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Article / Статья

The influence of deep fluid dynamics and hydrocarbon recharge of the crystalline basement on the oil and gas fields genesis

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Влияние глубинной флюидодинамики и углеводородной подпитки кристаллического фундамента на генезис нефтяных и газовых месторождений

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The article presents an analysis of modern studies on the genesis of hydrocarbons. It is concluded that over the past decades, including in connection with the fundamental improvement of scientific equipment, new facts have appeared that cast doubt on the concept of exclusively biogenic genesis of hydrocarbons. By now, quite a lot of arguments have been accumulated in favor of oil and gas formation due to abiogenic synthesis reactions. For example, the presence of biomarkers in natural oil, which is one of the postulates of the organic theory, can be explained by filtration through layers containing organic matter. At the same time, the analysis of oil biomarkers in a number of superdeep deposits showed the abiogenic origin of oil. The organic hypothesis of the origin of oil is not able to adequately explain the existence of giant accumulations of oil and gas, for which the calculations of the generation potential of oil source suites are significantly inferior to the identified oil reserves.

In recent years, extensive factual information has been obtained on the existence of degassing processes of the Earth and the replenishment of the sedimentary cover with hydrocarbons from the depths through fluid-drainage channels in the crystalline basement. This process is accompanied by deep fluids, which are an intermediate, connecting link between the internal and external factors of the oil and gas basin. Deep fluids affect the formation of oil source rocks, generation efficiency, formation of physical properties of reservoirs, as well as the migration and aggregation of oil and gas. For the South Caspian oil and gas basin, a special class of geological structures of complex shape in the form of subvertical and subhorizontal geological bodies has been identified, which can serve as migration paths (drainage zones) and hydrocarbon accumulation zones. The formation of such a structure of intracrustal migration paths is explained by the process of transformation of clay minerals in elisional deposits. The possibility of such a transformation in the South Caspian basin is substantiated by studying the influence of clay content on fluid transfer processes.

Ключевые слова:
углеводородные ресурсы, разрез осадочного чехла, кристаллический фундамент, биогенный генезис углеводородов, флюидо-дренажные каналы.

Приведен анализ современных исследований о генезисе углеводородов. Сделаны выводы, что за последние десятилетия, в том числе в связи с принципиальным усовершенствованием научного оборудования, появились новые факты, ставящие под сомнение концепцию исключительно биогенного генезиса углеводородов. К настоящему времени накоплено достаточно много аргументов в пользу нефтегазообразования за счет реакций абиогенного синтеза. Например, присутствие биомаркеров в природной нефти, которое является одним из постулатов органической теории, может быть объяснимо фильтрацией через слои, содержащие органическое вещество. При этом анализ биомаркеров нефти ряда сверхглубоких месторождений показывает абиогенное происхождение нефти. Органическая гипотеза происхождения нефти не в состоянии адекватно объяснить существование гигантских скоплений нефти и газа, для которых расчеты генерационного потенциала нефтематеринских свит значительно уступают установленным запасам нефти.

В последние годы получена обширная фактическая информация о существовании процессов дегазации Земли и подпитке осадочного чехла углеводородами из недр через флюидо-дренажные каналы в кристаллическом фундаменте. Данный процесс сопровождается глубинными флюидами, представляющими собой промежуточное, связующее звено между внутренними и внешними факторами нефтегазового бассейна. Глубинные флюиды влияют на формирование нефтематеринских пород, эффективность генерации, формирование физических свойств коллекторов, а также на миграцию и агрегацию нефти и газа. Для Южно-Каспийского нефтегазоносного бассейна выявлен особый класс геологических структур сложной формы в виде субвертикальных и субгоризонтальных геологических тел, которые могут служить путями миграции (дренажными зонами) и зонами накопления углеводородов. Формирование подобной структуры внутрикоровых путей миграции объясняется процессом трансформации глинистых минералов в элизионных отложениях. Возможность такой трансформации в Южно-Каспийском бассейне обосновывается изучением влияния глинистости на процессы флюидопереноса.

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Introduction

According to the world and domestic classifications, hydrocarbons (HC) are considered as non-renewable mineral resources (non-renewable energy sources) [1–3]. The exhaustibility and irreplaceable character of HC reserves is based on the sedimentary-migration theory of HC origin, established in the last century and which is based on the exceptionally slow (tens of millions of years and more) subsidence and heating of oil and gas parent formations containing dispersed organic matter [4–6]. It is obvious that this process is not comparable with the rate of oil and gas extraction during field operation. Therefore, according to the mid-20th century, the dependence of annual oil production on recoverable reserves had the shape of a bell with a symmetrical increase in production at the beginning of commercial development and a subsequent decrease (K. Hubbert curve) [7]. Based on this model, a short-term peak of production was predicted with its subsequent decline despite the improvement of drilling methods and application of new oil production technologies (Fig. 1).

It took decades to ensure in practice that real oil production does not follow the Hubbert curve (Fig. 2), since this method does not take into account that oil in already developed fields and in adjacent areas may appear in other, previously unexplored stratigraphic complexes [8].

In addition, since the end of the last century it has begun the development of unconventional oil and gas fields, such as heavy oils and bituminous sands in Canada, Venezuela and some other regions, shale oil and gas, oil and gas from deposits in dense, previously unaccounted for sedimentary cover complexes [15–17]. The above-mentioned directions have created a new trend in the development of global hydrocarbon production for the long term. According to the report of the International Energy Agency (IEA), in the first quarter of the XXI century hydrocarbon resources will cover 85 % of humanity's energy needs; by 2030 the global energy consumption is expected to grow by 60 % [18]. All this together creates prerequisites for rethinking the planning of hydrocarbon production prospects and should be linked to the understanding of oil genesis on the basis of modern scientific data.

Problem statement. Materials and methods

Speaking about the arguments of the organic theory of oil origin, first of all, it is necessary to note the similarity of the composition of oil and organic substances (OS), on the base of which the concept of the main phase of oil formation was formulated by N.B. Vassoevich [19]. However, at that time there were no facts about the participation of microorganisms and bacteria in the formation of HC. These organisms repeatedly processing the original substrate significantly change its original properties over geological time [20].

At the same time, the organic hypothesis of the origin of oil is not able to adequately explain the existence of such giant accumulations of hydrocarbons with reserves of billions of tons as Athabasca (Canada), White Tiger (Vietnam). In Russia, geological strikes of this type include the fields of the South Tatar Arch, the Romashkinskoye oil field, unique in reserves. For this oil and gas production regions bituminous sediments of the Domanik Formation are not mature enough

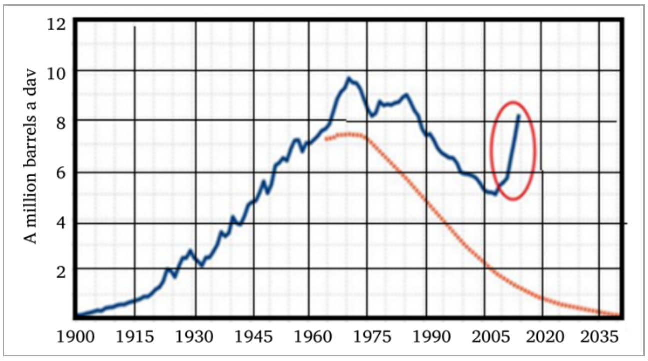

Fig 1. U.S. oil production (blue line) and the forecast by C. Hubbert (red line) [7]

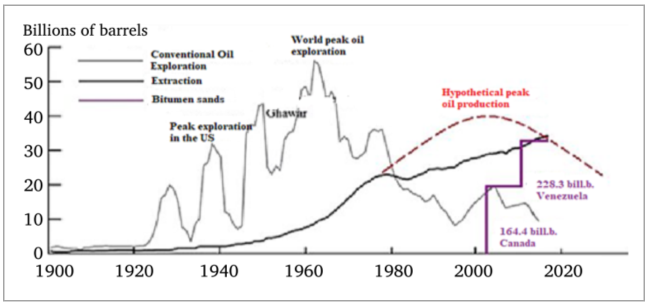

Fig. 2. Comparison of peak oil discovery (grey line), Hubbert peak oil production forecast (red dashed line), real world production of conventional (black line) and unconventional oil (purple line) [8]

to generate significant volumes of oil [21]. Calculations show that the generation potential of the Domanic deposits in the area of the South Tatar arch is significantly inferior to the established oil reserves [22, 23].

To date, quite a lot of arguments in favour of oil and gas formation due to abiogenic synthesis reactions have been accumulated. Thus, in recent decades it has been established that the scale of HC migration into the atmosphere and hydrosphere exceeds possible hydrocarbon generation in sedimentary basins by three orders of magnitude [24]. The presence of biomarkers in natural oil, which is one of the postulates of organic theory, can be explained by filtration through layers containing OM [25, 26]. The analysis of biomarkers of oil from superdeep fields of Azerbaijan performed by spectrometry and paramagnetic resonance methods allowed [27] us to draw a conclusion about the abiogenic origin of oil.

In general, in recent decades, the theory of the exclusively organic genesis of oil fields has been adhered to by a minority of teams of researchers, in whose works the calculation of potential HC reserves of oil fields is based solely on the generational potential of oil mother rocks [28–30]. Most researchers recognize a significant contribution to the world potential of reserves of abiogenic genesis of hydrocarbons, assuming polygenesis during oil and gas formation. According to the concept of polygenesis, HC generation occurs in the deep layers of the Earth due to inorganic synthesis, as well as under the influence of tectonic and seismic processes of the earth crust by transformation of sedimentary rock organic matter [31–33].

Thus, in recent years, extensive factual material has been obtained about the existence of processes of degassing of the Earth and feeding of the sedimentary cover with HC from the planet's interior through fluid-drainage channels in the crystalline basement [34, 35]. The mechanism of vertical migration of HC from the centre of generation into productive formations is explained by the pressure difference between them and is carried out with a certain periodicity as the breakthrough pressure is reached by a mixture of HC plugs, usually represented by fluid clay. At the same time, withdrawal of production from the reservoirs accelerates the processes of delivery of additional HC volumes by reducing the pressure in the reservoirs and shortening the time of reaching critical pressures [36]. In particular, according to the modern ideas on such process oil reserves of the Romashkinskoye field are recovered [37]. Essentially this turns hydrocarbon resources into renewable ones. The development of this assertion radically changes the dynamics of oil production due to the constant increase of reserves in the process of long-term exploitation of large fields.

Results. Concept justification

Depth fluid activity, which is widespread in large oil and gas basins, has been observed worldwide. Deep fluids as an intermediate, connecting link between internal and external basin factors undergo a series of organo-inorganic interactions and transitions through oil and gas formation and aggregation.

It is rather difficult to investigate the causes and sources of deep fluids observed in the oil and gas bearing basin, and although the sources of some fluids are clear, opinions about the causes of transformation of these fluids are contradictory mainly because the identifying features are unknown. According to the classification from [38], deep fluids are divided into three types:

– fluids formed in the deep parts of basins and originating from crystallizing foundations, they are usually located within a rigid crust and are called crustal fluids;

– hydrothermal fluids associated with the formation of HCs which result from the breakdown of crude oil during deep burial and thermal sulphate reduction;

– fluids of mantle origin.

The composition of intracrustal solutions and fluids is quite diverse with the presence of C-O-S-H fluids which exist predominantly as CO, CO_2, N_2, H_2, CH_4, SO_2 and H_2O and contain all hydrocarbon-forming elements. These fluids can be considered HC or HC-derived substances. In the formation of oil source hydrocarbon-bearing strata, deep fluids can improve the primary productivity of sedimentary reservoirs and form a favourable environment for the preservation of organic matter. The abundant CO_2 and CH_4 gases carried by deep fluids are rich sources of carbon for the earth's surface and ocean floor [39, 40].

According to the expert appraisal based on deep seismic tomography data, the carbon concentration per unit volume of the Earth's crust and upper mantle is 1.33 kg/m^3 [41]. Carbon in deep fluids is mainly derived from emission in subduction belts and the deep mantle, and deep carbon cycles include CO_2 capture (carbonates from subduction belt sediments sink with the oceanic crust into the interior of the Earth). Simultaneous belching of CO_2, HC, and carbonate melts to the Earth's surface and atmosphere occur together with ocean ridges, island arcs, mantle plumes, and other magmatic activity of tectonic zones (Fig. 3). The deep carbon circulation and surface carbon circulation together form the Earth's carbon circulation system, where the total carbon content is 90 % of the total planetary carbon content.

Taking these facts into account it is of great importance to reveal the nature of formation and structure of intracrustal deep fluid migration paths (drainage zones). Recent publications [43–46] have shown that in the South Caspian oil and gas bearing basin (SCB) a special class of geological structures of complex shape in the form of subvertical and subhorizontal geological bodies, which can serve as migration pathways (drainage zones) and hydrocarbon accumulation zones, has been identified (Fig. 4).

Moreover, several autonomous centres of oil and gas formation with their own areas of distribution and spatial and temporal evolution have been identified within the South Coastal Basin

These source kitchens form a basin of HC generation and are displaced relative to each other, with the lower boundary of oil and gas generation interval at depths of more than 12–15 km.

The upper boundary of the "oil window" is confined to hypsometric depths of 5–7 km. The formation of such a multifocal structure of intracrustal migration pathways is explained by the process of clay minerals transformation

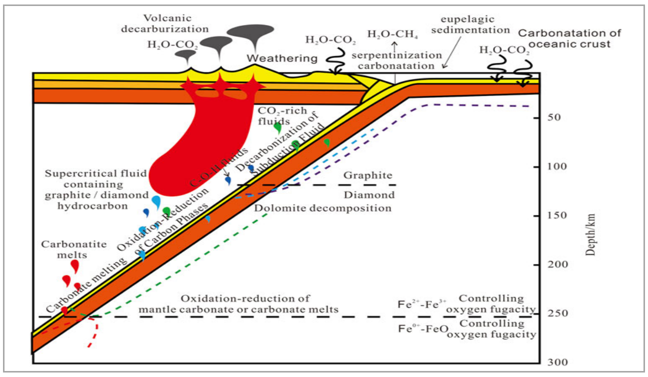

Fig. 3. Scheme of subduction carbon circulation [42]

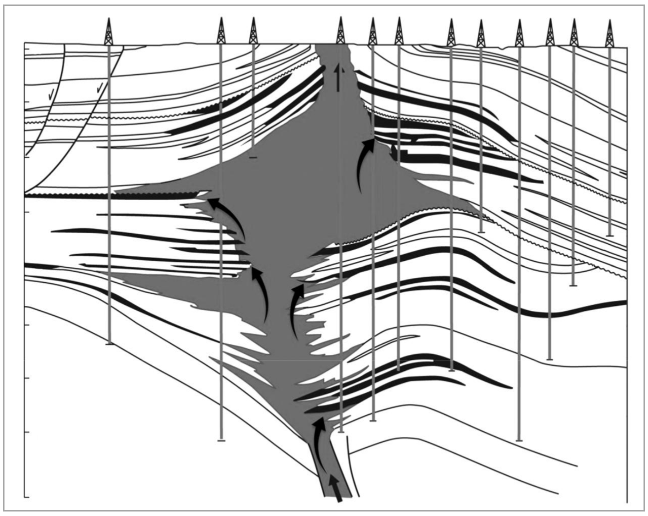

Fig. 4. Migration channels (drainage zones) with HC accumulation zones developed in the sedimentary cover by intracrustal solutions and fluids (SCB) [46]

Average values of Poisson's ratios for rocks

Rock	Poisson's ratio, *M*	Rock	Poisson's ratio, *M*
Plastic clays	0.41	Limestones	0.31
Dense clays	0.30	Sandstones	0.30
Clay shales	0.25	Sandy shales	0.25

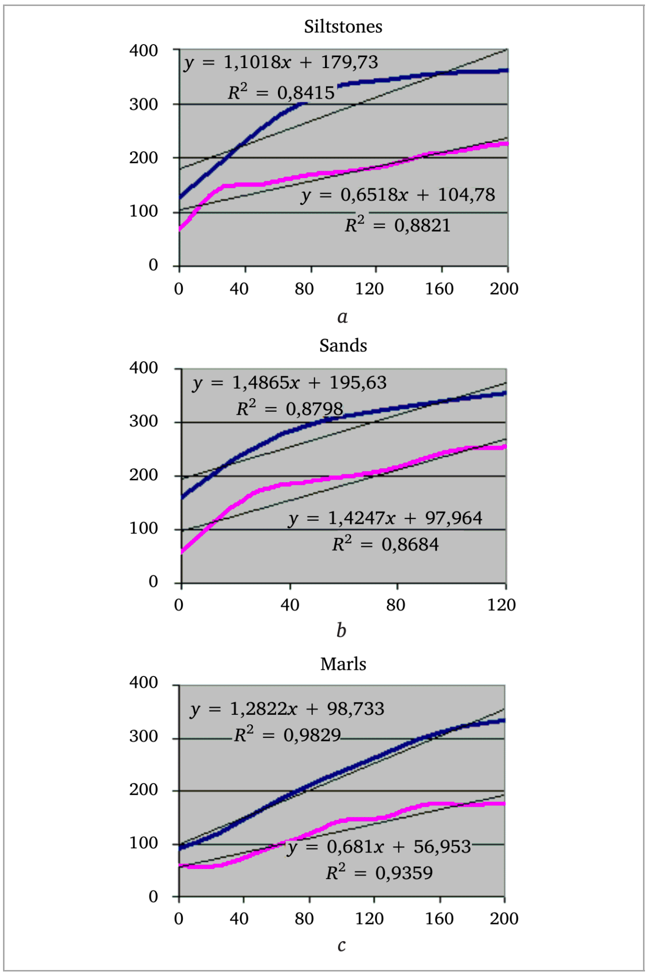

Fig. 5. Variation of hardness and yield strength at different values of all-round pressure: *a* – siltstones; *b* – sands; *c* – marls

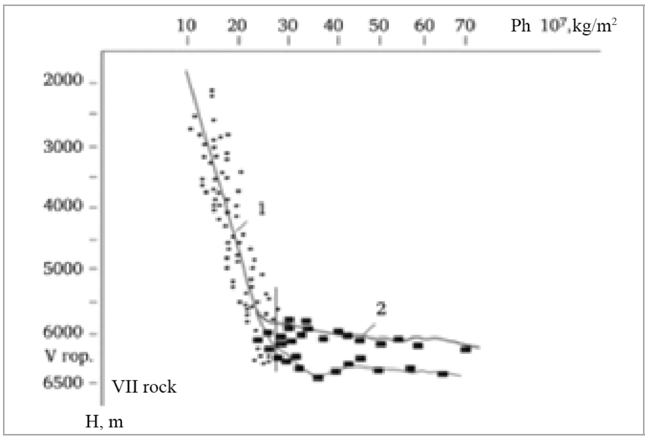

Fig. 6. Hardness variation of clayey rocks along the depth of the section (Umid field, SCB): *1* – averaged values; *2* – values in layers [49, 50]

in elision sediments. Thus, the transition of montmorillonite (smectite) minerals into illite leads to the release of huge masses of crystallization water, which creates ultrahigh formation pressures (UHFP). In turn, UHFPs cause the formation of natural fractures in sand formations, the formation of clastic dikes, "inclusion horizons" and mud volcanoes. The above mentioned processes contribute to the strengthening of oil and gas migration at great depths through fluid-drainage channels and subsequent formation of commercial HC accumulations [45, 46].

In domestic oil and gas exploration practice, clay content is characterized by the clay content coefficient Vsh, and in foreign practice – by the Vshale factor, reflecting the clay content in the oil reservoir volume. According to the results of studying the influence of clay content on fluid transfer processes in the SCB, it should be mentioned the following. In general, the sedimentary section here is characterised by high values of clay (0.01 mm) and sandy (>0.1 mm) fractions (19–30 % on average). Siltstone fractions account for the bulk of the volume (40–62 %). The mineral composition of clays in this area is montmorillonite-hydromatic with the predominance of montmorillonite. The average content of montmorillonite is 42.5 %, hydromica 37 %. The amount of kaolinite in clays is 8.8 %.

In addition to reservoir properties, clay content has a significant effect on the structural strength of reservoirs, indirectly characterized by Poisson's ratio values. The table shows the Poisson's ratio (M) values for the main rock types. Examples of changes in hardness and yield strength of sands, siltstones and marls at different values of all-round pressure are drawn from [47, 48] and are shown in Fig. 5. As follows from Fig. 5, siltstones under pressure conditions up to and including 25 MPa fractured elastoplastically. Thus hardness and yield strength of silurites in atmospheric conditions are equal to 58.8 and 42.7 107 N/m^2, respectively.

Hardness and yield strength of clays under atmospheric conditions are 23.9 and 8.0 respectively – (107) N/m^2, and at all-round pressure in the range of 25–50 MPa 31.8 and 19.1 respectively – (107) N/m^2. These variations are confirmed by the definition of clay hardness values in natural occurrence (Fig. 6). At values of all-round pressure within the boundaries of 25–50 MPa, the clays passed into the plastic state and did not collapse.

Comparing the yield strengths of silty clays and clays, it is possible to notice that the values of the yield strength of silty clays increase in the range of all-round pressure 0.1–200 MPa from 42.7 to 114.3 – (107) N/m^2, i.e. 2.6 times, and for clays from 7.98 to 55.8 – (107) N/m^2, i.e. 6.9 times.

These results are in agreement with the data that sedimentary rocks, including oil-source rocks, at great depths, when the thermobaric effects become more severe, turn into a viscoelastic state and often subjected to fracturing, acquiring secondary reservoir properties [47–49]. Thus, when the hydrostatic equilibrium in the basin is disturbed, underconsolidated clays start to "float" and, under compressive stresses, to be forced out, which in some cases leads to the formation of clayey diapirs or, with sufficient energy potential, to the development of mud and gas-mud volcanoes [51, 52]. It is known that in some cases mud volcanism indicates the destruction of crystalline basement rocks (CBM) and can be an indicator of the crushing zone at the bottom of the sedimentary cover or the CBM over which it is formed [53–56].

Thus, within the SCB, which is a geodynamically and tectonically active region with a large number of natural oil and gas outlets, vertical unloading of deep fluids in the subcrustal layer section is provided by the system of deep faults (fluid-drainage channels) [57–59]. The mentioned system of deep faults serves as fluid-drainage channels for inflows of liquid and gaseous fluids, which form the oil and gas generation potential of the known oil and gas bearing basins, including the South Caspian Basin.

Conclusion

Thus, the mechanisms of fluid-drainage channels may be related to the process of clay minerals transformation in elision sediments, with the release of huge masses of crystallization water. As a result, UHFP similar to hydraulic fracturing occur in the boundary sand formations.

In confirmation of the stated assumptions the changes of deformation and mechanical properties of clayey rocks depending on depth were estimated and possible values of physical and mechanical properties of cover rocks depending on the depth of occurrence were determined. Models of variation of physical and mechanical properties of clayey rocks were compiled with prediction of drainage zones at great depths.

The system of deep faults serves as fluid-drainage channels for inflows of liquid and gaseous fluids, which form the oil and gas generation potential of the known oil and gas bearing basins, including the SCB. The processes of degassing of the Earth and feeding of the sedimentary cover with hydrocarbons from the Earth's interior through fluid-drainage channels in the crystalline basement turn its hydrocarbon resources into renewable ones.

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