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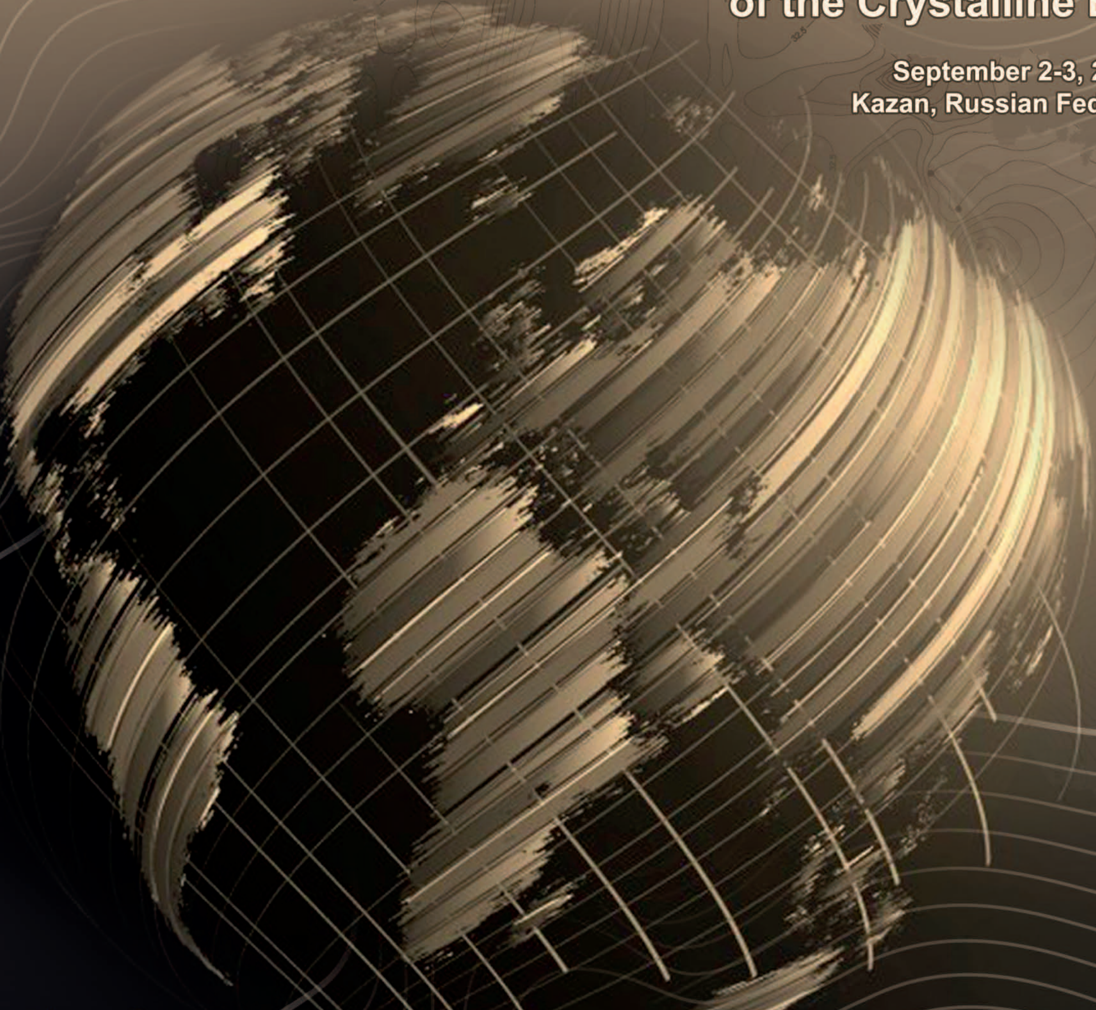
RESULTS

International Scientific and Practical Conference
«Hydrocarbon and Mineral Raw Potential of the Crystalline Basement»

September 2-3, 2019
Kazan, Russian Federation



To the anniversary of
Prof. RENAT MUSLIMOV 85 YEARS

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Table of Contents

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EDITORIAL

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RESULTS of the International Scientific and Practical Conference «Hydrocarbon and Mineral Raw Potential of the Crystalline Basement» and meaningful action to accelerate the use of this potential

R.Kh. Muslimov

1. The conference, goals and objectives

The 23rd International Scientific and Practical Conference "Hydrocarbon and Mineral Resources of the Crystalline Basement" was held on September 2-3, 2019 in Kazan (Rusian Federation) within the framework of the Tatarstan Petrochemical and Chemical Forum.

Organizers of the Conference: Office of the President of the Republic of Tatarstan, Ministry of Industry and Trade of the Republic of Tatarstan, Russian Academy of Sciences, Academy of Sciences of the Republic of Tatarstan, PJSC Tatneft, CJSC Neftekonsorzium, Kazan branch of the Federal State Budgetary Institution "State Reserves Committee", OJSC "Kazanskaya Yarmarka".

The conference was attended by 427 specialists, representatives of 98 organizations, including companies of the Republic of Tatarstan – 42, the Russian Federation – 47 (including Moscow, St. Petersburg, Bashkortostan, Tyumen, Samara and other regions), 24 specialists from far and near foreign countries like China, Italy, Canada, Viet Nam, Egypt, Kazakhstan, Uzbekistan, Belarus, Azerbaijan.

Presentations were made by representatives of academic and university science: the Russian Academy of Sciences, the Siberian Branch of the Russian Academy of Sciences, the Academy of Sciences of the Republic of Tatarstan, leading universities and research universities.

36 reports were presented and discussed, including 14 plenary, 22 oral at the round table and 54 poster sessions. A collection of works has been published, which includes 90 reports.

Why did such a conference take place in Kazan?

The answer is simple – the Republic of Tatarstan has had successful half a century of experience studying the role of the crystalline basement (CB) in the formation, reformation and replenishment of the resource base. The problem of studying CB was posed in 1936 by B.M. Yusupov. Why do we turn to this problem today when the world has significant resources of conventional oils (hard-to-recover reserves), unconventional hydrocarbons (HC) (heavy oils, natural bitumen (NB), oil and gas shales, dense rocks, etc.), and the media scare the onset of the era of electric vehicles and a reduction in the consumption of hydrocarbons?

We proceed from the fact that conventional and some non-conventional hydrocarbons that are available for modern production and use are, firstly, distributed on the planet very unevenly both in area and in section; secondly, a significant part of them is located in difficult geological conditions (large depths of land and sea, complex reservoirs, high pressures and temperatures), in difficult climatic conditions (shelves of the northern seas, deeper objects, remote, uninhabited territories, etc.). All this complicates and increases the cost of their development, making production in some cases unprofitable. In addition, the production capacities of shale deposits and dense rocks are characterized by rapid exhaustion.

As for electric vehicles, unlike electricity, oil, gas, coal are primary energy resources (PER), and electricity does not belong to this category. Its production requires PER. The history of the use of oil and gas shows an increase in the directions of their use by man. So, oil and gas as the most convenient resources for use by a person in his life will always be needed and in an ever-increasing amount.

The main goal of the conference is an in-depth study of the hydrocarbon and mineral resources potential of the bowels and the role of the crystalline basement in replenishing oil and gas deposits of sedimentary cover during the Earth's degassing.

Conference Objectives:

- consideration of world experience in prospecting, exploration and development of fields confined to the rocks of the crystalline basement;
- generalization of the data accumulated over the past 40-50 years on the role of CB in the formation of oil fields in the sedimentary cover;
- assessment of the CB role in the reformation and replenishment of oil and gas fields of sedimentary cover from the Earth's bowels and the impact on the development effectiveness of conventional oil fields;
- the genesis of oil and the mechanisms of oil fields formation in the CB and sedimentary cover.

2. World experience in prospecting, exploration and production from deposits in the CB

The world has gained some experience in the prospecting, exploration and development of oil and gas fields in the CB. A.I. Timurziev believes that

"A feature of oil fields in the basement, contrary to generally accepted ideas, based on elementary ignorance and suppression by the official science of facts, is the exceptional richness and productivity of accumulations of "basement oil".

A lot of reports on the oil and gas potential of the CB at the conference were made on the well-known fields of the Vietnam shelf. For these conditions, a set of basic criteria for the oil and gas potential of the basement in the Kyulong basin was identified and justified, including: geodynamic, tectonic, fluidodynamic, structural-geomorphological, petrographic, which allows it to be purposefully used to assess and predict the prospects of such structures in the basement rocks.

T.A. Kireeva notes: "In many cases, the oil-bearing basement in the overlying rocks of the sedimentary cover shows a manifestation of hydrochemical inversion. This is manifested both in Western Siberia (Krasnoleninsky and Surgut arches), and on the shelf of South Vietnam, where an inversion of hydrochemical zoning is noted over the oil-bearing granitoids of the White Tiger structure at the bottom of the sedimentary cover, which is absent in the neighboring structures, the basement of which has no or slight oil-bearing (Dragon structure)".

T.A. Kireeva formulated the hydrochemical characteristics of the oil-bearing basement:

1. The preservation of the hydrochemical inversions zones in the aquifers of the lower sedimentary cover indicates the potential oil basement.

2. In the presence of a normal hydrochemical section in the sedimentary cover, the oil content of the basement is unlikely.

3. The receipt from the basement of concentrated (M > 200 g/l) calcium chloride type brines can be considered as a clear sign of the oil absence in the basement, because it has already passed into a sedimentary cover, and endogenous brines have occupied the basement cavities.

A.E. Desyatnikova and P.A. Shakhov offer criteria for the search for basement softening zones in order to increase the efficiency of production drilling.

S.A. Punanova states: "It is worth recognizing that the naturally destroyed crystalline rocks of the basement are a global geological phenomenon. Despite the proven commercial success, the delay in the implementation of many projects stemmed from the fact that the discovery of hydrocarbon fields in the basement historically occurred more likely by chance, and not as a result of targeted exploration programs. Nevertheless, in recent years there has been a successful change in this trend, which leads to numerous discoveries and an increase in the number of developments in the basement".

M.Kh. Nguyen, E.Yu. Goryunov cites the criteria for oil and gas presence in the CB on the example of offshore fields in South Vietnam.

In almost all CB reports, there is a close relationship between the oil content of the sedimentary cover and CB, when oil was found in the latter. No industrial oil has yet been found in the Republic of Tatarstan (RT), but oil and bitumen occurrences have been, and a close relationship has been established between the features of the geological structure of the basement and the structure of the sedimentary cover. Here, not only the influence of the block structure of the CB on the sedimentary cover is noted, but even the change of some rocks in the CB to others has influenced the details of the geological structure of the deposits in sedimentary rocks (changing the structure of the structural plan of rock thicknesses, etc.).

The connection between the CB and the sedimentary cover was most fully covered by the specialists of Tatarstan: R.Kh. Muslimov, I.N. Plotnikova, L.M. Sitdikova, V.G. Izotov, R.R. Khasanov, R.S. Khisamov, N.S. Gatiyatullin, V.G. Bazarevskaya, D.S. Danilov, L.M. Shirokova and others), as well as specialists from other regions (V.A. Trofimov, E.Yu. Goryunov, N.A. Kasyanova, A.V. Lobusev, M.A. Lobusev, A.V. Bochkarev, Yu. .A. Gutorov).

Unfortunately, most of the conference participants admitted that the discovery of hydrocarbon fields in the CB was largely random. This indicates the importance of research on the development of reliable criteria and methods for the search for oil and gas in the CB. In the meantime, it is necessary to apply methods for searching for fracture zones (reports by G.N. Erokhin, M.Ya. Borovsky, and others).

The discussion showed that it was time to generalize the data according to the search criteria for oil and gas deposits associated with the CB. Then the search for oil in the CB will be conducted on a scientific basis.

3. The origin of oil

The problem of the oil origin sounded in most reports. Discussions on this issue have been ongoing almost from the very beginning of industrial oil production. This was especially characteristic of Russia. The country has taken the path of supporting organics and all kinds of oppression of inorganics (lack of funding, prohibition of publication of scientific papers, conferences, etc.). In those years, a biogenic theory of the origin of oil developed, and abiogenic theory was tried by single scientists – enthusiasts of their craft. This went on almost until "restructuring". All this naturally did great harm to the development of science. I remember 1968 when, at the All-Union Conference on the Origin of Oil (Moscow, 1968), an outstanding scientist N.A Kudryavtsev and his supporters – abiologists were obstructed. At many conferences, symposiums, meetings on this issue, these discussions took place according to the same scenario – everyone did not strive for some kind of truth, but considered his main task to destroy the opponent in any way.

What do we have now?

It is proved that HC is synthesized both in an organic and inorganic way.

Synthesis is better at high temperatures and pressures. Therefore, the main oil fields of the Republic of Tatarstan are located in areas with a greater depth of subsurface. However, Zakirov, using polycondensation synthesis of hydrocarbons on the surface of a water-saturated mineral matrix of rocks, succeeded in synthesizing n-alkanes ($C_{12}H_{2птт}$) from CO_2 and H_2O at room temperature and atmospheric pressure. Moreover, the reaction proceeded at a high speed.

Acceleration of hydrocarbon formation processes in natural conditions will be initiated by catalysts (natural minerals), the set of which is quite large here.

From modern positions, it can be said that these disputes (in the manner in which they were conducted) were unproductive and contributed little to elucidating the mechanisms of this synthesis and the formation of oil and gas fields.

The basis of oil and gas origin is the synthesis of carbon and hydrogen. Today we know that it occurs in both biogenic and abiogenic (mineral) way. There is no other way. Moreover, this synthesis can occur in different geological conditions (both high temperatures and pressures, and lower, when natural catalysts play a large role).

Obtaining abiogenic HC was done in the laboratories by various scientists. In the 30s of the last century B.M. Yusupov explained the variety of oils in the composition and properties as the contacts of hydrocarbons with rocks and fluids along migration routes.

A review of reports and different opinions suggests that both biogenic and abiogenic concepts are correct. Even the fact that a person with his meager (compared to nature) capabilities was obtained experimentally by HC from a biogenic and mineral source indicates the presence of biogenic and abiogenic synthesis. Those scientists (so far not so numerous) are right who recognize both paradigms. This is already a big progress. Therefore A.I. Timurziev in his report "The fundamental oil of sedimentary basins – an alternative to the shale scenario for the development of the Russian fuel and energy complex (on the example of Western Siberia)" did not have to fall upon Academician A.E. Kontorovich for his adherence to the theory of biogenic synthesis, and he should be criticized for the absolute rejection of the abiogenic synthesis of hydrocarbons. This criticism would be fair. Unfortunately, Aleksey Kontorovich himself was unable to attend the conference, but the title of his report was eloquent: "Oil deposits in the crystalline basement and their genesis. I can't keep silent anymore". Of course, we know what he wanted to say on the issue under discussion (from his previous reports and publications). In that dispute A.I. Timurziev and A.E. Kontorovich operates in the "best" traditions of disputes about the origin of oil of the 20th century. The role of bad traditions is great.

Also, Aleksey Emilievich should not be criticized for his new paradigm, based on focusing the industry on the development of small fields, increasing oil recovery factor and developing hard-to-recover oil reserves in exploited fields. RT has been successfully implementing this paradigm since the 80s of the last century, when an intensive decline in oil production began in the supergiant Romashkino field. Now it is time for Russia too. However, the effectiveness of working with the so-called depleted giants would be significantly higher using the reorganization and replenishment mechanism, which was discussed at the conference.

4. Formation (generation) of oil and gas fields

Issues of oil origin at the conference were central. The main emphasis was on abiogenic oil. Although advocates of a mixed (polygenic) paradigm spoke out. Hydrocarbon synthesis occurs only in biogenic and abiogenic ways.

Thus, disputes (discussions) between the two paradigms of the origin of oil were essentially unproductive. They did not bring any benefit to the joint efforts of scientists in the synthesis of oil. And most importantly, they diverted the attention of researchers from the most important scientific and practical problem – the formation of oil and gas fields. That was a mistake. The very form and content of the discussions did not contribute to the progress in solving the most complicated problem – the knowledge of the laws governing the formation of deposits. The joint work of supporters of biogenic and abiogenic theories on the formation (generation) of oil fields (deposits) would be much better.

There are many concepts of the oil origin today. This apparently happened due to confusion in terms: the genesis (called the origin) of oil and the formation of oil deposits. The latter was confused with the origin of oil. But it has already formed by combining hydrogen and carbon. Under certain conditions, an oil field is formed from this compound by migrating it into traps of various origins. The conditions for the formation of deposits are described a lot. Even the laws of formation and distribution of oil and gas fields have been formulated, depending on geological conditions. The latter has nothing to do with the origin of oil.

The most complete problem of the origin (synthesis) with the formation of oil and gas fields is described in the report of A.A. Barenbaum: "The scientific revolution in the problem of oil and gas formation: deep degassing and the hydrocarbon potential of the subsoil in the light of new ideas". The author proposes biosphere concept of oil and gas formation as a most comprehensive one. He classifies oil and gas as the planet's minerals replenished during the exploitation of deposits, and considers the deposits themselves to be traps of mobile carbon circulating through the earth's surface in three cycles of the cycle of ~ 10^8-10^9, ~ 10^6-10^7 and ≈ 40 years. The rate of replenishing hydrocarbon deposits in this cycle is determined by development technologies and generally depends on the level of modern production and consumption of oil, gas and coal in the world.

It should be noted the main point of the new biosphere concept – the circulation of carbon and water through the earth's surface into the interior (into the mantle) and into the biosphere. This cycle, obviously, takes place in most concepts of the formation and reformation of oil deposits. This is the universality and greatest appeal of the new paradigm of A.A. Barenbaum. In his paradigm, he tried to combine the genesis of hydrocarbons and the formation of deposits. A.A. Barenbaum gives the main role in replenishing reserves of exploited deposits to the third biosphere cycle, which, according to the author, is 40 years. But this statement is not confirmed by the facts of long-term exploitation of oil fields. If the biosphere cycle was mainly used to replenish the reserves of the long-exploited Romashkino field, then for 70 years of its operation we would have produced 1.7 times more oil (than in fact) or the remaining reserves here would be 23.6 times more than today on the official balance sheet. What is the matter?

The fact is that the recharge processes, we believe, go through the existing oil supply channels in the CB, and the rates of natural recharge are tens, hundreds of times less than the production rate. If everything went along to Barenbaum paradigm, then we, the geologists working at the Romashkino field, would have seen this process visually 40 years ago. But we sensed the existence of the recharge process (rather than determined). Then, analytical geological and geophysical and geophysical studies were carried out to identify this process on the Minnibaevsky area of the Romashkino field. These works were successful.

A.A. Barenbaum believes that the rate of replenishment is determined by development technologies and the level of oil consumption. In Soviet times, they took everything they could give from the field, using the most advanced technologies in the world, but they could not fix the reserves. In order to fix this feed, it is necessary to apply special technologies that provoke this feed. But we did not have them then and do not have them today. There are ideas on how to do this, but given the current state of the industry and the attitude of oil companies, this is not yet possible. Too complicated and expensive.

Thus, it is impossible to consider the process of replenishment of exploited oil fields in the third cycle of A.A. Barenbaum. Apparently this cycle is not related to replenishment. We need to study the question of where the hydrocarbons of this cycle disappear. And the big doubt is that this cycle is so short. Too seductive and unrealistic.

The question of the duration of all three cycles of A.A. Barenbaum obviously needs additional research and justification.

The report of V.K. Utoplennikov "The geodynamic conditions of mixtgenetic formation of oil fields in the basement of South Vietnam" was of great interest. It talks about the conditions for the formation of deposits.

The author identifies three oil generation zones: mantle-asthenospheric – abiogenic synthesis; subduction-dissipative – biomineral synthesis; stratospheric – biogenic synthesis.

The mechanism outlined by the author seems to be the most realistic in the specific conditions of South Vietnam. It falls under the organic and inorganic synthesis of hydrocarbons and shows their role in the formation of deposits in CB.

S.A. Punanova in her report "Oil and gas potential of the crystalline basement and the formation of non-structural traps of a combined type in it" gives another mechanism of formation.

In the Cuu Long basin of Viet Tam, through the contact of protrusive granites of the pre-Cenozoic basement with the Cenozoic sedimentary cover, lateral migration of fluids took place from the oil-source strata of the Oligocene age to the basement – into voids and zones of increased fracturing, into the formed fissure-cavernous reservoir of a combined type.

Other geochemical features of the oils occur in the erosion protrusions of the crystalline basement, however, the genetic proximity of the oils from the basement and from sedimentary formations also appears. Here the oil forms a zone of hypergenesis. S.A Punanova writes: "It is worth recognizing that naturally destroyed crystalline rocks of the basement are a global geological phenomenon".

V.R. Shuster and S.A. Punanova made an attempt to investigate the prospects of oil and gas potential of the pre-Jurassic deposits and basement formations in 25 exploratory areas with gas and gas condensate deposits.

To identify promising objects, taking into account the high probability of detecting complex (non-structural) type traps in deep-seated sedimentary deposits and basement formations, it will be necessary to use modern seismic exploration technologies of CDP 3D waveforms using scattered waves, which are especially effective in the basement formations, where stages are still distinguished at the pre-drilling stage zones and areas of distribution in the context of unconsolidated reservoir rocks.

L.E. Zagranovskaya and O.A. Zakharova lead various types of deposits in the CB.

A.P. Zapivalov leads deposits in CB in rift systems.

If the processes of hydrocarbon synthesis are more or less clear, then the processes of formation of oil and gas deposits are diverse and depend on a variety of geological conditions. Knowing them requires high technology, geological and geophysical, laboratory and other studies, a high level of analysis and generalization of natural processes. This is the complexity of the problem. The variety of geological conditions for the formation of deposits should be the subject of a detailed study, especially in complex areas and unconventional objects such as shale deposits in the United States, Bazhenov deposits of Western Siberia, Domanic of the Volga-Ural oil and gas province.

5. Reformation, re-feeding, replenishment of reserves of exploited fields

The pivotal issue of the conference was a discussion of the consequences of discovered a quarter of a century ago an important natural phenomenon by the Russian scientists – replenishment of oil and gas in fields at the late stages of their development. Currently, in oil and gas geology, a scientific revolution is taking place that has led to the idea that oil and gas are indestructible minerals of our planet, the replenishment of which in field depends on the technology of field development.

Most scientists today associate this phenomenon with the flow of hydrocarbons from the basement. Therefore, many reports focused on an in-depth study of the crystalline basement as a supplier of oil and gas to sedimentary cover deposits.

The facts show that the use of this phenomenon in practice, with a careful attitude to traps, will open the possibility of exploiting oil and gas fields as inexhaustible sources of hydrocarbon raw materials. The transition to such field development technologies is one of the most urgent tasks posed by modern geological science to the country's oil and gas industry today.

Tatarstan geologists have been involved in the hydrocarbon potential of the CB for about 50 years. During this time, they moved from the idea of oil searches in the CB near the South Tatar Arch to the necessity and expediency of a priority study and assessment of the role of the crystalline basement in the formation, reformation, replenishment of oil and gas fields due to the inexhaustible hydrocarbon potential of deep degassing of the Earth.

It was proved that the crystalline basement plays a role in the constant "recharge" of oil deposits in the sedimentary cover with new resources due to the inflow of hydrocarbons through hidden cracks and gaps from the depths of the Earth. It was shown that the South Tatar arch has a single source of oil generation for oil and natural bitumen deposits, as well as the formation of deposits due to vertically ascending migration of oil and gas fluids through faults that cut through the crystalline basement and lower horizons of the sedimentary cover.

Subsequent in-depth seismic studies of the CDP, presented on regional profiles in the Samara region, in Udmurtia and, most importantly, on the Tatseys geotraverse, which crossed almost the entire Volga-Ural oil and gas field, led to the most important conclusion that the structure of the earth's crust and upper mantle beneath large oil accumulations is fundamentally different from other territories.

Subvertical anomalies are observed under most of the fields listed by the geotraverse, but most of all under the Romashkino and Novo-Elkhovsky giant fields.

Based on the data with a large number of oil and gas fields of the world discovered in the rocks of the CB, and our research, it is possible to consider the CB of the Russian Platform as an object of independent search. But it is extremely expensive and technically difficult to carry out conventional oil and gas exploration work in the CB. The lack of search technologies and drilling techniques in the extremely difficult geological conditions of the CB has led us at the present stage to abandon the immediate implementation of this idea. In its place the idea came of getting oil from CB through sedimentary cover deposits, using the mechanism of "feeding" sedimentary cover fields.

The most convincing argument in favor of the natural replenishment of oil reserves in the developed fields is the numerous facts of oil production excess in a number of fields over the estimated balance and recoverable oil reserves, which we wrote in the book "The role of the deep degassing of the Earth and the crystalline basement in the formation of the Earth and natural replenishment of reserves of oil and gas fields". Over the years, this difference increases. For some fields, it becomes difficult to justify the volume of oil production due to their constant depletion (in this case, it is necessary to raise the estimated parameters – porosity, oil saturation, oil recovery factor, to the maximum theoretically possible). On such objects, the perception of completion has gone through all stages: hypothesis-theory-experience-observation.

A.P. Shilovsky tried to connect the oil content of the sedimentary cover with the trap inflow of magical substance into the sedimentary cover. The report is interesting, but in RT the question remains unstudied.

Many reports were devoted to search criteria for decompression zones and methods for their detection (A.E. Desyatnikova, P.A. Shakhov, T.A. Kireeva, S.A. Punanova, M.V. Rodkin, M. Emanuel Hossein, G.P. Kayukova, R.R. Lukyanova, etc.).

Thus, the constant replenishment of production deposits is an indisputable fact. But it has not yet received universal public recognition.

V.A. Trofimov makes recommendations for searching for sites where recharge is most likely possible: "It has been established that fields with accumulated production volumes exceeding geological reserves are confined to: the boundaries of large tectonic blocks; to areas of reduced sulfur, tar and asphaltenes". Detailed work on the localization of feeding centers is detailed in the reports of R.Kh. Muslimov and I.N. Plotnikova.

Currently, in matters of abiogenic oil, RT specialists have adopted as a priority the concept of feeding sedimentary cover fields from the depths of the Earth through the CB rocks through oil supply channels, crushing zones, and fractures of different generations. Despite the global scale of these processes, there are many ambiguities, mechanisms, scales, paths and driving forces. All this is due to the lack of reliable methods of localization and study of the mechanisms of these processes. Seismic data show zones of fracture, crushing, channels, but there is no guarantee that they really are hydrocarbon transport channels (can be healed, filled, fracture products, etc.). From observations of long-exploited fields, it can be concluded that processes are relatively slow, which usually pass by our attention.

The development of the field's reserves by modern methods is carried out by temps significantly larger than the recharge.

The slow refueling process against the background of the rapid extraction of oil makes many doubt the very possibility of refueling (report by R.Z. Mukhametshin "The facts of the renewability of reserves in the developed oil and gas fields").

Moreover, we are doing everything against the functioning of these processes, developing these areas together with the entire reservoir using intensive waterflooding systems at relatively high reservoir pressures. On the other hand, if we tried to initiate the processes of replenishment by artificial pressure reduction, we would (as shown by many years of research at the Romashkino field by M.V. Belonin, R.S. Sakhipgareev) contribute to a decrease in the permeability of the reservoirs. This is especially harmful for fractured formations. All this speaks of slow-running recharge processes and the need for targeted measures to intensify this process (hydraulic fracturing, the use of crack fixers, optimization of pressures and fluid withdrawals). This contributes to the fact that we do not visually see the results of this recharge and cannot quantify it. However, for a number of deposits (sites) we know reliably how much oil was taken. If more recoverable reserves, and especially balance reserves, were selected, then the recharge mechanism works. All of the above indicates the complexity of the problem. The disbelief in the very existence of the recharge processes is even greater difficulty. I'm not talking about supporters of biogenic synthesis (they will always be opposed). But even some researchers who do not so abruptly deny abiogenic synthesis introduce a spirit of doubt into the theory of fueling.

6. Practical steps for using the recharge processes of exploited oil and gas fields in development design

With the development of civilization and geological exploration, hydrocarbon production on Earth is growing, but at the same time, the proven and so-called initial potential resources (IPR) of HC are growing. Thus, by the beginning of the last century, oil IPR was estimated at about 5 billion tons (this is not much more than modern annual oil production). The Earth itself provides us with HC and, obviously, will provide further.

Since we do not know all the processes of their synthesis, all possible ways to obtain hydrocarbons, why not assume the reverse carbon production from the rocks of the earth's crust? In addition, when using HC as a fuel, carbon remains as a combustion product (CO_2, CO) and can, according to A.A. Barenbaum, create man-made deposits.

At the conference, the role of CB and recharge in the formation of oil deposits in shales and dense (currently considered non-reservoirs, but oily) rocks in the sedimentary cover (reports by R.Kh. Muslimov and I.N. Plotnikova) was weakly sounded. Despite the extremely poor knowledge of this problem, it becomes (against the backdrop of the shale revolution) particularly important.

Given this important direction, we have to admit that in-depth study of CB becomes the most important task of science today and in the future.

The conference identified priority areas of work on CB:

- the study of the fields relationship of sedimentary cover with a crystalline basement, understanding that knowledge of the geological structure of the CB is the key to the search for oil in the sedimentary cover;
- study of the oil and gas generated and oil conducting role of CB;
- study of the established phenomenon and the role in the constant "feeding" of oil deposits of sedimentary cover with new resources due to the inflow of hydrocarbons through hidden cracks and gaps from the depths.

It is emphasized that the data obtained on the reorganization of deposits and replenishment of exploited deposits of sedimentary cover allow at the present stage to begin the practical implementation of fundamentally different approaches to the development of oil fields. The experience of the Republic of Tatarstan shows that this must be done through innovative design of development processes.

7. Innovative approaches to the development of oil fields based on the process of Earth degassing and replenishment of hydrocarbon reserves

Such design should be based on a mixed (polygenic) theory of the origin of oil and gas, the formation and reformation of industrial accumulations of oil and gas.

A lot needs to be done to move from modern development design (without reformation and recharge) to design with these processes in mind.

First, science and oil companies need to develop a methodology for constructing geological and geological-filtration models of long-exploited oil and gas fields, taking into account the processes of reorganization and replenishment of hydrocarbon reserves by feeding them from the depths of the Earth due to degassing of the bowels.

Secondly, the Academy of Sciences of the Republic of Tatarstan, together with the oil companies of Tatarstan have to develop appropriate instructions based on the provision that the monitoring system should be two-level. The first level is the analysis of geological and field data and the identification of potential areas of migration of hydrocarbons into the deposits based on the use of geological and field anomaly criteria established earlier in the Republic of Tatarstan. The second level is the geochemical studies of oils and gases dissolved in them both within the wells with signs of anomalies and in adjacent areas of the reservoir.

Thirdly, it is necessary to envisage the use of proven technologies for field exploitation in full (at the level achieved) of enhanced oil recovery methods, bottomhole zone treatment and regulation of development processes in areas where there is no recharge. And where it is, create conditions for its activation (pressure reduction, acceleration and increase in the volume of recharge) by artificial means.

It is also necessary to begin work on modeling the processes of reformation and replenishment of oil reserves in the long-term developed major fields of the Russian Federation and the Republic of Tatarstan.

Currently, scientific organizations of the Republic of Tatarstan are scientifically ready for such work. The case is oil companies, organization and financing of these works.

8. The world's growing interest in the study of CB

The growing interest in the world should be noted on the problems of hydrocarbon search and the assessment of the role of CB in the formation, reformation and migration of oil and gas fluids. Particularly noteworthy is a review report by T. Köning (Calgary, Canada), "exploring in Asia, Africa and the Americas for oil & gas in naturally fractured basement reservoirs: best practices & lessons learned".

The reports on the prospects in Kazakhstan (M.N. Babasheva, S.N. Nursultanova: "Prospects for the oil and gas potential of the basement of the South Turgai basin"), in Uzbekistan (E.S. Abdulaev et al., "Show great interest in the topic under discussion"). The hydrocarbon potential of the Paleozoic formations of the basement of the oil and gas regions of Uzbekistan"), in Azerbaijan (V.Sh. Gurbanov, N.R. Narimanov: "The forecast of the oil and gas potential of the basement of the South Caspian megabasins"). The latter focuses on the study of the relationship between CB and sedimentary cover.

9. Priorities

Unfortunately, the management of the country's geological service practically did not take part in the issues discussed at this conference. There was only one report of the General Director of the State Reserves Committee I.V. Shpurov. In his report, he did not speak at all on the issue at hand.

The following statement by A.A. Barenbaum is very alarming.: "The lack of a universally recognized paradigm regarding the origin of oil and gas – and this is a key issue in oil and gas geology, according to paragraph 3 of T. Kuhn's theory, casts doubt on the fundamental ability of oil and gas geology to solve this problem. Kuhn's verdict that in such a situation "All members of the scientific community seem to be engaged in science, but the combined result of their efforts hardly resembles science in general," is convincingly confirmed by the years of irreconcilable struggle of supporters of organic and mineral hypotheses on oil and gas formation".

First, the origin of oil in petroleum geology is not the only key problem. We have a lot of them. These are the problems of prospecting, exploration, development of oil fields, oil displacement and enhanced oil recovery processes, the mutual influence of CB and sedimentary cover, etc.

Secondly, the struggle of supporters of biogenic and mineral theory was not useless. Those and other scientists made a great contribution to the development of science, which allowed today to come to the recognition of both synthesis, which contributes to this direction to move forward in the formation and reformation of oil deposits. The disadvantage was the manner of these discussions and the error in the substitution of concepts – the synthesis of hydrocarbons and the formation of deposits.

Thirdly, petroleum geology as a science has constantly evolved. It simply could not fail to develop, as it deals with specific objects of research. The fact is that all deposits are unique in their structure. There are not even two identical deposits in the world. Each field is individual and requires individual approaches to its development and development of reserves.

Therefore, here scientists who offer their opposite recommendations are often right. So a grid of wells of the same density for one object may be excessively dense, and for another very rare. Or, the use of surfactants to increase the oil recovery factor in one case gives a positive effect, in the other – a negative effect, and in the third – no effect. It all depends on the clay component in the rock. There are hundreds of such examples. There is nowhere without science. Therefore, oil science must not be criticized. It should not be proposed to remove the concepts of “abiogenic” and “biogenic” carbon (of course, both are just carbon, but separation is necessary for understanding the source), CB, oil source formations, degassing. All this exists and is used to understand each other. The concept of “initial potential resources” is necessary, but the concept of geological reserves is even more necessary. This is the start from which we have to begin if we want to determine the future effect of recharge.

According to Alexander Losev, member of the Presidium of the Council on Foreign and Defense Policy, financier and mathematician, “technological degradation is occurring in the world and, in essence, the destruction of science. Everywhere. Everything is replaced by technologies that allow you to quickly recoup costs. Project financing triumphs in science, grants are allocated for a period of 2-3 years. If scientists do not give returns in 3 years, funding will cease”.

But in general, any real science finds a way out of any impasse.

In the regions, they better understand the issues of studying CB and deep abiogenic oil and are ready to work scientifically on these problems. Of course, it would be good to draw up an all-Russian program on the problems of deep oil. But today, the management of the geological service of the industry is not at all ready for this.

The conference considers it necessary:

- The State Reserves Committee to change the methodology for calculating reserves, which includes both conditioned and substandard reservoirs and interlayers in the reserve calculation object;

- ask the Central Reserves Commission to develop a methodology for identifying and accounting for additional hydrocarbon resources through reformation of fields and replenishment from the depths of the Earth’s bowels;

- the Central Reserves Commission to create a methodology for innovative design of oil field development at a late stage of operation, taking into account additional resources obtained through the reformation of deposits and replenishment of hydrocarbons from the depths of the Earth;

- The Ministry of Natural Resources should ensure the development of instructions on methods for research and monitoring the processes of reformation and replenishment of hydrocarbons from the depths of the Earth at a late stage in the exploitation of an oil and gas field.

Naturally, it is necessary to provide centralized funding for the development of these documents.

A.I. Timurziev considers fundamental oil an alternative to shale. However, it would not be worth raising the question. The resources of shale oil and gas are huge. True, this includes hydrocarbons of dense rocks, the resources of which are greater than those of shale origin. But these are extremely difficult geological conditions, the development of which is difficult and expensive.

What the United States did to mine these hydrocarbons is worthy of all praise and respect. However, they did a technical miracle, not an attractive development of these resources. Indeed, the design oil recovery is 8-10%, which extremely small. Mastering these resources will always be expensive. Technique and technology will develop, and geological conditions will be continuously complicated (this is the law in the geological part of the development of deposits in any region). It is necessary to deal with these objects. But not all countries can do this.

The resources of abiogenic deep hydrocarbons are inexhaustible. They are designed for the entire life of planet Earth. Therefore, we call them renewable. Many people know this, but this is not visible in the foreseeable future. The reason is that the current situation with oil and gas prices (as it is considered non-renewable) suits everyone (oil industry workers, gas workers, producer countries and even hydrocarbon consumer countries, for which price stability is most important).

This situation may continue indefinitely. But the problem of prospecting and searching is very complex and long, and the use of reorganization and replenishment processes is also very complex, knowledge-intensive and costly. But the theory of renewability and the ability, due to these processes, to provide all the needs of an ever-growing and demanding comfortable life of the world’s population is too attractive. They need the usual and most convenient types of resources – oil and gas. This is not only energy, but also much more necessary for the life of the population.

The conference was successful, with the benefit for the further development of the issues of in-depth study of CB.

Unfortunately, it failed to adequately cover the problems of using the processes of formation of oil fields in the design of field development systems. This direction was most significant in the report of R.Kh. Muslimov, a little in the report of S.N. Zakirov, in a report by A.F. Yartiev and V.A. Iktisanov, as well as at V.A. Trofimov.

REVIEW ARTICLE

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Exploring in Asia, Africa and the Americas for oil & gas in naturally fractured basement reservoirs: best practices & lessons learned

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Abstract. Oil and gas occurs in basement reservoirs in many parts of the world. The reserves of basement fields are as small as one or two million barrels of oil or gas-equivalent to as much as almost 2.0 billion barrels of oil as in Libya's Auguila-Naafora field. Exploration for oil and gas in basement has been remarkably successful in the past decade with important discoveries in basement in Indonesia, United Kingdom, Norway, Chad, and Argentina. In order to successfully develop basement oil and gas fields and also to avoid costly mistakes, all available geological, geophysical, reservoir engineering and economic data must be closely studied. Also, it is very important to study analogues of basement oil and gas fields worldwide in order to understand why some fields are very successful and others turn out to be failures.

Keywords: crystalline basement, oil and gas fields, fractured reservoirs, weathered rocks, world best practices, exploring, developing

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Introduction

Basement rocks are important oil and gas reservoirs in a number of basins in the world including Asia (Indonesia, China, Viet Nam, & India), Russia, Middle East (Yemen), Africa (Algeria, Libya & Egypt), South America (Venezuela & Brazil), USA (California, Kansas, Oklahoma & Texas), and the North Sea (UK West of Shetlands & Norway) (Fig. 1). The basement reservoirs include fractured and weathered granites, quartzites, metamorphics and volcanics.

The basement oil and gas play has intensified in the past decade with significant basement discoveries in the United Kingdom (Lancaster and Lincoln oil fields), Norway (Rolvsnes oil field), in Chad (central Africa), Argentina, and in 2019 a major gas discovery was made in basement in Indonesia.

The author has followed this subject closely for over 35 years since being involved in 1982 with the development of the Beruk Northeast basement oil pool in Indonesia. He has also been involved with evaluating basement oil discoveries in Angola and Uganda. He hereby shares his knowledge and experience.

This paper provides a technical review of select basement oil and gas fields in Asia, Africa and the Americas. Also reviewed is "best practices" for exploring and developing basement fields. Although this paper reviews mostly "success stories" there are also failures since basement reservoirs can be very complicated and unpredictable. Accordingly, two basement fields which proved to be economic failures, Dai Hung (Big Bear) in Viet Nam and Beruk Northeast in Indonesia, are also reviewed.

The biggest oil and gas fields among the basement fields occur within basement which is heavily naturally fractured. The opinion of this author is that the best rock types are fractured quartzites or granites since they are brittle and thus fracture optimally (Koning, 2019).

Fractured gneisses are poorer reservoirs since they can be massive, dense or slabby with open fractures parallel to the direction of foliation.

Rocks such as gneisses and schists are ductile and tend to "smear" and not fracture when subjected to tectonic stress.

Phyllites and slates are the least attractive since such rocks are not brittle, rather they are thinly bedded, fissile and ductile and fracture poorly.

Weathered granitic basement can also be an excellent reservoir such as in the Auguila-Naafora oil field in Libya as described later in this paper.

The following is the preference scale for basement reservoir rock types:

Fig. 1. Global distribution of oil & gas fields in basement reservoirs

- Fractured quartzites (*most preferred rock type*);
- Fractured granites;
- Fractured carbonates;
- Weathered granites;
- Fractured gneisses;
- Weathered gneisses;
- Fractured schists;
- Weathered schists (*least preferred rock type*).

Oil and gas fields in basement require the same geological criteria as conventional oil and gas fields which includes reservoir rocks (fractured or weathered basement), oil & gas source rocks adjacent to or overlying basement, structural closure, and cap rocks which seal off the basement reservoirs.

ASIA BASEMENT OIL & GAS FIELDS
VIET NAM

The largest oil field in Viet Nam is the giant-size Bach Ho (White Tiger) basement oil field. Other basement oil fields include the Dai Huang (Big Bear), Ca Ngu Vang (CNV), Rong (Dragon), Rang Dong, Ruby and Su Ten Den fields with oil reserves ranging from 100 to 400 million barrels of oil (Koning 2019, Chung-Hsiang P'An, 1982).

Bach Ho (White Tiger) Oil Field

This is a giant oil field with estimated reserves of 1.0 to 1.4 billion barrels recoverable (Hung & Le, 2004). The field was discovered in Viet Nam's Cuu Long Basin by Mobil in 1975 with oil found in Oligocene sediments draping a major basement structural high (Fig. 2). Due to the political situation, Mobil, a USA oil company was not able to develop the field and exited from Viet Nam. However, in 1988 VietSovPetro discovered oil in the underlying fractured and weathered Precambrian granite basement. Oil production peaked at about 280,000 barrels of oil per day in 2005. The oil production is 95 % from the basement reservoirs and 5 % from the Oligocene sediments. Bach Ho's production declined to 140,000 barrels of oil per day in 2009 and has continued to decline to 65,000 barrels of oil per day in 2018.

The oil is stored in macrofractures, microfractures, and vuggy pores within the fractures. Matrix porosity within the granite is negligible. Most of the fractures inside basement are at high dip angles of 40-75 degrees. Porosity in the fractures is only 2-3 % but permeabilities are excellent at ten to thousands of millidarcies. Flow rates have been measured at up to 14,000 barrels of oil per day per well. Bach Ho's giant-size reserves are due to the oil column having a very significant thickness of 1,500 meters.

Dai Hung (Big Bear) Oil Field

A contrast to the success of Bach Ho is provided by the development and production history of the Dai Hung Field where oil and gas is hosted in a similar granite-granodiorite matrix. In 1993, Australia's BHP led a consortium that won the bid to develop this field and predicted the field would produce 250,000 barrels of oil per day. A full-scale production platform was installed but very disappointingly by the mid-1990's the field was producing only 25,000 barrels of oil per day and output declined rapidly and in 1997 BHP left the consortium announcing the field was not profitable.

Malaysian state oil company, Petronas took over as operator but failed to raise the output beyond

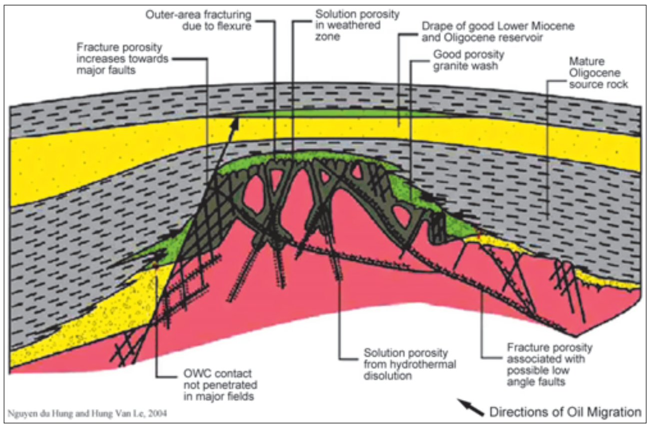


Fig. 2. A two-dimensional model of the play concept for the Cuu Long Basin, Viet Nam (Hung & Le, 2004)

10,000-15,000 barrels of oil per day and left in 1999. In 2000, VietSovPetro, operator of the Bach Ho and Rong fields became operator of Dai Huang but was only able to produce about 5,400 barrels of oil per day. The "lessons learned" from Dai Huang is that it is very important to fully understand the geological, geophysical and reservoir complexities of such a basement field prior to embarking on full-scale production.

Ca Ngu Vang (CNV) Oil Field

The CNV Field was discovered in 2002 and is the deepest oil-bearing structure in the Cuu Long Basin with the top of basement at a depth of 3,700 meters. CNV is a buried hill field as is the Bach Ho Field and produces from fractured Precambrian granites. The operator of the field is United Kingdom-based SOCO International. The CNV-3 well was the longest measured depth well in Viet Nam at 6,123 meters with over 2,000 meters of basement penetrated in a near-horizontal well bore (Fig. 3). The well tested both oil and gas at a rate of 13,040 barrels per day of oil & gas equivalent.

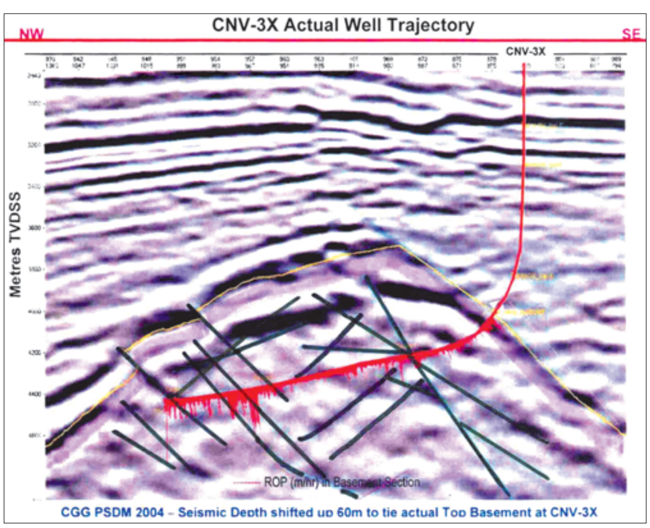


Fig. 3 Seismic section and CNV-3 well trajectory through CNV Field, Viet Nam (SOCO Int. website, 2011)

INDONESIA

Suban Gas Field, South Sumatra

The Suban gas field was discovered in 1999 by drilling deep into basement. Approximately 5 TCF (trillion cubic feet) of gas was discovered in fractured granites. Highly prolific gas wells were drilled on the basis of the wells being highly deviated and oriented perpendicular to the dominant fracture system. The success of Suban has led to further successful exploration for gas in basement in Sumatra due to the need for more gas as the Indonesian economy continues to expand. Gas from the Suban Field has been pipelined to the huge Duri heavy oil steam flood project in Central Sumatra as well as to Singapore for electricity generation. The American oil company ConocoPhillips is the operator of the field.

Kali Berau Dalam Gas Discovery, South Sumatra

In 2019 the Spanish oil company Repsol announced that their Kali Berau Dalam-2 exploration well had made a major gas discovery in fractured pre-Tertiary basement rocks. This discovery extends the basement gas play 150 kilometers to the northwest of the Suban Field. The well was reported too have flowed at a rate of 45 million cubic feet of gas per day.

Repsol mentioned that the discovery found at least 2 trillion cubic of gas. On an oil equivalency basis this equals 330 million barrels of oil. For Indonesia the Kali Berau Dalam discovery is very significant since it is the largest oil or gas discovery in Indonesia in the past 18 years since the Cepu discovery in 2001. Indeed, petroleum industry analysts have stated that this discovery is one of the ten biggest discoveries in the world in the last 12 months.

Beruk Northeast Oil Pool, Central Sumatra

This basement pool appeared to be very promising based on the flow rate of 1,680 barrels of oil per day from the discovery well, Beruk Northeast-1 drilled in 1976 (Koning & Darmono, 1984) (Fig. 4, 5). The oil-bearing reservoir drilled by the discovery well was a fractured quartzite and radiometric age dating established a Permian age for the quartzite. The discovery was followed up by four development wells, none of which were drilled deep into basement thus the operator Caltex (Chevron-Texaco) did not know about the presence of multiple shallow underlying oil-water contacts. The field produced only 2 million barrels of oil when rapid water influx terminated the life of the field and rendered it noncommercial.

The "lessons learned" was that wells need to be drilled sufficiently deep into the basement rather than simply touching or "tagging" into the top of the basement.

Tanjung Oil Field, Kalimantan

The largest oil accumulation in basement in Indonesia is the Tanjung Field in the Barito Basin,

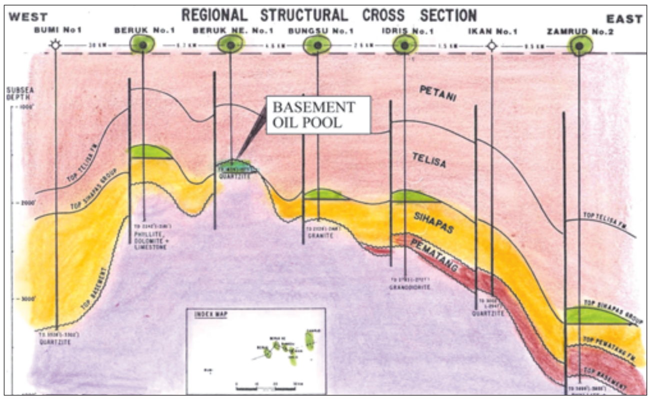


Fig. 4. Regional cross-section through the Zamrud-Beruk area, Central Sumatra basin. The Sihapas is a Tertiary-age sandstone which produces oil throughout this area. The Sihapas pinches out onto basement at Beruk Northeast where the Telisa shale provides a top seal to the underlying fractured basement of the Beruk Northeast oil pool (Koning & Darmono, 1984).

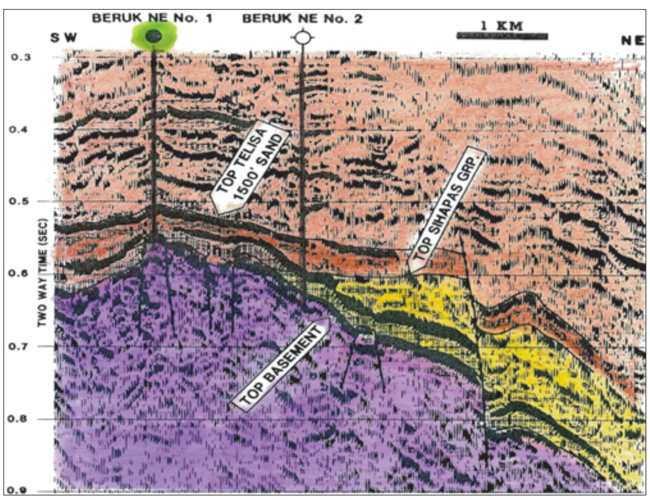


Fig. 5. Seismic line across the Beruk Northeast oil pool. Note the Sihapas sandstones pinch-out on the flank of the basement high. Accordingly, the oil-bearing basement high is capped and sealed by Telisa Formation marine shales (Koning & Darmono, 1984)

southern Kalimantan. This field has produced over 70 million barrels of oil from Eocene sandstones and conglomerates overlying a faulted basement high and it has also produced over 20 million barrels of oil from basement rocks including volcanics, pyroclastics and metasediments.

CHINA

Yaerxia Oil Field

The Yaerxia Field is an onshore oil field discovered in 1959 and is the first basement "buried hill" field ever discovered in China. The oil is produced from Paleozoic phyllites, slates, and meta-sandstones. The wells are moderately productive with 12 wells producing less than 70 barrels of oil per day, 3 wells producing at 200 barrels of oil per day and 2 wells producing at 875 barrels of oil per day. The wells are not highly productive since the phyllites and slates do not naturally fracture optimally. Similarly, phyllites and slates do not produce good reservoirs when they are weathered.

Dongshenpu Oil Field

This field is located onshore central China and like the Yaerxia oil field is an example of a Chinese "buried hill" basement oil field. The Dongshenpu oil field was discovered in 1983 and the reservoir consists of Precambrian granites, granulites, diabases, and hornblende gneisses. The rocks have no primary porosity but porous reservoirs were developed by weathering and natural fracturing. The discovery well tested at 1,570 barrels of oil per day and subsequent development drilling has found the oil column to be 400 meters thick. The reserves in this field were estimated at approximately 190 million barrels of oil.

MALAYSIA

Adang Utara Oil Field

Malaysia's first basement oil discovery occurred in 2005 with the drilling by Petronas of Adang Utara-1 in the southern Malay basin, offshore Terengganu. The well was drilled to a total depth of 2,610 meters including 120 vertical meters of basement penetrated. The flow rate of the discovery well is not available. However, 6 appraisal and development wells have been drilled. Flow rates from basement were as low as 159 barrels of oil per day to as high as 2,116 barrels of oil per day. The flow rates are much dependent on the wells optimally intersecting the oil-bearing basement fractures. No reserves information has been published on Adang Utara.

INDIA

India is the third largest consumer of crude oil in the world, after USA and China. India's oil and gas demand has significantly outpaced its domestic production. In India, basement exploration is not a new concept with established oil production from fractured and weathered basement in the Assam and Assam Arakan Basin, as well as in the Mumbai, Krishna Godaveri, Cauvery, and Cambay Basins. With the gradual decrease in large, easy-to-find oil pools, there is a shift in the focus of exploration from conventional sedimentary reservoirs to exploration in basement.

An example of an Indian basement field is the Mumbai High which is located offshore from India's west coast. This field was discovered in 1976 and produces from both basal sands and fractured Precambrian granites. Wells in basement have produced at rates of 465 to 2,575 barrels of oil per day.

Another example of an Indian basement field is the onshore Padra Field which produces oil from Deccan Traps volcanic basement. This consists of layered basalts laid down by episodic lava flows which occurred in the Upper Cretaceous-Paleocene time period. The fractured and weathered basalts contain oil columns of up to 300 meters in thickness. The Borhalla oil field in northeastern India in the Assam Arakan basin produces from fractured basemen and is another example of a basement oil field in India.

AFRICA BASEMENT OIL & GAS FIELDS

LIBYA

Major reserves of oil occur in basement in Libya. The Auguila-Naafora Field is a multi-billion barrels accumulation discovered in the mid-1960's in the Sirte Basin. The reservoir consists of hydrothermally altered fractured and weathered Precambrian granite. The field is a prominent horst block created at the onset of rifting in Middle to Upper Cretaceous time (Harding, 1984) (Fig. 6). The discovery well which found oil in basement was tested at 7,627 barrels of oil per day. Thick excellent oil source rocks onlap the basement high and also act as the ultimate seal to the accumulation. The source rocks are Cretaceous-age basinal marine dark shales.

Primary porosity in the granite is low (2-3 %) but hydrothermal alteration and weathering have led to about 6 % porosity in the weathered zone and a maximum of about 11 %. The weathering at the top of basement varies from as little as 5 meters to as much as 200 meters. There are sufficient open fractures in the basement structure to ensure effective fluids communication throughout the accumulation and to guarantee good production rates.

Reserves are estimated at 9.0 billion barrels of oil in place of which 90 % occurs within basement and 10 % in the overlying sediments. Production by 1984

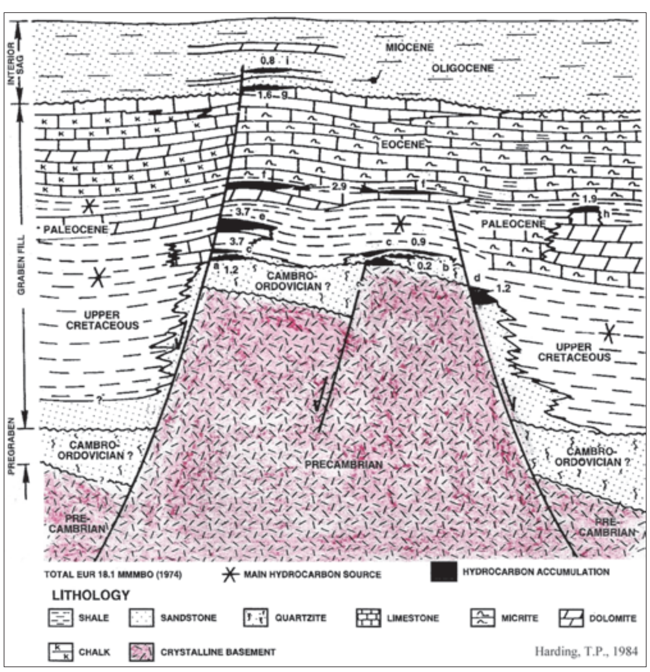


Fig. 6. Typical horst structure, Sirte Basin, Libya (Harding, 1984)

was 820 million barrels of oil. The field is estimated to have ultimate production of 2.0 billion barrels, which is equivalent to a 22 % recovery factor. Basement's share of the production is estimated to be 1.8 billion barrels of oil.

Accordingly, in the view of this author, Auguila-Naafora is the largest basement oil field in the world and is the prime analogue for geoscientists who are searching for major oil or gas accumulations in basement.

EGYPT

The Zeit Bay basement oil field is located in the offshore Gulf of Suez and was discovered in 1981. The initial discovery well had an oil column of 260 meters. Approximately 1/3 of the field's reserves are in basement and 2/3's in the overlying sediments. Basement consists of granites, meta-volcanics, meta-sediments and dykes. Flow rates in basement vary from 700 to 9,000 barrels of oil per day.

SOUTH SUDAN

About 40 wells were drilled in the Melut Rift Basin of which two wells flowed oil from basement at undisclosed flow rates. The reservoirs are granites and granitic gneisses. The Lower Cretaceous Renk formation is the major source rock in this basin. There is little public domain information on South Sudan's petroleum geology but based on regional geology one would expect that there is a high potential for oil and gas in basement in South Sudan's rift basins.

CHAD

In 2013 the China National Petroleum Company (CNPC) made the Lanea-1 oil discovery in the Bogor Basin in granite basement in a buried hill structure with 1,000 meters of relief. This has been followed up by 5 more oil and gas discoveries in buried hills. The reservoirs are fractured granite and hydrothermally leached granite, the latter being the best reservoir facies. The source rocks and top seals are Early Cretaceous lacustrine shales. The oil column is 1,500 meters thick and the average well productivity is 1,500 barrels of oil per day. The reserves have been estimated at approximately 100 million barrels of which 70 % is in basement and 30 % in the overlying granite wash.

ANGOLA

In 1968, USA's Gulf Oil Corporation drilled and completed Angola's first basement oil discovery, well 61-1 in the onshore area of Angola's province of Cabinda (Koning, 2014) (Fig. 7, 8). The well flowed 600,000 barrels of oil on an extended flow test. Additional development drilling proved that 61-1 is a one well pool. A second basement oil discovery was made by Gulf at 37-3 which tested up to 60 barrels of oil per day from basement. Neither of the Cabinda discoveries were

Fig. 7. Intensely fractured Precambrian granite in a fracture corridor in the interior of Angola. This potentially would be an excellent basement reservoir (Koning, 2014).

Fig. 8. Precambrian age granitic gneiss in the interior of Angola. Note the vertical and oblique orientation of the fractures which indicates this would be a complicated potential oil-producing reservoir. Note also that it is not intensely fractured like the granite in Fig. 7. Accordingly, this reservoir would be inferior in comparison to the reservoir which outcrops in Fig. 7 (Koning, 2014).

commercial. However, no oil company has deliberately searched in Angola for oil in basement and the basement oil play remains totally under-evaluated.

NORTH AMERICA

CANADA

Canada is the world's four largest oil producer with production of 4.5 million barrels of oil per day. The world's top oil producer is the USA with production of 12.6 million barrels of oil per day, followed by Saudi Arabia at 11.8 million barrels of oil per day, followed by Russia at 11.4 million barrels of oil per day.

In view of Canada having such prolific petroleum geology, it is anomalous that there is no production from basement anywhere in Canada. This may be attributable to the absence in Canada of good oil or gas source rocks overlying basement which would feed oil or gas into basement. In addition, in Canada the basement oil and gas play is poorly understood thus there has never been a deliberate, highly-focused effort to explore for oil and gas in basement. Also, in Saudi Arabia there is no oil or gas production from basement. The absence of basement oil and gas production in Saudi Arabia may be due to the same reasons as in Canada.

CALIFORNIA

The state of California produces currently about 0.5 million barrels of oil per day. This production is almost entirely from Tertiary Miocene age sandstones and conglomerates except for the following fields which produce from basement reservoirs:

1. Playa de Rey Field, Santa Monica area. Production from fractured Jurassic schists.
2. Santa Maria Field, Santa Barbara area. Production from fractured Jurassic sandstone basement.
3. Willmington Field, Long Beach area. Production of 22 million barrels of oil from fractured Jurassic schists.
4. Edison Field, Bakersfield area. Production of 20 million barrels of oil from fractured Jurassic schists.
5. El Segundo Field, western Los Angeles area. Reservoir is fractured Jurassic schist in the west half of the field and fractured Jurassic schist conglomerate in the eastern half with oil tested up to 4,500 barrels of oil per day from the basement at a depth of about 2,150 meters.

KANSAS

Oil is produced in the state of Kansas from the top of fractured Precambrian quartzites which occur in buried hills. The oil source rocks are the overlying Pennsylvanian age shales which also form the cap rock. Kansas has approximately 10 small pools which produced about 150,000 barrels of oil per well. An example is the Orth pool which produced about 1 million barrels of oil from 15 wells.

The production of oil from these small pools is commercially viable since the shallow depth of the basement reservoirs results in modest drilling costs. The area where these basement pools occur is an area with extensive oil production from conventional oil fields and related existing oil production infrastructure including pipelines and oil gathering stations. Accordingly, connecting the basement wells into the existing oil infrastructure is not expensive.

OKLAHOMA

The 15-kilometer diameter Ames structure in northwestern Oklahoma is a meteor impact structure created when a meteor struck in Middle Ordovician time. Oil and gas production is obtained from the brecciated Precambrian granite as well as from the overlying Cambro-Ordovician Arbuckle dolomite.

TEXAS

In northern Texas in the Panhandle-Hugoton area, oil is produced in the Anadarko Basin from fractured Precambrian rocks (Manwaring & Weimer, 1986). These oil pools, including the Apco Field, consist of basement highs which resulted from structural deformation and paleo-weathering. The oil is believed to have migrated from the Devonian Woodford Shale into basement along ubiquitous fractures, and accumulated in open fracture zones associated with faults.

The depth of production averages 1,060 meters. Basement oil production ranges from as low as 1 barrel of oil per day to as high as 700 barrels of oil per day. Drilling within a fault zone does not assure basement production. Other geological factors are equally important to basement oil accumulations and production which includes fault orientation, fracture type, mineralization within the fractures, degree of weathering, basement subcrop elevation, lithology, fault intensity, and proximity to fault-associated fracture zones. Proper drilling methods into basement is equally important as well as appropriate treatment of the basement reservoir during the completion of the well.

SOUTH AMERICA

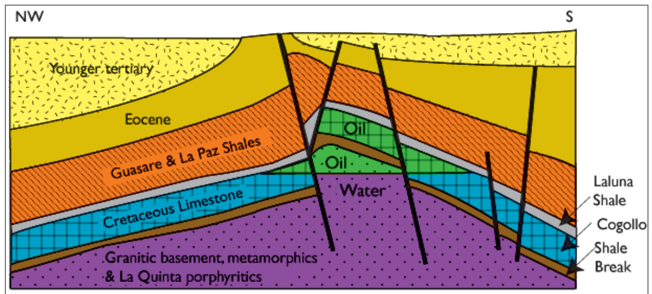
VENEZUELA

The giant-size La Paz oil field is located in the Maracaibo Basin in the interior of Venezuela. The field was discovered in 1944 and up to the year of 1992 has produced 830 million barrels of oil from the La Luna limestones and 325 million barrels from the underlying fractured basement reservoir (Landes et al., 1960, Talukdar et al., 1994, Koning, 2003, Koning, 2018). After the discovery of the field, due to the strong production performance of the La Luna reservoir, the geoscientists and reservoir engineers speculated that the reservoir was obtaining production support from a deeper reservoir. Accordingly, 30 years after the discovery of the field a well was drilled into the underlying basement and discovered the La Paz basement field.

The discovery well produced at a rate of 1,000 barrels of oil per day from the La Luna limestone. Basement wells have had initial production rates of up to 11,500 barrels of oil per day but the average initial production rate is 3,500 barrels of oil per day (Fig. 9).

BRAZIL

The only field in Brazil which has produced oil or gas from basement is the Carmopolis Field in the onshore Sergipe sub-basin. This field has produced oil from Cretaceous sandstones and the underlying basement. The depths of all reservoirs are very shallow, ranging from depths of 400 to 800 meters. The oil gravity ranges from 24 to 30.5 degrees API. Approximately 85 % of the oil production is from the overlying sediments and



Vertical section through the **La Paz field, onshore Venezuela**. Aprox 830 MMbls oil produced from low porosity Cretaceous limestones and 325 MMbls produced from fractured granite basement. Maximum IP of basement wells was 11,500 BOPD average IP of 3,600 BOPD. Average penetration into basement is 500 meters (1,700 feet). Source rock is the Laluna shale which is also the cap rock for the limestone reservoir.

Fig. 9. Vertical section through the La Paz field, onshore Venezuala (Landes et al., 1960, Talukdar & Marcano, 1994, modified by Koning, 2000).

15 % from basement. Approximately 35 million barrels of oil has been produced from basement.

ARGENTINA

The Octogono Field is the only field in Argentina to have produced oil or gas from basement. This field was discovered in 1918 in the onshore Neuquen basin and produced oil from the sediments overlying basement. Deeper drilling almost a century later focused on the basement and resulted in oil discovered in basement which in 2015 provided oil production of 3,000 barrels per day (Velo et al., 2014).

The primary source rock in the Neuquen basin is the organically-rich Vaca Muerta Formation (Spanish for Dead Cow) which is of Late Jurassic to Early Cretaceous in age. In the Octogono Field, the primary basement lithology is Paleozoic granite. All permeability and storage has resulted from fracturing and alteration. Fracturing in basement resulted from the uplift of basement more than 1,000 meters above the ground rocks. Six alteration zones corresponding to differential weathering has been identified.

The recovery factor in basement is estimated at 25 % due to expansion of a 300 meters gas cap. The oil column in basement is 300 meters. The discovery of oil in basement and the ongoing development of the basement reservoir has given new life to the Octogono Field.

EUROPE

It is beyond the scope of this paper to review in detail recent significant successes in Europe exploring for oil and gas in basement. Hurricane Energy, based in the UK, has made significant oil discoveries in the offshore West of Shetlands area. The reservoirs are fractured Precambrian granites. Flow rates of up to 9,800 barrels of oil per day was obtained in 2019 from the Lincoln discovery. The Lancaster Field commenced production in June, 2019 and is producing 17,000 barrels of oil per day from 2 production wells.

In recent years, oil has been discovered in basement in Norway. An example is the Rolvsnes field which will soon be placed on production with the oil being produced from fractured and weathered Precambrian granites.

Best practices for discovering and producing oil from fractured & weathered basement reservoirs

Exploration wells should be drilled highly deviated rather than vertical in order to optimally intersect the dominant fracture system. Production wells should be drilled perpendicular or near-perpendicular to the dominant fracture system.

Highly focused 3 dimensional (3D) seismic such as CGG – Veritas' CBM (Controlled Beam Migration) is needed to define the fracture systems in basement oil & gas fields.

Coring in fractured basement is difficult and not welcomed by the drilling engineers. Nonetheless, extensive core is needed to provide critically important information on the lithologies and reservoir parameters. Some of the cores should also be radiometrically age dated in order for the geoscientists to understand the complexities of the reservoir.

Development wells should be drilled sufficiently deep to fully drain the reservoir. For example, in the La Paz basement oil field, Venezuela, wells are typically drilled 500 meters into basement. In China's Dongshenpu "buried hill" basement field, the oil column is 400 meters thick and development wells typically are drilled through most of the reservoir.

Exploration wells should not just "tag" the top of basement since this will not allow for full evaluation of the basement and could result in an important discovery being "left behind". Indeed, the Suban gas field, South Sumatra was not discovered in the mid 1980's by Caltex (Chevron-Texaco) despite a major exploration program since the wells were drilled through the sedimentary section and then merely tagged into basement. The underlying giant basement gas field (5 trillion cubic feet of gas) was subsequently discovered in 1999 by Gulf Canada and Canada's Talisman Energy by drilling deep into basement.

There are a number of cases worldwide, such as the giant-size La Paz Field in Venezuela where oil in the basement was discovered much later (30 years) in the life of the field with the attention initially focused on producing oil from the overlying sedimentary reservoirs. A second example of this is the Octogono oil field, Neuquen Basin, Argentina which was discovered in 1918 and produced oil from shallow sediments overlying basement. Finally, almost a century later, basement was drilled and evaluated and now provides reserves and production upside. Production in 2015 from basement averaged 3,000 barrels of oil per day and continues to increase and has given a new life to this aging field. The La Paz and Octogono fields highlight that operators of oil & gas fields producing from sediments draped over basement highs should consider drilling a well down into the basement. High resolution 3D seismic will help with defining the best location to optimally intersect the fractured or weathered basement.

Weathered "rotten" granites can also be excellent reservoirs as one can observe in outcrops in tropical areas where heavy rainfall can leach out feldspars and less resistant minerals and leave behind an excellent reservoir. The high mafic minerals in schists, phyllites and slates negates the creation of secondary porosity by weathering. Likewise, granites and quartzites are more likely to produce attractive, highly porous "granite wash" sands whereas eroded schists and gneisses do not produce such good reservoirs.

Geologists, geophysicists, reservoir engineers, and economists must study proven analogues of basement oil and gas fields worldwide in order to fully understand any basement discoveries they are attempting to develop.

Conclusions

In the past, oil and gas fields in basement were discovered mostly by accident. The conventional way of thinking in the past was that basement is mostly tight and did not warrant exploring. However, today there are a few companies who are highly basement-focused and have been especially successful in finding oil in basement. They are SOCO International in Viet Nam & Yemen and Hurricane Exploration in the United Kingdom's West of Shetlands area. Hurricane's recent successes can be viewed as a "basin revival play" for the mature North Sea basin.

Basement reservoirs are very unusual in comparison to conventional sedimentary rock oil and gas reservoirs since the basement reservoirs are in crystalline rocks. Accordingly, to successfully work with basement rocks, a special "mind set" is required which is open to all of the complexities associated with crystalline rocks.

This author believes that significant oil and gas fields remain to be found in Asia, Africa, the Americas and worldwide. Unconventional geological thinking and risk-taking has led to many of the world's major oil and gas discoveries and such strategies will reward the explorers searching for oil and gas in basement.

Understanding basement reservoirs is not only important for oil and gas, but this knowledge is also very relevant to the need to reduce the world's Green House Gases (GHG). Carbon dioxide (CO_2) can be captured an injected into fractured or weathered basement and thereby can be safely and permanently stored. Also, a commodity which is increasingly in short supply in the world is helium. Economic helium is derived from the radioactive decay of uranium and thorium in basement rocks and granite washes. In Canada's province of

Saskatchewan, significant programs have commenced exploring for helium in basement reservoirs.

Lastly, the reader is referred to one of the first papers published on oil and gas in basement which was the classic paper by K.K. Landes et al. in 1960 in which it was states: "*Commercial oil deposits in basement rocks are not geological "accidents" but are oil accumulations which obey all of the rules of oil sourcing, migration and entrapment; therefore in areas of not too deep basement, oil deposits within basement should be explored with the same professional skill and zeal as accumulations in the overlying sediments*".

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Oil and gas possibility of crystalline basement taking into account development in it of non-structural traps of combined type

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Abstract. In this communication, from the perspective of modern views, the following issues are highlighted. A brief overview of the regions – large oil and gas bearing basins, in which hydrocarbon deposits are currently being developed in the deposits of the crystalline basement, is provided. The problems of non-anticline-type collector traps, usually non-structural, combined, widely developed in basement deposits, are considered. The existing characteristic features of oils in deposits from a crystalline basement are voiced. As a result of the study, ever-increasing volumes of world oil production from base sediments were noted, the difficulty of identifying and classifying traps in it, and the almost lack of originality of the composition of oils in the foundation compared with oils in the overlying or adjacent parts of the sedimentary section, are shown.

Keywords: crystalline basement, oil fields, hydrocarbons, combined traps, oil composition, oil and gas potential

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Introduction

The problem of oil and gas content of the crystalline basement has occupied the minds of scientists and manufacturers for the second century, as it has great scientific and economic importance in connection with the focus on increasing the resource base of countries – oil producers. The International Scientific and Practical Conference "Hydrocarbon and Mineral Resources of the Crystalline Basement", held in September 2019 in Kazan, aroused great interest of the scientific community, testifying to the relevance and significance of the stated problems. As noted in the work (Muslimov, Plotnikova, 2019), it was in Tatarstan in the second half of the 70s. after receiving the inflow of deep carbonated highly mineralized liquid from a depth of 5099 m in the well 20,000-Minnibaevskaya, the study of the crystalline basement for its oil content began. Thanks to the staging of broad and comprehensive research, there is a huge scientific and production potential in this region.

Regions and countries with hydrocarbon fluids in the crystalline basement

Recent publications (Gutmanis et al., 2013; Trice, 2014; Koning, 2003, 2019) provide publicly available information on hydrocarbon reservoirs (HC) in fractured crystalline formations and their resources from about 30 countries. The deposits of the crystalline basement are large oil and gas reservoirs in various parts of the world.

In South America, basement fields are being developed in Venezuela and Brazil. In North Africa, the extraction of oil and gas from the basement is carried out in Morocco, Libya, Algeria and Egypt. Significant reserves in the basement ledges are known in Russia (the oil and gas basin of Western Siberia), as well as in China. In the USA, the most significant hydrocarbon production from the basement includes a number of areas: California (Wilmington and Edison), Kansas (Eldorado and Orth) and Texas (Apco). In Southeast Asia, Viet Nam is the main source of oil production. The recent large discovery of gas in Tertiary fractured granites in the south of Sumatra led to active exploration of basement deposits in Indonesia.

Although basement fields have been exploited for many decades, since the mid-90s., interest in their development has particularly increased due to a number of cumulative factors. These include: the momentum gained from major discoveries in Viet Nam and Yemen; the emergence of modern borehole tools (especially borehole logging images and acoustic logging), new seismic methods (for example, shear wave seismic attributes) and complex drilling methods. The increase in oil prices also contributed to the reassessment of those drilling projects on the basement that were previously considered high-capacity or uneconomical.

Oil and gas accumulations in the basement are open in deposits with a significant oil-bearing floor and are not always in the roof of the basement. So, in the Hugoton-Penhandle field (USA), oil comes from weathered granites from the interval 458-1068 m, in La Paz field (Venezuela) – from fractured basement rocks in the depth interval 1615-3350 m. The thickness of oil-saturated in the Auguila-Naafora field parts of the basement is 450 m, in Zeit Bay – 330 m, in Oymash – the interval of oil-saturated basement is 3612-3850 m, on the White Tiger field the oil content of the granitoids of the basement is about 2000 m (3050-5000 m) (Shuster, 2003). Koning (2019) presents several orthodox cases of world practice when fields in the basement are discovered many years after the discovery and long-term operation of the sedimentary stratum of the basin. For example, there is a giant La Paz field in Venezuela, in which the oil in the basement was discovered much later (after 30 years) of exploitation and production from overlying sedimentary deposits. Now, taking into account the basement, the maximum production is 11500 bbl/d, and the initial production averaged 3600 bbl/d. Similar developments occurred in the Octongo oil field in the Nequen River Basin in Argentina, which was discovered in 1918 in sedimentary deposits lying above the basement. The second life of the field began only at the end of the last century. The oil was obtained from the basement, the production of which averaged 3000 bbl/d.

The most famous examples of successful development of reservoirs in the basement are the coastal areas of Viet Nam, where the Cuu Long basin accounts for 95 % of hydrocarbon production in the country, and 85 % of this value falls on the fractured granite basement. Marib Al Jawf has large reserves of the West Yemen oil and gas basin. The development of chalk sand formations at the Kharir field began by SOCO in 2004, and already in 2005 Hunt Oil successfully continued the production of hydrocarbon fluids from basement rocks. Four drilled wells on the basement (depths up to 3383 m) showed high results (up to 6500 bbl/d). Other important discoveries were made in Argentina at the Cuyo and Neuquen fields. Hydrocarbon fluids here are obtained from destroyed Permian-Triassic volcanic rocks (up to 11,000 bbl/d) (Gutmanis et al., 2013; Koning, 2003).

Type of traps prevailing in crystalline basement fields

Assessing the prospects of oil and gas potential is impossible without studying the formation and structure of traps. As world practice in oil and gas exploration shows, combined traps account for almost 5 times more deposits than reservoirs – HC reservoirs controlled by one leading factor (lithological, stratigraphic, tectonic, geodynamic, hydrogeological, etc.). The importance of assessing the nature (type) of traps and their prospects in terms of resources is evidenced by long-term studies conducted by a group of specialists (Dolson et al., 2018). The authors show the importance of discovering deposits in the world reserves of hydrocarbons with traps of various origins: combined, stratigraphic, structural. Moreover, the traps named as “unknown” are allocated to a special type, which has not yet found a classification term. Most likely, we mean “traps” of shale formations, clinoform structures, as well as traps in the protrusions of the crystalline basement, if, as a result of weathering, the latter serve as a reservoir of hydrocarbons.

The basis of the methodology for searching for oil and gas deposits in complex traps is the interpretation of the seismic data of the CDP performed in accordance with modern requirements of geological exploration in conjunction with drilling materials, and well logging based on seismic and geological analysis. When searching and exploring oil and gas deposits in traps of a complexly shielded type, including a non-anticlinal structure, the combination of geological and geophysical methods and the rational sequence of their application is not less, but, apparently, even more important than when searching for structural objects. Prediction and subsequent discovery of hydrocarbon deposits in traps of the type under consideration is a more laborious scientific search, during which all available geological and geophysical materials are used and generalized from a certain angle. High-resolution three-dimensional seismic survey helps determine the best location for the optimal intersection of fractured or weathered basement rocks (Krupin, Rykus, 2011; Oknova, 2012; Petroleum Geology..., 2018).

For a long time, when setting up exploration work of the reservoir in the basement rocks, they were underestimated. However, in various regions of the world, accumulations of oil and gas in the rocks of the basement are open and industrially developed. HC accumulate in intrusive, effusive, metamorphic and cataclastic rocks of the basement with secondary porosity. Cataclasites (associated with rock faults that are formed during brittle deformations at high pressure values) have high secondary porosity. The formation of cataclasites plays an important role in the total secondary porosity of deformed base rocks. The presence of oil and gas reservoirs in metamorphic and igneous rocks is a universally recognized fact; obviously, the time has come to consider cataclastic rocks as reservoirs when setting up exploration work (Morariu, 2012).

According to a number of researchers (Dmitrievskii et al., 2012), based on a detailed study of the hydrocarbon deposits of the Viet Namese shelf, a differential pressure is created as a result of heat shrinkage processes, which ensures that micro-oil from overlapping sedimentary rocks is drawn into the cooling intrusion. Active fluid dynamic processes lead to the formation of additional capacity throughout the entire volume of the granite intrusion and the accumulation of hydrocarbon fluids within it. The influence of deep fluids provokes not only the formation of voids, caverns and cracks, but also a drastic change in the structure of granitoids with the formation of a crumbling substrate. Oil production in such zones reaches 2 thousand tons/day (Shuster, 2003).

Figure 1 shows the trend in the reservoir properties of granitoids at the White Tiger field, which indicates that with this type of fracturing and with a decrease in porosity, the permeability of the reservoir remains almost constant with depth and quite high (Huy et al., 2012).

Here are some examples of the structure of hydrocarbon fields in the crystalline basement, indicating the complexity and combination of trap types (Fig. 2, 3).

Oimash field is located in the Karakiy district of the Mangistau region and is located 50 km from the city of Aktau (Republic of Kazakhstan). The field was discovered in 1980, and in January 1981, the industrial oil and gas potential of granite intrusion was established. The first inflow of oil from granites with a flow rate of 248 m^3/day through 9 mm nozzle was obtained in well 12 from the interval 3720-3773 m. Metamorphic and igneous rocks of the Paleozoic age basement and Meso-Cenozoic sediments of a platform cover with a maximum thickness of 4450 m were discovered by deep drilling. Hydrocarbon accumulations in massive fissure-cavernous igneous and metamorphic rocks are, as a rule, confined to buried ledges of the basement, broken by faults into blocks and covered by metamorphic or sedimentary rocks. Based on the results of testing, 4 deposits were identified, of which three were oil and one gas-oil. Industrial oil and gas potential has been identified in the Lower Jurassic, Middle Triassic, Paleozoic host rocks and granite intrusion (Krupin, Rykus, 2011). The main oil reserves are associated with Paleozoic granitoids (Fig. 2).

According to (Krupin, Rykus, 2011), processes of different tectonic intensities, which appeared in several stages during the Mesozoic geological history of the region, are of great importance in the implementation of capacitive properties at the Oymash field. They affect all types of rocks of the Early Mesozoic and Paleozoic granite intrusions, creating in them differently oriented discontinuous disturbances, zones of fracturing, cataclase and milonitization.

The Lankaster field, discovered in 2009 on the shelf of Western Scotland (water level 160 m) at a basement depth of 1,220 m, had reserves of up to 25 million barrels of oil. Rising up to 8000 bbl/d in 2017, a message appeared about the discovery by Hurricane Energy of another major field on the shelf of the North Sea off the coast of the UK (Halifax structure), whose reserves are estimated at up to 1 billion barrels of oil. Hurricane Energy believes that Halifax and Lancaster are two parts of the same giant oil basin. The structure of oil reservoirs – complex combined traps, is shown in Fig. 3.

Figure 4 shows the distribution model of the Fault zone grid and Weathered interval over tonalites/granodiorites of the acid igneous rock family (Tonalite/Granodiorite) with explanations needed when planning exploration wells taking into account the model of fault zones (Trice, 2014)

Geochemical features of hydrocarbon fluids in basement fields

The main source of oil in the fields of the crystalline basement is the organic matter (OM) of the oil source sedimentary strata encircling the ledges of the basement, which is recognized by most researchers dealing with the problem of hydrocarbon accumulations in the basement. That is why the geochemical features of the

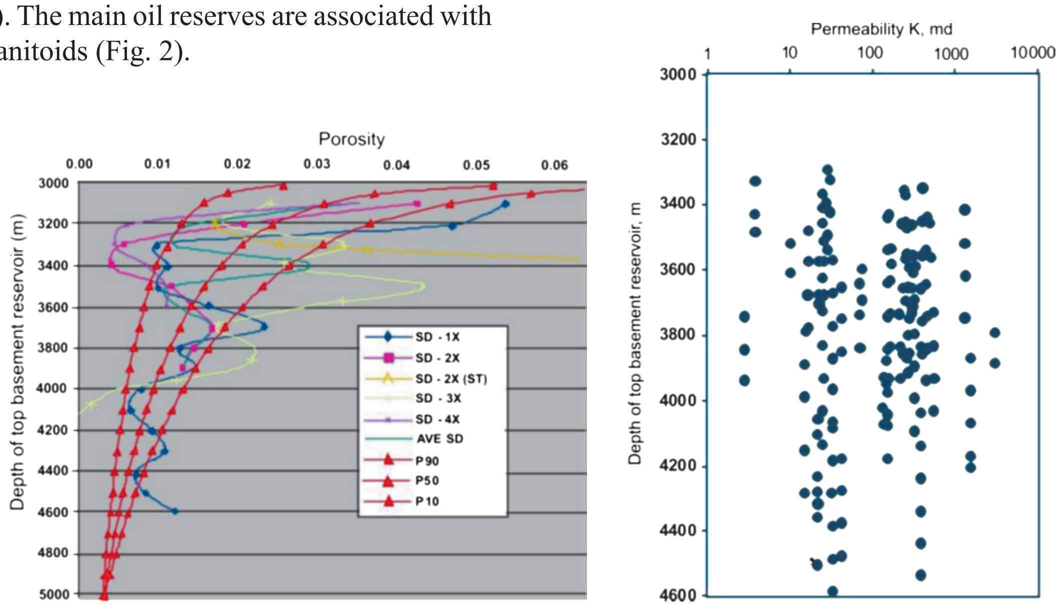

Fig. 1. Change in porosity and permeability of basement rocks in different wells with depth at the White Tiger field (Huy et al., 2012)

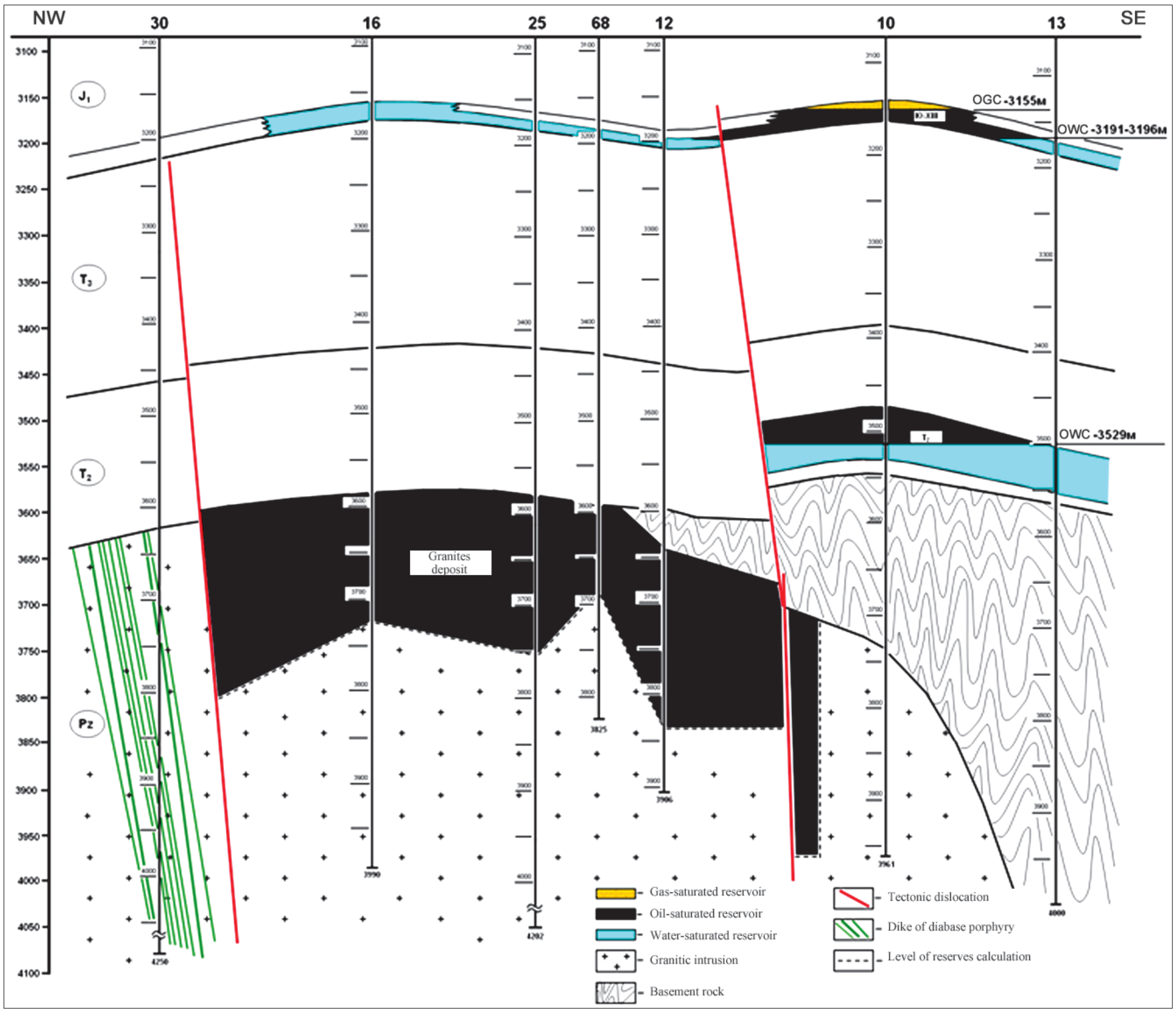

Fig. 2. Oimash field, geological profile along the well line 30-25-12-10-13 (Krupin, Rykus, 2011)

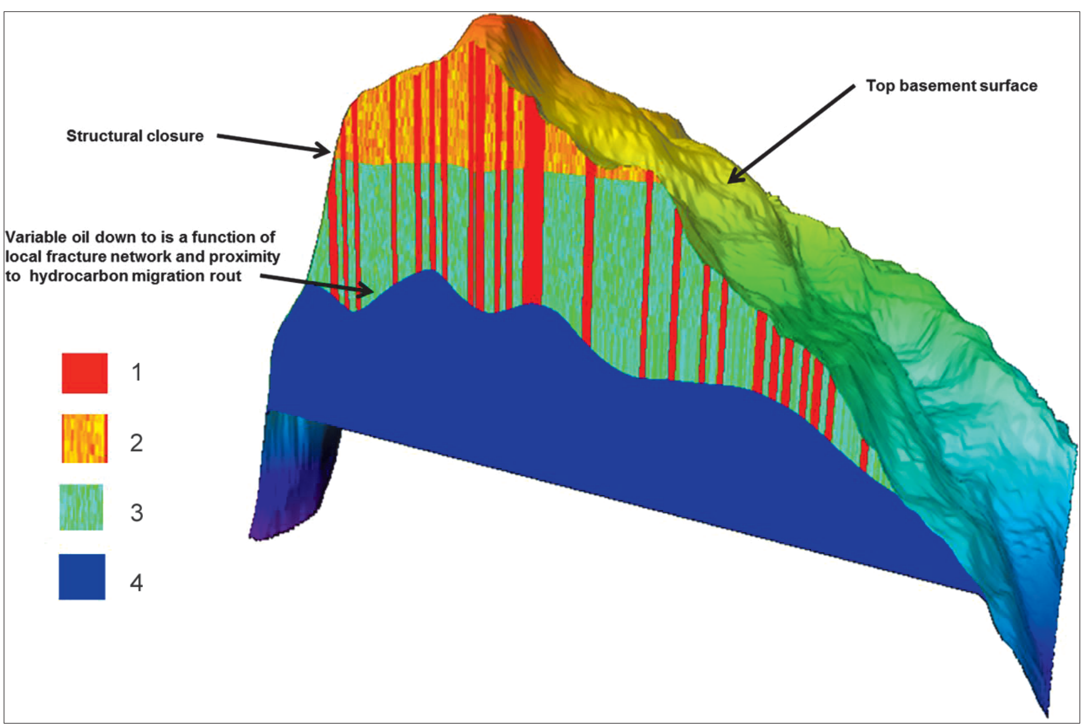

Fig. 3. A volumetric conceptual 3D model of the reservoir of the Lankaster field, constructed through the crest of a crystalline array, depicting the distribution of fluids in a reservoir-trap (Trice, 2014). 1 – fault zone in an oil-saturated formation; 2 – predominantly oil-saturated formation (pseudomatrix in the circuit structure); 3 – reservoir with highly variable water saturation; 4 – water-saturated layer (pseudomatrix outside the circuit structure).

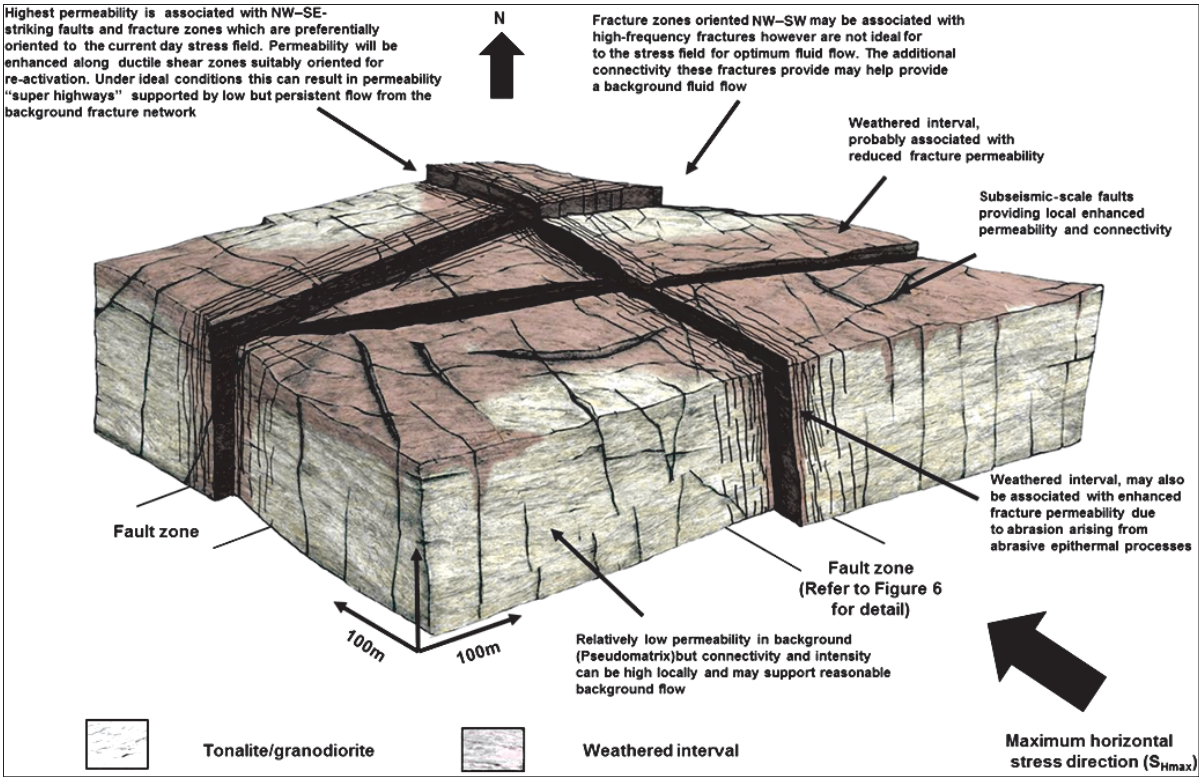

Fig. 4. A conceptual model of a fracture network in the Lankaster field (Trice, 2014)

fluids of the basement fields obey the same laws as the oils occurring in the sedimentary strata of oil and gas basins. In the sedimentary section of the Earth's crust, according to the vertical evolutionary zonality of the formation and transformation of hydrocarbons associated with an increase in depth, temperature gradient, pressure and type of source organics, the composition of the hydrocarbon systems generated in the bowels is transformed – from heavy oils to light and condensates. Their characteristic features are associated with the processes of ontogenesis. Oils contain clear traces of the initial OM, which generated this oil.

According to (Karimov et al., 2019), in the Kyulong basin of Viet Nam, through the contact of the protrusive granites of the pre-Cenozoic basement with the Cenozoic sedimentary cover, there was a lateral migration of fluids from the oil source strata of the Oligocene age to the base – into voids and zones of increased fracture (Fig. 5), into formed fractured-cavernous reservoir of an unconventional trap of a combined type.

The oils from the deposits in the basement and in the Lower Oligocene at the White Tiger field are characterized by close values of almost all the studied hydrocarbon parameters, which correspond to the oils of the mesocatagenesis zone. Such proximity is indicated in many works (Shuster, 2003; Dmitrievskii et al., 2012; Serebrennikova et al., 2012; Punanova et al., 2018, and others). The molecular mass distribution of n-alkanes indicates the generation of oils by organic matter containing coastal algae or land plants; the conditions for its sedimentation are suboxidative. Biomarker

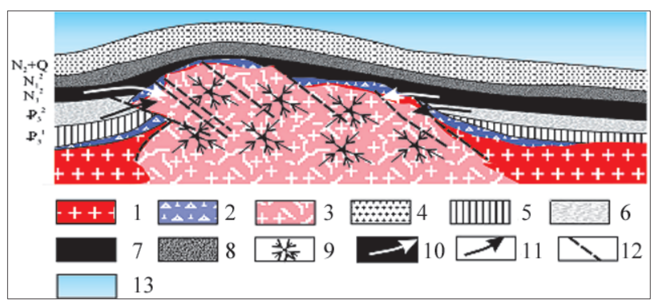

Fig. 5. A fragment of the model for the formation of oil deposits in the granite arrays of the Kyulong basin (present) (Kerimov et al., 2019). 1 – basement; 2 – area of disintegrated granites (protrusion); 3 – weathering zone; 4– Pliocene quarter; 5 – zone of overripe OM; 6 – the main zone of gas formation; 7 – the main zone of oil formation; 8 – zone of immature OM; 9 – conditional areas of hydrocarbon accumulation; 10-11 – the direction of movement of hydrocarbons: 10 – gas phase, 11 – liquid phase; 12 – breaks; 13 – water layer.

parameters confirm the maturity of these fluids. The sedimentary Oligocene and base oil are also close in Trace Element (TE) characteristics (determined by the Dalat Institute for Nuclear Research, Viet Nam): they have low concentrations of V and Ni (0.14 and 3.5 g/t in the basement, and 0.10 in the Lower Oligocene and 2.2 g/t), and in the predominance of Ni (V/Ni <1) they form the nickel type of metallogeny (Fig. 6).

Close results were obtained in detailed geochemical studies (Mosca et al., 2019) conducted in the Cuu Long and Nam Con Son basins (Viet Nam). Data on carbon isotopes in oils and extracts from organic matter indicate a non-marine sedimentation environment. The stage

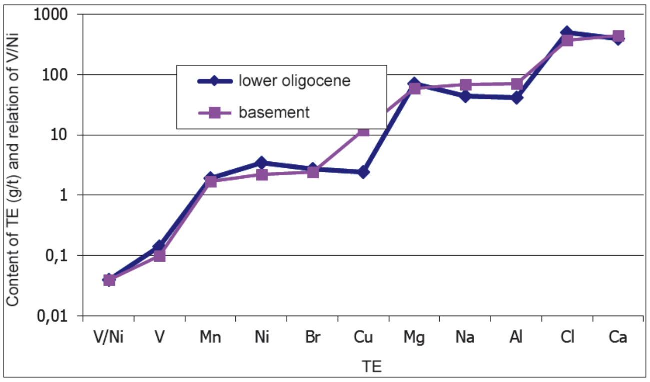

Fig. 6. The content of TE in oils of the White Tiger field

of oil maturation corresponds to the mesocatagenetic stage (refractive index R_0 = 0.78-0.84 %). An analysis of biomarkers based on C_{27}-C_{28}-C_{29} steranes, a high ratio of tricyclic terpanes C_{26}/C_{25}> 1 and a low ratio of C_{29}/C_{30} <1 for hopanes in OM, typical of lake sediments, similar to the distribution of these hydrocarbons in the oils of the Cuu Long basin, confirms them of lake origin and connection with hydrocarbon generation by sedimentary strata of the Oligocene and Miocene. The predominance of light HC together with a very high ratio of pristane/phytane (7-14) is consistent with the generation of oils from OM deposited in an acidic medium. In addition, the content of small amounts of tricyclic terpanes, in significant homogopans (up to C_{33}), the dominance of C_{29} steranes over C_{27} indicates the contribution of terrestrial OM.

At great depths, with active tectonic processes, an additional supply of hydrocarbon fluids containing increased concentrations of light compounds (from C_5 to C_{13}), usually more catagenically transformed (Mosca et al., 2019), can be observed. This is quite clearly confirmed by the data on the Trace Element composition of naphthides, which are characterized by a set of more migratory capable elements (As, Hg, Eu, La, Nb) with respect to V, Ni, Mo, Co and the nickel specialization (Punanova, Rodkin, 2019).

An interesting area for determining the origin of hydrocarbons in the structures of the pre-Jurassic basement of the West Siberian oil and gas basin is the Rogozhnikovsky group of fields of the Krasnoleninsky arch with a Permian-Triassic rock complex at the base. About 100 wells have been drilled here, opening more than 10 km of pre-Jurassic rocks, and almost 30 % of them are reservoirs. The source of oil in this complex can be both the Lower Jurassic oil source Togurian pack and the Late Paleozoic sedimentary deposits. The work (Korzhov et al., 2013) presents the results of experimental studies on the feasibility of interlayer migration of oil hydrocarbons in the near-contact zones of the basement and cover based on the determination of the most migratory saturated hydrocarbons in the rocks of productive Jurassic and Pre-Jurassic sediments of the CP765 North Rogozhnikovskaya well. To clarify the lithological conditions of inter-layer migration of hydrocarbons and the possibility of deep “recharge” of deposits, a detailed lithological-petrographic description of core material was performed. The authors concluded that the oil deposits in the Triassic rocks of the weathering crust were formed as a result of the inflow of hydrocarbons from the lower parts of the Tyumen Formation. The content and molecular mass distribution of saturated hydrocarbons are evidence of inter-layer movements of Jurassic oils into the reservoirs of the weathering crust and basement. Based on the analysis of geological and geochemical indicators, a number of researchers also believe that the oils of the Jurassic and Pre-Jurassic complexes (the zone of contact between the basement and the cover) in the Shirotniy Priobye, Shaimsky, Krasnoleninsky, Khanty-Mansiysk regions of the West Siberian oil and gas basin form a physicochemical characteristic close to hydrocarbon composition group with a single fluid dynamic system and a common focus of oil and gas formation. Only Jurassic deposits are recognized as oil deposits. At the Tolumsky field of the Shaimsky district, it is assumed that the formation of deposits in the upper part of the Paleozoic complex and the Vogulka layers of the Jurassic (1800-2000 m) occurs due to the migration of hydrocarbons from the Upper Jurassic deposits, in particular, the Mulimyinsky suite, which is the oil source. The results of geochemical studies of oil from the Rogozhnikovsky field in the upper part of the Triassic effusive rocks (Turin series, depth interval 2568-2607 m) in the Krasnoleninsky arch indicate that the main source of the pre-Jurassic oils could be clays of the Sherkalinsky Formation of the Lower Jurassic, which have significant generation potential (Korzhov et al., 2013; Punanova, Shuster, 2012, 2018; Shuster, Punanova, 2016; Shuster et al., 2011).

The geochemical characteristics of the oils when they occur in the erosion protrusions of the crystalline basement are different, however, the genetic proximity of the oils from the basement and from sedimentary deposits also appears here. Under these conditions, oil forms in the hypergenesis zone. And a striking example is the oil accumulations of the Mara and Western Mara deposits (Venezuela) (Punanova, 2014; López, Lo Mónaco, 2017). The density of oils reaches 0.991 g/cm^3, sulfur content – 5.54 %, asphaltenes – 18 %. The oils of the Western Mara region (erosive crystalline ledge) are classified as very heavy, with very high sulfur contents (5.6-6.2 %), enriched due to chemical weathering and loss of light fractions with trace elements with industrial concentrations (in g/t) of V (954-999) and Ni (91-96). The oils of the Mara region are medium-heavy, with a lower sulfur content (2.5-3.0 %), V (206-260) and Ni (14-24) (Fig. 7).

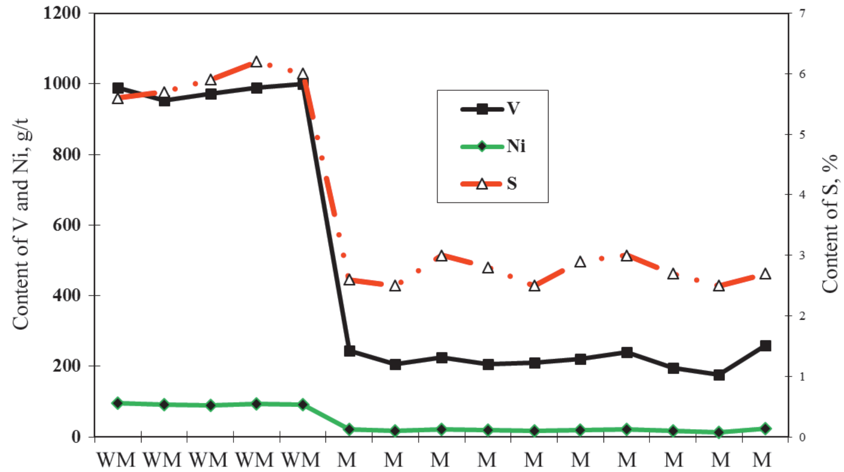

Fig. 7. Changes in the content of vanadium, nickel and sulfur in the oils of the deposits of Venezuela Western Mara (WM) and Mara (M) (according to analytical data (López, Lo Mónaco, 2017))

Geochemical data on the content of biomarkers (López, Lo Mónaco, 2017) indicate that the oils of both regions are genetically unified, are associated with the marine type of the initial OM and are generated by the oil source layer of the La Luna formation (analogous to Domanica), and the observed differences in physicochemical properties and the content of elements are explained by biodegradation processes, which manifested themselves on a large scale in the Western Mara area.

Afterword

It is worth recognizing that the naturally destroyed crystalline rocks of the basement are a global geological phenomenon. Despite proven commercial success, the delay in the implementation of many projects stemmed from the fact that the discovery of hydrocarbon deposits in the basement historically occurred rather by accident, than as a result of targeted exploration programs. Nevertheless, in recent years there has been a successful change in this trend, which leads to numerous discoveries and an increase in the number of developments in the basement.

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DISCUSSION ARTICLE

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Mixgenetic concept of of oil and gas fields formation in basement and sedimentary cover on the shelf of South Vietnam

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Abstract. According to the geodynamic model of oil and gas formation, the most favorable conditions for the oil and gas fields are formed in the mobile zones of the Earth's crust, especially in areas of active continental margins, characterized by high seismicity, the presence of deep faults, the development of subduction and riftogenic processes. Therefore, it is logical that most of the world's oil and gas deposits are concentrated in rifts or in the vicinity of paleo- and modern subduction zones.

The study of the unique oil deposits in the granite basement of the White Tiger field, using data from other fields in the world, allows concluding that the formation of oil deposits in the basement can occur not only due to the resources of adjacent oil and gas deposits.

Taking into account modern geodynamic ideas, in the context of the Earth's internal geospheres, at least three oil generation zones can be distinguished: mantle-asthenospheric abiogenic synthesis; subduction-dissipative biomineral synthesis; stratospheric-biogenic synthesis.

Obviously, all these three zones, as a single open system for the generation of hydrocarbons, will be interconnected only in conditions of deep faults, active continental margins and other parts of the Earth's crust. This suggests that there are deep generation zones, which are currently fueling the developed fields.

Keywords: subduction, riftogenic processes, geodynamics, granitoid basement, Earth's crust, deep faults

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In the geodynamic model of oil and gas formation developed in recent years, three of the most favorable geodynamic regimes are distinguished for this process: rift, subduction, and stratiform.

The combination of these modes found its unique embodiment on the continental shelf of South Vietnam, where a close spatial relationship of oil and gas fields with rifts and subduction zones is traced (Utoplennikov et al., 2005; Areshev et al., 1996a, 1996b; Areshev et al., 2001)

The formation of the geological main features and the development history of the southeastern outskirts of the Asia-Pacific region is due to the interaction of three megalithospheric plates: Eurasian, Indo-Australian and Pacific.

In the southeastern part of the Eurasian Plate, the shallow Sunda shelf and the deep-water Philippine Plate stand out in the convergence zone of these megaplates and are, in fact, a system of paleo- and modern subduction zones and rifts (Fig. 1).

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The widespread development of rifts is a characteristic feature of the continental shelf of Vietnam.

Within the southern shelf, the structural reflection of these processes was the formation of the South Konshonsky, Mekong, Malay, West Natunsky and other rifts. Their structure is complicated by internal uplifts – buried oblique blocks limited by oncoming fall faults in the pre-Cenozoic crystalline basement – the White Tiger, Dragon, Sea Turtle, Conchon, and others, which are collision zones of paleosubduction. In the interblock depressions, the accumulation of terrigenous sedimentary, including oil source strata, was represented by layers of dark gray and black mudstones of the Lower Oligocene.

Strong tectonic fracturing and variability in the secondary processes of the basement and sedimentary cover rocks have contributed to the formation of hydrocarbon (HC) accumulations in them, which migrated into the host sedimentary rocks (Areshev et al., 1996c). This was especially pronounced in the Mekong (Cuu Long) rift basin, in which the ledges of the basement are characterized by a large volume of oil-saturated granites (White Tiger, Dragon, Black Lion deposits) and others, with oil and gas levels up to 2000 m (Fig. 2).

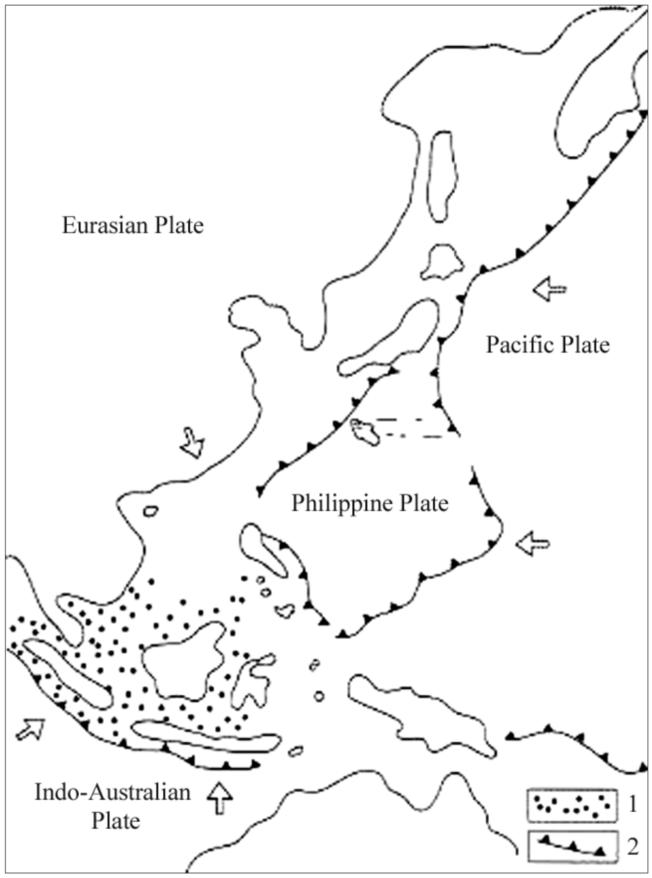

Fig. 1. The position of the plates in Southeast Asia and the northwestern part of the Pacific Ocean: 1 – Sunda shelf; 2 – subduction zones, arrows indicate the direction of tectonophysical stresses (Park, 1993).

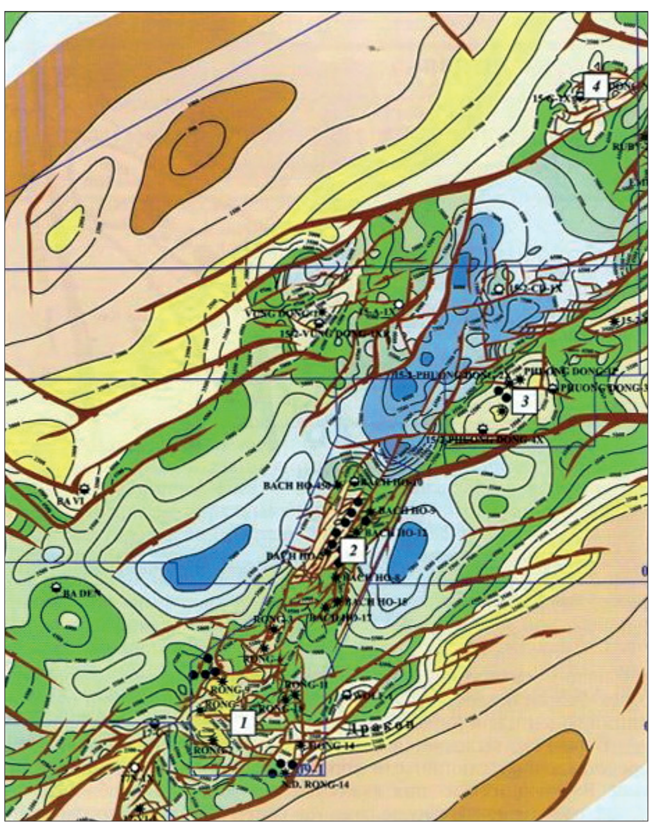

Fig. 2. The layout of oil and gas fields in the Cuu Long basin: 1 – Dragon; 2 – White Tiger; 3 – Rang Dong; 4 – Black Lion.

The large oil reserves identified in the granitoid protrusions of the crystalline basement on the southern shelf of Vietnam suggest that the formation of oil fields was not only due to the oil resources of the Oligocene deposits. An additional source of hydrocarbons could be the organic matter of oceanic crust sediments, which are drawn into the mantle in the zones of subduction of lithospheric plates during subduction processes.

In the upper rear parts of the deepening lithospheric plates, where the crust heating is still relatively small, a temperature regime is created favorable for the sublimation and thermolysis of organics located in the sediments of the movable plate. At this stage, sedimentary rocks are almost completely freed from nutrients, and droplet-forming oil and thermal gas are formed. Together with thermal waters, abundantly contained in oceanic sediments, under the influence of superhydrostatic pressures, hydrocarbons were unloaded in the marginal parts of the continental crust and in the bowels of accretionary prisms.

In subduction zones, favorable conditions are also created for inorganic oil synthesis. The components necessary for the formation of synthetic oil are abundantly found in submantle crust zones.

A significant part of them is represented by carbon dioxide and water, which are extracted from sinking sedimentary rocks and feed the upper layer of the mantle. In addition, the deep zones of the Earth are enriched with CO, CO_2, CH_4, H_2, on the basis of which, as is commonly believed, natural synthesis of oil is possible. It is necessary, first of all, to allocate CH_4 and H_2, which make up a large part of the deep fluid gases and ensure their reducing character.

According to (Gold, 1986), methane in the bowels of the Earth at high pressures behaves like a liquid. It is a good solvent and is therefore able to tolerate heavier hydrocarbons, organometallic compounds and trace elements, which are then deposited at relatively shallow depths due to pressure drop.

As they move toward the Earth's crust, reducing deep fluids are enriched with components from mantle rocks, including metals such as Fe, Ti, Ni, Co, Cr, capable of playing the role of catalysts or being their component (Lurie et al., 2003).

An indication of the mantle methane-hydrogen reducing fluid used to transfer ore elements to the upper horizons of the lithosphere can be found in the presence of native zinc copper (native brass) in the granites of the basement of the White Tiger deposit (Dmitrievskii et al., 1992). Silver-barite mineralization was also noted there.

Findings of native brass associated with sponge gold and native chromium in mineralized crushing zones of igneous rocks in Yakutia are associated with the flows of deep reducing fluids of methane-hydrogen composition coming through a system of tectonic disturbances. It is characteristic that the polytype modification of gold found in association with zinc in Yakutia corresponds in structure to the gold phase obtained by laboratory tests in a stream of hydrogen at a temperature of about 600 °C (Khodyrev et al., 1985). Thus, it can be assumed that the methane-hydrogen stream in the basement of the White Tiger already existed at the high-temperature pneumatolytic stage of the development of the granitoid array. In addition to the above, we also note that the formation of native gold, silver, zinc, aluminum, and iron was discovered in Kamchatka in the modern ore-forming hydrothermal system Uzon, in the thermal fields of which oil leaching is observed (Karpov et al., 1985). Here, native metals arrived with deep fluid flows through a system of steeply falling tectonic disturbances that inherited the zone of a deep fault.

As is known, various metals are used as catalysts for industrial inorganic synthesis of hydrocarbons, primarily Fe, Ni, and Co. Under natural conditions, Fe-Mn-containing silicates, aluminosilicates, and ore minerals can be natural catalysts. According to (Rudenko, Kulakova, 1986), "almost all rocks with a silicate and aluminosilicate composition and containing heavy metal oxides even in low concentrations have sufficient catalytic activity for polycondensation processes". This is also indicated by M.I. Novgorodova (Novgorodova, 1986), assuming that in a medium where CO, CH_4, H_2, H_2O are present, at temperatures of 250-450 °C, hydrocarbon synthesis is possible under the catalytic effect of ore minerals, mainly magnetite and finely divided layered aluminosilicates (mica, chlorites clay minerals).

Among the various ways of synthesizing hydrocarbon mixtures, the possibility of using bifunctional catalytic systems including, in addition to the metal component, aluminosilicate catalysts of acid-base action – clays and zeolites (Ione, 2000) is also indicated. It was shown that in the presence of metal oxide systems mixed with clays, SiO_2, Al_2O_3 and zeolites at 220-450 °C and pressures from 1 to 100 atm, HC synthesis with a wide variation in the content of naphthenes, iso-paraffins and aromatic compounds in their composition is possible (Ione, 2000).

Thus, the above suggests that under natural conditions the most active process of the catalytic synthesis of hydrocarbons at elevated pressures and temperatures can occur in rocks with a high content of minerals – aluminosilicates and silica, acting as catalysts in the reaction of inorganic components of gas: carbon monoxide, hydrogen and methane.

Such rocks, represented mainly by granitoids, compose almost the entire granite shell of the Earth's crust (before the seismic section of Konrad).

Hydrocarbon gases, penetrating the faults and weakened zones into the upper horizons of the lithosphere, have filled the fractured-pore space of the rocks of the Earth's crust. Approximately at depths of 3-10 km, where the temperature and geobaric conditions are most favorable for the formation of oil, its synthesis took place.

Analysis of gas-liquid inclusions in the basement rocks of the White Tiger field showed the presence in the bubble voids of minerals, in closed pores and microcracks of both light and heavy hydrocarbons up to hexane, which indicates the oil nature of the gases. In some quartz grains in granites, inclusions of gasoline fractions are noted, but hydrogen and methane are predominant (Table 1)

Under the microscope, traces of oil are observed in microcracks, small pores, kaolinized feldspar crystals, in cleavage cracks of biotite, and in clusters of fine crystalline zeolite-lomontite (Fig. 3).

It is obvious that the aluminosilicate minerals composing granitoids played the role of natural catalysts here. Secondary changes in minerals that occurred under the influence of auto-metasomatic processes contributed to a more active manifestation of their catalytic properties.

As is known, in heterogeneous catalysis, the activity of the catalyst depends on the size and properties of its surface, i.e. the catalyst must have a porous structure or be in a highly dispersed state. In granitoids, for example, epimagmatic kaolinite $A_{14}[Si_4O_{10}](OH)_8$, which aggregates provide highly dispersed contact with the reacting substance, corresponds to feldspars. It should be noted that Ti, which is invariably present in a small amount in igneous rocks, is a good activator for Al-Si catalysts.

It forms not only independent minerals (sphene, sagenite, etc.), but also freely integrates into the structural positions of the crystal lattices of layered silicates, isomorphically replacing Si in silicon-oxygen tetrahedra, which enhances the action of titanium as an activator.

Comparison of the compositions of mobile oil from the reservoir zones of oil-saturated granitoids at the White Tiger field with hydrocarbon substances from a dense low-permeability matrix showed that their bitumen differ in the composition of paraffins and biomarkers, while the matrix bitumen are less mature. Apparently, the limited amount of microvoids in the rock matrix did not show the full potential of the hydrocarbon fluids contained in them, their resource was exhausted and the isomerization process did not proceed further.

There is a vertical zoning in the oil distribution at the White Tiger field: relatively light and almost identical oils in the basement and in the Lower Oligocene terrigenous complex and medium oils in the Upper Oligocene and Lower Miocene deposits. This fact, apparently, can be explained by the fact that, in contrast to geologically isolated oils in sedimentary rocks of the Upper Oligocene and Lower Miocene, base oils and Lower Oligocene deposits are associated with a deep source of oil fluids characterized by a lower density.

It can be assumed that such a deep source is represented by at least two reaction zones: the mantle-asthenospheric and subduction-dissipative.

The mantle-asthenospheric oil generation zone is located in the thermobaric conditions of the warmed upper mantle (asthenospheric protrusion) and submantle subcrustal zones. Thermodynamic calculations and

H_2 cm^3/kg	CH_4 cm^3/kg	C_2 - C_6 cm^3/kg	Total all gas-liquid inclusions cm^3/kg	CH_4	i C_4	i C_5
				$C_2 \div C_6$	n C_4	n C_5
9,8 (46)*	20,8 (46)	8,0 (46)	38,7 (46)	9,6 (46)	2,3 (21)	1,0 (44)
1,9-20,2	0,2-140,5	0,1-82,4	6,2-210,4	0,6-25,2	0,7-15,3	0,2-5,0

*Table 1. The composition of gas-liquid inclusions in granitoid rocks of the basement of the White Tiger field (CPB). * The numerator indicates the average content and the number of analyzes (in brackets), the denominator – the spread of values.*

Fig. 3. Granite. Dark brown bitumen in the leaching pores in plagioclase. Increase × 40 Nicoli + Depth 4307 m, Well BT 448.

experimental data show that the synthesis of petroleum hydrocarbons is already possible at temperatures of 700-1100 °C (Ione, 2000; Rudenko, Kulakova, 1986). It was shown that the geostatic pressure corresponding to such temperatures not only inhibits the thermal destruction of hydrocarbon systems, but also stimulates the polymerization and synthesis of hydrocarbons (Kropotkin, 1986).

If at temperatures above 1000 °C there is a mostly unstable equilibrium mixture of CH_3 and H radicals, then at the turn of 700 °C a stable state of CH_4 radicals is achieved, paraffins and light gasoline fractions are formed.

Thus, in the mantle-asthenospheric zone, the initial stage of oil radicals' generation and the abiogenic synthesis of predominantly light oil systems are carried out.

Under the influence of global geodynamic processes, expressed in the lithospheric shell of the Earth's crust in the form of deep faults, cracks, subduction zones, etc., favorable macrokinetic conditions were created for emanational degassing of the Earth's interior. At the same time, a powerful halo of invasion of asthenospheric petroleum hydrocarbons arose, which, together with a methane-hydrogen stream, rushed under great pressure into the upper horizons of the lithosphere.

A subduction-dissipative oil generation zone is formed in the Zavaritsky-Benioff zone when the oceanic crust submerges beneath the continental crust. In this case, due to the dissipation of viscous friction energy, the subducting crust can be heated up to 1000 °C and more. This heat is sufficient for the palingenic processes, i.e. partial remelting of the solid substance of the crust or its transformation into a visco-plastic state. However, at the initial stage of deepening to 10-12 km, the crust warming up is still relatively small and there are areas with a temperature regime of 150-450 °C, which is favorable for thermolysis and sublimation of nutrients, which are dragged along with oceanic sediments into the sub-zone.

In the same areas, under conditions of high warming and pressure, not only the processes of organic matter transformation into hydrocarbons of the oil series occur, but also mineral abiogenic synthesis of oil is carried out with the catalytic participation of aluminosilicates and ore minerals that make up the rocks of the sialite crust.

Both primary hydrocarbon fluids and products of deep mineral oil synthesis flowing from the asthenospheric foci of the upper mantle also passed through the subduction zone of oil generation.

The active geodynamic situation that existed throughout geological history in the South-Asian region and, in particular, in the area of the modern shelf of southern Vietnam, led to the appearance of deep faults and cracks in the Earth's crust. The resulting pressure drop contributed to the appearance of macrokinetic conditions for the migration of deep oil to the upper horizons of the lithosphere. The oil released from different oil generating zones along the route was mixed, enriching each other with biogenic and abiogenic hydrocarbon radicals.

Reaching the Earth's surface, gas-oil mixtures mainly dispersed in space, without forming industrial clusters.

Only with the formation of rifts in the Oligocene time on the continental shelf of Vietnam, the filling of rift depressions with terrigenous sediments and the overlap of the basement ledges with a powerful sedimentary cover, the formation of industrial oil accumulations became possible.

In other words, buried rift structures were a kind of trap for deep oil. In turn, in the sandy-clay rocks of the rift depressions, their own oil-generating processes proceeded according to the principles of the organic sedimentary-migration concept. The maturation of oil in the oil source strata was facilitated by the inflow of deep heat, as indicated by increased positive temperature anomalies in the White Tiger, Dragon and other oil-bearing areas of the South Vietnamese shelf. Apparently, the main coolant was methane-hydrogen fluid, which has a very high heat capacity. Under its influence, in the zones of increased permeability of the crushed crust, which are rift structures, the accelerated formation of petroleum hydrocarbons occurred.

In addition to the temperature factor, the rifts are characterized by seismic activity, the flow of highly heated deep fluids, consisting of water vapor, hydrogen, carbon dioxide, methane and other components. All this also favorably affected the conversion of organic matter (OM) to oil.

This type of oil generation, which occurs as a result of catagenetic transformations of organic matter in the geological structures of the Earth's sedimentary shell, could be called stratospheric, and the zones in which these processes take place are called stratospheric oil generation zones.

Within the stratosphere, the processes of oil and gas formation occur in various geological settings. This occurs most actively in the conditions of rifts, especially the intercontinental sea rift. Large hydrocarbon reserves are known for platform margins and within the foredeep. The processes of oil and gas formation are much weaker under conditions of syneclise, not complicated by rifts, as well as intra-platform and some intermountain troughs characterized by a depressive geodynamic regime.

Unlike subduction and riftogenic regimes, the depressive regime is characterized by a relatively lower heating of the bowels and, therefore, a more "sluggish" course of oil and gas formation (Gavrilov, 1998). To activate them, the initial precipitation is required to dive to a depth of 2-5 km, i.e. to get into the most favorable thermobaric conditions (to the main phase of oil and gas formation according to N.B. Vassoevich).

Thus, in the context of the Earth's internal geospheres, at least three oil generation zones can be distinguished:

- Mantle-asthenospheric abiogenic synthesis;
- Subduction-dissipative biomineral synthesis;
- Stratispheric-biogenic synthesis.

Obviously, all these three zones, as a single open system for the generation of hydrocarbons, will exist only in conditions of active continental margins, characterized by high seismicity, the presence of deep faults, and the development of subduction and riftogenic processes. Therefore, it is logical that most of the oil and gas fields of the Sunda shelf, including the shelf of South Vietnam, are concentrated in rifts or in the vicinity of modern or ancient subduction zones.

The proposed mixtgenetic concept of oil and gas formation not only brings together "organics" and "inorganics", but also significantly expands the potential of oil and gas resources in regions characterized by manifestations of global geodynamic processes. This is especially true for the active margins of the continents, which are influenced by convection movements of the warmed matter of the upper mantle and injections of asthenospheric plumes.

From the point of view of the mixtgenetic concept, there is an explanation for such a phenomenon that has attracted the attention of oil industry workers in recent years as the modern active generation of hydrocarbons and the renewability of natural oil and gas reserves.

It is known that in many fields the initially estimated oil reserves were repeatedly depleted during their long-term operation. Nevertheless, the prevailing point of view is the non-renewability of hydrocarbon resources, which is based on the classical "organic" theory of the genesis of oil and gas. In fact, many data indicate that oil migration processes are much faster than the proponents of the organogenetic sedimentation hypothesis suggested, as numerous examples of modern replenishment of hydrocarbon reserves in the bowels indicate (Gavrilov, Skaryatin, 2004). This is also confirmed by the White Tiger field, where many wells developing a basement continue to operate in the flowing mode for 12-15 years from the start of commissioning with a flow rate of about and more than 1000 t/d at the same time, cumulative production has long exceeded the estimated initial reserves.

It is obvious that, in addition to the geological redistribution of hydrocarbons during the operation of the fields, there must be some centers of modern oil and gas production and replenishment of depleted reserves. On the continental shelf of South Vietnam, such foci are, apparently, deep oil-generation zones, which, through faults and cracks in the lithosphere crossing the synthesis zones, can still feed oil deposits in rift and subduction oil-bearing structures and blocks of the crystalline basement.

In conclusion, we note that the authors consider the ideas about the existence of inorganic oil synthesis in the deep spheres of the Earth not as an alternative to the organic origin of oil, but as a powerful additional source of hydrocarbon raw materials. A mixtgenetic approach to the problem of oil and gas formation, combining two seemingly irreconcilable points of view, expands the search criteria and the possibilities of identifying promising areas. It also makes it possible to estimate hydrocarbon reserves in active tectonic zones with great optimism and to make cost-effective development of deposits, taking into account the likely replenishment of deposits during their operation.

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DISCUSSION ARTICLE

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New representations on oil and gas origin in connection with the opening of the phenomenon of reserves replenishment in exploited oil fields

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Abstract. New ideas about the origin of oil and gas are discussed. They are caused by the discovery of the phenomenon of replenishment of oil and gas reserves in exploited fields. This phenomenon was discovered by the Russian geologists a quarter of a century ago, and a little later it was theoretically justified on the basis of the biosphere concept of oil and gas formation. As a result, the well-known «organic hypothesis» and «mineral hypothesis», which have long time competed in oil and gas geology are being replaced by new representations today, according to which oil and gas are the inexhaustible useful fossils of our planet. And their deposits are traps of movable carbon that circulates via the Earth's surface in three main cycles with periods of ~10^8-10^9, ~10^6 -10^7 and ≈ 40 years. The 40-year carbon biosphere cycle, which was not previously taken into account at all, plays a main role in replenishment of deposits. Its accounting makes it possible to balance the carbon and water cycles in the biosphere, taking into account the economic activities of people and modern formation of oil and gas in the bowels, and also open up the possibility of exploiting deposits as constantly replenished sources of hydrocarbons.

Keywords: oil and gas origin, carbon circulation via Earth's surface, replenishment of reserves exploited deposits

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Introduction

In the early 1990s, geologists of our country noticed that a number of fields where oil and gas production was suspended due to the collapse of the USSR, the war in Chechnya and/or property redistribution, began to produce industrial hydrocarbon inflows (HC) again after a few years. It was possible to notice these inflows in deposits that have been in operation for 50 years or more (Muslimov et al., 1991; Sokolov, Guseva, 1993; Dyakonov, 1998; Korneva, 1999; Smirnova, 1999; Ashirov et al., 2000; Zapivalov, 2000; Korchagin, 2001; Gavrilov, Skaryatin, 2004; and others). First, inflows were tried to be associated with an underestimation of the amount of recoverable reserves, or with the recharge of deposits from neighboring unproductive formations. However, by the 2000s, the widespread prevalence of this phenomenon became apparent, which led geologists to conclude that there is a constant inflow of new portions of hydrocarbons into the deposit. This phenomenon was not supposed to be known at that time as the organic and mineral hypotheses of oil and gas formation, which, according to the author (Barenbaum, 2014), was the reason for the scientific revolution by T. Kun (Kun, 1977), which occurs today in oil and gas geology. The revolution began with the birth of a new oil and gas paradigm a quarter century ago in our country. Its essence was first understood and formulated by B.A. Sokolov and A.N. Guseva (1993), stating: "oil and gas are renewable natural resources, the development of which should be based on a balance of hydrocarbon generation volumes and the possibilities of their extraction in the process of field exploitation".

In the early 2000s, these new views on oil and gas received the necessary theoretical justification in the biosphere concept of oil and gas formation (Barenbaum, 2004, 2014), which, based on more general concepts (Barenbaum, 2010), linked the formation of hydrocarbons with the circulation of carbon through the Earth's surface three cycles. Of these, the longest cycle of ~ 10^8-10^9 years is caused by the immersion of carbon-containing rocks during subduction of lithospheric plates and, as a whole, as a result of geodynamic processes. The second ~ 10^6-10^7 years is due to the conversion of organic matter (OM) and carbonates in the Earth's crust during sedimentation. And the third, fastest – 40-year cycle is associated with the carbon cycle in the biosphere, including its underground part. This biosphere cycle is a consequence of the transfer of CO_2 from the atmosphere to the sedimentary cover by meteogenic waters during their climatic cycle.

At present, the carbon cycle system on Earth is in a state close to dynamic equilibrium (Barenbaum, 1998, 2004, 2014). Moreover, due to participation in the biosphere cycle, all cycles are closely interconnected and occur above the Earth's surface, which plays the role of a geochemical barrier, mobile carbon mainly circulates in the form of CO_2, and under it is restored to HC. Crossing the surface, and being part of either living organisms or mineral aggregates, it participates in oxidation-reduction processes, changing the chemical form and isotopic composition. Under the Earth's surface, carbon turns into hydrocarbons, which, due to low solubility in water, form their own accumulations in the form of oil and gas under favorable conditions.

Before the creation of the biosphere concept, a debate between proponents of organic and mineral hypotheses was on the question, which of the two geological cycles dominates the formation of oil and gas. The first claimed that the cycle was ~ 10^6-10^7 years, and the second that ~ 10^8-10^9 years. Cycle was not supposed to participate in the oil and gas formation of the biosphere. But it is plays the main role in replenishing the hydrocarbon of the developed fields.

The fact of the matter is (Barenbaum, 2012) that the volumes of carbon fuels consumption in the world are so great today that by extracting oil, gas and coal and burning them on the surface, a human being thereby violates the equilibrium between the cycles that has been developed on Earth over millions of years. As a result, carbon from the geological cycles enters the 40-year biosphere cycle. Being included in the biosphere cycle, this carbon replenishes the vacant traps of exploited deposits, however, it is mainly deposited on the shelf of the oceans and seas in the form of aquamarine methane hydrates (Barenbaum, 2007, 2017).

At present, a firmly established fact can be considered that the main mechanism of oil and gas formation in the bowels is the polycondensation synthesis of hydrocarbons from carbon and hydrogen oxides, which occurs in a water-saturated mineral matrix of rocks mechanically activated by natural seismotectonic processes (Chersky et al., 1985). This mechanochemical mechanism, called "geosynthesis" (Zakirov et al., 2013), was actually established by domestic scientists 40 years ago and was officially approved as Scientific discovery No. 326 in the USSR (Trofimuk et al., 1982). With this mechanism, the hydrogen donor in the hydrocarbon is water, and the carbon is organic matter, water-soluble CO_2, and readily soluble carbon-containing minerals.

The essence of the phenomenon is that, under the action of seismotectonic processes in rock minerals, intracrystalline defects are generated (Chersky et al., 1985). Diffusing to the surface of mineral grains, these defects form an energy-saturated layer that reduces the Gibbs energy of chemical reactions (Semenov, 1959). As a result, reactions that are thermodynamically possible at a temperature of 500 °C or more in a mechanically activated mineral matrix of rocks can also occur under "standard" conditions (T = 25 °C and P = 1 atm.). Such reactions, as shown by V.I. Molchanov (1981, 1992) and N.V. Chersky, V.P. Tsarev et al. (1984, 1985, 1986) include the decomposition of H_2O with the evolution of hydrogen, which is involved in the synthesis of hydrocarbons from carbon oxides (CO and CO_2). It should be emphasized that the composition of oil during field operation may vary (Barenbaum, 2017). At the exploration stage and at the initial stage of field development, "old" oil comes to the surface, which was formed in accordance with the ideas of the supporters of the organic hypothesis from the buried OM in the cycle of ~ 10^6-10^7 years. This oil may include OM and chemofossils deposited in the host rocks also in the carbon cycle of ~ 10^8-10^9 years. However, in the process of field development, especially in the late stages of their exploitation, hydrocarbons are accumulated in appreciable quantities in the released traps, which were also formed during geosynthesis from CO_2 and H_2O. As a result, "young" light oil, which arose in 40-year biosphere carbon cycle.

The mineral hypothesis insists on the fact that hydrocarbons are synthesized, but not formed from OM of sedimentary rocks. Thus, supporters of the organic and mineral hypotheses are right in their own way, but on different issues: the first is that the source of carbon in "old" oils is dead OM, and the second is that hydrocarbons of all oils are formed as a result of synthesis, although not specifying its mechanism.

This mechanism is geosynthesis. Irrefutable evidence of its participation in the formation of hydrocarbons of non-biodegraded oils, natural gases, and bitumens is given in (Glebov, 2002; Barenbaum, 2007a, 2019; Barenbaum, Ablya, 2009). The biosphere concept goes beyond this conclusion. Theoretical calculations of the balance of carbon and water during a cycle through the Earth's surface, based on the results of laboratory experiments (Barenbaum, Klimov, 2015), lead to the conclusion (Barenbaum, 2018) that a large volume of underground (meteogenic) water containing CO_2 is destroyed during geosynthesis, and the process mainly occurs in the upper ≈ 5 km layer of the Earth's crust. At the same time, if H_2, the overwhelming part of CH_4, dissolved in air N_2, and non-reacted CO_2, which has arisen from water, is degassed into the atmosphere, then liquid and solid hydrocarbons, as well as some methane, remain in the bowels, creating large accumulations in geological structures – traps. Thermobaric conditions and the quality of the traps define whether there will be oil or gas in them. If there are good impermeable beds, gas accumulates in the deposits, and not very good impermeable beds – oil.

Another important conclusion is (Barenbaum, 2012) that the volumes of oil, gas, and coal mined in the world today are so great that the geochemical system does not manage to utilize the CO_2 generated during their combustion. As a result, the CO_2 content in the atmosphere increases, the processes of subsoil degassing and methane hydrate deposits on the World Ocean shelf are intensified, and the rate of filling of exploited fields with anthropogenic oil increases.

In all these processes, the 40-year biosphere cycle plays a major role. Its contribution to the replenishment of hydrocarbon reserves in exploited fields is incomparably higher than geological cycles with characteristic times of ~ 10^6-10^7 years and ~ 10^8-10^9 years, with which proponents of the organic and mineral hypotheses, respectively, associate the formation of oil and gas. The participation of different cycles of off-gas formation is inversely proportional to their periods; therefore, the biosphere cycle contributes ~ 10^4 times more to the replenishment of deposits than the first geological cycle and ~ 10^7 times more than the second.

The above results are reflected in many publications of the author. This article draws attention to the fact that the proposed explanation of the replenishment phenomenon actually “transfers” the solution to the problem of the origin of oil and gas from the exclusive conduct of oil and gas geology to the jurisdiction of other sciences. The author qualifies this fact as a scientific revolution in oil and gas formation. Its essence is discussed below with the involvement of the general theory of scientific revolutions T. Kun (1977).

Theory of Scientific Revolutions of T. Kun

T. Kuhn showed in his fundamental work that scientific revolutions are a natural stage in the development of mature natural sciences in which revolutions occur according to a scheme that is uniform for all sciences. The main provisions of this theory are as follows:

1. The basis of each mature science is a paradigm – a certain body of knowledge, which for a fairly long time has been recognized by a certain scientific community as the basis of its practical activity.

2. In their development, all sciences are experiencing crisis conditions. A symptom of a crisis is the presence of an anomaly, i.e. a certain natural phenomenon whose existence is not assumed by the paradigm or even contradicts it. Anomalies are almost always present, and overcoming them within the framework of the existing paradigm is the most important task of any science. Only anomalies lead to the crisis, which, firstly, occupy a prominent place in this science, and, secondly, for a long time resist scientists’ attempts to include them in the paradigm.

3. The absence of a universally recognized paradigm calls into question the existence of this science. All members of the scientific community seem to be engaged in science, but the combined result of their efforts hardly resembles science in general.

4. Crisis ends with one of three possible outcomes: 1) normal science, in the end, is able to solve the problem that causes the crisis; 2) the problem, despite all efforts, is not amenable to solution and is left to the inheritance of future generations. And 3) the crisis is resolved as a result of the scientific revolution, which leads to the emergence of a new contender for the place of the old paradigm.

5. The latter case is the main path of development of science. There are two requirements for the new paradigm. The first is that it must solve some controversial and generally conscious problem that cannot be solved in any other way, and the second is to promise to maintain the ability to solve all other problems that have accumulated in science thanks to the previous paradigms.

6. When changing the paradigm, significant changes usually take place in the criteria that determine the correct choice of problems and their solutions. Some old problems may be transferred to another science or declared completely “unscientific”. Other problems that were previously not significant in the new paradigm may themselves become prototypes of significant scientific achievements.

7. Such a restructuring is very painful for the scientific community. Any mature science is aimed at developing those phenomena and theories whose existence the paradigm obviously implies. New phenomena are often overlooked altogether. Scientists, in line with normal science, do not set themselves the goal of creating new theories, usually they are also intolerant of others creating such theories.

The specifics of the scientific revolution in oil and gas geology

Transition to the new oil and gas paradigm of B.A. Sokolov and A.N. Guseva (1993) in oil and gas geology is fully consistent with the theory of T. Kuhn. Everything is needed here: the discovery of an anomalous phenomenon – replenishment of oil and gas at exploited fields, and the futile attempts of geologists over the past 25 years to solve this problem, and, finally, the emergence of a new contender for the place of the old paradigm – the biosphere concept of oil and gas formation. However, to understand the essence of this revolution, it is important to emphasize that, following T. Kuhn, gas-oil geology in its present state is not able to solve the problem of oil and gas formation. For the first time, the biosphere concept has become a science (Barenbaum, 2013, 2015). But what was before the biosphere concept? What problems has oil and gas geology been solving for at least the last 100 years? The situation here is as follows. All this time there have been two hypotheses – "organic" and "mineral", which played the role of independent scientific paradigms in oil and gas geology. Supporters of the first argued that oil and gas arise in the deposits themselves from organic matter coming "from above" – from the Earth's surface. Whereas the latter insisted that gas and oil hydrocarbons enter the fields "from below" – from deep Earth bowels, where they are formed. Each of the paradigms was supported by a large number of supporters and relied on the results of numerous experiments and theoretical studies. Nevertheless, this did not eliminate the known difficulties inherent in the paradigms themselves, which did not allow the scientific community to make the final choice in favor of one of them. Adherents of different paradigms blamed each other for these difficulties, but did not take it personally. The absence of a universally recognized paradigm regarding the origin of oil and gas – and this is a key issue in oil and gas geology, according to Section 3 of T. Kun's theory, casts doubt on the fundamental ability of oil and gas geology to solve this problem. Kuhn's verdict that in such a situation "All members of the scientific community seem to be engaged in science, but the combined result of their efforts hardly resembles science in general," is convincingly confirmed by the years of irreconcilable struggle of supporters of organic and mineral hypotheses on oil and gas formation. This fight is happening today. However, its purpose is not to establish the truth, but to dissociate itself with the supporters of the opposing side and identify weaknesses in their position. The key concepts used by both sides in their confrontation fully reflect the ups and downs of this struggle. Here are some of them: "organic and inorganic carbon", "oil and gas potential of the subsoil", "biogenic and abiogenic genesis of hydrocarbons", "sedimentary cover", "crystalline basement", "deep degassing", "oil source formations", etc. In the biosphere concept, these concepts are either devoid of physical meaning or not important. So, it is obvious that in nature there are no "organic" and "inorganic" carbons, but there is simply carbon, which changes its isotopic composition during chemical reactions. The phrase "oil and gas potential of the subsoil" loses its meaning. What kind of "potential" can we talk about if hydrocarbons are continuously replenished in deposits, and the speed of this replenishment depends on the technologies of field development, as well as on (Barenbaum, 2015), whether hydrocarbons are consumed in the region where they are extracted, or transported from places production over thousands of kilometers? In addition, in connection with the revision of views on the origin of oil and gas, oilmen are tasked with turning the fields being developed into "inexhaustible" hydrocarbon sources (Barenbaum, 2015). The concepts of "naftidogenesis" and "polygenesis", as well as the "mixgenetic" genesis of hydrocarbon oil are deprived of their foundations. According to the laws of chemistry there is neither "biogenic" nor "abiogenic" formation of hydrocarbons. And there is one mechanism – mechanochemical geosynthesis, based on the discovery of Russian scientists (Trofimuk et al., 1982). This mechanism refers to the reactions of polycondensation synthesis of hydrocarbons from carbon oxides (CO, CO_2) and hydrogen (H, H_2O), which are widespread in nature (Rudenko, 1969). Water serves as a hydrogen donor in hydrocarbons during geosynthesis, and carbon matter can be organic matter, water-soluble CO_2, and carbon-containing minerals. Geosynthesis occurs in a water-saturated mineral matrix of rocks mechanically activated by seismotectonic processes, and is accompanied by the decomposition of a large mass of groundwater into oxygen and hydrogen. It is the process that creates degassing, and not the intake of CH_4, H_2, CO_2, N_2, and other gases through the "degassing channels" from the "deep bowels" of the Earth.

The consequences of the scientific revolution

The above views are presented on the formation of oil and gas on our planet, initiated by the discovery of the phenomenon of replenishment of deposits and its explanation on the basis of the paradigm of B.A. Sokolov and A.N. Guseva. These ideas, while upholding the conclusions and recommendations of organic and mineral hypotheses on the search for new oil and gas fields, substantiate previously unknown possibilities of exploiting already discovered fields as "inexhaustible" sources of hydrocarbon raw materials. On the whole, new views on the origin of oil and gas are in very strong contrast with the ideas of organic and mineral hypotheses, so the transition to them is hardly a scientific revolution in the problem of oil and gas formation. Therefore, we focus on a number of provisions of new ideas, which the author considers as the result of a scientific revolution in oil and gas geology.

- Oil and gas are the inexhaustible minerals of our planet, formed during the geochemical cycle of carbon in the biosphere and water through the Earth's surface. Currently, this system of the cycle is in a state close to dynamic equilibrium, which provides a balance between the descending and ascending flows of carbon during its circulation through the surface.

- In the system of the carbon cycle, three interacting cycles should be distinguished: two geological ones with characteristic times of ~ 10^8-10^9 and ~ 10^6-10^7 years and climatic ≈ 40 years. The first cycle (geodynamic) is associated in part with the subduction of lithospheric plates. The second cycle (sedimentary) is due to the burial of OM in sedimentation processes. And the third (biosphere) cycle is caused by the transfer of water-dissolved CO2 from the atmosphere to the sedimentary cover by meteogenic waters during their climatic cycle.

- All three cycles are involved in oil and gas production, but in different ways. The processes of the first cycle at times of ~ 10^8-10^9 years form large geological structures that serve as hydrocarbon traps and today act as oil and gas fields. The processes of the second cycle take part in filling these traps with hydrocarbons formed from OM of sedimentary rocks over a period of ~ 10^6 years. And the third cycle is the modern process of oil and gas formation due to the climatic cycle of water.

- The mechanism of hydrocarbon formation from OM (second cycle) and from groundwater CO_2 (third cycle) is the same. This is the mechanochemical geosynthesis of hydrocarbons in a water-saturated mineral matrix of rocks activated by seismotectonic processes, leading to the formation of gas-oil hydrocarbons and free hydrogen H_2.

- Replenishment of exploited hydrocarbon deposits is a consequence of modern economic activity of people. Removing oil, gas and coal from the bowels, a person violates the carbon cycle system that has developed on Earth over millions of years. As a result, carbon, which previously participated in long geological cycles, enters the 40-year biosphere cycle, where it is redistributed over all reservoirs of the biosphere.

- Maintaining a state of dynamic equilibrium, the biosphere system removes excess carbon from the biosphere cycle through various processes. In one of them, excess carbon entering the Earth's surface is converted into hydrocarbons, which fill the vacated traps of the developed deposits. It is this process, and no other, that replenishes depleted deposits with light hydrocarbons.

- The formation of aquamarine methane hydrates, which are now deposited on the shelf of the World Ocean in places of underground water flow from the continents, is even more effective (Barenbaum, 2007). Methanohydrates act as "chemical" carbon traps in the form of methane. According to some estimates (Solov'ev, 2003), methane hydrates contain more than half of all known hydrocarbon reserves of our planet. Moreover, as calculations show (Barenbaum, 2017a), the amount of methane hydrates themselves is growing by about 0.5 % per year. In addition to methane hydrates on the shelf of the World Ocean, conventional hydrocarbon accumulations are actively forming today (Barenbaum, 2015).

Conclusion

Summing up, the author of the article is convinced that these new ideas in the future will certainly receive recognition from experts who today adhere to the positions of organic or mineral hypotheses. However, it is still difficult to predict when this happens. Time will tell.

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DISCUSSION ARTICLE

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Replenishment of oil deposits from the position of a new concept of oil and gas formation

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Abstract. The article is devoted to the problem of replenishing of oil reserves and considers it (the problem) in the aspect of deep degassing of the Earth. Based on an analysis of the results of a long-term study of the Precambrian crystalline basement in the territory of Tatarstan and adjacent areas, a number of new criteria are formulated that allow us to identify the processes of deep degassing of the Earth within the studied region.

The article provides a brief overview of current views on the problem of replenishing oil reserves, considers options for possible sources and the mechanism of replenishment of hydrocarbons in the developed deposits. The arguments in favor of the modern process of deep degassing within the South Tatar arch and adjacent territories are examined, which are unequivocally confirmed by: the dynamics of the hydrochemical parameters of the deep waters of the crystalline basement obtained in the monitoring mode at five deep wells; uneven heat flux and its anomalies, recorded according to many years of research under the guidance of N.N. Khristoforova. The degassing processes are also confirmed by the dynamics of gas saturation of decompressed zones of the crystalline basement recorded in well 20009-Novoelkhovskaya, the dynamics of gas saturation of oil of the sedimentary cover and the composition of the gas dissolved in it, identified by oil studies in piezometric wells located in different areas of the Romashkinskoe field; the seismicity of the territory of Tatarstan, as well as its neotectonic activity. As criteria proving the existence of a process of replenishing the reserves of the developed oil fields of the South Tatar Arch, the features of the deep structure of the Earth's crust according to seismic data, as well as the results of geochemical studies of oils are considered.

Key words: replenishment of reserves, deep degassing of the Earth, criteria for oil inflow into deposits, origin of oil and gas, geochemical studies, tectonic activation, Romashkinskoe oil field, a new concept of oil and gas formation

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The absolute dependence of the existence on energy consumption and the key role of the energy sector in mankind, the development of other components of the economy have led experts for decades to constantly ask the question "How much oil and gas remains in the bowels of the Earth, and when will they end?". The paradox is that, despite repeated attempts to predict the timing of the fall in world oil production and the prediction that it will end in twenty to thirty years, oil does not end at all. And on the contrary, the volume of oil produced annually is not just stable, it is gradually growing, which, according to the widespread opinion, is due to the dominant influence of new production technologies and the development of unconventional resources, the development of which was previously unprofitable.

Against the background of a seemingly quite clear picture of the industry development, fundamental basic problems, such as the genesis of oil and gas, the mechanism and stages of the formation and completion of their fields, continue to be unresolved. The appearance that clarity has long been achieved in solving these problems is reflected on the one hand in classical textbooks and numerous scientific works and articles. On the other hand, the facts obtained thanks to many years of experience in the exploration and development of oil and gas fields and the development of fundamental Earth sciences give reason to believe that the formation of oil and gas fields have long failed to meet the outdated concepts of sedimentary basins, as closed systems, where the formation hydrocarbon accumulations stretch for tens and hundreds of millions of years, and the reserves of oil and gas fields traditionally belong to non-renewable natural resources.

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The fact of modern replenishment of the extracted hydrocarbon reserves – recharge of deposits was established in the last two decades. It makes significant additions to existing ideas and involves the consideration and discussion of those new conceptual foundations of naphthydogenesis, from the position of which this process, fixed by geological, geophysical, and geochemical methods, can be fully explained and taken into account in modeling and development.

In particular, the replenishment of oil reserves has already been repeatedly considered on the example of the Romashkinskoe field both from the position of deep degassing of the Earth (Muslimov et al., 2019) and from the position of the continued generation of light hydrocarbons from high-alumina gneisses of the Greater Chemshan series (containing up to 15 % graphite) under the influence of high temperatures and deep hydrogen (Gavrilov, 2008).

The almost complete restoration of reservoir pressure and oil production rates recorded in the fields of the Kinzebulatov group of the Republic of Bashkortostan after a 20-year break, in the works of I.A. Dyachuk is explained by the gravitational redistribution of oil in the deposits (Dyachuk, 2015).

In his works E.Yu. Goryunov, who conducted an analysis of the reserves in the deposits, the properties of hydrocarbons and reservoir temperatures for the Ural-Volga region, assumes the staged flow of hydrocarbons into the sedimentary cover and the modern migration of hydrocarbon fluids into the region's fields (Khalikov et al., 2014, Goryunov et al., 2014).

A.V. Bochkarev and S.B. Ostroukhov at a number of fields in the Volga and the Caspian Basin described the facts of gas condensate entering oil fields at the last stages of development and the restoration of reservoir pressure in them (Bochkarev et al., 2010, 2011, 2012, Dorofeev et al., 2014).

The restoration of the anhydrous and slightly watered oil production in the fields of the Tersko-Sunzhensky district after lengthy interruptions in development is described in the works of V.P. Gavrilov (Gavrilov, 2008).

O.N. Kasyanova proved the saturation of the developed fields with migration hydrocarbon fluids within the areas of development of modern geofluidodynamic processes (Kas'yanova, 2009, 2010).

The most difficult, debatable and unexplored issue is the source and mechanism of modern reservoir replenishment, as the views of experts diverge both on the nature and the presence of the substance entering the reservoir (Fig. 1), and on the sources of this substance (Fig. 2).

In our opinion, the fundamental factor in the formation and replenishment of oil and gas deposits is the deep degassing of the Earth. The explanation of the

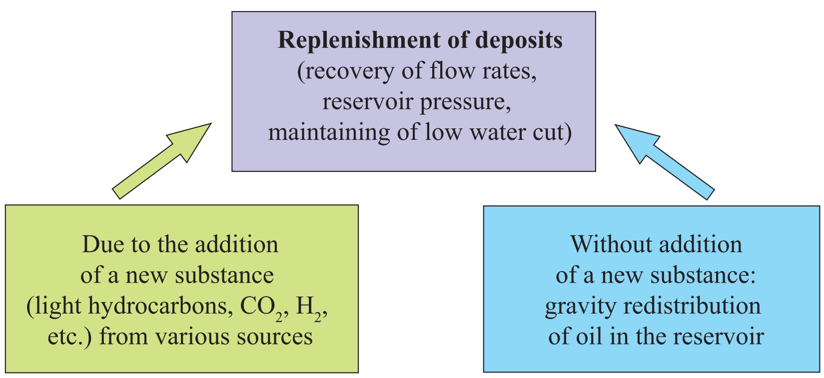

Fig. 1. Options for a possible mechanism for replenishing hydrocarbon deposits

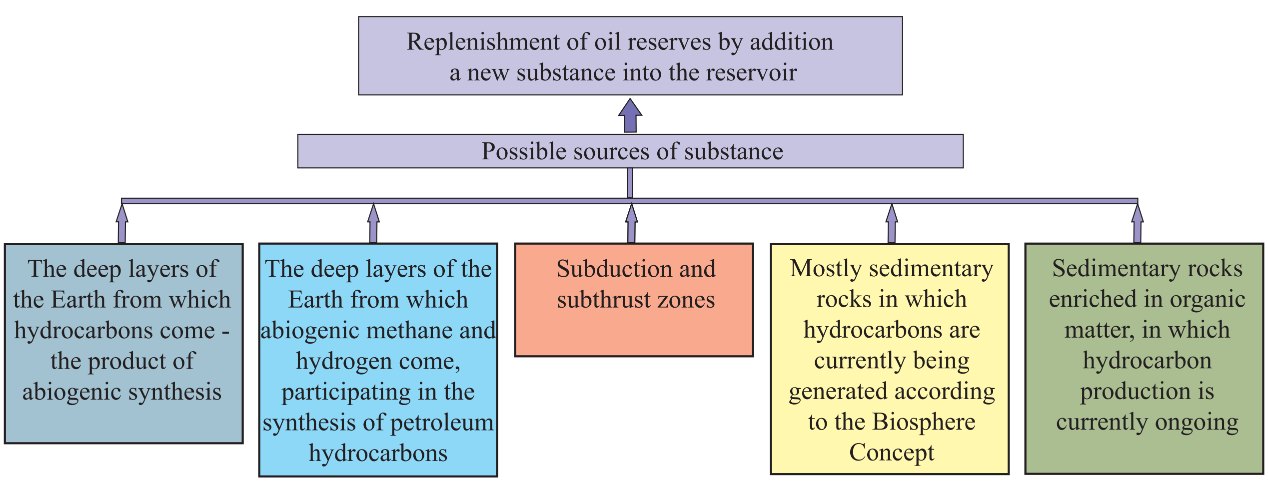

Fig. 2. Sources of replenishment of hydrocarbon reserves in the light of different views on the origin of oil and gas

ongoing modern development of open hydrodynamic systems, such as oil and gas deposits, deposits or their individual sections, requires the use of new geological paradigms and postulates of the so-called "non-linear oil and gas geology" (definition proposed by A.E. Lukin in 2004). The creation and approval of the theoretical foundations of renewing hydrocarbon reserves in developed formations is possible only on the basis of studying the deep degassing of the Earth – the global process of planet self-development, which determines the formation and development of high enthalpy, high-pressure fluid systems that generate a variety of geological events (Kropotkin, 1985, 1991, Lukin et al., 2018; Shestopalov et al., 2018).

An analysis of new concepts and models of naftidogenesis that have arisen over the past 50-60 years and are actively developing today, shows that each of them is based on different types of manifestations of gas discharges: the theory of degassing the Earth by P.N. Kropotkin (Kropotkin, 1985, 1991), the theory of abiogenic synthesis of hydrocarbons, developed by V.B. Porfiriev, N.A. Kudryavtsev, V.A. Krajushkin et al. (Krayushkin, 1984; Kudryavtsev, 1973; Porfir'ev, 1959), "fluidodynamic" concepts of A.N. Dmitrievskii, B.M. Valyaev, B.A. Sokolov, E.A. Abli (Dmitrievskii, 1991, Dmitrievsky et al., 2002, Pavlenkova, 2002), condensation model of O.Yu. Batalin and N.G. Vafina (Batalin et al., 2008), which develops the idea of B.M. Yusupov on the deep methane role in the formation of naphthides, a model for the development of restored fluid basement systems and sedimentary cover, created by R.P. Gottich and B.I. Pisotsky (Gottikh et al., 2007), the theory of naphthydogenesis by A.E. Lukin, based on the nonlinear nature of the main laws of oil and gas accumulation (Lukin et al., 2018).

All these theories, concepts, and models give the mantle source – the deep endogenous factor – either an absolute or dominant role in the formation of hydrocarbon deposits.

The acquisition of new knowledge and the formation of new ideas about the geodynamics, tectonic stratification of the Earth's crust, and the laws governing the formation and development of fractures in the sedimentary cover and the basement of oil and gas basins made it possible to look at macro-accumulations of oil and gas in the aspect of fluid dynamic processes and from the perspective of the deep structure of the crust and mantle under oil and gas by regions. The anomalous structure and energy instability of the upper mantle and the Earth's crust beneath large hydrocarbon accumulations was revealed by various geophysical methods and reflected in the works of N.K. Bulin, A.V. Egorkin, V.A. Trofimov, V.I. Sharov et al. (Bulin et al., 2000; Trofimov et al., 2002).

According to (Kas'yanova, 2000; Kayukova et al., 2012; Lukin et al., 2018; Muslimov et al., 2004; Plotnikova, 2004), it is erroneous to consider the sedimentary cover mainly as insulated, self-sufficient, closed (except for conductive external heating) system in which the conversion of organic matter leads to oil and gas accumulation. At present, a large amount of geological and geophysical information has been obtained that indicates the sedimentary shell of the Earth as an open, thermodynamically nonequilibrium, and unstable system with a non-linear nature of development. The exchange of matter and energy with the environment is its obligatory attribute, which ensures the functioning of the system in an active mode.

Since the formation and reorganization of hydrocarbon deposits is a consequence of cross-formation fluid systems development in first-order degassing pipes (Lukin et al., 2018), the concept of feeding oil and gas deposits and replenishing their reserves is determined by the main aspects of plumectonics and "cold" degassing in the understanding of P.N. Kropotkin. Consequently, replenishment of hydrocarbon deposits is possible primarily in those fields that are confined to currently active deep degassing pipes.

According to (Lukin et al., 2018), 20 criteria are justified that indicate the modern activation of the deep degassing of the Earth. The results of studying the crystalline basement (CB) in Tatarstan over the past 40-50 years made it possible to formulate additional criteria that indicates fluid and geodynamic activity as a reflection of the modern degassing of our planet.

Modern degassing processes within the South Tatar arch and adjacent territories are unequivocally confirmed by the following factors.

The results of monitoring the water composition of the decompressed zones of the crystalline basement. A study of the hydrochemical parameters of the deep waters in the crystalline basement in the monitoring mode showed that throughout the entire observation period, the salt and microcomponent composition of the water changed (Ibragimov et al., 2009; Plotnikova, 2004). The acidity of the waters, for example, being slightly acidic, in certain periods changed to acidic and slightly alkaline. In addition to acidity, the mineralization of water changed (Fig. 3): the content of chlorine, iron, boron, copper, and molybdenum in them. In some wells, this was accompanied by a decrease in the density of water, while in others, the density was maintained due to an increase in the iron content. At certain periods, in all the examined wells, gas indicators showed a surge in the content of hydrogen, methane, and in some cases helium. Similar changes were also found in the composition of water-soluble organic matter; spikes in the total nitrogen content were observed in all wells, which were sometimes accompanied by an increase in the content of bitumen carbon. An analysis of temporary

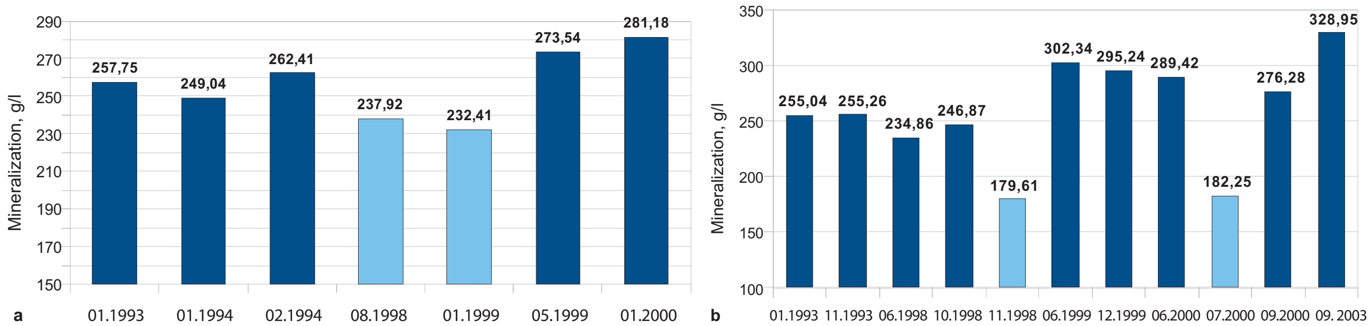

Fig. 3. The change in time of mineralization of formation water of the crystalline basement: a – well. 29419, b – well 966

variations in the gas-hydrochemical components of the groundwater in the CB showed their close relationship with the seismic activity of the territory. Total nitrogen, hydrogen, methane, and, to a lesser extent, carbon dioxide and helium, were identified as indicators of this relationship.

Uneven heat flow. Anomalies in the heat flow with an intensity of 10 mW/m^2 or more according to the data (Lukin et al., 2018) are the criterion for the modern activation of the deep degassing processes. The territory of Tatarstan according to N.N. Khristoforova (Khristoforova et al., 2000, 2008) is characterized by an uneven heat flow, which varies from 29 to 74 mW/m^2 within the Volga region. The thermal field also characterizes a pronounced heterogeneity. On the roof of the CB in Tatarstan, temperature differences reach 900 °C (Fig. 4), and at a section of 12 km – 600 °C. The colossal difference in the temperatures of the deep thermal field in such a limited space as the territory of Tatarstan clearly indicates in favor of active heat and mass transfer at the neotectonic and modern stages of development of the South Tatar arch and adjacent territories. The activity of the fluid dynamic processes of the South Tatar arch is indicated by the greatest warming of the CB, in comparison with the less warmed foundation of the Melekess Depression and the cold

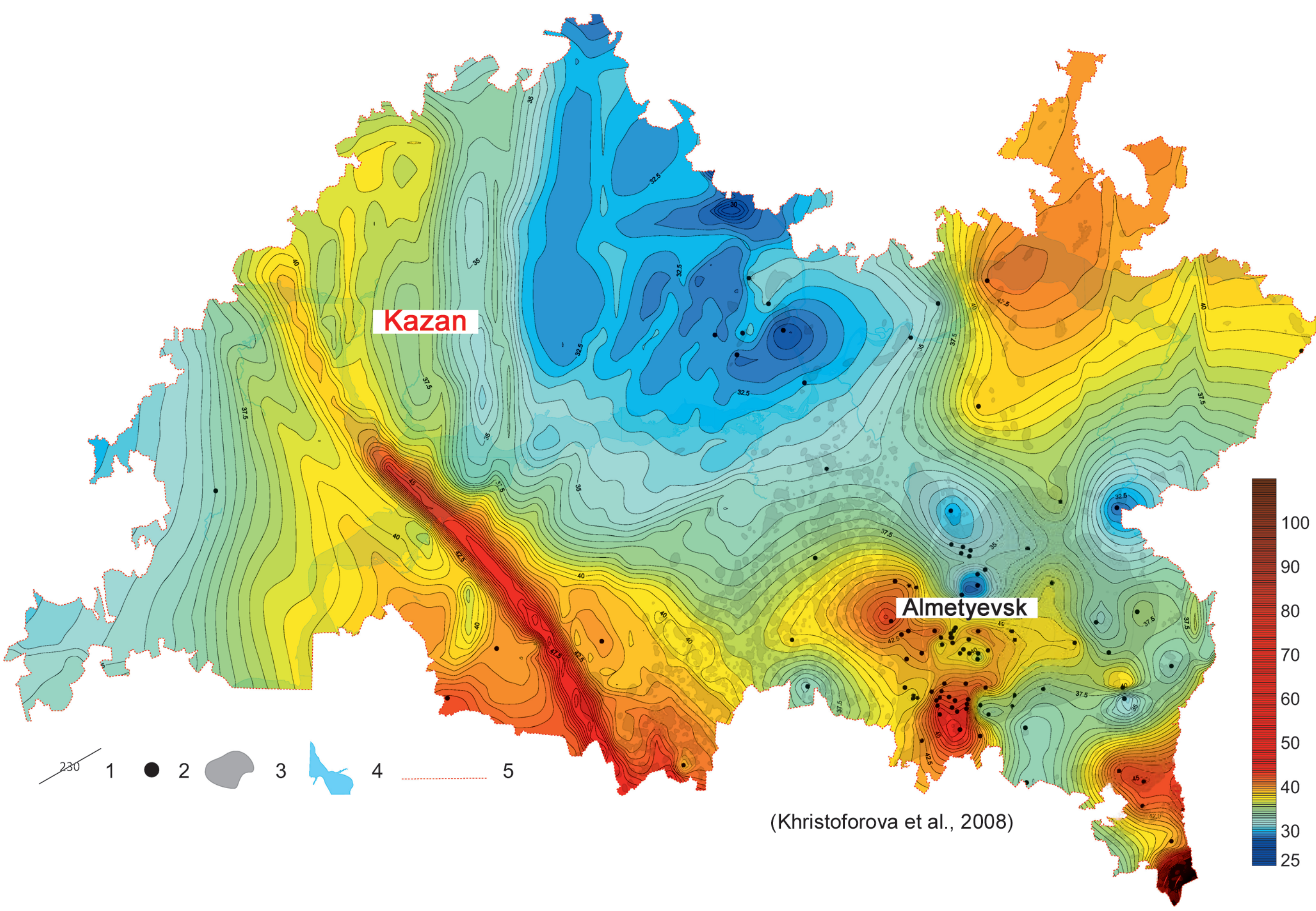

Fig. 4. Map of isotherms on the top of the crystalline basement (Khristoforova et al., 2008). Scale 1: 500,000. 1 – temperature isolines (^{0}C); 2 – location of wells in which temperature measurements were taken in the deep horizons of the sedimentary cover and basement; 3 – oil pool outlines; 4 – river network; 5 – district border of the Republic of Tatarstan.

CB of the North Tatar Arch, which practically does not contain oil deposits.

Modern fluctuations of temperature anomalies. Another factor indicating active modern heat and mass transfer are fluctuations and a change in temperature anomalies in the context of the crystalline basement (Khristoforova et al., 2000, 2008), recorded in the well 20009-Novoelkhovskaya after seismic events.

Dynamics of the total gas saturation of decompressed zones of crystalline rocks and gas composition. Monitoring the composition of gases in the well 20009-Novoelkhovskaya allowed us to establish that the gas saturation of decompressed CB zones varies over time (Fig. 5), in particular, periods of increase in gas indications of individual intervals are noted, despite cement filling of the wellbore (Plotnikova, 2004). Changes in the gas saturation of the intervals of the well section over time, including the periodic increase in gas readings after drilling and cement pouring in, indicate the presence of freely circulating gases, including hydrocarbon gases, in decompressed zones of CB and saturating them with formation water. The dynamics of gas saturation and gas-hydrochemical parameters of decompressed zones in the crystalline basement testify to the modern geodynamic and fluid activity of the latter.

The dynamics of gas saturation of oil sedimentary cover and the composition of the gas dissolved in it. An analysis of the composition of gas dissolved in oil made it possible to trace the dynamics of changes in the concentrations of methane, nitrogen, hydrogen, and carbon dioxide in oils from piezometric wells (Plotnikova, 2004) over a time period of more than 10 years. Significant changes observed in modern development, both in the composition of the gas and in the content of its components (Fig. 6, 7), indicate the frequency of activation of the entry of light hydrocarbons and other gases (CO_2, CH_4, N_2, etc.) into the sedimentary stratum and reservoir However, this does not exclude the fact that deep degassing occurs throughout the entire period, but is less active. It is possible that the introduction of gases is local in nature and is determined by the time periods of crack opening and the formation of open transit zones in the thickness of the crystalline basement and sedimentary cover.

Seismicity of the territory of Tatarstan. Another factor supporting the activity of modern deep degassing

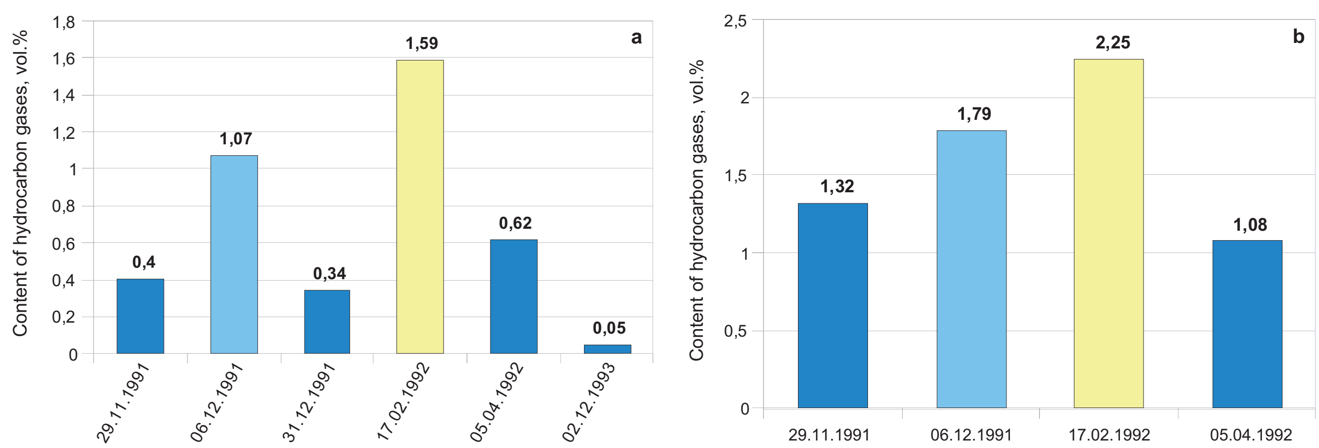

Fig. 5. Variations in the content of hydrocarbon gases in deep samples (OPT) of the mud in the well No. 20009-Novoelkhovskaya: a – at a depth of 5280 m, b – at a depth of 5300 m

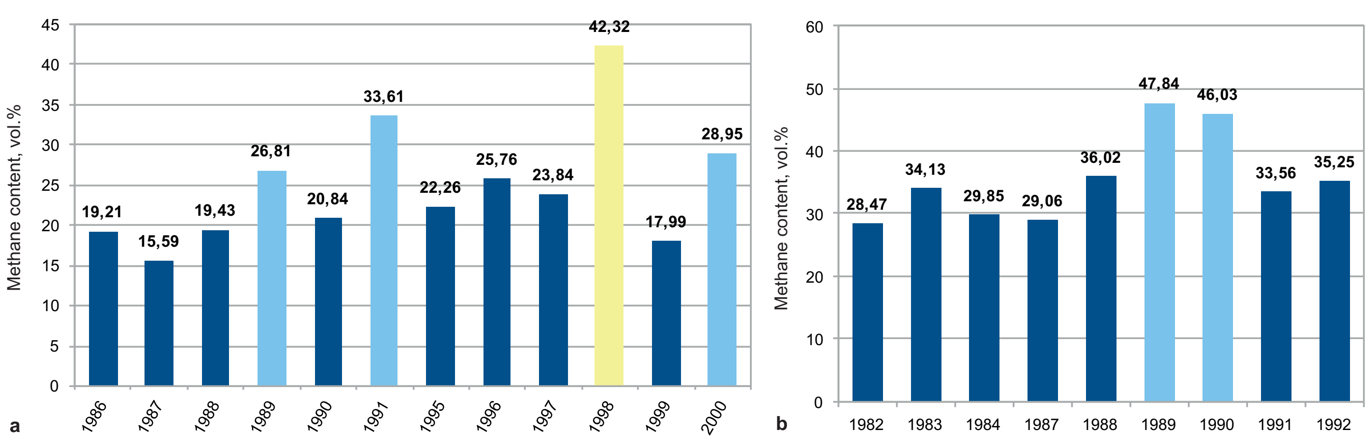

Fig. 6. An example of variations in the methane content in the dissolved gas oil of the Romashkinskoe field: a – Bobrikovian horizon, b – Pashian horizon

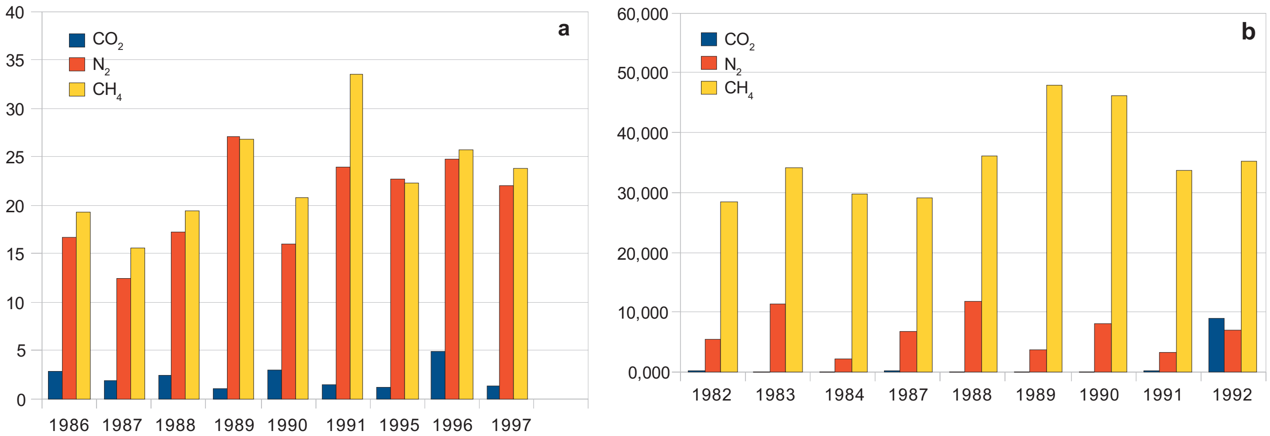

Fig. 7. Dynamics of methane, nitrogen and carbon dioxide content in dissolved gas: a – gas from oil from the Bobrikovian horizon of the Zelenogorsk area of the Romashkinskoe field; b – gas from the oil of the Pashian horizon of the Kholmovskaya area of the Romashkinskoe field

processes is the seismicity of the territory of Tatarstan, as well as the establishment of a stable correlation between the dates of seismic events and periods of decrease in the density of oil in piezometric wells and mineralization of formation water in the CB (Mirzoev et al., 2004).

Neotectonic activity of the Earth's crust. Another criterion that indicates the current activity of the deep degassing processes (Lukin et al., 2008) is the elevation of the Earth's surface by 25 meters or more over the past 3 million years. According to (Mingazov et al., 2012, 2014), neotectonic activation of the Earth's crust of the territory of Tatarstan over the past 1.5-2.0 million years has led to much more amplitude uplifts (Fig. 8). The uplift rate of the South Tatar arch during the neotectonic stage according to (Mingazov et al., 2014) reached 1-10 mm/year.

The neotectonic activity of the South Tatar Arch is evidenced by the sharp differentiation of the relief, where individual peaks reach elevations of 360-370 m, and river valleys, crashing into the arrays, drop to elevations of 150-160 m.

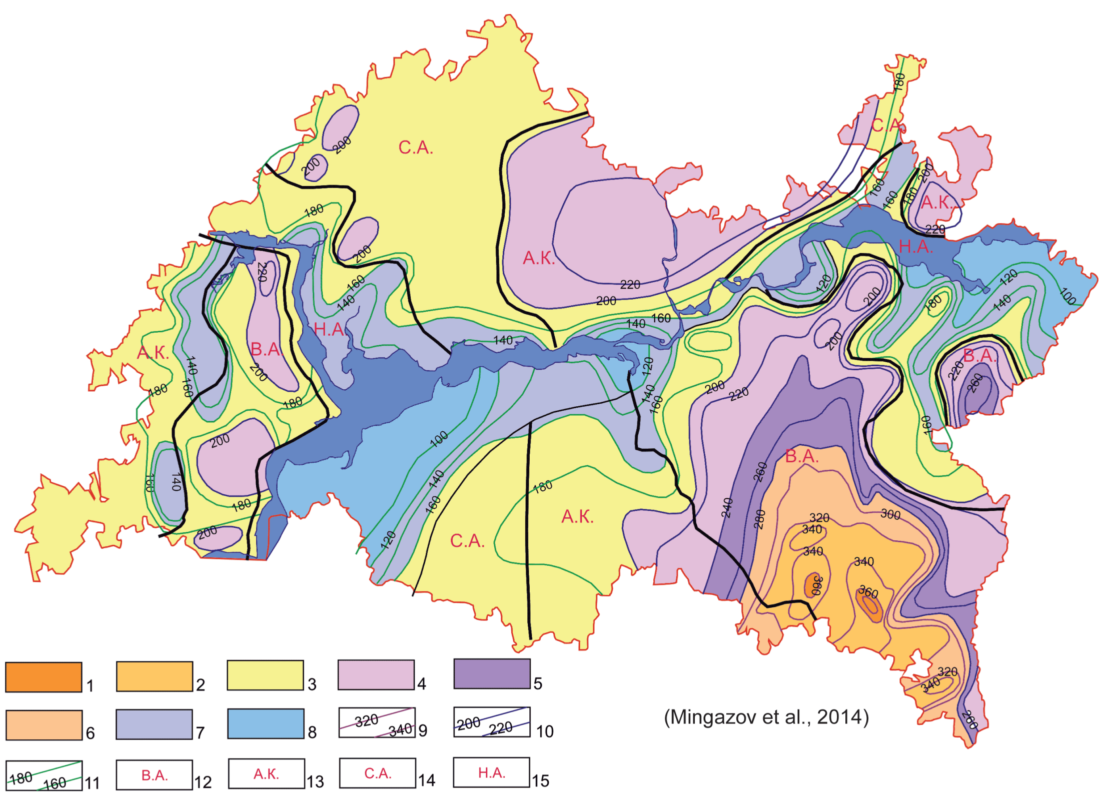

Fig. 8. Map of the latest tectonics of the Republic of Tatarstan (Mingazov et al., 2014). Average total amplitudes of the latest tectonic movements (m); 1 – 400-360; 2 – 360-320; 3 – 320-280; 4 – 280-240; 5 – 240-200; 6 – 200-160; 7 – 160-120; 8 – 120-80. Isolines of tectonic movements (m): 9 – during the period Pg3-Q; 10 – N1-Q; 11 – N2-Q. Modes of neotectonic movements: 12 – very active; 13 – active; 14 – weakly active; 15 – inactive.

In addition, a direct relationship was established between the activity of neotectogenesis and the oil potential of the South Tatar Arch (Mingazov et al., 2014).

Geochemical features of oil and bitumen. The idea of Romashkinskoe and a number of other oil fields as an open hydrodynamic system characterized by a multi-stage flow of oil and gas fluids into its reservoirs is also confirmed by the results of geochemical studies of oils (Ostroukhov et al., 2014, 2015; Plotnikova et al., 2013, 2014, 2017).

The presence of supply channels. The totality of the identified vertical and inclined structural and tectonic formations, which cut the sedimentary cover, the Earth's crust and upper mantle (Trofimov et al., 2002), reflects the role of degassing pipes in the development of open fracturing and are one of the main criteria indicating the possibility of activation of deep degassing processes and replenishment of hydrocarbon reserves of developed fields.

Thus, the results of the studies made it possible to expand the number of previously developed criteria (Lukin et al., 2018) indicating the activation of the deep degassing of the Earth. Using these criteria will allow us to differentiate the developed hydrocarbon deposits according to the principle of "renewable" or "non-renewable", which help localizing zones of hydrocarbon inflow, estimate the intensity of replenishment of reserves, and estimate the duration of this field on a completely different level.

Degassing processes recorded in decompressed zones of the basement and their periodic activation, the relationship of the block-fault structure of the basement of the South Tatar Arch with the phenomenon of modern hydrocarbon migration at Romashkinskoe and other fields (Muslimov et al., 2012; Plotnikova, 2004), geochemical studies of oil and bitumen of the sedimentary cover, which proved that the carbonate rocks of the Semiluk-Mendymian deposits are not a source of hydrocarbon inflow into the deposits of the terrigenous Devonian of the South Tatar arch (Ostroukhov et al., 2014; Plotnikova et al., 2013, 2014). I.e., these facts are a powerful scientific and practical basis for the creation of a concept of oil and gas fields' formation in the Volga-Ural anticline, involving multi-stage pulsed flow of hydrocarbon fluid systems in sedimentary cover pressure on transit zones of fracturing fields.

According to this concept, the replenishment of oil reserves is one of the manifestations of "cold" degassing and can be identified and localized using field geological and geochemical criteria considered in previous works (Muslimov et al., 2004, 2019; Plotnikova et al., 2014, 2017), and based on the use of the criteria for the manifestation and activation of the deep degassing of the Earth.

Today, when the relevance of replenishing oil and gas reserves is increasingly discussed on the pages of scientific publications, causing well-deserved interest among specialists of oil companies, comprehensive research is needed in the field of monitoring the flow and developing criteria for its registration and the quantitative-temporal (periodicity, duration) assessment (Muslimov et al., 2019). The criteria developed earlier for the deposits of Tatarstan are the basis for these studies in other regions.

Conclusion

Despite the fact that the existence of oil replenishment in the developed deposits is justified and proven by many examples, the study of this process and its consideration in planning development, estimating residual reserves, constructing field models and assessing the "life" of fields has not yet begun, since the replenishment process itself requires comprehensive detailed research. First of all, it is necessary to determine the spatio-temporal patterns of changes in the properties of oil and dissolved gas, the fluid regime of the reservoir, flow rates, and pressures. It is necessary to localize the inflow zones, determine their sizes, modes of fluid activity and its relationship with modern geodynamic processes and the development of fracture fields, estimate the volumes of incoming fluids and determine their composition.

At the stage of regional work, search and exploration of oil and gas fields, the geological exploration complex, along with traditional research, should include studying the deep structure of the sedimentary basin, assessing modern geodynamic activity, as well as obtaining information about a complex set of heat and mass transfer processes that are multiphase pulsed and controlled geodynamic regime (Lukin et al., 2018).

The same work can be carried out at the developed fields. In addition, they require special comprehensive geological-field and geochemical studies in the monitoring mode for a long time to obtain quantitative parameters of hydrocarbon inflow.

It is advisable to organize monitoring of the geological and production indicators and geochemical characteristics of oil and dissolved gas from the first years of development in the fields, which are just beginning to be developed, so that already in the early stages it is possible to localize the inflow zones and select a competent reservoir stimulation system.

Undoubtedly, these studies are very complex and go beyond the scope of routine work stipulated by licensing agreements and development projects. However, the unique information that will be obtained in the course of such work will reveal abnormal areas of deposits where oil production rates and low water cuts will be stable over time, ensuring high production at the field.

The monitoring system should be two-level. The first level is the analysis of geological and field data and the identification of potential areas of hydrocarbons migration into the deposits based on the use of geological and field criteria of anomaly. The second level is the geochemical studies of oils and gases dissolved in them both within wells with signs of anomalies and in adjacent areas of the reservoir (Plotnikova et al., 2017; Muslimov et al., 2019).

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The features of crystalline basement fields development

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Abstract. The article is devoted to research and development of deposits in granitoid reservoirs. The basis is the analysis of the development of the unique White Tiger field. Positive and negative experience in the development of this field deserves attention, for example, for the fields of the Timan-Pechora basement and other oil and gas provinces. Particular attention is paid to geological and geophysical, fluid studies of wells, the results of the operation of wells and reservoirs in general. Considerable difficulties are created when creating 3D geological and hydrodynamic models of deposits in granitoid reservoirs. As a result, there is a need for new laboratory and downhole research and the creation of laboratory and other equipment. It is concluded that for research and development of deposits with granitoid reservoirs, experience in the development of conventional deposits is not enough. A number of relevant recommendations are proposed.

Keywords: granitoid reservoirs, crystalline basement fields, features of geology and development, studies of wells and deposits, modelling

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One of the most promising areas of prospecting and exploration of oil and gas fields is associated with the basement. The long-term successful experience of oil production from the White Tiger field in the granitoid basement on the shelf of Vietnam is widely known. For a long time (more than 30 years) this field provides Vietnam with high volumes of oil production. Up to 90 % of oil production is made from the basement. However, the exploitation of this field posed a number of problems to the scientific community in the oil and gas industry. The article is devoted to the consideration of relevant tasks from the point of view of developing new, in terms of problematic, oil and gas fields.

The basement of the White Tiger field within the central zone of the uplifts of the Mekong Depression is of the pre-Cenazoic (T-J-Cr) age (Utoplennikov et al., 2005). It is composed of various plutonic rocks, mainly of granitoid composition, and is divided into three complexes of different ages: Hon-Hoai – Late Triassic, Din-Kuan – Late Jurassic, Ka-Na – Late Cretaceous. The Ka-Na complex, being the most productive, is represented mainly by granites. It composes almost completely the central arch of the field and individual blocks of the northern and southern arch. The granites of the Ka-Na complex are propped up, and in separate blocks, fields of the earlier Hon-Hoai and Dean-Kuan complexes break through. They are fragments of island arcs, paleosubduction and paleorift zones.

For Russia, the basement of the Timan-Pechora oil and gas province deserves attention. Despite the different ages of consolidation, it has much in common with the basement of the Mekong Depression on the Sunda shelf of Vietnam in terms of the composition of their formations, the history of geological development, and tectonic structure.

Most researchers determine the basement age of the Timan-Pechora plate as the Baikal (V-R). Granitoid arrays are of greatest interest for the search for hydrocarbon deposits. They form large undulating uplifts representing fragments of island arcs, microcontinent, and rifts (Utoplennikov et al., 2019).

If the expected discoveries of oil deposits in the basement will relate to granitoids, then we should expect extremely limited zones of oil inflow to the wellbore associated with fractures (both natural and man-made). Using conventional methods of geophysical well surveys (GIS), it is problematic to isolate such zones. It is necessary to adapt GIS methods to new possible situations.

In addition, improving methods for mapping oil and gas deposits both in area and in section are required. It is extremely necessary to forecast the reservoir properties of the reservoir, taking into account the material composition and the stress-strain state of the rocks.

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The pre-computer era revealed the incorrect methodology of laboratory experiments of terrigenous reservoirs, and, consequently, the calculation of reserves, the results of 3D computer modeling and the creation of new development technologies (Zakirov et al., 2007b; Zakirov et al., 2008b; Zakirov et al., 2012). Nevertheless, the pre-computer research methodology in the fields of physics and petrophysics, laboratory research, geophysical and hydrodynamic studies of wells, has not undergone significant changes. The research methodology for the pre-computer era is called the Absolute Pore Space Concept (APS Concept). The research methodology for the computer age (which began in 2000) was called the Concept of Effective Pore Space (EPS Concept) (Zakirov et al., 2007b; Zakirov et al., 2008b; Zakirov et al., 2012; Zakirov et al., 2006) .

The basics of the EPS Concept were reported and discussed at an expanded meeting of the Central Development Commission (CDC Rosnedra) (Zakirov et al., 2006). At the Rosnedra CDC meeting, the EPS Concept was approved by the following clause: To recognize the need to switch to the compilation of 3D geological and hydrodynamic models of reservoirs based on the concept of effective pore space (Session of the Central Commission for the oil and gas development, 2006).

This excursion into the past is given because the EPS concept has not yet been included in the life of the oil and gas industry of our country. It is despite the fact, that the EPS Concept allowed the creation of new field development technologies that could not be created when focusing on the obsolete APS Concept. As an example, we refer to articles (Zakirov et al., 1988; Kusanov, 2011) about the technology effective for carbonate reservoirs by one of the authors of this article. The article (Zakirov et al., 1988) outlines a new technology for the vertical-lateral cycling process. This technology has been effectively implemented at the unique Karachaganak field. It was created thanks to the ideas of the EPS Concept. Such a development technology could not be created, and therefore implemented, if we follow the APS Concept.

The EPS Concept and the vertical-lateral cycling process technology are discussed in this paper because, despite the recognition of the Central Committee of Rosnedra, they still have not received widespread implementation even in conventional oil fields. In particular, we refer to an article (Zakirov et al., 2007a) devoted to a new technology, which was never implemented by anyone, of vertical-lateral waterflooding at the final stage of oil field development.

The authors give the cited deviations because in the future, cited and other examples should not be allowed in the upcoming more complicated fields for development. We also do not deny that in order to overcome the corresponding problems, a variety of laboratory and field studies will be required to introduce a new, adequate Concept of effective pore space (instead of the unrealistic Concept of absolute pore space).

In the case of basement reservoirs, representative deep oil samples should be taken with minimal depressions. Based on their research, forecast should be made of the change in oil composition with depth. Appropriate work is needed to build the most accurate fluid model of the reservoir. Forecast errors of only this model can have irreversible consequences from the point of view of further oil production. Since the allocation of an additional phase with a decrease in pressure with its subsequent dissolution in the process of increasing pressure is not an equilibrium process at all stages of the process under consideration. These processes cannot be described by the equations of local thermodynamic equilibrium (Lobanova, Indrupskiy, 2012).

Fortunately, in relation to the White Tiger field, the issue with the fluid model practically does not arise. However, when switching to less permeable reservoirs, serious problems are potentially possible with high-quality deep oil sampling, if only because of the phenomenon of adsorption of oil components on the rock surface (Shcherbyak et al., 2017). When sampling, capture of free oil components is possible. Therefore, the extraxtion process itself may introduce errors in the assessment of oil composition. A separate problem is the requirement to preserve the conditions of the natural state, because a single degassing can disrupt the structure of the liquid phase due to the precipitation of resins and paraffins.

The problem of determining the reservoir parameters of the constituent rocks in the laboratory is closely related to the question of sampling. In relation to the basement fields, it makes sense to abandon numerous laboratory experiments and go on to determine the properties of the reservoir in a natural occurrence. To do this, the conduct of specialized hydrodynamic research of wells (well test) suggests itself. In the limit, in addition to traditionally determined parameters, when combining well testing with well logging, it is possible to differentially determine reservoir properties along the well path, with simultaneous assessment of reservoir properties and dynamic parameters of multiphase filtering, including relative phase permeability curves (RPP) and capillary pressure functions. Appropriate methods for terrigenous reservoirs are reflected, for example, in (Zakirov et al., 2003; Indrupskiy et al., 2008; Zakirov et al., 2008a). It is important that this overcomes the problem of the practical impossibility of determining the three-phase functions of relative phase permeabilities in laboratory conditions. Instead, the corresponding relationships are reliably determined at the scale of the formation.

The problem under consideration is especially important for 3D computer simulation, since when constructing a 3D model, it is necessary to integrate different-sized data related to various characteristic spatial steps. Let us suppose that at the lowest level (corresponding to the smallest spatial step), only equations are used. And the hydrodynamic specialist wants to transfer the measured parameters to a larger, rougher scale, actually performing the upscaling procedure. Will the same equations be executed on a larger scale? The answer is no (Zakirov, 2007). It turns out that when switching from scale to scale, the type of equations being solved changes its form. Additional terms appear that require their adequate definition.

But with regard to scaling in the oil and gas industry, the task is somewhat simplified. It is necessary to correctly recalculate the absolute phase permeability, realizing that when switching from scale to scale, the matrix of the absolute permeability tensor is completely filled. But with respect to phase permeabilities, the following remarkable theorem holds: if in the 3D geological model all the model cells are assigned one RPP curve, determined, for example, on a core, then RPP scaling is not required. The best agreement between the results of calculations on the 3D hydrodynamic model compared to the simulation on the 3D geological model will be obtained without any scaling of the RPP functions.

Thus, if the RPP functions are determined as a result of well exploration, the stage of scaling is overcome by determining the RPP at the reservoir scale. In this sense, the determination of RPP based on a digital core does not overcome the problem of scale. This is an interesting lesson for service companies and mathematicians, but it has nothing to do with development problems.

In theory and practice of developing conventional oil and gas fields, deformation processes in terrigenous reservoirs have long been identified (Strizhov, Khodanovich, 1946). Therefore, a need arose for appropriate laboratory equipment and experimental techniques. The required equipment and research methods were developed by an American professor (Fatt, 1958). Until now, it was his ideas that have been used and applied in relevant laboratory experiments.

Unfortunately, the Fatt technique suffers from a lack of consideration of reservoir conditions in the study of deformation processes. One of the article authors has created and implemented a realistic methodology for conducting deformation studies in terrigenous reservoirs. Corresponding experiments proved the necessity of conducting deformation experiments only when natural reservoir conditions are taken into account (Zakirov, 1998).

Examples of the studies results of natural deformation processes are shown in Fig. 1-3. Experiments were carried out to reduce and restore the inter-pore pressure (experiments were conducted at the Gubkin Russian State University of Oil and Gas) on three core samples. Obviously, the results presented do not agree with the conventional ones.

Unfortunately, to this day, both the equipment and the methodology for conducting studies of deformation processes in carbonate and granitoid, fractured reservoirs are lacking. But it is precise that one will have to deal with in research experiments, in the design and development of real deposits, with "new" properties and parameters. This is also evidenced by the pilot laboratory studies begun by the authors.

So science and technology are in dire need of research in developing the basement fields. The article does not address the issue of technical weapons for exploration and maintenance. Today, even with reference to conventional fields, the equipment and technology for testing, completion and liquidation of production,

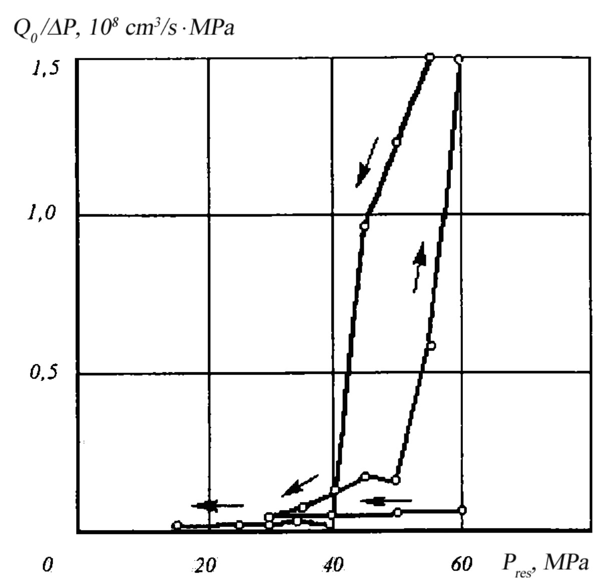

Fig. 1. The dependence of the productivity coefficient on the changing in-situ (reservoir) pressure for core No. 298 (well No. 8 of the Tengiz field)

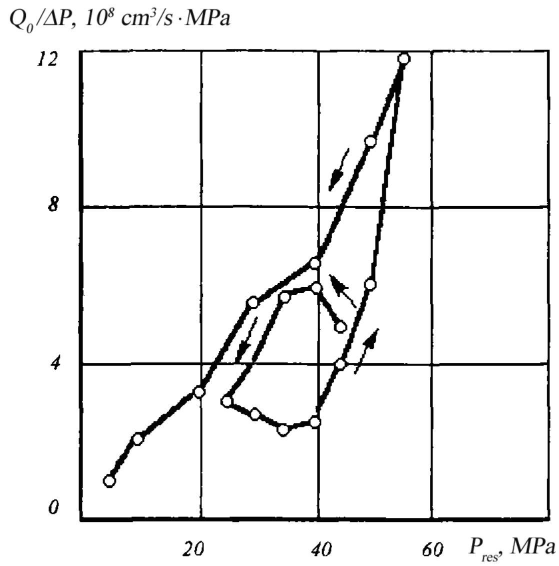

Fig. 2. The dependence of the productivity coefficient on the changing in-situ (reservoir) pressure for core No. 150 (well No. 8 of the Tengiz field)

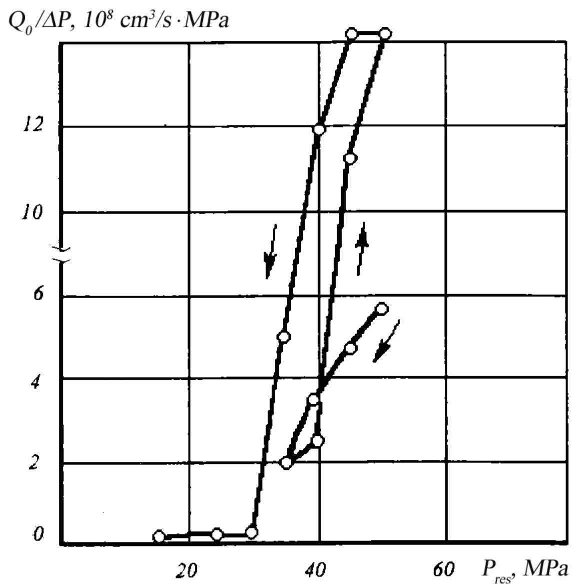

Fig. 3. The dependence of the productivity coefficient on the changing in-situ (reservoir) pressure for core No. 150 (normal to stratification, well No. 8 of the Tengiz field)

injection, prospecting, exploration, and observation wells are not suitable (Zakirov et al., 2016a; Zakirov et al., 2016b). The authors' concerns and considerations for overcoming serious environmental problems are not taken into account or solved by anyone. The corresponding problems, figuratively speaking, must be foreseen and resolved in advance even regarding conventional fields.

A reliable determination of fluid contacts is imperative. The absence of an initial oil-and-gas concentration at the White Tiger field and the zonal deterioration of the reservoir properties downward due to the intersection of tectonic disturbances predetermined the vertical distribution of injection wells. The inability to exploit deep producing wells with an acceptable production rate forces them to turn into injection wells. As a result, the development system was formed, not on the basis of scientific ideas, but due to the peculiarities of the geological structure. Fortunately, an effective system with oil displacement based on a bottom-up hydrodynamic model was implemented in practice, taking into account the structural features of the subduction-obduction model.

However, the existing system for maintaining reservoir pressure in some cases was not effective enough. There were a number of injection wells with an accumulated injection volume of millions of cubic meters of water. Water injection into these wells was not very effective, because in the mode of connectivity of fractured-cavernous zones of faults, water flows from such injection wells to production wells, without carrying out useful work to displace oil.

The reserves of the field even within the limits of the developed blocks of the White Tiger field were revised several times, always upward. From the theory of solving inverse problems, it is known that the drained pore volume is the first parameter determined fairly confidently from the development history. Therefore, we should remove the restriction on the amount of oil reserves in 3D geological and hydrodynamic models and not tie them to the calculation of reserves. Artificial retention of reserves at pre-fixed levels leads to a significant distortion of the structure of the 3D model. Recent experience suggests that the oil and gas reserves, even with competent estimates, are not unshakable. This is due to the deep flow of oil and gas. Negative reserves also arise due to depressurization of wells and equipment.

The adaptation of the development history in an automated mode is effective only if there is factual information about the flow rates of the components and the pressure in the wells. If these parameters are not present, then no fine-tuning of the 3D model is possible.

Therefore, in the basement fields, development control should be maximized. It is advisable to switch to the use of intelligent wells using all kinds of sensors, with interval-wise control of inflow to production wells and control of injection zones into injection wells. Then, information on the occurring in the processes in the volume of the reservoir will continuously accumulate in 3D hydrodynamic models due to the assimilation of these measurements. It is desirable that the principles of 3D geological modeling are not violated during adaptation (Zakirov et al., 2014).

Based on the updated reservoir model, it is possible to automatically control the operation of production and injection wells, taking into account the limitations of the operation of ground equipment, including limiting parameters of pipeline capacity (Zakirov, 2000; Zakirov, Zakirov, 1997).

As a result, the development of basement fields will become more efficient and adaptable to the conditions of the processes occurring in the reservoir. It will be possible to manage the development in a closed cycle, based on a permanent 3D reservoir model (Zakirov et al., 2015).

The development system must be formed in such a way as to allow its adaptability to changing reservoir conditions. It should also provide information by measuring indirect parameters, additional exploration and the specified location of the sealing wells and new prospecting and appraisal wells with the maximum possible deepening into the basement body and taking into account the geological model of its structure. But most importantly, due to a well-organized system of reservoir pressure maintenance, it is possible to effectively displace oil to production wells, with maximum coverage of the void space by water flooding (Zakirov et al., 2002).

The main conclusion from the foregoing is as follows. Oil and gas subsoil use is not adequately prepared for scientifically sound, environmentally friendly technologies for oil and gas production from the most difficult in terms of geological conditions basement fields.

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DISCUSSION ARTICLE
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An in-depth study of the crystalline basement of sedimentary basins is a dictate of the time

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Abstract. The history of studying the crystalline basement in the Republic of Tatarstan, the state of implementation of the super-deep drilling program is given.

The scientific substantiation of the replenishment of exploited oil and oil-gas fields is provided by feeding them with deep hydrocarbons through oil supply channels connecting the deep source of hydrocarbons with sedimentary cover deposits. The crystalline basement is of interest for the search for hydrocarbon deposits, but its role as a transit for replenishing deposits of hydrocarbon sedimentary cover in the process of constant degassing of the Earth is more attractive and justified. To use these processes, a fundamentally new approach to the construction of geological and hydrodynamic models of oil fields is proposed, taking into account the fundamental principles of geological science on the formation and reformation of oil deposits and the deep processes of Earth degassing.

Prospects are substantiated for the development of "old" fields that are in long-term development, for the calculation of oil recovery factor taking into account oil entering the reservoir from the depths of the Earth, the need for adjusting methods for calculating and accounting reserves, changing levels of material balance, and scientific and practical suggestions for accounting when calculating reserves and designing the development of fundamental principles of field geology.

Further prospects for the introduction of hydrodynamic development methods and their significant expansion due to the opening of the processes of replenishment of sedimentary basin deposits with deep hydrocarbons and the reformation of deposits at a late stage of development are shown.

Keywords: crystalline basement, degassing of the Earth, formation and reformation of oil deposits, hydrocarbons, replenishment

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The problem of hydrocarbon prospecting in the thickness of the crystalline basement in the Republic of Tatarstan (RT) was first raised by B.M. Yusupov in 1936, who insisted on deep oil prospecting drilling along the ancient basement in the northwestern regions of Tatarstan, including Kabyk-Kupersky area, where oil manifestations were established in it. The author argued, "the idea of the futility of the crystalline basement is outdated, since the oil and gas potential of the basement is an indisputable fact" (Yusupov, 1982).

However, targeted drilling to assess the oil and gas potential of the crystalline basement (CB) in the Republic of Tatarstan was not carried out until the early 70s of the last century.

A super-deep drilling program on a crystalline basement for various regions of the Republic of Tatarstan (Muslimov et al., 1980) was developed in 1969 in Tatarstan under the guidance of Professor V.A. Lobov. The theoretical concept of the abiogenic genesis of oil, created by outstanding scientists N.A. Kudryavtsev, P.N. Kropotkin, V.B. Porfir'ev, V.A. Krayushkin and others, was the scientific basis of a comprehensive program for studying the deep bowels of Tatarstan, the beginning of the implementation of which is dated to the 70s of the last century.

The program has combined the following main areas:

- Targeted drilling of the Precambrian base with parametric ultra-deep wells (to a depth of 5-7 km);
- Deepening the crystalline basement into the rocks for the first hundreds of meters by individual exploration wells drilled into the productive horizons of the Devonian;
- Opening of local ancient erosion-tectonic protrusions of the Archean-Proterozoic strata;
- Opening of basement rocks at 550 m by exploration and some production wells.

The main objective of this program was to search for structural inhomogeneities in the body of CB, decompressed permeable zones with circulation of gas-saturated solutions and possible accumulations of hydrocarbon fluids.

As a result, it was possible to approve the drilling of the first ultra-deep well No. 20000 on the crystalline basement on the Minnibaevskaya area of the Romashkinskoe field, which was drilled in March 1973 (Fig. 1).

Based on unique geological data from the well 20000, it was justified to drill another superdeep well 20009-Novoelkhovskaya (the discovered basement thickness was 4077 m) (Muslimov et al., 1976; Muslimov, Kaveev, 1988).

Amazing and unexpected results of drilling these wells and testing about 20 objects in them made it possible to assess the potential oil-prospecting object of the crystalline basement (Fig. 2).

But with the transition of Russia to the capitalist system, this program didn't last for long, not to mention its completion. By inertia, for some time, work was still being done on testing the objects allocated for research in an ultra-deep well 20009. In modern Russia, there are currently no conditions for continuing work on the study of CB associated with the drilling of super-deep wells. Currently, management requires research in order to

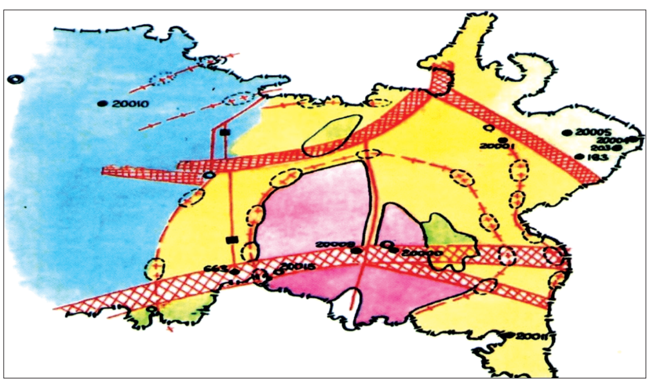

Fig. 1. Project map of the super-deep wells of the Republic of Tatarstan

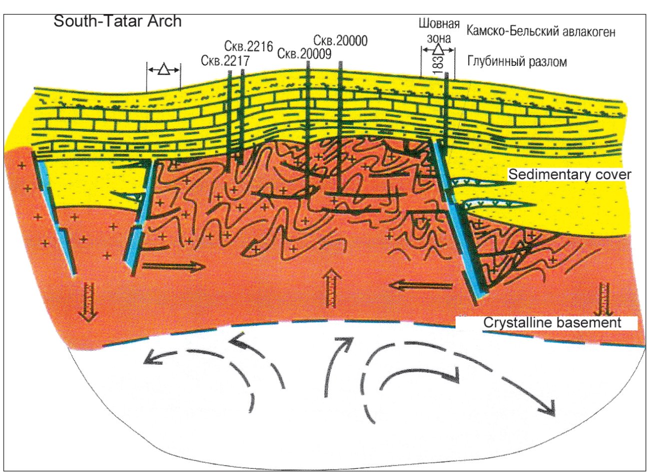

Fig. 2. Hydrodynamic model of the Tatar arch

quickly obtain practical results. But the most important thing that in the leadership of the geological and oil and gas industries today there are no figures with deep state thinking, able to analyze global trends and predict the development of industries for 40-50 years in advance. Such titans were in Soviet times. This is evidenced by the very fact of drilling superdeep wells in the CB in the Republic of Tatarstan. When in an atmosphere of monopoly domination of the biogenic theory of the oil origin and the widespread ban on research on the abiogenic origin of oil, these experts supported our projects on forbidden topics, overcoming their rejection of these views. Without their support, work on the CB in the Republic of Tatarstan would not have been possible. Today it is not necessary to expect the start of some powerful breakthrough work.

But our geologists, specialists and scientists should not despair and need to fully use the results of unique 40-year research on this issue in the Republic of Tatarstan.

Briefly, these results are as follows:

1. The close connection of fields in the sedimentary cover and their structure with geological structure of the basement. This connection is traced not only in higher order structures, but also in details (A.V. Postnikov, L.P. Popova). By studying the geological structure of the basement, we facilitate the search for oil in overlying fields. We can say that the knowledge of the basement is the key to the search for oil in the sedimentary cover.

2. The oil and gas generating and oil conducting role of the basement, as the following factors may indicate (Muslimov et al., 1998; Muslimov, Plotnikova, 1998):

- The genetic identity of oils from the Paleozoic complex of the South Tatar Arch and the bitumen of the basement. It argues for the dominant role of vertical oil migration, which lacks a sufficient source in the sedimentary cover over the South Tatar Arch;

- The confinedness of sedimentary cover oil fields to faults in the basement makes it possible to consider it both as an intermediate link in the migration of oil and gas fluids and as an independent search facility;

- A distinct tendency to increase gas readings, expand the spectrum of methane homologs and the relative increase in the content of its "heavy" homologs (pentane and hexane), the appearance of helium with increasing depth;

- A clear discrepancy between the initial forecast resources of Tatarstan, from which more than 3.5 billion tons of oil has already been extracted, and obtained on the basis of geochemical analysis of Paleozoic dominicites with an estimate of their oil source material in the amount of only 709 million tons for the entire sedimentary stratum, indicating the impossibility of industrial hydrocarbon accumulations due to the oil generating potential of sedimentary rocks.

3. Justification of the search for hydrocarbons in the rocks of the crystalline basement. There are very good reasons, obtained recently as a more in-depth study of the basement. Based on seismic profiling and deep sounding data, a plastic-scaly basement structure was established.

4. The role of the crystalline basement in the constant "feeding" of oil deposits in the sedimentary cover with new resources due to the inflow of hydrocarbons through hidden cracks and gaps from the depths. We have shown the existence on South Tatar Arch of a single oil generation source for oil and natural bitumen deposits. The formation of deposits occurs due to vertically ascending migration of oil and gas fluids through faults that cross the crystalline basement and below the sedimentary cover horizons. This is indicated by temperature research of N.N. Khristoforova (Khristoforova et al., 1999) (Fig. 3).

CDP seismic surveys carried out in the Republic of Tatarstan in the late 1980s and early 1990s on profiles passing through superdeep and parametric wells turned out to be informative. Subvertical dynamic anomalies were revealed from them (Trofimov, 2014) (Fig. 4).

Naturally, the results of such studies required a deeper study of the problem. 20 years ago in Tatarstan, a group of specialists from the Tatneft association, TatNIPIneft, Kazan State University, Arbuzov Institute of Organic and Physical Chemistry under the leadership of R.Kh. Muslimov and I.F. Glumov conducted research on the phenomenon of replenishing the oil reserves of the terrigenous Devonian deposits of the Romashkinskoe field. It was aimed at solving problems of great scientific and practical importance for increasing the recoverable oil reserves of the developed fields (Plotnikova et al., 2011; Plotnikova, Salakhidinova, 2017).

An analysis of the geological and field data of the long-term operation of production wells of the Romashkinskoe field made it possible to justify the presence of modern hydrocarbons into the industrial oil reservoir of the Pashian horizon of the Romashkinskoe field (Plotnikova, 2004; Plotnikova et al., 2011; Plotnikova, Salakhidinova, 2017) and to located inflow of new portions of hydrocarbons. When analyzing geological and field data, a number of criteria were developed that made it possible to single out from the total number of production wells those in which hydrocarbon inflow was most likely recorded. Such wells are called abnormal. Comprehensive analysis of geological and field data performed at TatNIPIneft 2005-2006 led by R.R. Ibatullin, S.G. Uvarov, allowed to distinguish from the entire well stock those that met certain criteria of anomalies. Wells with accumulated oil production of more than 0.5 million tons, working life of more than 40 years, accumulated oil and water factor of not more than 0.5 m^3/t, growing production rates (more than 100 tons/day) during the course of at least 5 years during the period of falling oil production were attributed to abnormal wells.

Figure 5 shows the ratio dynamics of average production rates of abnormal wells to average production rates of normal wells over 40 years of their operation. As you can see, the maximum values of this parameter were recorded in 1962, 1976 and 1991, that is, with a frequency of 14 years. Moreover, the difference in the flow rates is more noticeable in the early years of development, then it damps as the technogenic impacts on the formation intensify and the total use of in-circuit water injection under excess injection pressure is made. Then, against the background of a decrease in water flooding, the intensity of its manifestation increases again.

The inflow of light hydrocarbons into the Devonian terrigenous formations is confirmed by the dynamics

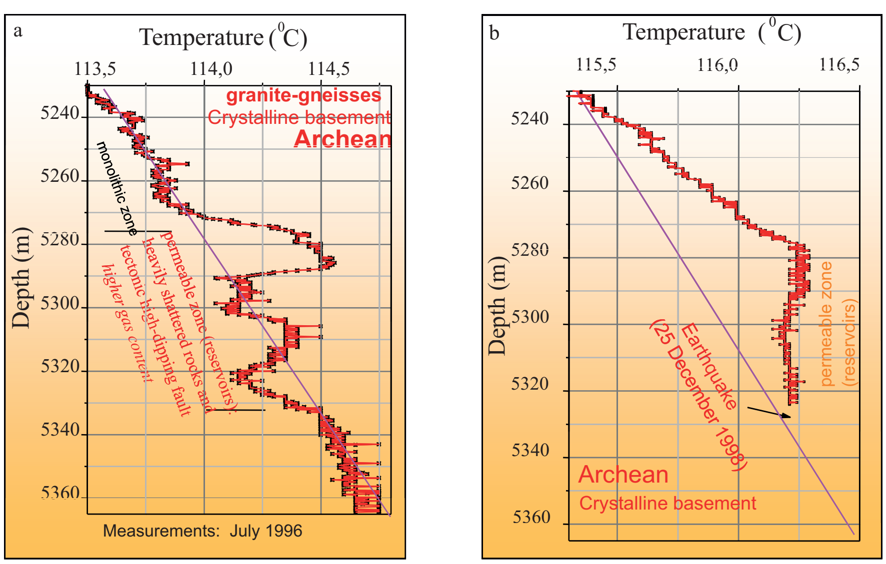

Fig. 3. a – Insteady-state temperature regime (1996, July). Thermogram of super deep well 2009-Novoelkhovskaya. b – Steady-state temperature regime (1999, January). Thermogram of super deep well 2009-Novoelkhovskaya (Khristoforova et al., 1999).

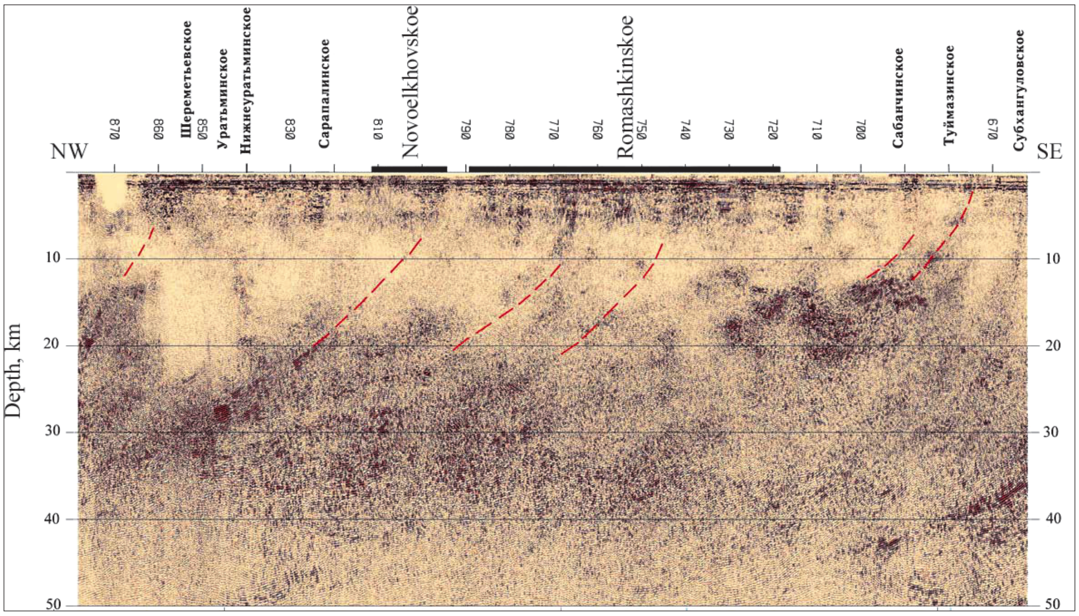

Fig. 4. Illustration of the confinement of oil fields of the South Tatar arch to subvertical dynamic anomalies. The latter, in turn, are associated with the deep structures of the Earth's crust (Trofimov, 2014).

of oil densities, recorded according to the results of the analysis of density changes in piezometric wells.

An analysis of the dynamics of oil density (Fig. 6) from 184 piezometric wells located within the oil fields of Tatarstan (including Romashkinskoe) showed that from 1982 to 1998 the density decreased twice - in 1985 and 1995 (10 years). In 1991, a relative decrease in density was also noted (against the background of three previous and three subsequent years). At the Romashkinskoe field, the dynamics of oil density (according to 58 piezometric wells) is somewhat different. Its minimum values were recorded in 1983, 1985 and 1994.

It should be noted that the revealed frequency of decreasing oil density primarily indicates the frequency of light hydrocarbon and other gases (CO_2, CH_4, N_2, etc.) entering the sedimentary stratum and reservoir, however this does not exclude the fact that deep degassing occurs throughout the entire period, but less actively (Plotnikova, 2004).

The geochemical study of oils from abnormal wells unequivocally testifies to their difference in a number of parameters obtained according to group, elemental, chromatographic and mass spectrometric analyzes and as a result of isotope studies (Ashirov et al., 2000). The results of the studies allow us to differentiate oil from abnormal and normal wells, as well as to identify the relationship of the chemical composition of oils with the geodynamic situation of the area.

As a result, we can conclude that there is a fact of migration of hydrocarbons from the zones of basement destruction to the sedimentary cover over zones of numerous faults and we can say with full confidence that the lower horizons of the Romashkinskoe field are fed by the " breathing " basement.

Numerous analyzes carried out allow us to re-examine oil fields as an ever-developing, fueled by hydrocarbons from the depths of the subsoil.

The confinement of the oil migration paths to the

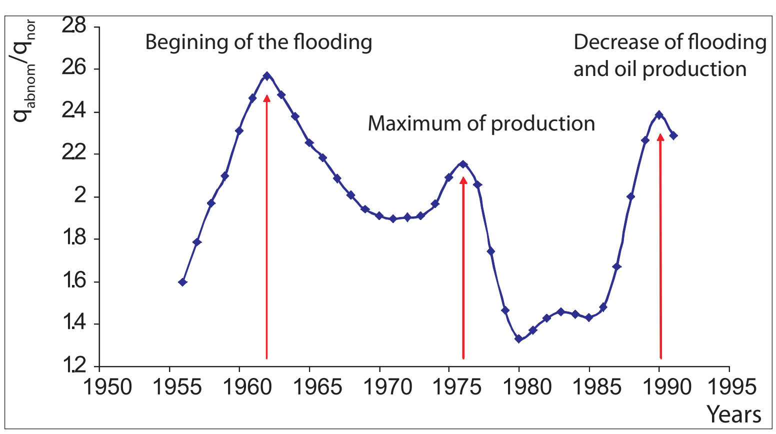

Fig. 5. The dynamics of the ratio of average production rates of abnormal wells to average production rates of normal wells of Minnibaevskaya area over 40 years of their operation (Khisamov et al., 2012)

fault zones, the young age of the oil deposits, as well as the occupancy of the structures by less than 100%, suggest that the process of formation and reformation of oil deposits continues, and thus, the presence of modern oil migration and replenishment of reserves is under development.

This process can be argued from the point of view of the inorganic origin of oil, since the process of deep generation of hydrocarbons and their continuous discontinuous flow into the upper horizons of the earth's crust and sedimentary cover is natural, subject to certain geotectonic conditions.

Traditionally, until recently, it was customary to attribute the reserves of oil and gas fields to non-renewable natural resources, and to associate the formation of deposits with a long (millions of years) period of hydrocarbon generation and their transfer in a droplet state by formation water to the place of trapping. However, the natural release of oil and gas to the day surface, observed over centuries and millennia, as well as the degassing of the rift valleys of the World Ocean and the suction of oil and gas jets at its bottom, established in the second half of the last century, made us doubt this.

Classical examples of the restoration of oil deposits in the Caucasus region, Volgograd Volga region, Tatarstan, considered in the works of N.A. Kas'yanova, M.N. Smirnova, R.Kh. Muslimov et al., V.P. Gavrilov, A.V. Bochkarev, S.B. Ostroukhov et al. have initiated the study of the influence of modern geodynamics on the oil content of the sedimentary cover and the reformation of oil and gas deposits during their long-term development, including the restoration of reserves of previously depleted deposits and changes in the phase composition of hydrocarbons in them. To date, a large number of cases of excess hydrocarbon production over estimated reserves at many fields in Russia and the CIS countries have been recorded. Deposits of the Tersko-Sunzhensky district of the Chechen Republic, Western Kuban, Volgograd region, the Republic of Tatarstan, Samara region, Ishembay and Kinzebulatov groups in the Republic of Bashkortostan - this is not an exhaustive list of objects where the fact of replenishing deposits has already been proved (Ashirov, 2000; Bochkarev, 2010; Gavrilov, 2007; Earth Degassing..., 2006; 2008; 2011; Goryunov et al., 2015; Zapivalov, 2012; Kazantsev, Kazantseva, 2007).

Detailed studies of this process in a monitoring mode, carried out at the Pamyatno-Sasovsky field (Lower Volga region) of LUKOIL-VolgogradNIPImorneft LLC in the period from 1998 to 2002, demonstrated not only the need to study the spatio-temporal patterns of the fluid regime of the reservoir, but also the practical feasibility of organizing similar monitoring studies at any developed oil field (Kas'yanova, 2010).

We do not even need to look for more convincing factors for replenishing hydrocarbon reserves in exploited fields. The phenomenon of recharge can already be considered not just a hypothesis. We see this recharge visually and even evaluate it.

So far, only one way can be proposed to determine the volume (quantity) of oil obtained through recharge. From the total oil production at the facility that we know reliably, we subtract the production from the conventionally exploited deposit (site) from the state-owned reserves, then oil production from modern enhanced oil recovery methods, then production due to the reorganization (regeneration) of the deposit. The remainder can be taken as a contribution to the total oil production from the reservoir in question.

The work should begin by analyzing the state and compiling a fundamentally new innovative project for the development of the field.

To do this, we need a completely new model of a higher generation, new technologies for field and analytical research of the reservoir, new technologies for oil recovery and assessment of the role and volume of reformation of deposits and deep recharge. Moreover, the reformation can occur in two ways: without taking into account the recharge and taking it into account. Reformation without taking into account recharge occurs during the long-term operation of deposits due to gravitational factors, changes in fluid flows in the reservoir and other phenomena associated with development processes. In this case, geological

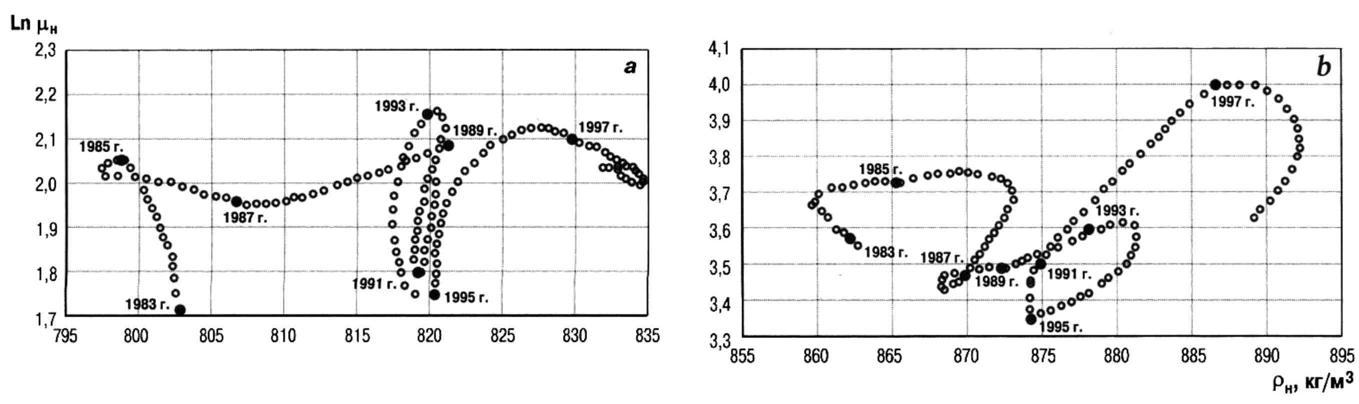

Fig. 6. Changes in the density and viscosity of Devonian (a) and Carbon (b) oils from the Romashkinskoe field during development

(balance) reserves do not change, and recoverable reserves increase. Recharge strengthens these processes and increases both geological (balance) and recoverable resources of the reservoir. Studying the problem revealed a lot of questions.

First of all, it is necessary to solve the problem of reliable accounting of geological and recoverable oil reserves of fields without taking into account recharge. This task seems trivial, but a problem nevertheless exists.

The industry has long overdue the need to reassess the geological resources of all oil and gas fields, since the balance and recoverable reserves, in the old, long-established sense, leave overboard the so-called substandard reservoirs and layers. According to experts, they can make up to 15-20 % of the approved. Moreover, geological reserves mean the entire amount of oil in the bowels, regardless of whether it can be extracted from the bowels today or not (Zakirov, 2006; Muslimov, 2003).

Such a geological model should be based on a fundamentally new approach than is currently accepted in the official documents of the State Reserves Committee of Russia. It should include not only the so-called "conditional reservoirs", as is officially accepted, but also the so-called and substandard oil-containing formations, as shown in (Zakirov et al., 2009; Muslimov, 2012). In this model, faults, crushing zones, and fractures, obtained using various methods of seismological studies and which can serve as oil supply channels, should be shown. As a result, we get a modern, fundamentally new geological model of the field (deposit).

Further, to build the necessary fundamentally different geological and filtration model, the basic geological model should be supplemented by constant monitoring and its adjustment as new data are obtained on changes in the geochemistry and geological properties of the reservoirs, including the composition of oil and dissolved gas, reservoir temperature, dynamics of flow rates, pressures, gas factor, etc.

Extraction due to enhanced oil recovery methods must be considered separately. For the Romashkinskoe field, the methods for increasing the oil recovery factor at the late stages of development were generalized in our work (Muslimov, 2014). The main techniques are as follows: the allocation of small block sizes, isolated geological bodies, the use of modern hydrodynamic enhanced oil recovery methods, then the use of tertiary enhanced oil recovery methods of a higher generation (additional production of residual reserves in the areas developed up to the design level of recovery factor), the use of forced fluid withdrawal.

In exploited fields, it is necessary to organize special integrated geological-field and geochemical studies in monitoring mode for a long time to obtain quantitative parameters of hydrocarbon inflow. This work is very complex and goes far beyond the scope of routine work stipulated by licensing agreements and development projects.

All this requires changes in the documents of the Central Design Commission for the design of development.

In addition to accounting for the volumes of deep recharge of deposits, it is necessary to evaluate production due to the reorganization (regeneration) of deposits in time. According to the hypothesis put forward by the mechanism of oil reservoir regeneration, residual oil, migrating through the pore channels under the action of a pressure gradient, which is caused by the difference in the specific gravity of the displacing agent and the residual oil, will accumulate at the top of the reservoir and flow to the area where the internal energy supply for it will be minimal under given thermodynamic conditions (Dyachuk, 2015).

The replenishment and reformation of the deposits determine the expediency and necessity of using hydrodynamic methods for developing oil deposits as the most suitable for the natural conditions of the deposits formation by the migration of fluids.

Firstly, it must be assumed that the recharge processes are not going on in all developed fields. Basically, they are characteristic of the largest oil and gas fields, and in supergiant fields (Romashkinskoe, Samotlor, Urengoy) they can be counted in dozens. In small and medium-sized fields, the significance of these processes will be significantly lower, or they will not be at all.

Secondly, it should be borne in mind that this recharge is pointwise and it is necessary to determine how to look for these recharge sections.

To solve the problem of the practical use of recharge processes, approval of new documents on the organization of reserves calculation, on the design of development systems, and instructions on the study and monitoring of recharge and reorganization of deposits (Ministry of Natural Resources) is needed.

We'd most like if the features of stable production of long-developed fields, taking into account reformation and replenishment, would initiate a wide discussion of the problem with the aim of changing the rules and design methods for developing oil fields with new approaches to determining the geological reserves of oil and gas fields, based on the fundamental principles of geology. These discussions mobilize the general public to make fundamental changes to the science and practice of developing hydrocarbon deposits. Obviously, this may push official bodies (the State Committee for Reserves, the Central Control Committee, and others) to overdue changes. Then these changes can become a reality by the middle of this century.

The need for detailed geological studies of the crystalline basement receives an additional impetus due to the established relationship between shale and similar sedimentary deposits with the crystalline basement.

The experience of the USA and other Western countries shows great prospects for the oil and gas content of tight rocks, which they believe are based on shale formations. But the latter, based on the experience and accumulation of these types of rocks, are only part of the general concept of tight rocks. At the conference (Earth degassing..., 2006) it was said, "On the one hand, the concepts of" shale oil and gas "and" oil and gas of dense rocks "can be considered inconsistent, primarily because of the criteria for their allocation, and on the other, it must be understood that the latter completely absorb the first. The term "crude from tight rocks - low permeability reservoirs", which is the most general and commonly used in the US oil industry, is more often used today to denote the whole variety of unconventional oil sources, for the production of which special technologies are required, including drilling horizontal and branched-horizontal wells, multistage hydraulic fracturing, microseismic and microscan observations".

The South Tatar arch is a very young structure that experienced a rise on the border of the Neogene and the quarter. The tectonic activation on the vault continues today, which leads to the filling of significant traps with new portions of young oil (Mingazov et al., 2012) In long-trapped traps, oil becomes younger due to the inflow of light and ultralight deep oil, and ultralight-permeable section rocks also accumulate ultralight oil having a very high penetrating ability.

In the USA, light oil is first extracted. But this produced oil is only part of the incoming deep oil due to the low efficiency of the adopted oil recovery technologies. Therefore, the oil recovery factor is extremely low (8-12 %). This indicates great potential for creating new technologies for oil displacement from the deep part of oils of these mixed traps.

Currently, efforts need to be concentrated on the creation and development of methods for extracting young deep oil from mixed reservoirs. The issue of extracting the organic part of hydrocarbons of such deposits (from kerogen) can be resolved only in the long term.

However, obtaining information for the second direction should be carried out now, using wells drilled on the terrigenous Devonian, to collect information on the mineral composition of the Sargaev-Rechitskian complex, its fluid saturation, OM content, its thermal maturity, and the generation potential of these deposits. All of these studies, which are currently underway, will determine the distribution boundaries of Domanic facies rocks in the context, provide all the necessary information about it, and significantly reduce the cost of studying shale strata in the future, when the introduction of technologies for in-situ processing of shale becomes profitable.

As for simply ultra-low permeability rocks, which make up a significant part of the sedimentary deposits of the Republic of Tatarstan, the presence of kerogen is not necessary. There may be oil only in the first group. Accordingly, other technologies are needed that are not exclusively associated with in-situ pyrolysis of hydrocarbons.

The foregoing requires increased attention to the study of the crystalline basement and especially its relationships with fields of sedimentary cover of any genesis and geological structure.

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INFORMATION

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Project

DECISION
of the International Scientific and Practical Conference «Hydrocarbon and Mineral Raw Potential of the Crystalline Basement»

In the period of September 2-3, 2019, the 23rd International Scientific and Practical Conference "Hydrocarbon and Mineral Resources of the Crystalline Basement" (hereinafter referred to as the Conference) was held in Kazan (Russian Federation) as part of the Tatarstan Petrochemical Forum 2019.

Organizers of the Conference: Office of the President of the Republic of Tatarstan, Ministry of Industry and Trade of the Republic of Tatarstan, Russian Academy of Sciences, Academy of Sciences of the Republic of Tatarstan, PJSC Tatneft, CJSC Neftekonsorzium, Kazan branch of the Federal State Budgetary Institution "State Reserves Committee", OJSC "Kazanskaya Yarmarka".

The main goal of the conference is to conduct an in-depth study of the hydrocarbon and mineral resources potential of the the bowels and the role of the crystalline basement in replenishing oil and gas deposits of sedimentary cover in the process of Earth degassing.

The conference was attended by 427 specialists, representatives of 98 organizations, including companies of the Republic of Tatarstan – 42, the Russian Federation – 47 (including Moscow, St. Petersburg, Bashkortostan, Tyumen, Samara and other regions), 24 specialists from far and near foreign countries like China, Italy, Canada, Viet Nam, Egypt, Kazakhstan, Uzbekistan, Belarus, Azerbaijan.

Presentations were made by representatives of academic and university science: the Russian Academy of Sciences, the Siberian Branch of the Russian Academy of Sciences, the Academy of Sciences of the Republic of Tatarstan, the National Academy of Sciences of Belarus, the National Academy of Sciences of Ukraine, the National Academy of Sciences of Azerbaijan, leading universities and research universities.

36 reports were presented and discussed, including 14 plenary, 22 oral at the round table and 54 poster sessions. A collection of conference proceedings has been published, which includes materials from 90 reports as part of the conference program.

The basis for successful development of oil and gas fields is the creation of modern models of the geological structure of oil and gas basins and territories, oil and gas fields and the processes of their exploration and development.

As a result of discussion of reports and exchange of views by the conference participants, the following recommendations were developed:

1. Research organizations should pay special attention to strengthening work on the study of prospecting, exploration and development of oil and gas fields, partially or completely lying in the crystalline basement (CB) of sedimentary basins. It is necessary to take into account the semi-century experience of studying the crystalline basement of the Republic of Tatarstan and the Volga-Ural Oil and Gas Province.

2. The priority areas for in-depth study of the crystalline basement of sedimentary basins at the present stage are:

2.1. Studying the relationship of sedimentary cover deposits with a crystalline basement, understanding that knowledge of the geological structure of the CB is the key to finding oil in the sedimentary cover.

2.2. The study of the oil and gas generating and oil conducting role of the basement, as evidenced by the following factors:

- the genetic identity of oils from the Paleozoic complex of the South Tatar Arch and the basement bitumen, arguing for the dominant role of vertical oil migration, which does not have a sufficient source in the sedimentary cover over the South Tatar Arch;
- the confinedness of sedimentary cover oil deposits to faults in the foundation makes it possible to consider it both as an intermediate link in the migration of oil and gas fluids and as an independent search facility;
- a distinct tendency to increase gas readings, expand the spectrum of methane homologues and the relative increase in the content of its "heavy" homologs (pentane and hexane), the appearance of helium with increasing depth.

2.3. The study of the established phenomenon and the role in the constant "feeding" of oil deposits of sedimentary cover with new resources due to the inflow of hydrocarbons through hidden cracks and gaps from the depths. In the Republic of Tatarstan, the existence of a single source of oil generation in the South Tatar Arch (below the sedimentary cover) for oil and natural bitumen (NB) fields was shown; the formation of deposits occurs due to vertically ascending migration of oil and gas fluids through faults that cut through the crystalline basement and lower horizons of the sedimentary cover.

Studies in this direction have led to the conclusion that there is a fact of migration of hydrocarbons (hydrocarbons) from the zones of basement destruction to the sedimentary cover over zones of numerous faults, which indicates that the lower horizons of the Romashkino field are "fed by the "breathing" basement. The analysis allows us to re-examine oil fields as an ever-developing, fueled by hydrocarbons from the depths of the subsoil;

3. The recharge process can be argued from the perspective of the inorganic origin of oil, since the process of deep generation of hydrocarbons and their continuous discontinuous flow into the upper horizons of the earth's crust and sedimentary cover is logical, subject to certain geotectonic conditions.

4. World experience indicates high prospects for the search for oil and gas in the rocks of the crystalline basement. But the search for oil in the CB can be recommended only in areas where accumulations of oil in the CB have already been identified, i.e. where there are the most favorable geological conditions for this (relatively shallow depths of the CB, small thickness of the sedimentary cover, fracturing and fragmentation of rocks, etc.).

In most regions, due to the lack of hydrocarbon prospecting methods in CB, large depths, drilling complexity and the high cost of work, CB research for HC searches should be carried out in limited volumes, without expensive drilling of deep and super-deep wells.

5. When searching and exploring oil and gas fields, we should proceed from the new concept of oil and gas deposits in a sedimentary cover, consisting of:

- traps including a reservoir and an imperbeale bed;
- deep reservoir – a supplier of hydrocarbons;
- an oil supply channel (fractured zones) connecting the deep reservoir with sedimentary rocks.

In this case, the presence of oil source strata – sources of subsoil degassing – was implied.

6. To consider it necessary to create a new methodology for the search and exploration of oil, oil and gas and gas fields, based on the modern concept of the hydrocarbon field, the key link of which should be the search for oil supply channels (faults, crushing zones, fractures) in deep-seated rocks of the CB.

7. The data obtained on the reformation of fields and the replenishment of exploited fields of sedimentary cover allow at the present stage to begin their practical implementation of fundamentally different approaches to the development of oil fields. The experience of the Republic of Tatarstan shows that this must be done through innovative design of development processes.

Innovative approaches to the development of oil fields on the basis of taking into account the Earth's degassing process and replenishing hydrocarbon reserves should be based on the abiogenic theory of the origin of oil and gas and the formation of their industrial accumulations.

8. For such an innovative design for the development of oil fields, fundamentally new geological and geological-filtration models should be built (in contrast to the State Reserves Committee official documents currently adopted). They should include not only "conditional reservoirs", as is officially accepted, but also the so-called substandard oil-containing formations. In these models, faults, crushing zones, fractures, obtained using various methods of seismic and geological studies and which can serve as oil supply channels, should be shown. As a result, we get a modern, fundamentally new geological model of the field (deposit).

9. To recommend the Academy of Sciences of the Republic of Tatarstan the following:

9.1. Together with other scientific organizations of the Republic of Tatarstan, to develop a methodology for constructing geological and geological-filtration models of long-exploited oil and gas fields, taking into account the processes of reorganization and replenishment of hydrocarbon reserves by feeding them from the depths of the Earth due to degassing of the bowels.

9.2. To generalize all geological and geophysical materials obtained during the long-term study of the crystalline basement in the territory of Tatarstan and to prepare for printing a monograph on the results of studying the crystalline basement. For this, it is necessary to develop and approve at the meeting of the Scientific Council of the Academy of Sciences of the Republic of Tatarstan on geology and development of oil fields the structure of the monograph and the team of authors. The monograph should be the result of many years of research on the structure and prospects of the oil and gas potential of the Precambrian crystalline complex, reflect the high importance for science and production of the results obtained, contain primary, initial information on the results of drilling wells that opened the foundation to a considerable depth.

10. In order to organize a monitoring system, the Scientific Council of the Academy of Sciences of the Republic of Tatarstan on geology and development of oil fields, together with the oil companies of Tatarstan, develop appropriate instructions based on the provision on a two-level monitoring system. The first level is the analysis of geological and field data and the identification of potential areas of migration of hydrocarbons into the deposits based on the use of geological and field anomaly criteria established earlier in the Republic of Tatarstan. The second level is geochemical studies of oils and gases dissolved in them both within the wells with signs of anomalies and in adjacent areas of the reservoir.

11. To consider it necessary to conduct (primarily in the largest, long-exploited fields) special integrated geological-field and geochemical studies in the monitoring mode for a long (taking into account the development history) time to obtain quantitative parameters of hydrocarbon inflow.

12. To recommend scientific and industrial organizations to begin work on modeling the processes of reformation and replenishment of oil reserves (“recharge”) in the long-term developed major fields of the Russian Federation and the Republic of Tatarstan.

For this the following is needed:

- to organize special field studies to determine the rate of oil accumulation in the boreholes of highly watered wells and transfer wells to a selection that does not exceed the inflow rate;

- to carry out experimental work on the selection of promising areas for the search for channels for replenishing hydrocarbons from the depths of the bowels.

13. For the practical use of the identified processes of reformation and replenishment of long-term exploited deposits with hydrocarbons from the depths of the Earth’s bowels, it is most appropriate to use hydrodynamic methods for developing fields that are built taking into account the increase in oil production due to the reformation of deposits and recharge from the depths of the Earth’s bowels. These methods are the most developed and correspond to the peculiarities of the geological structure of deposits (especially at a late stage).

14. To ask the Central Reserves Commission to ensure the creation of a new innovative design methodology for the development of oil and gas fields, taking into account the identified processes of their reformation and replenishment from the depths of the Earth’s bowels.

15. To consider it necessary to introduce the developed equipment and technology for the construction of wells opening cracked reservoirs of the crystalline basement and other dense rocks in order to prevent colmatization of rocks of primary opening and completion of wells.

16. In order to accelerate the use of processes of reformation and replenishment of oil and gas fields at a late stage of development, a number of practical steps must be taken:

16.1. To ask the State Reserves Committee to change the methodology for calculating reserves, which includes both conditioned and substandard reservoirs and interlayers in the reserves calculation facility;

16.2. To ask the Central Reserves Commission to develop a methodology for the distribution and accounting of additional hydrocarbon resources through the reformation of deposits and replenishment from the depths of the Earth’s bowels;

16.3. To ask the Central Reserves Commission to create and approve a methodology for innovative design of oil field development at a late stage of developmeny, taking into account additional resources obtained through the reformation of fields and recharge from the depths of the Earth;

16.4. To ask the State Reserves Committee and Central Reserves Commission, the Federal Agency for Subsoil Use – Rosnedra to organize the performance of these works and approve the relevant documents.

16.5. To ask the Ministry of Natural Resources of Russia to organize the development of instructions on the methods of research and monitoring the processes of reformation and replenishment of hydrocarbons from the depths of the Earth at the late stage of the exploitation of an oil and gas field.

17. Modeling of unconventional oil fields (shale deposits, dense rocks) for the purposes of prospecting, exploration and assessment of forecast resources to carry out over large areas of development of promising objects.

To localize the areas of interest of the oil companies of Tatarstan, to conduct special studies (seismic location of the side view, seismic location of emission centers, low-frequency seismic exploration, a combination of methods for studying areal variations of the gamma field, gravity exploration and modern methods of interpretation of seismic data).

18. To consider as a priority for science and oil companies in Tatarstan the creation and development of methods for extracting young deep oil from mixed fields of shale and dense deposits and the role of CB in the formation of these deposits.

19. The following recommendations to the oil companies of Tatarstan:

19.1. To create the necessary conditions for the innovative design of oil field development systems of varying complexity (providing core science, a full set of geophysica surveys and geological research data) and take a direct part in the innovative design of field development.

19.2. To ensure the phased compilation of geological and filtration models, the implementation of a multi-model approach to the creation and improvement of geological and technological models of oil and gas fields.

19.3. To actively use hydrodynamic models to solve various optimization problems for managing the process of developing oil, gas and gas and oil fields: determining optimal bottomhole pressures, optimizing the density of the wells, optimal placement of wells in the field, drilling a sealing grid of wells, drilling horizontal wells, etc.

19.4. To begin work on research and modeling of reformation and replenishment of oil reserves in the long-term developed major fields of Russia and the Republic of Tatarstan.

Based on all the accumulated data, build models on which to calculate, determine the rate of reservoir regeneration in the development process and the amount of hydrocarbon recharge from the depths in order to increase the recovery factor, predict the role of re-formation and replenishment of fields due to degassing of the subsoil in the total volume of oil production in the field.

20. To ask the Ministry of Natural Resources of Russia to assume the functions of the central authority in developing concepts for introducing new technologies (especially on problems of hard-to-recover oil).

For this the following should be taken:

20.1. The Ministry of Natural Resources should undertake financial support of the landfills to test new effective technologies – positively evaluated by the expert and analytical community.

20.2. The expert council under the Ministry of Natural Resources is obliged to become a decision-making body for evaluating various innovations.

21. To determine the Institute of Oil and Gas Problems of the Russian Academy of Sciences as one of the main platforms for the development and evaluation of the effectiveness of modern technologies in the oil and gas field.

22. To ask the leadership of the Republic of Tatarstan to apply to the Ministry of Natural Resources of Russia with a proposal to develop a federal target program for the study and practical use of the problems discussed.

The main components of this program could be the following provisions:

- selection of long-term developed fields located in different geodynamic conditions (Volgo-Ural, Western Siberia, Ciscaucasia), where the most probable natural replenishment of reserves;

- organization of scientific training sites at these fields for a comprehensive study of modern recharge, including monitoring of field, geochemical, and geophysical parameters;

- A detailed study of the geological structure of the crystalline basement at these deposits.

23. To ask the Ministry of Natural Resources of Russia to consider the problems of deep hydrocarbons and the role of the crystalline basement in replenishing the reserves of exploited oil and gas fields.

24. In the relevant committees of the State Duma and the Council of the Federation of the Russian Federation to consider bills that change the funding of scientific and other organizations aimed at improving the efficiency of the oil and gas industry.

25. To consider it necessary in the draft law on Subsoil ”to fix the procedure for assessing forecast mineral resources, testing and recording its results”, to provide for the procedure for compiling reports on geological results of works and evaluating forecast resources; and also regulate the mechanism for testing and presenting the results of the assessment of forecast resources to include information in the state cadastre of deposits and manifestations of minerals.

26. To ask the Ministry of Natural Resources of Russia to regulate the procedure for creating scientific training grounds for prospecting and exploration work in order to obtain geological information on oil and gas resources located in the bowels, especially in unconventional objects (crystalline basement), and to conduct a geological and economic assessment of forecast resources.

27. To forward the decision of the conference to the Ministry of Energy and the Ministry of Natural Resources of Russia and invite the heads of these ministries to take into account in their current work the recommendations set forth in this Decision on the problems discussed.

Organizing Committee

President of the Academy of Sciences
of the Republic of Tatarstan
M.Kh. Salakhov

Chair of the Program Committee
R.Kh. Muslimov

ORIGINAL RESEARCH ARTICLE

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Manifestations of deep degasing into the water column and upper part of the Pechora sea sedimentary section

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Abstract. Studies of acoustic anomalies in the water column and seismoacoustic anomalies in the Quaternary sediments of Pechora sea and their relationship with deep hydrocarbon sources were conducted by the Institute of Oceanology of the Russian Academy of Sciences and the Geological Institute of the Russian Academy of Sciences in the 38th cruise of RV "Akademik Nikolaj Strakhov" in 2018. Mapping of free gas manifestations presents an additional indicator of tectonic activity and the fault network frame, which provides the flow of fluids from deep horizons. Comparison of high-resolution seismic survey data with deep seismic survey data shows that the fluid in the upper part of the section is first accumulated under the bottom of Jurassic-Cretaceous sedimentary sequences, which are fluid-resistant. Local dislocations of fluid trap lead to further rise and redistribution of free gas in Quaternary sequences. Natural or artificial break of their integrity results in the release of gas into the water column from near-surface accumulations that were found in the form of "bright spot" anomalies on seismic-acoustic records. Mapping of sound scattering objects in the water column shows the degassing areas, which are usually located above the deep faults. "Bright spots" of free gas in the Quaternary sequences have a variety of shapes – multi-tiered and inclined. Gas breaks into the water column occur near the edges of these anomalies. Systematic mapping of the considered phenomena is a necessary element in the preparation of the area for industrial operation.

Keywords: sound scattering objects, seismic acoustic, faults, degassing, bright spot

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Introduction

The Pechora sea has a good geological and geophysical study of deep seismic methods and drilling, the results of which are summarized in the State geological map of the 3rd generation (State geological map..., 2013) (Fig. 1). The hydrocarbon potential of this region is huge and the Prirazlomny field has already been put into operation from the platform in the sea. Drilling in the Pechora sea has experienced accidental gas emissions. When drilling with the "Bavenit"-AMIGE drilling ship in the Pechora sea in 1995, 60-70 km west of Vaygach Island, a gas deposit was discovered at a depth of 50 m below the bottom inside sandy sediments under a permafrost layer with ice presence. The resultant gas discharge into the water column created an emergency for the drilling vessel, and the aeration continued for several days with gradual attenuation (Bondarev et al., 2002; Bogoyavlensky, 2015). The upper part of the section of the sedimentary sequence in this region, as in other parts of the Barents Sea (Solheim et al., 1998), is characterized by strong variability in the composition, thickness of the Quaternary sediments and diamicton (Krapivner, 2018; Dunaev et al., 1995), occurring in eroded Mesozoic complexes (Shipilov, Shkarubo, 2010), and the presence of frozen rocks (Krapivner, 2018), which are a fluid seal for free gas. These formations cannot be investigated with the resolution of seismic studies of the section to depths of up to 10 km using signal sources with frequencies up to 100 Hz.

The upper part of the section studies are carried out using seismic-acoustic systems based on sparker sources (frequencies up to 1000 Hz), profiler with frequency-modulated signals (frequencies from 2 to 16 kHz) or parametric profiler (Levchenko, Merklin, 2003). Detailed mapping of the upper part is also accompanied by multi-beam echo sounder, usually with the possibility of registering an acoustic field in a form similar to side-scan sonar and recording sound-scattering objects in the water column. The degree of geological certainty of the Pechora sea by seismic-acoustic methods is very high. In

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the course of these studies, in addition to the separation of Quaternary sediments into seismic stratigraphic complexes and seismic facies according to the characteristic features of the wave field, gas saturation facts were established in weakly consolidated rocks of the upper part of the section (Kostin, Tarasov, 2011; Rokos et al., 2001). It is indicated that accumulations of free gas are confined mainly to permafrost zones in the region of sea depths of 50-70 meters and smaller.

As a result of studies of the 13th cruise of the RV “Akademik Sergey Vavilov” (Institute of Oceanology of the Russian Academy of Sciences, 1998) (Levchenko, Merklin, 2003), many acoustic anomalies were identified in the Pechora sea associated with the migration of hydrocarbons from deep deposits into the upper part of the sedimentary section and into the zones of cryolithogenesis development. Accumulations of hydrocarbons in the form of gas lenses are observed in the Cretaceous complexes, the roof of which in the Pechora sea according to the frame network profiles 2008-2009 is located at depths of up to 300 meters (section KS1004, well Pomorskaya-1) (Kazanin et al., 2011). In the presence of tectonic dislocations (sections KS0928 and KS0932), hydrocarbons can migrate into the upper part of the section and into the water column with the formation of the observed acoustic anomalies of various configurations depending on the relationship with the cryolithozone. A study of these phenomena associated with deep hydrocarbon sources was continued on the 38th cruise of the RV “Akademik Nikolaj Strakhov” (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018), the scheme of which is shown in Fig. 1. In this work, we used data from the SeaBat 8111 multi-beam echo sounder (Denmark) with a sonar mode and EdgeTech 3300 non-parametric profilograph (USA). In addition, materials of 2D CDP seismic reflection method were used.

Degassing in the marine extension of the Varandey-Adzvinsky structural zone

One of the areas of the 38th cruise of the RV “Akademik Nikolaj Strakhov” was the drilling site in 1995 at the “Bavenit” drilling ship (Bondarev et al., 2002; Bogoyavlensky, 2015) where a gas emission was recorded (Fig. 2). The position of the test site on tectonic structures is such that it covers thrust faults extending almost to the surface to extend the Varandey-Adzvinsky structural zone to the water area near the emergency well. When approaching the polygon, the

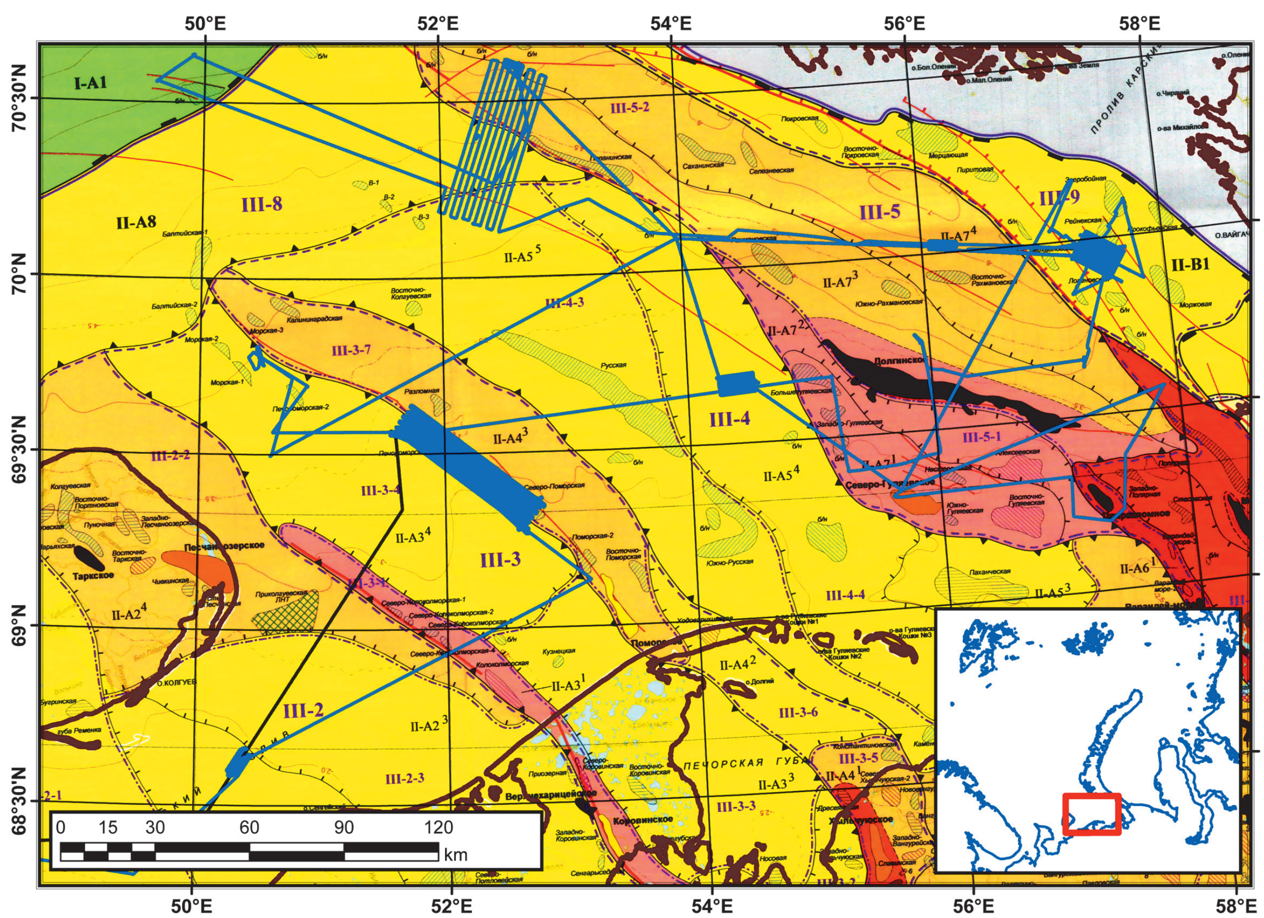

Fig. 1. Scheme of the 38th cruise of the RV “Akademik Nikolaj Strakhov” (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018). Seismic acquisition profiles are shown with a blue line. The oil and gas forecast map from the set of the State geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic basis. In the inset – the position of the main plane table within the Barents sea.

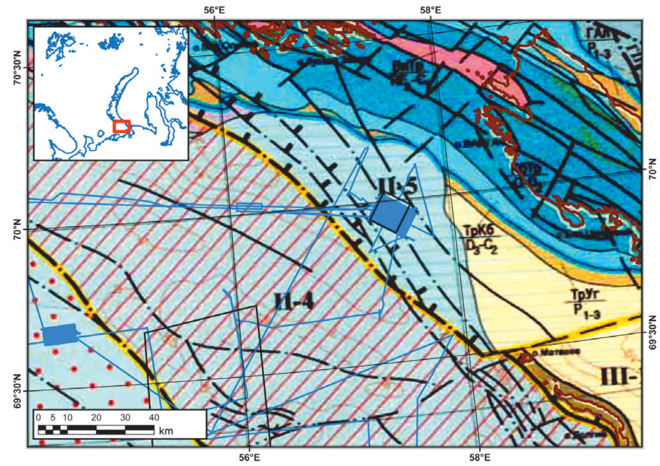

Fig. 2. Scheme of the 38th cruise of the RV "Akademik Nikolaj Strakhov" (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018) and the poligon (black square) in the drilling area in 1995 at the "Bavenit" drilling ship (Bondarev et al., 2002; Bogoyavlensky, 2015), located on the marine extension of the Varandey-Adzvinsky structural zone. As a topographic base, a tectonic map from the set of the State geological map R-39-40 of the 3rd generation was used (State geological map..., 2013). In the inset – the position of the main plane table within the water area of the Pechora sea.

seismic section of CDP 078917 was crossed (Fig. 3), in the upper part of which an anomaly of the "bright spot" type is visible above the sheared thrust structures of the Varandey-Adzvinsky zone. The fluid nature of the anomaly is unquestionable due to a sharp increase in the amplitude of the negative phase in the anomaly and an inversion of polarity in the northeastern edge of the anomaly. Let us note that, judging by the section, the source of fluid is thrusting complexes, which lie with the northeast bearing azimuth, which, according to the data of (Sobornov, 2018), can be of the Early Paleozoic age and be a source of upward migrating hydrocarbons. Jurassic-Cretaceous complexes with clayey rocks lying on the eroded surface can be fluid-resistant, but small dislocations of the bottom of sedimentary complexes at a depth of about 600 ms in this area form channels for fluid to leak into the overlapping Jurassic-Cretaceous complex and Quaternary sediments.

Figure 4 shows the sub-latitudinal section obtained by the EdgeTech 3300 profilograph in the frequency range 2-6 kHz through the area of boreholes 480 and 481 (Bondarev et al., 2002). In the amplification mode tuned to the bottom reflectors, it can be seen (Fig. 4A) that there was degassing in the central part of the section, according to the data (Bondarev et al., 2002). It is represented by an acoustically transparent record that does not show signs of acoustic stratification. In the amplification mode tuned to visualize the sound scattering objects in the water column (Fig. 4B), it can be seen that no anomalies of seismic acoustic recording are observed above this zone. This indicates that, most likely, after a well penetrated through frozen rocks 23 years ago, the free gas accumulated in the vicinity of the drilling zone entered the water column and the plastic frozen environment closed its channel. Acoustic stratification of the Quaternary deposits is present in the western part of the section. The presence of local anomalies of the "bright spot" type in individual recording segments

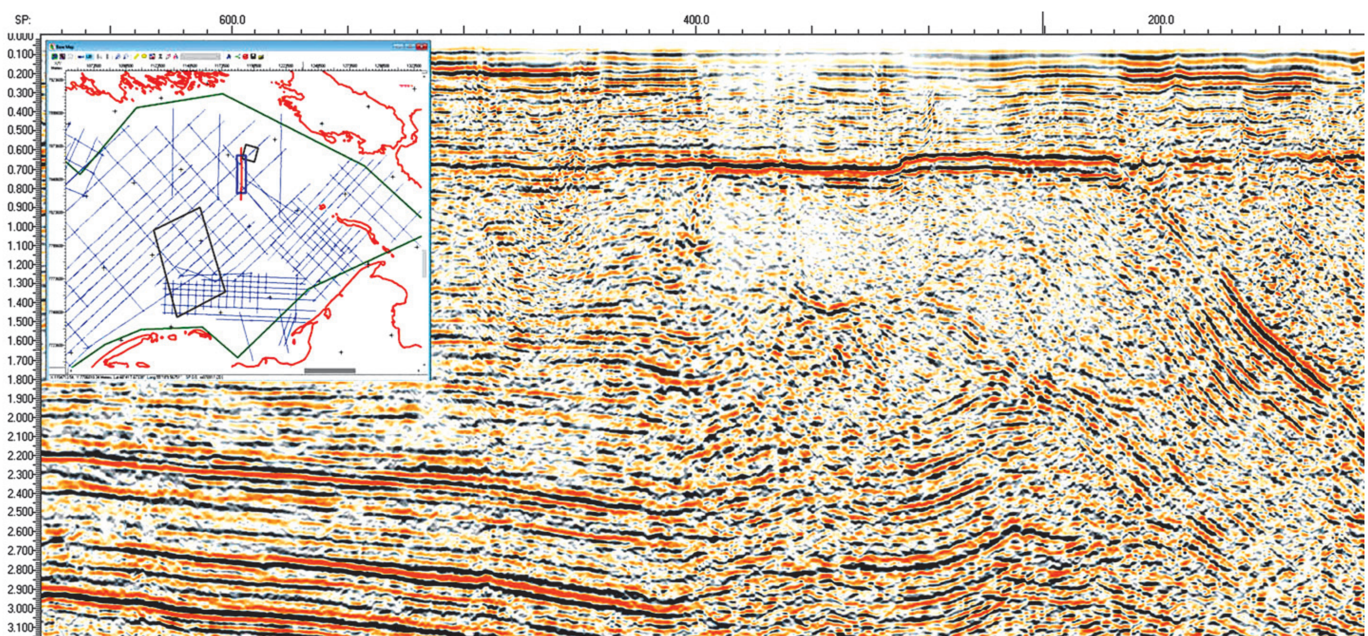

Fig. 3. A fragment of a section of the CDP 078917 (position on the inset). Vertical – seconds, horizontal – CDP assembly number in increments of 50 m.

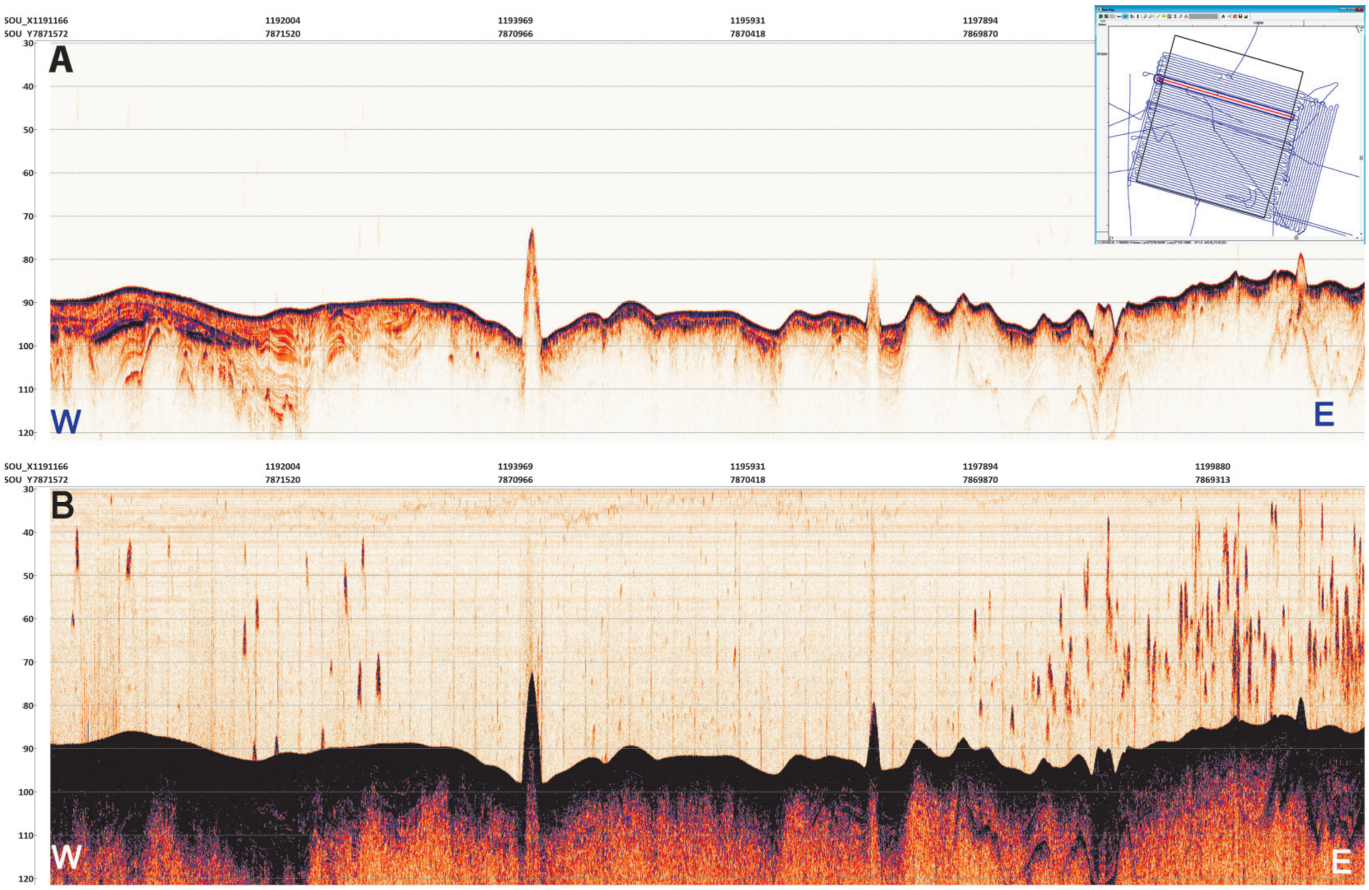

Fig. 4. Section ANS38-P3-26 obtained by EdgeTech 3300 profilograph in the frequency range 2-6 kHz (the position of the section within the polygon of Fig. 2 is shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. A – a section with gain in the range of bottom reflectors, B – a section with gain for the isolation of sound-scattering objecs in the water column.

indicates the accumulation of gases in this part of the section. The presence of rare sound scattering objects in the water column, both rootless, without anomaly binding to the bottom, and root, traceable from the upper sound diffuser to the bottom, shows a slight degassing from the bottom sediments, which is not catastrophic. This is evidenced by the presence of undisturbed "bright spots". In the eastern part of the section, there are much more signs of degassing, but there are no record of anomalies in sediments. Thus, there are various stages of degassing processes – accumulation with the formation of "bright spots", degassing through a system of natural channels, accompanied by attenuation of the amplitude in the anomalies, and catastrophic man-made degassing.

Records of water column anomalies obtained by the sonar mode of a multi-beam echo sounder at a frequency of 100 kHz (Fig. 5) show a similar distribution of sound scattering objects along the same profile. Since the swath angle across the vessel's movement is 150 °, sound scattering objects located on the side of the profile line fall into the record. In addition, the backscattered signal from the head parts of the sound scattering objects in the water column and from the root parts of the sound scattering objects is noticeably more efficient. The latter can be seen in the enlarged inset in the western part of the profile, which shows the ground origin of sound-scattering anomalies. Due to the large band of sonar sounding, unlike the profilograph, the assembly of anomalies from a wide shooting band is recorded. Fig. 6 shows examples of scattering data from the areas of the polygon adjacent to ANS38-P3-26 containing root and rootless sound-scattering objects. The examples show the ground genesis of the contrasting hydrophysical conditions that form the scattered signal, and are an indicator of the deep degassing processes in the area of work.

Degassing in the Varandey-Gulyaevsky tectonic block

Degassing in the Varandey-Gulyaevsky tectonic block (Fig. 2, block II-4 on a topographic basis) (State geological map..., 2013) has deep roots. Figure 7 shows a fragment of the CDP section 078681, in which at a depth of about 500 ms a bright spot with an increased amplitude of the negative phase is distinguished under the bottom of the Jurassic-Cretaceous complexes. This indicates fluid accumulation under the reflector. In several places on this section, and in particular on the presented fragment between gathers 150 and 200 above the reflector, heaving mounds are observed

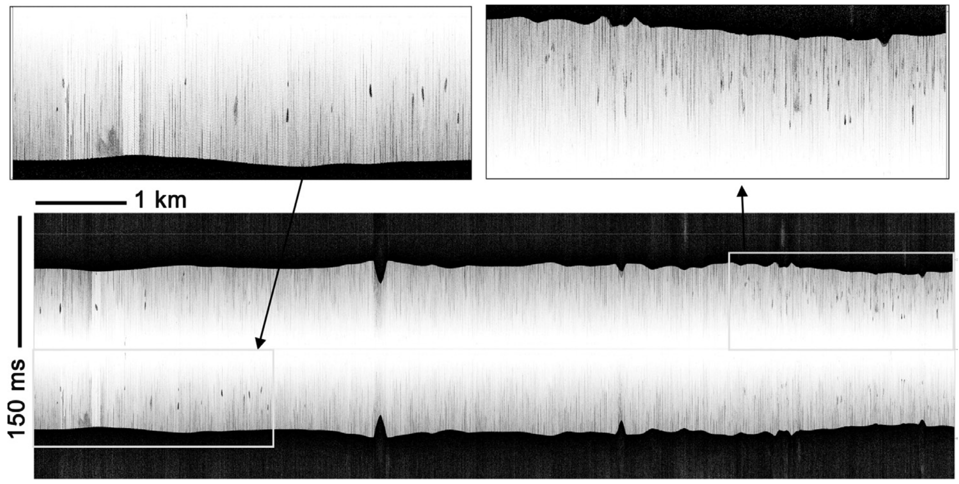

Fig. 5. Section ANS38-P3-26 according to the sonar mode of the SeaBat 8111 echo sounder, similar to side-scan sonar without applying the procedure for eliminating the water column. The inset shows sound-scattering objects in an enlarged view. This section contains interference from an electric spark source.

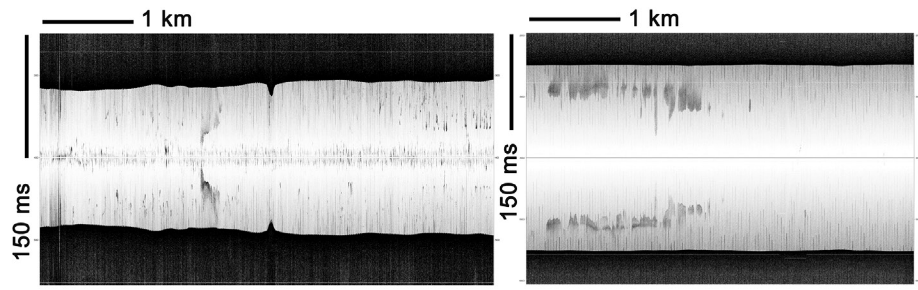

Fig. 6. Examples of sonar mode data for the SeaBat 8111 echo sounder from areas adjacent to ANS38-P3-26 without the use of the water column removal procedure containing root and rootless sound-scattering objects.

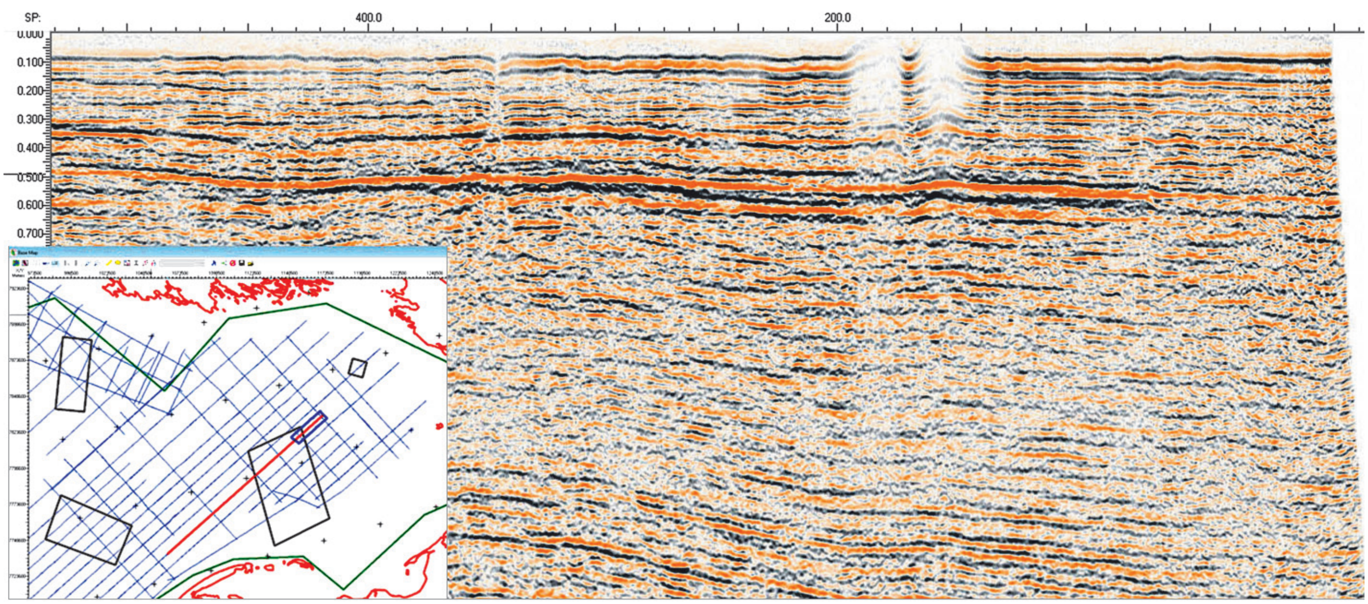

Fig. 7. A fragment of the section of the CDP 078681 (position on the inset). Vertical – seconds from the surface, horizontal – CDP assembly number in increments of 50 m.

with a visible drop in the instantaneous frequency of the reflectors and acoustic brightening. They are probably confined to the places where the fluid breaks to the surface in an area accessible for mapping by a high-frequency profilograph. This record indicates the local rise of weakly consolidated sedimentation under the influence of gases. The reason for the formation of these structures in one place or another is small local heterogeneities and tectonic dislocations in the Jurassic-Cretaceous sediments (horizon B), or deeper faults covering the section before the Paleozoic (Kazanin et al., 2011).

On the fragment of section ANS38-P2-04 (Fig. 8), located next to section CDP 078681, rare manifestations of acoustically stratified sediments with anomalies "bright spot" were found, over which ruptures along the horizon at a depth of about 10 ms are root sound-scattering objects in the water column. The observed configuration of the sound-scattering objects has the shape of gas flares, which in some cases have a root width of about bottom up to 100 m. The obtained wave field pattern indicates intense degassing processes that form gas caps in the upper part of the section, breaking into the water column in the weakened zones with the formation of characteristic sound-scattering objects.

Degassing in the frame of the Khoreyver block

The Khoreyver block (Fig. 9, index II-3 in the inset) westward passes into the mobile zone of increased permeability of the earth's crust (State geological map..., 2013), in which seismic-acoustic records with signs of degassing are traced. On the border of this block with the Murmansk-Kurentsov block in the northwestern part of the works (Fig. 1), a depression of the bottom topography with an amplitude of up to 20 meters is distinguished, which, according to the data (Krapivner, 2018, Fig. 5.11) marks the distribution of the paleorus channel. The intersection of this bottom structure is shown in section 9. Directly outside the zone, a structural feature of the sedimentary section is the presence of depression, the formation of which led to an inclined occurrence of clay sediments, initially deposited horizontally. This is indicated by the presence of angular disagreement on the eastern side of the depression. The cause for the depression formation could be an impulse of intense degassing, which continues at present, as evidenced by the "multi-level" bright spots observed in the section. On the other hand, the trigger for this catastrophic process could be neotectonic activity with a tensile component, along the axis of which the paleo-channel was oriented. The formation of depression was multistep, since erosion section of the inclined layers in the eastern part is observed, and the sediments that seal it in the depression itself have the same inclination configuration. The channel adapted to depression led to the accumulation in its axis of a horizontally layered stratum saturated with bright spots.

Note that in the section of Fig. 9, bright spots are located either in the central part of clay sediments, or with an angle of incidence to the depression axis above the diamicton roof, below which the wave field is acoustically transparent. This suggests that the source of fluid is deep sedimentary complexes, breakthroughs of which are found in places where the integrity of the Quaternary sediments is impaired.

Section ANS38-038 (Fig. 10), which, according to the tectonic map (State geological map..., 2013) intersects the buried fault, contains intense anomalies formed by free gas and having the form of "flat" and "bright" spots. The strong randomization of all underlying reflectors and the complete loss of coherence of the acoustic foundation most likely indicates that fluid breakthroughs come from deeper horizons than the foundation. Also, there is a deflection of the reflectors and the formation of a characteristic depression, subsequently leveled by sedimentation. In addition, we note increased amplitude along the reflectors with a slope suitable for depression,

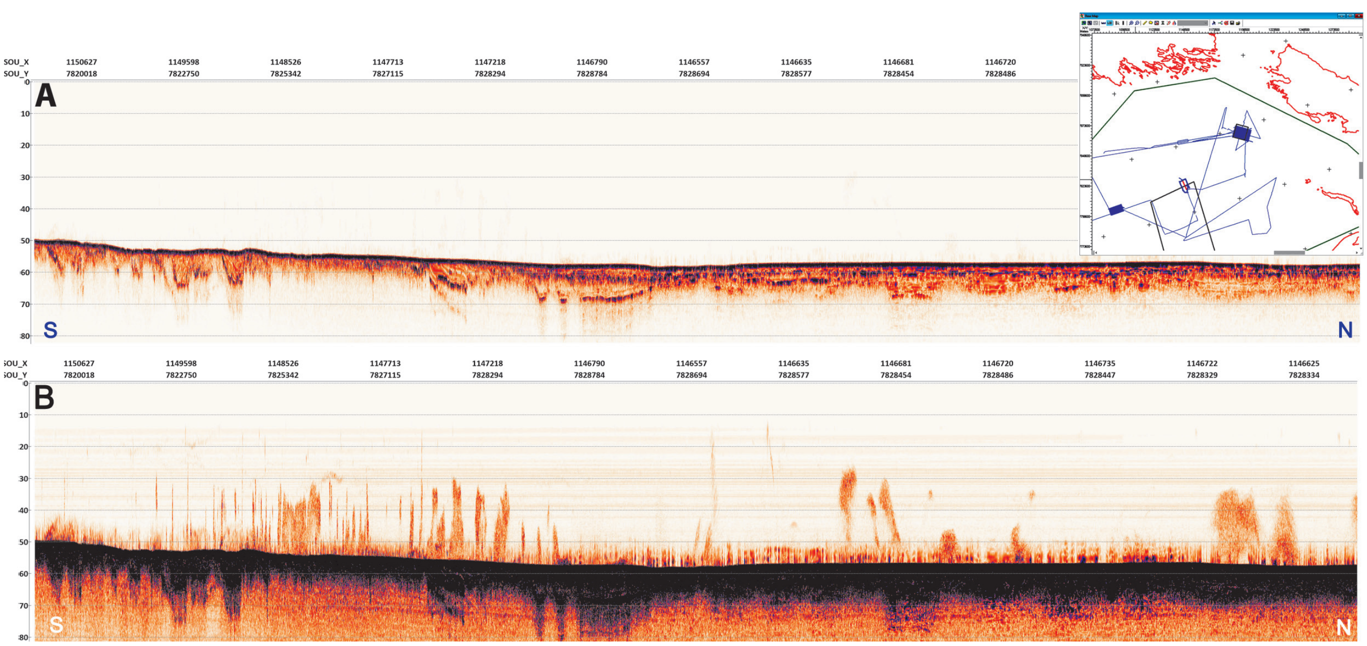

Fig. 8. Section fragment ANS38-P2-04 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. A – a section with gain in the range of bottom reflectors, B – a section with gain to isolate the SRA in the water column.

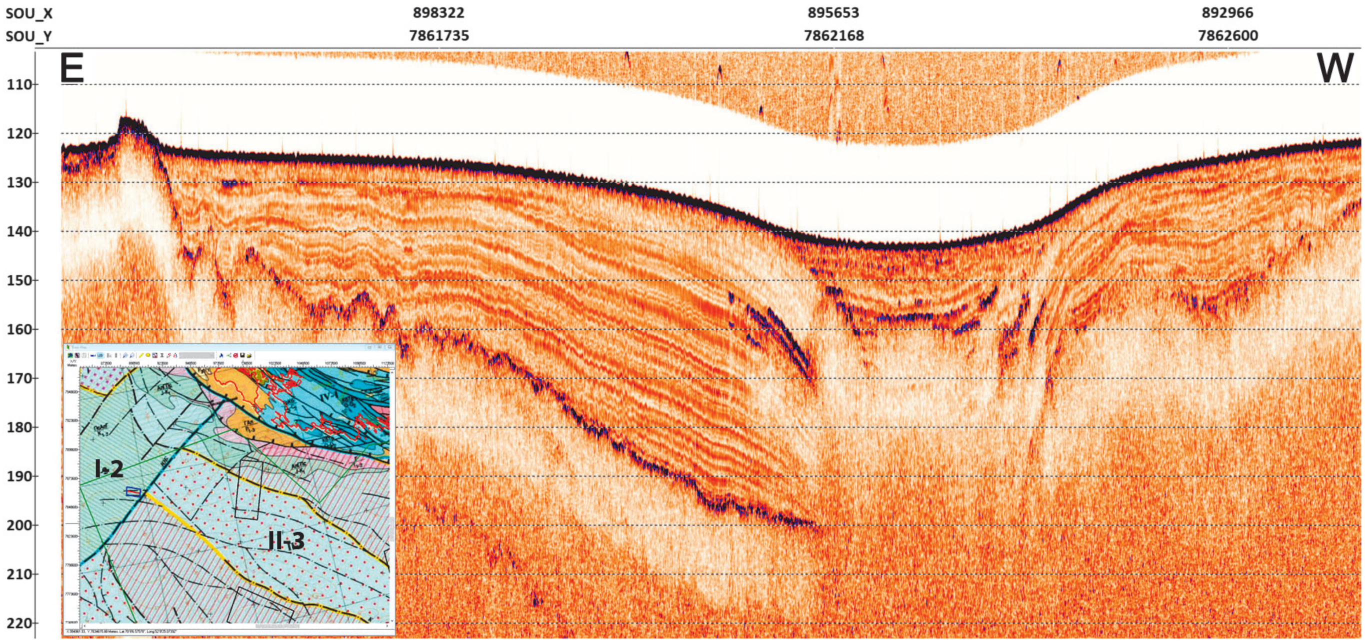

Fig. 9. Section fragment ANS38-014 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. The automatic gain control window is 40 ms long. In the inset, a tectonic map from the set of the state geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic base. I-2 – Murmansk-Kurentsovsky block. II-3 – Khoreyver block.

which indicates a fluid migration upstream. An elevation is formed on the eastern flank of the depression, exceeding the level of the undisturbed horizon. This indicates that a disjunctive dislocation was formed under compression. In the west of the section (Fig. 10), buried pockmarks were noted, under which low-contrast gas pipes are traced.

Synthesis

Mapping of free gas manifestations in acoustic anomalies in the water column and in seismic-acoustic anomalies in the upper part of the section forms an additional indicator of tectonic activity and the frame of the fault network. Apparently, fluid flows from deep horizons in which deposits of industrial importance are formed. Comparison of the seismic-acoustic survey with the data of the deep CPD sections shows that the fluid in the upper part of the section first accumulates under the bottom of the Jurassic-Cretaceous sedimentary complexes, which are a fluid-resistor located on older eroded complexes. Small local disturbances in fluid uptake lead subsequently to the uplift and redistribution of free gas in the Quaternary complexes. The latter are characterized by strong variability of thickness and lithology, and also contain frozen areas, which, along with clay deposits, are fluid-resistant. Natural or artificial violation of its integrity leads to gas discharges into the water column from near-surface accumulations in the form of "bright spots" on the record. Mapping of sound-scattering objects in the water column shows degassing

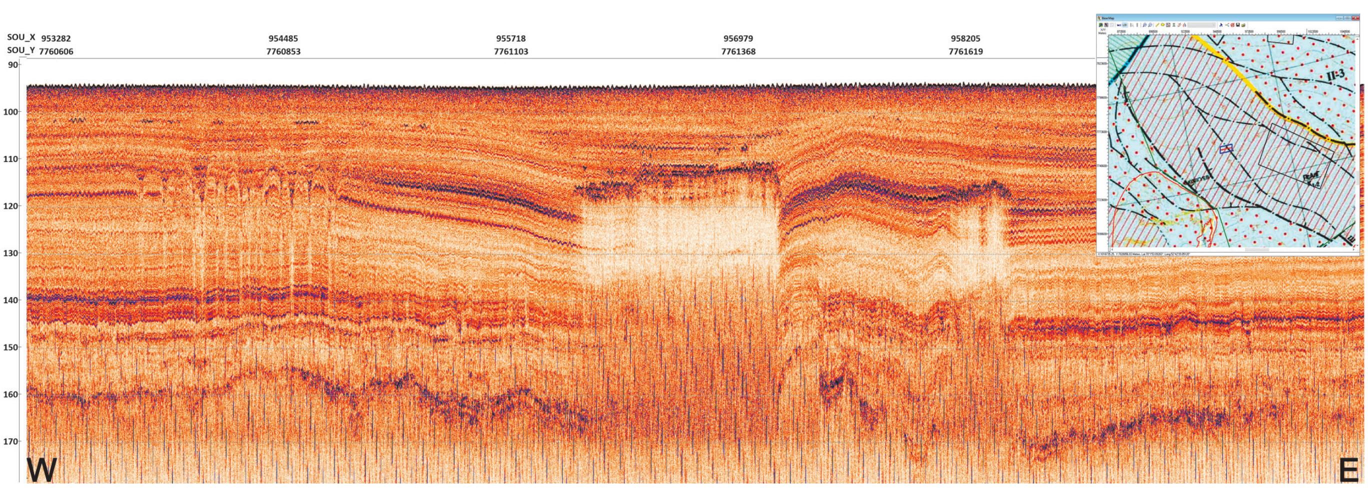

Fig. 10. Section fragment ANS38-038 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. In the inset, a tectonic map from the set of the state geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic base. II-3 – Khoreyver block.

areas, which are usually located above deep faults that displace ancient complexes up to the Paleozoic. This fault network also determines the distribution of paleochannels within the Pechora sea. The "bright spots" of free gas in the Quaternary complex have a diverse shape, sometimes multi-tiered, sometimes tilted, and gas breakthroughs into the water column occur, as a rule, near the edges of these anomalies.

A systematic mapping of the phenomena considered – sound-scattering objects and bright spots – is a necessary element in preparing the area for industrial operation. The features of the mapping technique of time-varying formations of sound-scattering objects are described in (Sokolov et al., 2017).

Conclusion

Let us formulate brief conclusions.

1. Free gas from deep sources forms two-level accumulations near the bottom surface of the Pechora sea – near the base of the Jurassic-Cretaceous complexes occurring on eroded older complexes disturbed by the fault network and in impermeable zones of the Quaternary sediments.

2. The tectonic, lithological, and thermal heterogeneities of the Quaternary sediments lead to the release of gas into the water column and the formation of abnormal sound-scattering objects, monitoring of which shows the state of permeability and activity of the stratified environment on which engineering is being conducted.

3. Seismoacoustic recording of the studied phenomena of degassing in the water column has the configuration of root sound-scattering objects, and in the upper part of the section there is a set of bright and flat spots with different slopes, sometimes with a multi-tiered structure. Anomalies in the water column are usually concentrated near the edges of the anomalies in the Quaternary sediments.

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Geochemical characteristics of terrestrial organic matter in the Upper Paleozoic complex of the Vilyui syneclise and some features of its transformation under thermobaric conditions at great depths

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Abstract. A combination of geochemical methods were used to study organic matter from Permian rocks in the central part of the Vilyui syneclise (East Siberia) penetrated by the Srednevilyuiskaya-27 ultra-deep well in the depth range of 3370-6458 m. This study discusses variations in the pyrolysis indices (HI, T_{max}), hydrocarbon type content (hydrocarbons-resins-asphaltenes), vitrinite reflectance (R^0_{vt}, %), organic carbon content (C_{org}), as well as some trends in the saturated and aromatic hydrocarbon compositions of bitumen extracts from the Upper Paleozoic rocks. Below a depth of about 4.5 km (late mesocatagenesis), the hydrocarbon type composition is characterized by a sharp decrease in the content of asphaltenes from < 30 % (at 4.5-5.0 km) to < 15 % (at 5.0-5.5 km), which are not detected at greater depth. In turn, the resins became the dominant constituent (~ 50-70 %), whereas hydrocarbons account for < 20 % at depths down to 5 km and < 40 % at greater depth. These depths are also characterized by a predominance of saturated hydrocarbons over aromatic compounds with a decrease in the relative contents of high molecular weight compounds in both fractions, as indicated by mass chromatograms. The hydrocarbon index (HI) of organic matter decreases to the first tens from the depth of 4.9 km and to the bottomhole (6519 m); the temperature of the maximum hydrocarbon yield (T_{max}) varies between 570-580 °C, showing a slightly increasing trend. Our results show that the generative potential of organic matter from the rocks within the studied depth range (4.9-6.5 km) has been exhausted and that the terrestrial organic matter undergoes significant changes under severe temperature and pressure conditions at great depths.

Keywords: terrestrial organic matter, hydrocarbon type composition, pyrolysis, catagenesis, ultra-deep well, Vilyui syneclise, chromatography-mass spectrometry

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Depleting oil and gas reserves in the upper horizons of sedimentary basins are becoming a pressing issue worldwide. This requires a thorough evaluation of hydrocarbon accumulations at great depths: the lower boundary of their distribution, the peculiarities of their conversion under severe pressure-temperature conditions, changes in their composition, etc. The deepest well in Siberia, Srednevilyuiskaya-27, was drilled in 1984-1986 down to 6519 m and penetrated the sedimentary cover to the top of the Carboniferous to study the geological structure and assess a potential for deeply buried hydrocarbons. This well is located within the Khapchagai megaswell, to which the largest fields of this petroleum area are confined: Srednevilyuiskoe, Tolon-Mastakhskoe, Sobolokh-Nedzhilinskoe (Fig. 1). In this study, we present the results of the analysis of organic matter (OM) in the Upper Paleozoic strata represented by irregular interbedding of sandstone, siltstone, and mudstone. Permian strata grade into relatively deep marine, coal-rich Carboniferous facies deposited in a shallow-water marine environment (Kontorovich et al., 1994; Tectonics, geodynamics..., 2001). The current understanding of the lithologic, stratigraphic and structural setting of the studied part of the sedimentary section of the Vilyui syneclise is based on the data of Grausman et al. (1980). Core samples collected from the 3370-6458 m interval characterize the following strata: kn – Kyundei (3226-3480 m); hr – Kharyya

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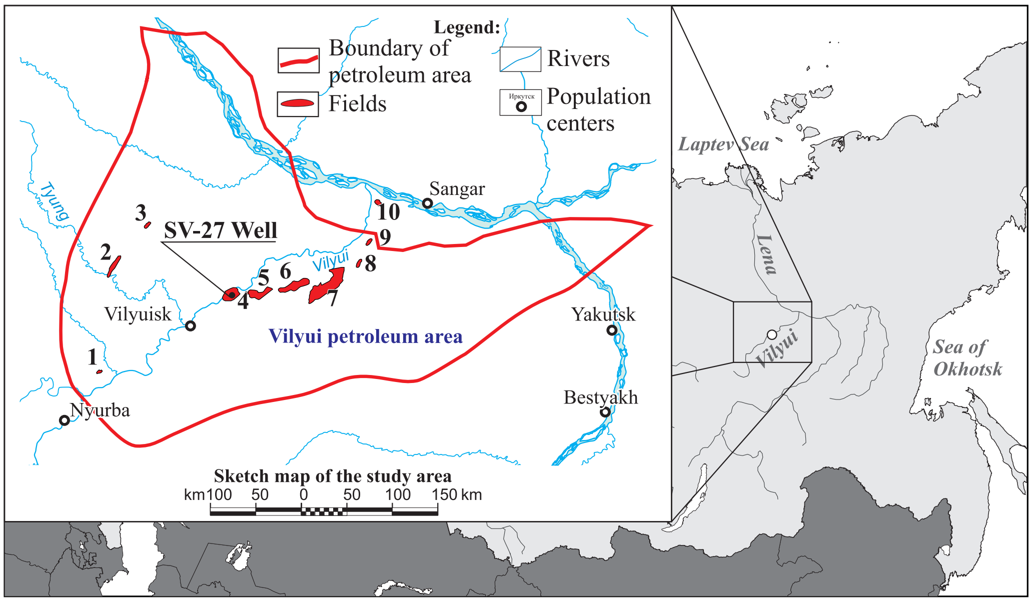

Fig. 1. Location of the Srednevilyuiskaya-27 (SV-27) well in the territory of Vilyui petroleum area. Fields: 1 – Nizhnetyukyanskoe; 2 – Srednetyungskoe; 3 – Andalakhskoe; 4 – Srednevilyuiskoe; 5 – Tolonskoe; 6 – Mastakhskoe; 7 – Sobolokh-Nedzhelinskoe; 8 – Badaranskoe; 9 – Nizhnevilyuiskoe; 10 – Ust-Vilyuiskoe.

(3480-3887 m); hm – Khomustakh (3887-4305 m); kb – Kubalangda (4305-4696 m); hrb – Kharbalakh (4696-5143 m); cc – Chochos (5143-5663 m); jn – Yunkyur (5663-6073 m); jr – Yuren (6073-6519 m).

Since the late 1980s, much of the attention of the researchers has focused on the analysis of dispersed organic matter from Upper Paleozoic sediments of the Vilyui syneclise. Different research teams collected unique data on the variation of predominantly terrestrial organic matter in a relatively homogeneous section during its uniform catagenetic transformation. Kontorovich et al. (1988) presents the data on bitumen extracts, redistribution of hydrocarbon-type composition, and thermodynamic boundary of sharp compositional changes. In addition, these authors proposed a scheme for the destruction of hydrocarbons (HC) during apocatagenesis, including degradation, simplification of their structure, which occur simultaneously with condensation reactions of the structural blocks of asphaltenes (mainly aromatic) and their conversion into an insoluble phase. Melenevsky et al. (1989) examined the variations in pyrolysis parameters and presented the results of electron paramagnetic resonance (EPR) study. Bodunov et al. (1990) discussed changes in the composition of individual hydrocarbons and chromatogram patterns. Subsequent studies revealed the presence of unique compounds in the zone of strong thermal transformation (Kashirtsev et al., 2016, 2017). Polyakova et al. (1999) presented a summary on the hydrocarbon potential of deeply buried horizons by comparing data collected from ultra-deep wells (Tyumenskaya SG-6, Srednevilyuiskaya-27 and Bertha Rogers, USA). The authors analyzed in detail the variations trends in the generative potential with increasing degree of catagenesis.

In this study, we employ a larger number of samples than has been previously used to give a general geochemical characterization of the studied interval, to redefine the boundary of changes in the hydrocarbon composition of hydrocarbons, to trace the transition zone, and to calibrate the obtained parameters with the vitrinite reflectance data.

Methods

In this study, we used the results of the geochemical analysis of organic matter from 71 core samples collected from the Srednevilyuiskaya-27 well, including the level of organic maturity (R^0_{vt}, %), Rock-Eval pyrolysis parameters (HI, T_{max}), hydrocarbon-type composition (hydrocarbons, resins, asphaltenes), and organic carbon content (C_{org}) per rock. Organic matter was extracted from sedimentary rock samples with chloroform and asphaltenes were precipitated with petroleum ether. Maltenes were further separated into fractions by column chromatography. The saturated and aromatic fractions were analyzed by chromatography-mass spectrometry using the Agilent 6890 gas chromatograph with 5973N mass-selective detector. Vitrinite reflectance measurements were performed on a MSFP-2 microscope spectrophotometer. Quantification of organic matter was performed by Rock-Eval pyrolysis in the absence of oxygen, by double analysis of each sample. The total organic carbon content of rocks was determined on an AN-7529 carbon analyzer.

Results and discussion

In modern petroleum geology, catagenesis of organic matter is one of the principal indicators used to assess the hydrocarbon potential of a sedimentary basin, the degree of preservation of the trapped hydrocarbons within the accumulation, and the hydrocarbon generative potential of source rocks, because the relationship between the organic matter transformation and distribution of hydrocarbon accumulations has been established in many regions of the world. Based on the depth zonation of hydrocarbon generation and maturity levels of source rocks proposed by Vassoyevich (1967), Kontorovich (1976) and Neruchev (1973), we defined the boundaries of possible oil and gas generation in Upper Paleozoic sediments of the Vilyui syneclise (Fig. 2). Three zones of hydrocarbon generation were identified in the studied section based on 71 vitrinite reflectance sample analyses. The first zone of predominantly liquid petroleum generation comprises the Kyundei and much of the Kharyya sequences at depths ranging from 3370 (first measurement) to 3800 m. According to the classification of A.E. Kontorovich, this zone corresponds to late MC_2. Despite the fact that liquid hydrocarbons are produced during this catagenesis substage, the intensity of petroleum generation is much lower than that within the oil window, corresponding to substages MC_1^1-MC_1^2. A transition to the wet gas/gas-condensate generation zone is identified down the section. This zone comprises the lower part of the Kharyya, Khomustakh and almost the entire Kubalangda sequences (3815-4700 m) and corresponds according to the above classification to MC_3^1, MC_3^2. Zone III represents early apocatagenesis (AC_1, AC_2) and comprises the basal parts of the Kubalangda, Kharbalakh and Chochos sequences (4700-5500 m). This level of thermal maturity suggests the likelihood of dry gas generation. In the deeply buried Yuren and Yunkyur sequences, the processes of petroleum generation became replaced by thermal cracking of the liquid hydrocarbons and methane formation.

Table 1 shows the distribution of the total organic carbon (C_{org}) in the studied interval. The average C_{org} values of most samples are higher than the average crustal values reported for mudstones (Vassoyevich, 1972) (53 samples >0.9 %) with the maxima lying between 0.9 and 1.9 % (31 samples). The highest C_{org} values are calculated for clay-rich rocks (43 samples), which also indicates their high generative potential. In addition, biomarker analysis also indicates a close link between the oil rims of gas condensate fields within the Vilyui syneclise and organic matter from the Upper Paleozoic rocks (Kashirtsev et al., 2009). The slightly higher values reported for the upper part of the Late Permian section suggest that the residual generative potential (HI) of these rocks is not completely exhausted.

Figures 3 and 4 show Rock-Eval pyrolysis data. A comparison of HI with the catagenesis substages based on R^0_{vt} values reveals that samples with the level of thermal maturity corresponding to MC_2-MC_3^1 have higher residual HI (50-190 mg HC/g C_{org}), which decreases considerably toward the substage MC_3^2. The Kyundei, Kharyya, Khomustakh and much of the Kubalangda sequences forming the Upper Paleozoic section in the Srednevilyuiskaya-27 well to 4.6-4.9 km depth retain their petroleum generative capacity. At greater depths, the HI values of 5-20 mg HC/g C_{org} suggest that the generative potential of these rocks is completely exhausted. The temperature index of the maximum hydrocarbon yield (T_{max}) naturally increases

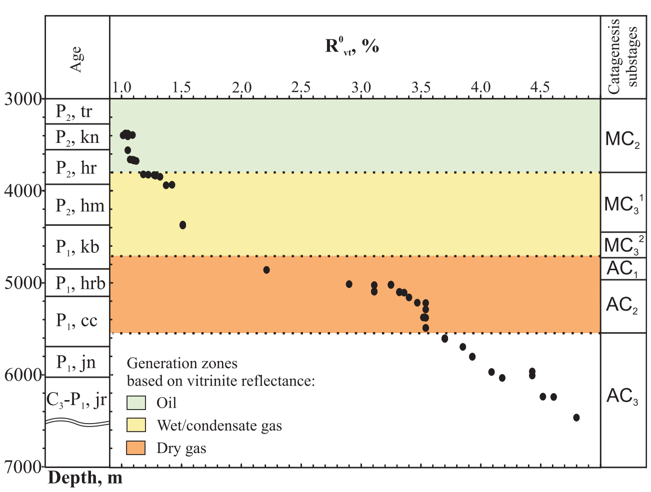

Fig. 2. Changes in vitrinite reflectance values (R^0_{vt}) in the Upper Paleozoic sediments

Distribution of organic carbon content by rocks [**average** (min-max) / number of samples]				
Sequence	Sandstone	Siltstone	Silt-rich mudstone	Mudstone
P_2, kn, Kyundei	-	**2.61** (*3.90-0.84*) / 6	**3.08** / 1	-
P_2, hr, Kharyyas	**0.45** / 1	**1.4** (*2.63-0.58*) / 6	**1.82** (*3.44-0.95*) / 11	-
P_2, hm, Khomustakh	-	-	**1.88** / 1	**1.48** (*1.80-1.15*) / 3
P_1, kb, Kubalangda	-	-	-	**1.33** (*1.44-1.22*) / 2
P_1, hrb, Kharbalakh	**0.16** / 1	-	**1.39** (*1.60-1.06*) / 5	**2.12** (*2.22-1.98*) / 6
P_1, cc, Chochos	-	-	**1.60** (*3.00-0.60*) / 14	-
P_1, jn, Yyunkyur	**0.2** (*0.2-0.1*) / 3	-	**0.70** (*1.40-0.20*) / 5	-
C_3-P_1, jr, Yuren	**0.1** / 1	-	-	**1.80** (*2.50-0.40*) / 3

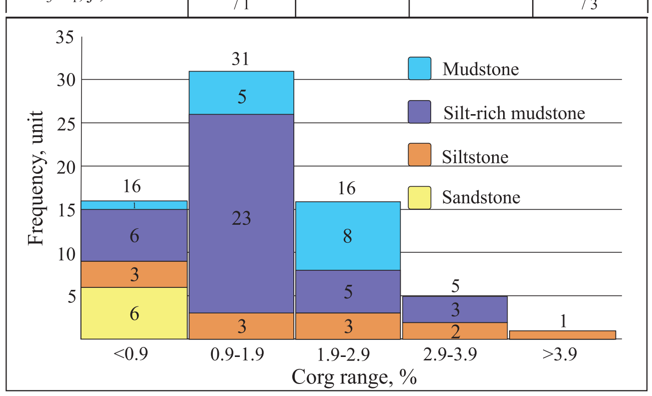

Table 1. Distribution of organic carbon content

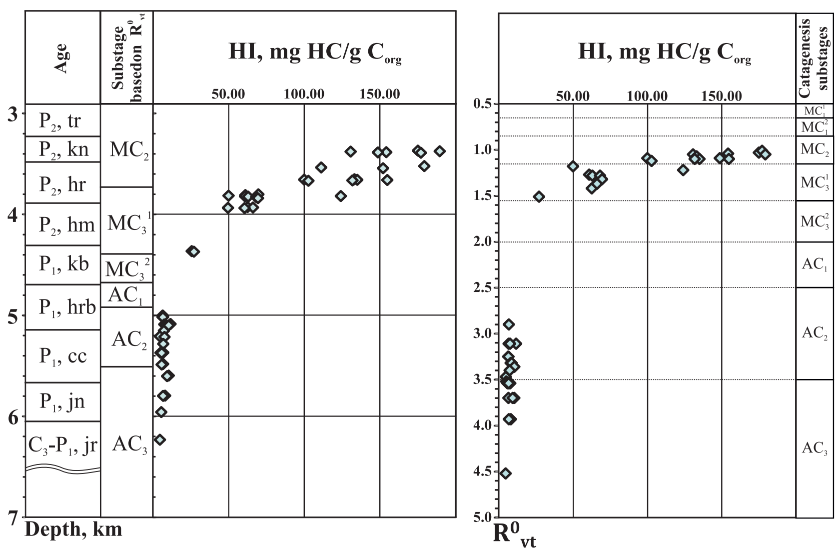

Fig. 3. Variation in residual HI in the well section (left) and with an increase in the vitrinite reflectance index (R^0_{vt}) (right)

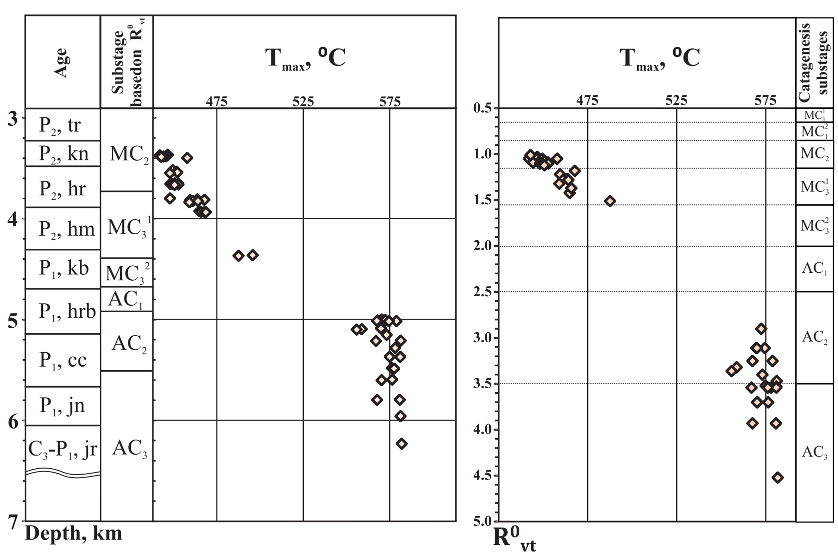

Fig. 4. Variation in T_{max} for the maximum yield of hydrocarbons (S_2 peak) in the well section (left) and with an increase in the vitrinite reflectance index (R^0_{vt}) (right)

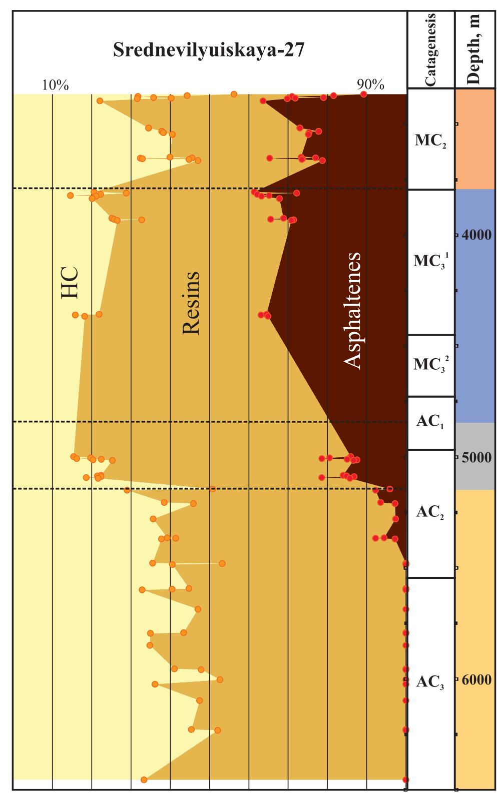

Fig. 5. Depth-dependent variation in the hydrocarbon type composition of bitumens

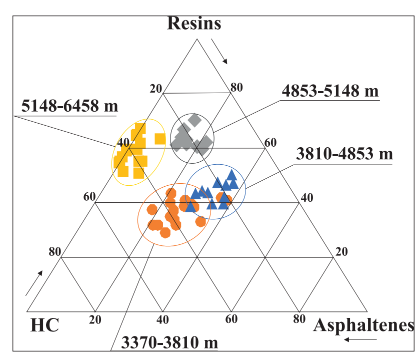

Fig. 6. Triangular plot showing variations in the hydrocarbon type composition of bitumens

with increasing depth and, accordingly, with the degree of catagenetic transformation. Additionally, a comparison of T_{max} and R^0_{vt} gives a correlation coefficient of 0.977. Therefore, the level of thermal maturity of the studied OM type (terrestrial OM from the Upper Paleozoic coal-bearing complex of the Vilyui syneclise) can be reliably evaluated using T_{max}. For example, T_{max} values of 440-460 °C represent the substage MC_2, T_{max} of 460-490 °C shows MC_3^1, T_{max} of 490-525 °C corresponds MC_3^2, and T_{max} >525 °C represents AC. Based on the Rock-Eval pyrolysis and vitrinite reflectance data, we propose the following depth zonation of liquid petroleum generation in the Upper Paleozoic section: oil window down to 3.6 km (R^0_{vt} – 1.1 %, average HI – 150 mg HC/g C_{org}); base of the gas window at 4.9 km (R^0_{vt} – 2.5 %, average HI – 60 mg HC/g C_{org}).

Figures 5 and 6 show variations in the hydrocarbon type composition of bitumens for depths in the range 3370-6458 m, whereas variations in the composition of individual hydrocarbons are given in Fig. 7.

Close attention was paid to the distribution maxima and the ratio of higher homologues to lower homologues. Using this approach, we estimated the effect of severe thermobaric environment on the destruction of compounds with alkyl chain substituents of various lengths.

Chromatograms of saturated hydrocarbon fractions show n-alkanes and those of the aromatic fractions show n-alkylbenzenes as an example. These compounds in the analyzed samples represent a homologous series that displays the depth variation in the ratio of lower to higher molecular weight parts.

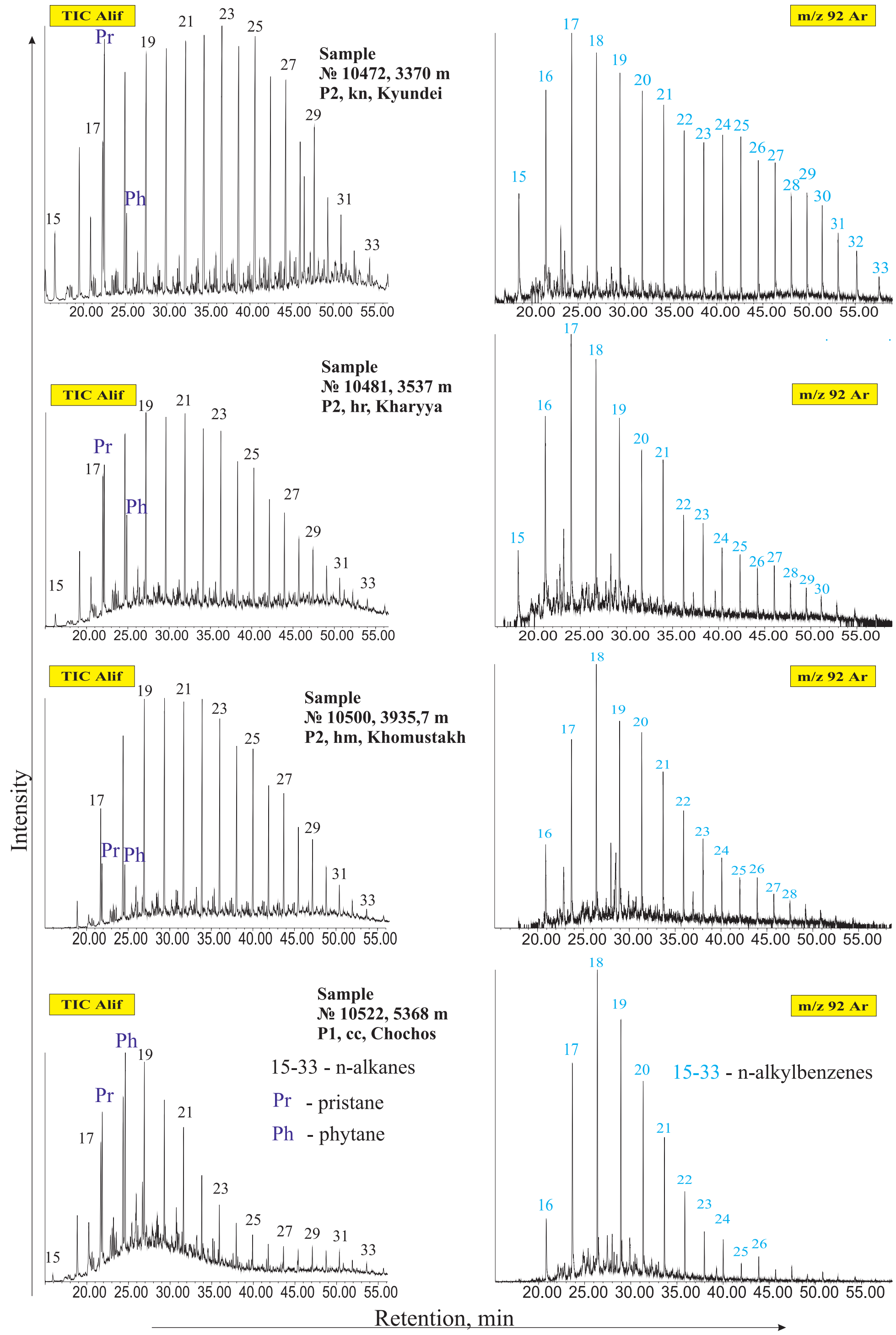

Fig. 7. Total ion current chromatograms (TIC) of normal alkanes and characteristic ions of n-alkylbenzenes (m/z 92)

At depths of 3370-3810 m, representing mid-late MC_2, the composition is dominated by hydrocarbons (35-45 %), while resins and asphaltenes account for <35 % and 25 %, respectively (Fig. 5). This interval is represented by rocks that retained their potential to generate hydrocarbons (they contain allochthonous bitumens, and primary migration is assumed within the Kyundei Formation based on a variation of the hydrocarbon content). For depths, representing the middle part of this substage, the total ion current chromatograms of the saturated fractions show the distribution typical of the continental OM, with peaks at C_{21-25} and a prevalence of pristane (Pr) over phytane (Ph) (Fig. 7). The n-alkylbenzenes have a bimodal distribution with a major peak at C_{16-20} and a small secondary peak at C_{23-26}. At the base of this substage, the main peak of n-alkanes is shifted toward the range C_{19-23}, Pr/Ph decreases, and the n-alkylbenzenes have lower relative content of the compounds with carbon numbers >22. In this depth interval, the processes of hydrocarbon cracking are observed toward the base of the substage, organic matter has high residual generative potential (HI), and processes of petroleum generation take place.

Down the section, at a depth representing late mesocatagenesis-apocatagenesis, we identified two intervals separated by a transition zone, which exhibit a drastically different distribution of these three components (Figs. 5, 6). The first interval, at a depths of 3810-4853 m, corresponds to MC_3^{1-2} – early AC_1. The bitumens display a decrease in the relative content of hydrocarbons (15-25 %) and a slight increase in the relative content of resins (45-50 %). The asphaltene content is 30-35 % and decreases toward late mesocatagenesis. At this depth, the content of saturated hydrocarbons decreases as compared to aromatic hydrocarbons (Fig. 8). This can be caused both by migration and minor petroleum generation, as well as by aromatization of saturated hydrocarbons. The peak in the n-alkane distribution displays a shift toward C_{19} (Fig. 9) and when Pr/Ph reaches 1 phytane tends to dominate over pristane. Such variations in the composition of the saturated fraction have been described earlier (Kashirtsev et al., 2017).

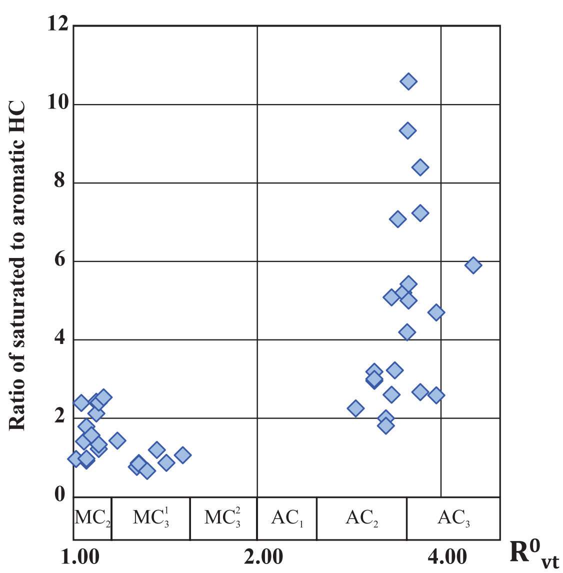

Fig. 8. Variations in the ratio of saturated to aromatic hydrocarbons with increasing catagenesis

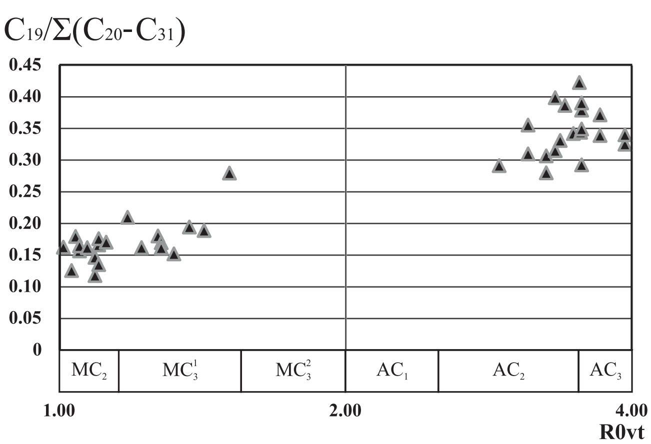

Fig. 9. Variations in the ratio of the relative contents of C_{19} n-alkanes to the sum of C_{20-31} n-alkanes with increasing catagenesis

N-alkylbenzenes have a distribution maximum at C_{18}, whereas the relative contents of compounds with lower carbon numbers decrease, and the peak heights of high molecular weight homologues continue to decrease. In this interval, the processes of cracking or condensation are not observed explicitly at the level of hydrocarbon type composition, but are evident in the distribution of the studied homologous series. The latter suggests that the restructuring of the substance at high temperatures begins before changes in the ratios of the components of the bitumen extracts (HC-resins-asphaltenes) become evident, as will be shown below.

The transition zone corresponds to the beginning of the substage AC_1 (thermobaric boundary at 4853 m). The hydrocarbon type composition is characterized by a dominance of resins (> 60 %), a sharp increase in the content of the saturated compounds (Fig. 8), and a lower relative content of n-alkanes with carbon numbers > 22. This substage is characterized by a sharp increase in resin content due to asphaltene destruction, and, probably, condensation of aromatic structures, as indicated by a decrease in their content of the hydrocarbon component. The homologous series of alkenes, dimethylkanes, alkylcyclohexanes with an odd-to-even-number predominance and four new diastereomers of C_{27} monoaromatic steroids are present only in trace amounts at this thermobaric boundary, but reach concentrations comparable to those of the common biomarkers at greater depths (Kashirtsev et al., 2016, 2017). These authors suggest that these unusual compounds are formed by the destruction of asphaltenes at high temperatures and the removal of occluded compounds.

The deepest interval (5148-6458 m) is represented by rocks with exhausted generative potential. This interval representing middle AC_2 is characterized by a dominance of hydrocarbons (40-45 %) and resins (55-60 %), and a decrease in the content of asphaltenes (<10 %), which are not detected below 5482 m. At the same time, a slight increase in the content of hydrocarbons (~ 5 %) and a decrease in the content of resins is observed with increased maturity level. This zone reflects a further structural simplification, e.g., dealkylation of large structures (mainly asphaltenes), resulting in the increased content of the hydrocarbon component, to form high molecular weight compounds, which then precipitate in an insoluble phase. At the same time, the saturated compounds are the dominant constituents. This can be caused either by enrichment due to the destruction of more complex structures, or by condensation of aromatic compounds, and their further structural incorporation into the resinous component. Kontorovich et al. (1973) noted that the number of paramagnetic centers (NPCs) in terrestrial organic matter increases with increasing degree of catagenesis, and two minima are observed.

In the Srednevilyuiskaya-27 well, one minimum corresponds to late AC_2 (Melenevsky et al., 1989). At this depth the predominance of saturated hydrocarbons over aromatic compounds was reported (Fig. 8). This ratio tends to decrease gradually toward the beginning of AC, which corresponds to an increase in the number of paramagnetic centers. Both saturated and aromatic compounds are present in almost equal concentrations by late mesocatagenesis, whereas the concentration of the aliphatic compounds increases sixfold and more at the beginning of AC_2-AC_3 (Fig. 8). Asphaltenes tend to precipitate completely at the same boundary. It is important to note that based on the data from electron paramagnetic resonance (EPR) spectroscopy (Dindoin, 1973), the aromatic compounds are the most probable paramagnetic centers in organic matter. Also interesting is the increasing number of paramagnetic centers after the above-mentioned minimum may be associated with the consolidation, polymerization, and aromatization of the kerogen structure under severe thermobaric conditions at great depths.

The above transitions in the hydrocarbon type composition of the bitumen follow the scheme proposed by Kontorovich et al. (1988): "...destruction of the liquid products played a prominent role during late mesocatagenesis and was the predominant process during apocatagenesis. The destruction, in turn, occurs in two directions. On the one hand, this can be described as further desintegration and simplification of the structure, following the scheme asphaltenes – resins – hydrocarbons and, on the other hand, condensation of individual blocks, mainly aromatic, and enlargement of the structure, according to the scheme hydrocarbons – resins – asphaltenes, up to the partial transformation of the soluble phase into insoluble one and its precipitation into kerogen." All transitions occur through the resins, because they represent a metastable component under thermobaric conditions. For example, Dobryanskii (1948, 1961) made the following conclusions on the resinous component of crude oils: this component "...is thermally unstable and can easily undergo polymerization, decomposition and overall compositional changes...." In addition, the author described an example when tar oils gave a bituminous distillation residue, while in methane oils the resins coagulated and precipitated as a solid phase or remained in solution in fractions enriched in complex polycyclic hydrocarbons.

Conclusions

A combination of geochemical methods was used to study organic matter in the Upper Paleozoic rocks within the Khapchagai megaswell of the Vilyui syneclise. Based on Rock-Eval pyrolysis and vitrinite reflectance data, we identified several zones of liquid petroleum generation with different phase composition in the sediments in which the generative potential has not been exhausted yet. In this study, we give the correlation of the determination of the level of thermal maturity based on temperatures corresponding to the maximum hydrocarbon yield (T_{max}) and vitrinite reflectance (R^0_{vt}), compare these indicators with those for organic matter from Upper Permian rocks, and provide characteristics of the distribution of organic matter in the rocks within the studied interval.

It was shown that the hydrocarbon type composition of bitumen extracts undergoes significant changes upon maturation (severe thermobaric conditions), which have been described in detail in the previous works (Kontorovich et al., 1988): disintegration and simplification of the structure, taking place together with condensation of the individual blocks and their transition to an insoluble phase. In this study, we traced these changes using a larger number of samples to redefine the depth and maturity levels. In addition, based on the differences in the hydrocarbon type and molecular composition, we identified four intervals in the well section, which differ in the effects of the destruction and condensation processes. We propose possible transition mechanisms between components and describe the mechanisms of noticeable transformations of bitumens at the molecular level during late mesocatagenesis, before sharp changes in the hydrocarbon type composition occur (increase in resin content, asphaltenes discharge). The results of this study can be used to predict the degree of preservation of hydrocarbon accumulations in deeply buried horizons.

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Hydrodynamic features of oil and gas bearing deposits of the southern areas of Ob-Irtysh interfluves

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Abstract. The results of study of hydrogeological conditions of oil and gas bearing deposit of the southern areas of Ob-Irtysh interfluves (southern regions of West Siberian basin) are presented. The hydrodynamic field is characterized by direct dependence and the presence of normal and increased pressure (formation anomalous pressure factor not exceed 1.13) is common in Apt-Alb-Cenomanian, Neokomian, Jurassic and pre-Jurassic complexes. The results of study of the reservoir properties and hydrodynamic conditions indicated that the elision water exchange play the dominant role in the modern hydrogeological structure formation. Two types of water drive system is established: elisional (lithostatical and termodehydrational) in the inner areas (southern part of Koltogor-Nyurol trench, Nyurol megadepression, Verkhnevasyuganskaya anteclise and other structures) and infiltrational within the territory of Barabinsk-Pikhtovskaya monocline. Elisional system is replaced by the elisional-termodehydrational at the depth 2.0-2.2 km. Large piezo maximum zones (southern part of Koltogor-Nyurol trench and Nyurol megadepression) become the inner regions of water pressure generation (the inner feed areas) with the maximal degree of hydrogeological closure of the interior. The region of piezo minima, tracing the structures of the Barabinsk-Pikhtovskaya megamonocline, relates to the external feed area. The hydrodynamic model of the southern areas of Ob-Irtysh interfluves is building for the first time and allow to predict the pressure change trends in the areas with poorly provided with the actual data.

Keywords: elision water exchange, hydrodynamic field, stratal pressure, inter-layer flows, West Siberian sedimentary basin, Ob-Irtysh interfluve

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Introduction

The structure of the hydrodynamic field of oil and gas bearing basins is taking its shape for a long time and is closely connected with the geological history, with the processes leading to consolidation of sedimentary rocks accompanied by the formation of elision water-pressure systems (Kartsev, Abukova, Abramova, 2015) and, as a consequence, by the appearance of increased and anomalously high formational pressure in the hydrogeological section. Since the beginning of prospect works for oil and gas in West Siberia, enormous factual material depicting the structure of the hydrodynamic field has been accumulated. Hydrodynamic studies of the West Siberian sedimentary basin (WSSB) have been carried out by B.L. Aleksandrov, G.D. Ginsburg, A.E. Gurevich, V.I. Dyunin, A.P. Kamenev, V.N. Kortsenshtein, N.M. Kruglikov, B.F. Mavritskiy, V.M. Matusevich, A.D. Nazarov, V.V. Nelyubin, D.A. Novikov, O.V. Ravdonikas, A.D. Reznik, (Kortsenshtein, 1977; Kruglikov, Yakovlev, 1981; Kruglikov et al., 1985; Matusevich, Bakuev, 1986; Aleksandrov, 1987; Shvartsev, Novikov, 1999; Shvartsev, Novikov, 2004; Nazarov, 2004; Matusevich et al., 2005; Dyunin, Korzun, 2005; Novikov, Lepokurov, 2005; Novikov, 2014; Novikov, Sukhorukova, 2015; Novikov, 2017; Novikov, 2017; Novikov, 2018; Novikov et al, 2018; Novikov, 2019). Due to a sharp reduction of exploration work in early 90-es of the past century, the flow of reliable geological and geophysical information had stopped almost completely.

Investigation of the hydrodynamics of the WSSB is of great fundamental and theoretical interest, first of

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all, from the viewpoint of solving theoretical problems considering the mechanisms of the formation of oil and gas deposits, substantiation of an optimal complex of hydrogeological criteria for the evaluation of the oil and gas bearing potential at the regional, zonal and local levels. Second, this is also important for the design of the development of hydrocarbon pools, for the prediction of complications connected with hole making, compilation of hydrodynamic models and recommendations concerning the operation of the systems maintaining the formational pressure, solving the tasks connected with the optimization of waterflooding of the deposits, hydrogeological substantiation of the objects of technical water supply to the fields, utilization of industrial waste waters and bottom water.

Materials and methods

According to the administrative division, the region under investigation is situated in the northern territories of the Norosibirsk Region and the adjacent territories of the Tomsk and Omsk Regions (Fig. 1). According to the oil-and-gas related geological zoning of the West Siberian province, the major part of the territory under investigation is situated within the boundaries of the Kaymys and Vasyugan oil and gas bearing regions.

The best studies reservoirs are Upper Jurassic ones (Yu_1 horizon), because they are the main object of development at the territory under investigation. According to the accepted hydrogeological stratification of the WSSB (Nudner, 1970; Kruglikov et al., 1985), five water-bearing complexes are distinguished within the lower hydrogeological stage in the region under study (Nazarov, 2004; Novikov et al., 2018; Sadykova et al., 2019). They are reliably isolated from the zone of active water exchange by the regional Turonian-Oligocene aquiclude (from top to bottom): Aptian-Albian-Senomanian, Neocomian, Upper Jurassic, Lower and Middle Jurassic, and pre-Jurassic. A specific feature of the geological structure is extremely high degree of nonuniformity and fragmentariness of the occurrence of Lower Jurassic sediments.

The evolution of any sedimentary basin, post-sedimentation transformations of water-embedding rocks starting from the silt stage in the early diagenesis and finishing with metamorphism stage, as a rule, is accompanied by the formation of elision water-pressure systems (Kartsev, Abukova, Abramova, 2015). An elision geostatic water-pressure system is understood as a system of hydrogeological basins confined to the sagging region of the earth's crust composed of a thick stratum

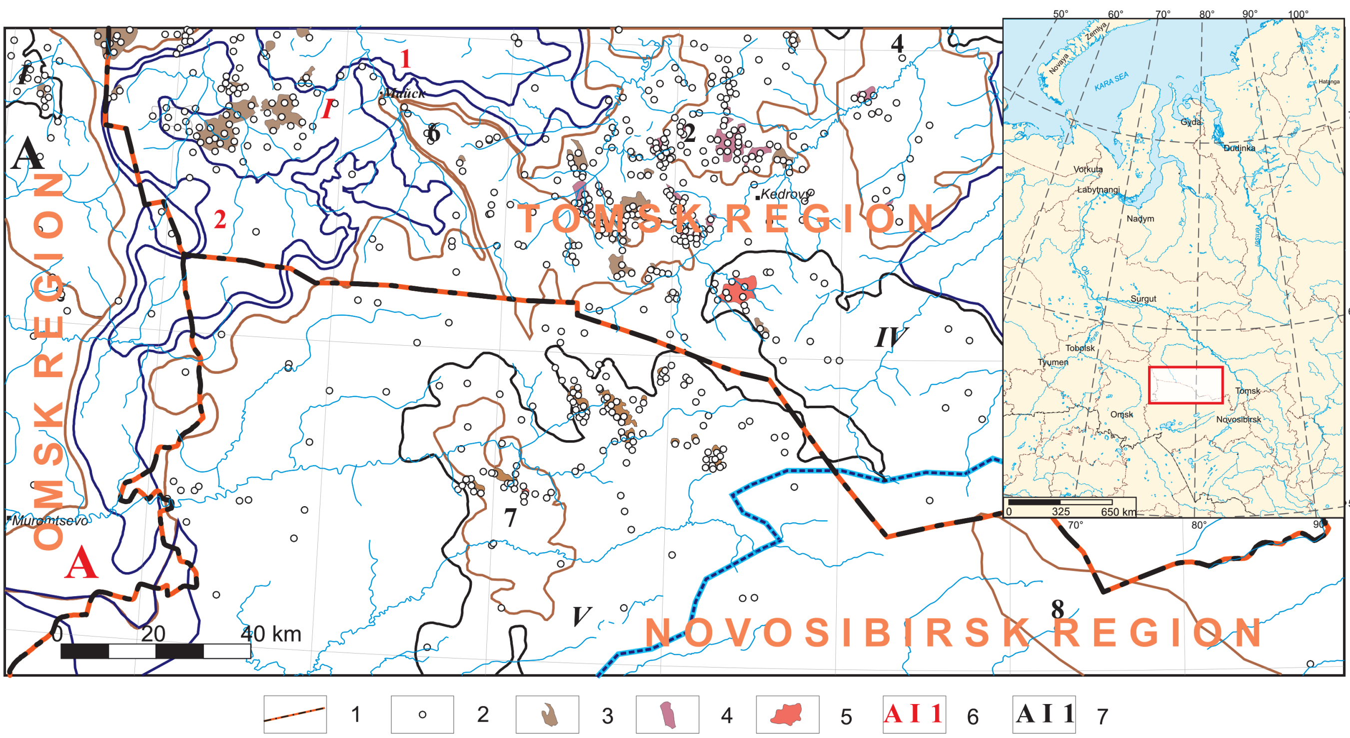

Fig. 1. Location of the studied area within West Siberia: 1 – administrative boundaries, 2 – fields: 3 – oil, 4 – oil-gas-condensate, 5 – gas-condensate and condensate; Tectonic elements: 6 – Negative; 7 – Positive. Names of tectonic elements are given on the map (Kontorovich et al., 2001): Negative: A – Koltogor-Nyurol Trench, I – Nyurol megadepression, 1– Centralno-Nyurol mezodepression, 2 – Yuzhno-Nyurol mesodepression, 3 – Bakchar mesodepression, 5 – Kyshtov inclined mesodownfold; Positive: A – Verkhnevasyuganskaya anteclise, I – Verkhnedemyansky megaswell, II – Parabelskiy inclined megaswell, IV – Kalgachsky inclined megaswell, V – Mezhovsky structural megaforeland, 1 – Kolpashevsky mezoswell, 2 – Pudinskoe dome-shaped mezouplift, 4 – Goreloyarskoe dome-shaped mezouplift, 6 – Lavrovskii inclined mezoswell, 7 – Western Mezhovsky dome-shaped mezouplift, 8 – Verkhneshegarsky mezobulge.

of sedimentary formations in which the feed region is the deepest submerged part of the collector stratum, so that water entering it moves towards the bed rise to the discharge regions. The main form of energy is the potential energy of the elastic deformation of the liquid accumulated in collectors as a result of consolidation of the deposits and pressing waters out of them. Several kinds of the systems are distinguished: 1) systems in which water pressure arises mainly as a result of water pressing from clay into the collectors; these systems are characteristic of relatively young sediments, mainly of the Mezo- and Cenozoic age, at a depth of 2.5-3.5 km; 2) systems in which the source of pressure is mainly solidification of the collectors themselves; these systems are characteristic of relatively ancient sediments. An elision thermohydration system is understood as a system of hydrogeological basins in which water pressure arises as a consequence of the excess amount of liquid during thermal dehydration of minerals, that is, water pressure is controlled by the geotemperature field; thermodehydration of the minerals is accompanied by the release of chemically bound water into the free phase, which leads to groundwater freshening in the deep parts of the hydrogeological basin (Kartsev, Abukova, Abramova, 2015).

Under the action of mechanical forces and physicochemical processes, the porosity of sedimentary rocks decreases, and they get consolidated. The major factor of consolidation is gravity, that is, the weight of the overlapping sediments, which increases with an increase in the thickness of the sedimentary cover (Vassoyevich, 1960). Because of this, the degree of consolidation of clay rocks is determined mainly by the geostatic pressure, while their physical properties depend on the depth of submergence or on the load value. In addition to the load, the value of sand rock consolidation is affected by physicochemical processes leading to the dissolution of the contiguous fragmental grains at their contacts. Two kinds of consolidation are distinguished: elastic and plastic (Levorsen, 1970). The rocks subjected to elastic deformation recover their initial volume and porosity in full or partially after the pressure is removed. However, if the rocks were subjected to plastic deformation, their initial volume and porosity are not recovered, even in part (Alekseev et al., 1982). Fragile deformations (cataclasis) of fragmental grains also occur in the sediments under consideration and cause a substantial increase in rock permeability (Antonellini et al., 1994). Gravitational corrosion of grains is also observed (Simanovich, 1978).

The present investigation is based on generalization and analysis of the whole factual material available till the present moment (the published and collected data) since the start of exploration work in the region (since 1950-es). The data include the results of tests of more than 445 objects, 217 wells, 84 exploration areas, including 368 measurements of formational pressure and the characteristics of more than 2400 inflows, as well as the data obtained in the laboratory core studies (more than 3400 samples). At the basis of structural layout made at the Trofimuk Institute of Petroleum Geology and Geophysics of the Siberian Branch of the Russian Academy of Sciences, the dependencies of formational pressure on depth, the grid models (Grid) of the distribution of formational pressure in the roof of 7 stratigraphic levels were built with the help of software packages GridBuilder, GridMaster and Surfer: Talitskaya series (Ᵽ_1); Kuznetsovskaya series (K_2); Senomanial horizon (K_2); Alym horizon (K_1); Bezhenovskiy horizon (J_3); U-10 bed (J_2); Pre-Jurassic complexes (T-Pz).

The next stage was correction of the plotted maps taking into account actual measurements of formational pressures in wells. The final stage was the development of a conceptual 3D model characterizing the distribution of formational pressures within the boundaries of the oil and gas bearing deposits in the southern regions of the Ob-Irtysh interfluve.

Results of investigation and discussion

The change of the porosity and permeability characteristics (PPC) of the rocks with the depth of their occurrence will be considered. In general, the porosity of sandstone and siltstone in oil and gas bearing sediments varies within a broad range from 0.70 to 43.5 %, regularly decreasing from the Aptian-Albian-Senomanian complex to the Lower Jurassic reservoirs (Table 1). It was established that the rocks dominating in the section are sand-siltstone with the porosity 10-20 %. The intervals with PPC increased up to 15-18 % were detected in the lower part of the sedimentary cover at the background of not very high porosity (Fig. 2).

Cumulative plots depicting the dependencies between the porosity of sandstone, siltstone, clay/argillite and the depth of their occurrence according to the results of petrophysical core studies are presented in Fig. 2a, b and c. One can see that the porosity of both the former and the latter decreases with depth. This dependence is also characteristic of permeability (Table 1). The rate of rock consolidation is relatively high for the depth of burial down to 1000-1500 m, and slows down with an increase in the depth (Burst, 1969; Perry, Hower, 1972; Alekseev et al., 1982; Magara, 1982; Dyunin, Korzun, 2005). Water abundance of the Mesozoic sediments also decreases regularly with an increase in the depth of the objects under investigation.

For instance, the average water flow rate in the Cretaceous complexes is 27-78 m^3/day, while in the Jurassic complexes it is 9-48 m^3/day. The highest collector characteristics are exhibited by weakly

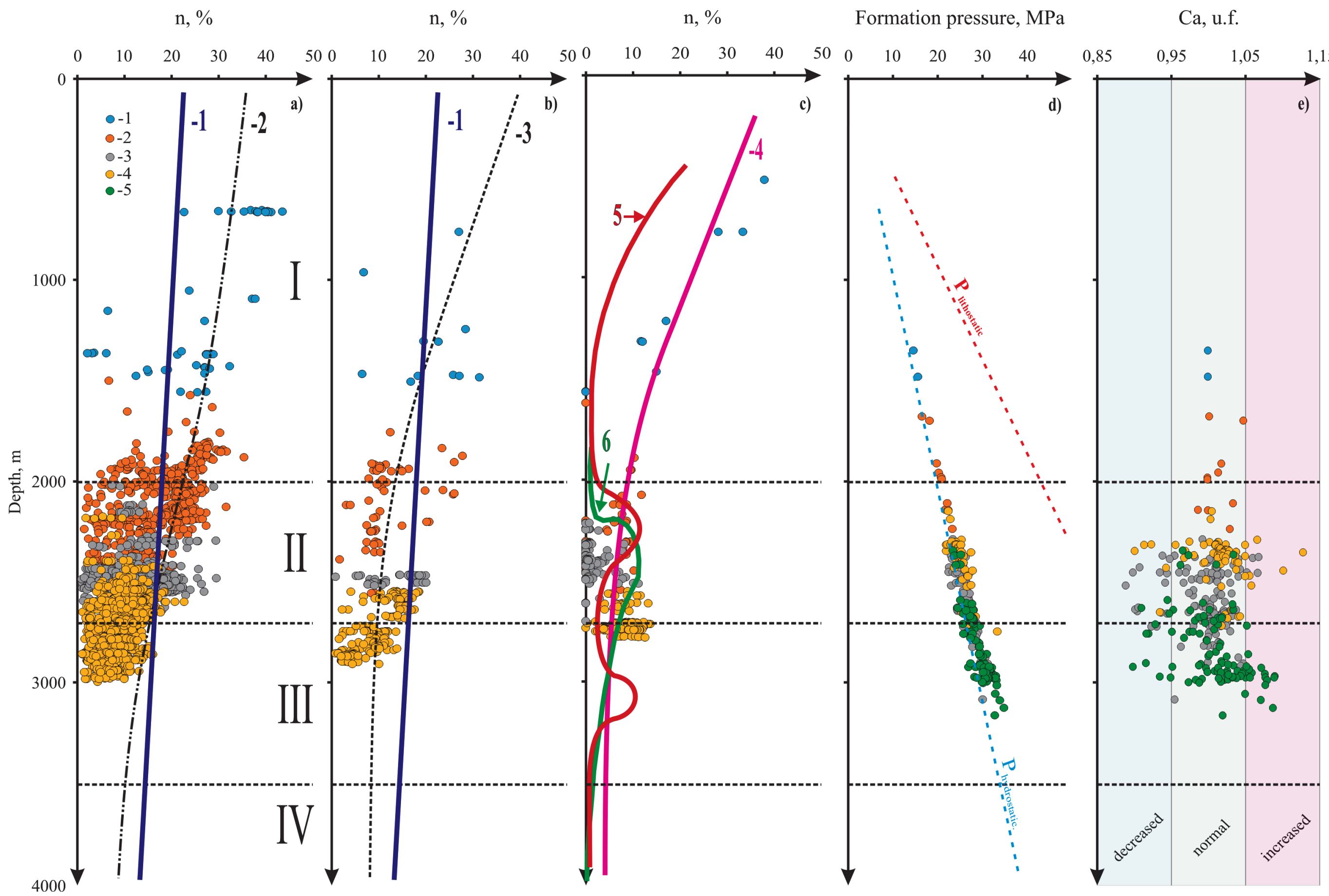

Fig. 2. Depthwise variation of filtration-capacity properties of rocks and hydrodynamic parameters of the sedimentary cover of WSSB. (a) Porosity of sandstones and siltstones – variation trends: (1) global (Ehrenberg, Nadeau, 2005), (2) in sandstones from central sectors of WSSB (Alekseev et al., 1982), (3) in siltstones from the above sectors (Alekseev et al., 1982); (b) porosity of clays and mudstones in central sectors of WSSB: (4) according to (Alekseev et al., 1982); Plots showing water release from the consolidating clays: (5) according to (Burst, 1969); (6) according to (Perry, Hower, 1972). Stages of sediment dehydration: (I) expulsion of free water, (II) expulsion of interlayer water (50 %) at a depth of 2.0-2.7 km (initial stage), (III) expulsion of the next portion (25 %) of interlayer water at a depth of 2.7-3.5 km (intermediate stage); (IV) expulsion of the last (25 %) water interlayer at a depth of more than 3.5 km (final stage); (c) formation pressure – aquifer complexes: (1) Aptian-Albian-Cenomanian, (2) Neocomian, (3) Upper Jurassic, (4) Lower-Middle Jurassic, (5) pre-Jurassic.

AS	n, %	P, μm^2	Pf, MPa	Ca, u.f.	Q_{water}, m^3/day
I	2.1-43.5 25.6(65)	2.0×10^{-3}-7.9 1.51(29)	14.6-15.6 15.1 (2)	1.00-1.00 1.00 (2)	7.0-864 78.2 (25)
II	1.5-35.4 17.1(668)	8.2×10^{-6}-5.6 0.17(440)	16.4-23.3 20.6 (10)	0.99-1.05 1.01 (10)	5.0-550.0 27.3 (159)
III	0.6-29.5 13.2(1166)	1.9×10^{-7}-1.8 0.04(799)	21.2-28.5 25.1 (104)	0.90-1.13 1.02 (104)	3.0-760 48.5 (166)
IV	0.3-22.7 8.6(973)	0.9×10^{-5}-0.14 2.0×10^{-3} (490)	22.5-31.1 26.6 (150)	0.89-1.07 1.00 (150)	3.0-256 9.1 (376)
V	-	-	23.4-44.2 29.5 (102)	0.90-1.09 1.01 (102)	3.0-1148 32.4 (335)

Table 1. Characterization of the hydrodynamics parameters along with the porosity and permeability characteristics of the oil and gas bearing deposits in the southern regions of the Ob-Irtysh interfluve. AS – aquifer system: I – Apt-Alb-Cenomanian; II – Neocomian; III – Upper Jurassic; IV – Lower Middle Jurassic; V – pre-Jurassic; n – porosity; P – permeability; Ca – anomaly coefficient of formation pressure = Pf/Pn, where Pf – formation pressure, Pn – normal hydrostatic pressure; the numerator shows the minimum and maximum values, the denominator shows the average (number of measurements); Q_{water} – rate of flow; "-" – lack of data.

cemented sands and sandstone of the Aptian-Albian-Senomanian water-bearing complex (horizon PK). Their porosity reaches 43.5 %, permeability is up to 7.9 μm^2, with the average value 1.5 μm^2.

This allows obtaining inflow up to 600-800 m^3/day and more. Because of this, in the majority of cases the groundwaters of the Aptian-Albian-Senomanian complex of West Siberia are used in the development of hydrocarbon deposits as the source for the operation of the systems maintaining the formation pressure (Novikov, 2005). Though the water-bearing horizons of the Neocomian water-bearing complex exhibit high PPC, they are affected by consolidation processes to a higher extent than overlying sediments. The sediments of the complex include permeable layers of A and B groups with the porosity within the range 1.5-35.4 %, permeability varying within the range $8.2 \cdot 10^{-6}$-5.6 μm^2, average water discharge reaching 27.3 m^3/day. Lower lying Jurassic water-bearing horizons include permeable layers of the J ground (J_1 in the Upper Jurassic and J_2-J_{17} in the Lower Jurassic). The porosity of the reservoirs varies within the range from 0.3 to 29.5 % with deterioration of the collector properties with depth. Permeability varies within a broader range: $1.9 \cdot 10^{-7}$-1.8 μm^2, that is, by a factor of several million. Water influx in wells decreases with depth while the PPC worsens. It should be stressed that Pre-Jurassic complexes (Triassic and older sediments) are only poorly hydrogeologically studied in the southern regions of the Ob-Irtysh interfluve. Water discharge varies during the tests of Pre-Jurassic objects from 3.0 to 1148 m^3/day (in idle objects it varies from 0.01), with the average value equal to 32.4 m^3/day, which is connected with the change of the pore-type collector for a cavernous, fractured and so on (Novikov et al., 2018).

The features of the structure and the extent of WSSB investigation over depth allow us at present to distinguish the Mesozoic-Cenozoic water-pressure system with characteristic water-embedding and waterproof complexes. Triassic and Paleozoic formations are penetrated by an insignificant number of wells at a relatively small depth, and their hydrogeological disintegration is impossible. The most essential hydrodynamic feature of the southern regions of the Ob-Irtysh interfluve is the manifestation of increased formational pressure in the Jurassic reservoirs starting from the depth of 2300-2350 m (Fig. 2 d, e). In general, the region under investigation is characterized by the direct hydrodynamic zoning and the development of normal and increased formational pressure; the coefficient of anomality (Ca) varies from 1.0 in Cretaceous water-bearing aquifers to 1.13 in the Jurassic ones (Fig. 2 d, e). Water-bearing complexes characterized by the hydrodynamic data to the smallest extent are the Aptian-Albian-Senomanian and Neocomian ones. It was established on the basis constructions and the available data for the Aptian-Albian-Senomanian complex that the formational pressure changes from several units to 15.6 MPa (1557-1626 m in the Mirnaya 410 well), Ca is 1.00. In general, an increase in the formational pressure is observed in the western direction (Fig. 3a). Formational pressure varying from 16.4 to 23.3 MPa was detected in the Neocomian water-bearing complex (2332-2374 m in the Bergulskaya 2 well 2), and Ca varies from 0.99 to 1.05, with the average value equal to 1.01. The largest values of formational pressure were detected in the south-western and north-western parts of the region under investigation in the southern part of the Koltogor-Nyurol trench and in the Nyurol megadepression, while the smallest ones were detected at the Verkhneshegar ledge in the south-east (Fig. 3b). Formation pressure in the Upper Jurassic water-bearing complex varies from 21.2 to 28.5 MPa (2774-2778 m in the Vostochno-Moiseevskaya 1 well), Ca changes within the range 0.90-1.13 (the Rakitinskaya 7 well, 2467-2485 m), the average value being 1.02. It was established that the formational pressure in the Upper Jurassic complex increases from the south-east (the Barabinsk-Pikhtovskaya monocline) to the north-west, to the structures of the Nyurol mega-depression (Fig. 4).

The Lower- and Middle-Jurassic water-bearing complex is characterized by the hydrodynamic materials to the highest extent. The measured formational pressure in it reaches 31.1 MPa within the range of 3006-3053 m in the Yuzhno-Tabagan 135 well. The Ca values in it are somewhat lower than in the Upper Jurassic water-bearing complex and vary from 0.89 to 1.07. An increase in the formational pressure with an increase in the depth towards the north-western and western directions is established. Increased pressure was also established in the Bakchar depression (Fig. 3 c). Formational pressure in the Pre-Jurassic sediments varies from 23.4 to 44.2 MPa (4520-4530 m, the Urmanskaya 6 well), Cavaries from 0.90 to 1.09, and the average value is 1.01. In general, the distribution of formational pressure in Pre-Jurassic sediments is similar to that in the overlying Lower and Middle Jurassic complex. The highest values were established in the north-western part of the region, and in the Bakchar depression, while the lowest value was detected in the south-east within the boundaries of the Barabinsk-Pikhtovskaya monocline (Fig. 3 d).

Results of the investigation of porosity and permeability, as well as the hydrodynamic characteristics of collectors in the hydrogeological section point to the dominating role of elision water exchange

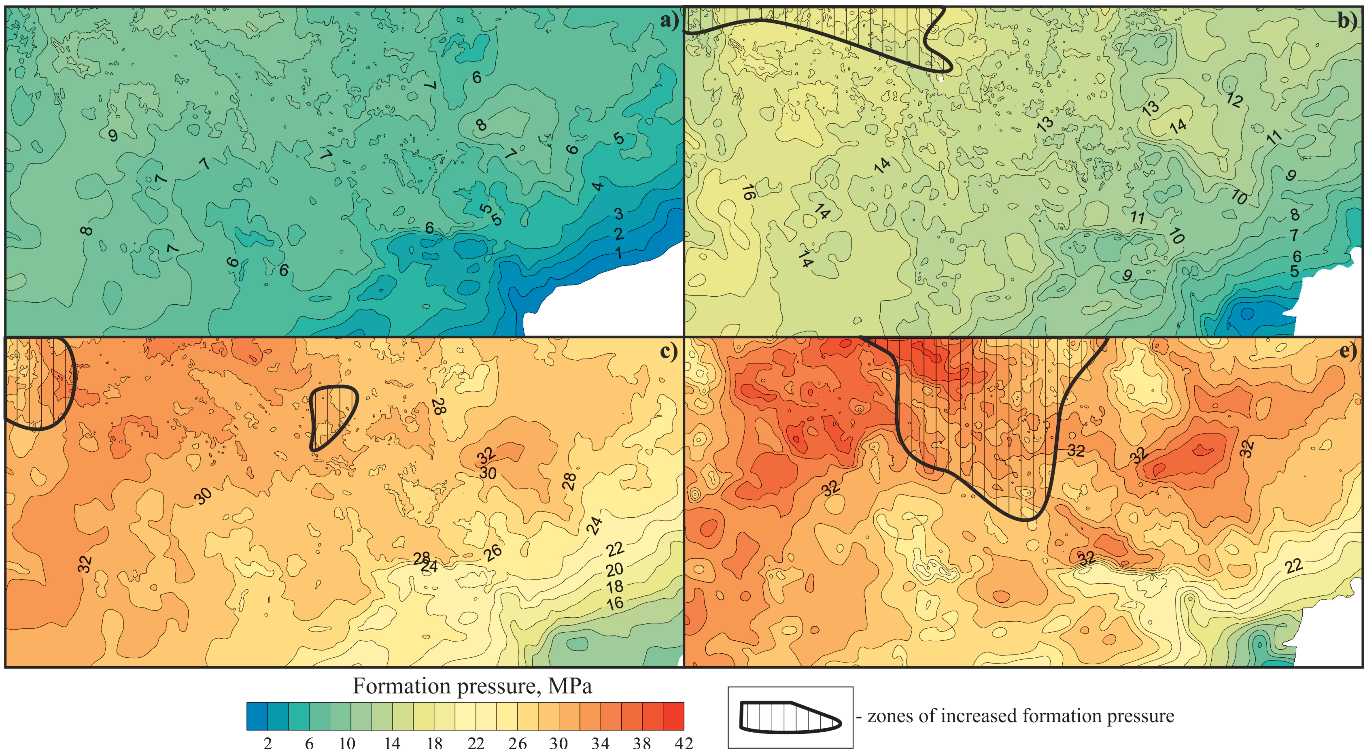

Рис. 3. Stresses in the hydrodynamic field of the Aptian-Alb-Cenomanian (a), Neocomian (b), Lower Middle Jurassic (c) and pre-Jurassic (d) aquifers complexes

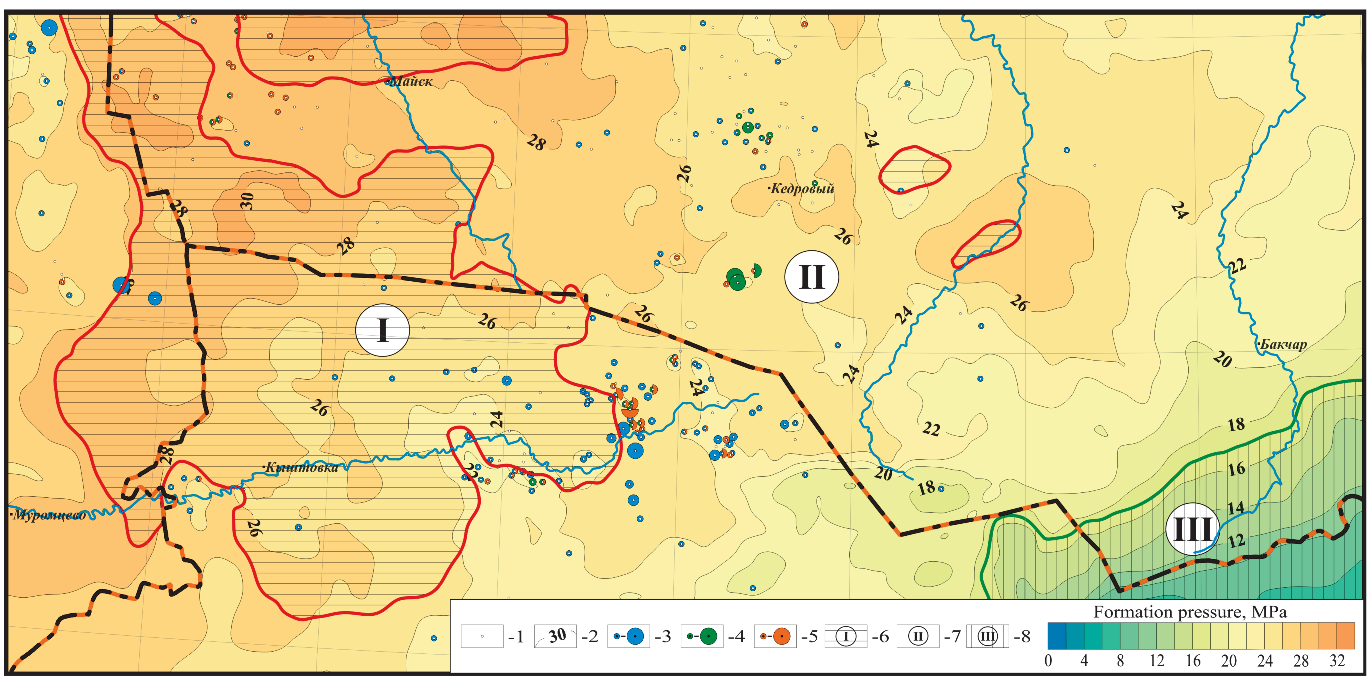

Fig. 4. Map of reservoir pressure of the Upper Jurassic aquifer with elements of regionalization of water-pressure systems. 1 – wells; 2 – isobars, MPa; Flow rates: 3 – water (from 3 to 1100 m^3/day), 4 – gas (1-450 thousand m^3/day), 5 – oil (from 0.1 to 450 m^3/day); zones of development of water-pressure systems: 6 – elision thermal-dehydrational; 7 – elision lithostatical; 8 – infiltrational.

in the formation of the modern structure of the hydrodynamic field. Two types of natural water-pressure systems were established: elision-based (lithostatic and thermodehydrational) in the internal regions (the southern part of the Koltogor-Nyurol trench, the Nyurol megadepression, Verkhnevasyuganskaya anticline and other structures) and infiltration-based, within the structures of the Barabinsk-Pikhtovskaya monocline (Fig. 4). The elision lithostatic system starts to attain the features of elision thermodehydrational one from the depth of about 2.0-2.2 km. Vast zones of piezo-maxima (southern part of the Koltogor-Nyurol trench and the Nyurol megadepression) at the present stage of the development of the water-pressure system of the region under investigation became the internal areas of water-head generation (the internal catchment areas) with the maximal degree of the hydrogeological closure of the interior. The region of piezo-minima tracing the structures of the Barabinsk-Pikhtovskaya megamonocline relates to the external catchment area.

It was demonstrated (Burst, 1969; Perry, Hower, 1972) that dehydration starts from the depth of about 2 km (wringing of interfacial water) with clayey minerals; this process includes several stages (Fig. 2 c). D.B. Shaw calculated the depth and temperature of clay dehydration for more than 2000 deposits in the USA; he established that the depth of dehydration varies within the range 1280-4850 m, and temperature varies within the range 83-111°C (Shaw, Weaver, 1965).

So broad depth range is first of all due to different values of the thermal flux at the deposits under investigation. Taking into account the results of geothermal studies of the sedimentary cover of West Siberia carried out by G.D. Ginsburg, A.D. Duchkov, Yu.G. Zimin, A.E. Kontorovich, V.A. Koshlyak, N.M. Kruglikov, A.R. Kurchikov, B.F. Mavritskiy, I.I. Nesterov, B.P. Stavitskiy, E.E. Fotiadi, G.A Cheremenskiy (Mavritskiy, 1960; Stavitskiy, 1964; Zimin et al., 1967; Fotiadi et al., 1969; Surkov et al., 1972; Nesterov et al., 1980; Kurchikov, 1981; Stavitskiy et al., 1981; Kurchikov, Stavitskiy, 1985; Kurchikov, Stavitskiy, 1986; Kurchikov, Stavitskiy, 1987; Nesterov et al., 1988; Duchkov et al., 1990; Kurchikov, 1992) and the results of our studies of the southern regions of the Ob-Irtysh interfluve, Fore-Yenisei sedimentary basin etc. (Novikov, 2011; Dultsev, Novikov, 2017; Novikov et al., 2018), we may assume that the elision geostatic (lithostatic) system within the region under investigation takes on the features of thermodehydrational system from the depth of about 2.0-2.2 km because the formational temperature exceeds 100°C.

To summarize, the detailed analysis of the available data allowed us to complied for the first time a conceptual 3D model characterizing the distribution of formational pressures within the boundaries of oil and gas bearing sediments in the southern regions of the Ob-Irtysh interfluve. The model allows predicting the constraint of the hydrodynamic field for the structures poorly provided by factual data, which is especially relevant for designing deep-hole drilling in the region (Fig. 5).

Conclusion

Water-pressure systems of the Cretaceous and Jurassic complexes in the southern regions of the Ob-Irtysh interfluve including the productive layers traced over a substantial territory are isolated from each other

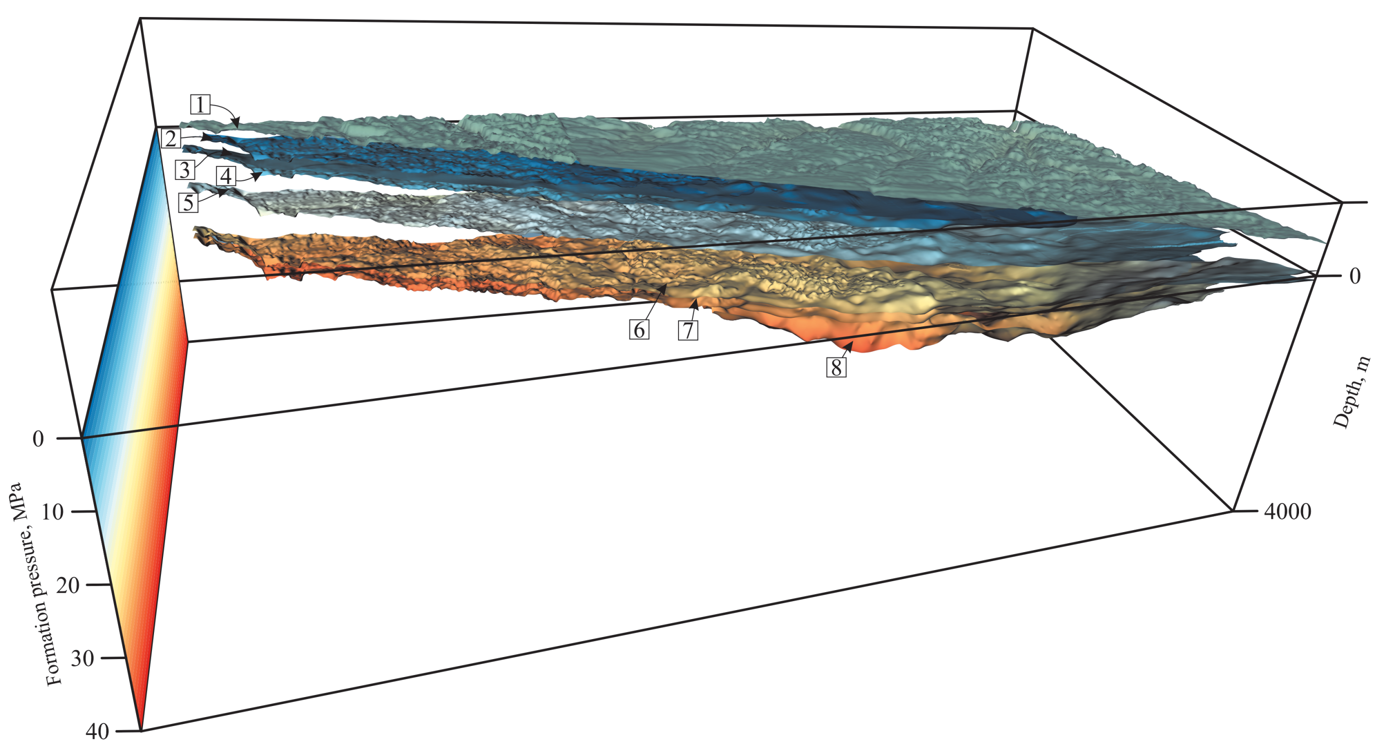

Fig. 5. Model of reservoir pressure distribution in oil and gas bearing deposits of the southern regions of the Ob-Irtysh interfluve. 1 – day surface; top of: 2 – Talitsky suite (P_1); 3 – Kuznetsovskaya suite (K_2); 4 – Cenomanian horizon (K_2); 5 – Alym horizon (K_1); 6 – Bazhenov formation (J_3); 7 – layer U-10 (J_2); 8 – pre-Jurassic deposits (T-Pz).

with reliable fluid-seal rocks. The isolated structure is disturbed only at local regions: in the systems of faults, tectonic disturbances and stratigraphic breaks. Hydrodynamic conditions change substantially even within one complex in which hydrodynamically isolated blocks are distinguished.

The hydrodynamic field of the region under investigation is characterized by the direct hydrodynamic zoning and the development of normal and increased formational pressure (Ca up to 1.13) in the Pre-Jurassic, Jurassic and Cretaceous water-bearing complexes. Results of the investigation of reservoir porosity and permeability, and the hydrodynamic characteristics of collectors in the hydrogeological section point to the dominating role of elision water exchange in the formation of the modern structure of the hydrodynamic field. Two types of natural water-pressure systems are revealed: elision-based (lithostatic and thermodehydrational) in the internal regions (the southern part of the Koltogor-Nyurol trench, Nyurol megadepression, Verkhnevasyuganskaya anteclise and other structures) and infiltration-based within the structures of the Barabinsk-Pikhtovskaya monocline.

The elision-based lithostatic system starts to retain the features of the elision-based thermodehydrational system from the depth of about 2.0-2.2 km. Vast zones of piezo-maxima (the southern part of the Koltogor-Nyurol trench and the Nyurol megadepression) at the present stage of the development of the water-pressure system became the internal regions of the generation of water head (internal catchment regions) with the maximal degree of the hydrogeological closure of the interior. The region of piezo-minima tracing the structures of the Barabinsk-Pikhtovskaya mega-monocline relates to the external catchment region.

The hydrodynamic model of oil and gas bearing sediments in the southern regions of the Ob-Irtysh interfluve allowing predictions of the trends of formational pressure changes in the structures poorly provided by the factual data has been compiled for the first time.

Acknowledgements

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Comparison of the potential of secondary and tertiary methods of influence on the formation for the production of hydrocarbon compounds from oil source rocks with high oil-generating potential

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Abstract. The work presents the comparison results of the quantitative and qualitative composition of hydrocarbon compounds that can be obtained as a result of secondary and tertiary methods of influence on organic-rich rocks (on the example of the Bazhenov Formation rocks) with a high oil-generating potential. It is shown that as a result of extraction of bitumoids presented in open pores, realisation the generation potential and the production of synthetic oil, it is possible to produce hydrocarbon compounds, the amount of which reaches 35 kg and 20 kg per 1 m^3 of rock, respectively. Products possess high maturity and are identical in composition to the oil extracted from these rocks by standard technology of development. It was found that with the development of appropriate technologies of subsequent influence on the formation by secondary and tertiary methods, oil production can be significantly increased in the future.

Keywords: oil source rock, oil-generating potential, hydrocarbon compounds, synthetic oil, gas chromatography with mass spectrometry detection

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Introduction

High-carbon formations are one of the key objects in the study of deposits and forecasting of hydrocarbon reserves and resources (Kontorovich et al., 1975; Prishchepa et al., 2014; Stupakova et al., 2015). They are the oil source strata, in which oil and gas are formed from the kerogen in the process of geological evolution. As a result of subsequent migration along the section, these hydrocarbons fill the conventional reservoirs. An assessment of the characteristics of the source rocks allows to determine how much oil was generated during the catagenetic transformation of sediments, how much hydrocarbon compounds (HCC) remained in the reservoir, and how much migrated to the overlying strata (Sannikova et al., 2019).

At the same time, high-carbon formations are subject to secondary transformations, changes in the mineral composition as a result of dissolution, the formation of new minerals, hydrothermal processes, and kerogen transformations, as a result of which a pore space is formed in the rocks that contains oil (Kalmykov, Balushkina, 2017). The development of fields with unconventional reservoirs in the oil source strata currently allows to increase the country's resource potential and compensate the decrease in oil production from conventional reservoirs.

Conducted researches have shown that the amount of oil varies significantly in high-carbon formations, it depends on the maturity of organic matter and the conditions of its formation, as well as on the occured secondary processes. At the same time, in the case of low maturity (stage of catagenesis PK3-MK2), most of the hydrocarbons in the rock are not in the form of oil, but in the form of physically connected or blocked hydrocarbons (Kalmykov, 2016). At the same time, kerogen is poorly transformed and in the future can generate a large volume of HCC as a result of further catagenetic transformations.

At low maturity, in most cases, the development of wells by drilling without additional technological work is inefficient and economically unprofitable. Therefore, companies are trying to develop various technologies to increase oil production. There are secondary and tertiary

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methods of stimulating the formation (Surgachev, 1985). Secondary methods of stimulation of a reservoir mean the injection of water, gas or reagents, allowing to extract already formed hydrocarbons. Tertiary methods involve exposure to the formation in order to convert organic matter, in fact, cracking in the formation. The use of these intensification methods will make it possible to extract fixed hydrocarbons from the rocks and partially realize the kerogen generation potential.

The characteristics of already formed HCC were previously considered in literature (Mueller, Philp, 1998; Tikhonova et al., 2019). These bitumen can have a sufficiently high maturity and be used as hydrocarbon feedstocks. In this case, it is important to understand where these or other bitumen are located in the rock and in which case they will be involved in the development. There are also a fairly large number of publications evaluating the prospects for tertiary methods of stimulating the formation (Popov et al., 2017). Assessment of the prospects for the formation of hydrocarbons from kerogen on the main high-carbon formations of Russia – the Bazhenov and Domanik suites – is usually based on experiments on rock hydro-pyrolysis (Bushnev et al., 2004; Bychkov et al., 2015; Popov et al., 2017; Kalmykov et al., 2017). The authors showed that under temperature exposure it is possible to partially realize the generation potential of kerogen and to obtain hydrocarbon systems of different compositions.

At the same time, the prospects for complex impact on the reservoir have not been previously evaluated. It is important to compare the capabilities of different development methods for oil-saturated high-carbon rocks; as well as to find out how the resulting products will vary in composition and how the amount of emitted HCC will vary. The aim of this work is to study the potential of secondary and tertiary methods of influencing on oil source rocks with high oil generation potential (for example, rocks of one deposit of the Bazhenov formation), and to compare the characteristics of the resulting products with oil obtained in the development of these rocks without special exposure technologies.

Experimental part

Materials and Reagents

To assess the prospects of secondary and tertiary methods of stimulating the formation, we used rock samples of the Bazhenov formation from one well located on the eastern side of the Frolovsky mega-basin. For the study, 3 samples were selected located in different parts of the section and differing in composition, previously determined by X-ray phase and X-ray fluorescence analysis methods (Table 1).

The following reagents were used in the work: *n*-hexane (Panreac, Spain), toluene (Panreac, Spain), methylene chloride (Component Reagent, Russia, for spectroscopy), chloroform (Himmed, Russia), KSKG silica gel 0.04-0.1 mm (Chromresurs, Russia) and silver nitrate (Labsintez, Russia), benzene (Component Reagent, Russia), ethyl alcohol (Flora of the Caucasus, Russia).

Research Methods

Pyrolysis. To determine the content of organic matter in the samples, its type and maturity, as well as the content of physically bound hydrocarbon compounds and to assess the generation potential, the samples were pyrolyzed before and after various actions on the Rock-Eval-6 device (France). The measurements on the device are described in detail in (Tissot, Welt, 1981; Espitalie, 1984).

Extraction. The extraction of bitumen from the rocks of the Bazhenov formation was carried out by the method of stepwise extraction using various solvents. Hot extraction by each solvent was carried out in a Soxhlet apparatus according to the international standard D5369-93. Chloroform, *n*-hexane and a mixture of ethyl alcohol and benzene in a ratio of 1:1 were used as solvents. To extract hydrocarbon compounds from open pores, the extraction was carried out on cylindrical samples 30×30 mm in size, to obtain bitumen from closed pores, the cylindrical samples were grind after extraction with all three solvents, and subsequent extraction was performed on the obtained powders. The extraction technique is described in detail in the article (Tikhonova et al., 2019).

Hydrothermal exposure. The obtaining of "synthetic" oil from the rocks of the Bazhenov formation was carried out by the method of hydrothermal exposure to samples in autoclaves in the presence of water. A sample weighing ~ 50 g is placed in an autoclave. Water is added to the sample in such a volume that, at the temperature of the experiment, the pressure of water vapor creates a reservoir pressure of 300 atm in the autoclave. The temperature of the experiments was 300 °C and 350 °C. The duration of the experiment was 7 days at a temperature of 300 °C and 12 hours at 350°C. The methodology and temperature selection are described in more detail in (Kalmykov et al., 2017).

Sample	Depth	Silicon	Clay minerals	Calcite	Dolomite	Pyrite	Albite	OM
23-097	2924.0	53.3	12.8	0.6	2.9	3.2	11.1	15.8
30-032	2911.1	32.6	23.1	2.6	0.0	5.4	11.7	24.7
32-116	2905.8	43.9	15.0	6.4	0.0	8.2	9.3	16.6

Table 1. The mineral component composition of the samples

Separation of hydrocarbon compounds. Separation of maltens from tar-asphaltene substances in the obtained extracts and synthetic oils was carried out by adding to the sample a 40-fold excess of *n*-hexane, keeping the solution for a day in a dark place and following filtering. The separation of samples into saturated and aromatic fractions was carried out by liquid chromatography. A glass chromatographic column with an adsorbent (about 1-2 g of a mixture of silica gel and silver nitrate in a 9:1 ratio) was washed with *n*-hexane, 5 drops of oil/bitumen were transferred into it, and washed 3 times with *n*-hexane to collect the saturated fraction. The aromatic fraction was washed off with toluene.

Chromatographic analysis. An Agilent 7890B gas chromatograph equipped with an Agilent 7693 Autosampler automatic sampling device and an Agilent 5977A MSD mass spectrometer (Agilent Technologies, USA) was used to determine oil hydrocarbons. Data collection and chromatogram processing was performed using MassHunter software (Agilent Technologies, USA). HP-5MS capillary column (30 m × 0.25 mm, 0.25 μm) with a stationary phase based on methyl (95 %) – phenyl (5 %) – polysiloxane was used. Carrier gas was helium; carrier gas flow rate through the column was 1 cm^3/min. The volume of the introduced sample was 1 mm^3. Evaporator temperature – 290 °C, interface temperature – 300 °C; temperature gradient for the separation of the components of the saturated and aromatic fractions of oils, extracts and pyrolysis products was used.

Calculation of geochemical parameters. For all samples studied, the geochemical indices CPI (Carbon preference index) and OEP (odd to even predominance) were calculated, which are reduced to a numerical representation of the prevalence of even *n*-alkanes over odd ones in a specific range of the carbon chain. The CPI and EOP indices are calculated using the following formulas:

$$CPI=0,5 * \left(\frac{C25+C27+C29+C31+C33}{C24+C26+C28+C30+C32}+\frac{C25+C27+C29+C31+C33}{C26+C28+C30+C32+C34}\right);$$

$$OEP=0,5 * \frac{C21+6C23+C25}{4*(C22+C24)}.$$

Results and discussion

The potential assessment of the studied samples of the Bazhenov formation can be obtained by analyzing the pyrolysis results of the samples. The results of the pyrolysis of the samples before extraction are shown in Table 2.

As can be seen from the pyrolysis results, the samples contain a large amount of organic matter (TOC value is more than 12 wt.%). Moreover, the samples have a high oil generation potential (the sum of parameters S1 and S2), ranging from 75 mg HC/g of rock to 105 mg HC/g of rock. Accordingly, the rocks from which the samples were selected can serve in the future as a source of a large number of hydrocarbon compounds. At the same time, the oil-generating potential characterizes both the already generated hydrocarbon compounds and the kerogen generation potential, which shows the amount of hydrocarbons that can be obtained in the future as a result of catagenetic maturation of rocks.

It is important to note that organic matter has high values of the HI hydrogen index, corresponding to ~ 500 mg HC/g TOC, and the parameter Tmax is 440 °C. This indicates a low degree of maturity of rocks, corresponding to the catagenesis stage MK1-2. Usually, for such stages of maturity, parameter S1 has lower values, rarely exceeding 10 mg HC/g of rock. These rocks can be attributed to rocks with a high saturation of hydrocarbons.

As mentioned earlier, secondary methods of stimulating the formation are aimed at extracting the hydrocarbon residues remaining after the traditional development of rocks, including compounds that are stationary due to their physical properties (for example, having a high molecular weight), as well as light compounds located in closed pores or physically associated with organic matter. To assess the prospects of secondary methods of stimulation on the studied rocks of the Bazhenov formation, it is necessary to assess the number of potentially recoverable compounds and their composition.

Estimation of the amount of HCC in the rock can be carried out based on the results of pyrolysis after extraction. It is worth noting that, according to the ideas about the structure of the rocks of the Bazhenov formation (Kalmykov, 2016), the pore space is divided into open and closed pores. To determine the amount of hydrocarbons in open pores, pyrolysis was performed after extraction of cylindrical samples. The amount of HCC in closed pores was estimated by the difference in parameters S1 and S2 after extraction of cylinders and powders. According to the results of pyrolysis, it was found that more than 90 % of light HCC (parameter S1) is in open pores and is about 12-15 mg HC/g of rock, while HCC with a high molecular weight (parameter S2) are distributed in open and closed pores approximately

Sample	S1, mg HC/g of rock	S2, mg HC/g of rock	Tmax, °C	TOC, wt.%	PI	HI, mg HC/g TOC	OSI, mg HC/g TOC
23-097	13.2	61.4	441	12.1	0.18	508	108.9
30-032	16.6	89.0	440	18.5	0.16	480	89.8
32-116	12.9	63.3	443	12.3	0.17	516	105.1

Table 2. The results of the pyrolysis of the studied samples

equally and make up about 10 mg HC/g of rock in each type of pore. The values of the main pyrolytic parameters after the extraction of powders are shown in Table 3.

The results show that for the extraction of light bitumen, which by their characteristics will be closest to oil, it is possible not to involve HCC located in closed pores. In this case, the total amount of hydrocarbon that can be extracted as a result of secondary methods of stimulating the formation for the studied rocks is about 35 mg HC/g of rock, which is a very high value for the rocks of the Bazhenov formation. It is also important to note that the proportion of light hydrocarbon in these rocks is about 40 %, which will allow to produce about 35 kg of light hydrocarbon from 1 m^3 of rock. Taking into account all the available hydrocarbons in the rock, the total value is about 90 kg.

The values of parameter S2 after extraction characterize the generation potential of kerogen. This parameter varies from 40 to 70 mg HC/g of rock, showing that in the case of the development of tertiary methods of stimulation of the formation, allowing to convert kerogen into HCC from 1 m^3 of rock, it will be possible to produce 100-170 kg of HCC as much as possible.

Thus, the results show that the rocks selected for research have high potential for the application of secondary and tertiary methods of stimulating the formation. In this case, the maximum amount of hydrocarbon produced by each of the methods can be considered commensurate. However, in order to assess the potential of using various technologies, it is necessary to determine how much the composition of the HCC obtained by different merhods is comparable with the composition of oil extracted from the field.

To compare the composition of recoverable hydrocarbons, a GC-MS analysis of the saturated and aromatic fractions of oil maltens extracted from the rocks of the Bazhenov formation of this field, hexane and chloroform extracts from open pores, hexane extract from closed pores, and “synthetic” oil was performed. In order to evaluate the potential of secondary methods of exposure, only hexane and chloroform extracts from open pores (cylindrical samples) were studied, and to compare the potential of closed pores hexane extracts from closed pores were studied. This choice of extracts is due to the low content of light HCC in closed pores, as well as the high proportion of asphaltenes (up to 95 %) in alcohol-benzene extracts from open pores.

At the first stage, a comparative analysis of the distribution of *n*-alkanes in hexane (Fig. 1) and chloroform (Fig. 2) extracts from open pores of rock samples located in different parts of the section was performed. As it was established earlier (Tikhonova et al., 2019), a comparison of the distribution of *n*-alkanes in the samples along the section allows to assess whether there is a migration of hydrocarbons in the reservoir, as well as to reveal differences in the generation of hydrocarbons in rocks of different compositions. As can be seen from Figure 1, the hexane extracts of the samples are completely identical. At the same time, the distribution of *n*-alkanes in chloroform extracts is somewhat different, although this difference can be considered insignificant, secondary minima and maxima on the curves are repeated, and the general appearance of the curves in the open pores is similar.

For hexane extracts from closed pores (Fig. 3), a local peak is observed for all samples, corresponding to an increased content of *n*-alkanes with a C22 chain length. Moreover, in general, the shape of the distribution curves is identical. At the same time, the presence of individual maxima and the absence of a pronounced peak for low molecular weight compounds (C16-C20) may indicate a lower maturity of hexane extracts from closed pores.

According to the results of the study of the variability of the distribution of *n*-alkanes in different samples, it is possible to note the absence of perceptible differences in extracts along the section. Such an identity indicates that, in the whole section, the process of substance generation was the same. Moreover, extracts from open and closed pores are significantly different from each other. The hexane extract in all samples has a maximum for light *n*-alkanes with a chain length of C14-C18, in the chloroform extract, the maximum shifts toward C17-C21, and a single peak is characteristic for the hexane extract in C22 (Fig. 4). Such differences show that, in closed pores, the maturity of HCC is significantly lower. Presumably, HCC from closed pores will require additional processing after extraction, which is associated with high costs. It is likely that the extraction of bitumen from closed pores in such deposits is less promising.

To assess the prospects of tertiary methods of stimulating the formation, these samples were subjected to hydropyrolysis at the following parameters: 300 °C for 7 days and 350 °C for 12 hours. The amount of maltenes and asphaltenes in the resulting “synthetic” oil is shown in Table 4. As can be seen from the Table, the number

Sample	S1, mg HC/g of rock	S2, mg HC/g of rock	Tmax, °C	TOC, wt.%	PI	HI, mg HC/g TOC	OSI, mg HC/g TOC
23-097	0.1	39.1	442	8.5	0.00	462	1.4
30-032	0.4	70.2	440	15.5	0.01	452	2.8
32-116	0.3	39.3	439	9.6	0.01	412	3.4

Table 3. The results of pyrolysis of the studied samples after complete extraction

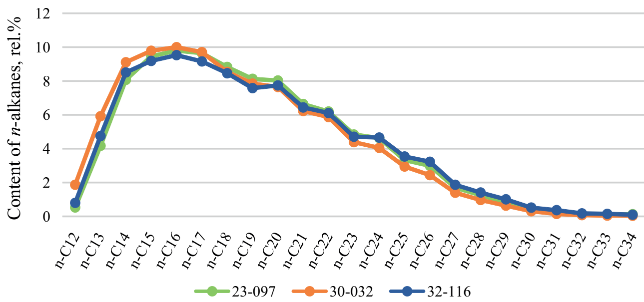

Fig. 1. Distribution of n-alkanes in open pore hexane extracts

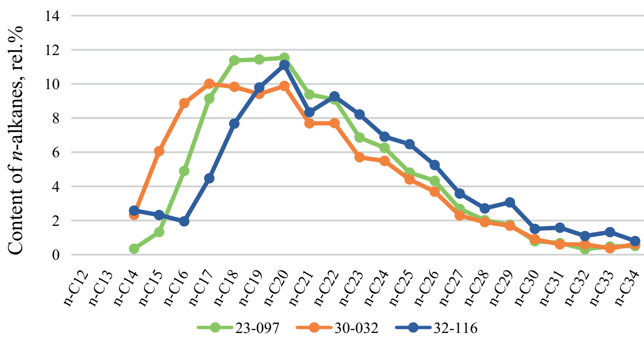

Fig. 2. Distribution of n-alkanes in chloroform extracts from open pores

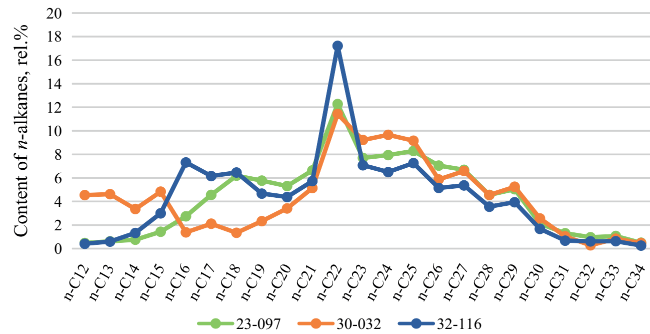

Fig. 3. Comparison of hexane extracts from closed pores

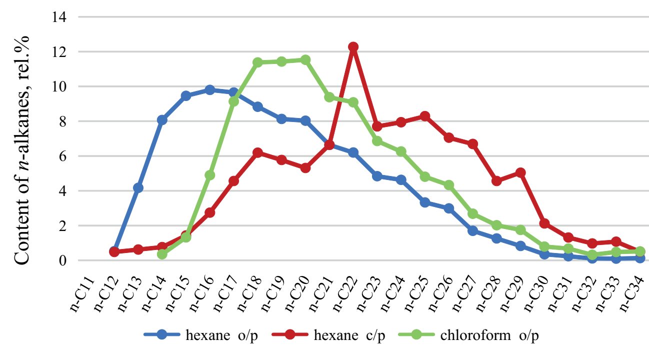

Fig. 4. Distribution of n-alkanes in various extracts of sample 23-097

of maltenes and asphaltenes with a mild exposure is comparable, and the total yield is 1-1.5 mg of HCC/g of rock. With increasing temperature, the majority of the resulting "synthetic" oil are maltenes (80-95 %). The total yield increases significantly, reaching 5-10 mg HC/g of rock. It is important to note that in both cases the realization of the generation potential amounted to about 5-10 mg HC/g of rock, which indicates a high yield of liquid HCC and a small percentage of the generated at high temeratures gas. Probably, the selection of optimal conditions will increase the yield of "synthetic" oil from these rocks.

The distribution analysis of *n*-alkanes in the resulting "synthetic" oils showed that the primary rather narrow maximum occurring in C14-C19 is present in the obtained HCC. At the same time, at elevated experimental temperatures, for all samples of "synthetic" oil, a second maximum is observed corresponding to the C25-C30 chain length, which is especially pronounced for sample 32-116 (Fig. 5). This indicates that under mild conditions of hydrothermal exposure (300 °C, 7 days), only weak bonds break, while at elevated temperatures not only hydrocarbons can detach from kerogen, but also secondary cracking of asphaltenes and other compounds with high molecular weight can occur, resulting in the formation of new *n*-alkanes. Most likely, the secondary peak is explained by non-optimal conditions for the production of "synthetic" oil, the selection of other conditions, as it was shown by previous experiments (Bychkov et al., 2015, Kalmykov et al., 2017), should lead to a monomodal distribution. At the same time, the varying of conditions can lead to secondary cracking of light compounds and the formation of gaseous hydrocarbons.

Since the first peak in the distribution of *n*-alkanes of "synthetic" oils obtained under different conditions is

Sample	Fraction	Weight of "synthetic" oil at 300°C, g	Weight of "synthetic" oil at 350°C, g
23-097	maltenes	0.0137	0.2826
	asphaltenes	0.0355	0.0376
30-032	maltenes	0.0338	0.3348
	asphaltenes	0.0158	0.0145
32-116	maltenes	0.0495	0.4190
	asphaltenes	0.0245	0.0971

Table 4. The amount of synthetic oil obtained as a result of hydrothermal exposure under various conditions

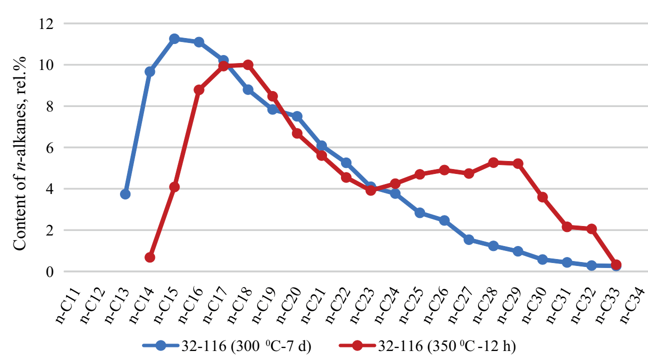

Fig. 5. Comparison of n-alkanes distribution in synthetic oils obtained from sample 32-116 under various conditions of pyrolysis

identical, and under optimal conditions the distribution will always approach a curve with a monopike, then for comparison with extracts and natural oil, samples of "synthetic" oil obtained using 300 °C in 7 days were used. The distribution results are shown in Figure 6. There is a similarity in the ratio of *n*-alkanes between the oil extracted during the development of rocks of the Bazhenov formation of this field, the hexane extract from open pores, and the hydropyrolysis products. Since the distribution of light hydrocarbons could be affected by the evaporation and sample preparation process, and *n*-alkanes with a longer chain length are identical in all samples, it can be argued that as a result of secondary and tertiary methods of exposure, it is possible to obtain hydrocarbons which composition is close to natural oil by this indicator.

At the same time, the obtained results of experiments on the production of "synthetic" oil may mean that when the temperature impact is applied to the rocks, the adsorbed hydrocarbons are extracted rather than the generation potential is realized. However, in addition to the appearance of a secondary peak for "synthetic" oils obtained at a temperature of 350 °C in 12 hours, an increase in the parameter S1 after the experiments (values reach 20 mg HC/g of rock, which is 25 % higher initial values), as well as the presence of compounds in synthetic oils that are absent in natural oils and extracts (Fig. 7) indicates precisely the receipt the generation potential products. As can be seen, a peak is present in the aromatic fractions of both "synthetic" oils, which presumably characterizes the presence of methylanthracene, which is not present in the hexane extract from open pores (the GC-MS method does not allow determining the position of the methyl group, further studies are required by the method GC-MS/MS or analysis of standart samples). In fact, the presence of these features indicates that, as a result of the temperature effect, the generation potential of kerogen is realized, and not only the output of the already formed HCC.

In addition to comparing the distribution of *n*-alkanes for oil, extracts, and "synthetic" oils, maturity parameters

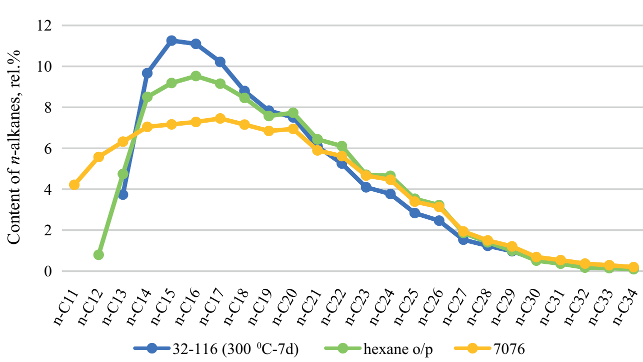

Fig. 6. Comparison of n-alkanes distribution in oil, hexane extract from open pores and "synthetic" oil (300 °C, 7 days) for sample 32-116

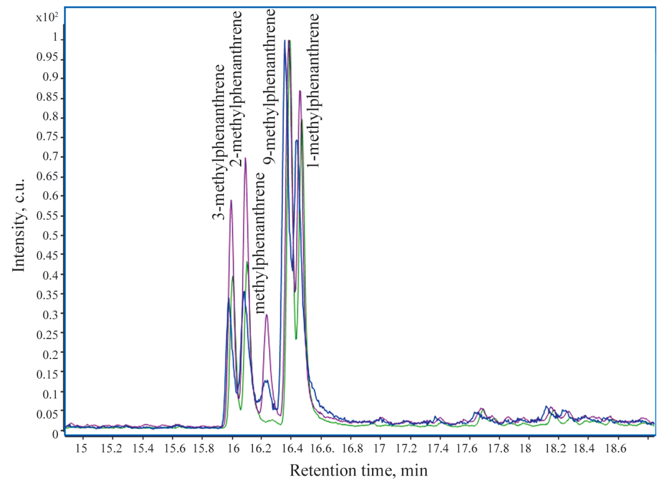

Fig. 7. Overlaying chromatograms of the aromatic fraction obtained for sample 32-116 in the study of "synthetic" oil at 300 °C, 7 days – the violet line; "synthetic" oil at 350 °C, 12 hours – the blue line; and hexane extract from open pores – green line. The registration mode of the selected ion is m/z 192.

were determined that made it possible to evaluate the identity of hydrocarbon compounds obtained in various ways by their conversion. The geochemical indices of CPI and OEP are shown in Table 5.

It has been established that these parameters for oil, hexane and chloroform extracts and "synthetic" oils are close to each other, which suggests that as a result of secondary and tertiary methods of stimulating the formation, the products will have a high degree of maturity, and hydrocarbon-containing compounds will not require secondary processing.

Another parameter that allows us to compare the studied HCC systems is the Pr/Ph ratio (Table 6). As can be seen from the Table, in the case of hexane extracts from closed pores, the lowest values of this geochemical parameter are observed. In chloroform extracts from open pores, the parameter also does not reach the value of 0.5, while in hexane extracts from open pores and in oil the values are identical and are about 0.6. Parameters

Sample	CPI			OEP		
	23-097	30-032	32-116	23-097	30-032	32-116
Hexane, o/p	0.97	1.01	0.98	0.90	0.90	0.89
Hexane, c/p	1.23	1.33	1.30	0.75	0.83	0.58
Chloroform, o/p	1.03	0.98	1.16	0.90	0.88	0.99
"Synthetic" oil, 300°C, 7 days	1.05	1.00	1.03	0.93	0.94	0.93
"Synthetic" oil, 350°C, 12 hours	1.12	1.00	0.97	0.96	0.94	0.96
Natural oil	0.99			0.93		

Table 5. Geochemical parameters of CPI and OEP calculated for the studied samples

Sample	Pr/Ph					
	Hexane, o/p	Hecane, c/p	Chloroform, o/p	“Synthetic” oil, 300°C, 7 days	“Synthetic” oil, 350°C, 12 hours	Natural oil 7076
23-097	0.59	0.27	0.43	0.66	0.72	
30-032	0.63	0.25	0.48	0.70	0.65	0.59
32-116	0.57	0.30	0.26	0.69	0.71	

Table 6. The ratio Pr/Ph for the studied samples

Sample	4 MDBT/1 MDBT					
	Hexane, o/p	Hecane, c/p	Chloroform, o/p	“Synthetic” oil, 300°C, 7 days	“Synthetic” oil, 350°C, 12 hours	Natural oil
23-097	1,67	1,69	1,45	1,69	1,53	
30-032	1,66	1,56	1,46	1,59	1,58	1,56
32-116	1,65	1,97	1,3	1,55	1,51	

Table 7. Geochemical parameter 4 MDBT/1 MDBT for the studied samples

for “synthetic” oils are also close to the indicated systems and are about 0.7. Thus, we can say that for this parameter, the indicated air-blast units are close.

Another parameter characterizing the maturity of HCC is determined by the ratio of 4-methyldibenzothiophene to 1-methyldibenzothiophene (Table 7) and for all systems lies within the error. This also indicates a high degree of thermal maturity of OM in all cases.

Conclusion

As a result of the work done, it was found that samples of the Bazhenov formation with high oil generation potential are promising for development by secondary and tertiary methods of stimulating the formation. In case of secondary methods of stimulating the formation, hydrocarbon compounds should be removed that are in the well in a physically bound state or fixed with bitumen plugs. For development it is not necessary to carry out rock destruction, for example, by hydraulic fracturing, to extract hydrocarbons from closed pores, since their maturity is lower, the composition is different from natural oil, and probably product recycling will be required. When extracting bitumen from open pores, their composition is close to the composition of natural oils extracted from the Bazhenov formation of this field, and the number of light hydrocarbons can reach 35 kg from 1 m^3 of rock.

At the same time these rocks are promising for tertiary methods of stimulation. The composition of the obtained “synthetic” oils is also close to the composition of natural oil. Moreover, when the rock is exposed to a temperature of 350 °C for 12 hours in the presence of water, it is possible to extract 15-20 kg of HCC from 1 m^3 of rock. At the same time, sorbed HCC will remain in the rock after thermal exposure. Selection of optimal conditions for stimulating the formation will increase the production of “synthetic” oil by this method. Additional research is necessary to evaluate whether adsorbed HCC will remain in the strata after the extraction of “synthetic” oil.

Thus, secondary and tertiary methods of stimulating the formation will allow for the future, when developing appropriate technologies, to significantly increase oil production from rocks of high-carbon formations with high oil generation potential, will not require secondary processing of the product, and can be used sequentially by summing the amount of hydrocarbons produced.

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Enhanced oil recovery from high-viscosity oil deposits by acid systems based on surfactants, coordining solvents and complex compounds

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Abstract. Physicochemical aspects of enhanced oil recovery (EOR) from heavy high-viscosity deposits, developed in natural mode and combined with thermal methods, using systems based on surface-active substances (surfactants), coordinating solvents and complex compounds are considered, which chemically evolve in situ to acquire colloidal-chemical properties that are optimal for oil displacement. Thermobaric reservoir conditions, interactions with reservoir rock and fluids are the factors causing the chemical evolution of the systems.

To enhance oil recovery and intensify the development of high-viscosity deposits, acid oil-displacing systems of prolonged action based on surfactants, inorganic acid adduct and polyatomic alcohol have been created. As a result of experimental studies of acid-base equilibrium in the systems with donor-acceptor interactions – polybasic inorganic acid and polyol, the influence of electrolytes, non-electrolytes and surfactants, the optimal compositions of the systems were selected, as well as concentration ranges of the components in the acid systems. When the initially acid system interacts with the carbonate reservoir to release CO_2, the oil viscosity decreases 1.2-2.7 times, the pH of the system rises and this system evolves chemically turning into an alkaline oil-displacing system. As a result it provides effective oil displacement and prolonged reservoir stimulation. The system is compatible with saline reservoir waters, has a low freezing point (minus 20 ÷ minus 60 ^oC), low interfacial tension at the oil boundary and is applicable in a wide temperature range, from 10 to 200 ^oC.

In 2014-2018 field tests of EOR technologies were successfully carried out to intensify oil production in the test areas of the Permian-Carboniferous deposit of high-viscosity oil in the Usinsk oil field, developed in natural mode and combined with thermal-steam stimulation, using the acid oil-displacing system based on surfactants, coordinating solvents and complex compounds. The pilot tests proved high efficiency of EOR technologies, as far as the oil production rate significantly increased, water cut decreased to intensify the development. The EOR technologies are environmentally safe and technologically effective. Commercial use of the EOR is promising for high-viscosity oil deposits.

Keywords: high-viscosity oils, enhanced oil recovery, physicochemical technologies, acid oil-displacing systems, surfactants, polybasic acids, polyols, coordinating compounds, acid-base equilibrium, CO_2, rheology, viscosity, the Usinsk oilfield, pilot tests

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Introduction

At present, heavy, highly viscous oils are considered as the main reserve of global hydrocarbon production, which determines the relevance of fundamental research work on the formation of new approaches to solving the problems of their most complete extraction from the reservoir (Romero-Zeron, 2016; Muslimov, 2012, Sheng, 2011). To solve the problem of increasing oil recovery of heavy, highly viscous oil deposits, a wide range of different methods is proposed. The most common are thermal methods based on reducing the viscosity of oil when heated, which increases the degree of its extraction from the reservoir (Ruzin et al., 2013; Hascakir, 2017; Burzhe et al., 1989; Kovscek, 2102). Various options of thermal effects are investigated using water vapor and hot water injection into the reservoir, as well as processes of in-situ dry and wet combustion, thermochemical heat generation due to

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reactions with reservoir water and rock, microwave heating, and geothermal heat. Of the thermal methods, the most effective method that has reached the stage of large-scale industrial use is the method of steam-thermal exposure by the stationary or cyclic injection of water vapor into the reservoir. However, the steam-thermal effect is a technologically complex and high-cost field development system. Therefore, it is promising to use physicochemical methods to intensify the development and enhance the oil recovery of heavy, highly viscous oil deposits in the form of non-thermal "cold" technologies and in combination with thermal steam effects (Altunina, Kuvshinov, 2007, 2008; Altunina et al., 2015).

In the work of the Institute of Petroleum Chemistry of the Siberian Branch of the Russian Academy of Sciences (IPC SB RAS), this approach is implemented by creating "intelligent" compositions based on thermotropic inorganic and polymer sol-forming and gel-forming compositions, as well as oil-displacing compositions with adjustable viscosity and alkalinity for injection into oil reservoirs with the aim of increasing oil recovery, generated directly in the reservoir, reducing the water cut in producing wells and intensifying oil production in complicated operating conditions, including high-viscosity deposits x oils developed both using thermal methods and without thermal exposure (Altunina et al., 2013, 2016a, 2017a, 2017b; Kuvshinov et al., 2017).

This paper discusses the physicochemical aspects of enhanced oil recovery of heavy oil fields developed in natural mode and in combination with thermal methods, using cyclic and stationary effects on the formation of chemically evolving surfactant-based systems, coordinating solvents and complex compounds. The factors causing the chemical evolution of systems in the reservoir are thermobaric reservoir conditions, interaction with reservoir rock and reservoir fluids. As a result of the chemical evolution of the injected systems in the reservoir, in the process of oil displacement, successively replacing each other, form effective oil displacing liquids with a high acid-base buffer capacity, adjustable viscosity, as well as emulsion and gas-liquid dispersion systems.

Acid-base equilibria in the systems "polybasic acid-polyol-water"

To increase oil recovery and intensify the development of high-viscosity oil fields, acidic oil-displacing compositions of a new type based on surfactants, coordinating solvents and complex compounds, in particular, coordination compounds of polybasic inorganic acids with polyatomic alcohols (polyols), chemically evolving directly in the formation with the acquisition of colloid-chemical properties that are optimal for oil displacement. As a result of experimental studies of acid-base equilibria in systems with donor-acceptor interactions – polybasic inorganic acid and polyhydric alcohol, the influence of electrolytes, non-electrolytes and surfactants on them, the optimal compositions and concentration areas of acidic compositions were selected.

In the "inorganic polyacid-polyol" systems, due to donor-acceptor interaction, complex acids are formed that are much stronger than the original acid (Shvarts, 1990; Shvarts et al., 2005). Donor-acceptor interaction allows increasing the acidity of oil-displacing compositions and increase the duration of their action in the reservoir by increasing the buffer capacity and expanding the range of the buffer action in the acidic pH range. The donor-acceptor interaction proceeds in the medium of an aqueous solution of a polyol, for example, glycerin, mannitol, sorbitol. Such a solution is a coordinating solvent, the polyol in it is a Lewis base, an electron pair donor. Lewis acids, for example, boric acid, dissolved in a coordinating solvent as well as aqua ions of some metals: calcium, magnesium, iron, and aluminum, are acceptors of the donor electron pair. A donor-acceptor chemical bond possesses the properties of a polarized covalent bond and is called a coordination bond. The interaction of the donor and the acceptor leads to the formation of a donor-acceptor molecular complex, called the coordination compound or adduct. The complex is a much stronger acid than the original Lewis acid. In Russia and abroad, this fact aroused interest in the study of the possibility of using complex acids in physical and chemical technologies for enhancing oil recovery.

Figure 1 shows a diagram of the formation of complex acid and its dissociation into ions by the example of the interaction of boric acid and glycerin.

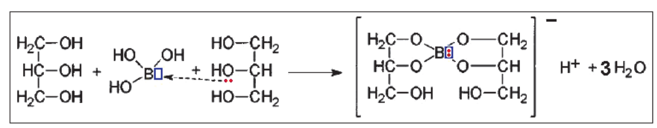


Fig. 1. Donor-acceptor interaction of boric acid and glycerin with the formation of complex glycerinboric acid

Glycerinboric acid of a stoichiometric composition shown in Figure 1, under the conditions of our experiments, is the dominant form of the coordination polyolborate complex.

The oxygen atom of the hydroxyl group in the glycerin molecule, the donor, transfers its lone electron pair to the free orbital of the acceptor, the boron atom in the boric acid molecule. As a result, a molecule of coordination compound, glycerinboric acid, is four orders of magnitude stronger than boric acid from one molecule of boric acid and two molecules of glycerin. Instead of boric acid in this scheme there may be a metal aqua ion with properties of a Lewis acid, for example, a doubly charged cation of calcium and magnesium or a triple charged cation of aluminum and iron. Molecules of the complex acid are able to interact with metal aqua ions due to their hydroxyl alcohol groups. Figure 2 shows the reaction scheme, which reflects the stereochemical feature of the glycerinboric acid molecule – its ability to form soluble outer-sphere cyclic complexes with metal ions due to terminal hydroxyl groups.

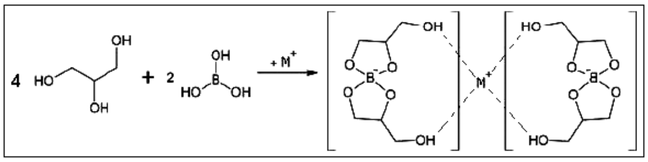


Fig. 2. Diagram of the interaction of glycerinboric acid with a metal cation in solution with the formation of a soluble outer-sphere cyclic complex

The scheme in Figure 2 is hypothetical, based on experimental results (Fig. 3) – abnormally high viscosity of glycerinboric acid in concentrated water-glycerin solutions of salts of divalent and trivalent metals.

With increasing concentration of metal aqua ions in solution, along with cyclic structures, the formation of polymer-like associates is possible, in which metal aqua ions play the role of bridges connecting the complex acid molecules to linear and branched spatial associative structures. As a rule, such a structure formation leads to a significant increase in viscosity. The method of regulating the viscosity and density of the salt additives of these metals may be useful for regulating the physico-chemical and rheological properties of the compositions. In addition, this interaction contributes to the compatibility of complex acids based on polyols with formation waters, especially with highly mineralized, with a high content of calcium and magnesium salts.

The system "boric acid-polyhydric alcohol-electrolytes-water" is of interest as the basis for a new type of oil-displacing fluids, effective at low reservoir temperatures, at which conventional oil-displacing fluids are ineffective. The physicochemical properties of this system are determined by the donor-acceptor interaction of polyhydric alcohols with boric acid, in which the acid anions act as a tetradentate ligand, which is a Lewis acid. As a result, in this system, depending on the pH and the nature of the electrolytes present, various coordination complexes of glycerin and boric acid anions are formed. When interacting with water-soluble non-ionic surfactants, these complexes form effective oil-displacing liquids with high wetting and washing ability.

Boric acid is a weak acid, its pK = 9.2, but with glycerin it forms a sufficiently strong glycerinboric acid (Rakhmankulov et al., 2003; Kreshkov, 1977), in which pK for a concentration of glycerin 1M is 6.5, for a concentration of glycerin 3.5M – 5.7 (Charlot, 1965). Glycerinboric acid and its salts are more soluble in water than salts of boric acid. This is due to the greater hydrophilicity of their molecules and the saturation of the coordination bonds of boron. Therefore, glycerinboric acid and its salts are well compatible with mineralized formation waters.

Experimental studies of acid-base equilibria in systems "boric acid-polyol-water" have been carried out at the IPC SB RAS. The pH values of the solutions were obtained by a potentiometric method using a glass electrode using a microprocessor laboratory pH meter manufactured by HANNA Instruments, the density by the pycnometric method. The measurement of the viscosity of polyol solutions was performed using a vibration viscometer "Reokinetic" with a tuning fork sensor. Studies of the rheological properties of solutions and oil were performed by rotational viscometry using a Reotest-2.1.M viscometer (measuring system of coaxial cylinders S/S2) and a HAAKE Viscometer iQ reometer (measuring system of coaxial cylinders CC16 DIN/Ti) at different shear rates and temperatures.

It was established that during the interaction of boric acid and polyols as a result of the formation of complex acids, the pH value of a 1 % solution of boric acid in aqueous-alcoholic solvents decreases from 5.9 units pH with an increase in the concentration of polyhydric

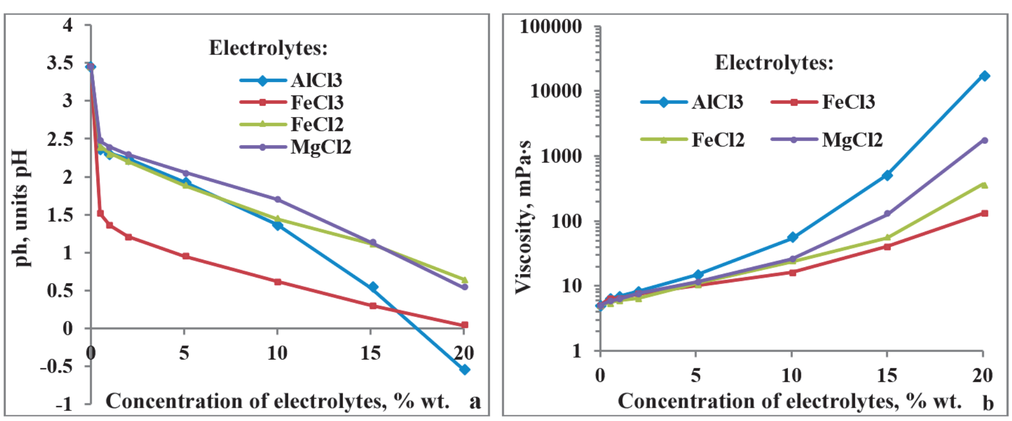


Fig. 3. Dependence of pH (a) and viscosity (b) of solutions containing 5 % wt. boric acid and 50 % wt. glycerin on concentration of electrolytes

alcohols in the solvent up to 1.7-2.7 units pH, 5 % solution – from 3.4 to 1.5-2.2 units pH and 10 % – up to 1.3-1.8 units pH, Figure 4a is given as an example. In this case, the viscosity of solutions significantly increases (Fig. 4b). The decrease in pH with increasing polyol concentration is monotonous, due to the continuous equilibrium shift of the ionization reaction coupled with the shift of the formation of boric acid complex with the polyol, which is confirmed by the calculated concentration constants of the formation and ionization of glycerinboric acid in the glycerin coordinating solvent.

As a result of studying the effect of electrolytes on acid-base equilibria of solutions in the water-glycerinboric acid system, it was found that aluminum chloride $AlCl_3$, iron $FeCl_3$, $FeCl_2$ and magnesium $MgCl_2$ (Fig. 3), exert a strong influence on acid equilibrium. The concentration of aluminum chloride in solution to 20 % wt. pH values decrease to minus 0.54 units pH (Fig. 3a) the viscosity values of the solutions increase to 17,500 mPa·s (Fig. 3b).

The addition of surfactants does not significantly affect the acid-base equilibria of solutions in the water-glycerinboric acid system and their physico-chemical characteristics of the solutions (pH, viscosity, density).

To increase oil recovery of high-viscosity oil deposits, along with acid-base properties, the rheological behavior of oil-displacing compositions is important. In this regard, the rheological properties of solutions compositions based on the surfactant-glycerin-oric acid-electrolytes system using rotational viscometry using the Reotest-2.1.M rotational viscometer (measuring system of coaxial cylinders S/S1) were investigated. At various shear rates, rheological curves of solution flow were obtained, and viscosity values were determined. It has been established that compositions based on the “surfactant-glycerin-boric acid-electrolytes” system are Newtonian fluids, that is, the dependence of stress on shear rate is linear, and the viscosity does not depend on shear rate (Fig. 5), despite the high values of solution viscosity.

Thus, the introduction of polyols, for example, glycerin, mannitol, sorbitol in the composition of oil-displacing compositions based on surfactants and polyatomic acids leads to an increase in their acidity, a decrease in pH and freezing temperature of solutions, an increase in their viscosity and density, and an improvement in their compatibility with saline stratum waters. The study of acid-base equilibria in systems “boric acid-polyol-water” with donor-acceptor interactions, studying the effect of electrolytes, non-electrolytes and surfactants, allowed us to establish the regularities of the formation of coordinating compounds and choose the composition and concentration of components to create acidic compositions with colloidal chemical properties optimal for oil displacement.

Physico-chemical and rheological properties of oil-displacing acidic compositions based on surfactants, boric acid and polyol

On the basis of the conducted research in the IPC SB RAS, an acid oil-displacing composition of prolonged action on the basis of surfactant, boric acid and glycerin adduct (GBK composition), realizing the concept of chemically evolving systems, was created. The composition is compatible with saline stratal waters, has a low freezing point (minus 20 °C ÷ minus 60 °C), low interfacial tension at the border with oil (below 0.001 mN/m at the border with oil of the Usinsk field). The density of the composition can be adjusted from 1100 to 1300 kg/m^3, viscosity – from tens to hundreds of mPa·s.

The composition is applicable to enhance oil recovery and intensify oil production by increasing the permeability of reservoir rocks and the productivity of producing wells in a wide range of temperatures, from 10 to 200 °C, most effective in carbonate reservoirs, in particular, the Permian-Carboniferous reservoir of the Usinsk field. The composition has a delayed reaction with carbonate rocks. High oil displacing ability, compatibility with saline stratal waters, reduction of clay swelling leads to additional flushing of residual oil from both highly permeable and low permeable zones of the formation.

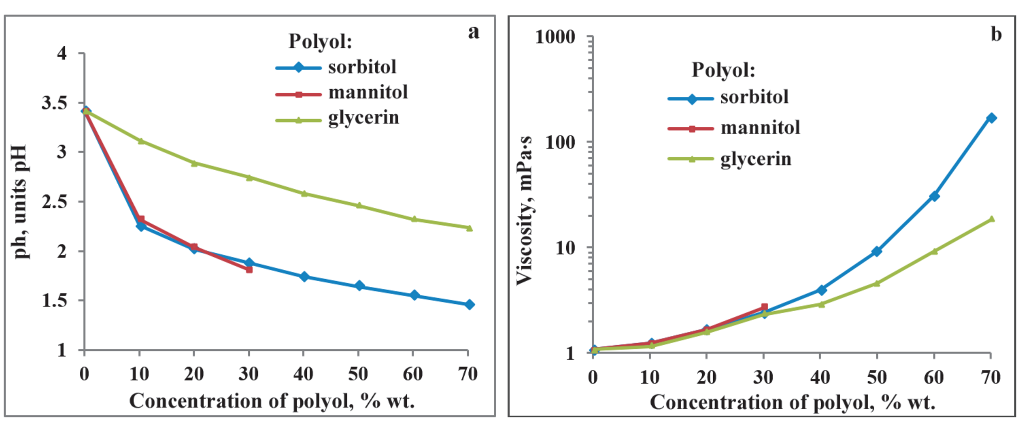


Fig. 4. Dependence of pH (a) and viscosity (b) of solutions containing 5 % wt. boric acid on concentration of polyol

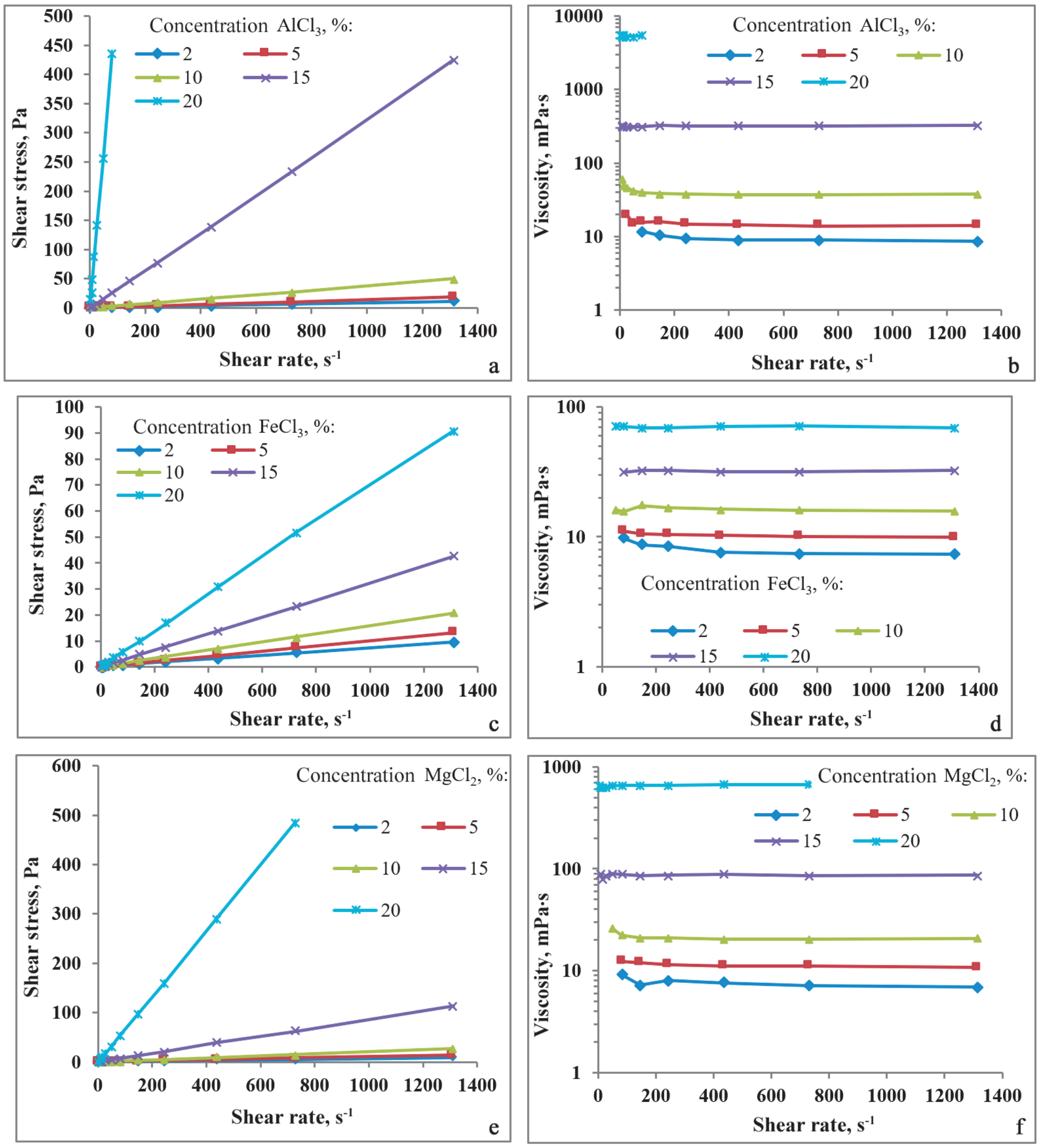


Fig. 5. Rheological curves of flow (a, c, d) and the dependence of viscosity (b, d, e) of solutions containing surfactants, boric acid, glycerin and electrolytes, on the shear rate

As a result of the interaction of the acidic composition with the carbonate reservoir, CO_2 is released, which dissolves in oil and reduces its viscosity, and contributes to an increase in the degree of oil recovery. In addition, at high temperatures, greater than 70 °C, the pH of the composition increases from 2.8-3.1 to 8.8-10.0 (Fig. 6), and it evolves chemically, becoming alkaline composition, providing effective oil displacement and prolonged exposure to the reservoir. After thermostating with the composition and carbonate reservoir at temperatures above 70 °C, the viscosity of the oil decreases 1.2-2.7 times (Fig. 7).

The method of rotational viscometry was used to study the rheological properties of the oil of the Usinsk field before thermostating and after thermostating of the original oil with the oil-displacing acidic composition GBK at temperatures of 70, 90 and 120 °C. At various shear rates and temperatures in the range from 20 to 90 °C, rheological curves of oil flow were obtained and viscosity values were determined (Fig. 8). Oil from the Usinsk field is a colloid-dispersed system with poorly pronounced non-Newtonian properties. Temperature control with an oil-driving acidic composition significantly reduces the oil viscosity. Oil loses its non-Newtonian properties and becomes a Newtonian fluid, that is, the dependence of stress on shear rate becomes linear.

In addition, the proton magnetic resonance (PMR) method using an AVANCEAV 300 Fourier transform spectrometer (Bruker) (Germany) found that oil-displacing acidic compositions of GBK have demulsifying properties. From the PMR spectra, it follows that the result of heat treatment of oil with GBK compositions at different temperatures is that the water content in the oil phase of the "oil-composition" system decreases; the higher the heat treatment temperature, the less water remains in the oil phase.

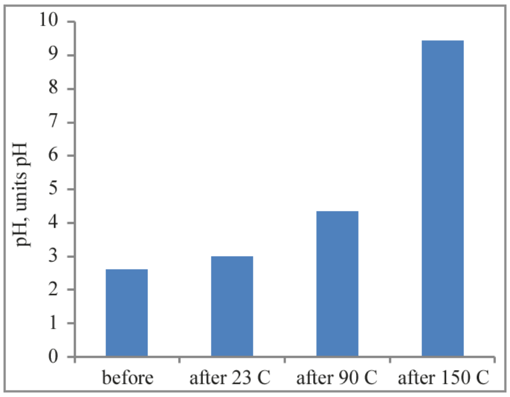


Fig. 6. The pH value of the composition of GBK before and after thermostating with a carbonate reservoir at different temperatures

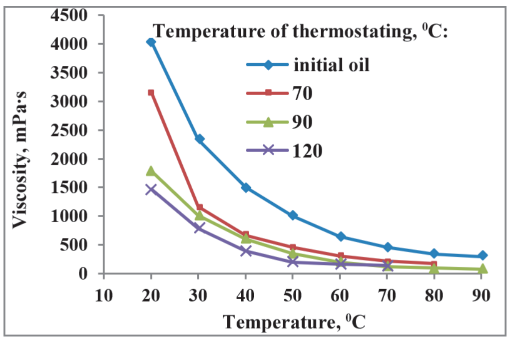


Fig. 7. Temperature dependence of oil viscosity of the Usinsk field before and after thermostating with the composition of GBK at various temperatures

Pilot works with the use of acid oil-displacing GBK composition

Acid oil-displacing composition of GBK of prolonged action on the basis of surfactant, boric acid adduct and glycerin can be used in the treatment of bottomhole zones of injection and production wells using different injection schemes: one rim, several rims, alternating injection of the rims of gas cylinder in different concentrations. When alternating injection of the rims of GBK composition, the rim of the composition is diluted 3-10 times (optimally 5 times), then the rim of GBK composition, diluted 2 times is first pumped, then the rim of composition, diluted 3-10 times, etc. After the total volume has been injected, the GBK composition is forced into the reservoir from tubing with a buffer volume of water (8-10 m^3). The exposure time of the GBK composition on the well bottom zone is from 12 hours to 1-3 days, for this period the well should be closed.

To increase oil recovery and to intensify the development of deposits of heavy, highly viscous oils without heat exposure, "cold" physical and chemical technologies have been proposed using "intelligent" oil-displacing compositions based on surfactants, coordinating solvents and complex compounds. To increase the flow rates of low-productive producing wells of the Permian-Carboniferous reservoir of the Usinsk field for oil and liquid without thermal steam effects,

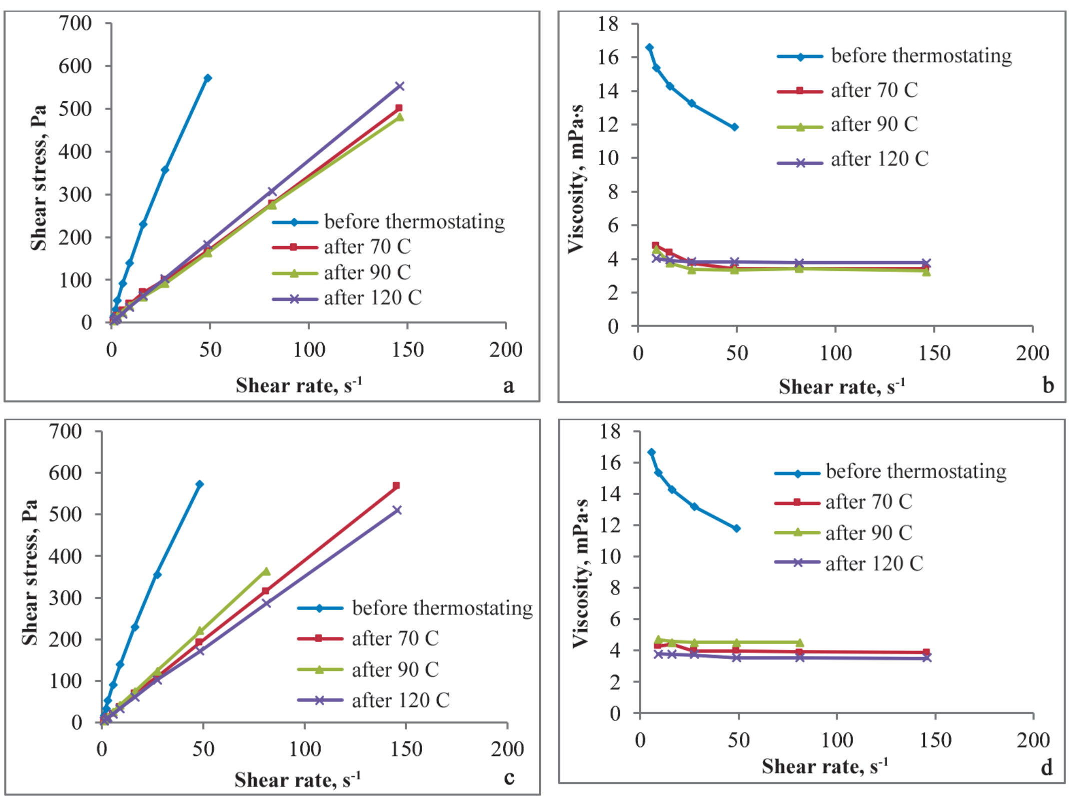


Fig. 8. Rheological flow curves (a, c) and the dependence of oil viscosity of the Usinsk field on the shear rate (b, d) before and after thermostating at different temperatures with the composition of GBK (a, b) and with the composition of GBK with the addition of carbonate rock (c, d). Measurements were carried out at 20 °C.

a reagent-cyclical was proposed (similar to a steam cyclic) with the use of acidic oil-displacing composition GBK of a prolonged action based on surfactant, boric acid adduct and glycerin. The rim of the surfactant composition is pumped into the production well, then water is pumped, after that an exposure of 7-14 days is made (similar to impregnation at the steam cyclic) and then the well is put into operation. Oil production is carried out in the form of low-viscosity direct emulsion. After completion of oil production in the well in the first cycle, the next cycle is carried out – injection of alternating rims of the surfactant composition and water, as in the first cycle, holding and then extracting oil from the well. As a result, there is an increase in oil production from both high-permeability and low-permeability zones of the formation.

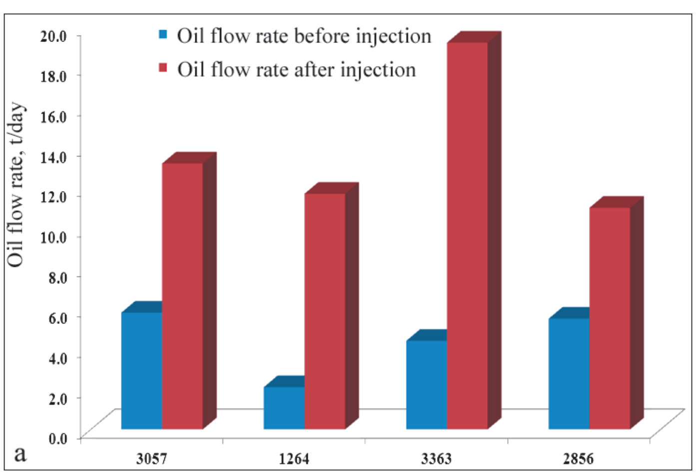
From May 29, 2014 to July 26, 2014, pilot works were carried out on the Permian-Carboniferous reservoir of the Usinsk field using the acidic GBK composition of prolonged action according to the reagent-cyclical variant. OSK LLC pumped the GBK composition into 10 low-productive production wells. The injection volume of the composition was in the range of 30-50 m^3, the volume of the concentrate of the composition was 9-15 m^3. Figure 9 shows the characteristic reaction of the wells immediately after injection, and Figure 10 shows a generalized schedule for increasing oil and liquid flow rates for all 10 wells in the observation period after treatment for 19 months and average monthly oil flow rates for individual wells before and after processing composition GBK (up to 19 months).

After injection of the GBK acid composition of prolonged action based on surfactant, inorganic acid adduct and polyol, an increase in oil flow rates by 5.5-14.8 tons/day, an increase in liquid flow rates by 15-25 m^3/day is observed. The average oil flow rate for one well before treatment was 80 tons/month, based on the results of 19 months after treatment – 185 tons/month, that is, the increase in oil flow rates amounted to an average of 104 tons/month per well. Additionally, the oil produced during the observation period of 19 months amounted to ~ 20,000 tons over 10 wells, ~ 2,000 tons/well; the effect was not over.

According to the results of the work carried out, the use of prolonged-action GBK acid composition to enhance oil recovery and intensify oil production by increasing the permeability of carbonate reservoir rocks and increasing the productivity of low-productive production wells was recommended for industrial use.

On the Permian-Carboniferous deposit of the Usinsk field in 2017-2018 the technology has been successfully tested to restore the injectivity of a horizontal well and enhance oil recovery under thermal effects by injection of an acidic oil-displacing GBK composition of prolonged action based on surfactant, boric acid adduct and glycerin. In 2017, in the South-Eastern experimental area of the Permian-Carboniferous reservoir of high-viscosity oil from the Usinsk field, LUKOIL-Komi LLC, jointly with the IPC SB RAS, a branch of LUKOIL-Engineering LLC, PermNIPIneft, and OSC LLC, injection of gelling and oil displacing compositions with the subsequent restoration of liquid injectivity and enhanced oil recovery using acidic composition based on surfactants, coordinating solvents and complex compounds: treatment of horizontal hot water injection wells 10GS and 11GS with compositions GALKA® and NINKA-Z in June-September 2017, followed by treatment of the 10GS well with GBK acid composition based on surfactant.

Inorganic gel-forming compositions GALKA® in surface conditions are low-viscosity aqueous solutions, in reservoir conditions – turn into gels. Gelation occurs under the action of thermal energy of the reservoir or the injected coolant, without cross-linking agents. For the preparation of compositions water of any mineralization is used, suitable for inhomogeneous formations with



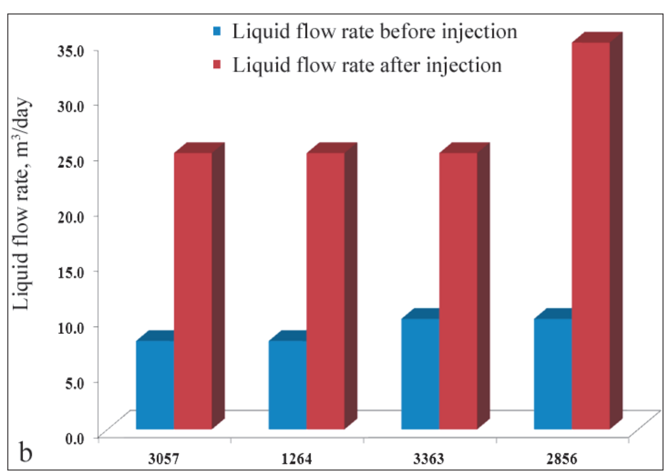


Fig. 9. Pilot work results using prolonged-action GBK acid composition on low-productive producing wells Nos. 3057, 1264, 3363, 2856 of the Permian-Carboniferous reservoir of the Usinsk field: an increase in flow rates for oil (a) and liquid (b) immediately after injection

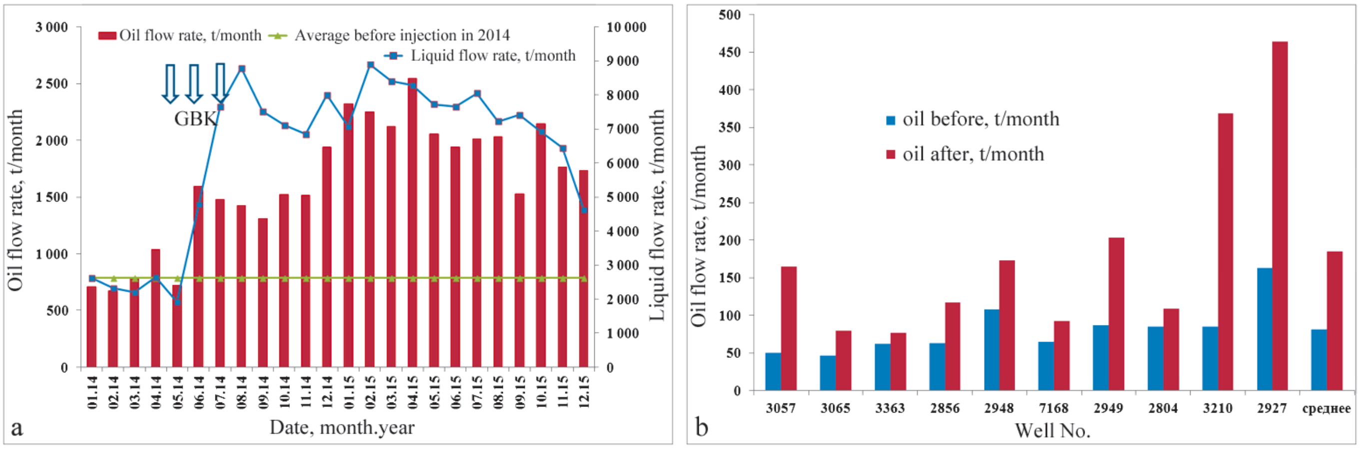


Fig. 10. Pilot work results using prolonged-action GBK acid composition on low-productive producing wells of the Permian-Carboniferous reservoir of the Usinsk field: (a) – a total of 10 producing wells, an increase in oil production rates, a decrease in water content; (b) – the average value of monthly oil flow rates for individual wells over the observation period of 19 months for individual wells before and after treatment with the GBK composition

permeability from 0.01 to 30 μm^2. The gelation time is from several minutes to several days in the temperature range 10-320 °C. With their use, five gel-technologies for enhanced oil recovery have been developed, which are industrially used in the fields of Western Siberia and the Komi Republic (Altunina, Kuvshinov, 2008, 2007; Altunina et al., 2015, 2017a). Ecological safety of the reagents, their harmlessness to humans makes it possible to widely use gel technologies in the fields of Russia and other countries.

The thickened composition NINKA-Z is simultaneously flow-diverting and oil-displacing composition, used to increase both the oil-displacement ratio and the coverage ratio of high-viscosity oil deposits developed by the steam-heat effect (Altunina et al., 2015, 2011, 2016b). In the formation, under thermal action, carbamide is hydrolyzed, forming CO_2 and NH_3, which, with the ammonium salt, provides an alkaline ammonia buffer system, optimal for oil displacement purposes. An increase in pH causes the hydrolysis of the aluminum salt to form an aluminum hydroxide sol, while the viscosity of the composition increases by 1-2 orders of magnitude, which leads to an increase in the formation's thermal coverage, the connection of low-permeability streams, a decrease in oil viscosity and its additional washing out. As a result, an increase in the reservoir coverage ratio, an increase in oil recovery factor and an increase in oil production occur.

The wells number 10GS and 11GS are located in the South-Eastern experimental plot (Fig. 11), pumping hot water into the lower development object. The southeastern section (cluster of wells 7OC) is a part of the southern current section. Until 2012, the site was developed in the natural mode.At the time of the implementation of the reservoir pressure maintenance system, the weighted average reservoir pressure was 8.58 MPa, the average daily fluid flow rate was 22 tons/day, the average daily oil flow rate was 10.4 tons/day, water content – 52 %. With the organization of simultaneous injection of hot water into wells No. 10GS, 11GS in December 2012 with an intake capacity of 400 tons/day (total daily injection of 800 tons/day), the reservoir pressure stabilized and at the time of analysis is 9.2 MPa, but as a result water breakthroughs sharply increased the water content of surrounding wells in February 2013, from 57 to 65 %, after which the injection volumes were adjusted. Since June 2013, wells No. 10GS, 11GS have been operated cyclically for 30 days, the daily injection capacity of one well is about 400 m^3/day. After switching to the cyclic injection mode, the average flow rate of the surrounding wells was 30 tons/day, the average oil flow rate was 9 tons/day.

On the injection well No. 10GS of 30-31.07.2017, measures were taken to inject the gel-forming composition GALKA® for the redistribution of filtration flows, to limit water inflow, pumped 100 m^3. Injectivity capacity before treatment was 720 m^3/day, after treatment – 640 m^3/day. Measures to inject oil-displacing and flow-

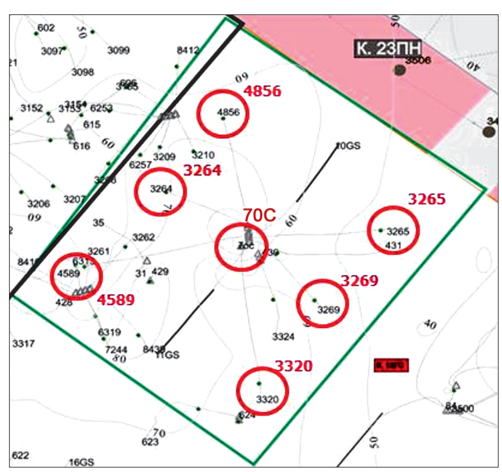


Fig. 11. Plot of pilot works in the area of the well cluster number 7OC

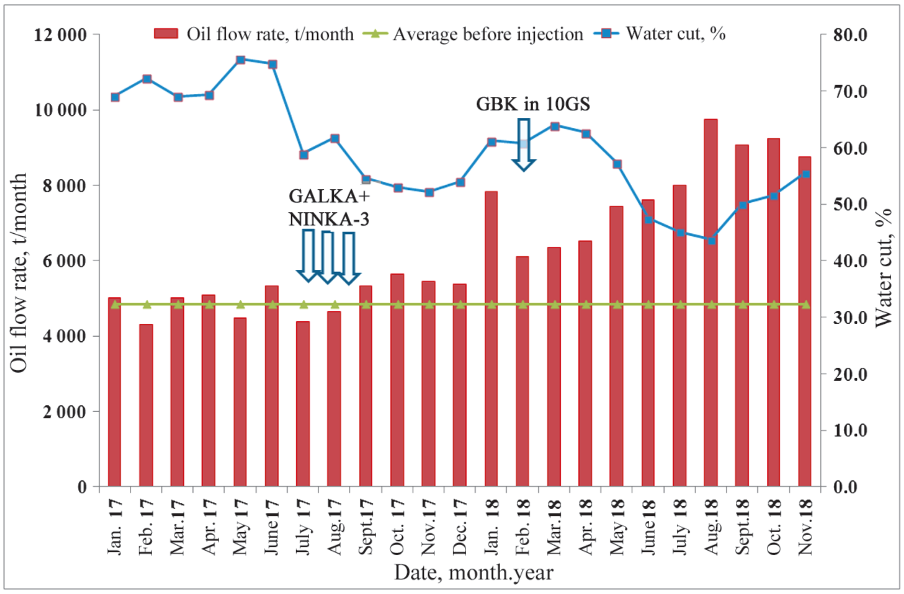


Fig. 12. Results of complex treatment with GALKA + NINKA-Z compositions, with additional treatment with the acid GBK composition of injection wells 10GS and 11GS in 2017-2018

deflecting composition NINKA-Z for leveling the intake profile and washing out residual oil were performed on 09-11.08.2017, 200 m^3 were injected. Injectivity capacity before treatment was 640 m^3/day, after 640 m^3/day. In general, according to the results of the work, the injectivity of the well is reduced by 80 m^3.

On injection well No. 11GS, on 27-28.08.2017, measures were taken to inject the GALKA® composition, 80 m^3 were injected. Intake capacity before treatment was 720 m^3/day, after 520 m^3/day. Measures for the injection of the composition NINKA-W were carried out on September 14-15, 2017, 160 m^3 were injected. Injectivity capacity before treatment was 510 m^3/day, after 520 m^3/day. In general, the results of the work show a decrease in the injectivity of well by 200 m^3. Due to the fact that the wells are located in one area of the reservoir and the injection of compositions was performed in approximately one period, then their influence on the production wells is considered together.

In December 2017, when the well No. 10GS was operating, there was an increase in pressure on the 7OC furnace, after which the furnace was transferred to a 2 mm choke, but this did not lead to a decrease in pressure. To reduce the pressure on the furnaces, the nozzle at well No. 11GS was increased. Indirectly, this indicates about a decrease in injectivity in the well number 10 GS. To intensify injectivity, a decision was made in the well No. 10GS to perform an bottomhole zone treatment using an oil-displacing acid GBK composition based on surfactant, boric acid adduct and glycerin. In January 2018, the acid composition was injected into the well 10GS 50 m^3, the edges of 5 m^3, with alternating changes in the composition: water concentration equal to 1:1 and 1:9, according to the developed technical plan and instructions for using the composition.

Figure 12 shows the work schedule for the 20 production wells in the area surrounding wells 10 and 11GS. The figure shows the moments of processing compositions. It can be seen that in the first months the effect was not too noticeable, which can be explained as a delay effect of 2-4 months for the treatment of production wells, due to the time of redistribution of the flow and passage of the fluid front between the injection and production wells, and a decrease in the injectivity in the well 10GS.

After carrying out measures to increase the injectivity at the well 10GS with the injection of the acid composition of the cylinder head, the graph shows a steady increase in oil production. The decrease in the water content was recorded almost immediately after treatment. The whole time of observation of the effect it was maintained. Currently, the duration of the effect is 14 months; additional oil production in the area is 35,400 tons, or ~ 4.2 tons/day for each production well, that is, there is an increase in oil production and development intensification, which confirms the effectiveness of the GBK composition and the proposed technology.

Thus, the possibility of using an acid GBK composition based on surfactants, coordinating solvents and complex compounds, if necessary, to restore or increase the injectivity of the injection well, including after treatments with gel-forming and/or highly viscous compositions, is shown.

Conclusion

To increase oil recovery and intensify the development of high-viscosity oil fields, acidic oil-displacing compositions based on surfactants, coordinating solvents and complex compounds have been created that chemically evolve directly in the reservoir with the acquisition of colloidal chemical properties that are optimal for oil displacement.

The main physicochemical factors for increasing oil recovery are the interaction of the initially acidic composition with a carbonate reservoir with the release of CO_2 and a decrease in oil viscosity by 1.2-2.7 times, leading to an increase in the pH of the composition and its transformation into an alkaline oil-displacing composition with a large buffer capacity. These factors provide effective oil displacement and prolonged impact on the reservoir in a wide range of dilution with water during in-situ filtration.

The presence of surfactants and polyols in the composition ensures its compatibility with mineralized formation water, low freezing temperature (minus 20 ÷ minus 60 °C), low interfacial stress at the interface with oil (below 0.001 mN/m) and applicability over a wide range of reservoir temperatures (from 10 up to 200 °C). Moreover, the compositions are Newtonian fluids with a high viscosity (from tens to hundreds of mPa·s), commensurate with the viscosity of the oil.

All reagents used in the GBK compositions are products of large-tonnage industrial production. The compositions have high manufacturability, including in the northern regions, since they are low-fouling, standard oil-field equipment is used for their preparation and injection.

The use on an industrial scale of acidic oil-displacing compositions of a new type based on surfactants, coordinating solvents and complex compounds that implement the concept of chemically evolving systems, as well as environmentally safe technologies using them that have high technological and economic efficiency, will extend the cost-effective operation of fields located in the late development stage, and to engage in the development of a field with difficultly recoverable hydrocarbon reserves, including deposits of highly viscous oils and deposits of the Arctic region.

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ORIGINAL RESEARCH ARTICLE

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Selection of optimal strength criteria for the terrigenous Pashiyan horizon of the Romashkinskoe field Tashliyarskaya area

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Abstract. In the process of oil reserves' development, the in-situ stresses change. Knowledge of rock failure constraints will allow prediction of behavior of rock when subject to subsurface stress change. In this study, we used the results of studies of the Pashiyan sandstone core samples recovered from the Tashliyarskaya area well No. 14403. Six sets of samples, each consisting of three samples taken from the homogeneous intervals at the same depth, were used to determine the ultimate tensile strength, uniaxial and triaxial compressive strength in the in-situ conditions. An analysis of the methods for constructing a rock strength certificate, and comparison of the strength criteria described in State Standard 21153.8-88, the Mohr-Coulomb linear strength criterion and the non-linear Hoek-Brown criterion are provided. The Hoek-Brown criterion has the advantage of describing a non-linear increase in strength with an increase in overburden pressure and more adequately reflects the properties of rock. For the first time, a comparison of applicability of strength criteria obtained by different methods and based on the laboratory core analysis was made to determine their practical applicability. Comprehensive studies of the strength characteristics have never been previously conducted, and the results obtained will serve as the basis for further analysis and application in order to improve the development of the terrigenous Devonian Romashkinskoe field.

Keywords: failure criterion, strength certificate, Mohr-Coulomb failure criterion, Hoek-Brown failure criterion, ultimate stress, tensile, uniaxial compression, triaxial compression

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In the process of oil reserves' development, the in-situ stresses change. Production enhancement operations (e.g., waterflooding, hydraulic fracturing) cause the reservoir pressure, the effective stress, stress regimes, and the reservoir temperature change both locally, and over the entire field.

Change of the in-situ stresses can cause failure of subsurface rock and alteration of the pore volume, activate the pre-existing flaws, change permeability of natural fractures, etc.

Knowledge of rock failure constraints will allow prediction of behavior of rock when subject to subsurface stress change. Ability of rock to withstand an external applied load without failure is referred to as the strength of a material. Ultimate strength of rock is determined by laboratory methods when rock samples are subject to tensile and compression loadings.

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The rock strength is defined by two components: the strength of the rock matrix and the strength of discontinuity interfaces (natural fractures, inclusions, flaws, etc.). The conditions that cause failure of the subsurface rocks can be described by the stress criteria, also known as the strength criteria. When discussing failure of rock it should be remembered that compressive strength of the geological material exceeds the tensile strength.

To describe strength criteria, the subsurface rock mechanics usually uses strength criteria defined via stresses, whereby, minimum and maximum principal stresses are only used, while the intermediate principal stress is ignored, as rule. A curve enveloping the ultimate stress circles built in the coordinates of the normal effective stress-shear stress (σ, τ) is a criterion known as a certificate of rock strength.

According to GOST R 50544-93 (State Standart, 1993), a certificate of rock strength is the relationship between the ultimate shear breaking stress and the normal stress acting on the subsurface rocks. Graphically, it is expressed as a curve enveloping stress circles.

The procedure to obtain a certificate of rock strength described in GOST 21153.8-88 (State Standart, 1988), is based on the ultimate triaxial compressive strength of not less than three core samples at different lateral pressures, and the ultimate tensile and uniaxial compressive strength of two more core samples. Five circles in *σ-τ* coordinates are built and a smooth curve enveloping all five, or more, semicircles is drawn. The described procedure requires that at least five core samples should be used, which often cannot be satisfied in practice, because of scarcity of core material.

Another procedure based on the ultimate strength under compression shear loading described in GOST 21153.5-88 (State Standart, 1988) fails to meet production and research goals.

Both procedures mentioned above use circles in the *σ-τ* coordinates based on the ultimate strength of core samples. Presented below is an alternative procedure to obtain a certificate of rock strength. This is a calculation procedure that uses an empiric equation to determine the coordinates of the points of the enveloping curve:

$$\tau = \tau_{max}\left(\frac{\sigma_к^2}{\sigma_к^2+a^2}\right)^{3/8}, \quad (1)$$

where τ_{max} – maximum shear strength of the subsurface rock, MPa. It is assumed that fractures and pores are completely closed under the action of pressure; $\sigma_к$ – normal stress relative to the origin of coordinates transposed to the point of intersection of the enveloping curve and x-axis, MPa; *a* – parameter related to the shape of the enveloping curve.

Results of laboratory experiments on determination of the ultimate tensile and uniaxial compressive strength, as well as tabulated data given by GOST 21153.8-88 (State Standart, 1988) are used to calculate *τ* by Eq. (1).

In this study, we used the results of studies of the Pashiyan sandstone core samples taken from the Tashliyarskaya Area Well No. 14403. Six sets of samples, each consisting of three samples taken from the homogeneous intervals at the same depth, were used to determine ultimate tensile, uniaxial, and triaxial compressive strength corresponding to in-situ conditions. Table 1 summarizes the results of the laboratory experiments. Figure 1 illustrates building of a certificate of rock strength according to GOST 21153.8-88 (State Standart, 1988) procedure.

It is evident that the strength criterion does not describe accurately the circle built based on the ultimate strength and confining pressure values from the triaxial test. The compression created during the triaxial test increases the ultimate strength of a material compared to the ultimate strength obtained from the uniaxial test performed at the atmospheric pressure and zero confining pressure. It follows that it would be problematic to use GOST 21153.8-88 (State Standart, 1988) to obtain

No. of sample set	No. of sample	Core recovery depth, m	Sample size, diameter × length, mm	Test type	Ultimate strength, MPa
1	32	1625.6	30 × 60	triaxial compression	87.5
	31	1625.55	30 × 60	uniaxial compression	43.20
	33	1625.6	30 × 15	tension	2.90
2	35	1626.3	30 × 60	triaxial compression	61.0
	37	1626.35	30 × 60	uniaxial compression	25.58
	36	1626.3	30 × 15	tension	2.70
3	43	1628.43	30 × 60	triaxial compression	119.1
	41	1628.4	30 × 60	uniaxial compression	43.48
	42	1628.4	30 × 15	tension	3.50
4	45	1629.33	30 × 60	triaxial compression	144.9
	47	1629.36	30 × 60	uniaxial compression	61.27
	46	1629.33	30 × 15	tension	5.70
5	51	1630.43	30 × 60	triaxial compression	119.0
	49	1630.4	30 × 60	uniaxial compression	75.69
	50	1630.,4	30 × 15	tension	3.90
6	54	1632.25	30 × 60	triaxial compression	78.0
	56	1632.28	30 × 60	uniaxial compression	41.45
	55	1632.25	30 × 15	tension	4.40
Average			30 × 60	triaxial compression	102.0
			30 × 60	uniaxial compression	48.45
			30 × 15	tension	3.85

Table 1. Ultimate strength of core samples under tension, uniaxial and triaxial compression

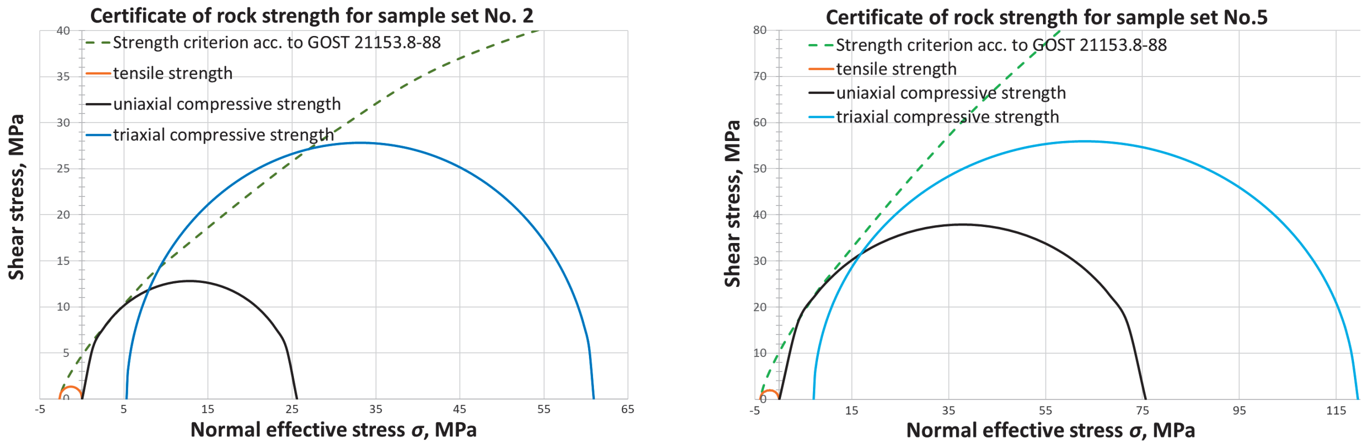

Fig. 1. Certificate of rock strength according to GOST 21153.8-88 for sample sets Nos. 2 and 5

certificates of rock mass strength based on tests under in-situ conditions.

The Mohr-Coulomb linear strength criterion (Coulomb, 1776) does not satisfy the requirements to description of the rock mass ultimate strength:

$$\tau = C + \sigma \cdot tg\varphi, \quad (2)$$

where τ – shear stress, MPa; C – cohesion, MPa; σ – normal stress, MPa; tgφ – slope of strength criterion curve.

Mohr-Coulomb failure criterion is based on the Mohr' hypothesis of shear stress dependence upon normal stress, and the Coulomb's hypothesis of cohesion force.

Figure 2 illustrates the Mohr-Coulomb linear failure criterion. One can see that in the region of the tensile strength the criterion is not tangent to the circle, while the region beyond the ultimate strength is overestimated.

As an alternative to the GOST 21153.8-88 (State Standart, 1988) procedure and the Mohr-Coulomb equation, we have considered the Hoek-Brown failure criterion. In contrast to the Mohr-Coulomb linear failure criterion, the Hoek-Brown criterion is a non-linear relationship and has a parabolic form. It is an empirical failure criterion that describes non-linear increase of the ultimate strength of rock at increase of the effective stress.

The Hoek-Brown criterion is based on the Evert Hoek's brittle rock failure tests and the parabolic Mohr envelope obtained from the Griffith theory to determine the relationship between the shear and normal stresses at failures in rock masses. Having connected appearance of fractures with propagation of fractures and failures of rock masses, Hoek and Brown offered correction factors to adapt different parabolic curves to the laboratory triaxial tests (Hoek, Brown, 1980). So, the Hoek-Brown criterion has an advantage over the considered earlier approaches in describing the non-linear increase of strength of rock with increase of confining pressure.

Kumar P. (1988) gives the following form of the Hoek-Brown equation:

$$\sigma_1 = \sigma_3 + C_0 \cdot \sqrt{m \cdot \frac{\sigma_3}{C_0} + s}, \quad (3)$$

where σ_1 – maximum confining load at triaxial failure test, MPa; σ_3 – minimum confining load at failure, MPa; C_o – strength at uniaxial compression, MPa; *m, s* – material parameters.

The parameter *s* varies from 1 for intact rocks to 0 for disturbed rocks. The values of the parameter *m* are derived from laboratory tests. This parameter relates to the rock brittleness, the less the *m* parameter, the more plastic the rock mass.

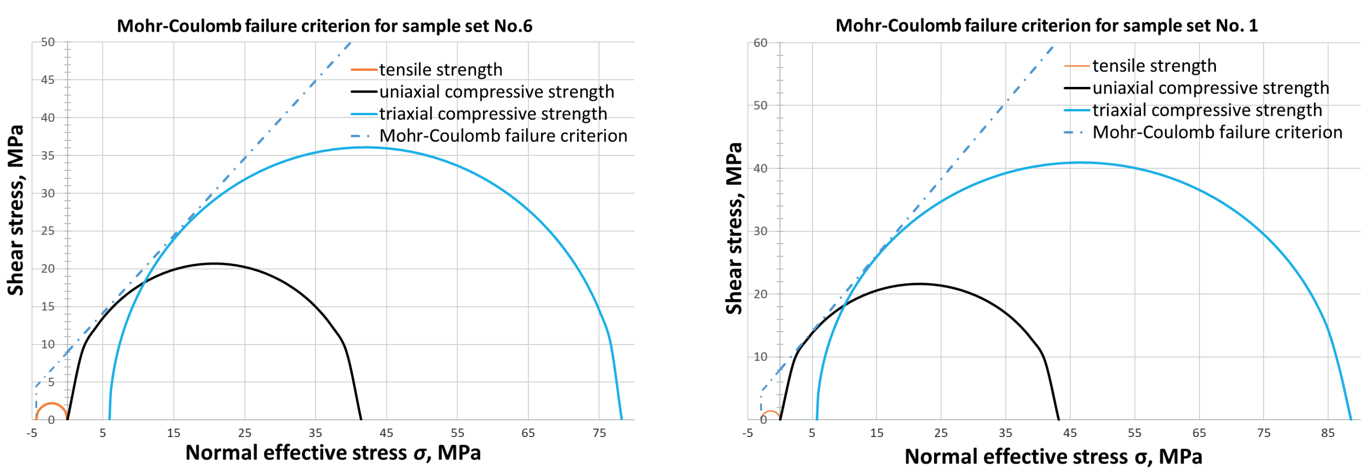

Fig. 2. Linear Mohr-Coulomb failure criterion for sample sets Nos. 1 and 6

When laboratory data is not available, reference data obtained by Hoek and Brown are used. For example, the m parameter may vary from 15 to 24 for sandstones (Zoback, 2010).

The Hoek-Brown criterion relates the major and the minor stresses, and to transform it to the parameters of normal and shear stresses, Kumar offered a method to calculate the tangent points in the coordinates (σ, τ) (Kumar, 1998):

$$\sigma = \sigma_3 + \frac{\sigma_1 - \sigma_3}{1+\sigma'}, \quad (4)$$

$$\tau = \frac{\sigma_1 - \sigma_3}{1+\sigma'} \cdot \sqrt{\sigma'}, \quad (5)$$

$$\sigma' = 1 + ma\left(m\frac{\sigma_3}{\sigma_c} + s\right)^{a-1}, \quad (6)$$

where σ – normal stress, MPa; τ – shear stress, MPa; σ_1 – maximum confining load at failure, MPa; σ_3 – minimum confining load at failure, MPa; σ' – differentials σ_1 and σ_3 relationship; σ_c – strength at uniaxial compression, MPa; a, m, s – material parameters.

The parameters a, m, and s are selected using the following relationship:

$$\frac{\sigma_1 - \sigma_3}{\sigma_c} = \left(m\frac{\sigma_3}{\sigma_c} + s\right)^a. \quad (7)$$

For the Pashiyan sandstone formation, we took the a parameter as 0.5, the s parameter as 1, for the purpose of unification. As for the m parameter, we determined it using Eq.(7). The results are summarized in Table 2. For the sample set No. 1, the a parameter was set to 0.54 to achieve a good description of the stress circles and to satisfy the conditions of Eq. (7).

From Figure 4, one can see that for the sample set No. 6, full description of stress circles in the region of tensile stress was not achieved, and the missing portion was approximated.

No. of sample set	Parameter		
	a	*s*	*m*
1	0.54	1	17
2	0.5	1	18.2
3	0.5	1	33
4	0.5	1	33.4
5	0.5	1	12.7
6	0.5	1	14.3
Average rock parameters	0.5	1	21.4

Table 2. Values of a, m, s parameters for sample sets

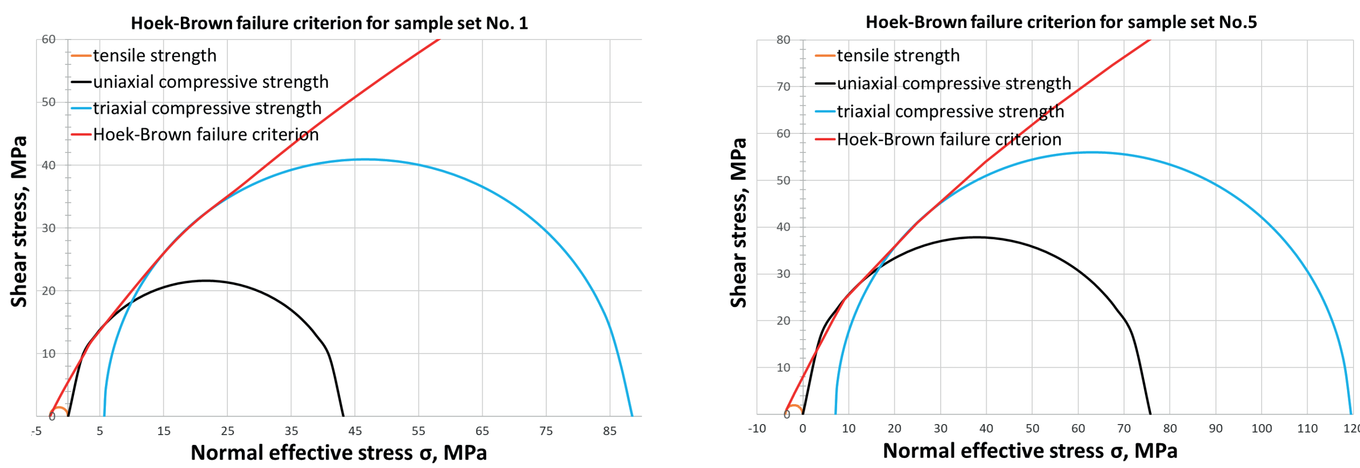

Fig. 3. Hoek-Brown failure criterion for sample sets Nos. 1 and 5

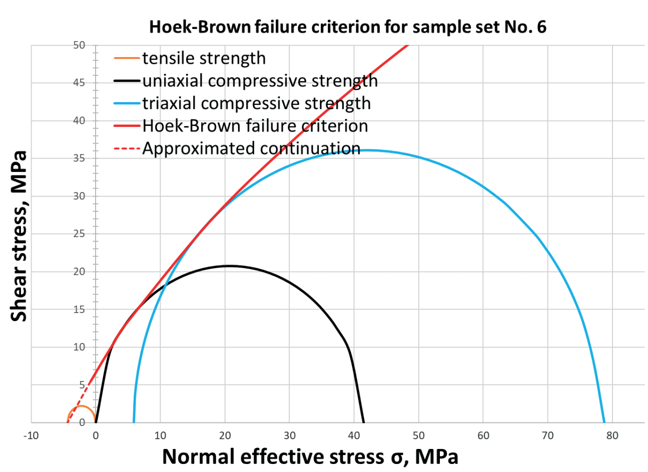

Fig. 4. Hoek-Brown failure criterion for sample sets No. 6

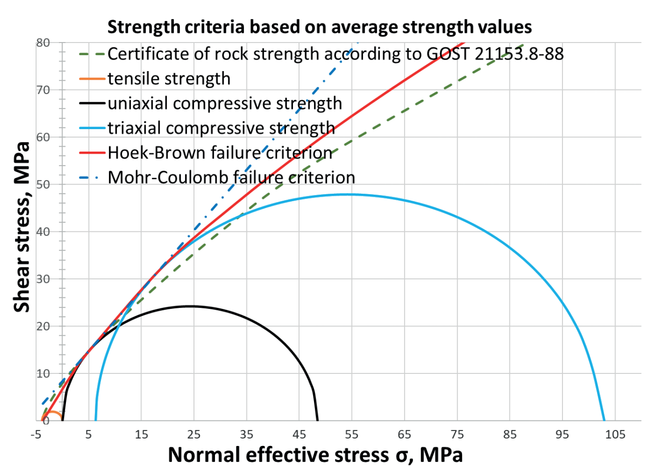

Fig. 5. Strength criteria based on average compressive strength values obtained from all sample sets under study

To determine the generalized parameters of the Pashiyan sandstone formation, we used average values of the ultimate strength determined from laboratory experiments. The parameters *a* and *m* were set to 0.5 and 1, respectively, while the s parameter was taken as an average of all values from the tests and equals to 21.4. Figure 5 shows the obtained strength criteria according to the GOST 21153.8-88 (State Standart, 1988) procedure, the linear Mohr-Coulomb failure criterion, and the Hoek-Brown failure criterion based on the average values for the Pashiyan sandstone formation.

From Figure 5 it is evident that the Mohr-Coulomb linear failure criterion overestimates the region of the tensile strength, the strength criteria according to the GOST 21153.8-88 (State Standart, 1988) procedure underestimates the boundary in the region of the compressive stress, while the Hoek-Brown criterion satisfactorily describes the stress circles in all stress regions-tensile, uniaxial, and triaxial compressive stresses.

Conclusion

For the first time, a comparison of applicability of strength criteria for the Pashiyan formation of the Romashkinskoe oil field obtained by different methods and based on the laboratory core analysis was made to determine their practical applicability.

Comprehensive studies of the strength characteristics have never been previously conducted, and the results obtained will serve as the basis for further analysis and application in order to improve the development of the terrigenous Devonian Romashkinskoe field.

The Mohr-Coulomb linear failure criterion is an empirical relationship based on data obtained by experiment, and, as such, is not reliable. The drawback of the Mohr-Coulomb failure criterion consists in its linearity, which compromises accuracy and affects results of calculations of, e.g., wellbore stability.

The Hoek-Brown criterion because of its non-linear nature more adequately reflects the properties of rock in the region of the tensile stress, and the region beyond the ultimate strength in the in-situ conditions. Being analytical, the Hoek-Brown criterion is convenient for practical application and numerical modeling of rock behavior in the Pashiyan formation of the Romashkinskoe oil field Tashliyarskaya area.

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SHORT COMMUNICATION

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To the experience of Shkapovsky oilfield development

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Abstract. The article formulates the main conclusions about the development of a large Shkapovsky oil field with an emphasis on the results of the development of the main objects – horizons DI and DIV of the terrigenous Devonian. The field was commissioned following the neighboring Tuimazinsky and Serafimovsky fields, taking into account the experience of a scientifically organized system for the development of these large platform oil fields in the Volga-Ural oil and gas region. It is shown that this experience was not taken into account much, especially in relation to the unsecured needs of oil production with capital construction, material and technical supply and social facilities.

The potential of the field was realized in 18 years. Intra-contour and focal flooding, production technologies using electric centrifugal pumps (ESP), chemicalization of oil extraction processes, primary collection and transportation of products, oil, gas and water treatment technologies, etc., accelerated the development. Shkapov engineers and scientists own a number of innovations: realizing high development rates, means of preventing and eliminating salt-paraffin deposits, the introduction of double-barrel drilling, the development of high-performance ESPs, separate development of facilities, etc. At the same time, tasks were solved on eliminating ecological imbalance in the bowels and the environment, housing and public works.

The current urgent problem of the field's additional development is the activation of the production of residual oil reserves from oil and watered zones drilled with an unreasonably rare grid of wells. The final oil recovery coefficients of the Devonian objects are expected to be high, but, according to the author of the article, could reach CU 0.6.

Keywords: oil field, oil and gas reserves, in-circuit flooding, marginal flooding, development pace, oil recovery

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The large Shkapovsky oil field is characterized by an extremely uneven distribution of oil reserves across the section: 98 % of the total initial recoverable reserves (IRR) was concentrated in the Devonian terrigenous strata (production horizons DI and DIV), and only 2.0 % accounted for the remaining six objects. Of these six, the most significant IRRs were in the strata of the Lower Carboniferous (1.0 %). The share of five carbonate objects was about 1.0 % of the initial total IRRs.

In connection with this circumstance, the priority decisions in the design of the development of the field were aimed at the scientific and methodological support of the maximum development of reserves from the terrigenous Devonian objects. Scientifically based decisions on the development of the remaining objects were formed after the completion of the main development period of horizons DI and DIV, which amounted to 18 years.

The development of the Shkapovsky field took place "without proper infrastructure support" (according to the terminology of Prof. V.N. Schelkachev): in the undeveloped forest-steppe area for the first 12 years (1955-1967), they got maximum oil production under pressure from decision-makers, without ensuring elementary oil field facilities and social facilities. The government did not have the necessary material and monetary funds, but unreasonable calculations of oil production wishes existed beyond measure. As a result, after the mentioned 12 years, they received an intensive drop in current oil production. People in power were not interested in the experience of the neighboring unique Tuymazinsky field, where development and commissioning were much more reasonable. The indicated experience allowed a world-famous scientist V.N. Shelkachev to be qualified as the "Academy of the Oil Industry" (Schelkachev, 2004). But when developing the Shkapovsky field, this experience did not seem to exist.

With intensive drilling and development of the Shkapovsky field, a shortage of the most essential was constantly revealed: in drill and tubing, cement, chemicals, electric and sucker rod pumps, etc. They introduced advanced double-barrel drilling technology when two wells were drilled from one base. But the resulting time savings were often not able to use due to the lack of casing for lowering the conductor or production casing. In a number of completed wells, run-off conductors were not cemented at all, and sometimes they were removed to equip newly drilled wells. Such «innovations» turned into technological and, most importantly, environmental harm to the bowels and the environment. Almost half of the families of the working village Priyutovo, where the oil producers of Shkapovo lived, lived in barracks in difficult social conditions. There was also not enough money for housing construction. People lived and set records for production indicators, showing real heroism (this word cannot be replaced with any other suitable word) in the liquidation of accidents in pipelines and other facilities.

Only through the prism of the foregoing is it necessary to judge the pros and cons of developing the legendary field.

Despite the noted costs, the main development period of the Shkapovsky field turned out to be short: over 18 years, 75 % of the total IRRs were extracted (Lozin, Akhmerov, 2017). For large deposits, such terms are unknown to the author of the article. Once again, it has been proved that it is rational to put a field into development in one stage. Infill drilling has confirmed the correctness of the scientific concept of the optimal grid arrangement of wells. The necessity of thickening the grid to the optimum in certain areas has been proved (Lozin, Akhmerov, 2017). Infill drilling was born in the USA and was a real answer to the opinion of M. Musket regarding the uncertainty of the existence of a connection between the grid arrangement and oil recovery (Maloyaroslavtsev et al., 1969). By the way, this statement was formulated 80 years ago and has been no longer relevant, including in the United States. The development of the Shkapovsky field with closed drilling and the corresponding development of the waterflooding system proved the indicated relationship and at the same time showed that in a real heterogeneous formation the grid of wells should be irregular due to local compaction in individual sections. At the same time, it was proved that development with water flooding leads to a noticeable increase in the oil-water factor even in low-viscosity oils.

Separate development of horizons DI and DIV was also sustained (with rare exceptions due to insecurity of pumping equipment after the cessation of well flowing). This result should be considered as confirmation of one of the cornerstones of the rational development of oil fields, namely: scientifically sound allocation of development objects and their participation in the development of oil reserves. Passion for combining a number of formations into one object, often with sharply different reservoir properties, is not a rational principle of scientifically organized development.

Regarding other principles of field development

Regarding forced fluid withdrawal (FFW). The point of view is known that the development of the terrigenous Devonian of the Shkapovsky field was carried out at accelerated rates of fluid withdrawal. Liquid withdrawal from the DI horizon per one well was increasing and reached a maximum in the 90s. of the last century at the level of 175-208 tons/day. In the modern period, this indicator remains at the level of 170 tons/day. Similar dynamics are observed along the horizon DIV. At present, the selection for 1 well ranges from 150-170 tons/day. The figures cited indicate relatively high selections caused by high productivity coefficients (Musket, 1953). The following calculations indicate how figures given relate to the FFW. The potential production rates of wells of horizons DI and DIV calculated by the Dupuis formula are from 150 to 1200 tons/day. The realized production rates for individual wells reached 700-800 tons/day, and the average did not exceed (see above) 208 tons/day, i.e. ranged from 100 to 25 % of potential. The maximum possibilities of the FFW were not used, but it is indisputable that in some cases the FFW has been used. An analysis of the development indicators of areas with a FFW using many methods does not indicate cases of irregular growth in the current water cut. On the contrary, in some cases, a short-term decrease in water cut was observed. The constructed displacement characteristics (DC) confirm the technological effect.

The total technological effect of the FFW has never been calculated, but the point is that in the areas where the FFW was actually produced, the effect in the form of additional oil production is visible in the DC.

Studies have been performed showing that increasing the fluid withdrawal rate to a recovery factor = 0.4 allows increasing oil production accordingly, and then the connection is lost. An increase in fluid withdrawals at a subsequent stage allows a decrease in the rate of decline in oil production, while at the final stage the connection "recovery rate – oil recovery" does not appear.

Regarding development regulation. To maintain high production rates when stopping the flowing of wells, there was a problem of equipping them with high-performance submersible electric centrifugal pumps (ESPs) due to the lack of the required standard sizes. Domestic high-performance ESPs did not have a high pressure (and there was lack of them). Only after the purchase of imported high-performance ESPs with high-pressure characteristics, the problem was partially solved (due to the limited number of indicated ESPs). Needs were not provided for pipes for laying water conduits to newly mastered injection wells. New injection wells were connected to one conduit due to its extension from the «old» wells. Studies have proven that such a solution did not meet the provision of proper throttle response. Sometimes new production wells were mastered by connecting working wells to flow lines. What kind of development regulation could be discussed if design technological operation modes were not ensured? But the regulation «for the most part» was nevertheless ensured due to the geological and technical measures.

Regarding the water flooding. Waterflooding has passed all stages of improvement – from the contour (marginal) to the in-line contour (cutting rows into blocks) to focal-selective flooding. Under the conditions of real geological heterogeneity, confirmation has been received about the effect of injection at limited distances from the source (injection well) to the nearest and remote production, about rational injection pressures and the «rigidity» of the waterflooding system.

Regarding the well stock. This indicator ensures the fulfillment of all other indicators of oil production and field development, primarily economic ones. The quantitative expression of the well stock – production, injection and observation (piezometric) – in the design documents is determined by calculations. But in practice, distortions are observed. The category of wells "awaiting liquidation" is not regulated at all. The indicated category sometimes turns into a "pocket", where wells are placed for a long time that really require physical liquidation, but for various reasons, staying in this quality for a long time. At the early stages of the development of oil fields in the Volga-Ural province, studies were carried out aimed at obtaining production data on the average standard life expectancy of wells drilled 70, 60, 50 years ago. But this problem now does not seem to exist, and its important environmental content is obvious, including for the design of further development. In economic calculations, the complete drilling of old wells is laid, but there are no clear technical and technological regulatory boundaries. This is especially true for wells where deviations were allowed in the structures for cementing conductors, intermediate and production casing.

Regarding the rational development of oil-water zones. The gently sloping Shkapovsky brachyanticline, which controls the external and internal oil contours DI and DIV, caused the presence of wide oil-water zones, in which more than 50 % of the total oil IRRs were concentrated. A similar phenomenon was first encountered in the exploration of the giant Tuimazinsky brachiantclinal. Comparing the development of the Tuymazinsky field with the giant US field East-Texas, prof. V.N. Schelkachev consistently emphasized that the oil-water zones at the latter were drilled along a much denser grid. Actually, the Woodbine sand layer with high reservoir properties in the East Texas field over the entire vast area of its monoclinic distribution is lined with bottom water and drilled with an almost hectare grid. At the Tuymazinsky field, the drilling rig of the oil-water zones was 2-3 times less dense compared to the initially completely oil zone, where in turn the grid density averaged 20 ha/well. At the same time, 11 % of the Tuymazinsky area of oil-water zones was occupied by the so-called "contactless" areas, i.e. such, where the oil-unsaturated part is separated from the water-saturated impermeable layer. At the Shkapovsky field there were essentially no "non-contact" sites in the oil-water zones. The situation on large platform deposits is exacerbated by another circumstance. In the annular zones adjacent to the external contour of oil content, oil-saturated thicknesses are 1-3 m with water-saturated from 3 to 10 m.

Such an unfavorable ratio of oil-saturated and water-saturated thicknesses is compounded by increased geological heterogeneity and clayiness of the upper oil-saturated thicknesses. The oil reserves contained here are not produced. This is confirmed by well logging data for new wells.

The authors of the article (Yakupov et al., 2019), who examined the problem of additional development of oil-water zones in platform deposits using the example of Shkapovsky, rightly (following other authors) raise the question of additional development of oil-water zones using horizontal wells and wells with horizontal completion. The following scheme of oil reserves development using the indicated wells is given (Fig. 1):

The above scheme has to be recognized as relevant to modern reality. The high initial oil production rates from the horizontal wells and wells with horizontal completion in oil-water zones with moderate water cut are very rapidly reduced due to the sharp water cut, which casts doubt on the profitability of drilling. This is also shown in the article (Chekushin et al., 2015). The depressed scheme shown indicates a predominant gradient of involvement in the development of the middle and lower parts of the reservoir, which have the best properties compared with the upper and adjacent middle parts. The essence of horizontal drilling consists mainly in creating a cylindrical «funnel» of depression along the axis of the trunk. And this can be achieved

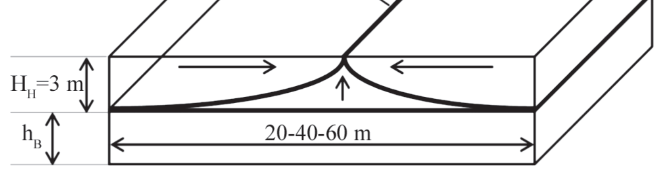

Fig. 1. The scheme for creating depression in water-oil zones in horizontal wells (according to (Yakupov et al., 2019))

only by selecting the technological mode of operation of horizontal wells, and not just by creating conditions for maximum extraction. It is also advisable to investigate the nature of the perforation of the horizontal well in the oil-water zones (maybe there are no perforations to be created below, etc.). This requires scientific research.

For all the expenses outlined today, it is indisputable that the oil recovery factor for the terrigenous Devonian of the Shatapovsky field is at least 0.565: for the DIV horizon – 0.58, for the DI horizon – 0.55, which corresponds to the difference in oil viscosities. In the author's opinion, the oil recovery factor could have been more – not lower than 0.6.

The article does not consider all the development lessons of the Shkapovsky oil field. These include, for example, ideas about the prospects for further development of the field using enhanced oil recovery technologies, of which the most attractive is the technology of exposure using liquid carbon dioxide. There are approximate calculations about the effectiveness of this technology, but this is the topic of another article.

Conclusions

To conclude, the main lessons of the development of the Shkapovsky oil field testify to the viability of the following principles:

1) The feasibility of entering the field in one stage;

2) Equity of separate development of facilities;

3) Selection of the optimal well grid arrangement for a real operational facility with drilling of infill wells in local areas of a heterogeneous geological environment;

4) The rationality of the high pace of development due to reservoir properties of deposits;

5) The inevitability of high water-oil factor during development with water flooding, even for low-viscosity oils;

6) The feasibility of drilling the water-oil zones on dense grids using the capabilities of horizontal wells and wells with horizontal end;

7) Maximum technological efficiency of water-flooding with focal-selective schemes.

8) Creation of a system for monitoring environmental safety, anthropogenic pressure on the subsoil and the environment.

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