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MODERNIZATION OF THE RUSSIAN OIL INDUSTRY ON THE WAY FOR INNOVATIONS AND GLOBAL TRENDS

R.Kh. Muslimov
Kazan Federal University, Kazan, Russia

Abstract. The main task of the new Russian energy strategy until 2035 is formulated succinctly and accurately – the transition from resource-based to resource-innovative development of the oil industry. However, it does not have sufficient geological and economic assessment of proven and promising resources, and most importantly – there are no mechanisms for the implementation of tasks.

Powerful technical progress of the West in the exploration and development of unconventional hydrocarbon deposits has a great influence on the efficiency of conventional oil and gas deposits. It becomes possible to make the transition from the balance to the geological reserves and from the concept of absolute pore space to the effective pore space in matters of reserves calculation and development design.

US example on the stabilization and further significant increase in oil and gas production after a long period of its fall allows us to rethink these achievements for solving problems of the Russian Federation concerning a significant increase in the efficiency of hydrocarbon resources. All this should be applied taking into account the specific geological structure of deposits in Russia and the history of their development. At the same time in the oil industry the solution is required for fundamental problems: calculation of reserves, justifying oil recovery, building fundamentally new geological and technological models of deposits, innovative design of development systems, justifying the rationality criteria and principles of the rational development of fields.

Keywords: subsoil use, government support of subsoil users, reserves and resources of hydrocarbons, oil difficult to recover, non-conventional oil reserves, oil recovery factor, enhanced oil recovery methods, tax incentives, fundamental problems

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The peculiarity of the present development stage of the oil industry in the Russian Federation and the Republic of Tatarstan is that up to now science has dealt mainly with problems of active involvement into development of deposits with reserves difficult to recover. This problem also remains one of the most important in the perspective.

But for the further development it is not enough.

Powerful technical progress in the Western countries for the development of non-conventional hydrocarbons, heavy oil and natural bitumen in Canada, the USA, Venezuela, oil and gas shale revolution, research on other types have fundamentally changed the situation in the oil and gas sector and the global environment.

The complex international situations, price conflicts in the world market, serious sanctions imposed by the West against Russia, are an additional challenge to our country. Let us remember how through the use of established in the Soviet period of strong potential we got access in market conditions to reliable western techniques and technologies (the USSR lagged behind the West for 30-40 years in equipment for the oil industry), we ran this distance in 6-7 years.

Observations of a fundamental nature have been made on a new "Energy Strategy of Russia until 2035" (ES-2035), when considering it at the extended meeting of the Scientific Council of the Russian Academy of Sciences on the problems of geology and development of oil, gas and coal fields. The main observations are as follows: low validity to ensure production of oil resource base (lack of justifications for oil and gas potential, directions and volumes of geological exploration, in-depth analysis to ensure the growth of oil production, the absence of quality analysis and reserves structure, their authenticity, conditions and development of oil recovery factor, focus on the extraction of active reserves, which are already severely depleted and the meager share of producing reserves difficult to recover – only 4-5 % of the total production, the lack of specificity for innovative development of the fuel and energy complex.

The main task of the new Russian energy strategy until 2035 is formulated succinctly and accurately – the transition from resource-based to resource-innovative development of the oil industry. However, there is no defined mechanism for the implementation of all the objectives and tasks.

In-depth analysis of the oil and gas industry allows evaluating its close to a critical level: low volumes of geological exploration, poor replenishment of profitable reserves, low rates of oil recovery factor at the level of 35 %, steady increase in the proportion of oil hard to recover, for the development of which 3-5 times more money are required, a high degree of depreciation of the basic funds (almost 60 % in the oil and gas industry and 80 % in the processing).

The situation is exacerbated by the lack of reliable information base for the systematic analysis of the situation in the oil and gas sector at all levels, secrecy by oil companies of directions for replenishment of the mineral resource base and development of fields under the pretext of commercial confidentiality, lack of stimulation for investment and innovation mechanisms, sharp decline in professional government level of planning, forecasting, management and control over the processes of exploration, replenishment of reserves, rational development of fields on the part of the federal government entities.

As the experience have shown of the failure of previous development strategies, obviously, the authors are not able to make this important document as the real guide to actions because of inadequate assessment of the state of the oil and gas industry in Russia and world trends. Apparently, all these issues will be addressed at the regional level, as it has done in Tatarstan, where in 2015 addition was made to the development strategy of the fuel and energy complex till 2030.

But a single list of all necessary regulatory documents in the subsoil use shall be designated in its entirety, taking into account the need for clarification and processing of existing and development of new documents with a road map of performers, dates of compilation, review and approval order.

Creation of the rules and regulations in all areas of subsoil use is crucial in the development of oil and gas production. This is particularly evident in the development of oil and gas sectors of the United States.

Today we have a paradoxical situation: in the United States – the citadel of free enterprise, there is a strict regulation of subsoil use, which leads to the intellectualization of oil production and development.

The efficiency and simplicity of rules and regulations related to the provision of licenses and issues of land ownership led the US to a rapid increase in the number of licenses for subsoil use: by 2012 the number had reached 63000 (in Russia – just over 3000). The whole system of US oil and gas sector regulation is aimed at stimulating the subsoil users to apply new production methods (Kryukov, 2013).

It is important that individual states have their own significant niche in fostering innovations in the oil and gas sector. The dominant policy in the field of regulation of the oil and gas sector in the US is to stimulate subsoil users to take higher risks in testing and development of new innovative production methods.

The application of enhanced oil recovery methods is of special attention in the United States. The main objective of incentives – rewards of subsoil users for high financial costs and technical risks in testing and development of enhanced oil recovery methods compared with conventional methods of oil production.

The results of this approach for the subsoil sector are great. On the territory, where oil production is carried out since 1860 and oil is produced more than on any other area of the world, the US oil industry has achieved stunning results. After a long period of falling production, growth of oil production has been achieved (20-25 million tons a year). Especially Texas – the leading state in the oil industry – has advanced, where for 5 years by 2014 oil production has doubled, and over the next 5 years it is planned to be further doubled (Kryukov, 2013).

This is not only due to the development of a new type of resource – the so-called shale oil, but also through innovations in conventional oil of existing fields. This example is worth to be role model, and even obligatory for Russia and Tatarstan (Muslimov, 2014 a).

Unfortunately, Russia is continuing the neo-liberal course that focuses on market fetishism in the management of subsoil use and minimization of the government role in this process, leading to the de-intellectualization of the oil and gas complex. The main taxes are taken not for the performance results (profit), the degree and quality of deposits (rent payments), but for the right to produce oil and develop fields.

Moreover, the regulatory documents in the subsoil use either left over from the Soviet command-administrative system, or were badly reformatted to a market economy (which turned out to be unsound) (Zakirov et al., 2016). Let us show this on the example of the main subsoil document – “Classification of reserves and resources of oil and combustible gases”. Classification successfully worked in the Soviet era, but was replaced by a temporary in 2001.

It established uniform for the Russian Federation principles of counting and state accounting of field reserves and prospective resources of oil and combustible gases in the subsoil according to the degree of exploration and their economic significance, the conditions that determine the readiness of explored deposits for industrial development, as well as the basic principles for assessment of forecast oil and gas resources.

However, the practice of this classification is poor. Requirements to take on the state balance of reserves have been significantly weakened. Often excessive oil reserves were taken into the balance, about what others and we have repeatedly written (Muslimov, 2014 b).

Therefore it is impossible to be completely sure of the authenticity of official reserves of oil and gas (Kimelman, Poldobsky, 2010; Savushkin, 2010). In 2015, Russia on the international classification has lost about 16.8 trillion m^3 of proven natural gas reserves. Of course they really exist, but there is no justification of the reliability of these reserves (Zolotukhin, Levinbuk, 2016).

The oil situation is different. Compared to the Soviet period, the practice of approval of oil reserves has a trend of weakening attention to authenticity of oil reserves taken into the balance. This results in a lighter attitude toward C_2 category. In the development design and reports on oil reserves increment, as a rule all categories $A + B + C_1 + C_2$ are accounted. But the category C_2 counts as preliminary estimated. In practice, the conversion factors from the C_2 category to higher ones (verifiability factors) in different conditions are from 0.4 to 0.7-0.8, and sometimes higher.

Earlier the category C_2 was treated more carefully – the design was allowed for the reserves, when the share of the category C_0 did not exceed 20 % of the total amount received for the design of reserves. The State Reserves Committee had a tougher approach to the adoption of reserves categories C_1 and C_2. This provided higher reliability of received resource base both for the planning, and especially design for the development of specific fields.

But from 2016 the Russian Federation has a new classification of reserves and resources of oil and combustible gases. Here, the degree of reserves reliability is even lower than in the temporary classification of 2001 (Zakirov, 2016; Muslimov, 2016 b).

Category A includes reserves in areas drilled by production wells grid. It seems that the same requirement remains in the new classification of reserves. But in the old sense, and in the Western classifications, the concept of developed ones was added to drilled.

Practice and experience of development shows that not all reserves that drilled by project wells are produced. Depending on the complexity of geological structure, 50-80 % (rarely more) of reserves are involved in the development, drilled by project wells at full development by the project waterflooding system. It takes decades of additional various geological and technical measures to engage in the development of major (95-100 %) reserves of operational object (Romashkino field experience).

Earlier Category B has always been considered in the areas of actually drilled project wells. In the new classification of reserves we have more than vague notions: B_1 – prepared – the basic fund of production wells and re-allocated Category B_2 – estimated – dependent fund of production wells (while it is not quite clear what kind of dependent fund it is). Therefore, in category B we can include areas where wells-points are indicated on the map, rather than actually drilled. Based on the development experience, confirmation of project reserves in actual drilling is 70-80 %, less- up to 90-100 % (depending on the geological complexity of the area).

Even more uncertain situation is with category C_1 and C_2. In fact, if desired, categories B_2, C_1 and C_2 can be classified as B_1 according to the new classification of reserves, without conducting any work on the field, but simply placing the project wells on paper (Figure 1). In the West, specialists more accurately relate to the categories C_1 and C_2, as well as promising and forecast resources.

Based on the above it can be said that the introduction of the new classification and related documents will not improve, but worsen the situation in the domestic subsoil use, in the methodology of both calculation and accounting of reserves, and the reliability of calculating development parameters.

The same can be said about the documents accompanying the new classification of reserves – Regulation of development and the "Rules of designing of oil and gas fields development". In addition to them,

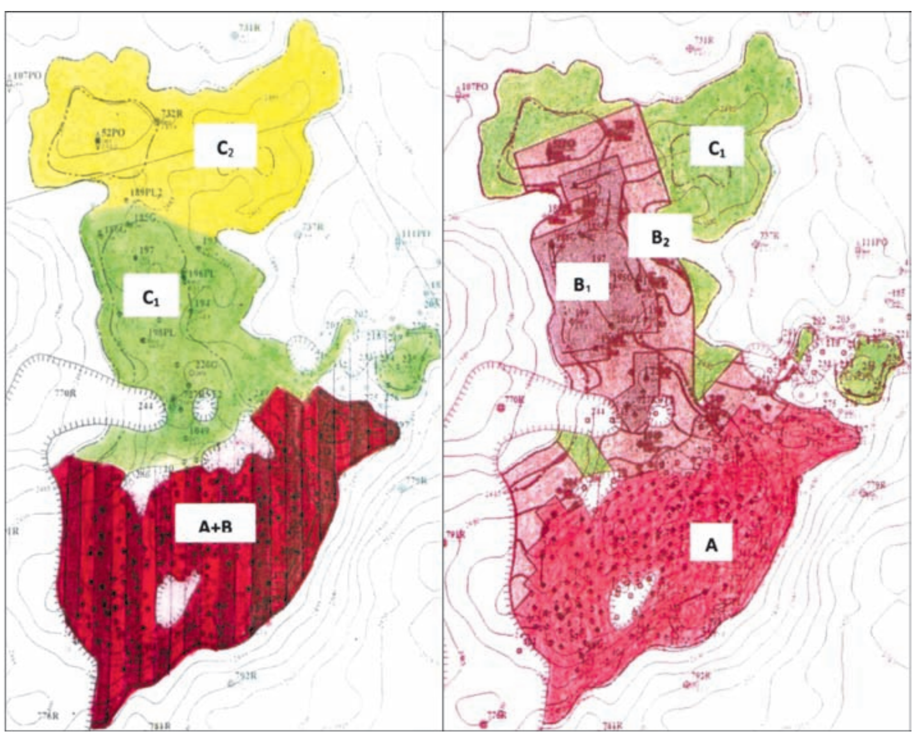

Figure 1. Example of comparing calculation plans for the current and new classification of hydrocarbon reserves.

hastily drafted temporary methodological guidance is now published on the calculation of mobile oil reserves for fractured and fractured-porous reservoirs of shale type (Zakirov, 2016).

The main advantage of Russia in the global oil and gas sector are huge reserves of mineral resources. Russia for proven oil reserves holds the sixth place in the world (after Venezuela, Saudi Arabia, Canada, Iran, Iraq), for gas reserves – the second after the United States. As for gas, it does not correspond to the real situation. We should restore with minimum efforts the 'potential' reserves 16.8 trillion m^3 of gas lost in 2015.

The 6th place for oil reserves also does not correspond to the real potential of Russia. The main reason is extremely low exploration degree of huge territories of the Russian Federation (Western and Eastern Siberia, the Far East, the North-European part of Russia), as well as being in its research infancy shelf in the Arctic, the northern and eastern, and even the Caspian and Black Seas, heavy oils and natural bitumen in Siberia and the Volga-Urals, dense, shale and the like deposits of Western Siberia and Volga-Ural oil and gas provinces. With these resources, the oil potential of Russia should be in the first lines of the world ranking of liquid petroleum resources. The first and second places in oil production, which Russia holds, are consistent with its current proven reserves.

But the situation is complicated. High depletion of large and medium-sized oil fields, providing hitherto the main production in the country, requires a decisive transition to a massive development of oil difficult to recover both at oil and new fields, as well as the development of unconventional hydrocarbon deposits both on producing fields and new prospective areas and territories.

The old oil-producing areas – the Volga-Ural oil and gas province, Western Siberia, North European, Southern regions of the country must remain the priority for stabilization of oil production (at least up to 2030). Conventional oil (including reserves difficult to recover), prospecting of non-explored lands, additional exploration of producing fields, massive, widespread use of modern enhanced oil recovery methods, development of tight reservoirs and residual oil reserves at existing fields with a high degree of depletion should remain as target objects.

In these areas it is necessary to strengthen the work on the development of the best part of unconventional resources: heavy oil of the Permian complex of the Volga-Ural oil and gas province, tight, shale deposits and the like, for example, Bazhenov Formation of the Western Siberia (Muslimov, 2016 f; Panarin, Fomin, 2016).

The next direction should consider works on the development of the most favorable resources of Eastern Siberia and the Far East in relatively small volumes.

The development of resources in the Arctic, the Arctic shelf and shelf of eastern seas is advisable to postpone to a later date because of the great complexity of geological and environmental conditions, lack of qualification to such works and high cost of hydrocarbons production in such difficult conditions.

This approach was already applied in Tatarstan and recorded in two documents: the updated energy strategy of the Republic of Tatarstan until 2030 and the "Concept of the study and development of unconventional hydrocarbon deposits in Tatarstan". The first document determines oil production levels, reserves preparation and ways to improve and develop reserves difficult to recover to existing and new fields. The second document considers ways of unconventional oil deposits development in Tatarstan (Muslimov, Shakirov, 2016).

This strategy provides stabilization and even some growth in Tatarstan oil production for the period to 2030 and at the same time creates conditions for further development of oil production by 2050 and over the longer term.

It would be nice to have such documents in other regions and the whole Russia.

For successful implementation of the above directions on the instructions of the President of Tatarstan R.N. Minnikhanov, the Academy of Sciences of Tatarstan has made up "Development program of priority research in the field of geology, engineering, oil extraction and oil processing in Tatarstan for 2015-2025".

It includes the following sections.

1. Ways and methods of exploration and development of unconventional hydrocarbon deposits in Tatarstan (tight reservoirs, shale deposits and the like, heavy oil and natural bitumen).

2. Assessment of the prospects and ways to increase the resources and recoverable reserves on long-developed (mature on the current definition) major fields of Tatarstan, commissioning of mobile reserves and exploring the possibilities of using immobile reserves, production of capillary held film oil, increased oil recovery, extending production from depleted reservoirs on tens and hundreds of years due to the investigation of the processes of deposits reformation, introduction of new enhanced oil recovery methods. The expected increase in recoverable reserves – is about 1 billion tons. At the same time the prospects of studying oil-bearing solid rocks and cap rocks of the sedimentary cover.

3. Improving the development of oil deposits in carbonate reservoirs in the low-profitable fields; ways to improve the development of heavy oil deposits in carbonate reservoirs (optimization of oil production and maximization of oil recovery).

4. Improvement of the theory and practice of application of enhanced oil recovery methods and

bottom hole treatment in Tatarstan fields with reserves difficult to recover (increase of recoverable reserves by 400 million tons).

5. Analysis and ways to improve the use of technologies of horizontal and multilateral drilling to increase the efficiency of oil field development (horizontal wells, horizontally branched wells, multilateral wells, lateral wells).

6. Creation of new development systems for oil fields located at the late stage of operation (IV stage of development in the modern sense), taking into account reorganization of oil fields and reservoirs.

7. Development of new methods for construction of geological and hydrodynamic models that fully considers the peculiarities of geological structure of objects and filtering in a formation. There are fundamentally new presentations about the processes of oil recovery (concept of the effective pore space), compared to the previously based for more than 70 years on the concept and calculation formulas of the absolute pore space.

8. Nanotechnologies at the exploration and development of hydrocarbon raw materials; the use of EOR of higher generations for very complex geological conditions of hydrocarbon occurrence.

9. Improving the methods of designing efficient development systems on the principles of innovative development.

It is envisaged to conduct the design at fundamentally new models to test new technologies in the field and at the experimental site.

10. Works on the study of the in-situ destruction of heavy oils, ensuring high conversion of high molecular components of heavy oil into light fraction in reservoir conditions and related technologies.

11. Scientific substantiation and development of organizational and legal measures to optimize the management and tax regulation in the sphere of subsoil use.

12. Improvement of methods of oil refining.

The foregoing concerns mainly the fundamental problems, the return on which is also outside of the planning period.

The foregoing rules, technical regulations and approaches to address the major issues of subsoil use in the US, which showed their high efficiency for the subsoil user, the government and society, are possible to fully implement in the Russian Federation.

While we understand that because of our mentality, we cannot repeat such measures to improve the efficiency of the development of new reserves categories, but something even remotely similar to this has to be taken. Otherwise, the backlog will deepen (Muslimov, 2016 d).

But the technologies for development of Western fields cannot be carried out on our fields with no additional studies and justifications. The reasons for this are as follows.

- In the world there are no two exactly same fields, they are different in the specifics of geological structure; furthermore they differ vertically (deposits with various properties) and horizontally (each reservoir has both vertical and zonal areal heterogeneity of its properties).

- Historically, the different ideology has been established of oil field development: the former Soviet Union focused on the technology of waterflooding, which applied from the start of operation, in the West flooding was used as a secondary method, and in the later stages of development, regard for well spacing and stages of drilling was different, as well as to the EOR methods.

For these reasons, we must create technologies for the development ourselves in our specific objects, but facilities and equipment should be western (of course, if we do not produce domestic ones of the same quality) (Muslimov, 2016 f).

The combination of domestic technologies with modern western equipment and facilities, adapted to the specific geological conditions of our fields and deposits, gives a synergistic effect, and will be called innovative and the best of them – high-tech. The latter is rare and mainly relate to modern geological and geophysical surveys of mineral resources.

Commissioning of reserves difficult to recover and non-recoverable reserves into commercial operation requires a substantial increase in new geophysical, hydrodynamic and especially laboratory studies. The design of development of multi-model, multivariate methods of stimulation, on the principles of innovative development also requires fold increase of costs.

The pilot tests are the final and crucial in this scheme. Only its results can be the basis for the mass replication of new technologies, the most effective for the specific geological and physical conditions. For deposits with reserves difficult to recover and non-recoverable reserves such works should be done at the experimental sites. The oil produced from such sites should have tax incentives for the duration of pilot tests (5-10 years). This would allow performing self-financing R&D and pilot tests (Muslimov, 2016 d).

Currently, Tatarstan followed the path of organizing scientific grounds for the creation and testing of new, innovative technologies. “Tatneft” has organized two scientific target sites “Bitumen” (solving problems and working out technologies of heavy oil and natural bitumen) and “Domanik” (technologies for extraction of oil from tight, shale and similar rocks). For small oil companies a major training ground of innovative technologies has been created, which aims to create and develop technologies for a wide variety of geological and physical conditions of small deposits with reserves difficult to recover (very heterogeneous deposits in carbonate reservoirs with heavy oil, clastic reservoirs with highly viscous oil, tight carbonate and clastic reservoirs, problematic deposits of hydrocarbons). According to our estimates at the involvement of the entire system for small deposits of Tatarstan we can obtain additional recoverable reserves of 400 million tons.

Testing of advanced technologies for the extraction of non-recoverable reserves can also be done at special projects approved by the Central Committee on Reserves, justifying the regime of granting tariff preferences for oil production in the period of implementation of the project up to the government co-financing of pilot tests (for very complex geological objects).

Implementation of already proven technologies should be carried out on the projects of innovation development of production in a particular field. In this case, tax incentives are required for the additional oil production through the use of new technologies. List of parameters for granting tariff preferences should be determined in accordance with the classification of reserves difficult to recover and non-recoverable reserves, for favorable categories of reserves difficult to recover (exemption from the mineral extraction tax) up to the maximum for the unfavorable categories of reserves difficult to recover and non-recoverable reserves (exemption from all taxes).

In any event, approaches to the development of reserves difficult to recover and non-recoverable reserves will be different than the development of conventional fields with a significant proportion of active oil reserves. All this will require additional efforts and resources. The increasing complexity of geological conditions will increase the cost of production of oil through the introduction of more complex and expensive EOR. More complex EOR (thermal, gas) are expensive, but less expensive methods (physical, chemical, etc.) may require infill drilling, which also makes them expensive.

The very system of taxation should be different for conventional fields with reserves difficult to recover and non-recoverable reserves. Inside these systems tax incentives should be applied depending on the complexity of geological conditions.

Since all technologies are introduced on the basis of projects (technological schemes) for the field development, the design itself is of particular importance. But here we have only disadvantages.

Despite the formal updating of standards, design is essentially maintained at the level of the 70-ies of the last century. Analogy method used by the authors of projects (especially the geophysical characteristics of deposits), the imperfection of simulation methods and hydrodynamic calculations, ignoring the generally accepted classical methods of solving problems of development, lack of in-depth professional analysis of reserves development, lack of control and regulation of the development process – all this lead us into the unknown.

All these problems lead not only to a short ‘life’ of projects, but also to a decrease in oil reserves. Especially unacceptable level of design of field development is related to fields with the main share of reserves difficult to recover. The lack of scientifically based systems of exposure, EOR and bottom hole treatment for specific geological and physical conditions of deposits does not allow to project the rational development systems with introduction of innovative exposure systems, to address the problem of optimizing production and maximizing oil recovery.

All development should be based on the innovative design of the development. In order to practically implement the innovative design system it is necessary to establish rules, standards and other regulatory documents, i.e. the efforts of government bodies, science and oil companies (Muslimov, 2014; 2016 a).

However, innovative design will not be effective if we use methods and simulating techniques used in practice today. They do not reflect the real picture of the geological structure of fields. But most importantly, these models do not take into account the geological features of accumulation and transformation of sediments and formation of oil deposits.

S.N. Zakirov rightly considers wrong the ideology of building models. According to him guidance documents require not to include ‘non-reservoirs’ into 3D geological models. That is, all (almost all) created 3D geological models in the country are defective. Since they distort the real geology of deposits (Zakirov et al., 2006).

To this day, thanks to the concept of absolute pore space, initial petrophysical parameters are based on the results of mass definitions of non-informative absolute permeability coefficient of gas and open porosity (of dry cores!).

In order to construct such models we need to solve the fundamental problems of development of the industry (Muslimov, 2016 f).

In Soviet times, there was the concept of balance reserves, which stood out from the geological, using the so-called conditional values of reservoir rocks.

Conditional values are boundary values of properties of hydrocarbon-saturated rocks that divide them into reservoirs and non-reservoirs, and also reservoirs with different field characteristics. These limit values are also called lower limits of productive reservoir properties (porosity, permeability and oil saturation). Objects that have parameters below the conditional are not included, and we simply do not take into account.

In the classification of 2001 the concept of balance reserves was absent and was automatically replaced by geological reserves, which was a gross mistake of the authors.

Especially evident this error in the calculation of reserves in carbonate formations, when thickness of only conditional layers is counted, whose share in oil-saturated part of the deposit (thickness from top to bottom of the formation or oil-water contact) – is referred to as oil-saturated thickness, in different deposits it is from 20-30 to 70-80 %.

This thickness is called the effective oil-saturated thickness. But the reserves development of involves the entire carbonate array. This leads to a significant underestimation of reserves and inadequate design of development technologies (Muslimov, 2016 e) (Figure 2).

Approximately the same position is for clastic strata, but here it is more hidden.

Existing methods of geological modeling and reserves estimation involve studying only that part of oil resources, which is extracted by conventional methods. At that, it is considered to be obvious that for reservoirs with parameters below the 'conditional', oil is not extracted at all. This oil is excluded from consideration in the reserve calculation stage. As a result, to date geological oil reserves are not known on any object.

In the development of deposits with the use of horizontal wells, 'drainage architecture' of the formation is changing dramatically, filtering surface is greatly increased; there are mechanisms of interaction between the fluid and the reservoir.

There is reason to assume that part of 'unconditional' oil will be involved in the development. On this basis, we believe that at the stage of geological modeling it is necessary to abandon the traditional consideration of only the balance reserves and study the characteristics of distribution of oil resources in the formation. In this case it makes sense to consider the strata as the entire hydrodynamic system that incorporates all, without exception, oil-saturated, weakly oil-saturated, water-saturated and tight interlayers.

In view of the above, there is a need to reassess the geological oil resources as balance and recoverable reserves in an old, steady sense leave behind unconditional reserves, and they, according to preliminary estimates, could amount to 15-20 % of the approved ones. Thus, the geological reserves should mean the entire amount of oil that is in the depths, regardless of whether it is possible today to extract (Muslimov, 2016 c).

This approach will increase the total resources and decrease the value of oil recovery factor. It seems appropriate to develop a methodology for calculation of geological reserves in view of the huge progress in the West in the field of geological exploration and existing experience for extraction of hydrocarbons from tight rocks (or even shale).

According to the concept of effective pore space, petrophysical relationships are necessary to be built on the results of realistic factors of effective permeability and effective porosity, because the degree of reliability of petrophysical relationships within the concept of effective pore space is significantly higher than in the concept of absolute pore space. Then it is then obvious that the accuracy of logging data to build 3D models will be much higher (Zakirov et al., 2009).

But to prepare information is not enough to build such models of currently used methods. First of all, it is necessary to significantly strengthen laboratory research of rocks and fluids saturating them. Until recently, we didn't have necessary equipment. Today, at least the Kazan Federal University has it.

Next problem is justification of oil recovery factor and measures for its increase, which is very important for the late stage of development, which is relevant for almost all the important fields in the Russian Federation.

The fact is that the whole vast amount of commercial, geophysical, hydrodynamic researches and analysts to build a geological and hydrodynamic models was limited to determining the extent of flooded areas and reservoirs, ultimately, to defining waterflood sweep efficiency K_{sw}. At the same time displacement coefficient K_d was defined during the initial resource estimation by laboratory methods.

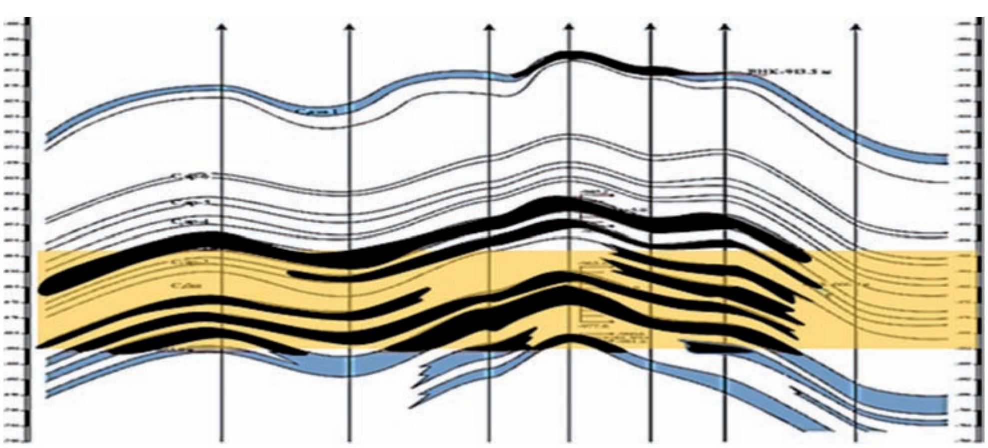

Figure 2. Berezovsk field. Schematic geological profile of productive deposits of the Middle Carboniferous.

It was determined by pumping water through the core, as is written in all the textbooks by "endless washing of the formation". There were no doubts in the determining the displacement coefficient. But with the accumulation of experience in the development, we noticed that the washed sections obtained in some cases very high values of displacement coefficient. In taking these values of K_d, in laboratory data K_{sw} had to be close to one or more, which in the conditions of real heterogeneous reservoirs is impossible.

Solving the problem of the reliability of displacement coefficient laboratory determination and transferring it to the commercial terms have not yet succeeded. A paradox: for the cores we have a maximum value of K_d (‘endless washing’), and in real formations it is more.

The paper (Zakirov et al., 2009) made the following conclusions: “In contrast to the common point of view, it is argued that determined on the basis of laboratory experiments values of oil displacement efficiency by water are underestimated in their magnitude”.

We can make a fundamental conclusion: in most cases, we have underestimated displacement coefficient, thus the analysis of oil recovery factor in depleted areas overstates displacement factor, i.e. on the basis of which the major (at least 80-90 %) geological and technical measures are performed. To achieve the project oil recovery factor we need to increase the volume of geological and technical measures in order to achieve the project displacement coefficient. So we need to drill more wells and more influence on the reservoir. Oil recovery factor in this case will be higher than those obtained currently in development design.

Simultaneously it is necessary to organize a broad discussion on the rational and optimal development of hydrocarbon deposits.

For the first time the term rationality was formulated by Academician A.P. Krylov as “...achievement of a given oil production at the lowest cost” (Krylov, 1955). This criterion of rationality has existed for more than half a century.

Then, in 1986, the Central Commission for the development of oil fields formulated another criterion of rationality, which is to ensure the national economy’s demand for oil at the smallest possible national economic costs and more complete extraction of oil from the subsoil.

In Soviet times, in accordance with the accepted criteria principles were formulated of rational development of oil fields, which have played a positive role in the exploitation of deposits (Shchelkachev, 2004).

During the years of market reforms a lot of problems have accumulated related to the replenishment of the mineral resource base, irrational use of mineral resources, causing irreparable harm to the development of the country’s most important oil fields.

The absence of a common formulation of rational development of oil deposits in the market conditions is non-allowable phenomenon. If we don’t have it, then, the targets are not designated, which to be achieved at the development of oil fields.

Justification of the initial Criterion was given by (Muslimov, 2003; 2014 b). In the latter work the wording was as follows: “the development of each of the oil (gas) field should be designed on the modern scientific and technological base, realized with modern scientific support, providing maximum profit at acceptable for the subsoil user payback of capital investment, achievement of the approved values of the current and ultimate oil recovery, observance of protection of mineral resources and environment, and should continue creating favorable conditions for the continuous improvement of production processes in order to achieve maximum economically allowable oil recovery”.

In today’s clarified version, it is as follows: “a rational system of development of oil (gas) field and arrangement of fields is deemed to be a system, which is designed in a modern scientific, technical and methodological basis, has passed the state examination, discussion and approval by the Central Committee on Resources and the State Committee on Reserves, is implemented by modern scientific support and government control, provides a balance of interests of the population, in particular, of the local population, as well as the subsoil user, compliance with environmental and subsoil protection requirements, the “Law on Subsoil” and regulatory documents, as well as positive social impacts and guarantees” (Zakirov et al., 2015).

Optimality criterion of field development in the market economy has closed on the NPV (net present value). In modern conditions it is not enough. It is known that the value of NPV, payback period costs depend on oil prices in the international and domestic market. Recent events convince anyone that there is no reason for the absolute priority of the most important component in the value of NPV – the oil price.

Subsoil users need high profit and a faster payback, and for population – long receipts from the exploitation of deposits (greater oil recovery factor). Therefore, in general, optimization of production and maximization of oil recovery is needed. This should be addressed at the design stage and examination of documents to develop the field on the principles of rationality.

In addition, each of the main economic criteria (NPV, IRR, ID, QAP) is not sufficient to select the option of field development. This decision should be made based on the values of integral indices in the interests of all stakeholders (government, including regions and municipalities, investor, subsoil user). Main stages and principles of the rational oil field development for design purposes are shown in Table 1.

Today, few people think about the question of how Russia should produce oil. Today, the strategy of oil production prevails “as much as possible”.

Different figures are given of oil production in the future – one more than the other. However, there is no rigorous scientific justification.

Based on the level of oil consumption in the US and other developed countries, it would be possible to

1. The harmonization of economic interests of the government and business
2. The innovative design of development systems: 2.1. Creation of real geological model using modern research methods, including at the nanoscale;
2.2. Selection of adequate geological structure of development technologies and EOR;
2.3. Designing with consideration of man-made changes in the characteristics of fields in the process of development;
2.4. Creation of a unified geological and hydrodynamic model that takes into account the availability of unconditional and possible permeability of interstratal sections;
2.5. Economic justification of design decisions.
3. Management of oil fields development
4. Implementation of modern technologies to ensure optimum dynamics of oil production and project oil recovery factors
5. The economy of oil field development: 5.1. Limit of object operation (limits of production profitability) under the current taxation system;
5.2. Tax incentives to ensure approved oil recovery factor;
5.3. Optimum rate of return;
5.4. Provisions for environmental protection of subsoil and environment.

Table 1. Main stages and principles of rational development of oil fields (by R.Kh. Muslimov).

identify the maximum level of oil production in Russia for the long term and to focus on its implementation in the ways of resource innovative development.

Excessively high levels of oil production do not make our people happy. Rather, it creates preconditions to deepen Russia's recurring economic and global crisis. This is very clearly written by E.T. Gaidar in his book "The Fall of the Empire". Let us remember the sad experience of the former USSR, which had the first place in oil production, and the level of life significantly lagged behind the developed countries.

However, to ensure an optimum level of oil production in view of the current threats to Russia we must on some kind of short period try to keep the oil at the level of 500 million tons. This is possible to implement with great potential of the Russian Federation, but at very great effort and radical change in the development strategy. The government must create favorable conditions in the oil subsoil use, fully adopting the US experience in licensing, access to the subsoil, planning, taxation, incentives and co-financing of significant industry projects, approach to innovation with the creation of innovative development environment, preparation of new and modernization of the existing regulatory documents on the full range of oil and gas subsoil use issues and performance monitoring.

The creation of such an intellectual environment with the support of the government innovations will contribute to the development of new (including high) technology in exploration, oil production and oil recovery enhancement in the specific geological and natural conditions of Russia. We should purchase modern development and production facilities and equipment (those that are not produced in Russia). Our science and specialists of oil companies can still perform this task.

However, today officials in the government, obviously, cannot perform the first problem: the creation of regulating subsoil documents, rules, regulations, stimulation of innovation and high technology. This is evidenced by the formation of new Russia for quarter of century. They will need to be changed. Fortunately there is some reserve in the bottom. It is a time when we can predict that if all this will not be done, the production in Russia inevitably falls. But its decline to level less than 400 million tons per year cannot be allowed for safety of Russia.

Most analysts of the Russian Federation have a clear understanding of the need to strengthen the works on oil and gas processing for the absolute increase in its volume and depth of processing. This will provide the desired economic effect at much lower production volumes. And here, as is usually done in Russia, we continue to talk a lot on this subject, but do almost nothing.

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Information about author

Renat Kh. Muslimov – DSc in Geology and Mineralogy, Professor, Department of Oil and Gas Geology, Institute of Geology and Petroleum Technologies, Kazan Federal University

Russia, 420008, Kazan, Kremlevskaya str., 4/5

Phone: +7 (843) 233-73-84

E-mail: davkaeva@mail.ru

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THE PROBLEM OF DEVELOPING OIL DIFFICULT TO RECOVER IN RUSSIA AND SOLUTION APPROACHES

G.I. Shmal
Union of Oil and Gas Producers of Russia, Moscow, Russia

Abstract. The article deals with problems of functioning and further development of the fuel and energy complex of Russia. As a result of negative trends the status of the mineral resource base of hydrocarbons in recent years is characterized by a reduction of proven reserves and an extremely low rate of production. In Western Siberia, as in other oil-bearing provinces of Russia, cost-effective oil reserves are reduced. It is now apparent that the prospect of oil production in Russia, the further development of the fuel and energy complex are anyhow related to the development of reserves difficult to recover that make up almost 2/3 of proven oil reserves. Technologies for production of such oil are very costly. The current state of tax policy and legislation for the development of 'complex' oil is simply unprofitable, as well as engagement of technologies that increase the recovery factor. The article highlights the main areas, in which we need to seek solutions to problems of Russian fuel and energy complex. New approaches to improve the situation, more effective mechanisms of the tax system are needed across the industry. Only the implementation of a new development model of the mineral complex will allow to launch new large-scale projects in the industry, which can not be considered and implemented without an integrated approach, apart from the solution of social and economic problems of development of the territory, active participation of the government, both at the federal and at the regional levels.

Keywords: fuel and energy complex, problems, oil difficult to recover, development, tax policy
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The processes of globalization, which the international community has faced in the last century, directly affect the scope of world energy. In Russia, taking into account our own competitive position in the global market, we understand the energy security issue as, first and foremost, to ensure the reliability of all countries and the entire population of the planet with energy resources.

The very problem of energy security brings to the fore one of the most important strategic objectives of our country. And it is clear to all: almost in all economic forums, summits it comes to energy supplies – in the depths of Russian world gas reserves are up to 40 %, oil – 13 %. In spite of the current relations with Europe, and the US efforts to reshape the architecture of global energy security, we must not abandon the planned line on the leading role in energy policy (Shmal, 2016).

State balance of mineral reserves in the Russian Federation accounts 2923 of oil fields, including 12 unique, with reserves of more than 300 million tons, 83 large – 60-300 million tons. The share of these categories accounts for 57 % of recoverable reserves and 58 % of domestic production. Gas reserves are included in 923 fields, including 29 unique – more than 500 billion m^3, 81 large – from 75 to 500 billion m^3; 71 % of reserves – in the unique, 22 % – in the major fields. 450 fields contain condensate (Shmal, 2016).

At the same time, recent events in the international arena – activities of oil and gas industry in the conditions of sectoral sanctions, instability of oil prices on world markets with the increasing cost of oil production in our country, as well as the continuing desire of our government to fill the federal budget in the face of declining state revenues at the expense of the oil industry – sharply exacerbated for oil and gas producers perennial national problem: what to do? How not to reduce investment in the Russian oil production in 2017 and subsequent years? How to solve one of the major problems of the industry – reducing the volume of reserves growth through geological exploration (GE) and the lowest proportion in the total growth of reserves in the Russian Federation (Table 1) mainly due to the slow pace of exploration drilling (Table 2).

As a result of negative catastrophically accumulating trends, condition of the mineral resource base of hydrocarbons in recent years is characterized by a reduction of proven reserves and an extremely low rate of reproduction. In the Yamal-Nenets and Khanty-Mansi autonomous districts oil production is falling, the share of the Tyumen and Tomsk regions in Russia's oil production has declined. In Western Siberia, as in other oil-bearing provinces of Russia, cost effective reserves of oil for extraction are declined.

Analysis of the efficiency of oil reserves growth in 2013 at a price of 50 $/b showed the following:

cost-effective reserves amounted to 146 million tons; low-profit reserves – 108 million tons; unprofitable reserves – 357 million tons.

The share of low-profit reserves increased from 36 % to 55 % in recent years.

Today, everyone understands that the prospects of oil production in Russia, the further development of the fuel and energy complex, one way or another, are related to the development of reserves difficult to recover. Almost 2/3 of the proven oil reserves are hard to recover, including: 13 % – heavy oil, 36 % – low permeability reservoirs, 14 % – areas under the gas cap, 4 % – small reservoir thickness.

The scale of this task is huge, in fact comparable to the development of Western Siberia. But the technologies of extraction of such oil are very costly, in the current state of tax policy and legislation, development of ‘difficult’ oil is simply unprofitable.

The only way to stimulate this for the oil industry is introduction of tax incentives.

Of course, over the past twenty-five years, we can find a lot of positive things in the life of oil industry. The geography of oil and gas has significantly expanded in Western Siberia. In the Khanty-Mansi and Yamalo-Nenets autonomous districts a number of oil and gas fields are put into development.

We recognize that the government and regulatory authorities of the fuel and energy complex do something to give opportunity for the oil and gas companies to work more effectively: in particular, the benefits provided by manufacturers for MET and export duties on oil fields with reserves hard to recover. However, these measures are clearly insufficient to address today’s systemic problems in the industry. The industry-wide we need different approaches to improve the situation, more effective mechanisms of the tax system.

Year	Number of fields	$A_1B_1C_1$ million tons	C_2 million tons	$ABC_1 + C_2$ million tons
2010	66	57,4	339,2	396,6
2011	34	27	224,9	251,9
2012	51	24,4	231	255,4
2013	49	29,2	122,9	152,1
2014	38	24,2	221	245,2

Table 1. Increase in reserves at new fields.

	2009	2010	2011	2012	2013	2014	2015
Funding budget/business, bn rub	<u>18,9</u> 150	<u>20,6</u> 170	<u>20</u> 205	<u>27</u> 225	<u>32</u> 240	<u>36</u> 270	<u>32</u> 336
Exploration drilling, million tons	0,46	0,71	0,75	0,8	0,82	0,99	0,82

Table 2. Exploration drilling.

Here is an example. In Norway, direct taxes are levied solely on the profits of companies, and not field belonging to them and include a tax on oil production in the amount of 27 % and a fee of 51 %. Special duty implies additional deductions and interest on capital expenditure, with a period of four years from the date of investment of the total amount, up to 5.5 % can be deducted each year. Moreover, the current losses of operators can be transferred. Also, under a license agreement the partners are entitled to a reimbursement of up to 78 % for exploration expenses (Shmal, 2016).

In place of reasonable financial policy we have adopted incomprehensible decisions, such as tax maneuver of the Ministry of Finance that oil companies regarded as ‘Operation Barbarossa’. As a result of such a ‘maneuver’ imbalances were created that led to the fact that the high load on the Western Siberia has increased even more. As a result, the volume of production drilling in the region has fallen.

It is the same in the legislative field. Speaking of the government policy in relation to the energy industry, the fact must be mentioned with bitterness that for more than two decades we have been waiting for the adoption of the new edition of the Russian Federation’s law ‘On Subsoil’, the laws ‘On Major Pipeline Transport’, ‘On stimulation of production on low productive fields’, ‘On the resource base of the country’, ‘On small and medium-sized enterprises – independent oil and gas producers’, technical regulation ‘On the safety of major pipeline transport and field pipelines’, the development of the federal laws ‘On government regulation of oil and gas industry’, ‘On the national energy security’, the formation of a block of laws ‘Oil and Gas Code’, entering the amendments dictated by the time to the Tax Code and the law ‘On technical regulation’.

This fact speaks volumes: both about the approaches to the management of economic processes, and government priorities. The legislation, which is important for us, has to give finally unambiguous interpretation of terms and definitions relating to the basic parameters of the entire oil and gas industry, including the concepts of oil difficult to recover; regulate the system of relations between the government and production companies; ensure proper uniform government control and supervision on the rational, comprehensive and effective development of fields of liquid hydrocarbons. Government regulation should be, finally, a basic component of the measures formation that would ensure the proper functioning of the fuel and energy complex and its efficient development.

Despite all the talk about the state of the resource base and the entire geological service of the country, which determine the future of the fuel and energy sector, investment in geological exploration fell fivefold.

If the government's financial unit does not hear the arguments of the professional producers and does not have strong long-term economic strategy, there is no question about demanding a reasonable policy, economically considered solutions.

In this case it is really hard to explain to those who make the final decision that today the majority of our fields are in the late stage, when they need extra care to preserve their capacity, to increase oil production and ultimate recovery, to save jobs.

We work mainly in the fields, which are developed from 30 to 70 years. For example, the degree of depletion of unique fields in the Nadym Pur Taz region reached 70-85 %. The size of discovered fields is reduced. We can only dream about the Romashkino, Samotlor, Fedorov fields. The average size of fields opened in recent years – 900 thousand tons (of recoverable reserves) (Shmal, 2016).

But we have no right to give ground – oil complex is with us, as well as Russia's interests. It is necessary to urgently develop and implement a set of measures aimed at stimulating exploration works and involvement in the development of new fields.

As is known, the further increase in oil production is hampered by lack of discovered and completed by exploration large oil fields, which are not put into the development. Oil difficult to recover requires large volumes of drilling, including horizontal wells. We have a very small amount of drilling – about 22 million meters that seems to be good parameter. But in the United States they drill 110 million meters, although previously they drilled by 70 million. Let us compare: 22 and 110 ... In the 80-s we've had about 50 million meters (Shmal, 2016).

The development of competitive oilfield service companies is behind. An urgent problem is the technical renewal of oilfield services equipment: domestic drilling rigs are not enough –previously "Uralmash" would make them 300 units per year, and now – 30. It is necessary to develop our own national base for the manufacture of equipment.

I agree with the position of Governor of the Khanty-Mansiysk Autonomous region – Yugra N.V. Komarova that the development of the fuel and energy complex is needed to be the national project of national importance, in view of the prevailing geopolitics. The involvement of reserves hard to recover should be a national project; domestic business should be supported; subsoil users have to be stimulated. This must be done without delay.

By the way, the ex-governor of the Tyumen Region V.V. Yakushev often gives a good example of the rapid development of 'difficult' reserves. Back in 2004, the regional government has signed an agreement with oil companies on the development of reserves of Uvagsky group of deposits belonging to hard reserves, and began to invest in infrastructure development in conjunction with production companies. In the same year, production was increased by 1.2 million tons, 9.6 million tons were produced in 2013, and in 2015 the bar has passed 10 million tons of production. Over the years, the help that was provided to the subsoil user amounted to about 100 billion rubles. The federal budget as a result of this work has received about 500 billion rubles. At the same time the governor emphasized that no one would get close to the fields, if the Region did not introduce a special tax regime.

Experts believe – if the tax on the extraction of minerals remained in the regions and went for the development of reserves difficult to recover, the question of the corresponding groups of deposits would be solved much more effective. But, unfortunately, MET became a federal tax, reducing the possibility of the regions in benefits distribution for 'difficult' reserves.

Let us take as the example Yamal. The specific volume of reserves difficult to recover in the oil production is 82 %. Almost all areas with reserves difficult to recover are developed at least by 50 %. However, the adopted changes in the tax code do not explicitly promote an increase of the oil production. We are talking about the top limit of the field depletion, after which it is impossible to use tax benefits – it is currently set at a very low level of 3 % of the total volume of reserves.

We've been a long time talking about the role of the regions in the fuel and energy sector development. It should definitely increase if we want to have a cost-effective production of oil. This is especially true with hard-to-recover reserves. As oil producers say – it is not areal drilling, here each individual well has its own face.

We got hectic, difficult time today. And we can understand the current mood in the financial unit of the Government – 'plug the holes' at the expense of incomes of the oil industry, to increase their contributions. But we must cease to live only by simple solutions and one of today's times, we must look forward and learn to count precisely. For example, the initiative only in the sphere of export duties in the next two years, will give to the government budget about 200 billion rubles. But the price for the decline in production will be much higher. The effect of the payments increase to the budget very quickly will come to the absence, and starting in 2018 will be completely negative.

Additional payments to the budget will lead to the freezing of new promising projects, especially small and medium-sized fields, including in Eastern Siberia, as well as to refuse to drill new wells. Discussed fiscal initiatives will hit the mature fields in Western Siberia, where the production is reduced. According to preliminary estimates, reducing the oil companies' investment programs can lead to a decrease in oil production in Russia in 2016-2018 a total of more than 11 million tons, including in 2018 to about 6 million tons.

Cost items	Tax assessment before 1.01.2015	%	Tax assessment after 1.01.2015	%
Geological exploration costs	2	0,5	2	0,5
Drilling cost	21	5,8	21	5,8
Other	16	4,4	16	4,4
Current cost	85	23,3	85	23,3
Export tax	39	10,7	25	6,8
Mineral extraction tax	75	20,5	123	33,7
Profit tax	15	4,1	10	2,7
Property tax	6	1,6	6	1,6
Other taxes	25	6,8	25	6,8
Profit	81	22,2	52	14,2

Table 3. The structure of the oil price, USD/t (365 d/t, the data of A.I. Varlamov).

In the current tax system it is unprofitable to engage in the implementation of technologies that increase the recovery factor.

Slowing down the development of new oil provinces can lead to problems with the implementation of Russia's obligations on eastward oil supplies.

Reduced investment will have other negative consequences. A topic such as import substitution, in relation to the oil industry could be considered closed, as orders from oil companies for the development of new equipment would be reduced significantly. Reducing orders to contractors would lead to job losses with all its consequences. Reduction of investment and consumption volume of resources and services would lead to closing up of business activity in related industries, such as machinery, metallurgy, drilling, oilfield, construction, and employment reduction of 1 million people in the current year.

Thus, taking from one industry, the government will have to solve problems in other industries, work with the social tension in the regions.

Another item of expenditure, which will inevitably be subject to audit, is geological exploration. Without it, development of the industry in the medium and long term is impossible, old fields are being depleted, and to discover new once resources and time are needed. The structure of the oil price according to A.I. Varlamov (Director General, Federal State Budgetary Institution «All-Russian Research Geological Oil Institute») is presented in Table 3.

Thus, the additional removal in the current conditions, very difficult for the oil industry of such a significant amount will be the beginning of regression, loss of stability, a reversal from the stable growth to reduction of all rates.

The draft of the Energy Strategy of the Russian Federation until 2035 marks the main tasks of the oil industry development in the near future:

- A stable annual production of oil with gas condensate at the level of 525 million tons, with its capabilities to increase in favorable global and domestic markets;

- Modernization and development of the industry;

- Increase of the oil recovery factor from 28 to 40 %;

- The development of hard-to-recover resources in the amount up to 17 % of total oil production, etc.

Initiatives to increase the fiscal burden on oil companies do implementation of these tasks almost impossible.

The Council of the Union of Russian Oil and Gas Producers highlights key areas, in which we need to seek a solution to these problems:

The first – the further improvement of subsoil use regulations, the use of such levers as licensing, innovation, tax policy;

The second – to stimulate reserves growth process through tax preferences, changes in the principles of obtaining a license for geological exploration of mineral resources, the revival of the geological sciences;

The third – the creation of favorable economic conditions for the establishment and development of small and medium-sized regional-oriented companies, the subject of the activities of which will be small and difficult fields of mineral raw materials;

The fourth – the coordination of central and regional efforts, providing them with a better interaction with the mineral resource businesses, improvement of management systems of oil and gas companies;

Fifth – the translation of legislation in the direction of creating an effective public administration system capable of implementing major changes in the oil and gas sector.

Experts of the Council of the Union of Russian Oil and Gas Producers believe that to successfully meet the challenges of overcoming negative consequences of the global financial crisis and the stabilization of oil and gas activities, it is necessary to adopt a comprehensive government program to support the fuel industry with the following urgent measures.

• In view of the prevailing geopolitical program, to make the development of the fuel and energy complex as a national project of national importance, which includes a separate special section of involving reserves difficult to recover.

• Provide tax breaks for the main taxes to the release of the newly commissioned capacity on planned production volumes.

• Enter a zero rate of mineral extraction tax for hard-to-recover reserves of new oil and gas fields in the extraction from the idle wells and wells that are in preservation, up to cost recovery for the start-up of wells in operation, as well as small fields (with initial recoverable reserves as of 1 January 2009 not more than 3 million tons).

• Provide deferred taxes for companies facing serious financial difficulties, to establish procedures for such delay.

• Concentrate government investment in the implementation of priority infrastructure projects.

• Compensate for interest rates on loans sent to the investment programs.

• The government should participate in the financing of R&D centers in the field of modern technologies for complex use of deposits.

• Create conditions for the development of new advanced technologies of hard-to-recover reserves: scientific grounds, which should become a platform for testing and implementing new methods of research and development of reserves difficult to recover, development of unconventional oil resources, and solution of environmental issues.

• Create conditions for wide application of import substitution for the equipment: today dependence of oil companies from imports is critical in nature: the share of imported equipment and technologies in general is up to 80 %, and in some categories – equipment for offshore projects or software can exceed 90 %.

• Develop own oil service; create a document at the federal legislative level that will stimulate domestic subsoil users. It is necessary to initiate the withdrawal from Russia of Western leading oil service companies and to set embargo on the delivery of the service equipment.

• Provide innovative development of Russian machine-building and service industry for the oil and gas and process industries.

• Provide the government participation in the investment of new projects, legislative solution of these issues.

• Develop tax breaks to oil companies according to the proportion of domestic equipment used in dealing with the issue of import substitution.

• Resolve issues related to the provision of rights for subsoil use (wells with low flow rate) to small and medium companies with the largest share of domestic equipment in the project.

• Oblige oil and gas companies to spend a certain proportion of research in national research institutes.

Such instruments must include:

- The development of domestic research institutes, testing laboratories, training of personnel;

- Regulated investment share of profits in the development of new technologies;

- Assist of domestic companies to conduct pilot tests;

- Government programs of unique types of equipment development with a focus on high-tech;

- Co-financing of investment projects aimed at launching new production facilities and modernization of existing ones.

Only the implementation of development new model of the mineral complex will allow launching new large-scale projects in the industry. All our previous experience shows that they cannot be considered, especially implemented without an integrated approach, apart from the solution of social and economic problems of the territory development, the active participation of the government, both at the federal and regional levels.

The most successful countries are making, applying planning techniques in the economy management, and skillfully combining the advantages of market and government regulation.

China already becomes a reference, which began in 1978 consistently and gradually to carry out conversions, which brought backward and poor country on the path of the highest rates of growth, sustainable and harmonious development. Its example was followed by Vietnam. From the post-Soviet countries, this type of model has been taken as a reference point in Kazakhstan and partly in Belarus.

The United States can be referenced as an example that has achieved shale oil production growth due to economic incentives. In recent years, The United States increases production to 20-25 million tons per year.

India successfully conducted under the government supervision the modernization and became the second fastest growing economy after China in the world. Transnational corporations and the national capital operate in the country, but along with this, the scheduled controller continues to operate defining strategic development targets implemented by five-year plans. Well-educated specialists helped to such a turn of events. The Indian institutes of technology are often not inferior to Western competitors. Now according to the number of qualified scientific and technical manpower, India is on one of the first places in the world. All this was the result of deliberate policy of the authorities.

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Information about author

Gennadiy I. Shmal – President of the Union of Oil and Gas Producers of Russia

Russia, 125009, Moscow, Degtyarnyy all., 9

E-mail: shmal@sngpr.ru

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THE FORMATION OF REGULATION SYSTEM AIMED TO DEVELOP MORE COMPLEX AND LESS CONVENTIONAL HYDROCARBON SOURCES

V.A. Kryukov
Institute of Economics and Industrial Engineering of the Siberian Branch of the RAS, Novosibirsk, Russia

Abstract. The paper considers problems of the formation and evolution of the institutional environment, which determines the direction of mineral resources development. It is noted that Russian approaches to justify and make decisions in the field of mineral resources development hardly consider the rapidly changing conditions of the functioning of the modern economy sector and go back to the features of the industrial economy. Strengthening of the economy role leads to the fact that the perception of rational strategies for exploration and development of mineral sources and fields significantly changes.

The most important aspects and features of the rules and procedures that determine the approaches to develop mineral resources in modern conditions include: increasing the role of knowledge, transition from the linear forms of interaction between participants in the process of prospecting and exploration of mineral resources to the network forms; alignment in time and within the framework of integrated technologies of previously disparate steps (these changes are largely due to the increase of volatility in the economy and the natural resources sector). Development of resource regimes in marked direction is associated with an increased degree of flexibility of the entire study system, regulating the use of the mineral resource potential of the country.

Keywords: resource regime, mineral resource potential, knowledge economy, irrecoverable losses, rational development

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Resource regime – composition, structure, direction of changes. The role of characteristics of assets and technologies

Natural resources sector is one of the leading sectors of the Russian economy (irrespective of how much and how often we talk and write about the need for innovation-directional development and the speedy overcoming of the so-called ‘orientation on raw materials’). This sector includes economic activities related to prospecting, exploration, development, production, transportation and primary processing of a wide range of mineral resources – not just oil and gas, but also solid minerals (from precious metals to common building materials).

The institutional structure of a country, of a sector of the economy has significant differences, not only because of the historical and cultural features. Such factors are important as the structure of the economy (the ratio of manufacturing and primary industries, for example), as well as the specifics and peculiarities of its assets in the leading sectors. In Russia, for example, not just the natural specificity of the assets plays an important role, but their so-called system-specific features that substantially define its current status, and the range of possible conditions that may be achievable in the foreseeable future (Kryukov, 2014). In doing so, to the system-specific characteristics of the assets we include features that are determined not as mush by peculiarities of the technology (known phenomenon of assets idiosyncrasy, marked by O. Williamson and put by him in the basis of the analysis of interaction between economic entities), but by features of applying the technology in question in a particular socio-economic system (more precisely, its practical implementation).

Institutional structure that provides development of mineral resources, as well as their subsequent use and distribution of effects and benefits obtained, is defined as ‘resource regime’ (or just ‘regime’).

Review and analysis of resource regimes of development and usage of mineral resources (and the whole of natural resources) was largely due to the fact that the neoclassical paradigm could not explain the differences in the socio-economic impact from the development of very similar sources of mineral resources in different countries and in different situations. By the early 1980s, a logical, consistent and analytically rigorous neoclassical theory of development and use of exhaustible resources has been formed (its synthesis is presented in papers (Dasgupta, Heal, 1974; Stiglitz, 1974)). A distinctive feature of the developed approach in its framework is the passive role of the government in carrying out the functions of the arbitrator and the guarantor of stable functioning of the private sector and the realization of entrepreneurial initiatives. The problem of social choice, associated with the development and utilization of mineral resources, in this case, is not considered and is not taken into account (especially environmental issues and, in general, environmentally sound development of natural resources). Also, it is implicitly assumed that the government is able to provide a selection of the best solutions from among all possible and available alternatives and development capabilities and the use of different types of natural resources.

Performing this role allows the government to ensure the country's optimal development and use of exhaustible natural resources. At the same time, of course, the social costs (externalities) shall not be accepted or considered. It is clear that the situation described above can be, rather, an exception and does not take into account not only the multiplicity of interests of parties involved in the development of natural resources, and that is especially distinctive for the current situation, the involvement in the development of new kinds of natural resources (related to the rapid development of technologies and the influence of the knowledge economy).

To a large extent the solution of social choice problems associated with the development and use of natural resources, corresponds to extending the neoclassical analysis by considering the interests of the different parties involved, as well as the forms and the scope of their cooperation in this process.

Forms and scope of cooperation constitute the institutional structure, which is defined in this case as a resource regime. Resource regimes may vary significantly and, in general, include:

a) the property rights that define access to resources;

b) a bundle of rules and procedures for determining (defining) transactions relating to the use of resources and the results of their development.

Variety of resource regimes leads to the fact that they, respectively, may also function very differently.

Social costs arise not only due to insufficient consideration of environmental factors, but because of such reasons as limitation at each moment of the best (by natural properties and economic characteristics) mineral raw materials, as well as due to exhaustion and therefore instability and socio-economic systems associated with them. Pioneering works in the field of resource regimes phenomenon are associated with the work of American researcher Oran Young (Young, 1981). The structure of resource conditions was first proposed and investigated by Young. In his opinion (with which the present author agrees), resource regime includes:

• rights (especially the right of ownership of natural resources – the most important element in the structure of the resource regime);

• rules – clearly defined guidelines or standards of actions of participants of natural resources development and utilization (their specific types in very different conditions, exploration and development);

• procedures – approaches to resolving ambiguity or conflict situations that arise in difficult conditions of practice.

It should be noted that features of various forms of property rights (including natural resources) were studied in detail, but this is not true for rules and procedures – about their correlation in a variety of countries and circumstances. Undoubtedly, the distinction between the rules and procedures lies in the detail presentation of development and use of subsoil plots, for example.

Rules – it is prescriptive guidance of certain requirements that are met with more or less clearly defined quantitative parameters of natural resources sources. At the same time procedures are focused on the search for compromise solutions (especially in solving problems of social choice) in poorly structured and unforeseen situations. The latter is especially important with an increase in the complexity and diversity of natural objects and problems of their development (that – see below – is a distinctive feature of modern processes).

In general, as noted in (Vatn, 2005, p. 252), three directions prevail in in the study of resource regimes. The first – the problem of access to natural resources; the focus is on distribution of natural resources sources. The second – formation of the costs of creation and the use of institutions that provide development and utilization of natural resources; emphasis is on the consideration of factors that determine the formation of transaction costs associated with it. The third – the effectiveness of various resource regimes; the emphasis is directed at issues of resource regime operation as well as on whose interests it represents, and the formation of which values it promotes.

There is no doubt that often there are situations in which the efficiency and rationality in the sense of a separate economic entity (or actor) can turn into its opposite by summing all individual effects and rational choices (this is what we are seeing in today's mineral resources sector in Russia) (Kryukov, 2006).

In addition to the fact that resource regime (as well as any institutional structure) is determined by historical, cultural and economic circumstances and conditions, a special role in its formation is played by two important circumstances (without diminishing the importance of priorities of the government economic policy and relative prices):

1) the peculiarities of natural resource;

2) the specifics of the development of techniques and technologies in the field of development and its further use (Elster, 1983).

Previously, we noted this fact in a very general way. Namely, (Kryukov, 2006), "World experience shows that, with the acquisition of skills of application of certain rules and procedures in the field of oil and gas operations control, the latter are increasingly formed on the basis of not direct guidance, but compilation and distribution of 'best practices'. Thus, the institutional structure (or resource regime) evolves with not only changes in asset characteristics (especially in connection with the transition of resource-producing provinces in the stage of maturity due to the depletion of mineral resources), but also the accumulation of experience in the formation of stable 'specific knowledge organizations' (or 'routines' – by definition of R. Nelson and S. Winter[1])."

At the same time "the institutional environment in the oil and gas sector in Russia is characterized by not only lack of effective procedures aimed at solving the problem of public choice, but effective rules for the use of natural resources. However, there is a desire to unify approaches to conflict resolution, as well as the 'transition' of subsoil conditions management procedures into bureaucratic coordination" (Kryukov, 2006).

The behavior of any company in the mineral resources sector is largely determined by the balance between the rules and procedures governing the prospecting, exploration and development of raw materials and energy sources. At various stages of formation and development of the institutional structure in the field of subsurface composition and ratio of the role of rules and procedures differ considerably.

Thus, there are always two ways to overcome the increasing complexity of reclaimed natural objects (see below):

a) more detailed regulation of the rules defining the process of development and use of natural objects (in preparation of design solutions and their possible revision);

b) the formation and development of procedures for the formation of mutually acceptable solutions (from the point of view of the government – at the federal, regional and municipal levels, as well as various companies – resource users).

In Russia, in the present time regulation of the activities of subsoil users is based on the requirements set forth in the permits (or licenses) for subsoil use. Gradually a transition to enhance the role of design solutions takes place parallel to the complication of the rules of their development (due to changes in characteristics of natural objects) and, moreover, clarification. However, this approach has a very serious drawback: changes in raw material source operating conditions (including economic) require a revision of the entire development project.

But this is very long and expensive process. Thus, there is a significant increase in transaction costs arising from the use of such an institutional structure. The functioning of a complex institutional structure is associated with elevated costs – from the government and resource users. The feasibility of such changes depends on the added social and economic benefits that can get government-owner of natural resources.

At the same time, the implementation of more complex and flexible measures in the field of control and monitoring of development and exploitation of natural objects, despite the costs involved, makes it possible to take greater account of the diversity of natural resources, expanding the sources and conditions of their development. From this point of view, this approach is able to take greater account of the interests of the government-owner of the subsoil resources and to limit the possibility of opportunistic behavior of subsoil companies. However, this approach involves a significant decentralization of mutually agreeable solutions and requires highly skilled specialists in the field of natural resource management (which can competently and responsibly participate in the implementation of procedures for resolving ambiguous situations).

The above-mentioned conflicts – in general – are quite obvious. However, the scope of these approaches is not obvious: on the basis of dominance rules of direct (prescriptive) actions or procedures for resolving potentially conflicting and ambiguous situations.

Particularly urgent to seek solutions to the above-noted problem in today's oil and gas sector in Russia gives rapid change of perceptions about the sources of hydrocarbons, as well as those technologies which are connected with it. It seems to the author, this trend has not only 'nature of oil and gas' – the rapid change in the composition of sources of mineral resources production and used technical solutions is virtually ubiquitous in nature (for many types of solid minerals, energy resources and so forth).

'Shale revolution' – features and characteristics. Resource regime and the 'learning process'

The oil and gas sector of the United States is an illustration (more precisely, the proof) of the significant role of social institutions during the development and utilization of mineral resources. At the beginning of the

[1] «The general term for all normal and predictable patterns of behavior of companies, will be 'routine'» (Nelson, Winter, 2000, p. 31).

2000s, almost all, without exception, researchers and specialists characterized it as having a high degree of maturity for the development of the conventional resource base. This meant that the main large conventional hydrocarbon deposits were identified; new discoveries have smaller size of recoverable resources; extraction of raw materials and energy resources gradually (and at the same time steadily) decreases. This fact (with a high level of domestic oil and gas consumption in the country) induces to increase imports of oil and gas.

However, for a long time in the United States (as well as many other countries around the world – from Argentina to Russia included), there are significant hydrocarbon resources associated with different geological conditions of their bedding structures. Such structures, on the one hand, cover large areas; on the other hand, occurrence of hydrocarbons is highly localized. This characteristic means complete or partial absence of hydrocarbon flows on the so-called productive horizons in the process of exploration and development.

For the purposes of our further analysis it is important to mention the fact that the project of the development of this hydrocarbon production source (not field, but a small portion of the immense geological formation area) at the same time is significantly reduced in size. At the same time, each such local project has a very significant specificity. Ultimately, it is ‘compressed’ to the project of construction of a single well and the choice of its operation mode (including the creation of an artificial reservoir by fracturing).

Thus, there is a complex problem. On the one hand, there is the decline in production from conventional sources of raw materials (such as conventional fields), on the other – a huge resource potential of non-conventional sources of raw materials (in the case of the US – shale deposits). Feature of the development of alternative sources of raw materials – shale deposits (or so-called tar sands in Canada) – the inevitable increase in costs when using traditional approaches and solutions, based, inter alia, on the action and compliance with the rules of direct prescriptive action.

One of the ways to solve the problem is the improvement of technologies and the development of institutional structure that corresponds to changing conditions. US have taken fully advantage of such an approach (Kryukov, Grinets, 2015). A distinctive feature of the implemented approach is focus on the formation of procedures aimed at achieving mutually acceptable solutions in the implementation of projects for construction and operation of the individual wells. The result is well known: oil production in the US increased for 2005-2014 by almost 100 %, gas production for 2004-2014 increased by more than 40 % (US Field Oil Production of Crude Oil, 2016; US Natural Gas Production (Gross Withdrawal), 2016).

The most important feature is that at the rising variety of oil and gas sources from shale deposits (primarily due to the specific conditions of the environment) it is not possible and feasible to implement an approach based on strict prescriptive rules.

A significant feature of the created resource regime is that the producers of shale oil, unlike their competitors, take months, not years for the development of raw materials – “they can ruin any predictions: if prices jump to $50 per barrel, in six months we just face another problem” (Nevelskiy, Overchenko, 2016).

The combination of new technologies and the resource regime adequate to the changed conditions led not only to an increase in production volumes, but also to a decrease in the absolute values of raw material production costs.

The competitive environment, a flexible system of assessment and decision-making (in conjunction with a significant decentralization of these procedures) ‘launched’ an action of ‘learning effect’. So, in 2003, US companies have only begun to combine the technology of horizontal drilling and hydraulic fracturing: Four Sevens Oil Company drilled on the field Barnett Shale its gas well, called Brumbaugh, the best in Texas. According Drillinginfo, for that purpose the company has used 10.6 million liters of liquid and 100 tons of sand. As a result, the peak value of gas production from the wells was 167.1 thousand cubic meters per day. However, already in 2013, Cabot Oil & Gas drilled the most productive gas well in the US, using four times more employees than Four Sevens Oil, 47.3 million liters of liquid and 6 thousand tons of sand. This enabled to produce 858 thousand cubic meters of gas per day, which is five times higher than the maximum level of production from well of Four Sevens Oil, made ten years earlier.

Currently, the method of horizontally branched wells, called ‘octopus’, is one of the most rapidly progressing technologies used in the US during the development of unconventional hydrocarbon deposits. According to American experts, this technology by eight times (!!!) improves drilling performance compared with conventional drilling technology (http://www.angelnexus.com/o/web/61109, 2014). This technology is an extension of the other technology, also established in our country – multi-well pad drilling. Not so long ago, as part of the development of shale hydrocarbons in the basin Paysens, company Encana has completed an impressive project on drilling on the same site of 52 wells. This site is less than 0.1 square miles. However, the technology has provided access to productive reservoirs in an area of full square mile.

It is important that while many previous successive jobs are combined – drilling of exploration wells combined with production drilling; exploration seismic survey – with well logging; measures to improve oil recovery start at a very early stage and 'integrated' in the production technology. For example, in the US the number of seismic crews reached its peak in 1981 – 8172 parties, by 1999 their number decreased by more than seven times – 1125 parties, and in 2000 the value was reduced to unobtrusive value – 63 parties. At the same time the number of drilling rigs decreased from 3970 units in 1981 to 1862 units in 2014 (United States Petroleum Statistics, 2014).

Launched 'learning effect' has such a significant 'safety margin' that, for example, the Ministry of Energy of the Russian Federation is compelled to state that "... In spite of the decrease in the number of drilling rigs by about 70% compared with 2015, according to Baker Hughes, shale oil production drops in much smoother pace. This demonstrates the inelastic supply of shale oil: the decline in oil prices has not led to a similar decrease in production. Companies extracting shale oil now optimize processes, achieve lower costs for oilfield services and reduce staff, providing a break-even point at a lower level – about 40 dollars per barrel, as well as solve financial problems by means of public offering and attracting capital stock (Tereshok, 2016)".

Seismic surveys are increasingly being integrated into the works performed in the process of drilling wells, which reflects the 'blurring' of the line between exploration and production wells. The main reason is the economic unreasonableness to carry out detailed purely geophysical and exploration surveys within the boundaries of quite well studied geological formation. On the other hand, the share of horizontal wells sharply increased (in the United States, taking into account the development of shale fields – 68 %), as well as productivity in drilling operations (more than five times over the past 10 years in terms of the depth of penetration per one drilling rig). It is assumed that the above-mentioned features are not unique to unconventional sources of raw materials in the US and Canada. In general, the nature and characteristics of the world's mineral and raw material base for many types of minerals undergo a similar change.

Such rapid changes would not have been possible within the scope of the resource regime based on the dominance of prescriptive rules.

Historical features of the development of oil and gas resources in Russia

The expediency of the strategic objectives, based on the growth of physical volumes of mineral deposits prepared for development, to a small extent consistent with modern concepts of efficient economy-oriented solutions to complex socio-economic and environmental problems. The distinctive feature of such a system is a focus on the use of prescriptive rules of direct action. It is based on 'industrial paradigm' of knowledge distribution, which is characterized by a linear unidirectional model of the innovation process with a gradual transition from basic to applied research, and then – to the implementation of the results into practice in the form of new products, processes and sequence of work stages.

At that, such an important task as increasing the flexibility of the entire oil industry functioning system (for a quick and effective response to changing conditions of exploration, prospecting and development of hydrocarbon fields) is not considered. Organization of the industry has been focused primarily on the search for solutions that provide a rapid return (usually in the short term). This involves regular transition from one new province to the other, identifying the major fields, the search for effective engineering solutions for commissioning of unique objects. Ultimately, this means a constant focus on economies of scale – to minimize cost per volume unit of extracted raw materials due to natural causes (in the application of technologies and approaches used for a long time).

Therefore, all of the interactions that are lined up in the Russian oil and gas sector and industries associated with them, were aimed primarily at improving, in modern parlance, manageability (handling with an emphasis on simplicity and transparency). Vertical hierarchical relationships were the main in this system – on the implementation of targets and their logistical support. This was manifested in all, not only in control, but also in the formation of technical and technological systems (from private technical solutions at device level to determination of the configuration of piping systems, well placement, measuring systems and scheduling) and in the accounting system (for example, classification of oil reserves was based on geological and technological principle – accuracy and validity of the definition of basic deposit parameters and all its characteristics).

All this was aimed at the implementation of the main tasks of central planning and control systems. The system worked very well in the case of large and unique objects and began to falter as soon as conditions of its operation changed (especially with regard to the size and extent of deposits depletion, as well as the strengthening of 'non-conventionalism' of involved raw materials).

Horizontal relations and interactions at the level of enterprises of different departments (for example, between the mining, geological, construction and transport companies) are practically absent. Ways to overcome the arising problems were in the development of 'missing' activities within an organization, or from the beginning of the 1980s, in the formation of 'supradepartmental' organizations (such as the Bureau of the USSR Cabinet on fuel and energy complex, the West Siberian interdepartmental territorial commission of the

State Planning Committee of the USSR, and others).

But unfortunately, winning the speed of development of deposits and timing of the high levels of production, we lost elsewhere: in the ultimate oil recovery, in operating costs for the production period, in the environment. For example, the widely used (and still used) waterflood technology: not clean water is pumped into the reservoir, but mineralized – more heavy and having high displacing properties. However, mineralization with displacing fluid leads to a drastic reduction in the service life of the equipment due to corrosion of the metal (especially quality of the metal, which was heading into the oil industry in the USSR). Therefore, costs of repair, replacement of equipment were increasing; the number of pipeline ruptures and spills of oil and corrosive liquid directly on the earth's surface were increasing.

Focus on fast terms of fields development and their commissioning not only led to complications in their development (redevelopment) in the future, but also to the fact that in the framework of universal management procedures we tended to universalize the rules for their exploration and development. One of the hottest topics of discussion in the oil industry of the USSR was, for example, the well spacing in justifying the technological scheme of development of conventional oil fields. Much effort and energy (and, in this regard, a lot of broken lives) was spent on the 'evidence' of the possibility of using the universal well spacing – the number of wells per area unit of the deposit.

The underlying reason lies not only in monopolizing the position of an organization in the system of study and development of design solutions, but also in simplicity and 'handling routine' process of functioning and development of the oil industry. It is easy to consider the investment, to control the development process, to evaluate the effectiveness of the criterion 'production/ costs'. However, in general, within the framework of the economic system, which was based on a rigid chain of command and was aimed at achieving the priorities that were largely determined on the non-economic basis, the desire for uniqueness and simplicity of production, decision-making and coordination was certainly dominant. The results of actions of this universal approach to the formation and use of prescribing rules to the deposits exploration and development is not difficult to predict: rising costs, steady decline in the degree of development of reserves.

The absence in the USSR and now in Russia of the so-called 'problem of unitization', when development projects of all areas are combined into a single design solution, is among the obvious advantages of the domestic design and arrangement system of the development of conventional deposits. Such problem did not exist in the system of centralized planning and control when connecting the owner of subsoil and subsoil user in one party. In this regard, for example, one of the leading specialists in the development of oil fields, professor V.N. Shchelkachev noted that there are "certain advantages of our domestic system, when each field owned by the government has been developed on a single plan" (Schelkachev, 2004).

To a large extent this was due not so much with the field development system, as with the absence in the planned system of the concept 'economic/ financial/ household risk'. Combining the efforts of several economic entities is necessary to reduce each individual risk and, thereby, increase investment attractiveness of the project. Understanding the practical impossibility of typical single-valued solutions for new unconventional sources of mineral resources, the difference in approaches to development in the case of objects that are at different stages of depletion, in different areas and developed in different time periods – all this with a certain difficulty steadily have worked its way in life.

The most important feature of the generated domestic model of exploration and development of oil and gas fields – is not so much the pursuit of universalization (which in itself is not so bad, but on the level of, for example, separate processing elements), as linear connection of all stages in a single chain. First, the transition is carried out from the identification of resources to the determination of reserves, followed by the dynamics of production, and then – justification for the field arrangement solutions; and only then calculation and evaluation of investment and performance. In this approach, all other circumstances seem less significant. These include the environment and conditions for the implementation of decisions, risk tolerance etc.

As indisputable result, in the oil and gas sector in view of the complexity of geological conditions, costs can have only one trend – a steady growth (we talk, of course, not about the absolute costs, but about specific ones). As noted in the December 2013 by analysts of the company "Finam", "Russian companies in the development of fields have traditionally been guided not by the expected return on investment, but production volumes. ... Companies are trying to apply new technologies to extend the life of oil fields. But it also leads to an increase in costs ... In addition, the oil production moves in Eastern Siberia and the North. But for this we need to build additional infrastructure. Infrastructure is built by "Transneft", which means that the tariffs for transportation of oil grow. ... Meanwhile, in the first three quarters of 2013 increased costs for oil production accelerated sharply. The average growth rate is 16.9 % compared to the average growth rate of 9.7 % over the last four years" (Analitiki: Dobycha nefti v Zapadnoy Sibiri …, 2016) (it should be noted that the devaluation of the ruble in 2014-2015 only mitigated this trend, but obviously did not suspend its effect).

Another estimate for the same period of time shows similar values: "Capital expenditures for the extraction in average rose faster than inflation (+ 15 % annually), which is explained by the increase in drilling depth and the rise in prices of services in drilling" (Arutyunyan et al., 2015).

In the planned economy, it was more or less clear and understandable: it was done by the government and at the government expense. In this economy, in which we are now, the answer is not obvious: the government has no money, and the business has their own ideas about efficiency. This presentation largely emerged as a response to poorly balanced and inefficient resource regime. It is characterized not so much by imbalance in rules and procedures for the development of subsoil, as the absence of many significant and important components. The most important of them is the lack of communication between production and reproduction of the resource base.

One of the reasons was that by the end of 1980 vast industrial and production potential had accumulated, especially in the form of discovered and previously introduced in the development of unique (with reserves of over 300 million tons) and large (with reserves of more than 30 million tons) fields. Until now, the role of the largest fields is very considerable: at the beginning of 2013 in the West Siberian petroleum basin more than 40 % of oil production was provided by 21 fields (from more than 770 explored within its limits). Therefore, the main motive of many companies for a long time – the intensification of production on previously entered and developed areas of mineral resources.

This explains why experts state that "... today, there is no actual clear criteria for field development, non-fulfillment of which is a violation of the project. During the so-called licensed amnesty, primary focus in the field of subsoil use regulation is transferred from the license on the development project. ... Rosprirodnadzor proposes to provide in the conditions of license agreements the possibility of adjusting production levels depending on the needs of the market" (Andrianov, 2015).

We do not intend to challenge the validity of such approaches, we note only that they can and should be considered as the basic units of formed system to ensure the best use of the oil and gas potential of the country. With the exhaustion of reserves in conventional fields and changing production conditions it makes little sense to follow once established design solutions. It is better to clarify and detail the major decisions in the monitoring mode (e.g., with yearly pace) based on wider application of agreed procedures for mutually acceptable solutions (many similar procedures have been developed in the world, including in view of the anti-corruption component).

The main strength of the established and still used resource regime lies in its focus on the exploration and the transmission for development of all new sources of mineral raw materials of conventional type. They include such occurrences and deposits of minerals in new areas and in areas of long-term development. At the same time, a distinctive feature of the current stage of the mineral resource potential development of Russia is a sharp decrease in development opportunities by engaging in exploration and development of previously discovered major (or relatively large) conventional fields of most minerals.

Among these are objects that are characterized by the presence of 'good' reservoir properties (in the case of deposits of hydrocarbons) and local structures, the presence of a significant content of minerals in volume unit, a relatively small depth of occurrence, a small distance from the created infrastructure objects, etc. All of these characteristics for most species and types of mineral raw materials today, unfortunately, turned out to be 'in the past'.

There is a certain contradiction between the significant mineral potential of the country and the growing complexity and heterogeneity of its composition. Resolution for the contradiction is seen not only in strengthening and intensification of geological study and exploration of new conventional fields, but also in the formation of a consistent resource regime that is adequate to the changed conditions.

Ways and directions. The processes of formation and changes of rules, regulations and procedures in the conditions of transformed economy

The solution for this situation is seen in the formation of conditions and environment that would stimulate reduction (firstly pace, and then the absolute values) of costs for the development of these sources of minerals. One of the main factors is other sequence and other time frames for the various phases (steps) of exploration and development of mineral projects.

What are the characteristics of interaction of design process of field development and its actual development in the present conditions? It is obvious that the project is constantly lagging behind reality. At the same time, once and for all the following of approved project leads to a significant deviation from its actual parameters (indexes). This, for example, leads to many misunderstandings and problems in the relations between subsoil users and the government (the shortfall of production or above-standard extractions are not welcomed equally and even punished). Constant revision and reassertion of the project is expensive and in many cases simply unreal. It is no coincidence therefore that leading experts in the field of exploration and development of oil and gas resources have noted that "the development of non-conventional, hard-to-recover oil and gas reserves using traditional methods and technologies is not rational. It is necessary to find and use innovative ideas, methods, technologies...” (Zakirov et al., 2016).

The solution is seen in the formation of flexible procedures for cooperation between the government and subsoil users. For example, there is a need for approval of not detailed project, but conceptual scheme for the object development and design that contains not only hydrocarbons, but also other minerals. Not the approval of reserves, but resource potential assessment – on the basis of ‘best practices’ and based on the interest of the investor in return of their invested funds. In the future with a certain periodicity – its clarification in a dialogue form rather than control over execution of rules of direct action.

Russia needs not only efficient (especially with ecological products) use of mineral resources, but, above all, oriented on the growth of social and economic return on the huge resource potential, which the country possesses. The latter involves the development of high technology and competitive industry for the production of machinery and equipment for the mineral resource sector, as well as the implementation of systemic effects in the processing and use of extracted minerals in the country. The costs at all stages of development of mineral resources and the qualitative characteristics of the equipment produced and manufactured products are of paramount importance.

Resolution for contradictions noted above is seen in the work on the three areas (Donskoy, Kryukov, 2014):

First. There is a need in adequate resource regime of the development of fields and natural objects previously granted for the use. This requires economic incentives, clear and consistent rules and operation procedures. Issues of the reasonable ratio of prescriptive rules and procedures for handling non-standard situations are among the priorities.

Second. There is a need to intensify work on the study, exploration and prospecting (primarily due to the financing of exploration by private sources) in conventional and new areas of production (including the Arctic, Eastern Siberia and the Far East, offshore and inland waters). The tool for this is in targeted economic incentives for geological exploration, reduction of administrative barriers in the provision of subsoil use, development of junior business.

Third. There is a necessity for new adequate resource regime of development of ‘poor’, ‘difficult’, ‘heavy’ deposits – low-margin, hard-to-recover resources (in the case of oil – low permeability and oil recovery).

The difficulty, however, is as follows. The current system of regulation, recorded, for example in the Law of the Russian Federation “On Subsoil”, is good for the development of promising sites and fields at the expense of exploration and survey- assessment work, financed by the government. But it works inefficiently when exploration and evaluation is necessary for: a) conventional fields with a significant depletion of reserves; b) new objects different from the conventional fields.

The first case is fields that are in a long-term development. They are characterized by an increasing localization – fragmented into separate sections of subsoil. This causes the change and redesign of the entire exploration and development system, causing a steady increase in costs. The second case is non-conventional objects (subsoil areas). Both options lead to a faster growth of costs for new or additional knowledge to develop or start development of subsoil areas. As a result, they can become economically inefficient even in the provision of benefits and preferences from among the now possible.

The solution is seen in promoting cost savings during the development of such fields. Scientific and technical progress and the competitive environment in all stages of development and mining provide it. Technological progress does not provide a return without a competition. This is evidenced by the Russian experience of tax privileges and preferences without changing the subsoil use regulation. It provides short-term effect, without creating conditions for increasing the contribution to the total production of new and non-conventional sources of raw materials.

To realize the potential of unconventional hydrocarbon sources there is a need for different configuration of the resource regime – from the property rights for the subsoil to the distribution of potential effects. For the formation of innovation-oriented and competitive environment in this area it is necessary to radically simplify the licensing and technical rules and procedures. It is advisable to issue licenses for the production of hydrocarbons in such areas on the basis of the application of the person concerned, without bidding and collection of a single payment for the use of mineral resources, in the boundaries stated by subsoil user.

Controller functions in this case are to quickly verify that the claimed area is not imposed on the territory of wildlife sanctuary and the defense lands, and is not subject to other restrictions. If everything is in order, a license is promptly issued, substantially free of the obligations related to geological exploration. They are not necessary, since the main geological risks have paid off: the absence/presence of minerals is already defined. The licensing will be given to subsoil areas that are confined not to supposed prospective structures, but to individual areas, sufficient for the implementation of modern technological solutions. The only license obligation is to start trial operation or pilot working out within 4-5 years. If during this time they could not work out the possible exploitation of the technology, the area may be transferred to another interested party.

In this system there is no need to insist on the approval of the reserves prior to their exploration and development, to coordinate design decisions with the government. If we are talking about the development of new technologies and approaches, project solutions agreement process on the basis of prescriptive rules, focused on the development of conventional deposits, is more than an obstacle. The only document required for the subsoil user, can be the project of land construction of the license area (the subject of urban planning expertise of the land part and environmental impact assessment).

The main emphasis is expedient to make to the environmental conditions of the commercial buildings construction (such as the requirements for hydraulic fracturing and horizontal drilling conditions), on the regularity of reports for the carried operations, unification of measurement conditions and reporting. A crucial role in the development of these fields is given to a security of transport and pipeline infrastructure, the presence of contractors with modern technologies and management skills. For new players (‘technological juniors’) it is advisable to ensure access to the refining capacities of vertically integrated oil companies. Otherwise, ‘the innovative oil’ will be processed in a ‘samovar’ way (illegally?). Also, access of innovative companies to sources of debt financing plays an important role.

The participants of the development of new and depleted objects have to include only the national oil companies, but especially small and medium-sized companies with the knowledge, experience and desire to work with such objects. Global fuel and energy complex has been developing dynamically due to a flexible and dynamic balance between the power of giants and flexibility of small and medium-sized innovators (in the countries involved in the active development of non-conventional reserves, more than 60 % of oil production is provided by such companies; ‘shale revolution’ – is largely the result of their active efforts).

Current knowledge and innovations in the mineral resource sector (which ‘set’ its modern trend), as a rule, have a different nature of origin, distribution and commercialization, which significantly differs from the industrial system. Influence of environment affects on the fact that traditional ‘linear model’ of involving all without exception natural resources is replaced by more complex ‘network structure’. Its distinguishing feature is the presence of constant ‘returns’ in the ‘linear model’ to the early stages or, vice versa, ‘running too far’ ahead, bypassing some of the following stages. These circumstances form the different ideas about appropriate temporal sequence of the various stages of the study, exploration and development of objects containing minerals. Based on these representations it is appropriate to consider questions of the relation of prescriptive rules and procedures aimed at finding mutually acceptable solutions in each case.

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Information about author

Valeriy A. Kryukov – DSc in Economics, Professor, Corresponding Member of the Russian Academy of Sciences, Deputy Director for Science, Institute of Economics and Industrial Engineering of the Siberian Branch of the RAS

Russia, 630090, Novosibirsk, Ac. Lavrentiev ave., 17

Phone: +7(383) 330-78-44

E-mail: kryukov@ieie.nsc.ru

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POLYMER FLOODING PROCESS TO INCREASE RECOVERY FACTOR

R. Castro[1], R. Pérez[1], G. Maya[1], H. Quintero[2], R. Jimenez[1], H. García[1], L. Quintero[3]
[1]Ecopetrol S.A. – Colombian Petroleum Institute, Bucaramanga, Santander, Colombia
[2]Universidad Industrial de Santander, Bucaramanga, Santander, Colombia
[3]Ecopetrol S.A. – Enhanced Oil Recovery Management, Bogotá, Cundinamarca, Colombia

This paper describes a methodology, developed at the Instituto Colombiano del Petróleo (Colombian Petroleum Institute) of Ecopetrol, for the theoretical evaluation, project design (screening, geological and engineering analysis, experimental evaluation, numerical simulation and financial analysis), pilot implementation and surveillance of the polymer flooding process which is a commercial Enhanced Oil Recovery (EOR) technology. Its principal objective is to improve reservoir sweep efficiency in mature and recent waterfloods.

The polymer flooding pilot test implemented in the south of Colombia by Ecopetrol includes two injector wells with irregular patterns. Polymer injection started in May 2015. At October 2016, cumulative polymer injection reached 1.5 million barrels distributed between both injectors at a polymer concentration range between 200-1500 ppm and injection rates between 2 000-3 200 BPD per pattern.

Production initial response has been positive with a cumulative incremental that exceeds the 63 000 barrels of oil with reduction of water cuts of up to 10 %. Additionally, polymer production has not been detected in any of the offset producers of pilot injectors. The polymer flooding pilot test have allowed the assimilation of learned lessons, best practices for continual improvement in the operation of such processes, incremental oil production; water cut reduction and increases in the fluid levels for the first row of offset producers. Based on the pilot success, the feasibility of expanding this EOR method in this field is being evaluated.

Keywords: Enhanced oil recovery (EOR), polymer flooding, experimental feasibility, numerical simulation, polymer flooding facilities

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1. Introduction

Use of polymer solutions to improve volumetric sweep efficiency based on a reduction of mobility ratios in waterflooding processes has become a standardized practice in the operation of different oil fields. Mungan, Smith and Thompson (1966) conclude that mobility of polymer solutions is affected by several factors such as the polymer concentration, type and size of molecule, water salinity, pH, capillary properties of the rock and crude oil type. The polymer flooding process is more effective in cases of heterogeneous fields containing moderate-viscosity crude oil. However, Mogollón and Lokhandwala (2013) provided evidences of good results in high-viscosity crude oil reservoirs.

The average recovery factor in Colombia is approximately 19 %, and about 90 % of the oil fields of the country are still producing at their primary stage. About 88 % of production comes from primary recovery, 11 % of secondary recovery and less than 1 % of production come from enhanced oil recovery (Castro et al., 2010). Different enhanced oil recovery pilots have been implemented as alternatives to increase oil production and maximize final recovery in Colombian fields.

This paper discusses the strategy, protocols and methodology used to design, implement and monitoring a polymer flooding project. It presents as an application case the stages of screening, area selection, experimental feasibility, numerical simulation, infrastructure, automation, execution and online monitoring of the polymer flooding pilot project.

In the experimental study, the selection of polymers was based on the following parameters: compatibility and solubility with the formation water, viscosity of the polymer as a function of concentration and shear stress, viscoelasticity (screen factor), filterability and rheological behavior studies. Even though the test protocols used were mainly based on the API RP63 standard (1990), other methods for selection of products (Levitt, Pope, 2008; Seright, Seheult, Talashek, 2008; Sorbie, 1991) were also considered. The technical and experimental evaluation process identified one company to supply and inject the selected polymer.

Execution of the pilot project started in May 2015. The injection facilities (single well type) used have allowed the displacement of more than 1.5 million barrels of polymer solution to the reservoir. Some results of this project are a decrease in water production and an increase in oil production and final expected recovery factor.

2. State of the art

The use of polymers in enhanced oil recovery processes dates back to the beginning of the 60s. Ever since, a high number of field tests have been reported in literature with a higher number of successful cases around the world since the 80s, especially in China, where oil production is significant thanks to CEOR processes (Weiss, Baldwin, 1985; Putz, Lecourtier, Bruckert, 1988; Putz, Rivenq, 1992; Delamaide, Corlay, Wang, 1994; Han, 1999; Du, Guan, 2004; Chang et al., 2006; Li et al., 2009; Wang et al., 2009; Zhang et al., 2016) and recently in projects developed in Canada, Oman, Surinam, Colombia, among others (Manrique et al., 2010; Buciak, Fondevila, Del Pozo, 2013; Standnes, Skjevrak, 2014; Maya et al., 2015 b).

Two types of polymers have been used for field applications: polysaccharides and polyacrylamides, being the partially hydrolyzed polyacrylamide (HPAM) the most widely used polymer in EOR applications (Manrique, Muci, Gurfinkel, 2007). In fresh water, due to charge repulsion of the carboxylic group, the flexible chains of the HPAM structure stretch raising the viscosity of the solution. In contrast, in high salinity water charges are neutralized or covered and the flexible chains of the HPAM structure are compressed resulting in solutions with lower viscosity (Sheng, 2011).

Some researchers concluded that polymer flooding may reduce relative permeability of the aqueous phase (Barreau et al., 1999; Zheng et al., 2000; Grattoni et al., 2004). On other part, Huh and Pope (2008) observed that residual oil saturation is lower after a polymer flooding process than after an analogous waterflooding process.

Interaction of the aforementioned parameters makes the flow of polymer solutions in porous media a very complex process. Additionally, uncertainties associated to reservoir characterization make the design and implementation of a robust polymer flooding project a challenge. A poor design and implementation of a polymer flooding project may even cause a reduction in oil production; thus, authors as Yuan (2009) highlight the importance of a representative numerical simulation before the polymer injection in the field as an essential step to be successful in the design and implementation.

3. Field case implementation and analisys

Implementation of recovery technologies is essential to increase the recovery factor in Colombian oil fields. In order to reach the production and reserve goals of the Company, Ecopetrol started an aggressive plan for implementation of waterflooding combined with the optimization in progress of such fields using conformance technologies and assessment of different EOR technologies as the injection of colloidal dispersion gels, polymers and surfactants (Castro et al., 2010; Castro-García et al., 2013 a; Castro et al., 2013 b; Castro et al., 2014; Maya et al., 2012; Maya et al., 2014; Maya et al, 2015 a; Maya et al., 2015 b; León et al., 2015).

Accordingly, the Instituto Colombiano del Petróleo (Colombian Petroleum Institute, ICP) of Ecopetrol developed an integrated methodology from the preliminary assessment to the field implementation at pilot scale including monitoring strategies of the polymer flooding process with the purpose of providing guidelines for the design, execution and optimization of this enhanced oil recovery process. This section summarizes the methodological analysis of the main stages executed in the pilot project of polymer flooding in Palogrande-Cebú Field, which was developed and implemented following the methodology created at ICP (Maya et al., 2015 b). According to the technical screening, the field characteristics are appropriate to implement polymer and surfactant-polymer flooding technologies as enhanced recovery methods.

Assessment and selection of pilot areas

As initial input, a detailed data gathering and analysis is required to assess the static and dynamic information of the reservoir. The review of every wellbore configuration status and of the injection/production history also represents a critical step to identify, rank and select potential areas for polymer flooding implementation. Basically, an area must have enough recoverable oil, hydraulic connectivity between injection and production wells active flooding patterns and, preferably, the sector must be confined to be selected (Castro et al., 2013 a).

The mobility ratio of Palogrande-Cebú Field during the waterflooding process has an approximate value of 7.5, indicating low efficiency of the secondary recovery process. The oil recovery factor is 27 %.

Selection of the area for the implementation of the polymer flooding pilot project was based mainly on the geological (e.g. stratigraphic correlations, petrophysical properties, determination of permeability variation coefficient, hydraulic connectivity between wells, etc.) and engineering analysis (e.g. historical analysis of injection/production, injection records, fracture pressure, etc.).

According to the methodology, the waterflooding process was reviewed to make technical and conceptual analyses.

Once the sector was chosen as the area with the best conditions to implement the pilot test, a detailed analysis for each well was developed in order to select the most appropriate pattern for polymer flooding. The patterns PG-34 and PG-37 were the best options to evaluate this technology (Figure 1).

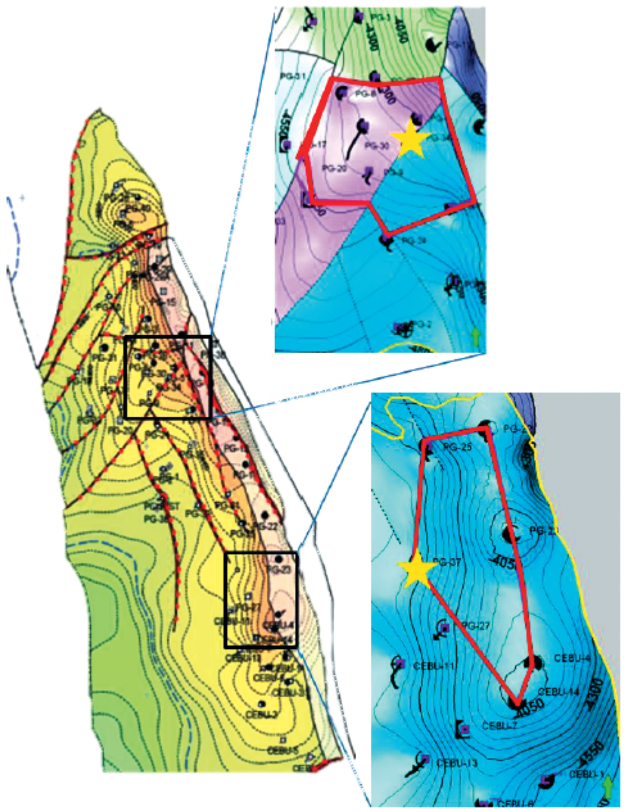

Figure 1. Patterns (PG-34 & PG-37) selected for the polymer flooding pilot project.

Experimental evaluation

The experimental evaluation was developed in accordance with the recommended practices for assessment of polymers used in enhanced oil recovery operations (API RP63). Basically, the behavior of viscosity of polymers at different concentrations and conditions was evaluated; filterability and rheological studies (mechanical degradation tests are conducted considering the wellbore conditions and the surface facilities). Finally, the thermal and chemical degradation are evaluated at reservoir conditions using the preparation water (field and synthetic) of the polymer solution (Figure 2).

Once polymer flooding was identified as the appropriate EOR technology to increase the oil recovery factor in Palogrande-Cebú field, the experimental study was developed to determine compatibility between HPAM polymers type and the reservoir rock / fluids, to estimate the optimal polymer concentration (required to reach the targeted viscosity value) and evaluate the mechanical, thermal and chemical stability of the polymer solution.

Through a market intelligence process, eight companies with experience supplying polymers and operating EOR projects were identified. In total, 13 polymers were evaluated and characterized in order to choose the products that shall have the best performance. Two polymers were discarded because they not were soluble in the water brine. All the polymer solutions evaluated were compatible with the reservoir fluids showing full phases separation and without evidencing emulsions in the aqueous phase.

To this project was decided to use water from the field injection plant an optionally, water from aquifer to prepare the polymer solutions for the pilot test. It is important to highlight that the water coming from the aquifer has very low salinity and hardness, with no content of iron or dissolved oxygen and is compatible with the reservoir rock and its fluids. In the reservoir conditions for all polymer solutions, the target viscosity

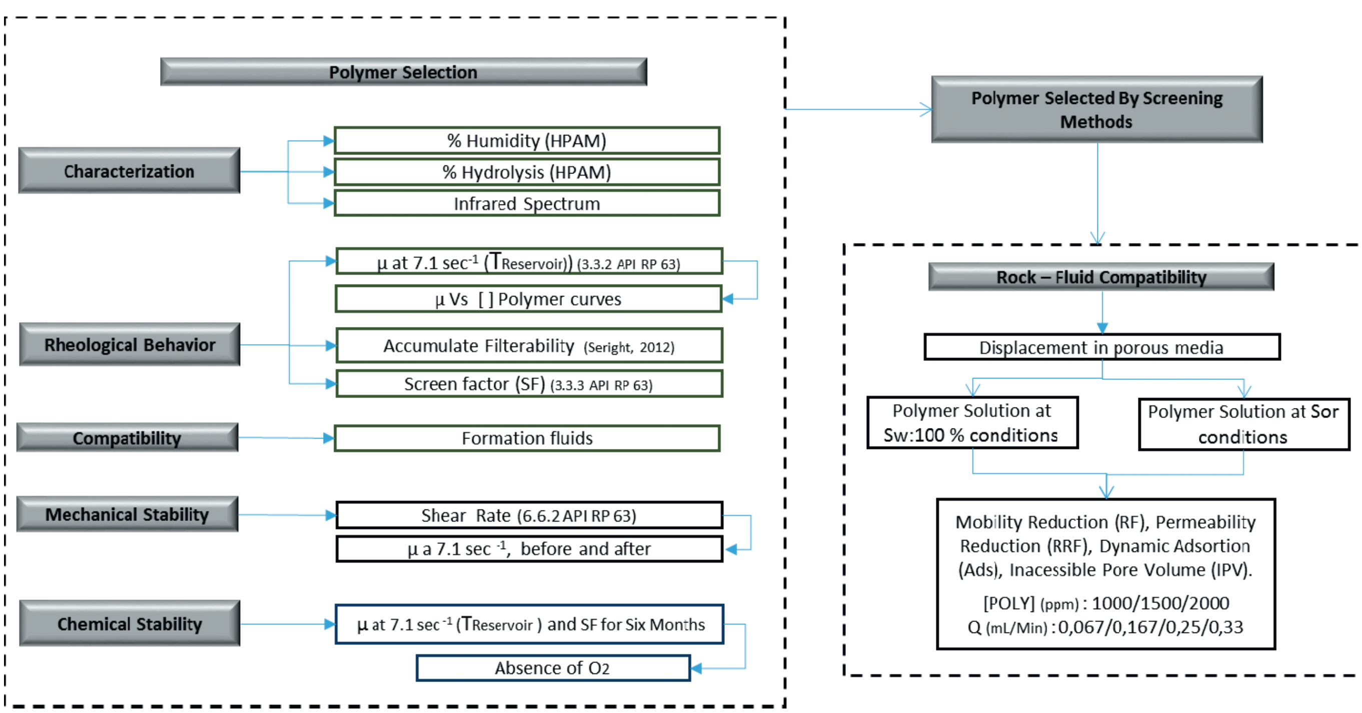

Figure 2. Selection and assessment of API RP63 polymer.

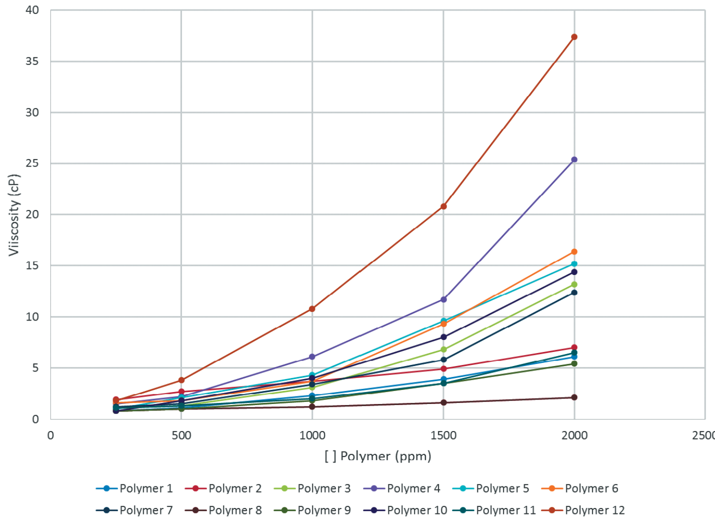

Figure 3. Polymer Viscosity vs. polymer concentration at 7.1 s^{-1} (62°C).

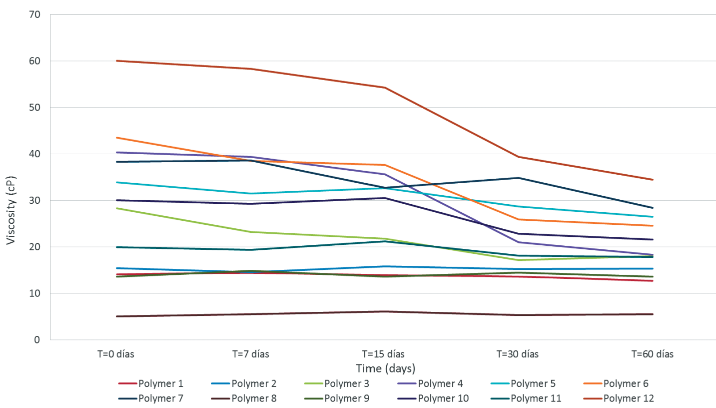

Figure 4. Chemical and Thermal Stability – Viscosity vs. Time at 7.1 s^{-1} (62°C).

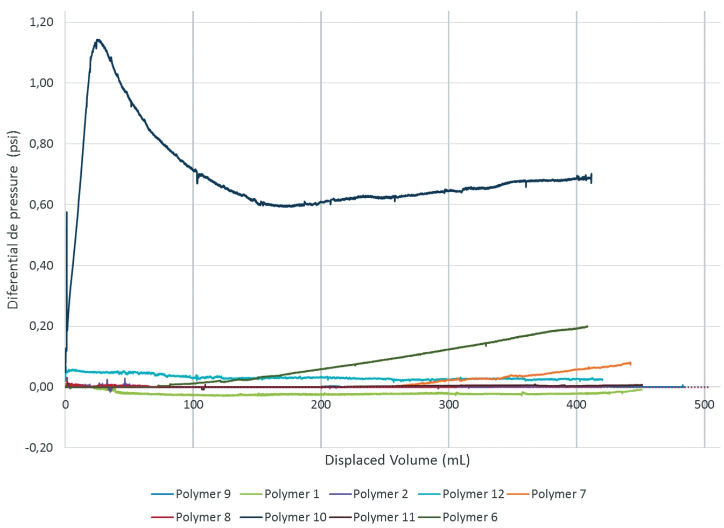

Figure 5. Accumulate filterability for polymer solutions at 1000 mg/L.

was obtained in acceptable concentration ranges (Figure 3). Thermal and chemical degradation tests showed that reservoir and water composition affect significantly (>25 % of loss viscosity) the viscosity of five of polymer solutions evaluated over time (Figure 4).

Additionally, considering the Accumulate filterability test as a very important parameter, one polymer assessed was dismissed since it caused plugging problems (Figure 5). Then, shear rates of up to 50 000 s^{-1} were applied to the polymer solutions in order to assess their mechanical degradation, simulating the potential shear effects caused from the pumps of the injection facilities to the perforations of the injection wells. Under these conditions, most of the polymers showed viscosity losses higher than 30 % (Figure 6).

Finally, based on the results of the viscosity, accumulate filterability and Thermal-Chemical and mechanical stability tests, polymers 8 and 9 approved all of them and were chosen to used in the project. The results were considered to determine the optimal concentration to be used in the polymer flooding pilot. A polymer concentration of 1500 ppm was determined to generate the target viscosity in water reservoir and 700 ppm in aquifer water at reservoir temperature.

Once polymers were properly evaluated at fluid/fluid level, linear displacement tests (coreflooding) were conducted using the selected polymer products in order to evaluate the main rock-fluid interaction parameters. The polymer adsorption was estimated in 39 μg/g of rock under irreducible oil saturation to water (S_{orw}), which is considered a low polymer adsorption.

The inaccessible pore volume (IPV) was estimated approximately in 16 %. This result is within the expected value for this type of polymers of low molecular weight (5-10 million Daltons) and the petrophysical properties of Palogrande-Cebú reservoir rock. The low polymer adsorption and IPV values are promising and suggest that polymer solution shall have a good viscoelastic and flow behavior in the reservoir. Aditionally, mobility reduction (RF) was estimated in 5.9 and permeability reduction (RRF) in 1.3 by coreflooding test injecting polymer solution at 1500 ppm in residual oil saturation conditions.

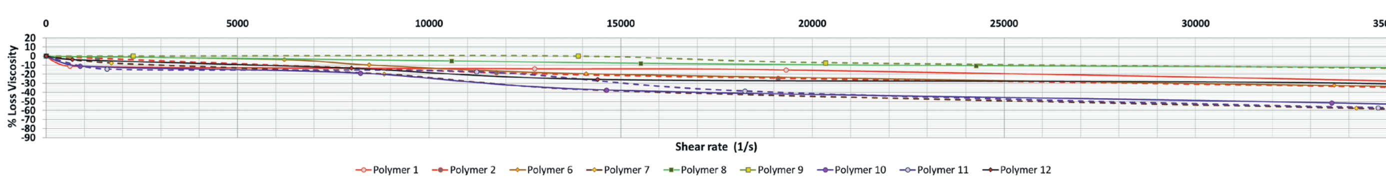

Figure 6. Mechanical degradation for sheer strength in polymers at 1000 ppm concentration (59°C).

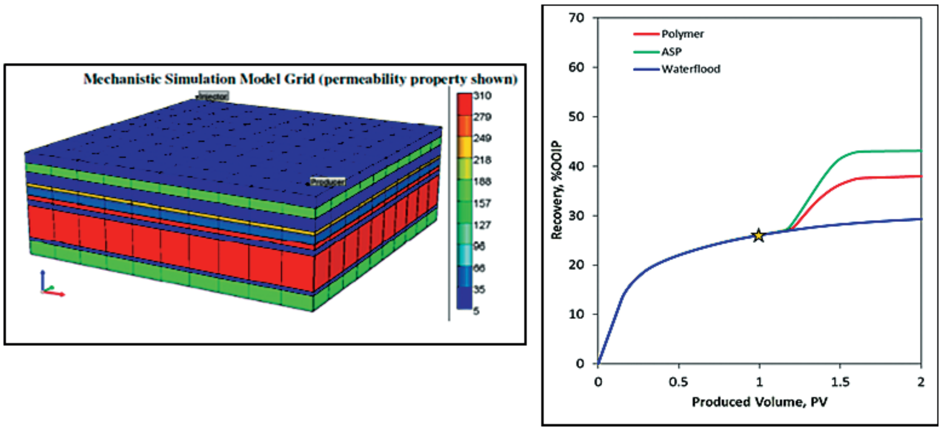

Figure 7. Mechanistic simulation model for Palogrande-Cebu field.

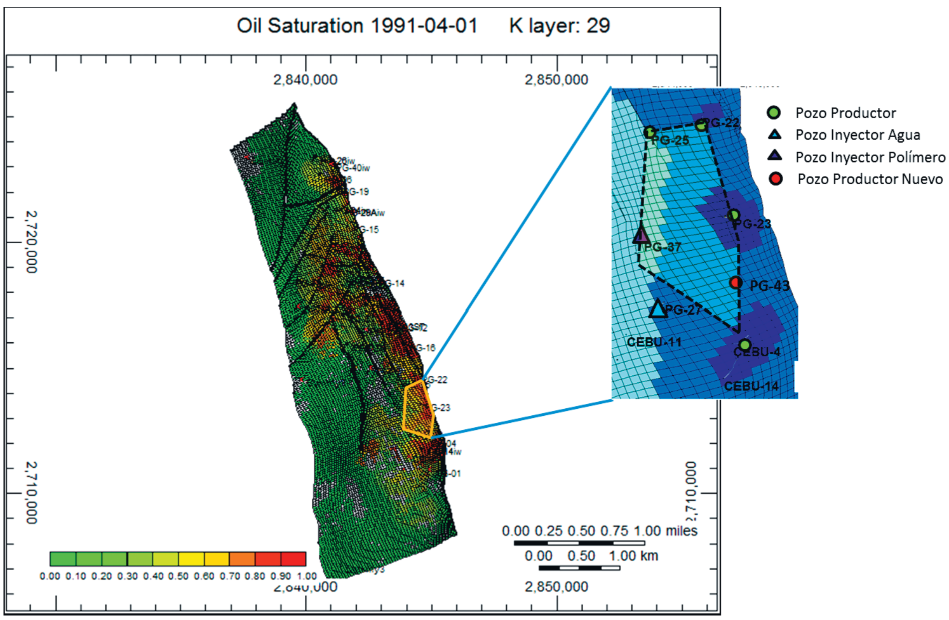

Figure 8. Field Model with pilot pattern PG-34, Palogrande-Cebú Field.

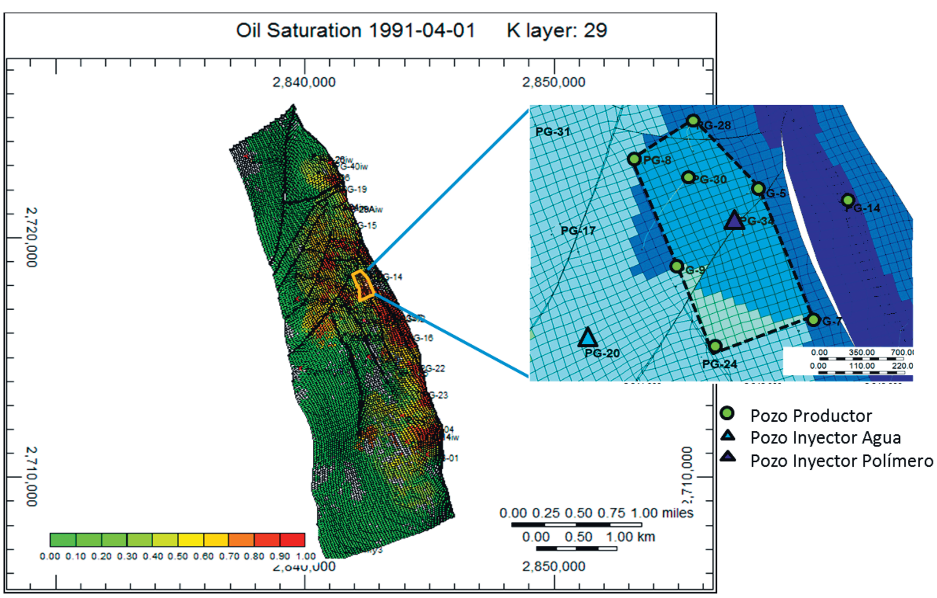

Figure 9. Field Model with pilot pattern PG-37, Palogrande-Cebú Field.

Numerical simulation and process design

Numerical simulation supports the design of the polymer flooding process since it helps to define the percentage of porous volume to be injected, operating conditions of the process, and estimated capacity of the surface facilities and different injection scenarios that may be assessed technically and economically.Numerical simulation is generally developed in commercial software (i.e. CMG STARS®).

Initially the numerical evaluation involves the construction of mechanistic simulation model using fluid (PVT) and reservoir data from the field and history matching. This model were used to evaluate different scenarios of injection from two different chemical EOR process: ASP and PF.

The results shows in terms of oil recovery a good response for both ASP and PF, achieving the oil production an incremental values of recovery between 8 to 20 % of OOIP (Figure 7).

Figure 8 and Figure 9 show the model used for the simulation of polymer injection for both patterns at field level. After history matching of the numerical model, different polymer flooding scenarios were evaluated. This analysis allowed identifying the performance of the pilot project under different injections schemes and operating conditions.

The behavior of the polymer solution is typically represented by four parameters. The first one is the dynamic adsorption, retention and/or trapping and its propagation in the reservoir rock. The second one corresponds to the inaccessible pore volume (IPV) that is important to model the porous fraction of the rock in which the polymer solution would not penetrate. The third one corresponds to the viscosity of the polymer solution and the sheer rates which are directly related to mobility reduction (RF) and the last one is the reduction of permeability in the reservoir after the polymer flooding process (RRF). The experimental evaluation generated key information required as input parameters for the numerical simulation of polymer flooding.

Figure 10 shows the oil recovery factor forecasted in the sector modeled for different injection scenarios of polymer solution in both well patterns (PG-34 and PG-37). The oil production shows an incremental of more than 300 BOPD (blue line) compared to waterflooding (red line) at the same operating conditions.

Based on a cost – benefit ratio, the best scenario identified during the simulation study was injecting a total of 0.2 pore volumes (PV) of polymer solution in each well pattern, using an average injection rate of 2 000 BPD (per pattern) and a polymer concentration of 1500 ppm. For all scenarios, after the injection of 0.2 PV of polymer slug, water injection was forecasted until 2040. Oil production response ranged between 12 and 16 months for the different scenarios evaluated.

Forecasts showed a cumulative incremental production of 480 000 oil barrels (bbls) and 482 000 bbls in offset producer well patterns PG-34 and PG-37, respectively. Additionally, the model also predicts an important decrease on the water cut.

With the purpose of determining the financial feasibility of the project, economic evaluations were performed in order to support the management decision-making process for the polymer flood pilot. Project economics presented positive results suggesting that polymer flooding technology is promising showing representative incremental production with regards the total cost of the pilot project.

The analysis of the simulation results were used to select the best strategy for the execution of the pilot project and to support the polymer flooding and injection facilities design.

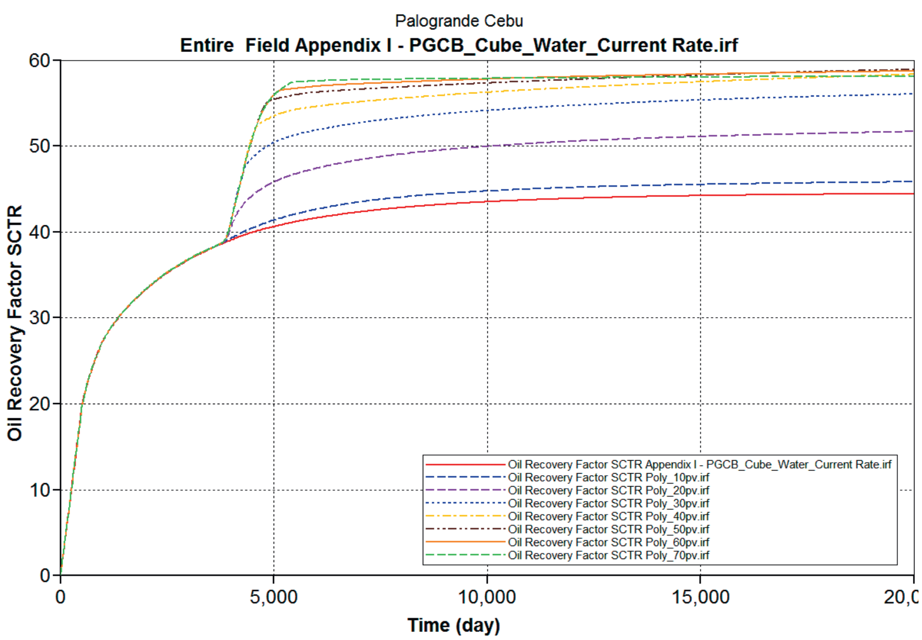

Figure 10. Simulation scenarios for polymer flooding vs. waterflooding.

Injection facilities for the pilot project

The polymer flooding facility usually is designed as a functional unit in a closed cycle of blending, dilution, pumping and final injection in the well with the goal of avoiding undesired losses and leaks in the process, as well as guaranteeing the quality and effectiveness of such process.

Surface facilities include water storage, power system and injection unit equipped with a solid polymer dosing system, blending and tanks for maturing, hydration and activation of the polymer, positive displacement pumps for injection and a nitrogen flow system in the entire unit to displace the oxygen avoiding polymer degradation.

The execution of this polymer flooding pilot project was decided to run two parallel flooding patterns in wells PG-34 and PG-37. For the modular injection unit installation, mechanical, civil, electric works and an area of approximately 2000 m^2 was required (Figure 11).

Figure 11. Polymer flooding pilot facilities in the injection wells.

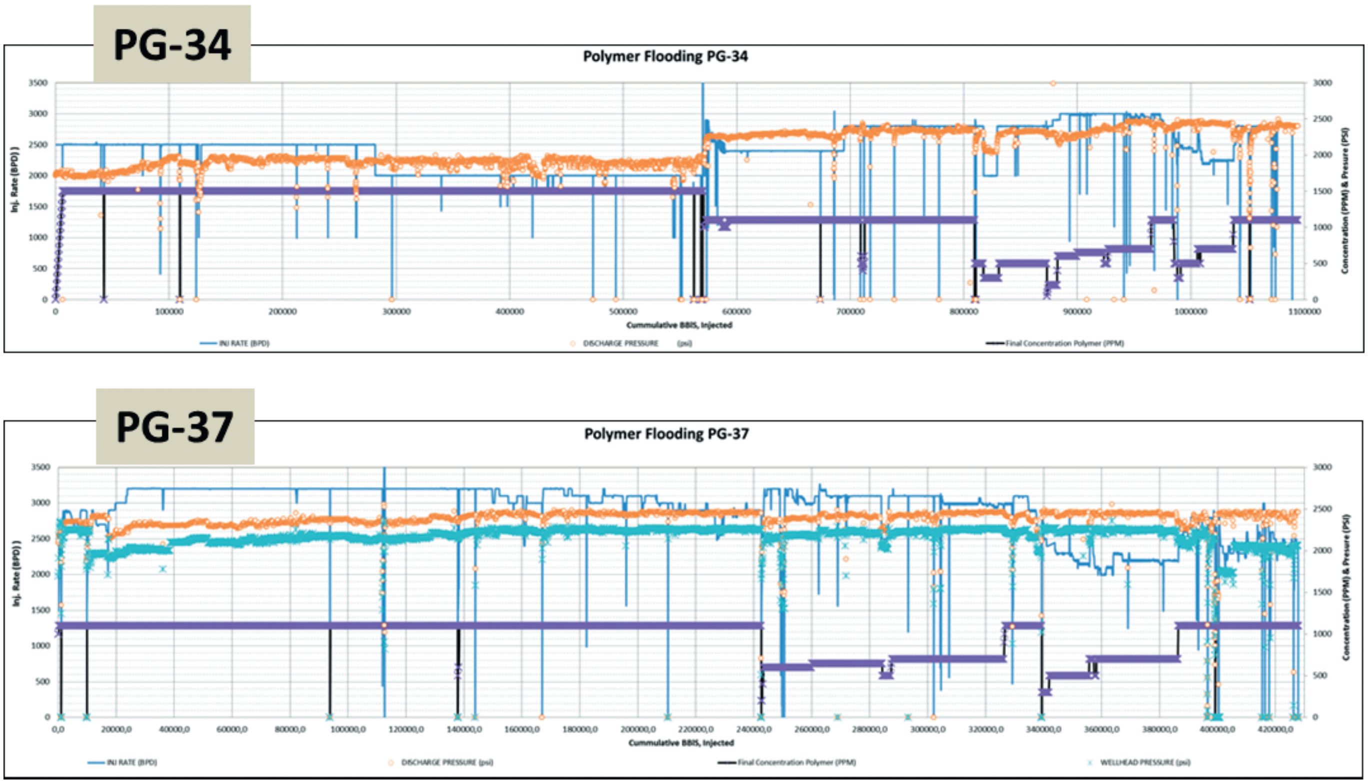

Figure 12. Behavior of flooding of patterns PG-34 and PG-37.

Process execution and monitoring of pilot project

The polymer flooding pilot project started in May 2015 in well PG-34 and nine months later in well PG-37. The main goal of this pilot project is to collect as much information as possible to understand the performance of this polymer flood to validate the technical and economic feasibility of the technology and assess, thus, its potential for a possible expansion to the entire field. As shown in Figure 12, because of different evaluations and operational issues, injection rates and the concentration of polymer were modified along the injection without exceeding the operating pressure limit.

During the execution of the pilot project, a permanent monitoring has been conducted to control polymer concentration and verify that the target viscosity was reached in the reservoir. Daily measurements of viscosity and filterability, and basic tests of injection water quality, as well as monthly tests of basic properties of the polymer lot used (humidity and hydrolysis) were made. Additionally, monitoring of the influenced producer wells in order to evaluate the produced fluids. During the pilot execution, no polymer production has been detected in any of the offset producers of pilot injectors. The fluid level over the pump and the presence of polymer in the produced fluids were continuously monitored.

The incremental oil production response was observed nine months after the beginning of polymer flooding. This production response was faster than the estimated in the numerical simulation studies. Figure 13 shows the historical behavior of oil production in the influenced production wells (green line).

Additionally, Figure 13 shows the base line (red line) and oil production forecasted (blue line) for the injection polymer solution in both well patterns (PG-34 and PG-37). The oil production patently has been improved showed a huge change in the declination slope despite problems faced during the operation (e.g. very often electrical failures, water restrictions volumes, contractual issues). In order to avoid wrong interpretation it is important to explain that the reduction of the production showed after the start up of the pilot is due to some wells were shut-in down for several months, nothing regarding to the polymer flooding.

Until October 31, 2016, cumulative incremental oil production of 63 KBO has been produced. Additionally, the water cut was reduced about 10 % since the injection of polymer began. The estimated cost per incremental barrel of the pilot is between USD 5-8.

After 1.5 million barrels of polymer solution injected in both patterns, it has been possible to increase the recovery factor in the influenced area. It is important to highlight, that during the pilot execution a positive response of the mobility control associated with the polymer injection and no polymer concentrations have been detected in the effluents of the production wells.

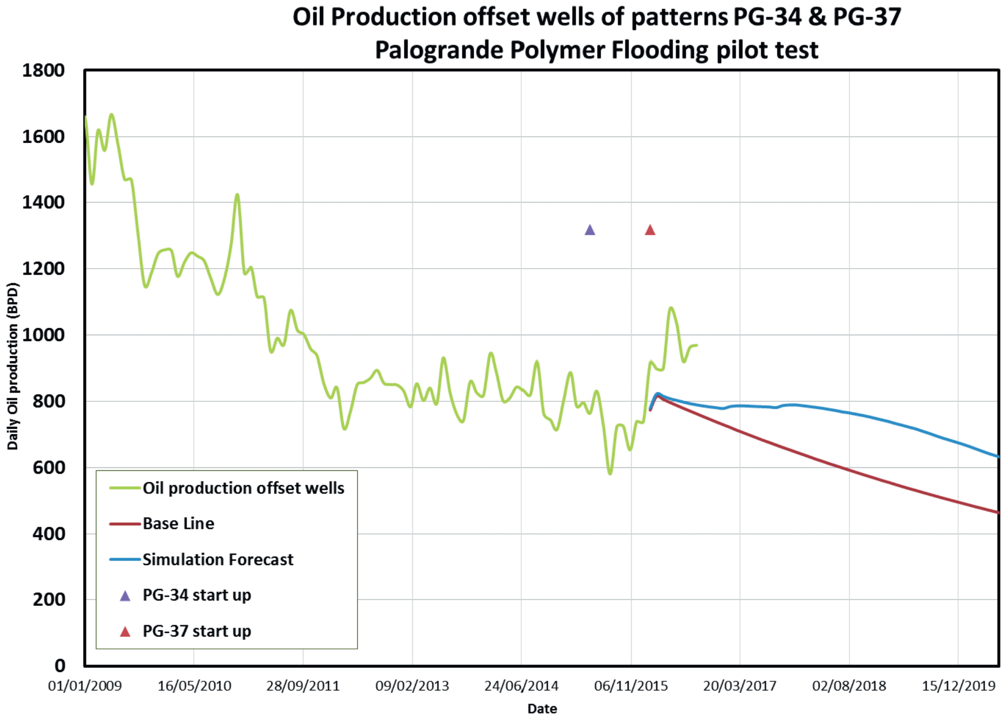

Figure 13. Pilot response of polymer flooding in Palogrande-Cebú Field.

Technical assessment	**Onshore/ offshore**	**Lithology**	**Temp. (°C)**	**Heterogeneity**	**Polymer**	**Formation water TDS (ppm)**	**Polymer injection water quality**
Successful	On.	Sand.	62	YES (DP < 1)	HPAM (5 – 10 MDa)	7 000-10 000	Formation water/ Freshwater
Well spacing (m)	**Polymer injection viscosity (cP)**	**RRF/ RF**	**Oil viscosity (cP)**	***Current*-Cumulative incremental oil (bbls)**	***Final Estimated*-Cumulative incremental oil (bbls)**		
200-300	3.3	1.3/ 5.9	9.4	63 000	962 000		

Table 1. Summary polymer flooding in Palogrande-Cebú Field.

A general description of the polymer flooding pilot in Palogrande-Cebú field is summarized in Table 1. The parameters related are in agreement with review reported by Standnes and Skjevrak (2014).

4. Conclusions

- After 1.5 million barrels of polymer solution injected in wells PG-34 and PG-37 of Palogrande-Cebú Field, an incremental oil production of 63 KBO and a reduction of water cut of up to 10 % have been reported. These results suggest that polymer flood technology represents a technically and economically feasible option to increase the recovery factor in the field.

- The methodology developed by Ecopetrol was successful for the assessment and implementation of the polymer flooding Project in Palogrande-Cebú Field covering the stages of selection of areas, experimental feasibility, reservoir numerical simulation, economic analysis, pilot implementation and monitoring.

- The most common event throughout any pilot project is the response to the continuous changes in operational variables. Manage of electrical failures, injection pressure increases, water quality problems, among others, are key to obtain correct information from the pilot.

- The reported cost per incremental oil barrel of the polymer flood pilot is promising and confirm that the technology could be considered for its expansion in Palogrande.

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Information about authors

Rubén Castro – Petroleum Engineering, MSc, Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847149

E-mail: rubenhe.castro@ecopetrol.com.co

Romel Pérez – Petroleum Engineering, MSc, Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847223

E-mail: romel.perez@ecopetrol.com.co

Gustavo Maya – Petroleum Engineering, MSc, Leading in EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847127

E-mail: gustavo.maya@ecopetrol.com.co

Henderson Quintero – Chemical Engineer, PhD, Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute / Universidad Industrial de Santander

Colombia, Santander, Kilometro 7 vía Piedecuesta
Phone: +57-3133954811
E-mail: henquinp@uis.edu.co

Robinson Jimenez – Petroleum Engineering, MSc, Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta
Phone: +57-76847152
E-mail: robinson.jimenezdi@ecopetrol.com.co

Hugo García – Petroleum Engineering, M. Eng., Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta
Phone: +57-76847392
E-mail: hugo.garcia@ecopetrol.com.co

Lexy Quintero – Chemical Engineering, Leading in EOR Management, Ecopetrol S.A.

Colombia, Cundinamarca, Edificio San Martín Piso 16
Phone: +57-12344000 Ext. 42253
E-mail: lexy.quintero@ecopetrol.com.co

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OIL-DISPLACING SURFACTANT COMPOSITION WITH CONTROLLED VISCOSITY FOR ENHANCED OIL RECOVERY FROM HEAVY OIL DEPOSITS

L.K. Altunina, V.A. Kuvshinov, L.A. Stasyeva, I.V. Kuvshinov, V.V. Kozlov
Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia

Abstract. To improve the efficiency of waterflooding or steam stimulation, enhanced oil recovery and intensification of development a thickened oil-displacing composition NINKA-Z has been created, based on surfactants with controlled viscosity and alkalinity, which is both water-diverting and oil-displacing composition. When exposed to the reservoir with compositions NINKA-Z there is an increase in the final oil recovery by increasing the rate and factor of oil displacement, and sweep efficiency.

The paper gives the results of laboratory studies of thickened oil-displacing composition for enhanced oil recovery from deposits with high temperature and for steam stimulation – solation kinetics, physical-chemical and rheological properties of the composition solutions. The composition has an adjustable viscosity and high oil-displacing ability; it retains, self-regulates in a deposit for a long time complex of colloidal-chemical properties, optimal for oil displacement purposes.

In 2014-2015 pilot tests were successfully conducted of the technology to enhance oil recovery using oil-displacing thickened composition NINKA-Z on the experimental plot of Permian-Carboniferous heavy oil deposit of the Usinsky field that being developed by steam stimulation. Pilot projects have shown high efficiency of the technology, significant effects were received on increasing oil production, reduction of water cut and intensification of development. The technology is environmentally friendly and technologically efficient. The technology is promising for the industrial use in heavy oil deposits.

Keywords: oil-displacing compositions, surfactants, alkaline buffers, urea, hydrolysis, CO_2, kinetics, rheology, viscosity, enhanced oil recovery, physical and chemical technologies, heavy oil, Permian-Carboniferous deposit, Usinsky field, steam stimulation, pilot tests

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Russia is among the top ten countries with the largest oil reserves, on this indicator only being behind countries of the Middle East and Venezuela. The main method of oil fields development in Russia is flooding, with its use about 95 % of oil is produced. Currently, most of the large deposits of Russia are in the late stage of development, the current water cut exceeds 80 %. The newly introduced fields are characterized by low permeability, high viscosity of oil and complex geological structure, i.e. reserves are classified as difficult to recover.

The share of oil reserves difficult to recover in Russia is constantly growing and now exceeds 60 % (including heavy oil – 13 %, low-permeable reservoirs – 36 %) (Yakutseni et al., 2007; Tarasyuk, 2014; Barkov et al., 2015). In these conditions the opportunity of oil reserves increment by increasing oil recovery is of particular importance. The increase of the final oil recovery factor by only 1 % will provide annual increase in production by 20-30 million tons. For effective development of hard recoverable oil reserves, it is necessary to create and widespread use of science-based technologies in oil production, development of new chemicals for implementation of technologies.

Permanent complication of conditions for profitable operation of oil and gas stimulates the emergence of new and improvement of methods used to enhance oil recovery. In the development of methods of enhanced oil recovery, a trend is clear to provide oil-displacing fluid with elements of self-regulation, enabling them to maintain their function in the formation for a long time. The Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences (IPC SB RAS, Tomsk) has implemented one of the options of this trend, based on the ideas of composition for enhanced oil recovery as a physical-chemical system with feedback.

These ideas served as the theoretical basis of physical and chemical principles of compositions selection on the basis of the surfactant considering thermodynamic and kinetic parameters of the system ‘oil – rock – aqueous phase’, affecting the displacement of oil from the porous medium. It was suggested to use alkaline buffering system with a maximum buffering capacity in the range of 9.0-10.5 units of pH to provide negative feedback in the oil-displacing compositions, enabling them to maintain, self-regulate complex of colloidal-chemical properties, optimal for oil displacement (Altunina, Kuvshinov, 2007 a, 2007 b, 2008; Altunina et al., 2019, 2011, 2014).

The choice of alkaline buffer systems is due to the important role of physical and chemical processes with the involvement of hydroxyl ions in the mechanism of oil displacement from capillary-porous media of the reservoir by aqueous surfactant solutions. Such interactions include neutralization of acidic groups, saponification of ester bonds, deprotonation of donor heteroatoms of asphaltene-resin oil components, association of the hydroxyl ions with aromatic fragments of molecules of oil components, influence on the structure of water and thus on hydrophobic binding, conformational mobility of hydrophobic surfactants parts. As a result of these interactions the interfacial tension and interfacial viscosity decrease at the interface of oil – water, rock wettability increases and surfactant losses are reduced due to reduced adsorption onto the rock.

Currently, the effective development of deposits of high-viscosity oils is carried out mainly with the use of thermal effects techniques. Steam is widely used as a coolant. Many researchers continually attempt to find the chemical additives to steam, improving its oil-displacing effect.

Theoretically, such additives should reduce steam condensation temperature, for example, for the mechanism of azeotrope formation or water solubility in compressed gases, should increase phase permeability of the steam-gas mixture and the like. To date, the best additive is carbon dioxide CO_2. The reasons for the favorable effect of CO_2 are well known – increase of phase permeability by oil, oil viscosity reduction, favorable change in the ratio of oil and water phase mobility.

The IPC SB RAS develops the impact on the heavy oil deposit by thermotropic oil-displacing compositions based on surfactants, which in the formation under the temperature of water vapor or hot water form CO_2 and ammonia buffer system. Physical-chemical mechanism of oil-displacing compositions based on surfactant and alkaline buffer solutions, generating CO_2 directly into the formation, is based on the kinetics of urea hydrolysis in the compositions with ammonia and carbon dioxide formation in the temperature range 70-250 °C.

Previously technology has been developed of the stimulation of NINKA® composition on heavy oil deposit based on surfactants, ammonium salts and urea, which are under reservoir temperature or injected coolant form carbon dioxide CO_2 and ammonia buffer system (Altunina, Kuvshinov, 2007 b; Altunina et al., 2003, 2010). Urea directly in the reservoir at a temperature above 70 ° C is hydrolyzed to form ammonia and CO_2. Carbon dioxide, in contrast to ammonia is much more soluble in oil than in water. Therefore, in the system ‘oil – water’ oil phase will be enriched in CO_2, water phase – in ammonia.

When CO_2 dissolved, oil viscosity is reduced 2-6 times (Altunina et al., 2003). Ammonia with ammonium salt forms alkaline buffer system with a maximum capacity in the range of pH 9÷10 optimal for the purposes of oil displacement. Moreover, thanks to the presence of alkalinity and surfactants, it contributes to further oil displacement, interfacial tension and destructuring decrease, thinning of viscous layers or films at the boundaries of oil – water – rock, worsening fluids filtering in the reservoir and reducing completeness of oil extraction (Altunina, Kuvshinov, 2007 b; Altunina et al., 1992; 2010).

In order to increase oil recovery, not only by increasing the oil displacement factor, but also by increasing the sweep efficiency, thickened oil-displacing composition NINKA-Z has been created with adjustable viscosity and alkalinity, which is both water diverting and oil-displacing composition. The composition is the result of research in the concept development of using reservoir energy or injected coolant to generate *in situ* of chemical ‘smart’ systems – compositions based on surfactants and alkaline buffer systems, preserving, self-supporting in the formation set of properties for a long time, optimal for oil displacement purposes (Altunina, Kuvshinov, 2007 b; Altunina et al., 1992; 2010).

NINKA-Z composition can be used to improve the efficiency of waterflooding or steam stimulation, increasing the ultimate oil recovery factor: for enhanced oil recovery from reservoirs with high natural reservoir temperature (above 70 °C), developed by flooding, as well as deposits of heavy oil with natural low reservoir temperature, developed by technology of areal injection of coolant (steam, hot water) and cyclic-steam stimulation for producing wells.

When injecting thickened composition NINKA-Z in the water or steam injection wells, controlled increase in viscosity of the composition occurs directly in the formation. This helps equalizing the mobility of displaced and displacing agents and increasing the sweep impact, reducing the viscosity instability of displacement front, limiting the working injected fluid breakthroughs in reacting production wells, and connection of low-permeability interlayers. Furthermore, there is an additional reduction in the oil viscosity and additional oil washing from washed zones. As a result, there is an increase in sweep efficiency, oil recovery and stimulation of oil production.

To obtain thickened composition NINKA-Z in the composition NINKA® based on surfactants, aluminum salt is additionally introduced, changing the concentration of which it is possible to adjust the composition viscosity. At temperatures above 70 °C resulting in urea hydrolysis directly in the formation pH of the solution increases, hydrolysis of aluminum ions occurs to form aluminum hydroxide (Altunina, Kuvshinov, 2007 b; Altunina et al., 1992; 2003), resulting in increased viscosity of oil-displacing composition after a certain time.

The research has been made to find out the influence of components concentrations of thickened oil-displacing composition NINKA-Z on rheological properties of solutions and sols in particular, the dynamic viscosity (mPa·s). Measuring of solution viscosity was performed by rotation and vibration methods using a vibrating viscometer with tuning-fork sensor "Reokinetika" (Bogoslovskiy, Altunina, 1985). At certain concentrations of aluminum salt, sol is formed directly in the reservoir – mobile free-dispersed system with high oil-displacing properties.

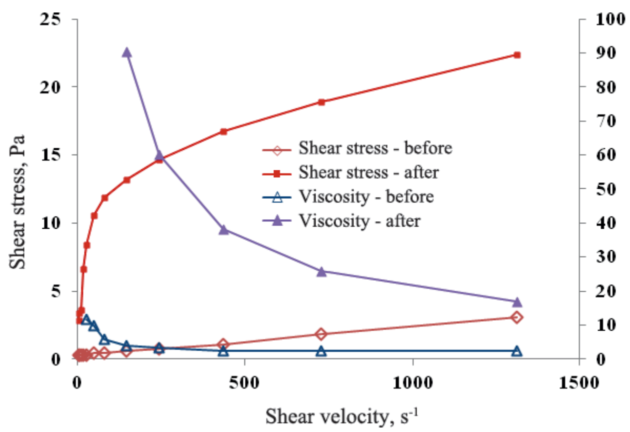


Figure 1. The complete rheological flow curves and the dependence of solution viscosity of sol-forming oil-displacing composition NINKA-Z with adjustable viscosity and alkalinity (2.5 % of aluminum salts) before and after 5 hours of thermal regulation at 150 °C: before thermal regulation composition solution is a Newtonian fluid, after the sol formation- viscoplastic fluid.

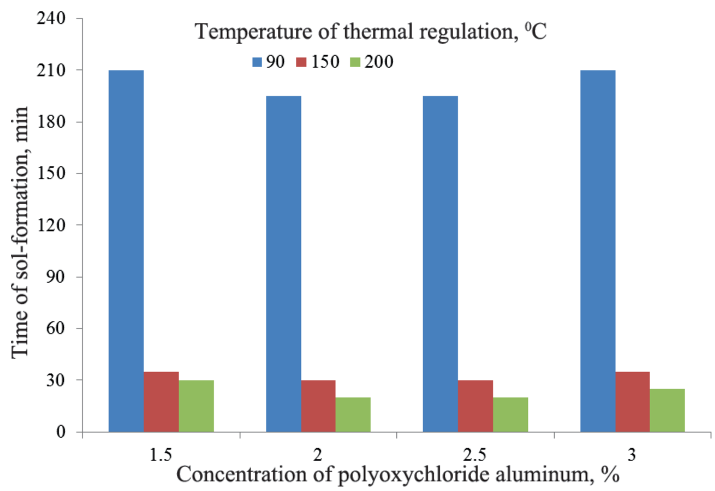


Figure 2. Thickening time (gel or sol formation) of sol-forming oil-displacing composition solutions with controlled viscosity and alkalinity, depending on the content of aluminum salt and thermal regulation temperature.

Figures 1 and 2 show the results of sol generation kinetics in the composition solutions at temperatures of 90, 150 and 200 °C.

Studies of sol formation kinetics and rheological properties of sols and solutions prepared at 90, 150 and 200 °C showed that after thermal regulation of solutions of sol forming oil-displacing composition with controlled viscosity and alkalinity, depending on the concentration of aluminum salt, viscosity of the composition solutions increases by 6-78 times, pH of the composition solutions after thermal regulation increases to 7.7-10.1 units pH.

As an example, Figure 1 shows the study results of rheological properties of the composition solution (concentration of aluminum salt 2.5 %) before and after the formation of a sol by thermal regulation at 150 °C for 5 hours. Measurements were carried out after cooling the solution to 20 °C. As can be seen from the figure, before thermal regulation, composition solution is a Newtonian fluid, after the sol formation – viscoplastic fluid having properties of both solid and liquid, and the ability to show the properties of elastic shape recovery after stress relief (Figure 1).

The time of sol formation in the solution of oil-displacing composition depends on aluminum salt concentration and thermal regulation temperature and ranges from 20-35 minutes at 150 and 200 °C and 3-3.5 hours at 90 °C (Figure 2), that is, by increasing the thermal regulation temperature between 90 and 150, 200 °C, the time of sol formation is reduced 6-9 times.

Research of the rheological properties changes of the Usinsk oil field after thermal regulation with solutions of sol-forming oil-displacing composition with controlled viscosity and alkalinity showed that after heat treatment at 150 °C of heavy oil from the Usinsk field with composition, oil viscosity as compared to the original oil (non-heat treated) is reduced by 2-3 times (Figure 3). Composition solutions have demulsifying action; the amount of water in the oil is reduced 10-220 times.

The developed compositions have the following physical-chemical parameters: pH of solutions – 3.4-4.1 units pH; pH of sols and gels – 7.7-10.1 units pH; viscosity of solutions – 1.6-3.5 MPa·s; viscosity of sols – 9.7-260 mPa·s; solution density – 1161-1178 kg/m^3; gel formation time – from several minutes to several days depending on the temperature and composition of the solution; freezing temperature – minus 20.4 – minus 21.2 °C.

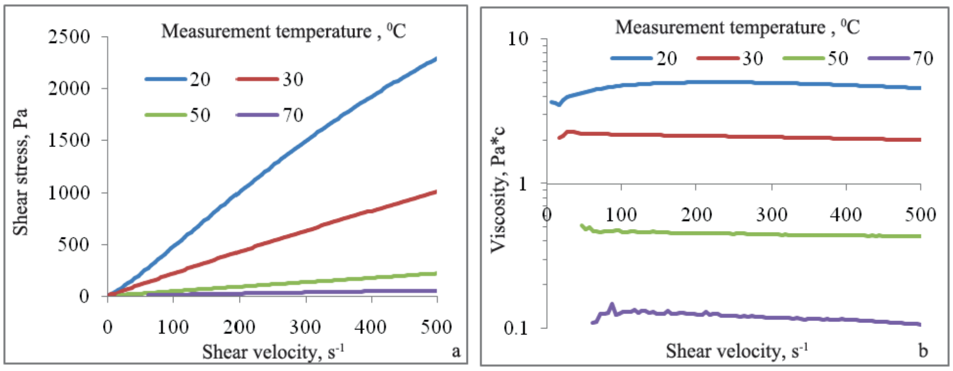
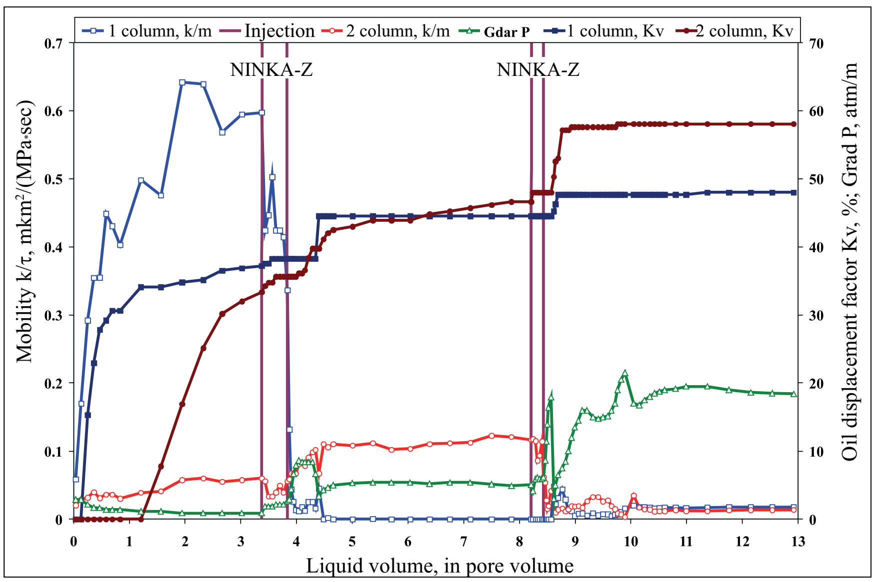


Figure 3. Rheological flow curves (a) and dependences of oil viscosity from Permian-Carboniferous deposit of Usinsk field and shear rate (b) after thermal regulation at 150 °C for 24 hours with solution of sol-forming oil-displacing composition measured at different temperatures.



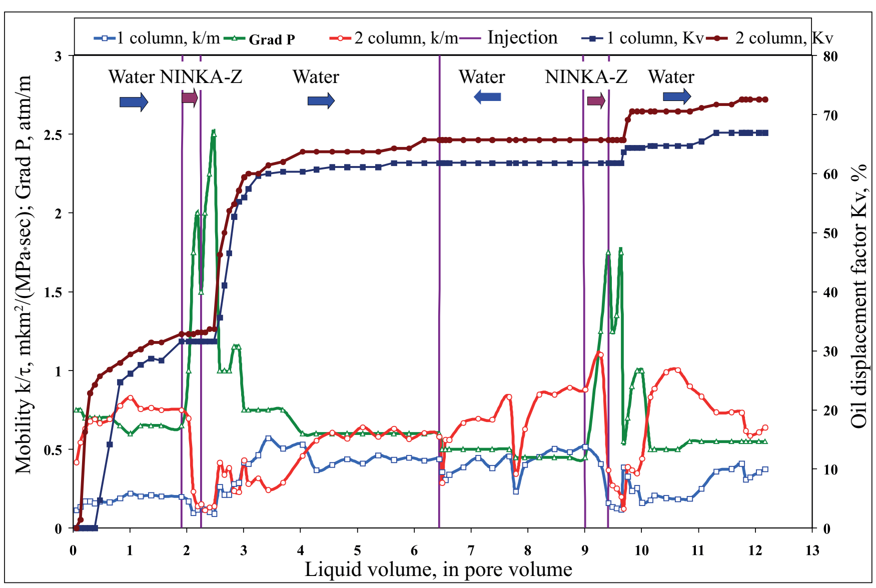


Figure 4. Alignment of filtration flows and additional wash of oil at 150 °C after injection of thickened composition NINKA-Z in heterogeneous oil-saturated reservoir model under conditions simulating steam stimulation on Permian-Carboniferous deposit of the Usinsk field. The initial gas permeability of models: (a) 1 column – 0.730 mm², 2 column – 0.091 mm²; (b) 1 column – 0.374 mm², 2 column – 1.918 mm².

Experimental study of filtration properties and oil-displacing ability of sol-forming compositions with controlled alkalinity and viscosity (thickened composition NINKA-Z) with respect to the conditions of heterogeneous reservoirs in Western Siberia, developed by flooding, and Permian-Carboniferous deposit of heavy oil of Usinsk field, being developed using steam and cyclic steam stimulation, showed their high efficiency.

So, on the basis of experimental studies we have found that the injection of composition with controlled alkalinity and viscosity – thickened composition NINKA-Z with thermal steam and cyclic steam stimulation on the formation with respect to the conditions of Permian-Carboniferous deposit of heavy oil of Usinsk field leads to a redistribution of filtration flows, reduction of filtration rate on highly permeable streaks and increase of the filtration rate on low permeable seams, leveling of fluid mobility in a heterogeneous reservoir model, which is accompanied by an additional oil wash from low-permeability zones, and zones of high permeability reservoir models.

This increases the factor of oil displacement by water in the whole model. Oil displacement factor increment ranges from 5 to 39 %, at the same high absolute oil displacement coefficients and low residual oil saturation are achieved (Figure 4).

On Permian-Carboniferous deposit of heavy oil of the Usinsk field, in the plot PTV-3, developed by cyclic steam and thermal-steam stimulation, according to the technological instruction the testing was conducted of the technology to enhance oil recovery, oil production stimulation and water shut-off using thermotropic sol-forming composition NINKA-Z. The work was carried by LLC "OSK" on the Usinsk field (Figure 5), LLC "LUKOIL-Komi".

Figure 5. Usinsk field on the map of the Komi Republic.

Permian-Carboniferous deposit of the Usinsk field is located in the depth interval 1100-1500 meters. At the initial conditions oil of Permian-Carboniferous deposit is characterized by high values of dynamic viscosity of about 710 mPas, due to the high content of asphalt-resin components. Permian-Carboniferous sediments have extremely inhomogeneous geological structure, reservoirs of complex type: cavern-porous, fractured-porous, fractured- cavern-porous.

Industrial development of the deposit is carried out since 1977. To date, deposit is half drilled by inclined-directional wells. A significant part of the deposit is developed on the natural water drive. In order to reduce the oil viscosity and enhance oil recovery in the steam stimulation zone, since 1992 areal steam injection has been applied and steam-cyclic treatment of wells has been held.

The current state of deposit development is characterized by high water cut at low development of geological oil reserves, which creates prerequisites for the use of various methods of enhanced oil recovery, in particular for the use of chemical compositions.

In 2014-2015 field tests were conducted of enhanced oil recovery technology by using thickened composition NINKA-Z on the experimental plot of steam stimulation (PTV-Southwest) in Permian-Carboniferous deposit of the Usinsk field (Figure 6).

In 2014, 485 tons of composition NINKA-Z was injected into 5 steam injection wells, located on the same plot. In August 2015 further 2 steam injection wells were treated on the same plot. Injection volume was 80-110 m^3 per well. Tracking the effect was carried out by 75 production wells of the plot. The effects of injections in 2015 was analyzed separately for 25 production wells surrounding treated injection wells; this effect is also taken into account in the overall operation dynamics of the plot in 2014-2016.

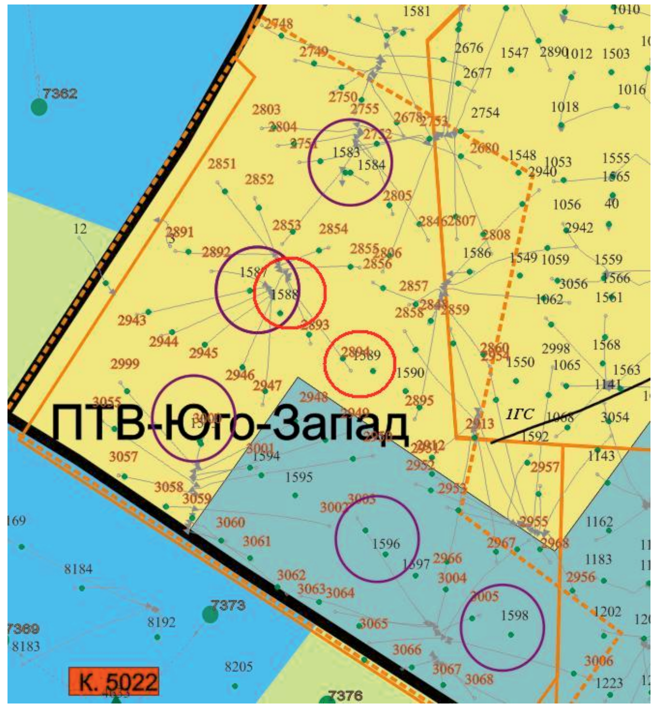


Figure 6. Map of the plot of PTV-Southwest in Permian-Carboniferous deposit of the Usinsk field; purple circles designate steam injection wells, in which the composition NINKA-Z was injected in 2014, red circles – in 2015.

According to the results shown in Figure 7 (according to the monthly operating reports as of August 2015), we can see a steady decline in water cut and increase of oil production after the injection, which is especially noticeable in 3 months after the treatment, due, apparently, to the speed of fluid front movement between injection and production wells. The total effect on the plot, according to different methods of assessment, is 60-80 thousand tons of additional oil production.

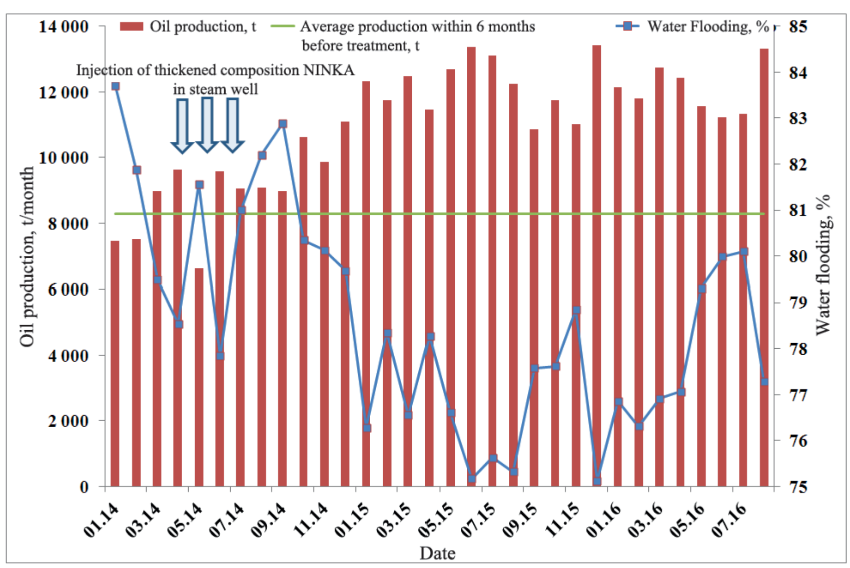


Figure 7. Production rate of oil and fluid before and after injection of NINKA-Z composition at thermal-steam stimulation in 2014-2015 on the experimental plot PTV-Southwest of Permian-Carboniferous deposits of the Usinsk field.

Figure 8 shows a reaction of producing wells on the plot PTV-Southwest on injection of thickened composition NINKA-Z in steam injection wells in 2014: dependence of cumulative oil production from accumulated fluid extraction; divergence of real and predictive curve before and after injection of the composition NINKA-Z, characterizing an additional oil production.

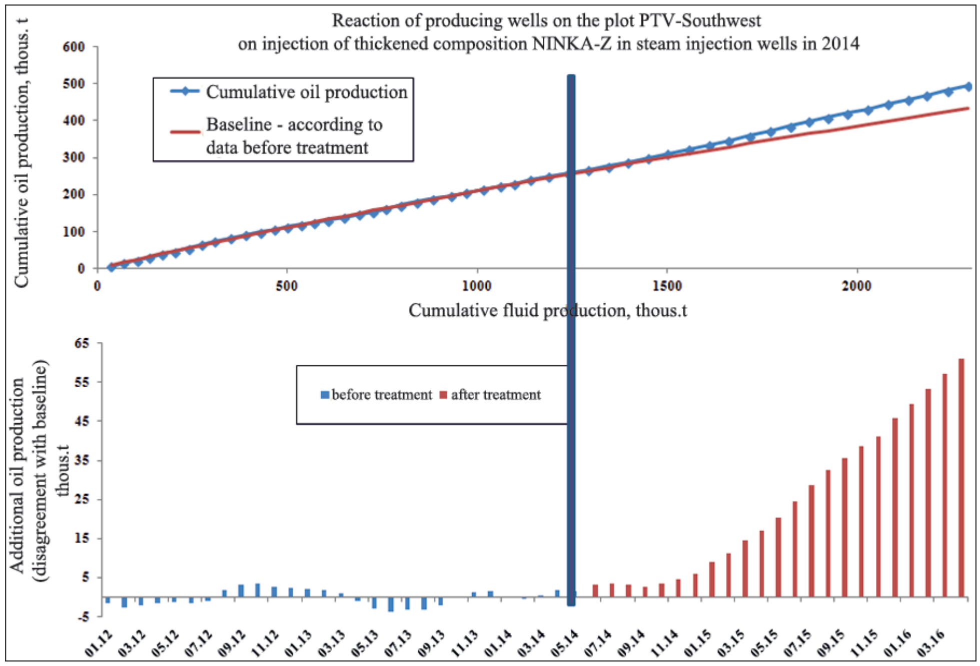


Figure 8. Dependence of cumulative oil production from cumulative fluid production and additional oil production on the plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field after injection of NINKA-Z composition.

Figure 9 shows the operation dynamics of others 25 production wells around the injection wells treated in 2015. The effect for this plot, calculated separately, is 9500 tons of additional crude oil, as of August 2016.

Figures 10-13 show typical responses of production wells on injection of composition NINKA-Z in the injection well. It is evident that the main front of the composition takes place in the drainage area of wells within 2-4 months after the injection. This is also confirmed by the sampling of these wells, which found reagents characteristic to composition NINKA-Z (urea, urea decomposition products and so forth). In these wells the greatest effect is observed on the additional oil produced, as in most hydrodynamically connected with the injection wells and thus fall under the injected composition.

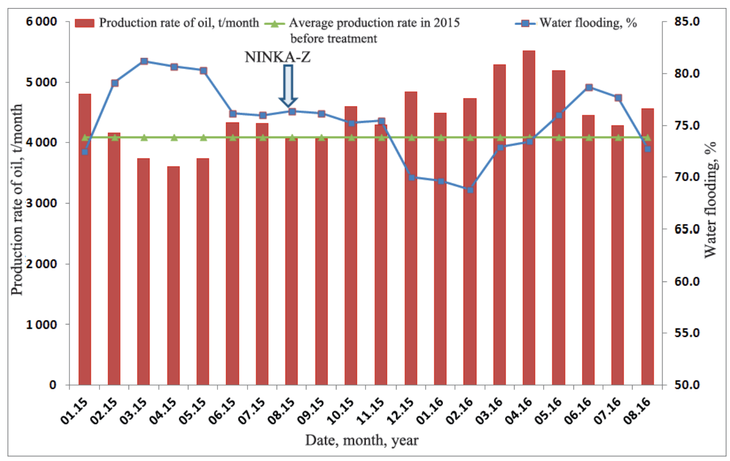


Figure 9. Production rate of oil and fluid before and after the injection of NINKA-Z composition at thermal-steam stimulation in 2015 on the experimental plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field.

In the production well 2949 (Figure 13), we can clearly see the effect of injected NINKA-Z composition both in 2014 and 2015. In this case, the effect of the second injection is more as steam injection wells 1589 is closer to the well 2949.

The results of the studies conducted show the prospects of the use of thickened oil-displacing compositions NINKA-Z with adjustable viscosity and alkalinity for enhanced oil recovery in Permian-Carboniferous deposit of heavy oil of the Usinsk field both by areal steam (hot water) injection, and cyclic steam stimulation.

Thus, thickned oil-displacing composition NINKA-Z with adjustable viscosity and alkalinity, low interfacial tension on the border with oil is both water-diverting and oil-displacing composition and can be used to improve development efficiency by increasing the sweep efficiency and the coefficient of oil displacement; it can be injected into the injection, steam injection and cyclic steam wells.

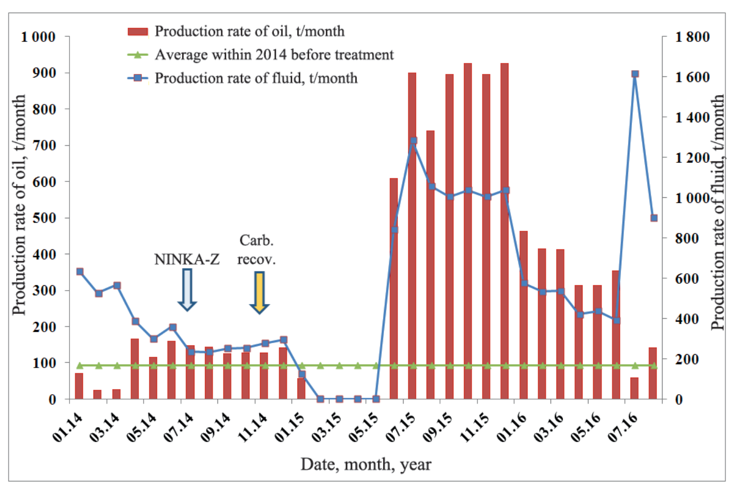


Figure 10. The effect from treatment with composition NINKA-Z in the production well 2946 at experimental plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field.

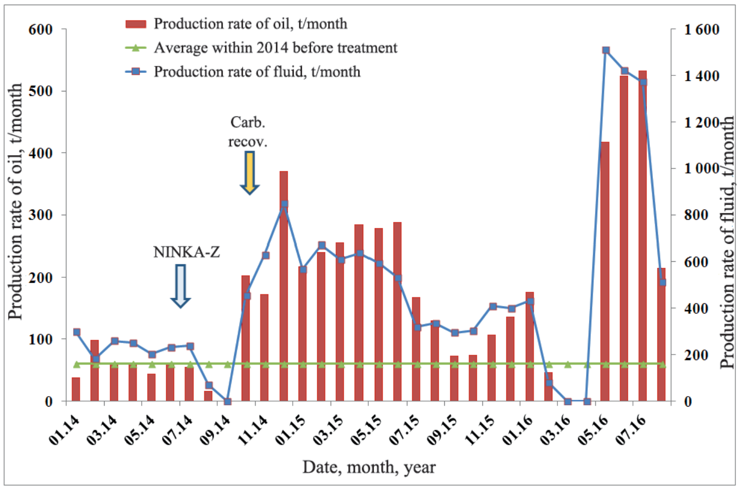


Figure 11. The effect from treatment with composition NINKA-Z in the production well 3059 at experimental plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field.

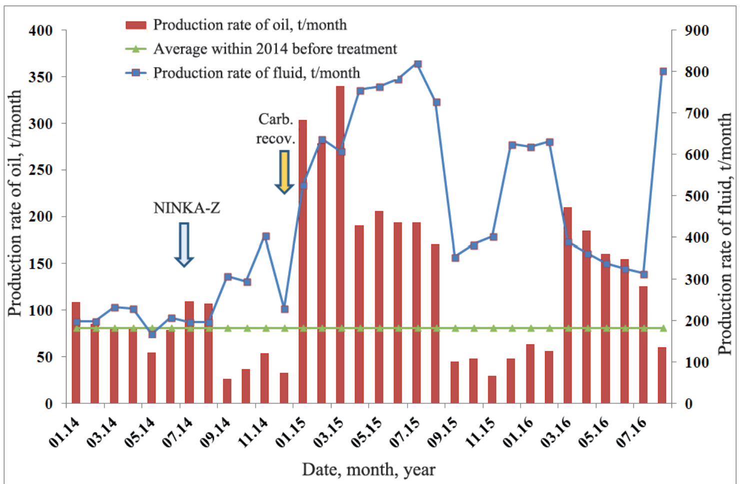


Figure 12. The effect from treatment with composition NINKA-Z in the production well 3066 at experimental plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field.

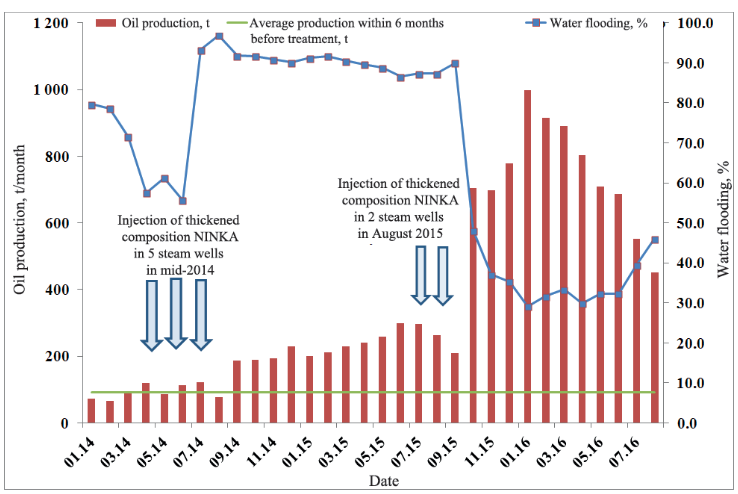


Figure 13. The effect from treatment with composition NINKA-Z in the production well 2949 at experimental plot PTV-Southwest of Permian-Carboniferous deposit of the Usinsk field.

Thickened oil-displacing composition NINKA-Z is a low-viscosity waxy fireproof liquid, making it technologically possible to apply in the winter season. For the preparation and injection of the thickened composition, standard oil field equipment is used in field conditions. Composition NINKA-Z is applicable to both early and late development stages with reserves difficult to recover, including heavy oil deposits.

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Information about authors

Lyubov K. Altunina – Professor, Dsc in Engineering, Head of the Laboratory of Colloidal Oil Chemistry, Director of the Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences

Russia, 634055, Tomsk, Akademicheskiy ave., 4

Phone: +7(3822) 491-623, 491-146

E-mail: alk@ipc.tsc.ru

Vladimir A. Kuvshinov – PhD in Chemistry, Leading Research Scientist, Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences

Russia, 634055, Tomsk, Akademicheskiy ave., 4

Phone: +7(3822) 492-411

E-mail: vak2@ipc.tsc.ru

Lyubov A. Stasyeva – Research Scientist, Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences

Russia, 634055, Tomsk, Akademicheskiy ave., 4

Phone: +7(3822) 492-457

E-mail: lkhn304@ipc.tsc.ru

Ivan V. Kuvshinov – Leading programmer, Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences

Russia, 634055, Tomsk, Akademicheskiy ave., 4

Phone: +7(3822) 492-411

E-mail: kiv@ipc.tsc.ru

Vladimir V. Kozlov – PhD in Chemistry, Research Scientist, Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences

Russia, 634055, Tomsk, Akademicheskiy ave., 4

Phone: +7(3822) 492-457

E-mail: kozlov_vv2004@mail.ru

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ANTICIPATING OPERATIONAL ISSUES FOR THE FIELD PILOT TEST OF AIR INJECTION IN CHICHIMENE

H. García, E. Niz Velásquez, M. Trujillo
Ecopetrol S.A. – Colombian Petroleum Institute, Bucaramanga, Santander, Colombia

Colombia possesses 53 000 MBBL OOIP, from which 36 % corresponds to heavy and extra heavy oil. Out of this, 19 000 MBBL (70 %) are located in reservoirs at depths greater than 6000 ft. This fact makes mature EOR processes such as steam injection very challenging, forcing Ecopetrol to look for other alternatives to improve the recovery factor for this type of reservoirs.

In situ combustion is a technology widely tested through the history of the oil industry. With applications since the early 40th´s, there have been very successful projects around the world such as Suplacu de Barcau in Romania and Balol and Santhal in India with recovery factors above 50 %; however several failures have been reported due to both reservoir conformance and operational malpractices.

Chichimene in situ combustion pilot is the first attempt for Ecopetrol to incorporate this technology that could be applied to at least 80 % of its heavy oil assets. It is important in every stage of the process to determine the possible operational issues that may come with the technology in order to establish the procedures and strategies to either avoid or mitigate the impact that these factors may have in the success of the test. Through analogy analysis as well as experimental tests run in the laboratory, a risk characterization and analysis was carried out and the most critical problems were identified for our specific case.

The Colombian Petroleum Institute of Ecopetrol then established four lines of research, one for each of the issues with high probability of impacting the Chichimene pilot: (1) Materials integrity for both bottom hole and surface equipment due to corrosion; (2) Characterization, preparation and treatment of emulsions from the in situ combustion process; (3) Temperature impact on sand consolidation; (4) Analysis of injectivity and connectivity through the target formation.

Keywords: in situ combustion, heavy oil, operational issues, emulsions, corrosion, sand consolidation, injectivity, connectivity

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Introduction

In situ combustion (ISC) is a process that consists on injecting air into the formation to generate a combustion front by a series of chemical reactions, where the heaviest hydrocarbons fractions are burned as combustible. These reactions are considered exothermic, which by means of increasing temperature, decrease oil viscosity, increasing the mobility of the crude, resulting in improved production and access to more reserves, representing an interesting option for the heavy oil reserves in Colombia.

The Chichimene field is located in the southwestern edge of the Llanos Basin, in Colombia, south of the town of Villavicencio, in Meta department (Figure 1). This field was discovered in 1969 and started its production in 1985. The current field production is close to 80 000 bpd with an Estimated Ultimate Recovery (EUR) by primary means of nearly 9 %. The formation of interest in this study produces heavy oil of 8° API from the Tertiary unit (San Fernando formation – T2). The field structure is associated with an elongated and asymmetric anticlinal, faulted on the eastern flank in direction N60E approximately. The in situ combustion pilot is located towards the structure's crest and exhibits low dip values (2° approximately) (Gómez, 2013).

The ignition is scheduled to occur at the end of 2016. Although ISC has not been applied before to extra-heavy oil reservoirs at such depths (8 000 to 9 000 ft), the high reservoir temperature (200 °F) is favorable for spontaneous ignition, and sufficient oil mobility enables the application of the process.

Other large reservoirs bearing a significant fraction of the Colombian oil resource exhibit characteristics similar to Chichimene.

This shows the potential for the expansion of ISC in Colombia, and eventually in other countries, as the technology boundaries are pushed further away than its current applicability limits.

Ecopetrol has partnered with renowned companies, universities and consultants with relevant experience in ISC. Currently, a state-of-the-art ISC laboratory operates at the Colombian Petroleum Institute, and capabilities for numerical modelling of the process have been developed.

The Chichimene in situ combustion pilot

The ISC pilot at the Chichimene field is made up of a single injector well (CH-174), two observer wells (CH-172 and CH-173), and three first-line producer wells (CH-95, CH-96 and CH-97). The first line wells are located at an approximate distance of 120 m from the injector well, forming an area of approximately 10 acres. Additionally, a second row of producers (the wells closest to the first line wells) are going to be included in the monitoring strategy with the objective of evaluating the influence of the process on these wells. Schematics of the geometrical distribution of the pilot wells are shown in Figure 2.

The sedimentary sequence of T2 stratigraphic unit, presents a high degree of lateral continuity in the pilot area. From the operational view point, this unit is subdivided into eight subunits, which are easily identifiable in the area due to the high correlation degree resulting from this type of sedimentary environments (Figure 3).

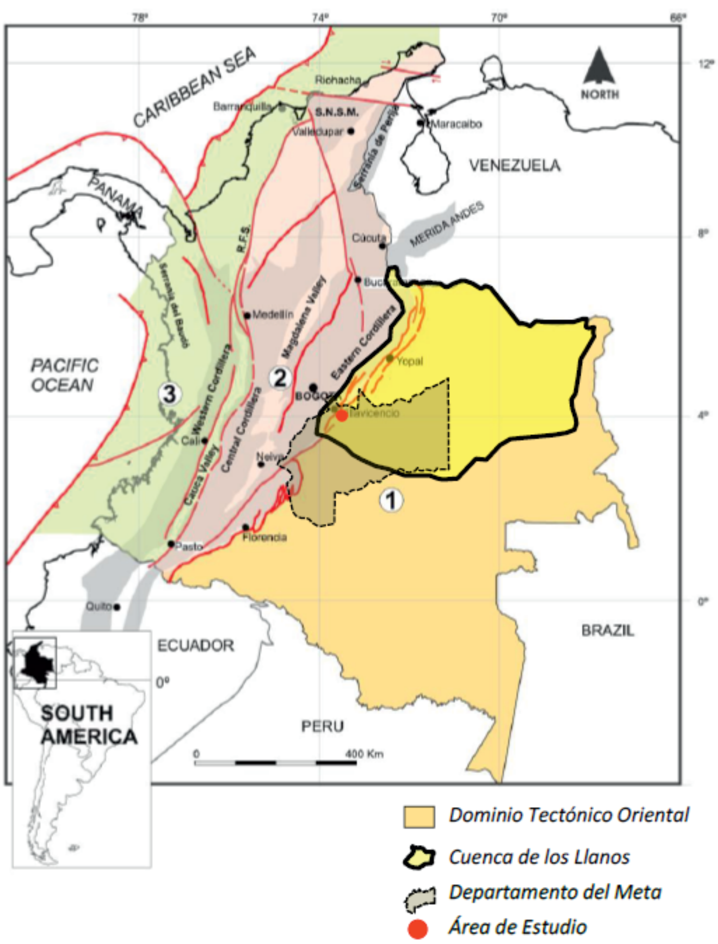

Figure 1. Chichimene field location map.

One of the closest second-line wells is producer CH-22. A fault separates the pilot area with the block where CH-22 is located and a structural jump of 140 ft compartmentalized the pool. However, there is sand-to-sand contact between the T2_40 unit at the injector block with the T2_60 unit at the CH-22 block, which suggests that the fault is not sealing (Figure 4).

It was assessed that two years would be sufficient to evaluate the performance of the ISC process. Numerical predictions yield incremental recovery close to 35 % OIIP. Ongoing activities of the pilot project include detailed laboratory studies and ignition predictions for preparedness.

Analisis of the most common operational issues in in situ combustion projects

Throughout the world many in situ combustion projects have been implemented in time, and most recently, due to the advancements in material integrity capabilities and the chemical characterization behind, the process is becoming a more attractive technology for heavy oils.

Table 1 presents the most common operational issues for in situ combustion projects reported in literature (Arias, Rodriguez, 2013).

After revising around 38 projects carried out from 1958 until 2013 (Arias, Rodriguez, 2014), it was found that the most impacting operational problems for in situ combustion are:

1. Incrustations: there are three facts associated with the air injection process that can lead to the appearance of incrustations (Crabtree et al., 1999):

- Incompatible mixtures between water injection and water reservoir when a wet process is implemented.
- The auto sedimentation by changes of temperature and pressure experienced by the reservoir fluid during

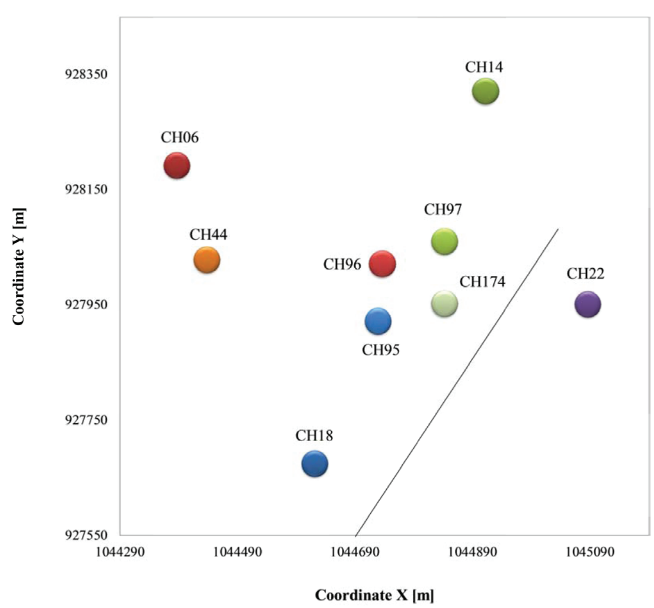

Figure 2. Schematics of the geometrical distribution of the pilot wells.

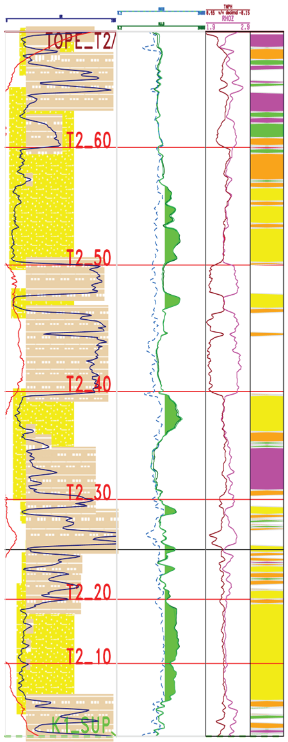

Figure 3. Sub-units of T2 formation.

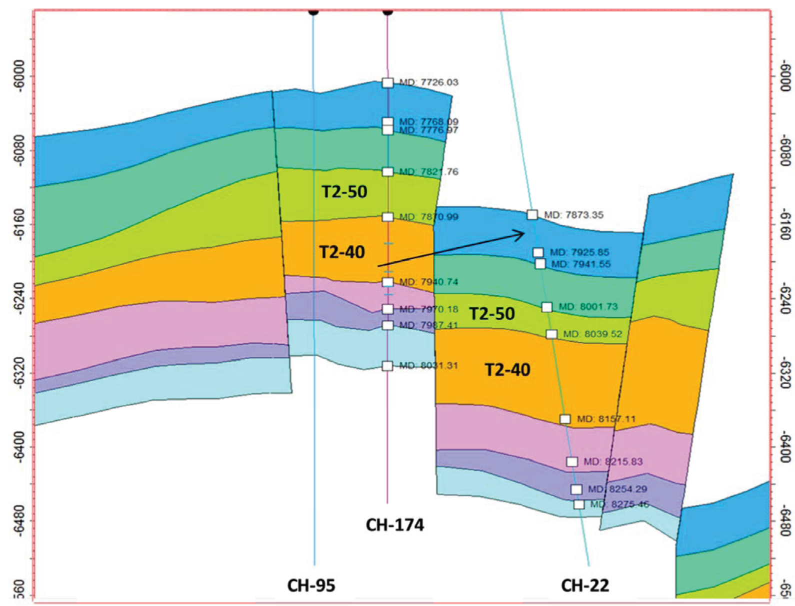

Figure 4. Fault between wells CH-174 and CH-22.

production, which modifies its composition such that the solubility limit of a certain mineral is exceeded and this precipitated as mineral encrustation.

- Release of combustion gases (CO_2): Water containing CO_2 becomes acidic and dissolves calcite found in the formation. Subsequent pressure drops that occur in the wellbore producer may cause the CO to be separated from the solution and precipitate carbonate residues, which causes additional pressure drop and therefore more precipitates leading to a decrease in well productivity.

2. Asphaltene precipitation: during the implementation of air injection processes, pressure, temperature and crude oil composition changes occur, which may cause asphaltene precipitation that can affect the porosity and permeability of the reservoir (Creek et al., 2007).

3. Sand production: can be expected at any stage during a production well life and happens mainly due to a mechanical failure associated to the resistance and the effective effort applied to the formation. It is a very common phenomenon on unconsolidated shallow sands. However, high temperatures experienced in the reservoir during thermal recovery methods can cause formation matrix cement loss, generating sand movements within the reservoir and sometimes to the well, causing serious blockage and compromising productivity. During in situ combustion implementation this issue can arise due to the following factors:

- Temperature increasing, which weakens the cement material of the matrix, causing resistance loss and then sand movement. Additionally, temperature rise may cause casing detachment and collapse.

- Flux rate increase causes fluids dragging and then more solids would move towards the production well (Gonzalez, 2005).

Excessive solids production can generate restriction in the fluid production rate and equipment may need replacement due to erosion.

4. Emulsions: generally speaking they are most likely found in presence of an emulsifier agent and enough energy for the emulsion to form. They can be found in any process during crude extraction. In presence of sand or corrosion the problem tends to worsen. For the case of the in situ combustion process, formed emulsions are very stable water-in-oil ones (Pineda, 2009). Factors influencing emulsions formation during in situ combustion are:

- Low temperature oxidation reactions, present during early combustion front formation. These reactions add components to the crude superficial activity that encourages the formation of emulsions. Crude oxidation decreases interfacial tension which contributes to the emulsions' stabilization (Mourits, Coulombe 1989).

- CO_2 formed during combustion can cause crude resines and asphaltenes colloids precipitation.

- Corrosion products such as Iron sulphides encourage emulsions stabilization.

- Condensed steam ahead of the combustion front present either in the formation or production facilities can be stabilized by micronic and submicronic drops from the emulsifier agents.

- Turbulent flux energy increase and the gas freed from the fluids in the reservoir can create emulsions as well, which are stabilized by the emulsifier agents created during combustion.

Problemas / Campos	Incrustations	Paraffins and / or asphaltenes	Sand production	Low injectivity	H2S and CO2	Emulsions	Corrosion
Balaria						x	
Balol			x	x	x		
Bellevue			x			x	x
Brea Olinda Ca				x			
Carlyle						x	
Countess	x			x			x
Esperson						x	x
Fosterton Northwest, Sask				x			
Hospah						x	x
Kyrock						x	
Lloydminster			x				
May Libby, La				x		x	x
Mene Grande			x				
Midway Sunset, Ca			x	x			x
North Tisdale	x			x		x	x
North Ward estes					x		x
Pauls Valley			x		x	x	x
Robinson Fry, Il						x	x
Schoonebeek, The Netherlands		x		x			x
Sloss, Ne						x	x
South Hospah						x	x
Suplacu de Barcau				x			
West Heidelberg							x
West Texas				x			

Table 1. Most common operational issues for in situ combustion projects.

5. Low injectivity and connectivity: due to the presence of organic and inorganic deposits. It is directly related to permeability and porosity, and inversely proportional to fluids viscosity present in the porous media. During the coke formation in the combustion process, porous media can be blocked, changing the preferential path to the production wells. Other problems such as sand production and emulsions can influence on the injectivity and connectivity of the system.

6. Mechanical failures: due to the high temperatures at which the cement is subjected during the process, it suffers loss of strength and changes as empty spaces between the formation and the cement are generated, which in turn allows free movement of casing and it can cause pipe buckling or collapse. Similarly, thermal processes can have several effects on both the casing and production pipe, such as buckling, erosion, stress, corrosion and melting.

7. Corrosion: generated by high temperatures in the bottomhole, oxygen in the producer well due to channelling or incomplete combustion, CO_2 and H_2S dissolved in water, wet air injection, products of some oxidation reactions, among others.

8. Channelling presented mainly by the presence of areas with greater permeability leading to early air irruption in the producer wells and therefore to a decrease of process areal sweep efficiency.

9. Compressors explosion and damage due to high temperatures, high vibration and excessive noise which creates unfavourable conditions for the system. Generally, the causes of these failures are the long operational life of the equipment and lack of maintenance.

Risk analisis and operational issues characterization for in situ combustion in Chichimene field

Using probabilistic methodologies, the operational issues were analysed in order to determine their impact and the chances of occurrence in order to focus resources on researching for mitigation and solution of the most threatening ones for the Chichimene pilot.

A qualitative risk analysis was carried out in order to first identify the most common issues reported in in situ combustion projects with similar characteristics to Chichimene field, second to evaluate their impact, and finally to estimate these issues' occurrence. The impact was evaluated taking into account process efficiency, production time loss, production volume loss, non-environmentally friendly substance release and economy. Figure 5 shows the qualitative analysis.

As seen in the figure the most critical operational issues were corrosion, emulsions, low injectivity-connectivity followed by sand production and H_2S and CO_2 production.

Following the risk analysis, a cause-effect analysis was performed in order to determine the relationship among the parameters influencing the main operational issues. In this way it is possible not only to graphically understand the most important parameters and issues but also to stablish solutions and mitigation strategies that can treat several issues as the cause is evident and it may be the source of more than one issue. Figure 6 presents an integrated cause-effect diagram for the analysed issues.

According to the perform analysis and the comparison between Chichimene field parameters and the parameters revised from the other in situ combustion projects, it is concluded that corrosion is the most critical issue that the in situ combustion pilot in Chichimene may face, as out of the operational ranges compared in the risk and the cause-effect analysis, 85 % of the parameters that contribute to this issue are present in the Chichimene case. For example, formation temperature for Chichimene is around 185°F and the temperature range for fields experiencing corrosion is between 65 and 221°F. The following issues were: corrosion, emulsions, sand production and injectivity – connectivity inferred the highest percentage compare to the other projects having these issues.

Ecopetrol stablished then four lines of research in order to characterize analyze, and stablish mitigation and control strategies for these four specific issues. However the monitoring and control strategy for the in situ combustion pilot includes all the possible issues observed in previous projects and the ones expected through the laboratory and simulation analyses performed throughout the project implementation.

The research were focused on these main topics: (1) Materials integrity for both bottom hole and surface equipment due to corrosion; (2) Characterization, preparation and treatment of emulsion from the in situ combustion process; (3) Temperature impact on sand consolidation; (4) Analysis of injectivity and connectivity through the T2 formation.

1. Analysis and selection of suitable alloy materials for the in situ combustion process

The first step in the feasibility analysis for in situ combustion implementation is the set of laboratory tests: RTO (Ramped Temperature Oxidation), ARC (Accelerating Rate Calorimeter) and Combustion Tube Test. These experiments were carried out with reservoir crude oil and rock. For the analysis, brine was synthetically prepared in the laboratory trying to match the chemical composition of the brine from Chichimene T2 formation field

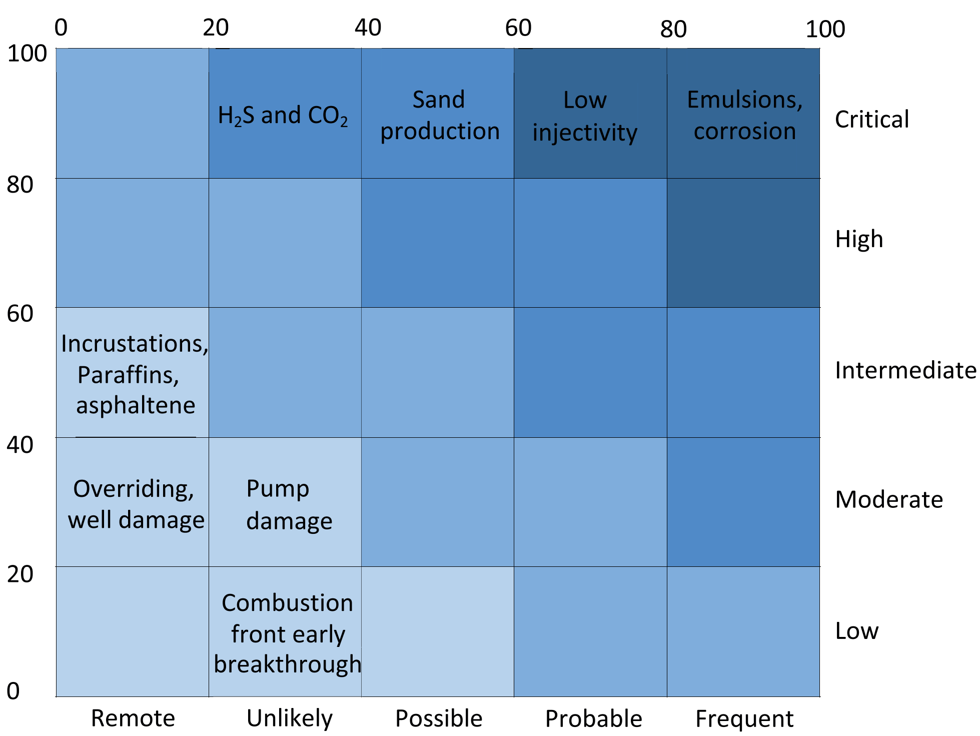

Figure 5. Qualitative analysis. Source: Arias, Rodriguez, 2013.

Each of these tests provides information regarding rock-fluids reactivity, kinetic of the oxidation reactions, and finally the percentage of each product detected during the process. The chemistry of the reactions includes CO_2, CO and H_2S production as well as the Oxygen introduced during the process. With these data an experimental design and the materials selection process was established.

In 1985 R. Zawierucha studied the behavior of several materials used for the in situ combustion process, indicating that the materials selection for this type of technology must be supported by laboratory and field tests taking into consideration the following:

1. Lab scale tube test immersion of several alloys over a wide temperature range and aggressive environment composition.
2. Electrochemical analysis.
3. Field tube test immersion with bottom hole coupons of different alloys for both production and injection wells.

The corrosion phenomena in oil fields are generally associated to the presence of CO_2 and H_2S, however diluted oxygen is another agent rarely found at reservoir conditions but common for reservoirs undergoing water or air injection such as in situ combustion. Affectation for H_2S is hard to predict because the iron sulfide (FeS) produced by corrosion is normally insoluble at regular pH, and can form a film that protects the material. In presence of carbon dioxide (CO_2) the pH experiences a decrease and then the iron sulfide becomes more soluble. Oxygen in presence of H_2S and CO_2 accelerate the corrosion process.

Historically, the in situ combustion projects found in the literature show a common characteristic: they all possess well infrastructure designed with conventional materials with P110 and N80 steels. Materials with better behavior include special alloys with high cost such as Incoloy, Inconel and Hastelloy, which can reach negligible corrosion values of an order of 0.025 mm/yr (1 mpy); however from an economic feasibility point of view it can become non profitable for the project development specially when it comes to a pilot level as Chichimiene. Some other alternatives include Chromium alloys that offer bigger resistance to several corrosive environments, especially the ones with Chromium content greater than 12 %.

Chichimene in situ combustion pilot presents conditions of 0.6 % of H_2S (6 000 ppm) and 15 % CO_2 molar concentration (150 000 ppm), that added to the depth, API gravity and temperature must be considered critical and particular for the project, making it hard to be referenced with previous in situ combustion projects in the world. These conditions represent a wide uncertainty for the definition of the suitable materials for casing and tubing, as well as the piping and equipment for the surface treatment facilities.

Bottom hole materials selection

Based on the operational and fluid composition conditions taken into account for the reservoir simulation, and the lab results of the combustion tube tests, simulation parameters were established for simulating the mechanical properties and the corrosion

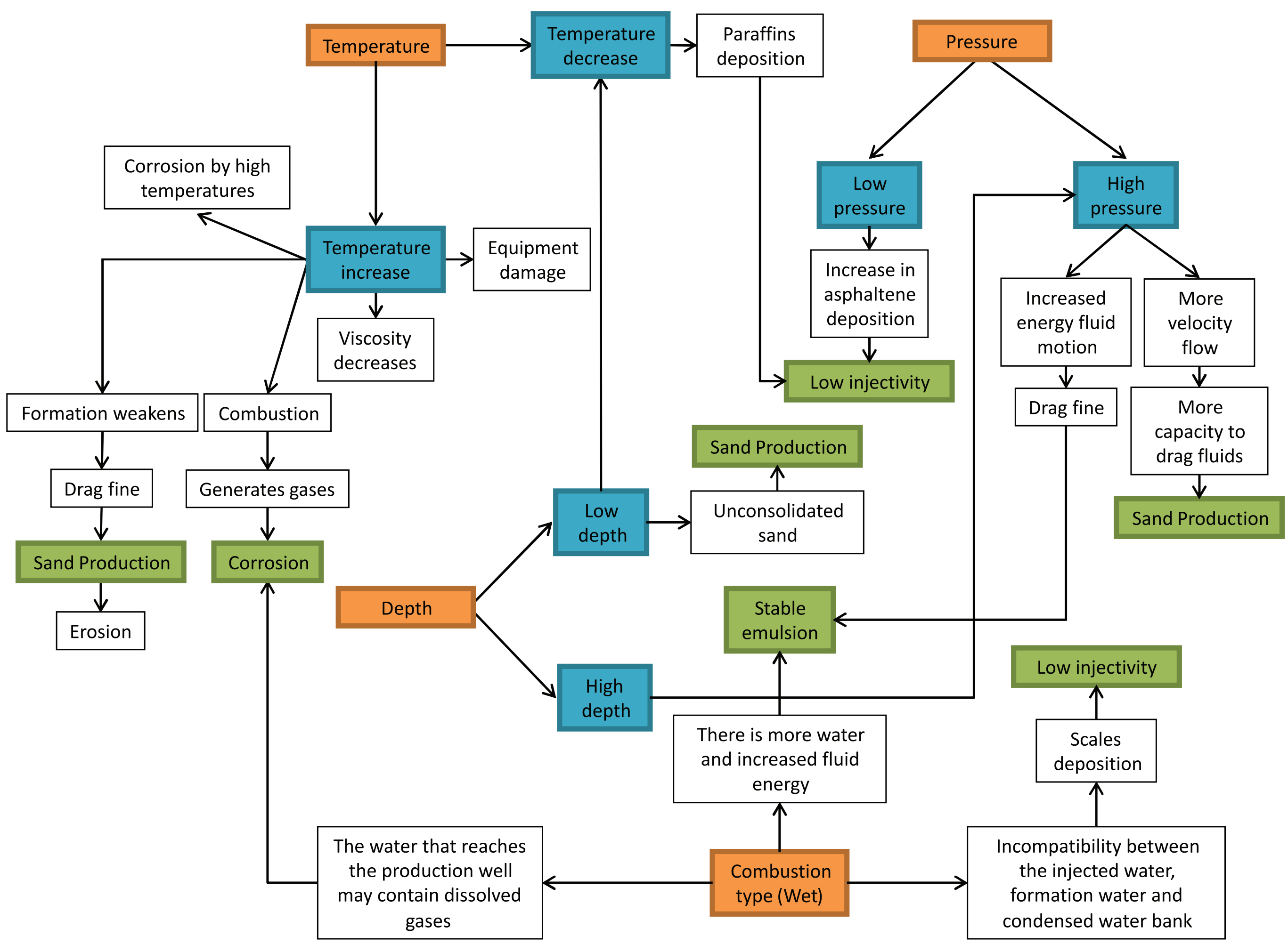

Figure 6. Integrated cause-effect diagram. Source: Arias, Rodriguez, 2013.

resistance of alternative materials for these conditions such as chromium alloys (13 % Cr), low alloy carbon steel, corrosion resistant alloy nickel based, and sour service steel. This simulation analysis was technical supported by Tenaris Tamsa of Mexico, through their software Osprey and Matsel, suitable for mechanical and corrosion conditions analysis respectively.

The mechanical parameters analysis allows one to determine that the common materials used for this purpose such as N80, P110 and Q125, including the ones with Chromium alloy are suitable to be implemented for the in situ combustion process.

The corrosion resistance analysis however, showed a bigger restriction in the usage of all the alternatives. The most critical condition observed through the corrosion resistance analysis is definitely the H_2S concentration due to the high susceptibility of its presence as SSC (Sulfate stress cracking) mechanical damage. Additionally, the analysis showed low CO_2 corrosion velocity values, probably as a consequence of the API gravity. The heavy oils with low gravity considerably minimize CO_2 corrosion as the corrosion products themselves ($FeCO_3$ and FeS) act as protection barriers.

Based on the operations parameters analysis, the literature review and the simulation analysis, where the most critical operation parameters was determined to be H_2S content, it was possible to establish the usage of materials manufactured to work in acid environments (sour services), which could perform more efficiently.

With these results, the integrated analysis was focused on verifying the materials suitability under mechanical resistance properties. In order to confirm the viability of using these type of materials with lower tension resistance, a more extensive mechanical properties analysis was performed. Several simulation analyses were run using higher safety factors compared to the industry standards. As a result, steel alloys with special manufacture for higher impurities control levels (99.9 % impurities free), is the most suitable for the process in Chichimene when it comes to bottom hole casing and tubing, as they offer a better performance for sour service based on the following aspects:

- Prevention in advance of any corrosion attack by SSC.
- Low chance of CO_2 corrosion attack, as the low API of the crude minimizes its effect on the materials.
- Usage of high safety factor for the design to ensure integrity of the well in case of any casing or tubing slimming.

Surface facilities material selection

The big challenge when it comes to surface equipment is the materials integrity preservation of static equipment given the critical conditions due to strongly-acid environments handling, which result on interior and exterior corrosion threats.

Interior corrosion refers to corrosion phenomenon that occurs inside the piping or structure, where there is an interaction between the material and its environment resulting on a material degradation. Corrosion under efforts and strongly-acid environments such as H_2S presence is known as a damage mechanism of assisted cracking typically found on highly resistant steels, only under certain effort conditions. SCC involves effort application, perpendicularly applied under partial pressure of H_2S higher than 0.34 KPa (0.05 psia). This damage mechanism results from the atomic hydrogen adsorption generated in the cathodic area by the sulfur corrosion acting over the surface material.

Exterior corrosion refers to the phenomenon that causes physical degradation or cracking due to the material surface interaction with external environment (air/soil). It can happen as a uniform material loss, or as a localized or isolated material loss or environmentally assisted cracking.

Based on this corrosion phenomenon, a simulation work is carried out, and through laboratory test each of the threats is analyzed under the operational parameters established during the design stage. These evaluation results allow establishing the materials susceptibility and their classification in the severe, high, moderate or low corrosion range according to the criteria included in the practicum standard NACE SP0775.

Corrosion threat by mechanical efforts from H_2S environments is one of the most critical ones for materials in a in situ combustion project, and it is important to take into account NACE MR0175 and API 57 norms in order to determine material susceptibility to SSC. In relation to the exterior corrosion, it must be monitored mainly for the buried infrastructure. For this purpose is necessary to estimate environmental parameters such as conductivity, humidity, texture, pH, sulfates, carbonates, acid number, resistivity and determination of sulfate / thiosulfate reducing bacteria.

Corrosion mitigation and management strategy

Having the threats and their impacts characterized, it is important to determine the actions to be taken in order to avoid materials inconvenient that could jeopardize the in situ combustion test success. First of all these analysis must be carried out prior the design stage, as it is important to design at required specifications to handled corrosive environments. Further actions include control and mitigation alternatives for the infrastructure, both bottomhole and surface facilities for each of the found threats:

1. Interior corrosion: materials selection, chemical treatment injection, corrosion monitoring (coupons,

tube test, water, crude and gas physicochemical analysis).

2. Corrosion under H_2S environment efforts (SS): materials selection, chemical treatment injection, SSC monitoring (including coupons, water, crude and gas physicochemical analysis).

3. Exterior corrosion: coating, cathodic protection systems.

Additionally it is important to perform a risk based inspection (RBI) for both wells and surface facilities with the objective of understand, identify and control risks associated to the pipes and equipment operations in order to optimize resources on infrastructure maintenance. For the surface facilities, the RBI is based on the initial design, simulation and operational parameters concept and criteria, from where the damage mechanisms are identified. For the bottomhole equipment the RBI is based on the operational conditions simulated, the mechanical design concept and criteria, that allow to identify and value the risk level as well as the most critical failures for the mechanical integrity of wells.

2. Characterization, preparation and treatment of emulsions from the in situ combustion process

Tight water-in-oil emulsions have been observed in field applications of the in situ combustion process. Crude oxidation at low temperatures (LTO mode: Low-Temperature Oxidation) results in an increased concentration of emulsifiers in the oleic phase (Turta et al., 2005). In this line of research, a strategy for dealing with this potential issue was set, and is described as follows:

1. Chichimene crude oil samples are subject to oxidation in a continuous flow reactor at conditions representative of the LTO region.

2. Synthetic emulsions are produced by mixing the oxidized crude oil with formation water at high energy.

3. The synthetic emulsions are characterized by describing their reological properties, Z-potential, abundance of functional groups (by mass spectrometry techniques) and water droplet size distribution.

4. Field samples (emulsions) are taken in an analogue field subject to in situ combustion, and characterized as described in the previous step.

5. The synthetic and field emulsions are compared and common compounds and physical properties are identified.

6. Combined treatment methodologies are proposed and tested in the laboratory, including dilution, chemical additives, heating and electrostatic means, for both synthetic and field emulsions.

The optimal temperature and flow conditions in the continuous flow reactor that led to stable water-in-oil emulsions were identified to be consistent with the LTO ranges. The characterization efforts evidenced chemical and physical similarities between the two types of emulsions. The treatment tests allowed identifying viable options for breaking the emulsions using the existing surface facilities.

3. Experimental study of temperature impact on sand consolidation for the in situ combustion process

Sand production during thermal recovery processes is a very common problem due to the high temperature in the reservoirs that affect the cements matrix and the mineralogical composition, as well as high flux velocity that encourage particules migration towards the production wells.

With the purpose of determining in advance the effect of these parameters in the in situ combustion implementation for Chichimene, geomechanical, mineralogic and morphologic analyses were carried out. These analyses focused on evaluating the sand consolidation response to mechanical efforts produced by the high temperature released by the oxidation reactions during the in situ combustion process. For the analysis several rock samples were exposed to several thermal treatments simulating the in situ combustion operational parameters to be observed during the pilot operation.

The developed methodology included sample interval selection point according to lithotype's identification, petrophysical analysis, morphological and mineralogical characterization through CMS (Confining Measurement System), SEM (Scanning Electronic Microscopy) and XRD (X Ray Diffraction), granulometric distribution and unconfined compression. The purpose of these analyses is the following parameters determination: Young module, poisson relationship, internal friction angle, mineralogical and morphological composition, porosity, permeability and rock grain density.

From these analyses it was evident the necessity of further experimental tests increasing the exposition time to temperature treatment in order to reply reservoir conditions under temperature exposition for long periods like it happens during combustion front advance. The punctual temperature exposition used for this first experimental attempt produced incoherent results between basic petrophysical analyses and the other techniques. However the results from the other tests showed encouraging results: mineralogical and morphological changes, low organic material loss, minor porosity changes in the combustion front surrounding area, stable Young module (changes under 5 %) and not significant Poisson relation changes (less than 10 %). These results indicate a moderate affectation to sand consolidation but in the combustion front area. The flux velocity is not big enough to drag fines all the way to the production wells.

Another important aspect from the analysis is the seal rock evaluation. The analysis showed a resistance increasing with temperature for the seal rock type 1. Seal rock type 2 didn´t show variation through XRD analysis, however it logged a shale content decrease after heating treatment with no impact in the T2 sand consolidation and process isolation within the target zone.

4. Analysis of injectivity and connectivity through the T2 formation

A short water injection test was carried out in injector well CH-174 soon after its completion, corroborating the order-of-magnitude estimate based on the petrophysical and geometrical properties of the well and formation. According to these figures, the design gas injection rates would be injected without producing pressure gradients that would in any case affect the operating ranges of the injection-production system.

The nitrogen connectivity test (NCT) was designed to have an approximate duration of three weeks. The aim of the test was twofold: 1) To determine the response of the injection-production system to the displacement of a compressible fluid through the formation, and 2) To identify flow patterns that would shed light on the appropriateness of the geometrical design and well configuration of the pilot.

A monitoring strategy was designed to obtain as much information from the NCT as possible. Four stages were identified for the sake of monitoring: 1) A baseline, a week before the nitrogen injection, to have a high-resolution zero line for gas rate, bottom hole pressure and gas compositions, 2) Detecting nitrogen breakthrough at the first-line producer wells (CH-95, CH-96 and CH-97 as seen in Figure 2), with frequent monitoring of artificial lift system parameters and gas compositions in these wells, 3) Redirecting nitrogen flow resulting in the most uniform distribution possible, using data and controls at the first-line producers and injection wells, and 4) To detect nitrogen breakthrough at the other surrounding producer wells.

Figure 7 summarizes the designed versus actual duration of each of the above-described stages. Nitrogen took longer to arrive at the three producer wells than anticipated by reservoir simulation. Uncertain parameters will need to be consistently adjusted in the simulation model to match this behaviour. However, the breakthrough times were very similar, occurring within 48 hours of each other, evidencing a uniform progression of the nitrogen front within the pilot volume. The homogenization stage lasted only three days, limited by the erratic performance of the artificial lift system under higher producing gas-liquid ratios, which ultimately resulted in shutting in the first-line producer wells and extending the monitoring time at the producers beyond. The monitoring was extended for longer than two weeks before the end of nitrogen injection. There was no nitrogen detected at any second-line well producer while the first-line wells were open.

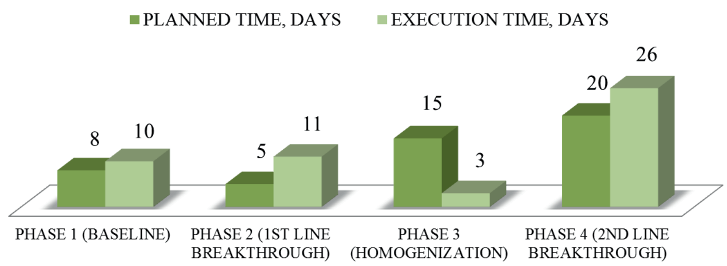

Figure 7. Duration of each of the NCT phases: Planned versus Executed.

The nitrogen transit times in the reservoir were found to be correlated with the distance between the injector and each producer well in all directions. This evidences a very favorable scenario for air injection, since reflects that the T2 formation is homogeneous in the pilot area and beyond. This observation was true even for the well CH-22, which is located at the other side of a fault in a sunken block (Figure 4). Reservoir simulations did not predict an early nitrogen appearance at this well, and the model needs to be updated for a better connectivity in this direction. These adjustments in the simulation model are crucial for a more effective prediction and monitoring during the in situ combustion.

In terms of the operational performance of the system, adjustments are needed in the artificial lift design, in order to avoid failure due to high gas production rates.

Summary of findings and final thoughts

In order to manage possible operational issues during the in situ combustion pilot test, it is important to carry out a series of experimental analysis. These experimental tests must be focused on characterizing the expected operational problems and then establishing mitigation and management strategies that diminish the impacts on the success of the process implementation. For the case of Chichimene, the most critical issues expected are corrosion, emulsions, sand production and lack of injectivity-connectivity. For each of these issues a monitoring and mitigation plan was established; however only during the pilot operation their real impact on the process will be verified.

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Information about authors

Hugo García – Petroleum Engineering, M. Eng., Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847392

E-mail: hugo.garcia@ecopetrol.com.co

Eider Niz Velasquez – Petroleum Engineering, PhD Research & Development, EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847598

E-mail: eider.niz@ecopetrol.com.co

Martha Trujillo – Petroleum Engineering, MSc Leading in EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847158

E-mail: martha.trujillo@ecopetrol.com.co

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STUDY OF THE UPPER PART OF THE SEDIMENTARY COVER AND SEARCH FOR HEAVY OIL DEPOSITS THAT OCCUR ON HIGHER LAYERS USING 2D CDP SEISMIC SURVEY ON THE TERRITORY OF TATARSTAN

R.S. Khisamov[1], V.A. Ekimenko[2], Zh.K. Dobrovolskaya[2], T.V. Morkovskaya[2]
[1]Tatneft PJSC, Almetyevsk, Russia
[2]TNG Group LLC, Bugulma, Russia

Abstract. The paper represents the results of experimental-methodical works of 2D CDP on the study of Permian- Upper Carboniferous interval of the section in order to develop techniques for the study of heavy oil deposits. As a result of 2D CDP seismic surveys the upper part of the sedimentary cover was studied in detail, including deposits of Tatarian, Kazanian, Ufimian tiers of the Upper Permian, Sakmarian, Asselian tiers of the Lower Permian and reflectors C3 and C3a in the Upper Carboniferous sediments, the depth of which does not exceed 500 m. The boundary of Neogene paleovalley is reconfirmed. Forecast is carried out for upper sand packs of Ufimian tier, which is associated with deposits of heavy oil.

Keywords: seismic survey, upper part of the section, heavy oil deposits, sand pack, well
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Introduction

Experimental and methodological works for the study of Permian – Upper Carboniferous deposits were held for the first time. To work out the methodology, the researches were carried out in the eastern part of Cheremshansky district of Tatarstan on sites Upper Karmalsky and Lower Karmalsky deposits of viscous oil (Dobrovolskaya, Morkovskaya, 2013).

For a detailed study of the Permian-Upper Carboniferous interval the seismic observations were carried out with 320-channel symmetrical arrangement with a pitch PP and PV 5 m, i.e. with the multiplicity of observations 160. During processing, calculation of datum static corrections was carried out by the first arrivals of refracted wave, and the magnitude of input statics corrections of the low-frequency component did not exceed 10 ms. This approach allowed us to consider the impact of topography and velocity anomalies in the upper part of the section.

Lithologic and stratigraphic binding of reflectors was made using data of seismic well logging and modeling of seismic wavelet based on the theoretical curves of acoustic logging, which allowed correlating reflectors along the profiles in the sediments of the Kazanian stage, from roofing surfaces of Tatarian, Ufimian, Sakmarian, Asselian and reflectors C_3 and C_3a in the sediments of the Upper Carboniferous. All of the above boundaries are characterized by different dynamic expression in a wave field and, as a result, quality of traceability (Figure 1).

Brief geological description of the target interval of the section

The studied area belongs to the Central bituminous area, "which corresponds to the large pole of bitumen accumulation located on the eastern edge of Melekess basin and the western slope of South Tatar arch" (Khisamov et al., 2006).

Upper Karmalsky and Lower Karmalsky deposits of heavy oil are located in the area of seismic operations, confined to the sand pack of Ufimian tier. The main reservoir for the accumulation of oil in the Upper Permian oil-bearing complex are Sheshminskian sandstones of Ufimian tier that occur in the upper pack of the horizon – sand pack $P_2u_2^2$, made of sand impregnated with viscous oil and thin interbedded sandstones and siltstones.

Virtually the entire Lower Karmalsky deposit from the roof to the formation bottom is water-flooded and washed in one degree or another. There is a certain similarity in the water-flooded nature of heavy oil reservoirs and reservoirs of massive type, operated a natural mode, for which it is difficult to build a current oil-water contact. Therefore, a lower limit of oil saturation is considered conventionally in the bottom of oil-saturated zone defined by quantitative and qualitative characteristics of laboratory core analysis and logging (Bazarevskaya, Tarasova, 2007; Yangurazova, 1997).

Upper Karmalsky heavy oil deposit is controlled by homonymous uplift complicated by a number of domes. The deposit was penetrated by 22 wells and is quite an extended lens, the size of 5.5 x 1.5 km of the northwest trending. Oil-saturated strata vary from 0.2 m (well 17 VK) to 15.5 m (well 418). The deposit is of structural and lithological type.

As it is known, the beginning of the Late Permian era was accompanied by a substantial restructuring of the structural plan of the territory. After a break in sedimentation, lagoon-marine and continental formations were formed. Early Ufimian time is associated with active lift of Paleo-Urals, where erosive processes were developed intensively. Streams of large masses of water, carrying detritus in the eastern regions of the platform, in Ufimian age covered a large part of Tatarstan. Thickness of deposited sediments gradually decreased in a westerly direction until all wedging out; their stratigraphic completeness and structural plans varied (Figure 2). In Early Sheshminskian time deposits of sand-clay packs were accumulated on hypsometrically lower areas of Sakmarian surface.

Research results

The obtained time sections display a distribution of Upper Carboniferous – Quaternary deposits, geometry of stratigraphic horizons and benchmarks, the nature of sedimentation, paleo-erosion and paleo-tectonics, and other features of the geological structure.

The first reflector at time sections is a boundary formed as the total impulse of the upper layers near the surface, characterized by a dynamically stable impulse with negative sign. According to the drilling, Quaternary deposits up to 20 m are developed ubiquitously at the surface; they are represented by diluvial and alluvial formations of sand, clay, gravel, loam, clay loams.

For the northeastern part of the studied area the feature is a partial washout of sand packs in the pre-Neogene time. Sediments of Neogene system, filling paleovalley of Sheshma River are mapped by the structural drilling. At the time section this site has the cross-section of paleovalley of irregular U-shape (steep, high sides, uneven bottom, transgressive occurrence on the eroded surface of various stratigraphic horizons (the deepest on the stratigraphy deposits, affected by pre-Neogene erosion, are rocks of Ufimian sand packs)) (Figure 3).

The thickness of Neogene sediments, composed of clay gray, brown, often greasy, plastic, calcareous, with fragments of shells pelecypods, gastropods, with interbedded sands of gray, fine-grained and medium-grained, polymictic in circuit area, reaches 105 m (well 397). Wave pattern: in the center – horizontal axis of in-phase, closer to the sides – chaotic form of recording, which is due to the fact that Neogene zone is narrow, deep and inhomogeneous, composed of rocks with different density, high-speed characteristics.

In areas of seismic profiles 05120301, 05120303 intervals are observed with weak seismic records that

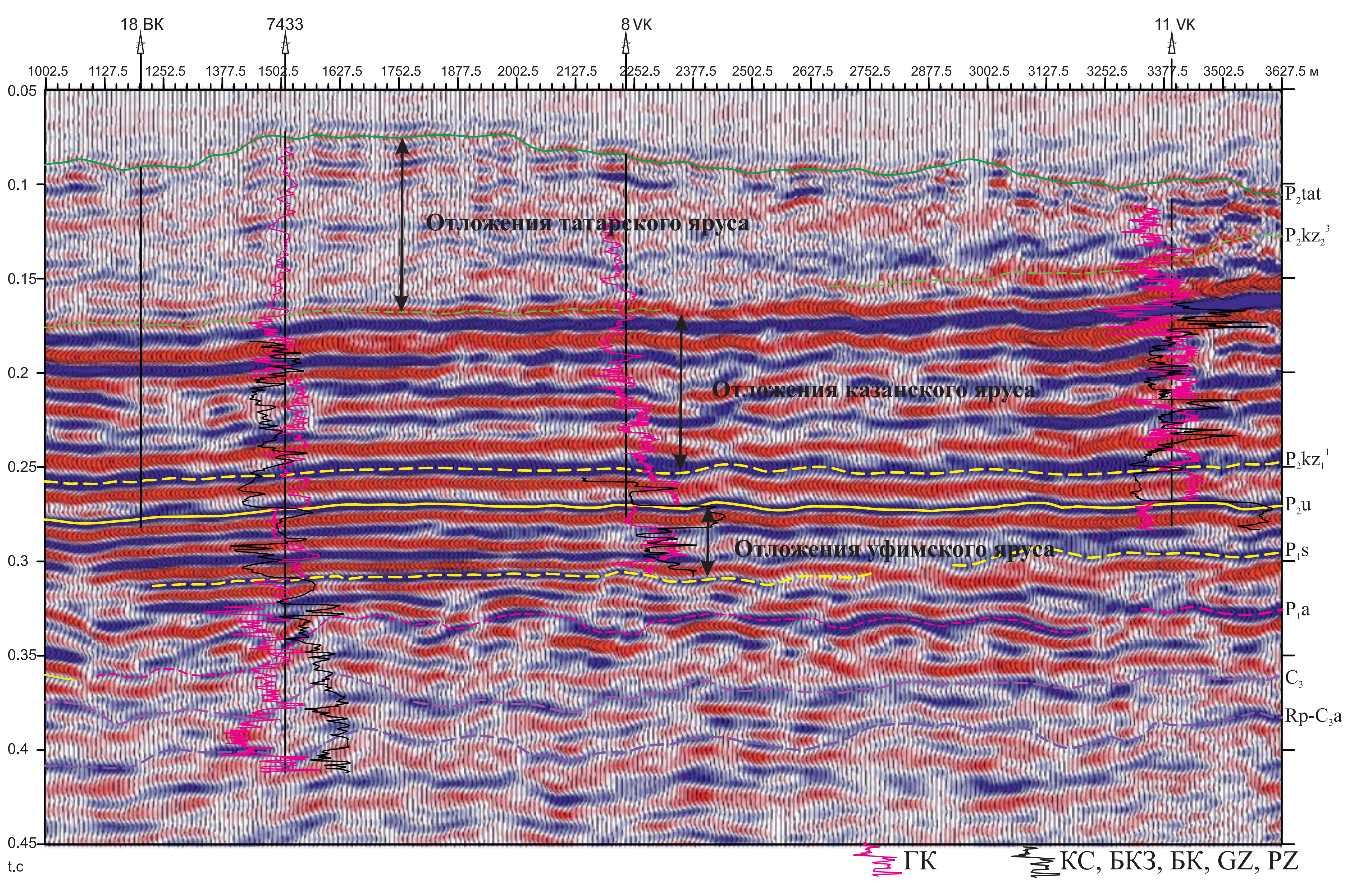

Figure 1. The nature of wave pattern in the range of Permian-Upper Carboniferous deposits.

match the stratigraphic binding according to the deposits of Tatarian stage. As the result of existed pre-Neogene and modern erosion they preserved not everywhere and not in full. Lithologically they are filled with multi-colored clays, siltstones, marl interbedded with sandstones, dolomite, limestone, gypsum, the total thickness of which reaches 50 m. Maximum thickness of deposits is observed in the range of pk 2.5-3502.5 of profile 05120301.

In the Upper Kazanian time there were four cycles of sedimentation, each of which was characterized by specific conditions and duration. However, sediments accumulated in these cycles are the alternation of small and medium-grained sandstone, siltstone, clay, marl, small cavernous dolomite, limestone, with inclusions of gypsum with different density and acoustic properties. In the wave field this interval is characterized, for the most part, by the horizontal stratification of reflectors with different configuration, traceability, dynamic expression.

On the border of the Tatarian and Kazanian deposits, as a result of sharp change of lithology, quite a contrast reflection in its dynamic characteristics is formed in the wave field. Thickness change of the Upper Kazanian substage from 58 to 204 m is controlled by the time interval change between the reflectors $P_2kz_1^1$-$P_2kz_2^3$.

The following reflection in the wave field is formed from the roof of Ufimian tier and is presented with a positive sign of the impulse. Reflection is dynamically expressed, correlated without difficulty.

Interval of the time section, concluded between

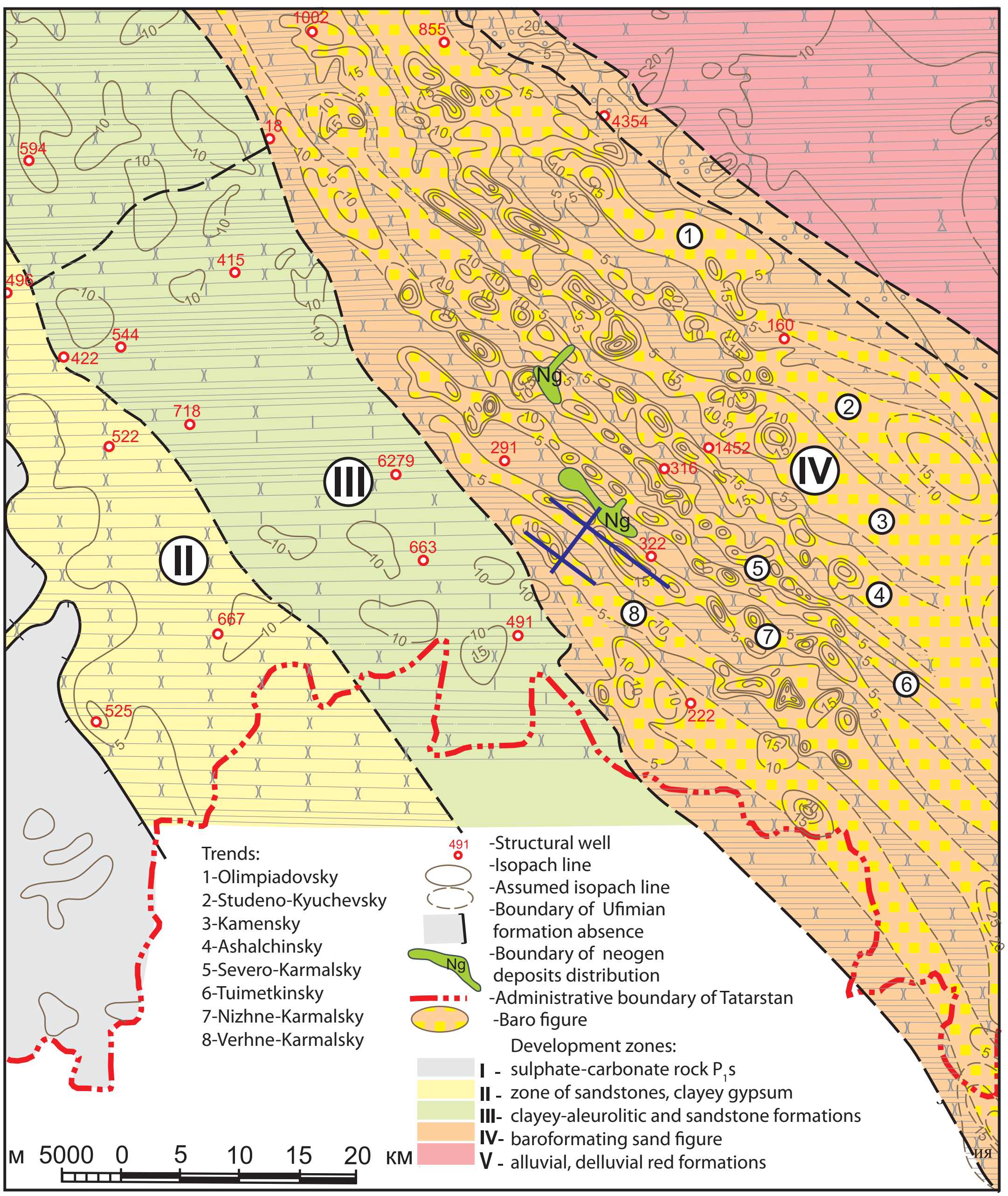

Figure 2. Lithofacies map of the Ufimian sand pack. South-Tatar arch. Note: the copy of Figure 2.1 to the report on 5/85 "Analysis of the geological prospecting and exploration results of bitumen deposits in the Tatar Autonomous Soviet Socialist Republic, the development of recommendations for their further maintenance and improvement of methods", TatNIPIneft 1987

the reflectors and P_2u and P_1s, displays the structure of Ufimian sediments, which within the territory are represented by Seshminskian horizon, 37.2-100 m thick in the area of the Lower Karmalsky deposit, and 33.1-79.0 m – in the Upper Karmalsky deposit. The tier consists of two packs: the upper – sand and lower – sand and clay.

The upper sand pack with thickness from 5.5 to 40 m,

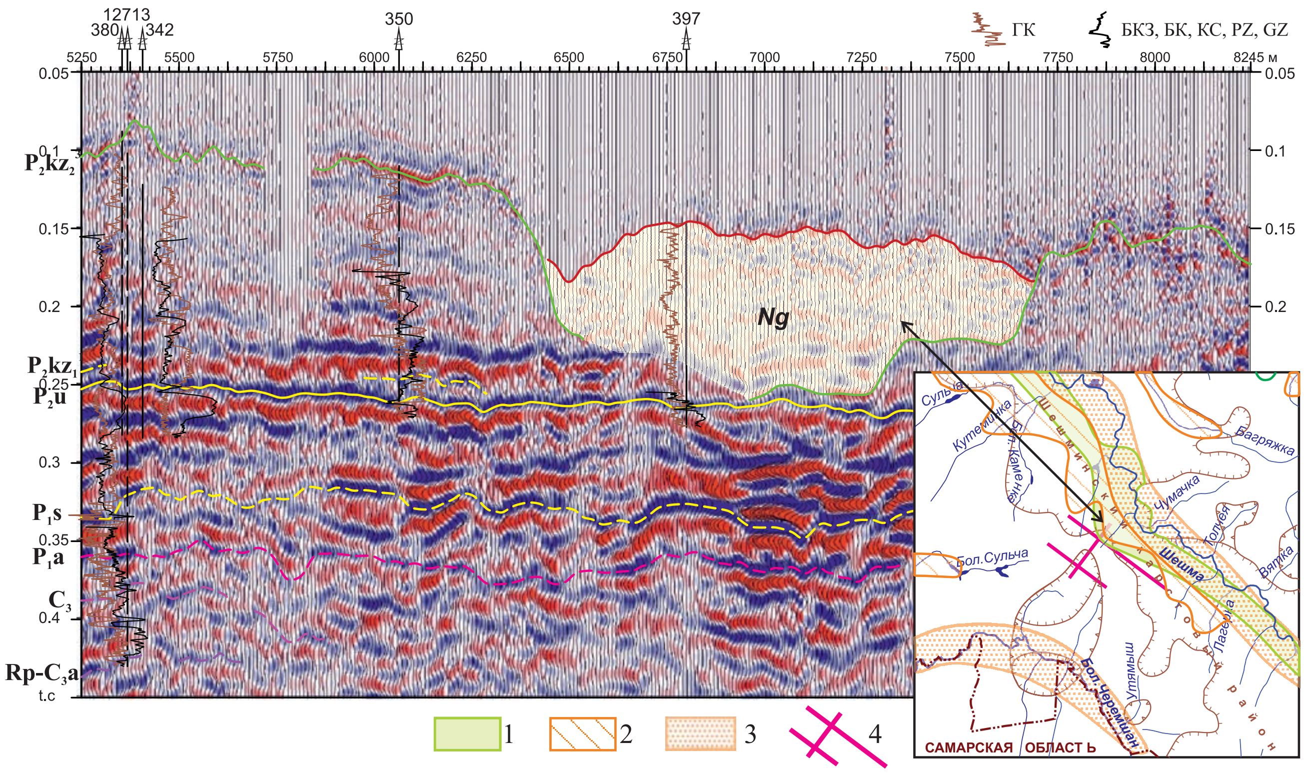

Figure 3. Display in the wave field of paleovalley of Sheshma River. Scheme of interrelations of pre-Pleiocene, Quaternary river valleys and karst in the Lower Permian deposits. 1 – pre-Pleiocene river valleys (according to N.V. Kirsanov, A.I. Bashlev, 1962); Quaternary river valleys: 2 – erosion, 3 – accumulative; 4 – profiles s.p. 5/12-3.

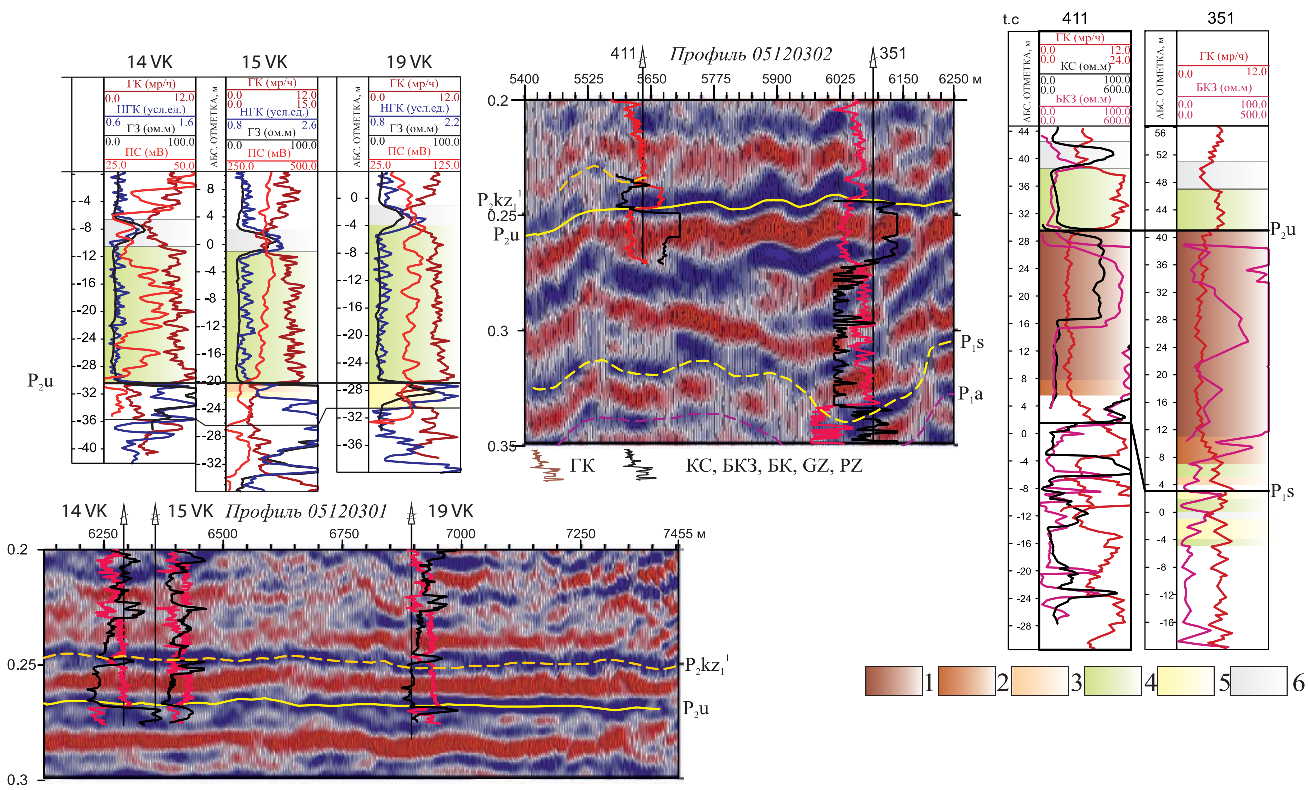

Figure 4. Changes in the wave pattern in the bedding of Ufimian sand pack. 1 – intensively bituminous sandstone; 2 – medium bituminous sandstone; 3 – weakly bituminous sandstone; 4 – argillaceous rocks; 5 – sandstone; 6 – limestone.

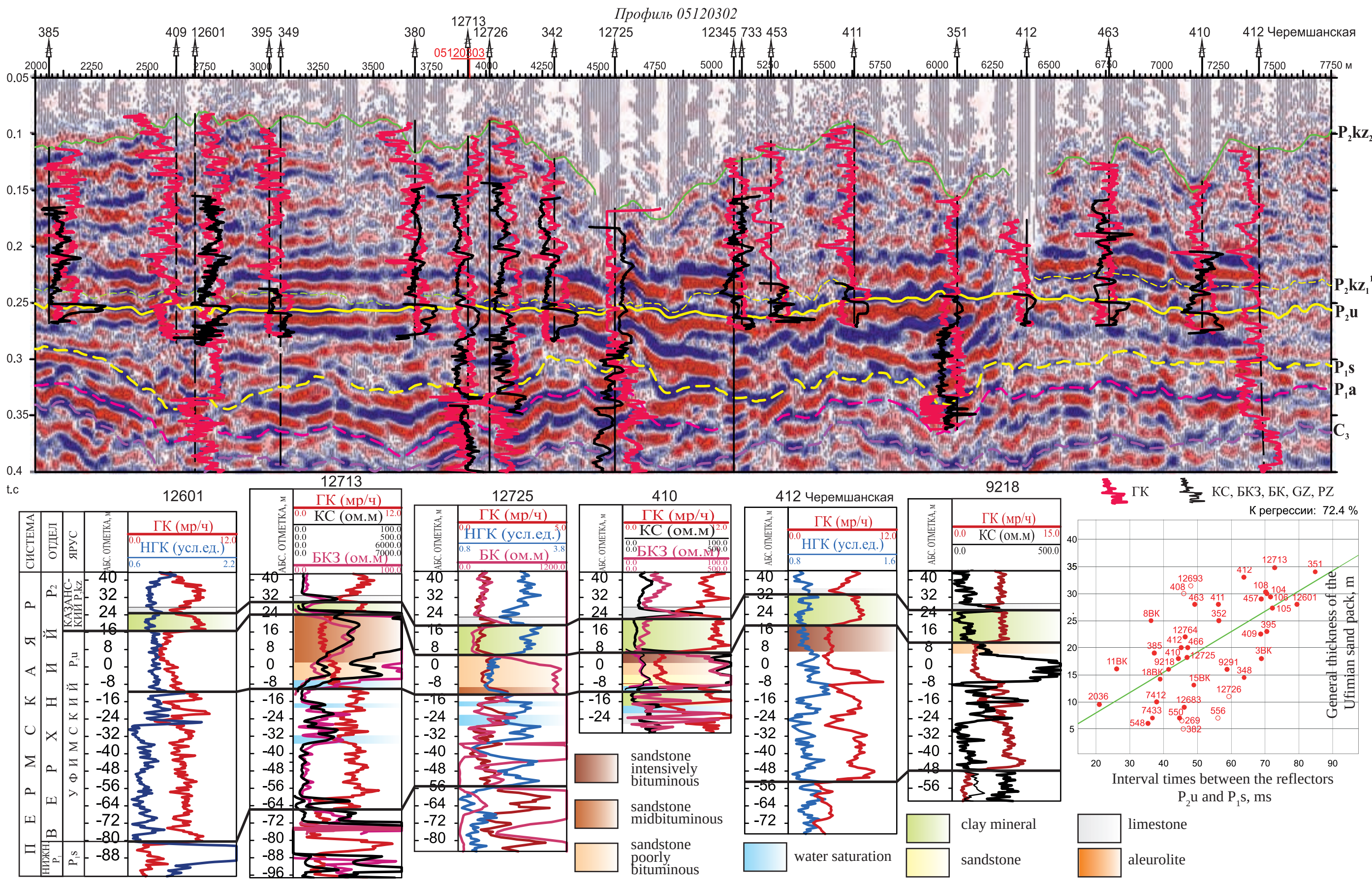

Figure 5. Prediction of correlations between changes in the interval times between the reflectors P_2u and P_1s and the general thickness of the Ufimian sand pack.

which is associated with the main deposits of heavy oil, is filled by loose, fine- and medium-grained unconsolidated sands and sandstones with thin interlayers of siltstone and clay –at the top, and thick, sturdy, calcareous, polymictic, thin sandstones – at the bottom. The thickness of the upper pack varies from 0.4 m to 35 m (well 80 Ashalchinsky). The biggest thickness of sand packs is associated with near-arch parts of uplifts.

In the wave field upper sand pack does not generate its own reflection, which is due to the absence at the bottom of benchmark with contrasting petrophysical properties. However, visually there is a relationship between the thickness of the pack, its saturation and dynamic characteristics of the reflector, registered under the roof of the Ufimian tier (Figure 4). When the thickness of the sand packs reaches 15-20 m in the wave field, there is a stable single-phase reflection with the negative sign.

With further increase of the sand packs the reflector thickens with decreasing amplitude, and, as a result, there is an interference of reflected waves with formation of two dynamically expressed reflectors of different polarity (area of well 12713). In areas of sand packs thinning in the area of wells 14VK, 15VK, 19VK the reflected wave is 'split' in the upper weakly expressed border (up to complete disappearance) and lower border with brightly expressed amplitude.

In the process of work, the attempt was made to find a correlation between changes in the interval time of the reflection with negative sign recorded under the roof of Ufimian tier and the thickness of the upper sand packs of Ufimian tier. But due to the above reasons, as well as the location of only a small number of wells on seismic profile line, correlation coefficient was not significant.

At the same time there is a relationship between changes in the interval times between the reflectors P_2u and P_1s and the total thickness of the Ufimian upper sand packs that gives grounds to assume a close relationship of paleorelief of underlying horizons and overlying compensating sediments. The regression coefficient was 72.4% (Figure 5). Thus, there is a probability in the forecast of productive sand pack of the Ufimian tier according to seismic data, provided that the testing of 2D seismic profiles will be performed on a uniform grid over the maximum number of wells.

Conclusion

We have obtained clear geological results: morphology of uplifts is adjusted, the interrelation is established between changes in the dynamic characteristics of reflection, recorded in the upper part of the Ufimian tier with thicknesses of productive sand packs of Sheshminskian horizon.

Thus, the study of the Upper Permian section interval, containing deposits of viscous oil, by means of seismic survey is advisable to perform at a dense and regular grid of profiles.

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Information about authors

Rais S. Khisamov – DSc in Geology and Mineralogy, Professor, Deputy General Director and Chief Geologist, Tatneft PJSC

423400 Russia, Almetyevsk, Lenin str., 75

Phone: +7(8553)307-117

Valentina A. Ekimenko – Deputy Director General and Chief Geologist, TNG Group LLC

Russia, 423236, Bugulma, Voroshilov str., 21

Phone: +7(85594) 4-18-23, 4-13-35

E-mail: ekimenko@tngf.tatneft.ru

Zhanna K. Dobrovolskaya – Chief geoscientist of interpretation group No.3 of Geoinform center, TNG Group LLC

Russia, 423236, Bugulma, Voroshilov str., 21

Phone: +7(85594) 7-75-55, ad. 1282

Tatyana V. Morkovskaya – Lead geologist of interpretation group No.3 of Geoinform center, TNG Group LLC

Russia, 423236, Bugulma, Voroshilov str., 21

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POROSITY MAPPING FROM INVERSION OF POST-STACK SEISMIC DATA

B. Das, R. Chatterjee
Indian Institute of Technology (Indian School of Mines), Dhanbad, India

Abstract. A seismic section oriented N-S passing through well "W" is considered for porosity prediction in offshore of Krishna-Godavari (K-G) basin. The gamma ray log trend indicates deposition of cleaning upward sediment. Coarsening upward, clayey-silty-sandy bodies, making a series of about 50-60 m thickness, have been evidenced from the gamma ray log. Porosity is mapped from transformation of acoustic impedance (AI). Post-stack inversion of seismic data is routinely carried out to derive AI and hence petrophysical properties in an area. We have been introducing here an uncommon approach of inverting post-stack seismic data into porosity from porosity log. The post-stack inversion for estimation of direct porosity is performed by utilizing an estimated porosity wavelet, low frequency model and model based inversion. This approach is implemented on clay rich, shaly sediments in shallow offshore. The total porosity for the depth interval of 1200-1600 m ranging from 1 to 40 % has been used as input for porosity inversion from the 2D post-stack seismic data of shallow offshore sediments at 31m bathymetry in K-G basin. This prediction is applied to dataset having good correlation between AI and porosity. In K-G basin, the porosity in Raghavapuram Shale varies from 13 to 30 % with maximum value of 40 % is observed in Paleocene sediments. The shales/unconsolidated sediments measure a high porosity with low impedance and the more porous sands are in an intermediate range. The predicted impedance and porosity values may be erroneous beyond the drilled depth because of non availability of well log data for calibration.

Keywords: Krishna-Godavari basin, Porosity, Seismic Inversion, Raghavapuram Shale
DOI: 10.18599/grs.18.4.8

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1. Introduction

In general conventional seismic interpretation entails picking and tracking laterally consistent seismic reflectors for the purpose of mapping horizon of interest, geological structures, stratigraphy and reservoir architecture. The aim of interpretation is usually to detect hydrocarbon bearing geological bodies, to delineate their extent, and calculate their volumes. Acoustic impedance (AI) mapping is a common approach for inversion of post-stack seismic data to delineate reservoir properties. Nowadays, pre-stack seismic inversion techniques are used for computation of impedances: P-impedance, S-impedance and density. These are further used for estimation of porosity, shale volume, lithofacies and water saturation from seismic data. Well information are available at hundreds of meters apart, therefore the objective of seismic inversion method for reservoir characterization is to delineate petrophysical properties for the interwell region or adjacent to the wells.

Observations on sonic log data provide good vertical resolution of geological strata, but are at sparse locations. In contrast, seismic method provides usual areal sampling but with noticeably lower vertical resolution. The integration of 2D seismic data of any area with porosity measurement at wells can significantly improve the porosity distribution in space. The petrophysical parameters are generally predicted from seismic inversion properties such as AI using multivariate statistics modelling, non-linear methods including neural network (e.g. Hampson et al., 2001; Leiphart, Hart, 2001;Walls et al., 2002; Pramanik et al., 2004; Calderon, 2007; Singha, Chatterjeee 2014; Singha et al., 2014). Objectives of this paper are to (a) transformation of AI to porosity mapping, (b) development of relation between porosity and acoustic reflectivity from post stack seismic data, as well as(c) direct inversion of post-stack seismic data to predict porosity from well log. The methodology is applied to 2D post-stack data of shallow offshore of Krishna-Godavari (K-G) basin.

2. Study area

The pericratonic rifted basin is holding multiple petroleum system aging Mio-Pliocene to Cretaceous age. The shallow offshore area (Figure 1) located at the north-eastern part of K-G basin is considered for porosity prediction from 2D post-stack seismic data.The study area contains sediments of Gollapalli Sandstone, Tirupati Sandstone and Raghavapuram Shale formations of Cretaceous age. The sands are deposited during the Upper Cretaceous by a prograding deltaic system that spread out into shelf and slope environments. The shallow marine environment with very slow rate of sedimentation, shallow bathymetry and the nearness to the provenance result the deposition of high gamma-high resistivity shale (HG-HR) sequence known as Raghavapuram Shale (Manmohan et al., 2003). The sequence is carbonaceous, organic rich, silty and with high radioactive: thorium and potassium content. The porosity estimation of Raghavapuram Shale in shallow water is very critical in reducing the drilling risk in this trend. Because the sandstones present in this formation tend to be thin and inter-bedded with shale, the high reflectivity has a dimming effect on the reflection images of sand-shale boundaries in this zone.

The seismic section belonging to shallow offshore of K-G basin show the geological horizon with its age (Figure 2). The faults are identified in the seismic section. The Paleocene top is observed at 420 ms. Seismic reflections are mainly attributed to unconsolidated silty sand/shale/mudstone occurring 400-580 ms of Paleocene age. Top of Raghavapuram Shale is observed at 850ms from seismic section of K-G basin. Top of Cretaceous and basement of Permian age are observed around 580 ms and 1200 ms respectively. The penetration of seismic energy into the underlying basement is significantly reduced. The basement top stands out as a prominent reflector between the overlying bedded sediments and underlying noisy section of the basement.

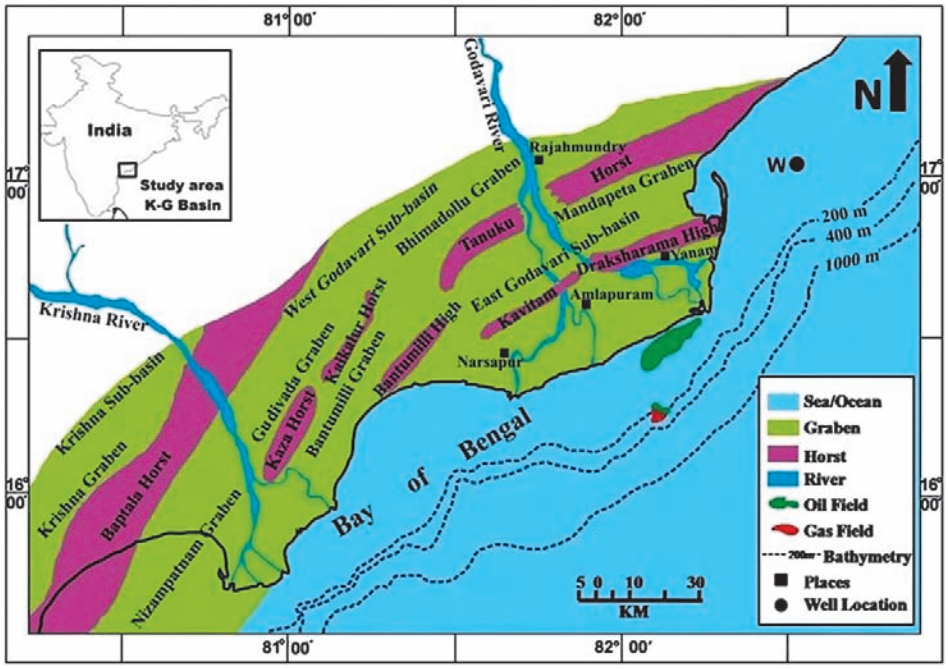

Figure 1. Location map of Krishna-Godavari (K-G) basin along eastern continental margin of India.

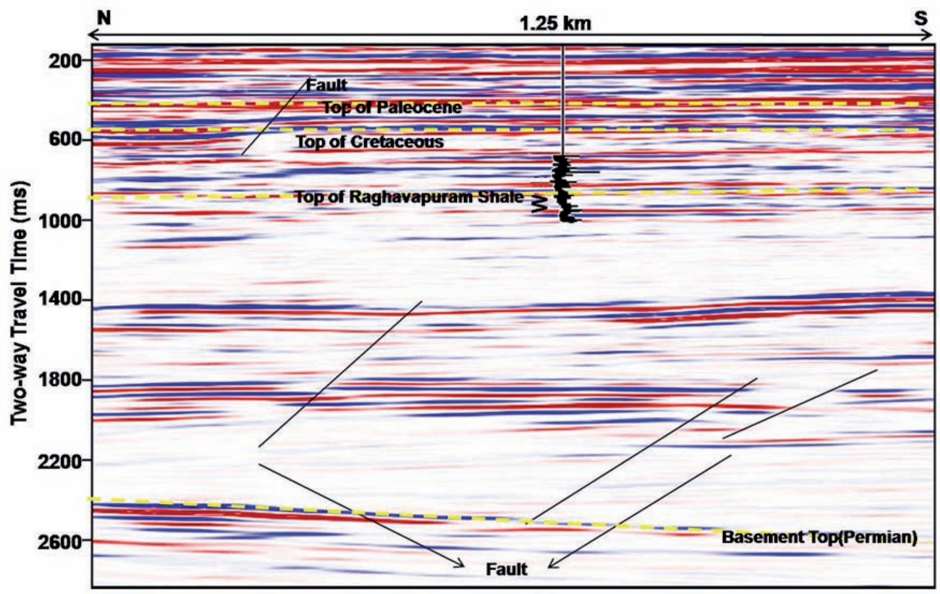

Figure 2. Interpreted seismic section containing a well "W" of K-G basin.

Depositional environment from Well log

The depositional environment of Early Cretaceous formation is of fluvio-deltaic setting with good sands development in channels and delta distributaries. The Late Cretaceous formations areof shallow marine setting with sand developments mostly in tidal channels, bars and sandy flats (Rao, 2001 and Shrivastva et al., 2008).The gamma ray and resistivity logs are called typicallithologyindicative logs for siliciclastic environments (Eichkitz et al., 2009). The log shapes in gamma ray with resistivity are related to sediment character and depositional environment (Rider, 2002). Shapes on the gamma ray log can be interpreted as grain size trends and by sedimentological association as cycles. Information about the sediments and sedimentary processes from the above logs may not be sufficient alone, due to some lithologies having similar natural radioactivity and electrical properties. Information from cuttings and cores is therefore often an essential component of depositional environmental analysis (Jipa, 2012). Figure 3 displays variable sandstone/silty sand body thickness patterns; including thick to thin, blocky to upward-fining log characters at greater depths (Figure 3). The gamma ray log shape in this well "W" and associated seismic signatures display the characteristics of singular or stacked package of sandstone/silty sand bodies of fining upward sequence.

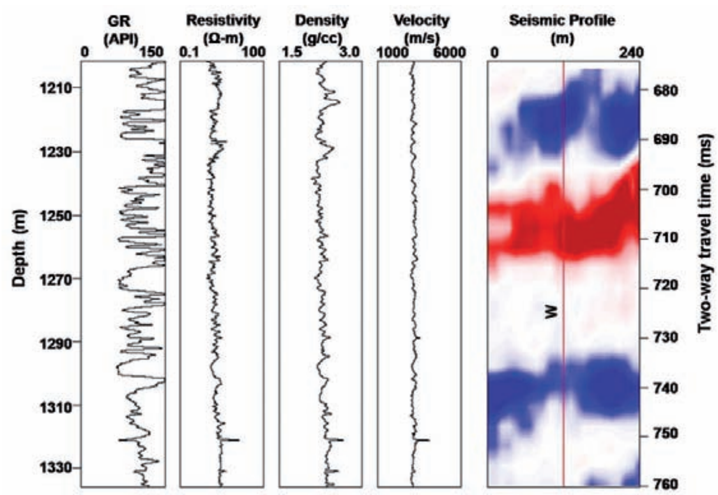

Figure 3. Well logs and corresponding seismic data from well "W" showing different depositional environment in the depth interval of 1200-1335 m. Red, peak of seismic trace and blue, trough of trace.

The shallow marine environment, shallow bathymetry, very slow rate of sedimentation and the nearness to the provenance resulted in the deposition of high gamma-high resistivity shale (HG-HR) sequence (Manmohan et al., 2003). The sequence is carbonaceous, organic rich, silty and with high thorium and potassium content.

3. Post-stack Seismic Inversion:

3.1 Transformation of AI to Porosity mapping

Post-stack seismic inversion has been widely used in the petroleum industry for subsurface geological inferences (e.g., lithology, porosity) based on seismic analysis tied to well logs (i.e., resistivity, sonic and density). The method increasingly confirms the usefulness of inverted seismic data and is informative for seismic interpretation (Buiting, Bacon 1999).

Post-stack inversion is used to transform seismic reflection data into acoustic impedance as it uses normal incidence reflections and requires only near-offset stack data (rather than full aperture stacked data) to obtain physically and geologically reliable results. Analysis of post stack seismic data has been used as an effective tool for hydrocarbon exploration in many areas around the world. The goal of seismic inversion procedure in the case of reservoir characterization is to map the physical properties such as porosity, water saturation and lithology for the inter-well regions.

For all seismic inversion methods, the earth can be represented by a stack of plane and parallel layers with constant physical properties (Leite et.al, 2010). The seismic trace s(t) can be represented by the convolution of the reflectivity series r(t) and band-limited wavelet w(t) and addition of random noise n(t). Mathematically seismic trace s(t) can be written as,

$$s(t) = r(t)*w(t)+n(t), \quad (1)$$

The acoustic impedance at ith layer is calculated as,

$$AI_i = \frac{R_{i+1} + R_i}{R_{I+1} + R_i}, \quad (2)$$

where R_i and R_{i+1} is the reflection co-efficient of *i*th and *i+1*th layer respectively.

Russel (1991) defines the model based inversion as an iterative modeling scheme in which the geological model is built and compared to the seismic data and the comparison is used to iterate to get the better model. The inversion requires the initial value of impedance. An initial model for the model based inversion is generated using the acoustic impedance logs calculated at the well location. The inversion algorithm modifies the impedance log to minimize the misfit between the measured and synthetic seismic data. As it is to be expected with impedance inversion, a good match between seismic and synthetic data can be achieved. Figure 4 is showing the match between the inverted impedance and well log data for two sections under the study area. The inverted acoustic impedance for the section is illustrated in Figure 5. The inverted impedance section around the well "W" is showing the low impedance at 800-900 ms.

The inversion methods require seismic data, low frequency model and a wavelet estimated from the data.

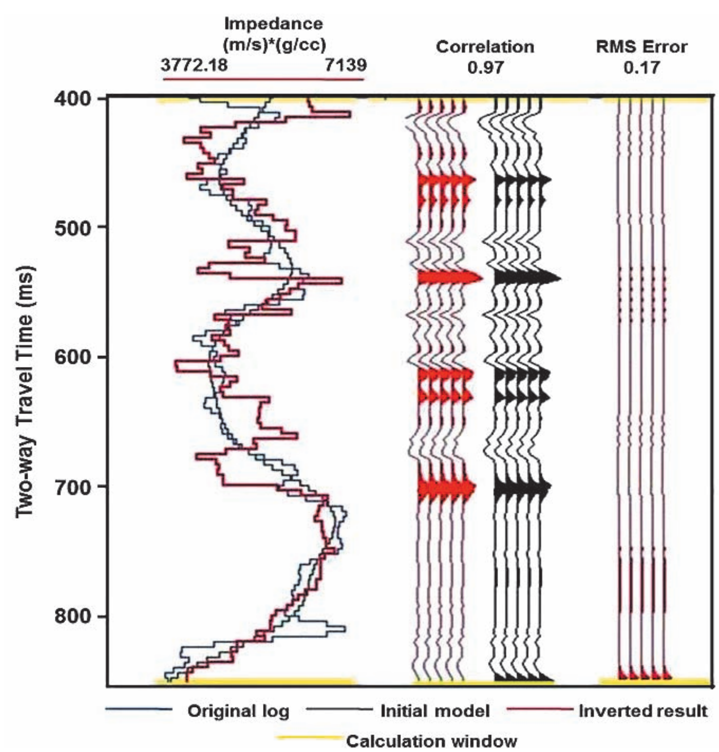

Figure 4. Post-stack seismic inversion analysis plot for a seismic line showing matching between the inverted (red line) and computed acoustic (blue line) impedance within calculation window (yellow line). The black curve indicates the low frequency impedance extracted from the observed impedance logs. The red and black seismic traces are the synthetic and real seismic data respectively.

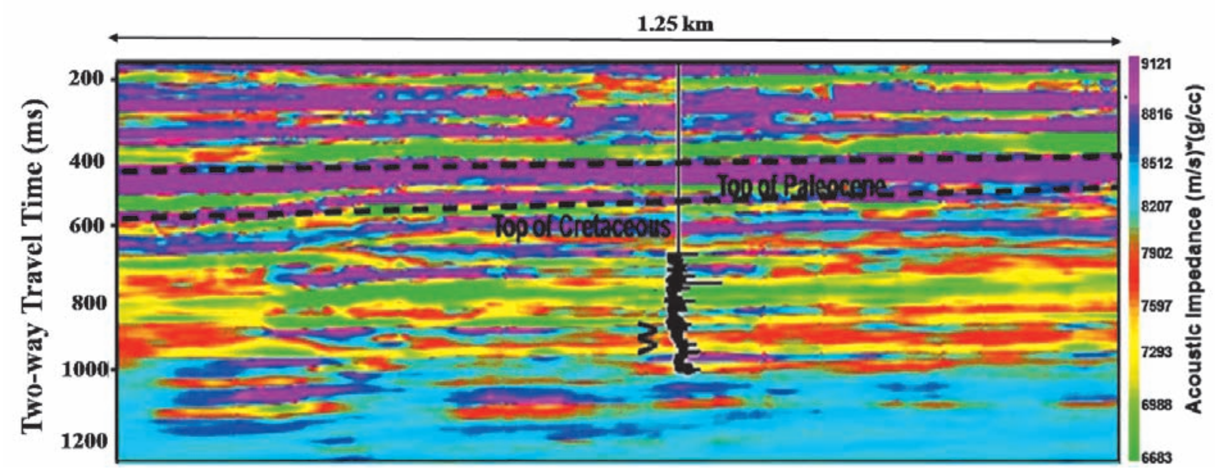

Figure 5. Inverted seismic section with lateral variation in acoustic impedance for the seismic section.

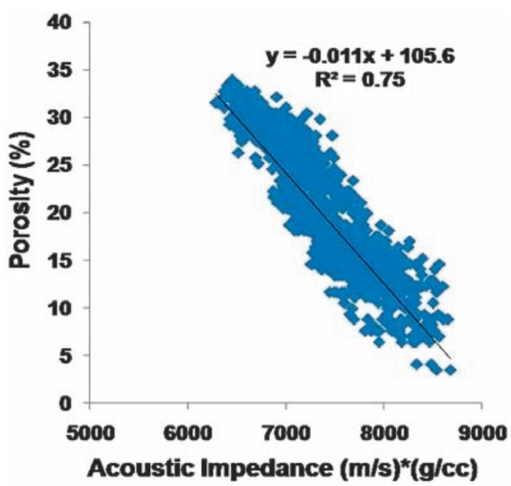

Figure 6. Crossplot between Acoustic impedance and density derived porosity for K-G basin showing good fit (R^2=0.75) to linear trend of lithology.

For accurate wavelet estimation P wave log is used for calibration of seismic data (Singha et al., 2014). A common way to extract porosity from seismic data is to employ acoustic impedance inversion. One can estimate porosity from the inverted AI using mathematical relation between AI and porosity derived from well log. Figure 6 is showing the best linear fit with goodness of fit (R^2=0.75) between AI and density derived porosity for the well "W". Density porosity is derived from the following equation (after Bateman, 1985):

$$\varphi_d = \frac{\rho_m - \rho_{\log}}{\rho_m - \rho_f}, \tag{3}$$

where ρ_m, ρ_f and ρ_{log} are the matrix density, fluid density and the bulk density of formation respectively. Here matrix density and fluid density are considered as 2.65g/cc and 1.1g/cc respectively.

The inverted acoustic impedance is transformed into porosity from the relations obtained from cross plot (Figure 6) using following equations (4) for seismic section.

$$\text{Porosity} = -0.011(\text{AI}) + 105.6 \tag{4}$$

Figure 7 is showing the porosity image of the seismic section.

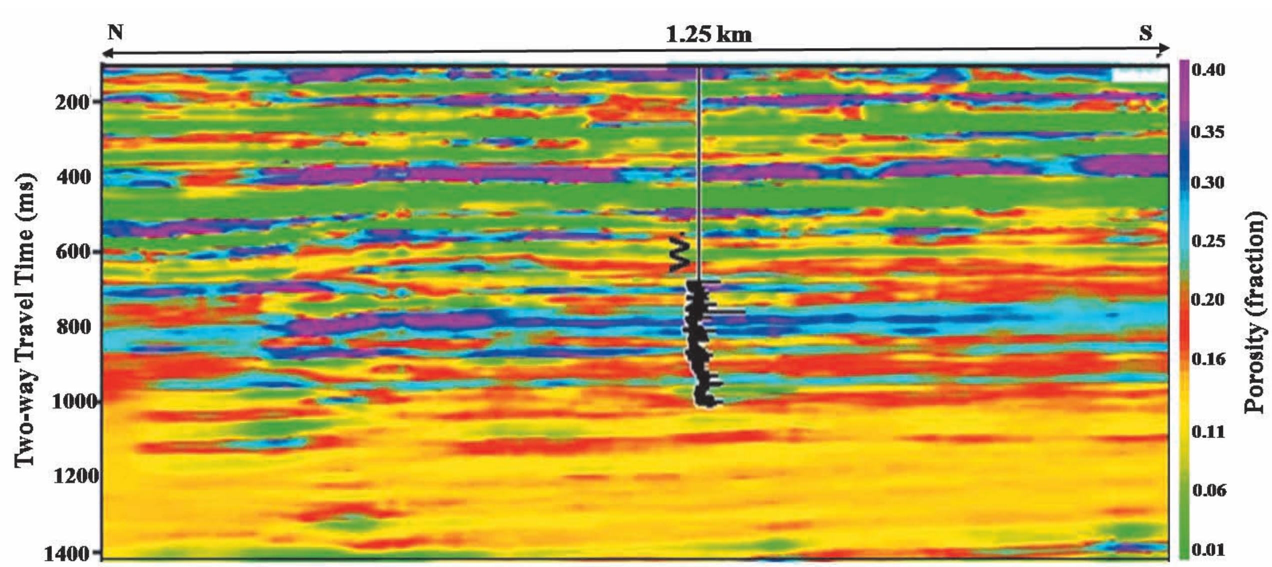

Figure 7. Inverted porosity section for the seismic section using transformation of AI to Porosity.

3.2 Direct Inversion of Post-stack Seismic Data to Predict Porosity

A modified approach using idea of AI reflectivity has been used to predict porosity from post-stack seismic inversion. The inversion procedure involves well to seismic calibration, wavelet extraction, estimation of low frequency model and model based inversion for seismic dataset of K-G basin (Maver, Rasmussen, 1995; Husse, Feary, 2005; Kumar et al., 2016). Porosity is computed from density logs available from a offshore well located at K-G basin.

Wyllie et al. (1956) has proposed formula for velocity (v) for porous rock as

$$\frac{1}{\upsilon} = \frac{\varphi}{\upsilon_f} + \frac{1-\varphi}{\upsilon_m} \tag{5}$$

where v_f and v_m denotes fluid and matrix velocity respectively. Assuming density and velocity of the matrix being much larger than respective values of the fluid, the AI (denoted by z) of the porous rock is given by (Rasmussen, Maver, 1996)

$$\log(z) = \log(\rho_m \cdot \upsilon_f) - \log\left(\frac{\varphi}{1-\varphi}\right) \tag{6}$$

Conversely, if the density and velocity of the matrix are not considered being much larger than respective value of fluids, we can expect less sensitivity of AI with respect to the porosity. Rasmussen and Maver (1996) provide a model between AI and porosity as given below:

$$\log(z) = \log(z_0) + n\log\left(\frac{\varphi}{1-\varphi}\right) \tag{7}$$

where z_0 and n denotes intercept and slope respectively.

The reflection coefficient is called AI reflectivity between layer *i* and *i+1* as given by Rasmussen and Maver (1996)

$$r_z = \frac{1}{2}\left(\log(z_{i+1}) - \log(z_i)\right) \tag{8}$$

And porosity reflectivity is defined as

$$r_\varphi = \frac{1}{2}\left(\log\left(\frac{\varphi_{i+1}}{1-\varphi_{i+1}}\right) - \log\left(\frac{\varphi_i}{1-\varphi_i}\right)\right) \tag{9}$$

$\log(z_0)$ of equation (7) contributes negligibly compared to $n\log(\varphi/(1-\varphi))$. Hence, the relation between porosity and AI reflectivity can be expressed by (Rasmussen, Maver, 1996, Kumar et al., 2016)

$$r_z = nr_\varphi \tag{10}$$

Equation (10) is used statistically for determining the slope, "n", referred to as correlation factor among AI and porosity reflectivity using log values. The case study from K-G basin will show the relation between porosity and AI reflectivity.

The AI and porosity logs are used for estimation of wavelet and low frequency models. Therefore, porosity wavelet is generated by multiplying the AI wavelet (computed from density and velocity logs) with the correlation factor. The estimated wavelet and a low frequency model enable the execution of seismic inversion. The accuracy of model based seismic inversion (Russell, Hampson, 1991) relies on the low frequency model which is determined by the root mean square (RMS) error between the well logs and the inverted AI or porosity.

3.3 Porosity Prediction in K-G basin

Shrivastava et al. (2008) have explained the geological structures with the identified hydrocarbon prospects on N-S seismic section passing through our study area. Figure 6 is showing the linear trend of the lithology between AI and density derived porosity with good fit of R^2 =0.75 for shallow offshore well in K-G basin. The porosity inversion using porosity reflectivity may be a good option for this type of dataset.

P-wave velocity and porosity varies from 2814 to 4090 m/s and 1 to 40 % respectively. The AI reflectivity from impedance log and porosity reflectivity from

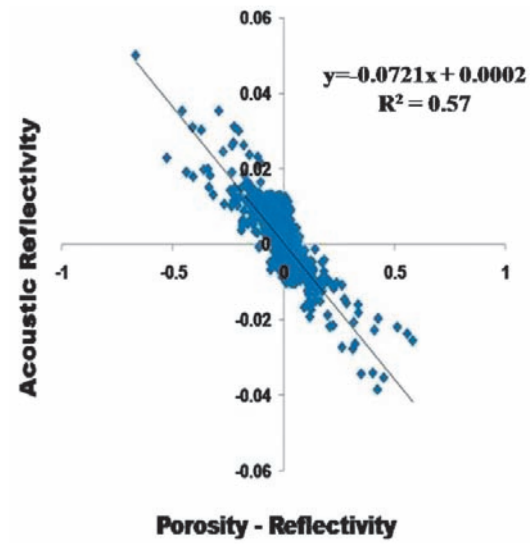

Figure 8. Crossplot between Acoustic reflectivity and Porosity reflectivity for K-G basin showing good fit which decides the correlation factor (n = -0.0721).

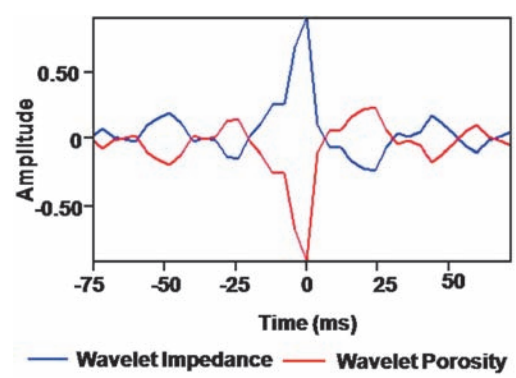

Figure 9. Extracted acoustic impedance wavelet (blue) and porosity wavelet (red) showing opposite polarity to each other for K-G basin.

porosity log using equations (8) and (9) are again computed respectively for this basin. The plot between AI and porosity reflectivity for this well at K-G basin is displayed in Figure 8.

The estimated AI and porosity reflectivity is showing a linear relationship,

$$r_z = -0.0721 r_\varphi \quad (11)$$

From above relation value of correlation "n" is found to be -0.0721. The porosity wavelet is derived from multiplication of AI wavelet with this factor.

We have derived a wavelet from seismic section of 1.25 km within the time interval 800-1000 ms (Figure 9). Porosity wavelet is generated using equation (11) from AI wavelet as shown in Figure 9.

The model based inversion is carried out to predict porosity using porosity inversion. The error analysis for inverted output and original logs are shown in Figure 10 a, b. The inverted porosity for this seismic section of K-G basin are shown in Figures 11.

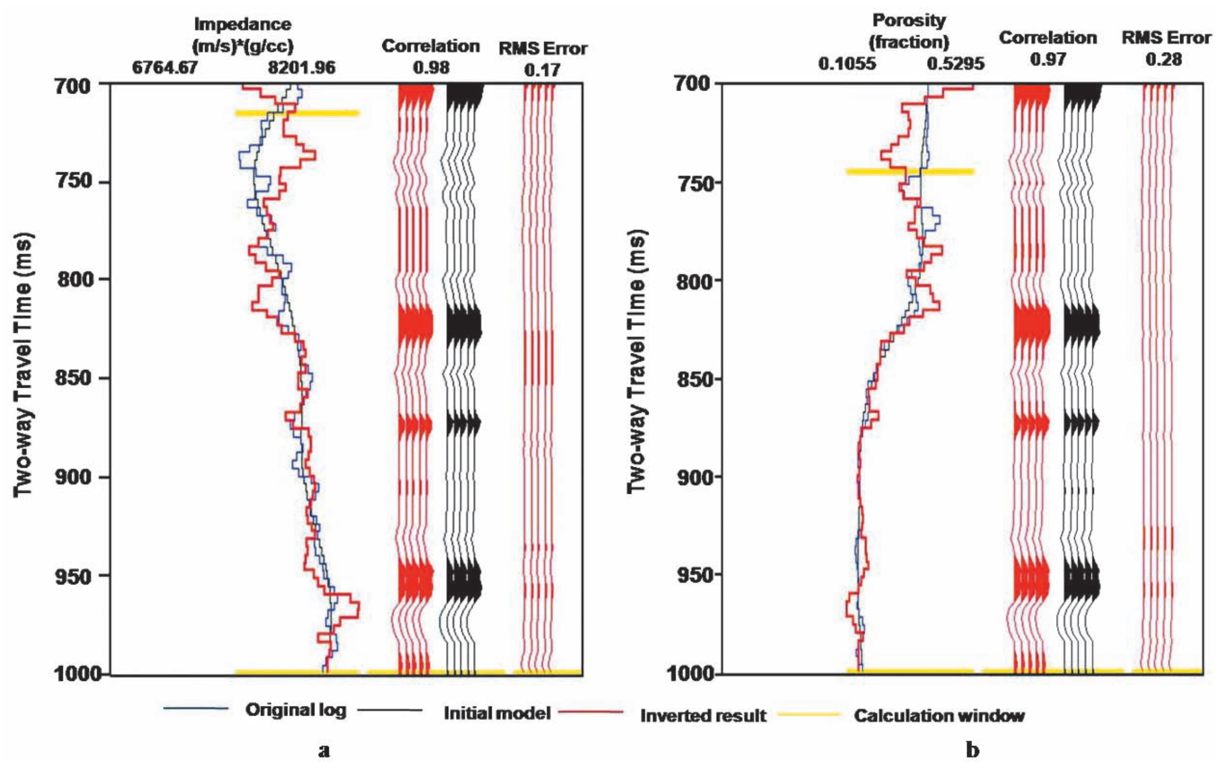

Figure 10. a) Post-stack seismic inversion analysis plot at well of K-G basin showing reasonable match between the inverted (red line) and computed acoustic impedance (blue line) within a calculation window (yellow line). The black curve indicates the low frequency impedance extracted from the acoustic impedance log. The red and black seismic traces are the synthetic and real seismic data respectively. b) Post-stack seismic inversion analysis plot at well of K-G basin showing reasonable match between the inverted (red line) and computed porosity log (blue line) within a calculation window (yellow line). The black curve indicates the low frequency impedance extracted from the observed porosity log. The red and black seismic traces are the synthetic and real seismic data respectively.

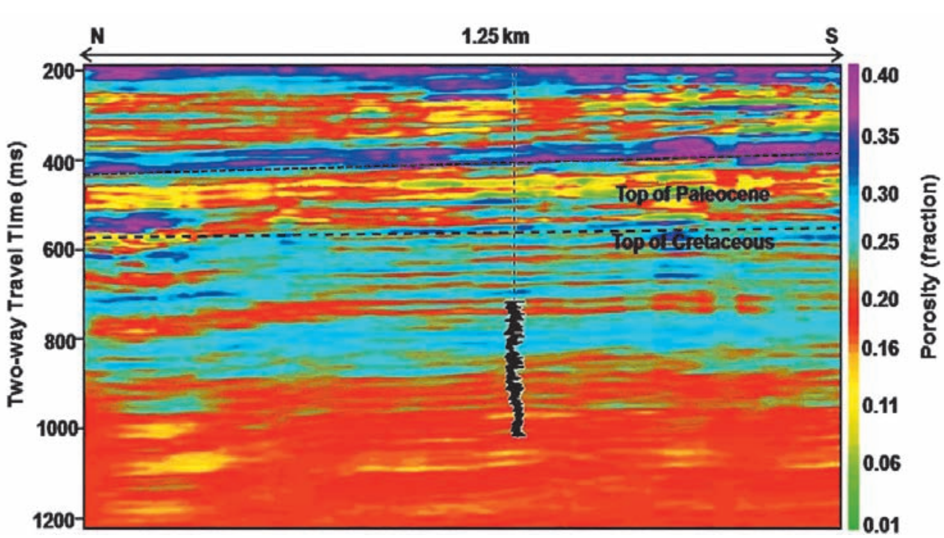

Figure 11. Inverted porosity section using direct inversion of the post-stack seismic section of K-G basin.

4. Results and Discussion

Acoustic impedance in the inverted seismic section varies from 6683 to 9121m/s*gm/c.c. This variation is due to sand, clay, siltstone and shale. Top of Cretaceous is observed in the well "W" at 1150 m and in seismic section around 580ms. Inverted porosity of the seismic sections vary from 1 to 40 % respectively. Porosity section follows the trend of seismic signature and structures of the study area. The high impedance zones observed in the both section having source rock potential show relatively less porosity compared to the porosity of low impedance zones. Lithologies of source rock generally vary across a continuum from wholly organic sediments (such as: coal), through siliciclastic shales and marls, to carbonates (Lφseth et al., 2011). High silica and carbonate content results in high impedance shales (Prasad et al., 2002). High gamma and high resistivity (5-10 ohm-m) Raghavapuram Shale is showing 16 to 35 % from 780 to 1200ms. This observation matches with the log signatures as noted by previous authors (e.g. Padhy et al., 2013). The porosity image of the seismic section in 950-1200 ms is ranging from 15 to 30 % in the Raghavapuram Shale.

This uncommon method of prediction of porosity is implemented to shallow offshore seismic data of K-G. Good fit of R^2=0.75 is observed between AI and porosity in K-G basin. Wavelet of 200 ms long from K-G basin is extracted for seismic calibration to achieve good inversion results. Model based inversion is carried out up to well drilled depth for both methods. RMS error for porosity prediction is found to be 0.28 for K-G basin. Porosity section follows the trends of seismic signature and structures K-G basin. AI varies from 6683 to 8512 m/s*g/cc and porosity ranges from 16 to 25 % characterizing Raghavapuram Shale in K-G basin. The interbedded high amplitude laterally continuous event (within 780 to 1200 ms) may be considered as potential of source rock in Raghavapuram Shale (Figure 11). Raghavapuram Shale is marked very clearly through direct inversion of AI for porosity mapping. Porosity predicted by transformation of AI shows 30 % whereas direct inversion estimates 25 %. Direct inversion of porosity estimation is close in agreement with the actual porosity of Raghavapuram Shale.

5. Conclusions

The direct estimation of porosity from seismic inversion has been implemented using porosity wavelet. The AI and porosity wavelet has the exactly opposite polarity due to negative trend between AI and porosity. This work demonstrated an uncommon porosity prediction methodology from post-stack seismic data. The high impedance zones observed in the seismic section of K-G basin having source rock potential show relatively less porosity compared to the porosity of low impedance zones. Top of Cretaceous is marked by high impedance and low porosity. Sediments of Palaeocene age is observed with low impedance and high porosity. The shales/unconsolidated sediments measure a high porosity with low impedance and the more porous sand are in an intermediate range. This porosity prediction is further to be validated with large numbers of wells or core porosity data in future.

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Authors are thankful to the Managing Director, GSPCL for their kind approval and sharing of seismic and well log data for academic purposes. The Ministry of Earth Science is acknowledged for providing financial support through the R&D project MoES/P.O./(Seismo)/1(138) 2011 dated 09.11.12.

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Information about authors

Baisakhi Das – Junior Research Fellow, Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, India

E-mail: baisakhi.das@gmail.com

Rima Chatterjee – Professor, Department of Applied Geophysics, Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, India

E-mail: rima_c_99@yahoo.com

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FORECAST OF FRACTURING AND FLUID-SATURATING AREAS OF CARBONATE ROCKS OF THE RIPHEAN OF KUYUMBINSKY FIELD BASED ON SIMULATION OF ELASTIC-MECHANICAL PROPERTIES (PROCESSING AND INTERPRETATION OF 3D CDP SEISMIC MATERIALS FROM KUYUMBINSKY REPRESENTATIVE AREA OF THE KRASNOYARSK TERRITORY)

V.A. Ekimenko, Zh.K. Dobrovolskaya, N.N. Belousova, K.N. Martynov
TNG Group LLC, Bugulma, Russia

Abstract. In this paper we consider a new approach to the forecast of increased fracturing areas of the Riphean carbonate rocks based on simulation of elastic and mechanical properties of well logging data, with the involvement of full-wave seismic acoustics. The main parameters used, characterizing the elastic and mechanical properties of the rock are the Poisson's ratio and Young's modulus. The forecast is made for fluid saturation of the Riphean strata on the basis of calculated cubes of basic elastic parameters λρ, μρ (Lame constants) and λρ / μρ, because they (the parameters) have the best ability to detect hydrocarbons. To evaluate the forecast quality monitoring wells were used that did not participate in the interpretation, which confirmed the forecasted model of the Riphean reservoir.

Keywords: seismic survey, Riphean deposits, fracturing forecast, elastic and mechanical properties, fluid saturation

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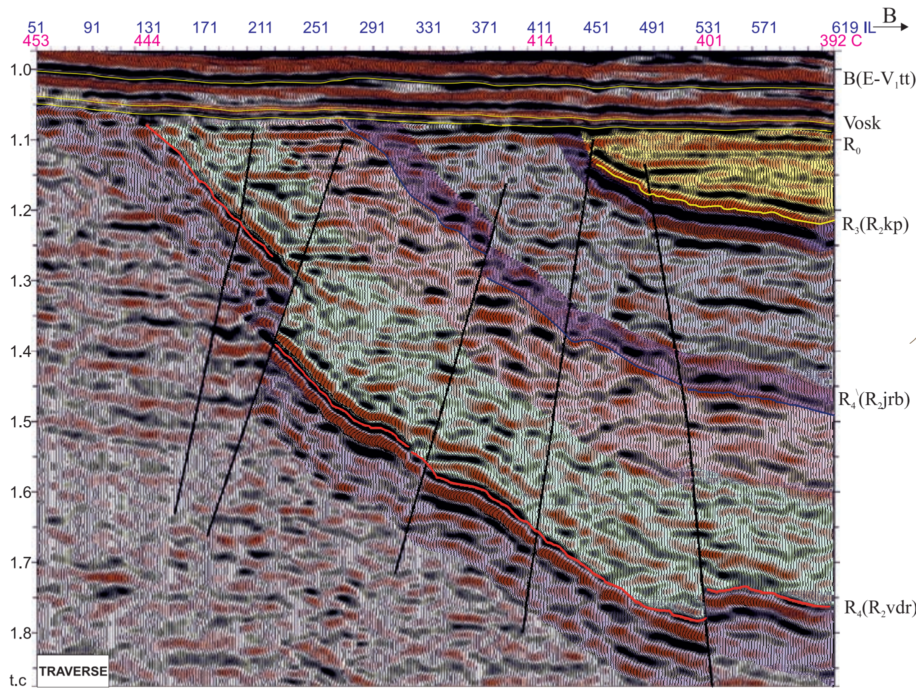
Site of seismic survey operations is located within Kuyumbinsky field in Eastern Siberia. Research objects are ancient deposits of the Riphean, the fluid saturation degree of which is controlled by fractured rocks.

Kuyumbinsky field was discovered in 1973 by drilling parametric wells K-1, which penetrated in the Riphean carbonate deposits gas reservoir with an initial daily flow rate of gas about 200 thousand m^3 (Kharakhinov, Shlenkin, 2011). In 1974 it was put on the state balance. The first commercial oil flow was obtained in 1977 in exploration well K-9; its production rate was 43.8 m^3/day. In the same year, oil was produced from the exploratory well K-2 with a maximum flow rate of 135 m^3/day (Kharahhinov, Shlenkin, 2011). Today, according to the value of the initial recoverable reserves of hydrocarbons, this field is classified as major. Oil in the field is light, with a low viscosity, relatively high gas content and saturation pressure, referred to the methane type.

Oil has low content of sulfur, resin, paraffine. Hydrocarbon deposits are confined to the ancient carbonate Riphean strata where fractures and caverns have a decisive influence on the formation of voids. Deposits are of tectonically shielded type, reservoir type – massive, fluid type – gas-oil, oil, gas condensate.

Kuyumbinskoye oil-gas-condensate field has a complex block structure and intensive disjunctive tectonics on Riphean deposits (Figure 1). The field is characterized by a high degree of litho-facies heterogeneity, variability of reservoir properties. In addition, a complicating factor for the study of the Riphean section of the interval is that the deposits are penetrated by wells at a shallow depth, and there is still no single common and approved scheme of stratigraphic subdivision of the Riphean deposits. Therefore, in the wave field stratification of reflectors in the Riphean section is based on the assumption that in the carbonate section the most stable reflections are formed from carbonate-clay strata (kopcherskian, dolgoktinskian, madrinskian, vedreshevskian formations).

In this connection, to successfully implement the exploration and development of such a complex and unique deposit, an in-depth analysis is required of all available information, in this case, the main focus is in the forecast of zones of increased fracturing,



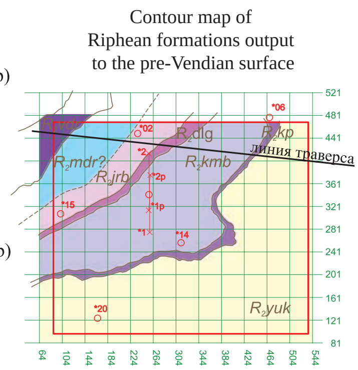


Figure 1. The nature of traceability of the Riphean formations in the wave field of a cube of corner amounts 14-26 o.

controlling fluid saturation degree using new seismic technologies.

Therefore, for the purpose of reservoir properties prediction, including areas of highly fractured Riphean deposits, a treatment was carried out with the implementation of time and depth migration and interpretation of seismic data in the amount of 100 km^2. Matched graph provided a good traceability of the main reflectors and yielded optimal resolution of seismic data in both vertical and lateral directions.

In addition, interpretation of well logging data was conducted. For lithologic and petrophysical characteristics of rocks the results of core analysis were used, including a description of thin sections, sludge; calculations, modeling was made of elastic and mechanical properties of rocks. On the basis of broadband acoustic data we calculated dynamic properties such as the ratio of interval times of the transverse and longitudinal waves, shear and Young's modulus, Poisson's ratio, shear and acoustic impedances, wave propagation speed (Dobrovolskaya et al., 2016).

In the interpretation process, fragility coefficients were calculated, the analysis of the changes of which together with the test results of formations, data of full wave sonic logging and FMI allowed to assume that rocks with fragility of more than 60% have an increased fracturing and may be the flowed. In addition, the intervals of increased fragility are characterized by high values of Young's modulus and low values of Poisson's ratio since zero values of Poisson's ratio correspond to absolutely fragile materials, and the maximum – to absolutely incompressible. More 'hard' rocks having high Young's modulus are more prone to cracking than rocks with low Young's modulus.

In the interpretation process in two well No.14 and 15 and the Riphean deposits we have found a discrepancy between the Poisson's ratios, calculated from the log data and the theoretical curves, which is probably due to the secondary voids of rocks.

Thus, the conclusions drawn from the interpretation of borehole material, have set the direction for further interpretation of seismic data.

To predict the most fragile and fractured zones in conditions of carbonate rocks a synchronous inversion was performed with obtain of cubes of Poisson's ratio and Young's modulus; a cross-plot analysis was conducted.

In addition, the fracturing assessment of the Riphean strata was carried out on the basis of Poisson's ratio cubes, calculated on the basis of multi attributive analysis using theoretical and calculated curves in the wells. The basis was the conclusion on the results of modeling of elastic and mechanical properties in wells about that intervals of fracturing rocks correspond to significant deviations in the direction of reducing the calculated values of Poisson's ratio from the theoretical ones. Analysis was performed within a small portion of pressure stabilization curve separately for each well; test intervals were adopted as analyzed intervals.

As a result on well sites where commercial oil, gas and gas condensate flows were obtained, we can observe in the histograms a significant deviation in the direction of reducing the calculated Poisson's ratios from the theoretical values. In the analyzed sections of wells, where no commercial inflows of hydrocarbons were obtained, calculated and theoretical values of Poisson's ratio are close enough (Figure 2).

Therefore, to identify promising areas with increased fracturing across the studied area cubic difference

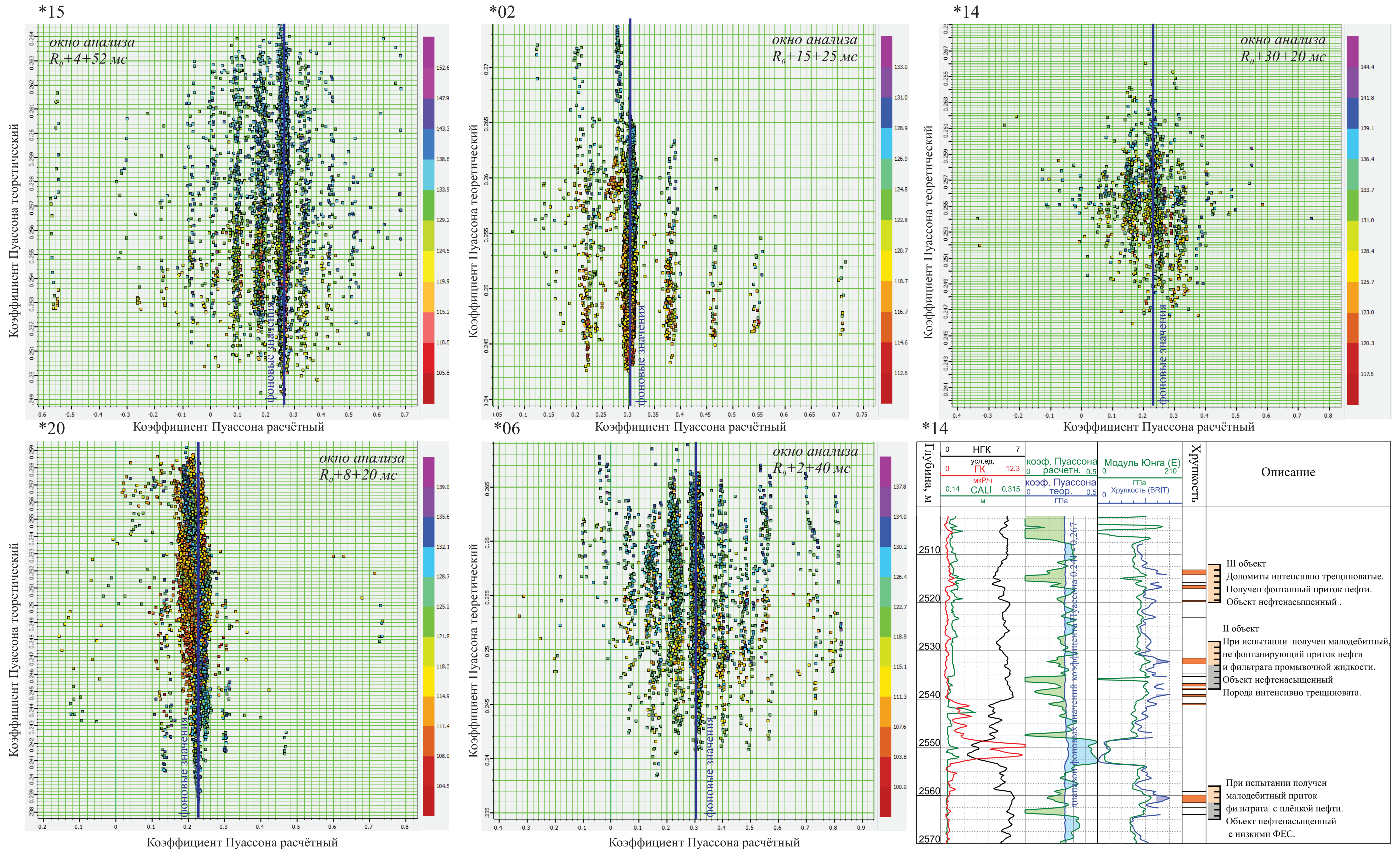


Figure 2. Evaluation of elastic and mechanical properties of the productive Riphean deposits using calculated and theoretical Poisson's ratios.

of Poisson's ratio was obtained; and the coefficients difference map was calculated for the upper range of Riphean deposits (analysis window is selected taking into account the test intervals in wells) (Figure 3). Potentially promising areas allocated for cubes 'ant-tracking' of the Young's modulus are characterized by a maximum difference of Poisson's ratio, which once again confirms their potentially high reservoir properties.

To predict fluid saturation of the Riphean strata, cubes of the basic elastic parameters λρ, μρ and λρ/μρ (Lame constants) were calculated, because they have the best ability to detect hydrocarbons (Voskresensky, 2001).

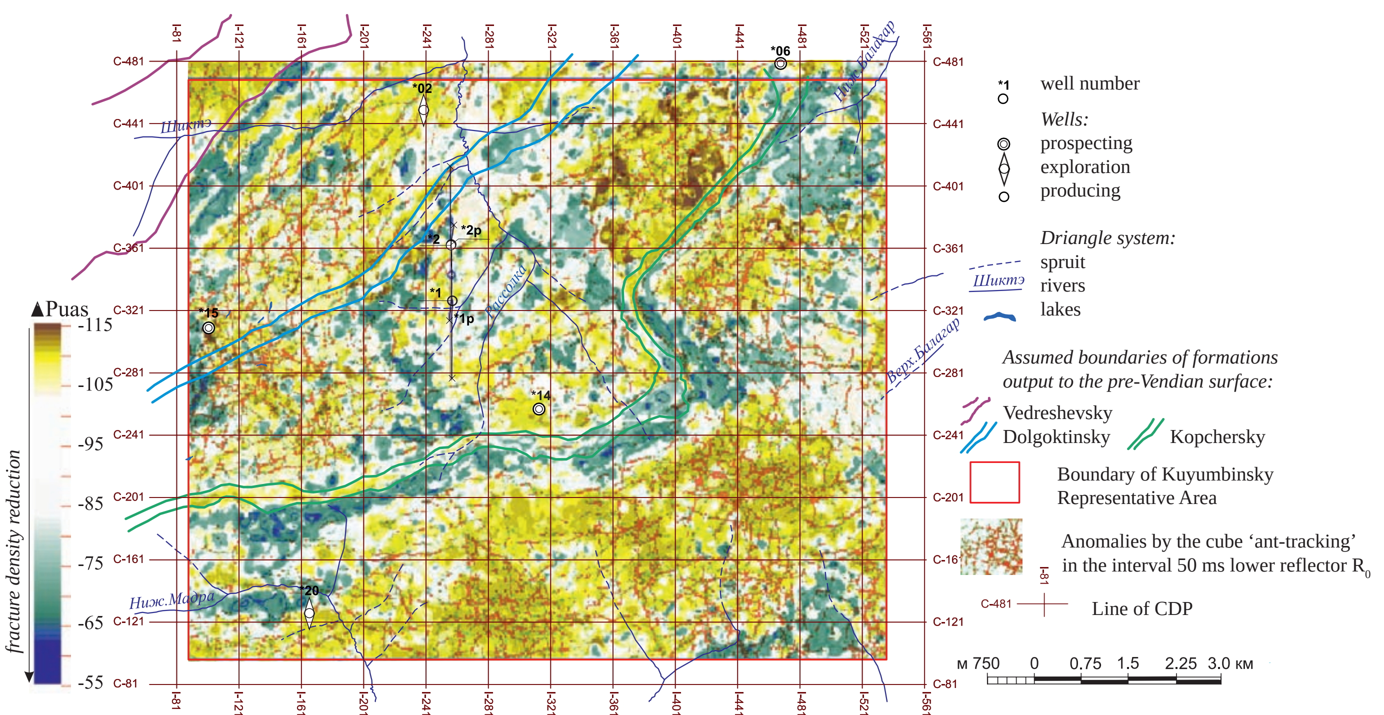


Figure 3. The difference map between the Poisson's ratios in the range of 20 ms below R_0, combined with anomalies by the cube 'ant-tracking'.

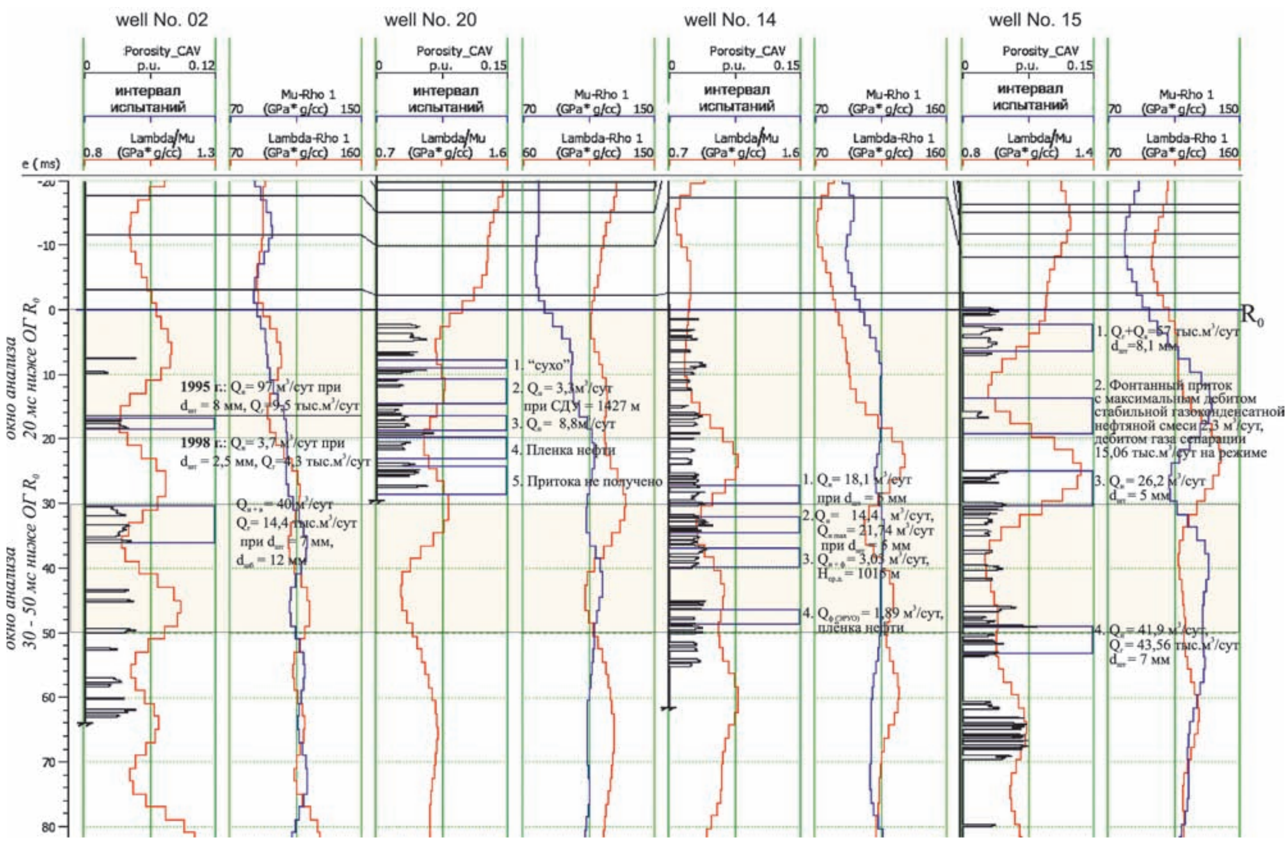


Figure 4. Change in the Lame constants curve shape and λρ/μρ parameter depending on saturation.

The module λ is the interesting to determine fluids. According to the research, set By Voskresensky for clastic rocks, gas-saturated sandstone is characterized by minimum values of parameters λ, λ/μ, shale – by maximum values, with the difference in percentage for parameter λ/μ is from 104 to 181 % and the maximum differences are inherent to low-speed strata. The above research results have been tested for high-speed strata of the Riphean carbonate deposits with the assumption that the differences will not be as significant. However, in the vertical sections of the cube low values of the parameter λρ correspond to the test intervals, in which commercial flows of oil and gas condensate were obtained.

Additionally, by the calculated cubes of λρ, μρ and

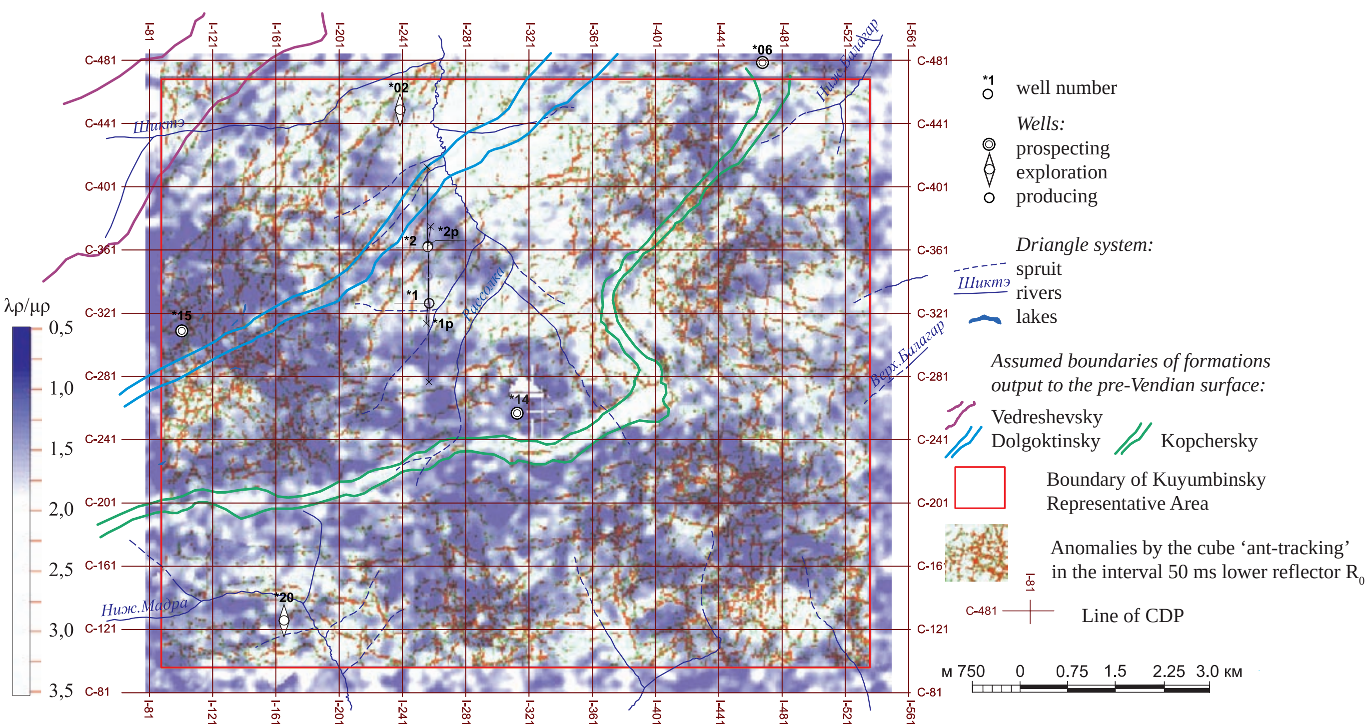


Figure 5. Forecast map of the fluid saturation for the upper part of the Riphean strata (analysis window of 20 ms below the reflector R_0).

λρ/μρ parameters, an analysis was conducted of changes in the shape of curves extracted from the attributive cubes with the test results in wells No 02, 20, 14 and 15 (Figure 4). As a result, it is noted that fluid saturation changes most strongly the shape of λρ/μρ parameter curve, curves of Lame constants also vary, but not so clearly. Therefore, by cube of λρ/μρ parameter maps were calculated in the windows of 20 ms (the upper producing interval in view of perforation intervals) and 30-50 ms lower of reflector R_0.

On the forecast map of fluid saturation, calculated for the upper interval of Riphean deposits, the most promising for the intensity of the observed anomalies is the zone allocated in the area of well No. 15 and further to the southeast (Figure 5). Additionally, the mapped area of output to the pre-Vendian surface of carbonate-clay suite kopcherskian formation, which in this region is the reference reflector that does not contain commercial hydrocarbon accumulations, is characterized by the absence of the low values of λρ/μρ and, therefore, is a screen for oil and gas deposits.

As a result, applied approach to the forecast zones of increased fracturing on the basis of modeling of elastic and mechanical properties in Riphean deposits according to the seismic data with the assistance of well information allowed us to achieve good results; monitoring wells were used in this case to assess the quality of the forecast, these wells did not participate in interpretive works that confirmed forecast model of the Riphean reservoir. Thus, the above approaches to forecast the reservoir properties of carbonate reservoirs on the basis of seismic data can be recommended for further use.

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Information about authors

Valentina A. Ekimenko – Deputy Director General and Chief Geologist, TNG Group LLC
Russia, 423236, Bugulma, Voroshilov str., 21
Phone: +7(85594) 4-18-23, 4-13-35
E-mail: ekimenko@tngf.tatneft.ru

Zhanna K. Dobrovolskaya – Chief geoscientist of interpretation group No.3 of Geoinform center, TNG Group LLC
Russia, 423236, Bugulma, Voroshilov str., 21
Phone: +7(85594) 7-75-55, ad. 1282

Natalya N. Belousova – Head of the TNG-Regions group, TNG Group LLC
Russia, 423236, Bugulma, Voroshilov str., 21

Konstantin N. Martynov – geoscientist, TNG Group LLC. Russia, 423236, Bugulma, Voroshilov str., 21

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THE PROSPECTS AND OPPORTUNITIES TO USE COAL BED METHANE AS UNCONVENTIONAL ENERGY SOURCE

M.P. Yurova
Oil and Gas Research Institute of the Russian Academy of Sciences, Moscow, Russia

Abstract. The article shows that the gas from coal beds (as unconventional source) in the near future may become one of the most important suppliers of energy, not only in the coal regions of the country, but because of its demand, in the market conjuncture. The emphasis is put on materials of Russian researchers who seriously study the problem of methane production from coal beds in Russian regions. The urgency of this problem is not only that gas is not sufficient in remote coal areas of our country, but above all in the fact that the risk of methane explosions in mines and loss of life is reduced. At this, a large amount of pollutants is ejected into the atmosphere, worsening environment and increasing the greenhouse effect. The article shows the specifics of finding methane in coal beds. More than 85 % of the gas is in the adsorbed in state (linked to the rock matrix). The article show the basic differences of gas production from coal beds from the development of the conventional gas deposits. Coal beds can be of different brands. The most valuable are strongly metamorphosed coals (vitrinite reflectance of 80 % or more). Being a rock of organic origin, coal is a fractured porous media. Cracks are formed either during coalification of rock or by tectonic motions, so the layers are divided into blocks. The block has sorbed gas, stripping in a diffusion form. The cracks and micropores have free gas, moving in them in the filtration mode. Coal permeability depends not only on the number of cracks, but also on their disclosure. Efficiency of methane extraction is time, reservoir pressure, permeability, wellhead pressure, etc. There are several stages of methane extraction, corresponding to different stress-strain states of the formation. The paper gives a value (83.7 billion m^3) of gas resources in coal basins of Russia. Pilot commercial production of gas from coal beds has been carried out in Russia from 2010 on the Taldinsky field of Kuzbass, where it is simultaneously utilized for local needs.

Keywords: unconventional gas, specifics of gas-bearing coal, development methods, resources of the country, prospects
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In recent years, the growth of energy consumption is constantly growing. According to the forecast of the International Energy Agency, demand for energy and electricity will grow by 50-70 %, respectively, in 2020 (Agapov et al., 2002). The specific amount of natural gas in the energy balance of the world in 2030 could reach about 30 % (Khryukin et al., 2009). In this regard, the recent interest in alternative energy sources is growing. One such source is a coal bed gas, total resources of which on the territory of Russia are up 83.7 trillion m^3 (Koshelets, 2012). Saving the trend for the production of the most affordable and cheap gas will lead to a transformation of the existing schemes to that shown in Figure 1. After several decades unconventional gas resources will become cost-effective and feasible (Figure 1) (Koshelets, 2012).

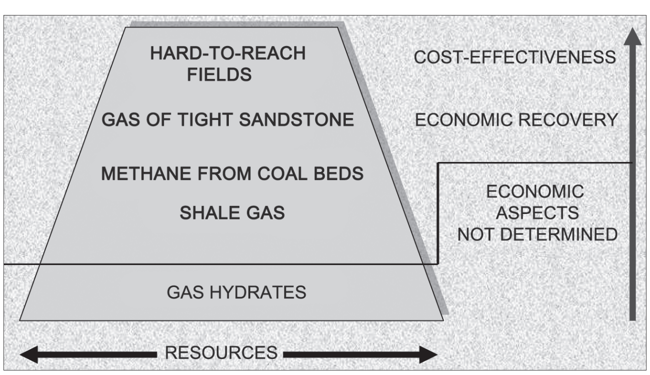

Figure 1. Forecast of the future structure of the global gas production.

The major developed sources are fossil fuels (solid, liquid and gaseous). Among them, coals and shales are the most proven in the commercial and exploratory stages. Advances of gas US companies allowed declaring the formation of the gas sub-sector in the extraction of methane from coal beds. The combination of the interests of the gas and coal industries can provide and significantly improve technical and economic, environmental and social conditions of the population of industrial areas.

Much attention and intensive development of this trend has been in the US for the last 10-15 years, where the volume of gas production from coal beds was up to 55 billion m^3 in 2010, in Canada – more than 9 billion m^3 in the same year. Australia has produced 5.5 billion m^3, China – 1.2 billion m^3, Russia – 6 million m^3 (Slastunov et al., 2012.).

Natural gas from coal beds for 90 % or more consists of methane. Methane is the cleanest of hydrocarbon energy sources; it does not contain harmful impurities such as nitrogen and sulfur compounds. Currently, commercial production of methane from coal beds is carried out only in the United States. More than 8 thousand wells are in operation, of which over 40 % are concentrated in the San Juan Basin. 10% of wells in this basin provide 75% of its production and 60% of the total annual production of coal bed methane in the United States (Khryukin et al., 2009).

The aim of such an approach in the United States is a degassing coal bed preparation rather than commercial production of methane. In some countries (China, India, Australia, Great Britain, Poland, Russia and Ukraine) there are pilot projects for development of gas resources from coal deposits (Ermolaev, Khaydina, 2008).

Materials of all kinds of coals (especially brown and others) contain various impurities, mineral components, sulfur, nitrogen, heavy metals, etc. During coal processing gaseous and aerosol products of oxidation of the carbon impurities fall to the atmosphere. Only during the energy coal combustion, each year about 90 million tons of sulfur oxide and 30 million tons of nitrogen oxide are ejected into the atmosphere. Together with ash, 60 thousand tons of lead, 50 thousand tons of nickel, 30 thousand tons of arsenic, and others pollute the atmosphere. The release of a relatively high proportion of CO_2 is a serious problem that causes the greenhouse effect and pollutes the atmosphere (Kreynin, 2008).

Methane is a negative factor in developing coal rocks, which leads to tragic consequences – loss of life, and its emissions pollute the environment, so the degassing of coal deposits with its subsequent disposal will help to reduce emissions of methane into the atmosphere and reduce the number of accidents in coal mines. In this case, the coal beds act as gas fields.

Conventional methods of production and consumption of coal turn coal regions into the ecological disaster zones. However, it should be understood that the flow rates of gas in coal beds are much lower than flow rates of gas fields, and the duration of operation of production wells will be determined by extraction rate of coal. In Russia only 10-12 % of methane is utilized that is released during coal mining and industrial extraction of methane from coal beds is not available.

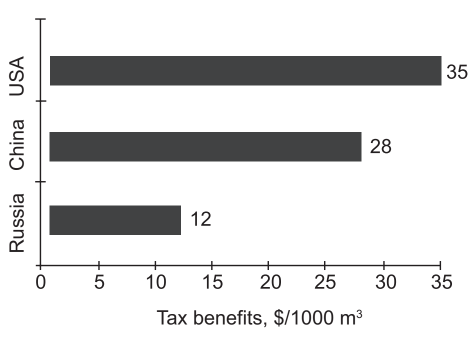

Figure 2. Comparison of tax benefits in the US, China and Russia.

The potential of coal beds in the Russian Federation is of limited use:

- Methane-air mixtures of vent streams are not used;
- The proportion of the methane-air mixtures use of degasification systems at the Vorkuta field does not exceed 40 % (boiler rooms use gas with a methane content of at least 25 %) in the Kuzbass – isolated cases of producing heat and power (mine named after S.M. Kirov, SUESK – Kuzbass) (Slastunov et al., 2012).

Despite strong interest in the development of coal bed methane in our country, the government support of this trend, as seen in Figure 2, is significantly (2 to 3 times) lower than in the United States and China. However, the results of gas production modeling from coal beds in the Kuzbass region have shown the importance of the legislative incentives for effective and rapid development of a new branch of the Russian fuel and energy complex (Khaidina, 2010).

The use of coal bed methane is greatly inferior to the conventional solid fuel (coal) production technologies. Technological solutions for the extraction of methane from coal beds are mainly based on the experience of the oil and gas industry. However, for efficient production of gas from coal beds it is necessary to take into account both natural and man-made factors. The specifics of the development of coal deposits is determined by the following factors (Slastunov et al., 2009):

- Geological conditions (deposit shape, the depth, temperature, gas pressure, etc.);
- Specificity of gas system – gas-bearing rocks;
- The possibility of further mining of coal beds.

Let us consider in more detail these features.

1. The basic form of the gas reservoir – reservoir arch, which is characterized by gas and the water displacement modes. In coal deposits marginal water is not available, the gas lies in shallow formations. Gas flow in the reservoir is determined only by its reservoir energy, which ranges from 2 to 6 MPa. Temperature of beds is 15-40 ° C at a depth of up to 100-1100 meters.

2. Coal deposits – coal of various grades. The porosity of coal beds does not exceed 5-8 %; at depths of 600-700 m coal beds are virtually impenetrable. Another feature is the interaction of gas with the gas-bearing rocks: 80-90 % of the gas is in a bound state, with different bound types (Table 1) (Slastunov et al., 2009).

Being a rock of organic origin, coal is a fractured porous media. Cracks are of different origin: either formed during carbonization, or by tectonic movements, due to which the coal beds are divided into blocks. The blocks contain mainly adsorbed gas, which is desorbed in the form of diffusion. The cracks and macropores contain free gas, moving along them in the filtration mode.

Fracturing, formed in the process of genesis, depends on the degree of metamorphism (vitrinite reflectance). Analysis of experimental data on methane adsorption on

Group	Form of gas saturation	Relative amount, %	Bound type	Energy of degradation, MJ/m^3
1	Free gas	5-6	Adhesive	0,09
2	Sorbed gas at surface and in macropores	8-10	Physical sorption	0,76-0,94
3	Sorbed gas in micropores Dissolved Gas crystalline	20-25 40-50 3-5	Volumetric filling Interstitial solution Chemical interaction	1,88-2,37 7,6-8,9 13,4-17,8

Table 1. The form and the energy of methane relation with coal.

Volatile yield	A (m^3/(t·K)) at p, MPa							
V, %	1	2	3	4	5	6	8	10
5	0,44	0,50	0,50	0,50	0,49	0,48	0,46	0,43
25	0,23	0,35	0,39	0,40	0,39	0,39	0,38	0,35
50	0,20	0,28	0,32	0,34	0,35	0,35	0,35	0,34

Table 2. The values of thermal methane adsorption coefficient.

coals shows the dependence of the sorption capacity of the temperature and is characterized by a coefficient A for coals of different metamorphic stages and at different pressures (Table 2) (Slastunov et al., 2009).

Analysis of coal degasification results shows that the maximum extraction of methane is observed in the mines, which produce mature coal (vitrinite reflectance of more than 80 %). Such coals emit methane during cracking on microcracks. Kinetics and gas-bearing of coal gas recovery are determined by factors such as the degree of metamorphism, depth, petrographic composition, mining and geological conditions of occurrence.

Coal structure comprises pores of 100 to 0.8 nm, with most of the porosity due to pore size, accordingly to methane molecules. Several classes of coal are identified by the nature of methane movement in different coal pores (Slastunov et al., 2009):

- Molecular pores (0.4-0.7 nm) are commensurate with the size of methane molecules (0.416 nm).

- Volmer pores (1-10 nm). The mean free path is less than the pore diameter of methane; therefore collisions of gas molecules with pore walls in such pores are greater than that between molecules.

- Knudsen pores (10-100 nm). In these pores the mean free path of the molecules is less than the pore size and the nature of the gas movement is molecular.

- Macropores (greater than 100 nm). These pores carry gas diffusion determined by the concentration gradient.

Cavitattion of coal related to fracturing is estimated at 3-12 %. The share of endogenous cracks is not more than 3 % of coal micro-cavitation (Slastunov et al., 2009).

Different parameters of coals fracturing (fracture density, fracture conductivity, etc.) correlate its permeability, which is directly connected with the degassing and methane recovery problems. The most important parameters of fracturing are: mean value of opening and density of cracks (or the average distance between cracks) (Table 3). (Slastunov et al., 2009).

The cracks and macropores contain free gas moving in the filtration process. 50-100 m^3/ton of gas can be released during the sudden release.

In order to increase the permeability hydrodissection-crack opening is conducted without a sharp drop in pressure. Closure of cracks is prevented by injection of the fixing material. In the near-well zone cracks re formed of 2-10 mm, the maximum crack opening is marked at a distance of 30-60 meters from the well (Slastunov et al., 2009). Hydrodissection differs from hydrofracturing with the fact that proppant is pumped into the pre-existing crack, unlike in made cracks in hydrofracturing. Development of a system of cracks in the coal bed exposed to the fluid pumping has several features.

The permeability of coal is determined not so much by the frequency of fractures, as the value of their opening. In this case the gas permeability of strong and tectonically undisturbed coals exceeds permeability of low-strength, highly tectonically disturbed coals for about 50 times (Slastunov et al., 2009).

Methane recovery efficiency depends on the time, formation pressure, permeability, pressure at the wellhead and other parameters. The high sorption capacity of coal and its low permeability determine the need for active exposure for effective methane recovery.

External factors influencing the sorption capacity, are pressure and temperature. The lower pressure and higher temperature, the lower the sorption activity of coal, so the efficiency of degassing binds with pneumatic force, thermal effects, and others.

Type	Degree of disturbance	Coal strength	Average distance between fractures in polished section, mm
I	Undisturbed	Strong	4,0
II	Low-disturbed	Quite strong	1,9
III	Highly disturbed	Incompetent	1,20
IV	Crushed	Soft	0,88
V	Abraded	Soft	0,56

Table 3. Classification of coal according to the degree of disturbance.

Indicators	Advance degassing	Production
Load increment on stope, mln un.fr.	3,3	-
Constriction of entries, mln un.fr.	under 0,4	-
Methane realization (at 100 y.e. /1000 м^3 CH_4) mln un.fr.	0,15	1,5
Greenhouse gas emission reduction, mln un.fr. / (thous. t CO_2)	0,18/(18)	under 0,23/(23)
Total:	4,03	1,82

Table 4. Economic indicators of advance degassing and methane production from coal beds (per well).

During the operation of the mine it makes sense to use complex methods of extraction of methane that combine ground wells drilled on the surface for reservoirs degassing, and underground wells, combined into a single system.

The basic principle of the concept of CBM mining – is a simultaneous extraction of methane at all stages of the development of coal deposits, taking into account changes in the filtration properties of coal bed under the influence of mining. It is proposed to allocate three stages of methane extraction, principally related to various stress-strain state of the reservoir (Puchkov et al., 2010):

1st period – production of methane from unbalanced array (mine design and construction);

2nd period – mine operation to the full development of reserves;

3rd period – complete gas depletion of the coal strata (extraction of methane from the old abandoned mine).

Since these periods are not clearly separated in time, it is the most efficient technology of using the same wells at all stages of the deposit development. This technology reduces gassing in a mine environment, also significantly increases the level of performance and safety of the miners, as well as reduces the cost of operations.

When closing the mines in the mine working a significant amount of methane is remained, 2-3 times greater than the selected volume. Gassing of them lasts many years to come. The solution is to use a stepwise approach to methane extraction during the entire period of development of the CBM field, which increases the efficiency of coal production by reducing gassing in the mine atmosphere, which raises the level of safety and performance, as well as reduces the cost of operations.

This technology should provide safe working conditions of miners, the economic benefits of coal mining and methane, beneficial use of methane produced, reducing the emission of methane into the atmosphere, which will significantly improve the ecological situation in the region. Table 4 shows the economic indicators of advance degassing and production of methane from coal beds (per well). According to these figures we can see the advantage of advance degassing (Slastunov et al., 2012).

Assessment and forecast of the main geological-field characteristics of coal beds is a non-standard task because of the complexity of the structure and form of methane being in the pore space (Desyatkin, Strelchenko, 2010).

In the first stage regional seismic survey is carried out and promising areas for coalbed methane production are identified. It is usually, 2D- or 3D-seismic survey. At the same time the results of regional and detailed seismic survey are interrelated. At the stage of the detailed work, detailed seismic profiling is carried out (when exploration wells are drilled in the CBM section) in order to build geological and geophysical models of the studied area. Geological and technological studies of wells include the study of mechanical speed, weight on bit, the dominant frequency of the drill string vibration, etc.

Geological-geophysical (including petrophysical) and technological research in the first stage of the study determine filtration-capacitive, mechanical properties, elemental and material composition of coal and coal-bearing rocks, as well as properties of such coals as volatile content, vitrinite reflection, humidity, gas saturation and others.

The gas permeability of coal beds is determined either by hydrodynamic methods, or on polished sections by the formula of Romm (Slastunov et al., 2009):

$$k_T = A\frac{b^3 l}{S} = Ab^3 L$$

where k_t – fracture permeability, 10^{-3} mm^2, A – numerical factor depending on the geometry of the fracture system, b – fracture opening width, mm, l – the total length of fractures, mm, S – area of the thin section, mm^2, L – specific length of fractures, mm.

Since the carbon core changes its characteristics when brought to the surface, the most common application received hydrodynamic methods.

In practice, the mining industry also uses a different parameter – the coefficient of gas or liquid filtration through the rocks. Filtration coefficient depends on coal grades (Table 5) (Desyatkin, Strelchenko, 2010).

Application of coal prospecting geophysics (V.V. Grichuhin) allows determining the material

Filtration coefficient, 10^{-5} m/min	Long-flame	Gas	Fat	Coking	Forge	Nonbaking	Anthracite
$K_{ф.max}$	4,24	3,50	13,70	3,50	3,27	3,40	9,70
$K_{ф.min}$	3,12	0,20	0,26	0,80	0,26	0,30	0,13
$K_{ф.ср.}$	3,68	1,45	2,45	1,54	1,30	1,63	1,74

Table 5. Limits of filtration coefficient change for various grades of coal.

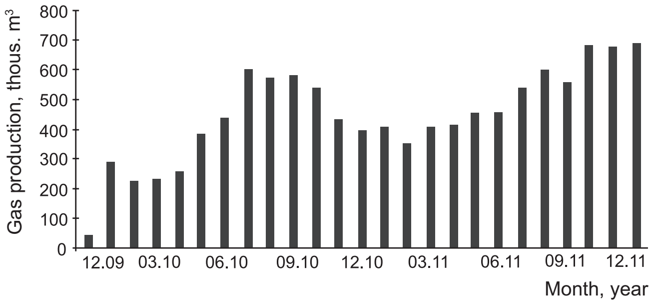

Figure 3. Extraction of coal bed methane in the Kemerovo region.

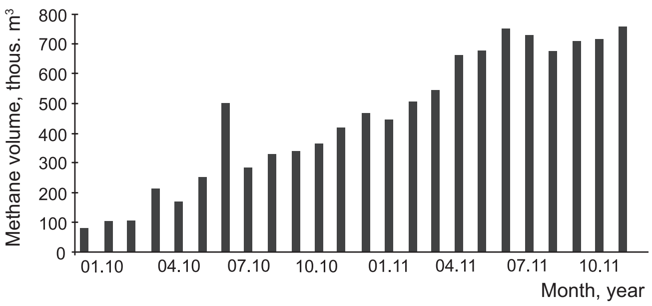

Figure 4. The use of coal bed methane in the gas-filling compressor truck station in the Kemerovo region.

and size distribution of the surrounding rocks, and stratificating the section. The results are used to construct geological and geophysical model – the basis for constructing hydrodynamic models, as well as for the calculation of reserves of coal and methane in the coalbed methane field.

Calculation of methane reserves in coal beds is a combination of the method of geological blocks normally used to calculate the reserves of coal and volumetric method of estimating reserves of gas (Puchkov et al., 2010).

Preparation of CBM fields to the industrial gas production involves three stages (Khryukin et al., 2009).

1st stage. Allocation of promising basins – large CBM fields. Preparation of feasibility study survey and assessment work on promising areas.

2nd stage. Selecting the most promising areas and places of laying exploration wells. Identification of the most promising permeable intervals.

Sampling of coal to assess their sorption and gas content. Selection of priority areas for exploration works.

3rd stage – Exploration: the trial mining, modeling to clarify the reserves, feasibility studies and field development process, flow diagram of pilot operation.

The main criteria to evaluate the high prospectivity of the basin are: the presence of large-scale resource base, high gas content and permeability, the presence of large gas consumers, efficient gas extraction technology from coal beds.

Russia has a huge variety of industrial resources on the quality of coal – from brown to anthracite. Total resources in coal bed methane of the main Russian coal fields, as described above, are estimated

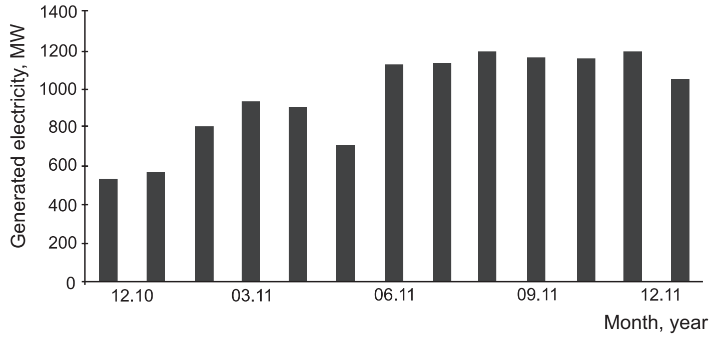

Figure 5. Electricity generation based on coal bed methane.

at 83.7 trillion m^3. Highly prospective basins include Kuznetsk (methane resources -13 trillion m^3), Pechora (1.3 trillion m^3) coal-bearing basins and Apsatsk mine with methane resources of about 55 billion m^3 (Khryukin et al., 2009).

The development of CBM basins such as the Tunguska, Lena, South Yakutia, Bureya, Zyriansky, will begin with a small-scale gas production to meet regional needs, although later to the development of technologies, extraction of methane will be produced and also be used as conventional gas deposits. In the case of the successful organization of gas fields in the highly prospective coal basins of Russia methane production level can reach 17-19 billion m^3 per year (Khryukin et al., 2009).

Industrial extraction of methane from coal beds is the science-intensive process and requires constant scientific support. From a scientific point of view, the problem of extraction of adsorbed methane in coal beds is not studied.

In Russia, production of coal bed methane on a commercial scale is at an early stage of its development (Surin, 2012). In the Kuzbass in 2009 JSC Gazprom has launched the first Russian field on methane production from coal beds on the Tallinn CBM field (Figure 3) (Surin, 2012).

On the first stage the task was worked out of trial operation of exploratory wells, equipment was selected that can be used in harsh conditions of Siberia, well modes were worked out, specialists were prepared, etc. Using the experience of the USA and Canada, own-patented designs were introduced that improve the performance of the wells.

On the field seven production wells are operated, new ones are drilled, technologies for using gas are developed. Sulfur components are completely absent in the composition of gas mixture. To meet the needs of the field and the population, gas-filling compressor truck stations are put into operation (Figure 4) (Surin, 2012).

The produced gas supplies not only to the gas-filling compressor truck stations, but also on the gas piston power plant for electricity generation for own needs of the local population and the field (Figure 5) (Surin, 2012).

In August 2010, exploration works started on Naryksko-Ostashkinsky area of Kemerovo region.

The total capacity of 25 discovered deposits is 60-80 m, prospective resources of methane (Cat. C) – 153 billion m^3 (Surin, 2012).

Using the experience of drilling wells in Tallinn field, on Narycksko-Ostashkinskaya multi well horizontal drilling is applied, which will allow improving the safety of miners due to the preliminary degassing of coal beds in mines under construction. Work is performed on the close cooperation of industrial organizations (JSC "Evraz", JSC "UK" YuzhKuzbassushl" and others) and design institutes (JSC "Gazpropromgaz", CJSC "Giprougol", etc.).

By 2025, it is planned to fully transform all Kuzbass consumers to the local gas (Surin, 2012).

Thus, in practice, it was able to demonstrate technological capabilities and the high demand for coal bed methane as an economical and environmentally friendly fuel. Pilot operation of Tallinn field continues.

Successful international experience, the availability of efficient technologies, a rich resource base, increase in the production cost of conventional gas, increasing demand for gas within the country and abroad – are the main factors of the necessity and feasibility of involving into commercial development of Russian CBM fields.

Technological solutions come to the foreground to optimize the cost, as well as an objective assessment of the prospects for production and sale of methane based on market conditions. And though it is premature to give an unambiguous assessment of coal bed methane prospects across the country, but it can be argued that Russia has all the necessary conditions to ensure that this new resource has become an important part of the future gas industry of the country (Koshelets, 2012).

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Information about author

Margarita P. Yurova – PhD in Geology and Mineralogy, Leading Researcher, Oil and Gas Research Institute of the Russian Academy of Sciences

Russia, 119333, Moscow, Gubkin str., 3

Phone: +7(499)135-71-81, e-mail: mpyurova@mail.ru

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RUSSIAN OIL WILL INCREMENT AT THE EXPENSE OF BAZHENOV FORMATION

A.T. Panarin, A.V. Fomin
Rus-Oil JSC, Moscow, Russia

Abstract. Depletion of oil and gas resources of conventional fields determines the search for new sources of hydrocarbons. The world's largest oil shale formation – Bazhenov Formation has the greatest long-term production potential in the country. Moreover, the BF is located in regions with developed oil and gas infrastructure and its development is of great social importance for the country. However, despite a fairly significant period of the formation research, many of the issues of the geological structure, allocation of productive zones and cost-effective methods of development remain unsolved.

Therefore, for a comprehensive study of this unique object it is necessary to attract a wide range of geochemical, geophysical and geological field methods. In recent years, the expansion of pilot projects carried out by both large and medium-sized oil and gas companies contribute to the cost-effective development.

Keywords: shale formation, Bazhenov Formation, geological structure, allocation of productive zones, cost-effective methods of development

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Russia is one of the recognized world leaders in oil and gas production, but depletion of conventional fields require seeking for a new resource base on scales comparable with the largest developed oil and gas provinces. Development of the Arctic shelf and huge potential of the largest shale formation in the world – the Bazhenov formation (BF) are considered as an equivalent alternatives. If the development of the Arctic shelf is associated with the creation of infrastructure in the severe conditions unfit for human residence, the Bazhenov Formation is developed in areas with existing oil producing infrastructure. Its development in Russia is of great social importance, as the decline in oil and gas production in Western Siberia will affect the economic condition of the country.

Thus, evaluation of the resource base of light oil from the BF ranges from 600 million to 174 billion tons (the middle of this range is greater than the total geological reserves of light oil from all known Russian oil and gas provinces combined). Development of reliable geological model of oil deposits in the BF, on which we can plan cost-effective development, is a major challenge for geologists. But there is no consensus among researchers about its geological structure, especially on the issue of allocation of productive zones. There are more than a dozen of geological models developed. Until recently, the main prevailing theory is that the main conductors of oil in the BF are clays rich in organic matter (OM), foliated and interstratified at the expense of abnormally high reservoir pressures (AHRP). Therefore, mechanized production, which creates a significant depression on the formation, is strictly contraindicated.

In 2007, on the basis of logging data in open hole, single core samples and geophysical studies of gusher wells, specialists of CJSC "MiMGO named after V.A. Dvurechensky" under the leadership of V.S. Slavkin developed a hypothesis that the main conduits of oil in the BF on Sredne-Nazymsky and Galyanovsky fields are dense and carbonized fractured interlayers (Slavkin et al., 2007). In fairness, it should be noted that one of the first, who started associating the BF productivity with dense interlayers, was M.Yu. Zubkov with his colleagues (1999 and 2002). Already since 2007 the BF on Sredne-Nazymsky field has been operated with the use of electric submersible pump and inflows were stimulated by means of hydrochloric acid treatment.

Later on the results of core study with 100 % removal, it was revealed that the main conductors of oil in the BF to the west of Shirotnoye Ob are secondarily transformed layers of radiolarites, which, depending on the nature of these transformations are aporadiolarian limestone, dolomite or aporadiolarian silicite (aporadiolarite). These interlayers are mostly of porous-fractured nature, porosity in some places reach 16 %, permeability – 10 mD. In the logging curves they have the appearance of dense layers.

The uniqueness of the BF as a shale formation lies not only in its size (more than one million km^2), but also in its natural gushers that distinguish it from other shale formations around the world. None of the formations is not characterized by such powerful natural tributaries. Gusher flow rates of the BF can reach hundreds of cubic meters per day, while more than a third of the well inflows were not received at all. The highest flow rate given in the official statistics is 1248 m^3/day for the well No. 141-P of the Salymsky field.

However, it should be noted that for an adequate structure model of this unique object it is necessary to attract the widest possible range of geochemical, geophysical, geological and field study techniques. Results of geochemical analyzes carried out under the guidance of M.D. Dakhnova showed an uneven distribution of the different components of organic matter in the section. Also attempts were made to determine the extent of reservoirs and evaluate their fluid connectivity using one of the methods of reservoir geochemistry (Dakhnova et al., 2007).

The BF is oil source strata, in which the conversion process of OM is not yet complete. Some formed hydrocarbons did not lose a genetic link to the original OM and are sealed in pores, which were formed due to the transition of solid organics into a liquid. This oil is also called proto- (micro) oil; in organic chemistry these hydrocarbons are called autochthonous. AHRP is formed in the BF due to them, by the fact that the volume of bitumen generated is more than of the original OM. Besides autochthonous (related) there are mobile hydrocarbons that lost connection with the original OM, but did not leave the oil source strata. They are called paraautochthonous and related oil – macro-oil. Figure 1 shows how we can distinguish paraautochthonous hydrocarbons from autochthonous. At its core, the method developed in the geochemical center VNIGNI under the leadership of M.V. Dakhnova, is an independent geochemical method of reservoir allocation in shale formations.

Currently, on the number of fields in Western Siberia pilot projects are carried out and oil is being extracted. Multanovsky oil field is located in Surgut district of the Khanty-Mansi Autonomous District of the Tyumen region, 85 km southeast from the town of Pyt-Yah and 110 km from the city of Surgut. Multanovsky field was discovered in 1999. Oil and gas bearing is confined to deposits of the Bazhenov, Vasyugan and Tyumen formations of the Upper and Middle Jurassic (layers J_0, J_{1-2}, J_{2-3}).

Exploration stage at the Multanovsky area began in 1971 by drilling of exploration well No. 2 by Pravdinsky oil exploratory expedition in the swell of the north dome of Multanovsky structure. From a depth of 2796 m (approximate roof of the BF) emergency oil and gas shows began. The well was eliminated without lowering the production casing. Exploration well No. 12 was drilled in 1999 in swell part of Multanovsky structure by JSC "Pravdinsky NGRE". From J_0 reservoir in the interval 2790-2819 m oil flow of 15.6 t/s was obtained. Geological and physical characteristics of formations in Multanovsky field are shown in Table 1.

Geological profile of productive deposits is shown in Figure 2. A comparison of core description, logging set, as well as test results in open hole and in production string for the well No. 12 is shown in Figure 3. It can be said that the BF reservoirs are made of tight interlayers, located deep in less dense rocks.

Formation J_0 on the results of core studies from the well No. 106 of Multanovsky field consists of bituminous mudstone, sometimes with interlayers of siltstone (up to 0.2 m) and sandstones (up to 0.4 m), uneven carbonized, dense, very strong with uneven, staggered, half-shell and crescent fractures with numerous lithoclasts of clay-carbonate material. Numerous fine cracks are traced, open and closed, hollow and made of white calcite.

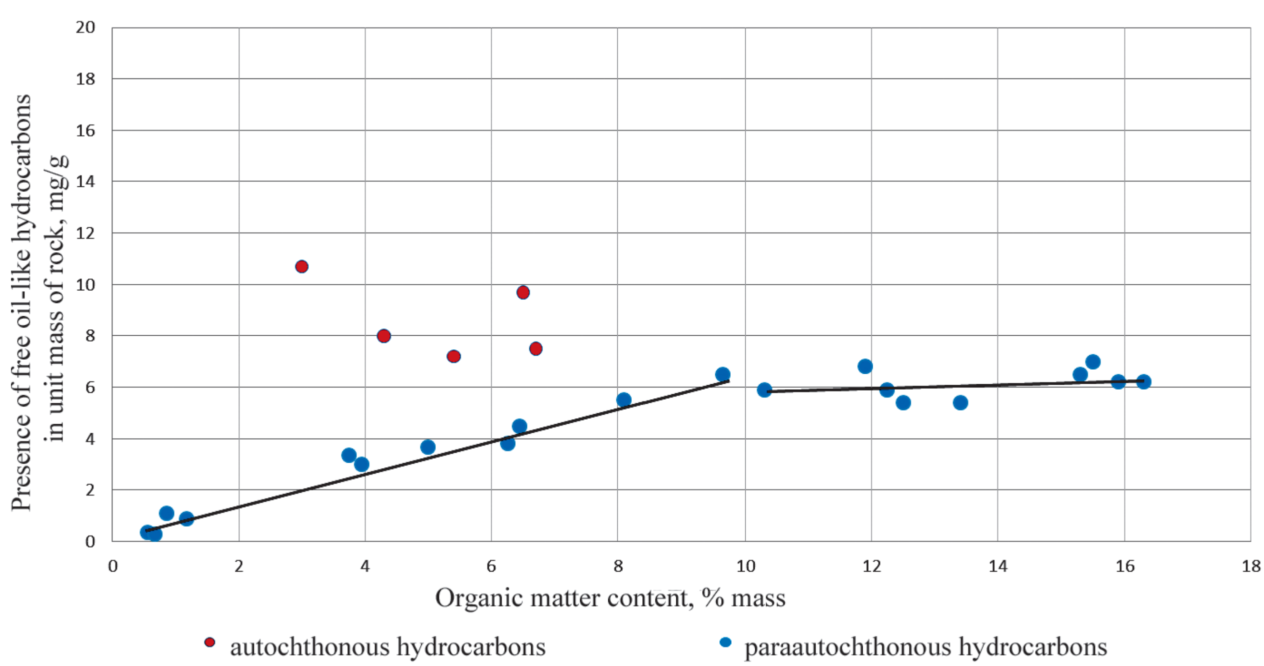

Figure 1. Comparison of the organic matter content and free oil-like hydrocarbons in one unit of the rock mass (according to the method of M.V. Dakhnova).

There are slight gas and oil effusions. According to the results of particle size analysis, sand fraction content in mudstones is 6.68-28.97, silt fraction – 30.21-34.90, politic fraction – 36.13-63.11 %. Sorting is average and good, S_0 = 2.89-5.37, the median diameter of grains – 0.01-0.05 mm.

Currently, two wells No. 25 and No. 33 are operated in oil reservoirs of Bazhenov deposits (J_0). Well No.25 was put into operation in November 2015 with oil flow rate of 17.6 t/s at a buffer pressure of 60 atm. Well No. 33 was put into operation from the drilling in December 2015 with a flow rate of 25.9 t/s. Since the development beginning of J_0 about 14 thousand tons of oil was extracted. Reservoir pressure in well No.25 dropped from 31.0 to 25.3 MPa.

In September 2016 in the process of drilling a project well No.11G when penetrating of the bottom of the Bazhenov deposit, there was a complete absorption of

No.	Characteristics	Formation J_0	Formation J_1^2	Formation J_{2-3}	
				Area of well No.12	Area of well No.9
1	Average depth of occurrence, m	2773-2865	2874,6-2912	2907,2-2927,6	2976-2986
2	Type of deposit	Massive	Layer-uplifted	Lithologically screened	Lithologically screened
3	Type of reservoir	Carbonaceous fractured-cavernous	Terrigenous porous	Terrigenous porous	Terrigenous porous
4	Area of hydrocarbon saturation, thous. m^2	13600	61600	61617	18528
5	Average gross thickness, m	28-30	13-23	26-27	
6	Average oil net pay, m	3,8	5,7	4,8	4,6
7	Porosity, %	10	16	15	15
8	Average hydrocarbon saturation, un. fr.	0,9	0,68	0,64	0,64
9	Permeability, $micron^2*10^{-3}$	5*	32.5	1,6	1,6
10	Net sand coefficient, un. fr.	not determined	0,08-0,63	0,1-0,22	
11	Reservoir compartmentalization, un.	not determined	2-13	3-5	
13	Initial reservoir pressure, MPa	31,0	29,5	30**	30**
14	Reservoir oil viscosity, mPa*s	1,67	0,86	2,14**	2,14**
15	Reservoir oil density, g/cm^3	0,783	0,715	0,825	0,825
16	Oil density at surface, g/cm^3	0,876	0,859	0,88	0,88
17	Absolute depth mark of oil water contact, m	not determined	-2810	-2889	-2919
18	Formation volume factor, un. fr.	1,22	1,4	1,15	1,15
19	Correction factor, un. fr.	0,82	0,714	0,87	0,87
20	Crude sulfur, %	1,51	1,84	1,63-1,7	
21	Oil paraffin content, %	2,39	1,27	2,45-2,62	
22	Saturation pressure, MPa	16,8*	24,7	8**	8**
23	Gas factor, m^3/t	73	133,9	30	30
24	Water density under reservoir conditions, t/m^3	not determined	1,014**	1,004**	1,004**
25	Productivity factor, m^3/day*MPA	not determined	0,86	not determined	0,01
26	Displacement factor, un. fr.		0,478	0,436	0,436

*Table 1. Geological and geophysical characteristics of the productive deposits of Multanovsky field. Note: *– by analogy with Salymsky group of fields. ** – by analogy with Ugutsky group of fields.*

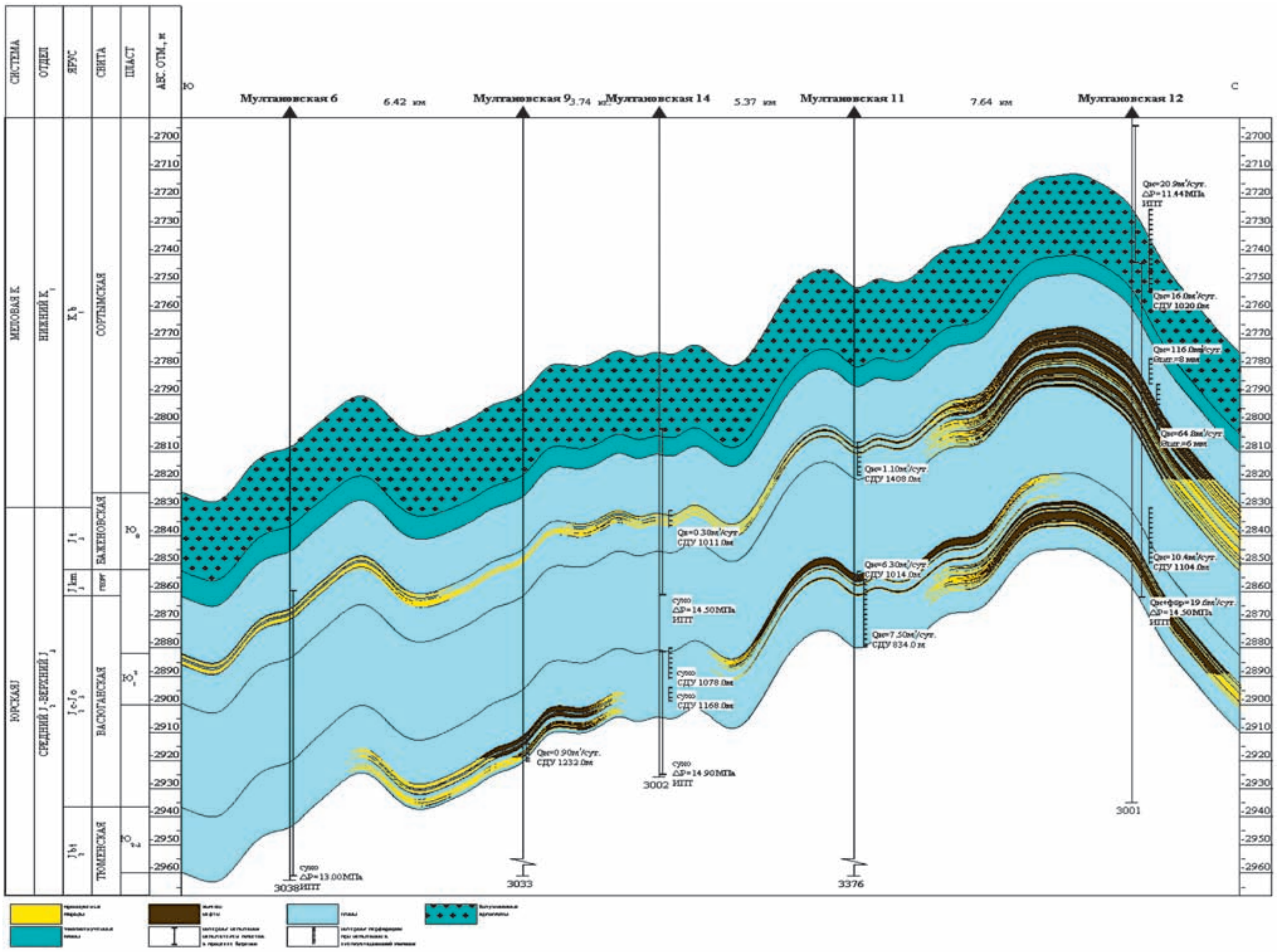

Figure 2. The geological profile of productive strata of Multanovsky field.

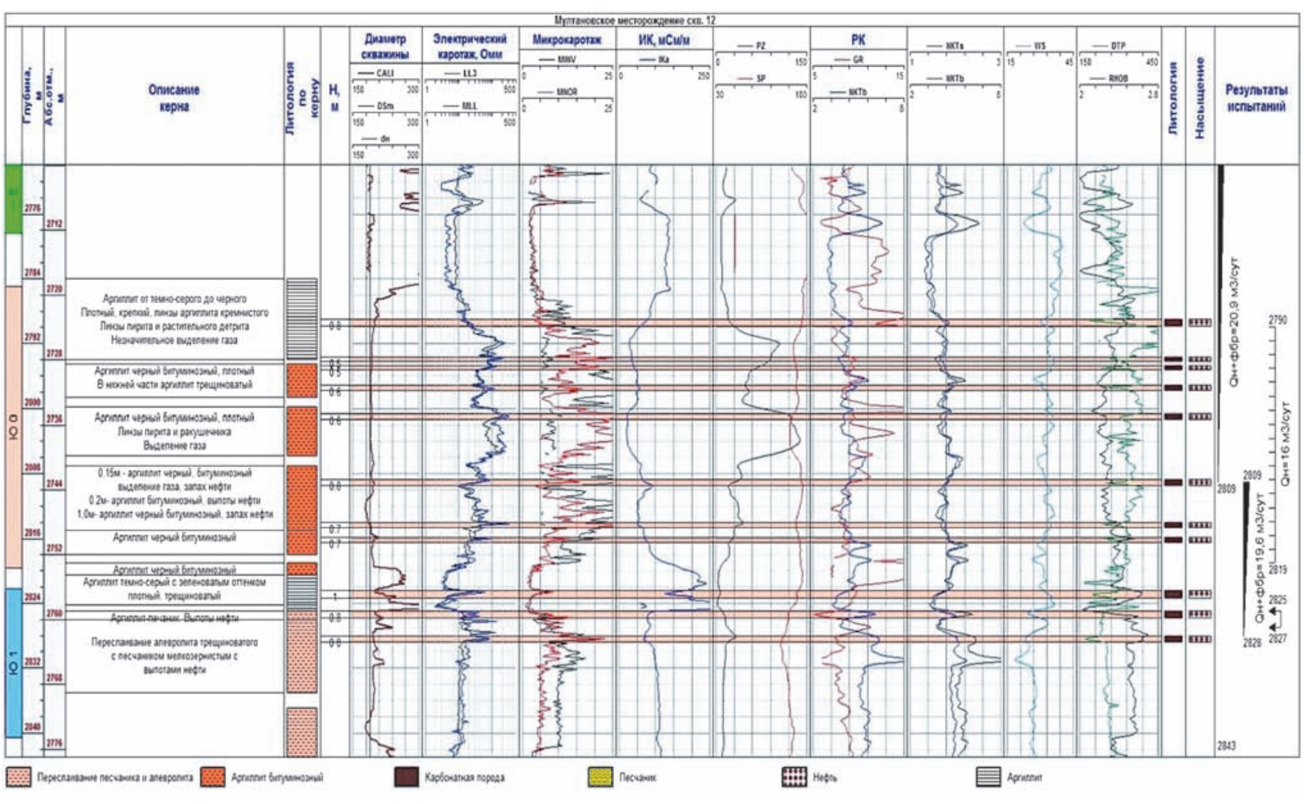

Figure 3. A comparison of core samples, logging, test results in open hole and in production string for the well No.12 of Multanovsky field.

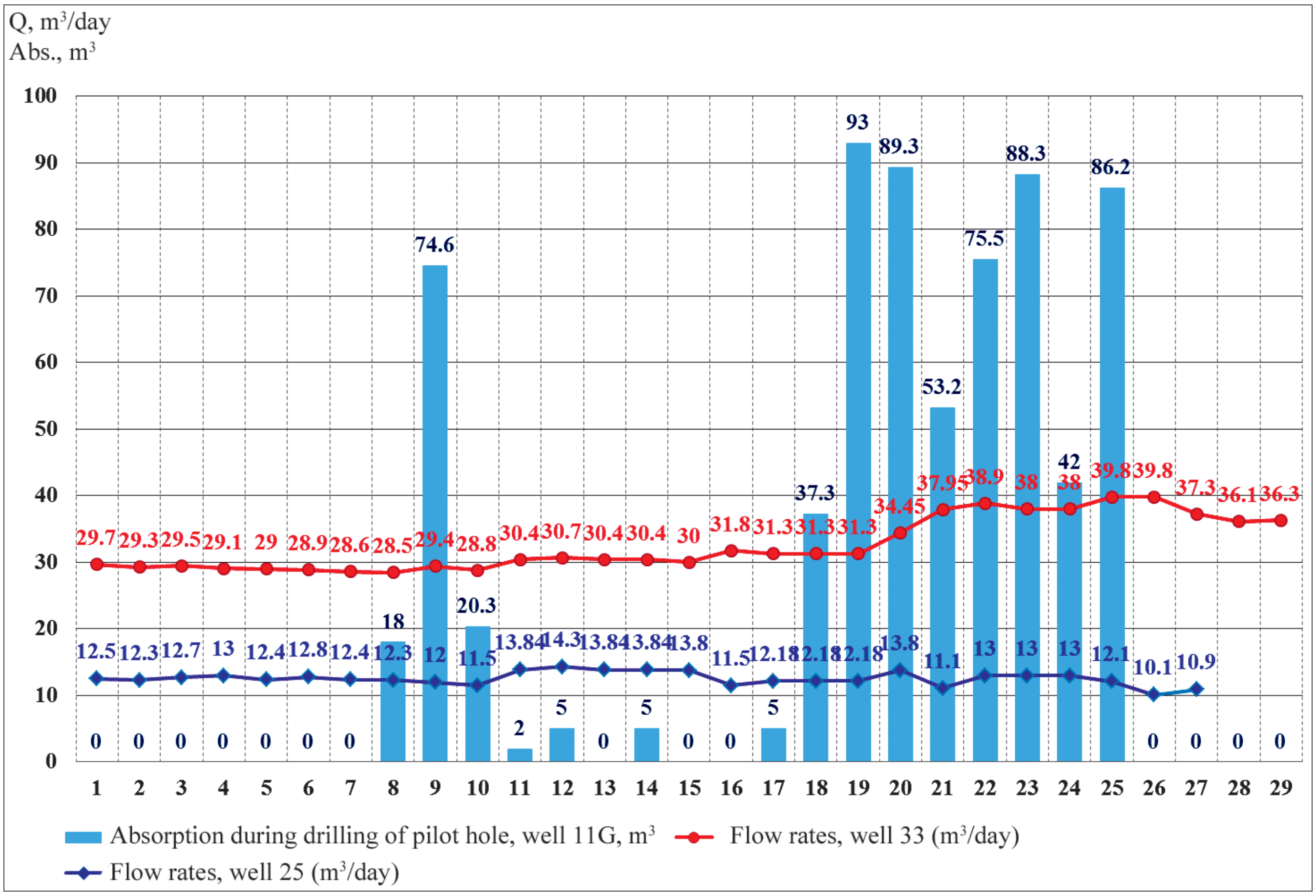

Figure 4. Analysis of the dynamics of production wells No. 25 and 33 depending on the absorption volume in the well 11G.

drilling fluid with loss of circulation. Total absorption was about 700 m^3 of drilling fluid and viscoelastic composition with different colmatants. As a result of this absorption, reaction was observed from wells No. 25 and 33. Dynamics of absorption volumes and flow rates is shown in Figure 4.

This experiment clearly shows that the production of oil from J_0 formation can be carried out with the maintenance of reservoir pressure, with possible injection of not only water, but also the alternation rims of viscoelastic compositions, polymer, fiber-dispersed systems and other physical and chemical methods of enhanced oil recovery. Fluid injection pressure and volumes into the reservoir, the impact technology and parameters definition of injecting viscous compositions, taking into account thin reservoirs-inductors capable of almost instantaneous transmission of the impact impulse through the formation, require further study and clarification.

However, the fact of a quick response of wells by flow rates, on the first cycle of drilling fluid leaving with total volume of 100 m^3 within less than two days, indicates the minimum relaxation time of the environment to the applied impact. It should also be noted that at the extraction of about 14 thousand tons of substantially anhydrous oil, reservoir pressure in the system dropped to 5.7 MPa, which confirmed by a small volume of drained reservoirs, along which the movement of fluids was carried out.

In the US, more than 150 thousand wells are drilled on hydrocarbon deposits in shale formations, the process of studying these deposits continues for more than 60 years, and only in 2010 the rapid growth of shale oil began (Panarin, 2015). In Russia, the issue is only being given due attention in recent years. Of course, that under favorable economic conditions (especially the price of oil) and certain tax benefits, share of shale oil in the total production of the country will steadily increase.

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Information about authors

Aleksandr T. Panarin – PhD in Geology and Mineralogy, Chief geologist, Rus-Oil JSC

Russia, 111033, Moscow, Zolotorozhskiy val str., 32

Phone: +7 (499) 258-57-05 (33205)

E-mail: a.panarin@Rus-Oil.com

Anatoliy V. Fomin – PhD in Engineering, First Deputy Director General, Rus-Oil JSC

Russia, 111033, Moscow, Zolotorozhskiy val str., 32

Phone: +7 (499) 258-57-05 (33157)

E-mail: AFomin@Rus-Oil.com

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INNOVATIVE DEVELOPMENT METHODS OF KEROGEN-BEARING RESERVOIRS THAT PROMOTE OIL GENERATING POTENTIAL

M.N. Kravchenko, N.M. Dmitriev, A.V. Muradov, N.N. Dieva, V.V. Gerasimov
Gubkin Russian State Oil and Gas University, Moscow, Russia

Abstract. In recent years, a very close attention is paid to the problem of search for development methods of Bazhenov Formation. For this purpose, there are at least three reasons. The first deals with the exhaustion of light oil. The second is due to a quantum leap in the knowledge of the geological and physical properties of reservoirs with reserves difficult to recover. Thirdly, the development of innovative technologies made it possible to develop deposits of unconventional hydrocarbons, which include heavy oil, oil of shale fields with low permeability.

Layers of the Bazhenov Formation are characterized by low porosity and permeability, heterogeneity of structure and composition, the presence of kerogen inclusions, high degree of anisotropy and low percentage of recoverable reserves. All this makes these layers to be the objects of study in the search for new technologies, which should take into account the need to change the structure of the reservoir, including its reservoir properties, to be carried out within the pressure and temperature corresponding to the zone of maximum generation. Experimental study of the kerogen properties, as the main source of additional generation of mobile hydrocarbons, allows not only to close the mathematical model, but also to numerically predict the choice of the most optimal methods of development based on the experience of the combination of the wave, thermal and chemical methods for the development of conventional fields.

The authors conducted an analysis of the current state of research of low-permeability reservoirs, and laboratory experiments on the decomposition of kerogen, generation of mobile hydrocarbon phase. A mathematical model was built based on physical and chemical processes occurring under the influence of heat waves and high pressure waves generated in the reservoir when using thermochemical methods.

Keywords: unconventional hydrocarbons, kerogen, thermochemical methods, decomposition kinetics, mathematical modeling

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Introduction

To date, the search for new effective methods of development of hydrocarbon deposits difficult to recover is as relevant as ever. From the set of proposed technological solutions, part of them essentially repeats the approaches to the development of conventional reservoirs with slight modifications in the sequence of operations. Part is in the testing stage, is used for certain types of resources, such as heavy oils; there is not enough sampling on the stimulation results for reservoirs of another type, for example, with low permeability and kerogen inclusions.

Mostly multiple fracturing techniques, methods of in-situ combustion and integrated EOR combining thermal and thermochemical methods are being tested for the development of low-permeability reservoirs. The 'modern innovations' suggested for hydrocarbons difficult to recover are not intended to search for fundamentally new methods of influence on layers, but basically use the special properties and qualities of the rock and saturating fluids, including those that take into account the generation of additional hydrocarbons in reservoirs, originally having a small the volume of mobile oil.

Another kind of hard-to-recover material is no exception to this trend, to which this paper is devoted, and which comprises a huge amount of the world's hydrocarbon reserves and potential reserves of Russia, namely, the reserves concentrated in kerogen-bearing reservoirs. This group includes the deposits of the Bazhenov and other oil and gas source formations.

Feature of considered deposits is that kerogen contained in the composition of their formation (in solid phase) has a oil and gas generating potential, through which it is able, under certain conditions, to be converted to certain mobile hydrocarbons. In nature, this process occurs spontaneously in the scale of geological time (millions of years) due to a gradual increase in pressure and temperature during sedimentation and is accompanied by a variety of slow-phase transitions and chemical reactions, to the course of which the mineral component of the formation, bacteria and other elements of the environment affect.

However, obtaining an additional inflow from kerogen is possible in a shorter time under artificial external influence (Karpov et al, 1998; Volkov et al, 2016). Therefore, the obvious conclusion is that the main task in the development of discussed class of fields is production of their potential reserves hidden in the kerogen and not counted in the calculation of reserves.

Theoretical bases and experimental studies of decomposition of solid hydrocarbons

For the preparation of hydrocarbons from the organic matter of kerogen in real time, an additional external influence is required on kerogen-bearing rocks, which, according to the researchers (Nesterov et al., (No.11) 1993; Bazhenova et al., 1993), is to ensure conditions of elevated temperature in the formation in the range 300-520 °C, and the presence of fractures in pore space, resulting in migration pathways for kerogen degradation products (Nesterov et al., (No.11, No. 12) 1993; Korovina et al., 2013). Otherwise, generation of liquid hydrocarbons from kerogen is inhibited regardless of the temperature (Korovina et al., 2013) and pressure level (Nesterov et al., (No.12) 1993).

At the same time a number of papers (Korovin et al., 2013; Kayukova et al., 2013; Volf, Petrov, 2006) notes the formation or increase in size and number of migratory channels and pores as a result of thermal effects on kerogen-bearing rocks.

Summarizing the results of studies in this field, it is necessary to point out that the process of conversion of kerogen organic matter is definitely connected with thermodynamic conditions (temperature, heating speed, size of kerogen formations, the presence of oxygen in the composition of kerogen-bearing rocks, etc.), and depending on them it can proceed differently.

In the world practice nowadays mainly thermal methods are implemented, combined with hydraulic fracturing and horizontal drilling. The main objective of these techniques is heating up rocks and increase their capacity. In Russia, thermo-gas method is considered as the most promising, used today in deposits of the Bazhenov Formation. Method is comparable to the in-situ combustion, however, instead of combustion, it includes low- temperature oxidation reaction.

All the technologies to a greater or lesser extent can be accompanied by the processes of generating hydrocarbons from kerogen.

However, often, the authors in describing the nature of the technology, designate production of immobile hydrocarbons, which are concentrated in low-permeability rock matrix as the main task, instead of generating processes. This situation stems from the problem of hydrodynamic description of filtration in conditions of kerogen-bearing reservoirs.

The mathematical description of multiphase filtration in kerogen-bearing reservoirs, arranged during the development with the use of any method, is complicated by the need to consider the features of rocks and the processes occurring in them, such as influx of mobile phase, increase in pore volume, change in reservoir properties and thermodynamic state of the system as a whole due to the absorption and release of energy during physical-chemical reactions of kerogen transition into hydrocarbons and others.

The aim of this study was to create a mathematical model of multiphase filtration in complex anisotropic formation that takes into account the presence of physical-chemical reactions and an additional influx of hydrocarbons due to their generation from kerogen.

Generating capability of heavy hydrocarbons can be assessed from the point of view of the thermodynamic potential as a metastability measure of heavy hydrocarbons. The possibility of decomposition of heavy hydrocarbons is characterized by a phase diagram P-T. Construction of the phase diagram and its analysis for kerogen will provide an opportunity to evaluate the best options for exposure, if the conditions of the process implemented will meet the metastable zone of solid (kerogen) phase.

According to the diagram of kerogen decomposition (Tissot, Velde, 1981), at depths below 1000 meters (with a pressure of about 107 Pa) kerogen at thermal exposure decomposes to liquid hydrocarbons, and at pressure of 108 Pa only gas is generated from solid hydrocarbons.

The paper (Karpov et al., 1998) studied the question of heavy hydrocarbons decomposition into methane and solid carbon at high pressure and temperature zone. The authors noted that in the layers in the temperature range from 170 to 230 °C the half-life of heavy hydrocarbons is the magnitude of geological time. This corresponds to the accumulation depth of geologically generated oil and solid carbon (up to 7 km), and carbon in a pair with a hydrocarbon gas (up to 10 km), which is consistent with the diagram B. Tissot and D. Velde on the occurrence and composition of the reservoir fluid.

However, it is noted that in the temperature range 300-700 °C, conditions of solid hydrocarbons decomposition may be realized in the deeper layers of rocks closer to the mantle, and the decomposition time can be reduced by thousands of years to few days. Temperatures in the hydrocarbon formations to depths of up to 7 km do not exceed 250 °C (Kontorovich, 1972). Since the rate of phase decomposition increases dramatically with increasing temperature, it means that at a depth of more than 7 km metastable hydrocarbons can exist – they decompose to a mixture of hydrocarbon gas and carbon solid.

Figure 1, P-T diagram of carbon shows the above results (Karpov et al., 1998) in the high pressure

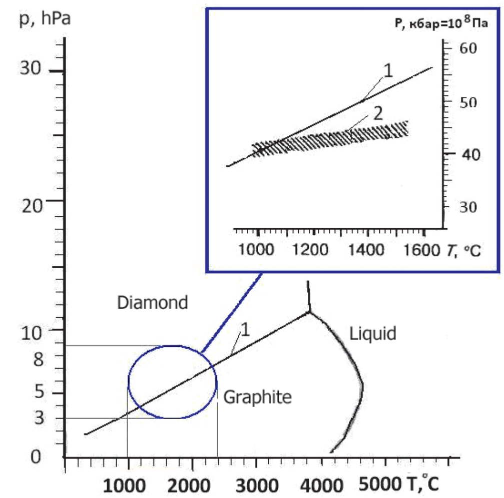

Figure 1. Phase diagram of the graphite-diamond (line 1) and the equilibrium zone for HC (line 2).

(about 10^8 Pa) and temperature range (about 1000 °C): shaded area corresponds to the boundary zone of solid hydrocarbons metastability. In the same paper it is noted that the HC equilibrium zone correlates with the equilibrium line of diamond-graphite (line 1).

Figure 2 shows the line of phase equilibrium for HC (Karpov et al., 1998), which compared with the equilibrium line of diamond-graphite (according to the correlation (Kravchenko, Nigmatulin, 1986), constructed from experimental data (Bundy, 1963)) and the reservoir conditions of kerogen existence for deposits in the Bazhenov Formation (Tarasova et al., 2012).

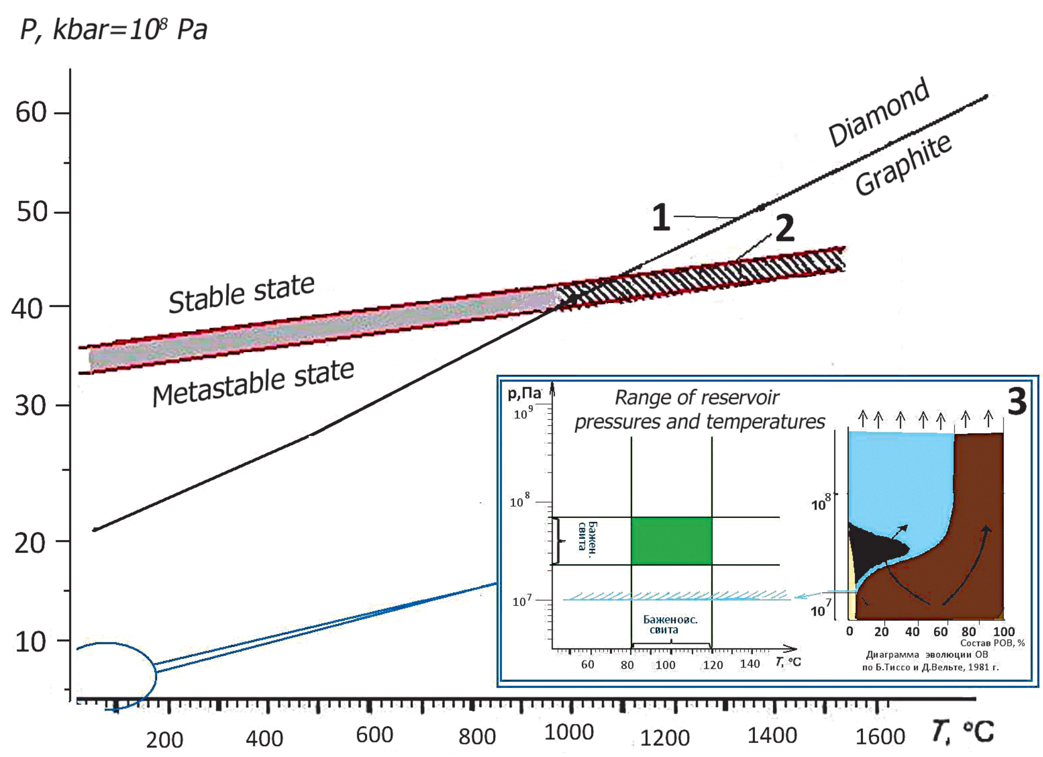

Figure 2. P-T diagram of solid hydrocarbons decomposition and analysis of kerogen in rocks of the Bazhenov Formation. 1 – line of the graphite-diamond equilibrium state. 2 – boundary of phase equilibrium for methane – heavy hydrocarbons. On the tab black color shows area of liquid oil formation, blue color – generation of the gas phase, brown – the presence of kerogen in the formation, green color indicates reservoir pressures and temperatures corresponding to the Bazhenov Formation.

Thus, non-conventional metastable non-flowing hydrocarbons above the equilibrium zone can be stimulated to decompose, only significantly increasing the temperature, stimulating the transition of kerogen in the metastable state. At the same time the energy transition barrier can be calculated from the difference between the internal energy of solid and decomposed hydrocarbon.

Mathematical model and calculation results

The proposed general mathematical model is based on the postulates of mechanics of interpenetrating multiphase continua, and analyzing the results of theoretical and experimental studies of different authors on the behavior of kerogen at different temperature and pressure conditions:

$$\frac{\partial}{\partial t}\left(mc\,\rho_в s_в\right)+div\left(c\rho_в\,w_в\right)=-J_1-J_3,$$

$$\frac{\partial}{\partial t}\left(m\rho_в\,(1-c)s_в\right)+div\left((1-c)\rho_в\,w_в\right)=J_1+J_2,$$

$$\frac{\partial}{\partial t}\left(m\,\rho_н s_н\right)+div\left(\rho_н w_н\right)=b_к J_1,$$

$$\frac{\partial}{\partial t}\left[(1-m)\rho_k\right]=-J_2-b_к J_1+J_3,$$

$$\vec{w}_в=-\frac{k_0 k_в}{\mu_в}\,grad\,p_в;\ \vec{w}_н=-\frac{k_0 k_н}{\mu_н}\,grad\,p_н,$$

$$\frac{\partial}{\partial t}\left[\sum_i \alpha_i\rho_i\,c_{vi}T\right]+div\left[\sum_i w_i\rho_i\,c_{vi}T\right]=\sum_i div(\lambda_i gradT)+JW_к$$

$$b_к=b_к(T,p,c,E_a),\ k_i=k_i(m).$$

where m – porosity; c – concentration of the chemical reagent in aqueous solution; S_w and S_o – water and oil saturation; Ww, Wo – filtration rate of water and oil phases, respectively; J_1 – the rate of mass change of the chemical reagent, spent on rock dissolution reaction per time unit; J_2 – the inflow rate of aqueous phase in the kerogen decomposition and rock dissolution per time unit; J_3 – the inflow rate of coke mass at the decomposition of kerogen, per time unit; v_k – function that relates the amount of spent chemical reagent with the amount of hydrocarbons formed from kerogen; k_0 – absolute permeability; k_i ($i = w, o$) – the relative permeabilities of water and oil, respectively); μw, μ_o – viscosity of water and oil, respectively; α_i – volume concentration of phases for $i = w, o, k$, which corresponds to water, oil and solid portions of the formation; ρ_i – actual density of phases for $i = w$, o, k (water, oil and solid portions of the formation); c_{vi} – the specific heat of phases for $i = w, o, k$ (water, oil and solid portions of the formation); λ_i – the thermal conductivity of phases for $i = w, o, k$ (water, oil and solid portions of the formation); J – intensity of kerogen decomposition; W_k – energy released by the decomposition of kerogen per mass decomposition unit.

Analysis of the available at the moment commercial and experimental studies of kerogen and data used in numerical simulations, has shown the absence of a single view of the kinetics of oil generating reactions.

Based on the analysis of kerogen phase diagram, the authors have set the phase transition kinetics of solid hydrocarbons decomposition on the same principle as the kinetics of the phase transition from graphite to diamond (Kravchenko, 1990).

At the first stage the simple isothermal multiphase filtration model was built with the kinetics of chemical reaction that only qualitatively defines transition of kerogen into liquid hydrocarbons by taking into account in the model of reactive agent, which provides start-up of kerogen decomposition reaction (Volpin et al., 2010). This model has allowed to analyze the filtering features in terms of increasing the porosity, and creation

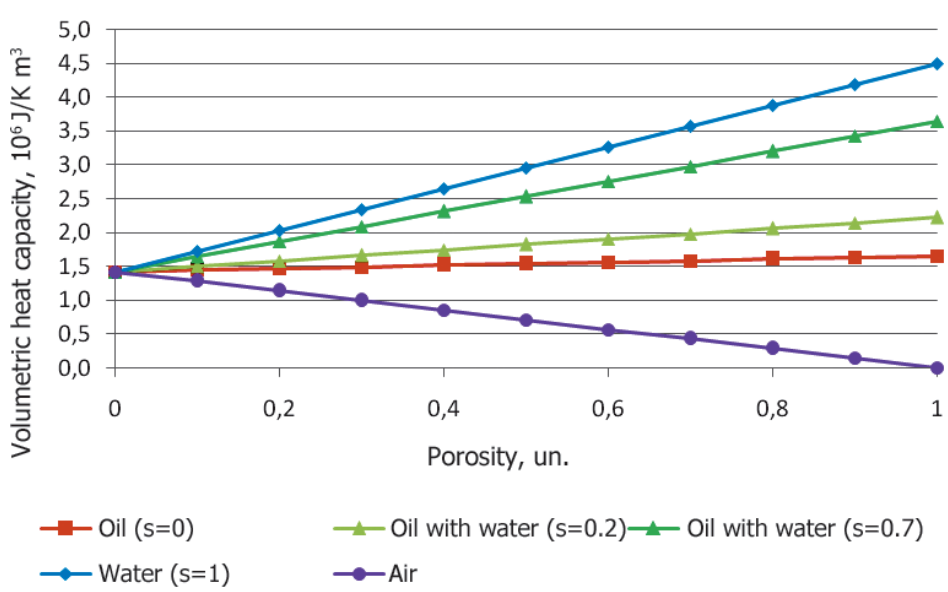

Figure 3. The volumetric heat capacity of sandstone saturated with different phases, depending on the porosity.

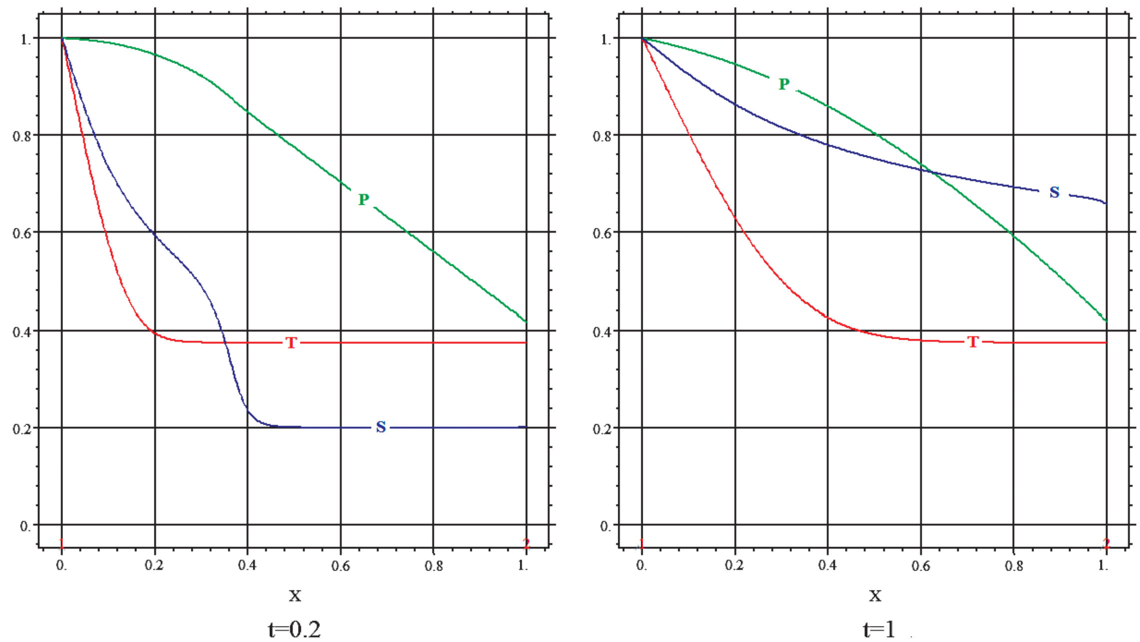

Figure 4. Comparison of pressure (green line), saturation (blue) and heat (red) wave propagation rates in a saturated reservoir (dimensionless time).

of additional inflow of liquid oil generated from solid kerogen matrix.

Sufficiently broad array of input parameters of the model revealed the relationships of field output data (the total amount of additional inflow, time of its achievement) obtained as a result of exposure (development method) with parameters reflecting the formation properties (e.g., oil generating potential of kerogen), and the process of fluid displacement (e.g., the rate of phase front propagation).

In particular, dependences of decomposition time of all kerogen mass were defined, which corresponds to implementation of the full potential of kerogen, depending on the rate of decomposition and injection rate of active agent into the formation. Also, the dynamics of the pore space changes, which affects the change in conductivity was found.

The next step in the simulation was a series of calculations (mathematical experiments), the purpose of which was to monitor the distribution dynamics of the reservoir pressure and temperature waves stimulated by a wave thermal gas-chemical exposure (Volpin et al., 2014) using binary mixtures (based on nitrate ammonium). The model allowed us to estimate ranges of the process parameters (pressure, volume of injected reactive and buffer liquids, the remoteness of reaction zone, etc.) with different arrangement of exposure, knowledge of which is necessary to ensure the safe operations.

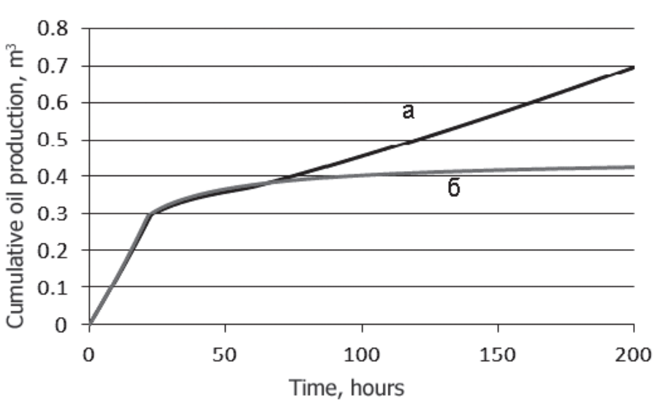

Figure 5. Dynamics of cumulative oil production at displacing it with an aqueous solution of chemically active substance: a) in the layer containing kerogen; b) in the formation and excluding kerogen decomposition.

By means of the model we can 'observe' the emergence in space of formed filtration field areas, taking into account the anisotropy of the reservoir properties distribution, and changes in porosity and absolute permeability in the reaction converting the kerogen into liquid hydrocarbons.

Separately, an analysis was performed of changes in thermal parameters of rocks at its saturation by different fluids, the results of which are taken into account in the model (Figure 3). Figure 4 shows the results of comparing the pressure, saturation heat waves propagation rates. As you can see, the pressure is set much faster in the formation than the two other fronts. Therefore, we can consider the wave and the heat task subsequently.

The comparison is carried out of filtration results in an inert formation and kerogen-bearing formation, taking into account the decomposition of kerogen to form mobile hydrocarbons (Figure 5).

The calculations are made that simulate actual commercial experiments to stimulate oil inflow by thermochemical effects on the some oil fields. The simulation results showed qualitative agreement with the results of actual field experiments; stepwise approach is justified to the analysis of the simulated technological process. On the basis of generalization of theoretical, experimental and field research in the wave, thermal and explosive effects on kerogen, the possibility is justified for effective application of thermo-gas-chemical exposure methods on kerogen-bearing formations such as the Bazhenov formation (Dieva et al., 2015).

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Information about authors

Marina N. Kravchenko – Associate Professor, PhD in Physics and Mathematics, Gubkin Russian State University of Oil and Gas

Russia, 119991, Moscow, Leninskiy pr. 65, buil.1

Phone: +7(903) 764-98-42

E-mail: dep.ngipg@yandex.ru

Nikolay M. Dmitriev – Professor, DSc in Engineering, Gubkin Russian State University of Oil and Gas

Russia, 119991, Moscow, Leninskiy pr. 65, buil.1

Phone: +7(925) 631-84-59

E-mail: nmdrgu@gmail.com

Aleksandr V. Muradov – Professor, DSc in Engineering, Gubkin Russian State University of Oil and Gas

Russia, 119991, Moscow, Leninskiy pr. 65, buil.1

Phone: +7(499) 507-88-35

E-mail: konoplyantseva.i@mail.ru

Nina N. Dieva – PhD in Engineering, Assistant, Gubkin Russian State University of Oil and Gas

Russia, 119991, Moscow, Leninskiy pr. 65, buil.1

Phone: +7(917) 599-17-49

E-mail: ninadieva@bk.ru

Valentin V. Gerasimov – Student, Gubkin Russian State University of Oil and Gas

Russia, 119991, Moscow, Leninskiy pr. 65, buil.1

Phone: +7(915) 405-51-30

E-mail: gerasimovvalentin@yandex.ru

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JUSTIFICATION OF OIL AND GAS POTENTIAL OF THE JURASSIC-PALEOZOIC DEPOSITS AND THE BASEMENT FORMATIONS OF WESTERN SIBERIA

V.L. Shuster, S.A. Punanova
Oil and Gas Research Institute of the Russian Academy of Sciences, Moscow, Russia

Abstract. In terms of perceived decline trend of oil production and reserves increment from the 'conventional' Cretaceous and Upper Jurassic deposits of the main region of Russian hydrocarbon production – Western Siberia, the paper considers oil and gas potential of the Jurassic-Paleozoic sediments and, mainly, the basement formations. It is the basement, along with deposits of the Bazhenov Formation, which is associated with a possible significant increase in resources of oil (gas) in Western Siberia.

In assessing the prospects for the oil and gas potential of the basement, the focus in the research was paid to the study of the structure, including reservoir properties of reservoir rocks and geochemical conditions of oil (gas) deposits formation. According to the assessment we suggested the most favorable directions of exploration, separate forecast for hydrocarbons is made.

Keywords: Western Siberia, basement, pre-Jurassic deposits, deposits of oil and gas, oil and gas potential, reservoir rocks, geochemical conditions, microelements, oil generating potential

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Russia's economic security has been based in recent years on the oil and gas industry, at the expense of which more than half of the country's budget is formed. This trend will probably continue in the coming decades.

Oil production is increasing year by year, at that increasing exports of oil (together with petroleum products), which in 2015 increased by 27 million tons and reached 416 million tons. The growth of oil and gas production makes it necessary to increase oil and gas resources and reserves.

Western Siberia is one of the main regions of Russia for oil and gas production. Replenishment of oil and gas production by increment of reserves and resources in Western Siberia is one of the main tasks of the country's oil and gas industry in the near future for 20-30 years.

In Western Siberia, the main oil reserves are concentrated in the Cretaceous and Upper Jurassic deposits. The promising new objects (areas of exploration works) include basal layers of the Lower and Middle Jurassic and thinning areas of Jurassic horizons (in the north of the territory), sedimentary and volcano-sedimentary rocks of Triassic filling graben-like depressions (here a large Rogozhnikovsky oil field has been discovered), formation of the weathering crust and areas of decompressed basement rocks.

Petroleum potential of the pre-Jurassic complex of Western Siberia has been enlightened in a significant number of publications, including (Schuster, 2003; 2008; Schuster, Punanova, 2011; 2013; 2014; Schuster et al., 2011;. 2014; Punanova, Schuster, 2012; Dmitrievsky et al., 2012; Schuster, Dzyublo, 2012).

Pre-Jurassic complex of Western Siberia has three subcomplexes (Table 1).

Subcomplexes	Age	Lithology	Type of cavernosity	Occurrence depth (km)
Transition subcomplex	Trias, Upper Permian	volcanic-clastic rocks (turin series), limestone and dolomite	porous-vuggy	1,5-2,5
Folded basement	Palaeozoic	metamorphic, magmatic dislocated rocks	fractured-cavernous	1,6-3,0
Consolidated basement	Archean-Proterozoic, in the middle of the basin – suboceanic (Triassic)	magmatic (with predominance of granitoid)	fractured-cavernous	5-6

Table 1. Schematic section of the pre-Jurassic complex of West Siberia.

In the transition complex on Krasnoleninsk swell, a number of oil fields was discovered in Nurolsky trough, including secondary reserves in the Triassic (Permian-Triassic) deposits in volcanic-clastic, carbonate rocks. The band of Triassic deposits stretches 1000 km long from Krasnoleninsky arch by a wide strip to the northwest of Western Siberia, the area of which is promising for oil and gas.

In the north of Western Siberia in the context of deep horizons, oil and gas potential is associated with sandy-silty sediments in Lower and Middle Jurassic and weathering crust at a depth of 3-4 km (Schuster, 2014).

Oxford and Bathonian rocks have the best reservoir properties. Carbonate deposits of Malyshev complex (J_{2-3} formation) at a depth of 3950 m (absolute elevation), apparently have regional oil and gas bearing.

On Nurminsky, Obruchevskt and Rusanivsky megaswells, in the waters of the Gulf of Ob significant prospects of finding hydrocarbon deposits are associated with both Lower-Middle Jurassic and Paleozoic sediments.

On the border of sedimentary cover and the basement in Western Siberia more than 50 deposits of oil (gas) have been discovered and, in addition, about 50 signs of oil have been obtained.

A significant contribution to the study of geological structure and oil and gas potential of the basement was introduced by a number of Russian (Soviet) and foreign researchers, in the first place, the French geologist Ragen (1979), R.Kh. Muslimov (1996, 2014) and the geologists of his school; M.N. Osipov (1982) and others.

With a relative degree of certainty about the oil and gas potential in the basement, the following is known to date (although a number of provisions are still being debated)

- Global oil-bearing of the basement;
- Complex heterogeneous geological structure;
- Sharp variation in area and section of reservoir properties and oil saturation of rocks;
- On a number of oilfields reservoir properties of rocks (and oil saturation) are preserved in the section of wells in the basement rocks at great depths from the surface (up to 2 km on the field White Tiger, Vietnam);
- We have proposed a possible mechanism for the formation of petroleum accumulations in the basement: due to the migration of petroleum hydrocarbons from the adjacent to the basement sedimentary source strata, enriched in dispersed organic matter; on an alternative version – oil fields in the basement are formed by deep fluids;
- Confining beds for hydrocarbon deposits in the basement can be both regional clay-argillic and carbonate rocks (as in Western Siberia), and zonal or local low-permeable granitoids (White Tiger field) and/or volcanic rocks;

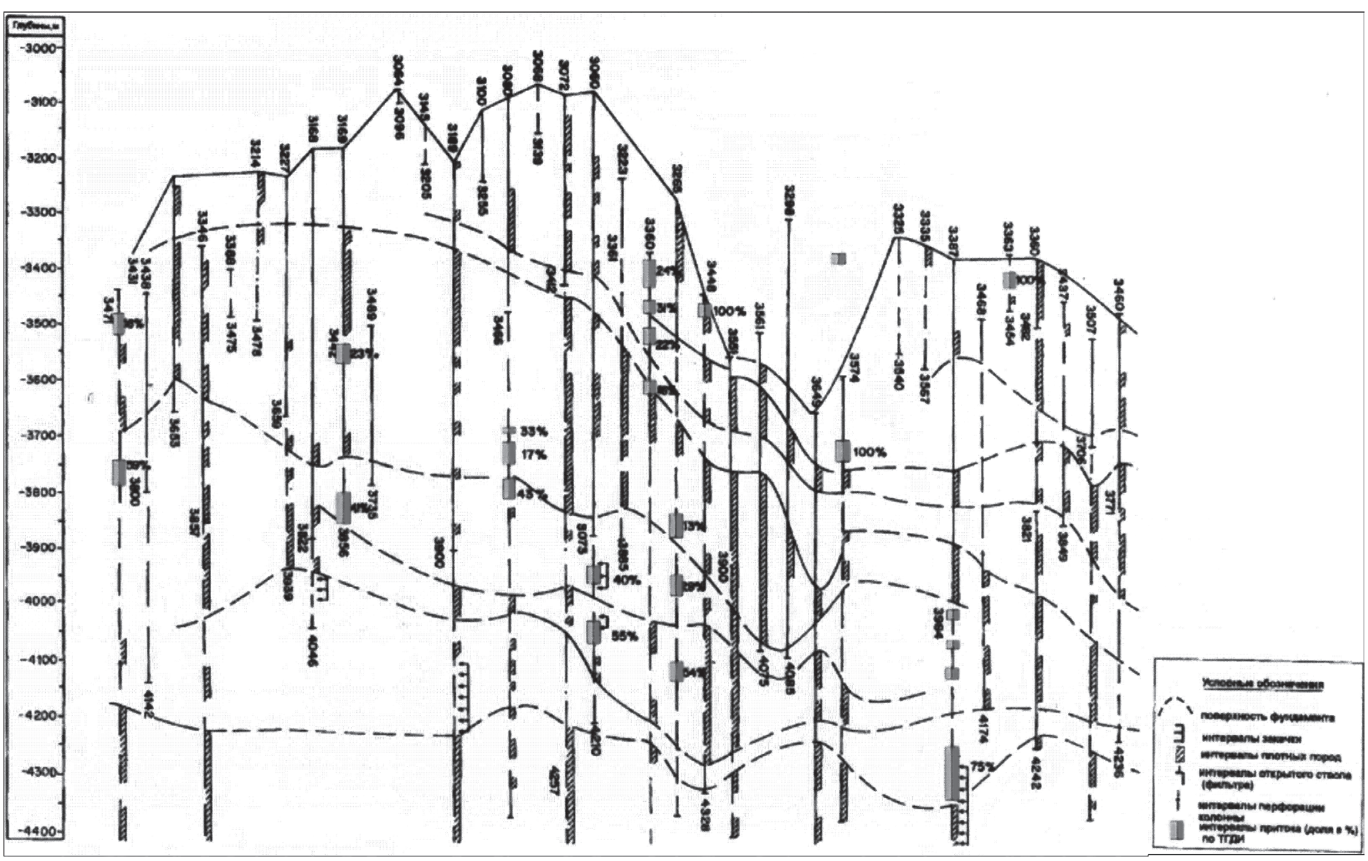

Figure 1. The White Tiger field. Microinhomogeneity of the fractured reservoir (3D seismic survey, logging, field-geological and hydrodynamic data) (Schuster, 2003).

- A sufficiently high hydrocarbon generating potential of sedimentary source strata that clothe the basement ledges in Western Siberia, allows us to evaluate the prospects of the basement as favorable for the formation of large oil and gas accumulations.

New geological-geophysical and geochemical data on deep horizons in Western Siberia, as well as modern innovative technologies of the interpretation of these materials allow with sufficient certainty to justify the high oil and gas potential of the Lower (pre-Jurassic) floor, including the basement formations.

Let us consider two of the most controversial and important geological factors in the assessment of oil and gas potential in the basement structures. They include disribution in the basement of reservoir rocks (and their oil saturation) and geochemical assessment of hydrocarbon generating potential of sedimentary source strata that clothe the basement ledges.

The authors studied in detail enough materials for Vietnamese oil fields in the formations of the basement in the period of work in the Russian-Vietnamese joint venture (1991-1995) in Vietnam. A possible mechanism of formation of oil deposits in the basement was justified in the White Tiger field, a model of this field structure (Schuster, 2003). Sharp filtration-capacitive heterogeneity in the structure of granitoid massif and sporadic oil-bearing of the deposit has been established (Figures 1,2). The following features of the crystalline basement structure have been defined.

As a result of non-uniform cooling of the pluton, tectonic processes that occur periodically during the granite massif existence, the impact on the emptiness of deep corrosive solutions and other geological factors, modern filtration-capacitive properties of the basement in the White Tiger field, revealed in drilled wells, are characterized by abrupt changes both in the well section, and area of the structure.

Moreover, the emptiness of rocks as a rule is fractured or fracture-cavernous, and distributed very unevenly to a considerable depth from the surface of the basemenet, up to 2000 m in some areas (Figure 1). The same pattern has been set according to a large factual material in Tatarstan by R.Kh. Muslimov (1996). Another feature of the basement structure established in the White Tiger field – is detection of the first reservoir rocks in the great depth (300-500 m on average) from the basement surface in some areas of oil deposits (in particular in the Northern swell of the White Tiger field, and also on the fields Kyulong, Dayhung, Vietnam).

This phenomenon can be attributed to uneven cooling of the pluton, faster on contact with the 'cold' sedimentary rocks, processes of weathering and the influence of deep hydrochemical solutions that 'heal' the fractures and cavities.

In addition, an important feature has been revealed of the distribution of oil saturated intervals in the basement deposits. In more than 20 wells thermohydrodynamic studies were conducted, in which intervals were identified of oil inflow into wells. In tested 500-800 meter parts of the section, 20-40 meter intervals of oil inflow were discovered in open hole, which were confined to the main part (60-80 %) of oil production rate of the well.

That is, in the basement thickness, zones or areas of maximum oil content were propagated (Figure 1). Seismic survey 3D CDP, held on the White Tiger

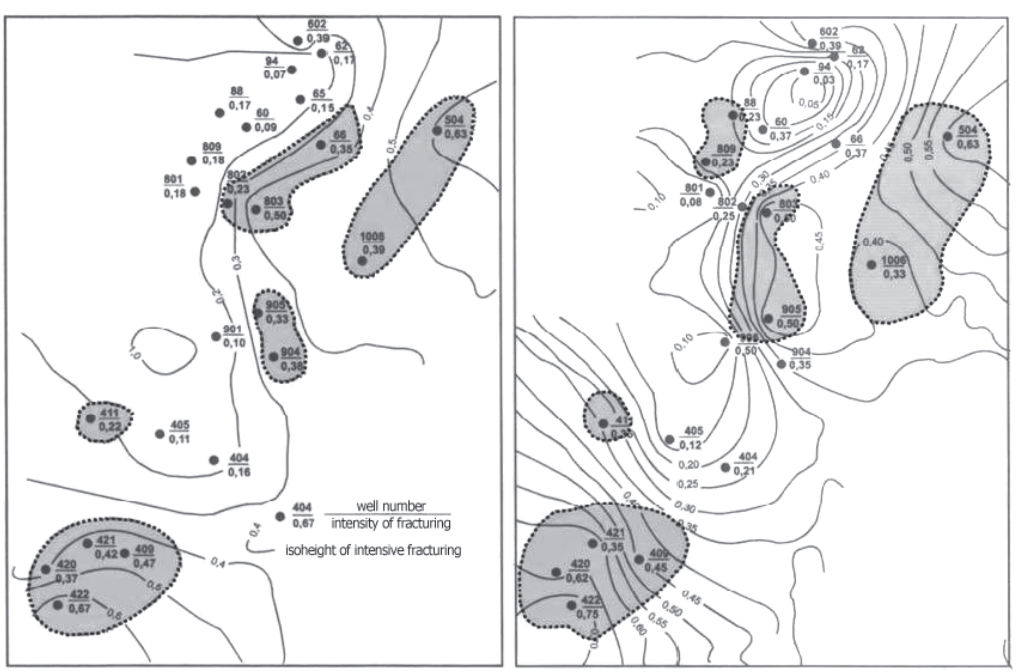

Figure 2. The White Tiger field. Distribution of fracturing in the basement rocks: a) distribution of the fracturing intensity in the penetrated basement (VING data, 1994), b) distrbution of the fracturing intensity in the range of 200 m below the basement roof (VING data, 1994).

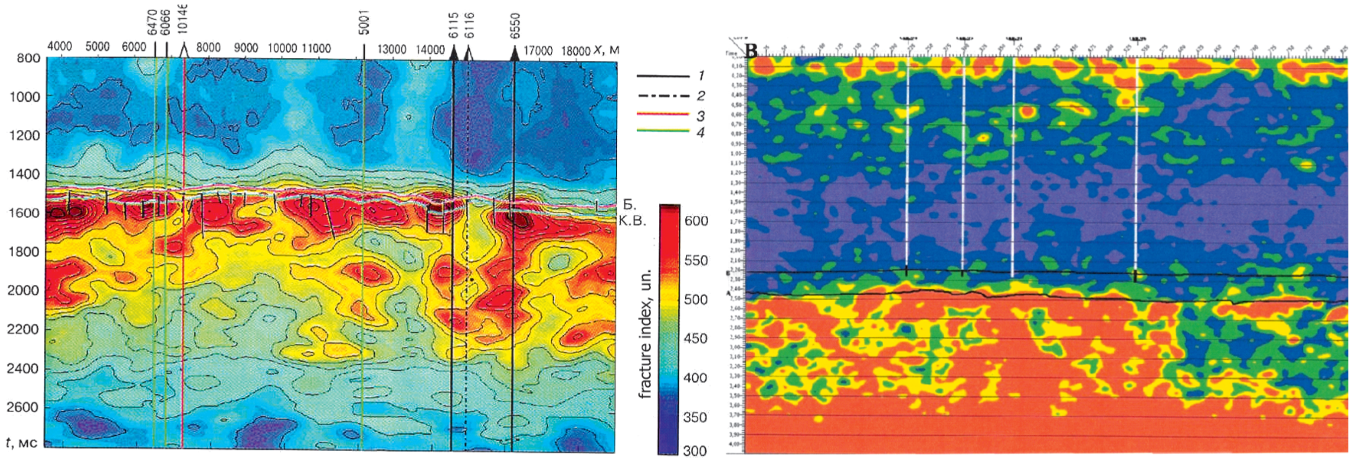

Figure 3. A) Vertical section of the fracturing field along the line with the sustained well test results of the weathering crust: 1 – oil inflow; 2 – oil film; 3 – dry; 4 – the test was not conducted. North-Danilovsky field (Kuryanov et al., 2008). B) Section of the scattered waves energy obtained by the wave CDP method. Ust-Balyk field (Kremlev et al., 2008).

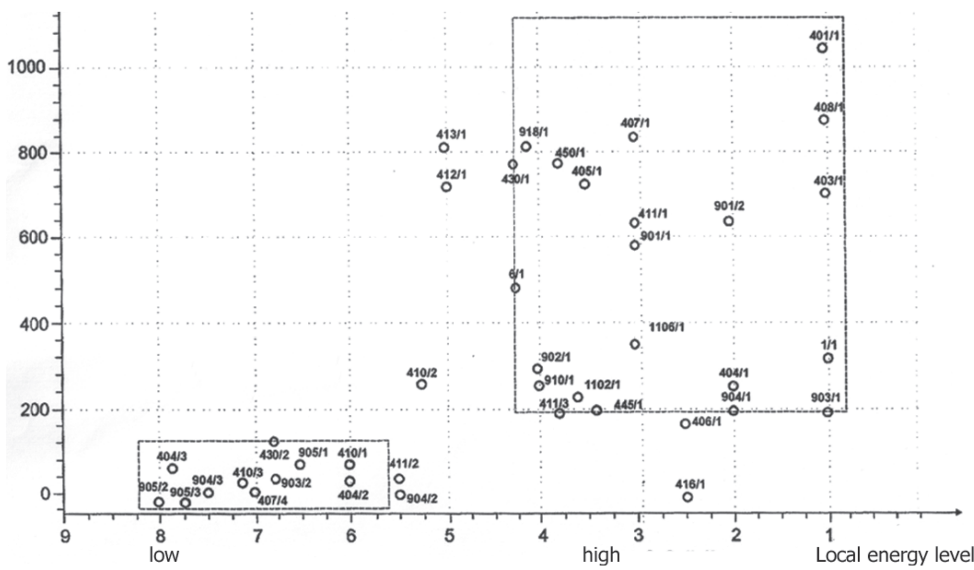

Figure 4. The relationship of the scattered component local energy of the seismic field and reservoir properties (flow rates).

field, allowed in the 1990s to map only the surface (propagation depth) of reservoir rocks. The internal structure of the strata was provisionally mapped by drilling data (logging, core, well testing results).

We have named such a model an uneven-cellular (Schuster, 2003). Assummed structure model can easily be adapted to the conditions of Western Siberia.

In Western Siberia, on numerous oil fields and newly drilled ultradeep wells (SG-6 and SG-7) as well as by core, logging materials, cavernous-fractured, fractured-cavernous-porous space is established, not only in the upper part of the basement (the weathering crust), but in decompressed rocks located at greater depth, below the basement surface (Khakhaev et al., 2008; Kurysheva, 2005). New seismic technology (using the scattered waves) allow today to map the zones and areas of reservoir rocks distribution in the interior of the basement (Figures 3, 4).

The uniqueness of this new seismic technology is determined by the fact that these waves are a response from clusters of irregularity pluralities, which are the fractures and cavities filled with gas or fluid on the falling edge of the elastic wave. The main feature of the scattered waves is their low intensity relative to other types of waves recorded during the seismic survey.

Over the last 10-15 years a number of different technologies for identifying weak scattered waves were developed by local geophysical groups on the background of reflections from extended horizons commonly used in seismic survey (Kuznetsov, 2004; Shlenkin et al., 2000; Kozlov, 2004; Pozdnyakov, 2004; Levyant, Schuster, 2002; Kremlev et al., 2008).

The effective parameter common to all methods is the energy of scattered waves. We (V.B. Levyant and V.L. Schuster) had used in the 2000s this method successfully on materials from Vietnam and India. For Vietnam data in recommended wells a significant flow rates of hydrocarbons were received. Relationship of oil production rate and local energy level is shown in Figure 4.

Focusing on the ‘volume’ of these zones and their location, we can reasonably predict petroleum potential in objects (ledges) of the basement (Kuryanov et al., 2008; Kremlev et al., 2008; Shlenkin et al., 2000).

In addition, based on the experience of exploring oil in the basement, including in Vietnam (Schuster, Takaev, 1997; Schuster, 2003), where the best reservoir properties in the basement are confined to acidic crystalline rocks (granitoids, adamelites), we can recommend the basement ledges with granitoids in the core as the priority objects (such a ‘strip’ of acid rocks is distributed in Shaim arch).

No less controversial and one of the important factors for justifying the petroleum potentional of the basement is the hydrocarbon potential of sedimentary source strata that clothe the basement ledges.

An analysis of the factual material and publications allowed us to join the point of view of scientists who believe that the main source of oil in the basement deposits is the OM of oil source sedimentary strata that clothe and adjacent to the basement. In some fields, where oil deposits were discovered in the basement, a number of indicators mark a close relationship of these oils with oil from sediments overlying sedimentary cover (Schuster et al., 2003). Thus, in the White Tiger field, oil extracted from deposits in the basement and in the Lower Oligocene, are characterized by close values of almost all the studied parameters.

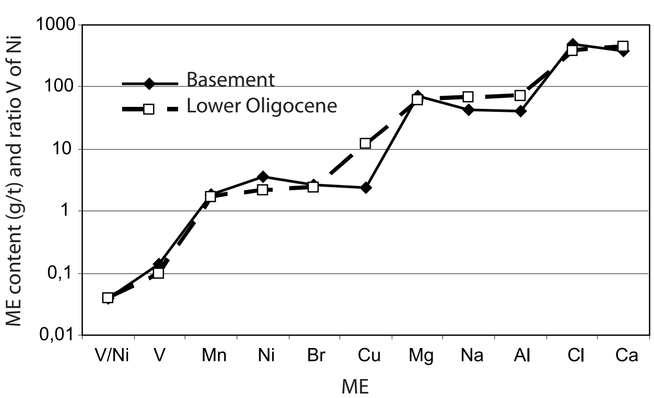

Figure 5. ME content in oil of the White Tiger field

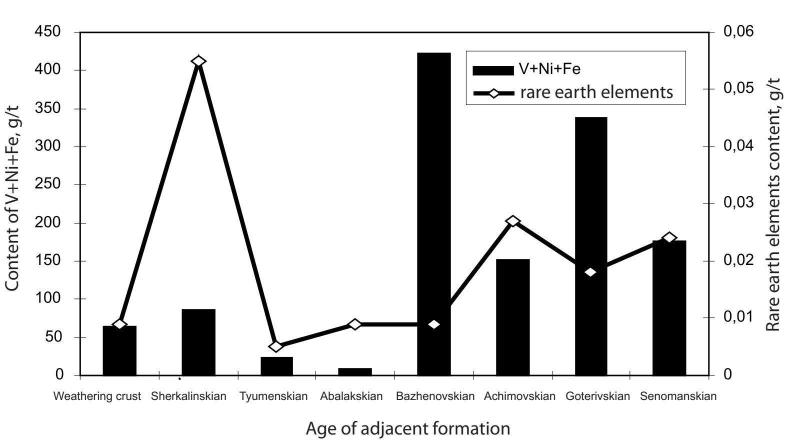

Figure 6. The distribution of elements in oil of Shaim area (data according to rare earth elements (Fedorov et al, 2010)).

This applies to the microelemental composition of oil (definition of microelements is given by Dalat Nuclear Research Institute, Vietnam). We drew attention on the presented Figure 5 on particularly indicative closeness of the oils on the genetic indicator – the ratio V of Ni, which in oil from sediments of the basement and Oligocene is significantly lower than one. Ni predominance over V describes the oil as the catagen converted.

Studying the composition of hydrocarbons (alkanes, terpanes and steranes) in the White Tiger field and organic matter from the deposits of fractured crystalline basement (Serebrennikova et al., 2012) revealed their fundamental difference. According to biomarker indicators these researchers have found that the source of oil was organic matter of mied coastal-algal and surface material of oxidation facies, and in addition, hydrocarbon composition shows a high degree of conversion of these oils.

Assessment of oil and gas potential in pre-Jurassic complex of West Siberia was carried out on a number of key geochemical parameters – the content and type of OM, staging of katagenesis, characteristic of generational kerogen abilities. Based on the analysis of hydrocarbon and microelemental characteristics of naphthides, it is concluded that there are two sources of oil generation, able to saturate the formation of the basement.

They are syngenetic organic matter of the sedimentary Paleozoic and epigenetic, generated organic matter of the sedimentary Jurassic and volcanic-sedimentary Triassic deposits. A significant difference in content of microelemental naphthides of Paleozoic and weathering crust of Jurassic sediments indicates on a separate center of oil formation in Paleozoic formations (Dmitriev et al., 2012;. Punanova Schuster, 2012).

This is especially fixed by comparing the content and ratio of biophilic elements of iron groups (V, Ni, Fe, Mo, Cu, of Zn) and rare earth elements (Fedorov et al., 2010) in oils and bitumen on fields of Shaim and adjacent regions (fields Khanty-Mansiysky, Danilovsky, Novinsky, Martymya-Teterevsky, etc.) (Figure 6). When comparing the concentration distribution in oil of various oil and gas complexes of the Shaim region, we have established a variety of accumulation trends of these groups of elements. It seems that such a distribution of micro elements in naphthides is explained by polygenic nature of their revenues in oil – from organic matter of oil-producing strata for biophilic and deep for rare earth elements.

Polygenic nature of micro elements source in oil was previously identified (Punanova, 2004). The presence of zones of high OM transformation in the pre-Jurassic deposits, confined to the linear elongated Triassic rift

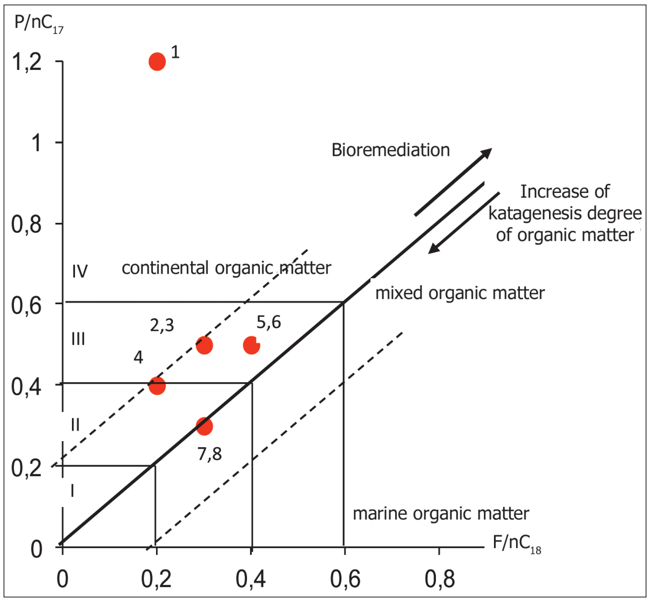

Figure 7. The ratio of isoprenoids and normal alkanes as an indicator of the thermal maturity of rocks and organic matter (chart of Connan-Gassou). Areas: 1. Malyginsky (Ach.); 2. Syadorsky (Ach.); 3. Tarminsky (J_{1-2}); 4-6. Kharasaveysky (J_{1-2}); 7-8. Bovanenkovo (J_{1-2}).

in the basement and large granite blocks and/or fluid-conducting faults (Kontorovich et al., 2008; Fomin, 2008) contributes to these processes.

Evaluation of hydrocarbon potential from the geochemical position is based on the isolation in the section of oil and gas source strata, which in a first approximation are fixed by the generating capabilities of oil and gas source deposits is determined by the results of the analysis Rock-Eval, reflecting the content and composition of organic matter and the nature of

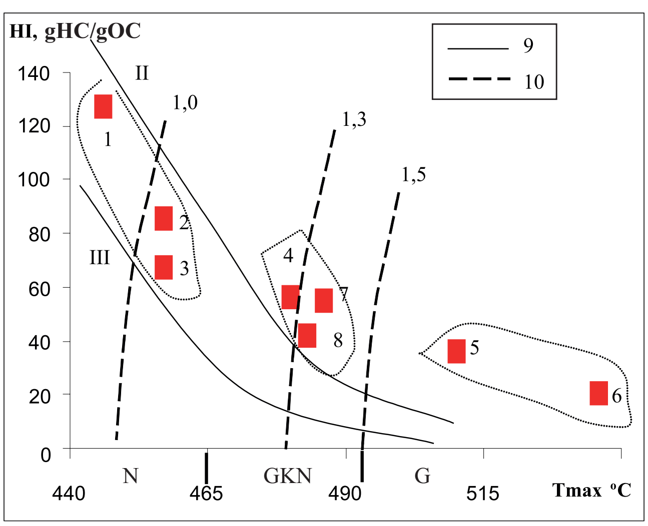

Figure 8. Dependence of hydrogen index from Tmax. Areas: 1. Malyginsky (Ach.); 2. Syadorsky (Ach.); 3. Tarminsky (J_{1-2}); 4-6. Kharasaveysky (J_{1-2}); 7-8. Bovanenkovo (J_{1-2}). Legend: 9 – lines, separating the facies-genetic types of OM (II and III), 10 – contour lines of vitrinite reflectance (R_0) values. Zones of hydrocarbon accumulations: N – oil, GKN – gas condensate-oil, G – gas.

catagenetic transformations. Study of catagenetic staging of organic matter is a necessary tool for geochemical evaluation of hydrocarbon potential, and in the first place, it refers to the deep, heterogeneous, sometimes dislocated Paleozoic deposits of the West Siberian oil and gas basin.

During katagenesis oil formation in significant scale starts from the end of PK_1 gradation, and goes to the middle of mesocatagenesis – MK_2. In the end of protocatagenesis bitumen formation sharply increases, in mesocatagenesis reaches its maximum intensity and later gradually fades as the depletion of oil source potential of organic matter. Interval of katagenesis scale from PK_3 to MK_2 (R_o = 0.4-1.15) is identified as the main phase of oil generation.

It corresponds in the sedimentary basins section to the main zone of oil generation (Vassoevich, 1967; Kontorovich et al., 1967). In this range of katagenesis gradations, processes of petroleum hydrocarbons formation are predominant over their destruction. Interval of katagenesis gradations from MK_{31} to AK_1 stands out as the main phase (zone) of gas generation.

Overall evaluation of the thermal maturity and type of OM was held by the ratio of isoprenoids and normal alkanes – Connan-Gassou chart (Figure 7). It is known that with increasing catagenetic conversion of organic matter therein increases the content of normal alkanes and the number of isoprenoid hydrocarbons falls. The graph conditionally allocates areas of abnormally high, high, moderate and low maturity of organic matter, as well as areas of mixed, sapropel and humic agents. The basic amount of samples falls into the moderate katagenesis zone and is characterized by mixed type of organic matter.

With increase of depth of sample occurrence (East-Bovanenkovo area, Lower Jurassic) the degree of organic matter conversion increases (high maturity zone) and the type of organic matter becomes more sapropel. On P/nC_{17} sample significantly stands out from the Achimov deposits of Malyginsky area. It is characterized by a lower conversion and humus type of OM. This is also evidenced by the higher ratio of pristane to phytane – 3.8. A second sample from the Achimov deposits of Syadorskaya area on the studied parameters in not significantly different from the Jurassic deposits.

To assess the possible oil and/or gas bearing an indicator Tmax is commonly used (maximum temperature of hydrocarbon output from the rock during its warming with the device Rock Eval) indicating the stage of OM evolution and generation of liquid or gaseous hydrocarbons (Kiryukhina et al., 2011). Figure 8 shows a dependence graph of the hydrogen index HI from Tmax taking into account the types of organic matter and R0 values. Comparative analysis of the graphic material allows locating three groups of points.

The first group corresponding to the Achimov deposits and the top of the Tyumen suite is characterized by an interval Tmax of 446 to 457 °C, which corresponds to the area of the 'oil window'.

Organic matter of Tyumen formation sediments (the second group of points) is characterized by a small scatter of values Tmax (from 480 to 486 °C), which gradually, with increasing the depth of occurrence, reaches very high values – 536 °C. Generation zone of gas-condensate-oil accumularions (East-Bovanenkovo area) is replaced by gas generation area (Kharasaveysky area). As the Tmax increases, HI values drop and the organic matter is classified according to this indicator, as lean, exhausted, lost its generting properties.

The conclusions drawn on the basis of hydrocarbon composition of dispersed organic matter involving pyrolysis data are confirmed by the analysis of the dependence of Tmax from the depth in various areas.

Comparison of geochemical assessments of Lower-Middle Jurassic and Triassic deposits of the Yamal Peninsula areas with the findings that were obtained previously according to estimates oil and gas potential of deep deposits of Nadym-Taz oil and gas region, has revealed the following. Deposits of the top of the Tyumen suite, studied in detail on the materials of ultradeep Tyumen well (SG-6) are located, as well as on the Yamal Peninsula, in the final stages of oil formation, and its lower classes and the underlying sediments of the Lower Jurassic fall into the zone of gas condensates and gas generation.

Differences lie in the fact that the depth of the main zone of oil generation in these different tectonic zones is on a completely different elevations. If on Urengoy uplift the lower boundary of the main zone of oil generation is recorded at a depth of 4250 m, at Urengoi and Tyumen, Samburg and Geological areas – up to 4750 m, then at the Yamal this boundary is raised much higher: up to 3000 m for the Tyumen Formation on the Kharasaveysky area and up to 3800-4000 m in Tyumen deposits on the Tarminsky area and Achimov deposits on the Malyginsky and Syadorsky areas (Chahmahchev et al., 2003; Punanova, Schuster, 2012).

Triassic sediments occurring in deep depressions and not everywhere in the studied area are penetrated on the East-Bovanenkovo and Bovanenkovo areas. By analogy with the well-studied Triassic deposits of the Urengoy ultra-deep well on the territory of Yamal they can be attributed to the gas generating. The depth of the Triassic deposits is 3-4 km. In the Yamal Peninsula the Lower-Middle Jurassic deposits of the Tyumen suite are attributed to the petroleum generating strata. They contain organic matter of a mixed sapropel-humus type (II-III type of kerogen).

On the territory of the Yamal Peninsula and the adjacent shelf most of the Lower and Middle Jurassic deposits are in the gas generation zone, that along with mostly humus type of OM provides extensive development of gas generation processes (Skorobogatov et al., 2003; Skorobogatov, 2014).

Thus, given the large productivity of the Lower and Middle Jurassic deposits and a favorable geochemical environment of pre-Jurassic deposits of the northern regions in the West Siberian oil and gas basin (relatively high content of organic carbon and chloroform bitumoid), high realized generation potential (moderate and sufficient katagenetic warm up of the bowels), in conjunction with other geological prerequisites (reservoirs and confining beds), studied sediments can be regarded as highly promising objects to discover new oil and gas fields.

In Western Siberia, the most favorable conditions for oil and gas accumulation have erosion tectonic ledges of the basement with granitoids in the core, divided into blocks (riftogenic geodynamic regime) and clothing sedimentary rocks that play the role of confining beds and oil source strata.

Confining beds for deposits of oil (gas) in the basement formations of Western Siberia can be Jurassic clay-argillic, carbonate confining beds and low-permeable basement rocks at the top of the crystalline arrays.

For the most of studied areas, where commercial and non-commercial oil flows were produced from the upper part of the section (weathering crust) – 50-100 meters, we have processed the actual material on 72 areas and, using geological and mathematical programs, have given the outlook for oil-bearing of deep basement horizons (Schuster, Punanova, 2013; 2014; Schuster et al., 2014; Bogoutdinov et al., 2015). When processing data in different programs – geological and mathematical program 'Vybor' and using fuzzy logic algorithms, we have obtained similar results. The most promising were exploration areas in the Krasnoleninsk swell and Shaim arch.

Conclusions

Using the new features of the basement heterogeneity mapping and isolation of reservoir rocks distribution zones and areas, as well as the evaluation of hydrocarbon generating potential of sedimentary source strata, that clothe ledges of the basement, we can reasonably allocate perspective objects in the basement, specifically choose the location and depth of project wells.

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Information about authors

Vladimir L. Shuster – DSc in Geology and Mineralogy, Professor, Chief Researcher, Oil and Gas Research Institute of the Russian Academy of Sciences

Russia, 119333, Moscow, Gubkin str., 3

Phone: +7(499) 135-72-21

E-mail: tshuser@mail.ru

Svetlana A. Punanova – PhD in Geology and Mineralogy, Lead Researcher, Oil and Gas Research Institute of the Russian Academy of Sciences

Russia, 119333, Moscow, Gubkin str., 3

Phone: +7(499) 135-72-21

E-mail: punanova@mail.ru

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