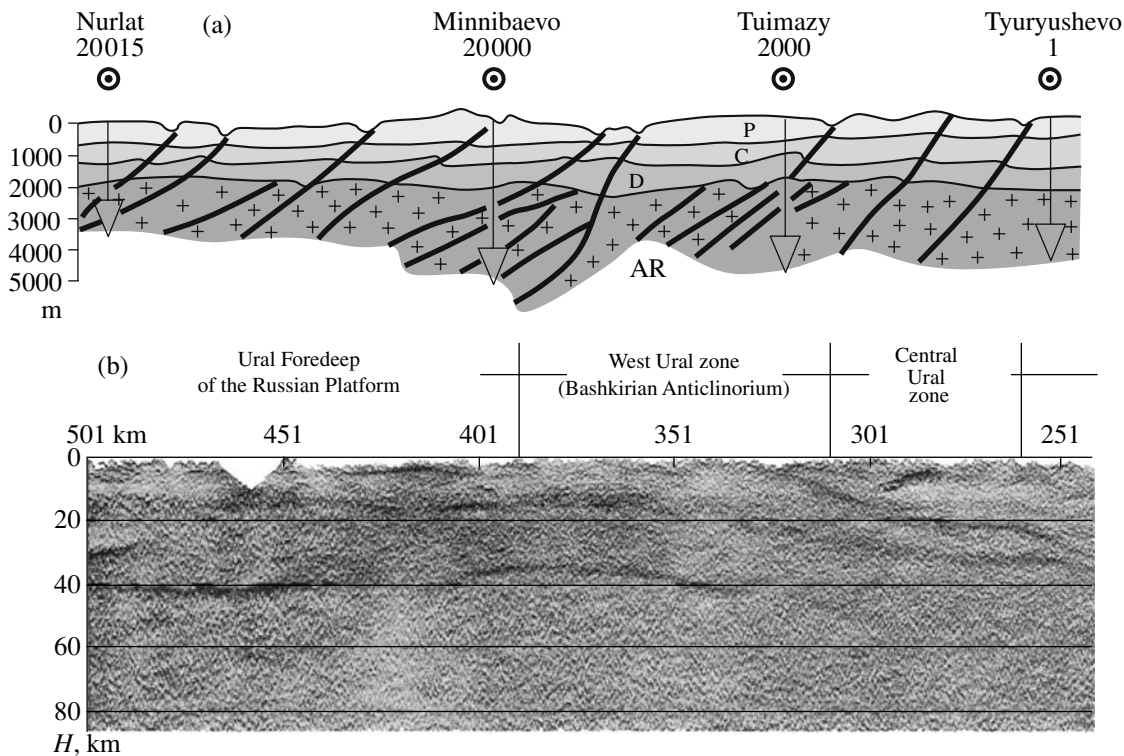


Fig. 1. Scheme of jointing and faulting zones in the upper crust: (a) schematic profile across the South Tatar Arch (Kamaletdinov et al., 1984); (b) section of the Earth's crust (1) based on the CDP data on the western Uralseis geotraverse (Gil'bershtein et al., 2001).

density of the fault network and, hence, tectonic deformation of the crystalline basement and sedimentary cover. Large-scale drilling in the crystalline basement of Tatarstan revealed numerous dilatation and jointing zones with different reservoir properties and degrees of fluid saturation (Fig. 1).

The Ural fold system played a great role in the formation of the study region. The system represents a paleosubduction zone, which has an immense petroleum potential. Hydrocarbons are scattered in the region over a large area and at a great depth. The paleocollision zone forms a highly permeable fault zone, which is activated in the course of tectonic motions. This is confirmed by the thrust-type structure of the region and the appearance of nappe dislocations at the crystalline basement [1, 4, 6]. The analysis of oil pool distribution over the area and in the sedimentary cover section within the Tatar arch revealed the close relationship of the petroleum potential of the sedimentary cover with faults and the block structure of the basement (Fig. 1). The faults serve as conduits for all the fluids and, particularly, hydrocarbon fluids.

Estimates of the depth-velocity characteristics in the western sector of the geotraverse (the Ural Foredeep zone) made it possible to elaborate a six-layer model of the crust, which included the mantle part of the lithosphere as well [1]. In general, the positive longitudinal wave velocity versus depth correlation is con-

sistent with the DSS data. However, the proposed model is characterized by the presence of two waveguides. One waveguide ($V_{\text{int}} = 5.7\text{--}5.9$ km/s) occurs in the upper crust at a depth of 8–15 km. Another waveguide ($V_{\text{int}} = 6.2$ km/s) overlies the *M* boundary in the lower part of the crust at a depth of 22–40 km. The first waveguide is confined to the upper “transparent” zone; the second waveguide, to the lower “semitransparent” zone. With consideration for depth-velocity characteristics obtained by other sounding methods, the first waveguide shows certain consistency with a decrease in “transparency” (increase in ECO energy) and an increase in velocity up to the point of loss of the waveguide property, for instance, at the interval of PK 400–420 km. This fact indicates a lenticular structure of the waveguide. It is of interest that small lenticular zones of anomalous conductivity are distinguished within the same depth interval [1, 5].

It has been established that listric faults play a great role in the fault tectonics of the crystalline crust. The faults are nearly vertical at the surface. They are less inclined at medium depths and flat at a depth of 10–20 km (Fig. 1). Pinchout sectors of faults form subhorizontal laminated zones, which serve as seismic boundaries underlying waveguides. According to some researchers, the upper crust slips along the middle and lower crust precisely along these zones, resulting in the for-

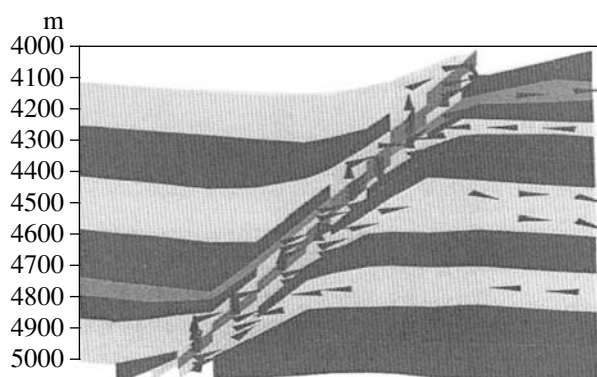


Fig. 2. Migration of fluids in the fault zone.

mation of gentle thrusts and nappes. Laminated zones in the middle crust are often named *detachment zones*.

3. Explanation of the existence of oil pools is mainly hampered by the following fact: the thickness of the sedimentary cover in the giant Romashkino oilfield does not exceed 2 km, and the cover lacks any substantial oil potential. The underlying rocks of the basement also lack such oil potential. Oil is most likely delivered from the Ural Foredeep.

The natural question arises as to what the mechanism responsible for the migration of hydrocarbons from their initial position and accumulation in relatively small areas of the present-day Romashkino oilfield is.

We believe that such a mechanism can be represented by dilatancy, which is developed in the course of shear deformations in jointing zones of waveguides and faults due to tectonic forces. Strong tectonic stresses are always active in the Earth's crust owing to global geodynamic processes. Stresses of variable intensity are functioning over the entire crust (changing in intensity) and can be measured by experimental (seismologic, geomorphologic, and mining mechanics) methods. Based on the height of mountains, the characteristic value of stresses acting in the crust is estimated at 200–300 MPa. The maximal height of mountains (hence, the intensity of stresses in the crust) is constrained by the limit of plastic deformation of rocks. The vacuum effect during dilatancy is governed by these stresses.

Under natural conditions at substantial tectonic stresses in fissured and fluid-saturated rocks of the crust, the dilatation mechanism of fluid migration can transport fluids over a considerable distance. The comparative analysis shows that this mechanism is the most intensive and universal one among all the possible mechanisms of fluid migration. For instance, thermal convection in a porous medium can also transport fluids. However, the latter mechanism is not universal and acts only under conditions of strong heating (for instance, during the emplacement of magmatic intrusions).

The mechanism of dilatation can function in both faults and thin fissured layers, which extend over a large area and correspond to waveguides on seismic records. According to seismic data, a waveguide is distinguished by low velocities and seismic wave attenuation. Magnetotelluric measurements revealed that its total electroconductivity is 200–2000 S. It is appreciably higher than in crustal layers overlapping and underlying the waveguide. Though waveguides are widespread in the crust and at different depths, one can outline certain regularity in their distribution in the continental crust. They are most abundant at the depths of 10–15 and 19–20 km. Their thickness varies from 1–2 to 15–17 km (generally, 4–10 km). Usually, the thickness increases in zones of tectonic activity. The velocity gradient between the waveguide and the host rock mass in the middle and upper crusts varies from 0.1 to 1.0 km/s. The velocity gradient tends to increase with depth.

Dilatation provokes oscillations of fluids in fissured zones. The oscillations can be self-excited vibrations or forced oscillations. Variations in the regime and amplitude of oscillations are governed by their dimensions. The greater the dimension, the longer their oscillation period. The oscillation period in large waveguides makes up about 10^4 yr or more. In faults, the period is lower and varies from 10^3 yr to hundreds and tens of years depending on the size of the fault.

The oscillations in the upper crust and specific nonlinear properties of the fissured medium provide the oriented migration of fluids. They drive fluids along all the possible directions, including horizontal and even downward directions regardless of the “common sense.” Fluids can migrate in a horizontal direction over great distances along waveguides located at a depth of 10–15 km. Similar (but more frequent) oscillations can occur in fault zones located at smaller depths. In the course of such oscillations, fluids can periodically migrate from a fault to surrounding massifs and back (Fig. 2). Thus, conditions are set up for a periodic “washing” of the upper crustal layers by fluids up to a depth of 10 km.

Migration of hydrocarbons from a waveguide to upper layers was studied based on specified material in several regions [2, 3]. These motions are rather rapid compared to slow oscillations in waveguides. Rapid breakthroughs of fluids were described by equations of isothermal filtration of two-phase fluid in the medium with the elastic skeleton. We solved the boundary problem of rapid breakthroughs for conditions characteristic of underthrust zones in the Karakul–Smushka zone, Astrakhan Arch, Verkhoyansk Foredeep, Volga–Ural region (eastern flank of the Caspian region), Timan–Pechora region, and others. We also considered geodynamic conditions of evolution of each region. It was approximated by a certain body with simple geometry. The grid specified for this body reflected with a sufficient degree of accuracy the structure of the region and its lithological, filtration, and HC-generating proper-

ties. Each structure was represented by rocks with average permeability $k_p = (10^{-13} - 10^{-14}) \text{ m}^2$ and porosity $m = 0.1$. The structure incorporated lithological screens in the form of low-permeable layers (for instance, clay laminae with $k_p = 10^{-16} \text{ m}^2$). More often, we discerned the concentration of the fluid flow along separate basins in 100, 200, and 300 yr. Variations in time intervals usually depend on the geodynamic evolution of the region. The time interval was reduced to tens of years in the case of intense faulting and thrusting in the petroleum basin confined either to an old subduction zone or an active rift zone.

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