The nature of the formation in clay strata of oil and gas saturated fractured reservoirs

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Abstract. Today, the production of hydrocarbons produced from clay strata of varying degrees of consolidation and metamorphization had widely developed in the world. Currently, there are many hypotheses on the formation of reservoirs in industrial oil-bearing clay rocks. The paper analyzes the mindsets on the occurrence of oil-saturated fractured clay reservoirs, presents factors affecting the distribution of radioactive elements, substantiates the mechanism of formation of fractured porosity in clay oil-saturated strata. Due to the lack of a generally accepted concept for the formation of unconventional clay reservoirs, the article proposes a new hypothesis for the formation of fractured reservoirs in these unique sections, based on a critical analysis of existing views.

1. Introduction

As we know, the natural reservoir in the classical sense is a pool with certain properties limited by fluid traps and that do not have effective porosity and permeability. As a rule, such fluid traps are clay strata, however, the production of hydrocarbons produced from clay strata of varying degrees of consolidation and metamorphization had widely developed in the world. Meanwhile, the natural clay reservoir has several specific features:

- located within the main zone of oil formation;
- reservoir rocks are represented by thin-sheet mudstones enriched with organic matter;
- the reservoir system consists of a permeable conductive fractured part and a poorly permeable porous matrix;
- there are horizontal, vertical and inclined cracks.

In natural clay reservoirs, the rocks are oil source as they are significantly enriched in oil-containing organic matter, i.e. they are of interest as hydrocarbon deposits and have high radioactivity [5]. In this regard, the relationship of these factors is of interest. On the territory of Russia, the characteristic representatives of such deposits are the Jurassic deposits of the Bazhenov Formation, the so-called Bazhenites of Western Siberia, the Khadum deposits, the Khadumites of the Eastern Ciscaucasia and others. For example, the radioactivity of bazhenites reaches 40–70 µR/h with an organic content of up to 8–18 % [3], and the khadumites of the Eastern Ciscaucasia are less enriched in organic matter, 0.4–9.3 %, and accordingly their radioactivity is up to 20–32 µR/h [7, 8].

Many researchers have studied the origin of reservoirs in such clay strata [2, 3–7, 9–12, 16, 17, 19–22], but the question remains unresolved.

2. Analysis of existing views on the occurrence of oil-saturated fractured clay reservoirs
Currently, there are many hypotheses on the formation of reservoirs in industrial oil-bearing clay rocks. Some authors associate the productive zones of the Bazhenov formation with faults that cause cracking [11]. Other researchers reject the leading role of disjunctive disturbances in the formation of collectors of the Bazhenov formation. In their opinion, the formation of the reservoir occurs due to auto-fracturing of the clay stratum by interlayer water and oil fluids resulted in the appearance of a porous-permeable medium with a predominance of horizontal cracks [4]. Some researchers attribute the development of fracturing to the stratification of clays as a result of increased pore pressure [17] during oil and gas formation or the specifics of changes in clay rocks at the catagenesis stage, the transformation of montmorillonites into hydromica leading to deconsolidation at appropriate temperatures and pressures. The main reason is water existing in an unbound state and going into free in the subzone of middle catagenesis. Such water has an increased ability to dissolve [10]. Other researchers suggest that [9] the lithification of rocks, for example, the Bazhenov Formation was accompanied by water squeezing, destruction of organic matter (OM). The occurrence of abnormally high reservoir pressure (AHRP) leads to a breakthrough of oil hydrocarbons and the formation of a fractured reservoir.

Results' analysis of wells tests, for example, in hadumites shows that inflows occur not only from intervals with increased bitumen content. Therefore, it is difficult to assume the validity of the hypothesis about the formation of void space only due to the conversion of organic material which explains the reasons for the occurrence of the reservoir in bazhenites. It is also impossible to explain the formation of the void space due to the AHRP which leads to an increase in clay porosity, and they acquire the properties of reservoirs. The fact that not a single well with AHRP has significant inflows of formation fluid despite significant pressure drops of up to 20 MPa, contradicts this interpretation of the mechanism of formation of void space in Maykop clay. Also, the calculated and analyzed pressure data for the section show that in all wells with tributaries, oil deposits are located in relatively low sections of AHRP zone. We believe that the opinion of P.S. Naryzhny, G.N. Chepak, V.I. Shaposhnikov [22] is unjustified. They believe that the views of A.A. Trofimuk and Yu.N. Karagodin [12] are most acceptable for Maykop clays. These researchers associate the formation of such reservoirs primarily with uneven triaxial compression of rocks. In their opinion, uneven triaxial compression of rocks should capture large thickness and form a continuous development of reservoirs with a predominance of vertical and inclined cracks in them. In fact, horizontal cracks prevail in the reservoirs. Wells test results indicate that the section of these strata shows individual parts represented by reservoirs, while others are not.

As can be seen from the brief review, the views on the formation mechanism of the reservoir do not have unity, although some ways proposed by the authors for the formation of void space in dense clay rocks might have occurred. As V.M. notes Dobrynin [6], perhaps these hypotheses complement one another.

In this regard, in the article, we propose a new hypothesis of the mechanism of mudstones deconsolidation and the formation of secondary porosity in them.

The fact that shale oil and gas are inherent in strata with significantly greater radioactivity, unlike the usual level of clay strata radioactivity, attaches importance to consider the spread features of radioactive elements on Earth.

### 3. Factors affecting the distribution of radioactive elements

Currently, researchers discovered many deposits of radioactive elements of various nature on the globe. The main mass of radioactive elements is concentrated in the upper granite-metamorphic and sedimentary layers of the earth's crust [5] composed of the lightest rocks. Moreover, the most saturated by radioactive elements is the upper part of metamorphic strata, i.e. granite-metamorphic layer, including zones of green shale, epidote-amphibolite and partially amphibolite facies of metamorphism [18]. Deposits associated with intrusions of granite lavas and modern uranium-bearing marine sediments or ancient shales, now represented by shales with a high content of organic material and uranium, are the most interesting for the issue under consideration. As for the deposits of radioactive...
ores associated with intrusions of granite lavas, some researchers noted that the number of radioactive elements varies within even one intrusion, and peripheral parts are often enriched [5]. It was also noted that within the same geological province, the concentration of radioactive elements in granitoids is noticeably higher in younger intrusions, and the concentration of uranium from the Early Hercynian intrusive complex to the Late Hercynian increases by about three times.

According to S.G. Neruchev [13, 15], from the Late Precambrian to the modern era, there are about twenty stratigraphic levels of precipitation, significantly enriched with planktonogenic organic matter, phosphorus, uranium and other elements that always accompany them, up to rare earth elements. Some of them, such as deposits of the Upper Vendian – Lower Cambrian, Upper Devonian – Lower Carboniferous, Upper Jurassic – Lower Cretaceous, Upper Cretaceous – Lower Paleocene, Middle Eocene – Upper Eocene have a wide intermittent global distribution on the globe. Others, such as deposits of the Lower Permian, Upper Triassic, Lower and Middle Jurassic, are less widespread in separate but rather large zones of the Earth. However, we judge the distribution of radioactive elements only by the results of studying them in the upper part of the cortex. The presence of radioactive elements in the subcrustal part of the Earth is only an indirect conclusion.

S.G. Neruchev [13, 15] also established the frequency of occurrence of epochs of uranium accumulation in 31–32 million years and their relationship with other geological phenomena. He concluded that the rhythmically manifesting epochs of an intense accumulation of sedimentary uranium, phosphorus, and planktonogenic organic matter reflect the general pulsating rhythm of the Earth’s development [14]. This corresponds to the time of revitalization of certain tectonic processes: phases of stretching of the earth's crust, stages of active riftogenesis and uncompensated diving, high seismic activity of the bottom of the basin and rather intense volcanic activity characterized by intensive removal from the subcrustal depths of a number of elements (P, U, V, Ni, Cu, Co, etc.). It caused a corresponding biosphere response. Moreover, in these epochs, astronomical masses of uranium accumulated in sediments. For example, only the Upper Permian sediments of the Rocky Mountain Phosphory formation have accumulated uranium, which, at its normal concentration, could be contained in no less than 5 volumes of the World Ocean. Considering other areas where uranium was also accumulated quite intensively in sediments in the Late Permian epoch, it turns out that in the Late Permian epoch uranium fossilized in the amount corresponding to its content in no less than 10 volumes of the World Ocean. A similar picture is also for the Volga part of the Late Jurassic and other periods. The manifestation of the deepest sources of uranium supply in several seas and oceans is also known at present [2]. Hydrothermal metal-bearing sediments of the Red Sea rift also have a significantly increased concentration of uranium. An increased concentration of uranium in sediments is recorded in the central part of the rift zone of the Indian Ocean and the Mid-Atlantic Ridge. In this regard, SG. Neruchev [13] concludes that in the era of increased activity of riftogenesis the manifestation of hydrothermal activity could be much larger and cause the influx of significant masses of some dissolved metals, including uranium with the increased concentrations' attraction to rifts.

A generalization of the materials showed [13–15] that numerous facts from different fields of science are in good agreement and mutually complement each other. They give a generally consistent picture within the concept of a periodic manifestation of the epochs of uranium accumulation and increased radioactivity of the environment in the history of the Earth which repeatedly provoked an intense response of the whole complex of biosphere organisms. We assume that in the rift zones with the downward and upward flow in the mantle, there is a certain conventional layer of matter enriched with radioactive elements and re-rises to the Earth's surface each 31–32 million years. This is the moment of the release of the largest accumulated thermal and other energies with the outpouring of a part of a substance with a high concentration of radioactive elements into the ocean. Such a periodicity of the epochs of uranium accumulation corresponds to figures determining the velocity of the ascending mantle flow at 18 cm per year [1]. It follows that raising the matter flow from the bottom of the mantle to the bottom of the crust will require 15–20 million years, and the full cycle will require 30–40 million years, i.e. this figure is in satisfactory agreement with the periodicity, cyclicity, of the epochs' manifestation of uranium enrichment in the waters of the seas and oceans. Differentiation of
the mantle material under the crust and a gradual increase in the depths of immersions of heavy and radioactive elements deposits occur within the ring structures. All this indicates that in the subcrustal part of the Earth there are gravitational differentiation and accumulations of metal elements, including uranium and other radioactive elements. The thermal model of the Earth and the formation of both deposits of radioactive elements and hydrocarbon deposits still underestimated their role. The increased radioactivity of the waters of the oceans and seas caused an intense response of the biosphere enhancing the mutation process, speciation and extinction of the least resistant organisms and the intensive development of the simplest microscopic and planktonic algae, representing the content of future OM and gradually removing excess phosphorus and uranium from the environment during fossilization of organic matter. This reinforced the role of radioactivity in the formation of hydrocarbons through the formation of classical oil source formations with a high content of organic matter in the form of simple planktonic algae, which developed rapidly due to the response of the medium to its high radioactivity.

4. Substantiation of the mechanism of formation of fractured porosity in clay oil-saturated strata

But how did the formation of fractured reservoirs occur in such strata of mudstones and why are these strata not reservoirs in all their thickness? To understand the mechanism of formation of reservoirs in the bulk of clay, mudstones, according to [21], we analyzed the patterns of decay of radioactive elements in four known radioactive series.

1. Uranium-Radium Series:

\[
\begin{align*}
92\text{U}^{238}(\alpha, \tau=4,4710^{6}\text{years}) \rightarrow & 90\text{Th}^{234}(\beta, \tau=24,1\text{days}) \rightarrow 91\text{Pa}^{234}(\beta, \tau=1,18\text{min}) \rightarrow 92\text{U}^{234}(\alpha, \tau=2,4510^{4}\text{years}) \rightarrow 90\text{Th}^{230}(\alpha, \tau=8,10^{4}\text{years}) \rightarrow 86\text{Ra}^{226}(\alpha, \tau=1,610^{6}\text{years}) \rightarrow 86\text{Rn}^{222}(\alpha, \tau=3,82\text{days}) \\
& \rightarrow 84\text{Po}^{218}(\alpha, \tau=3,05\text{min}) \rightarrow 82\text{Pb}^{214}(\beta, \tau=26,8\text{min}) \rightarrow 83\text{Bi}^{214}(\beta, \tau=19,7\text{min}) \rightarrow 82\text{Po}^{214}(\alpha, \tau=1,6410^{-4}\text{s}) \rightarrow 82\text{Pb}^{210}(\beta, \tau=22,3\text{years}) \rightarrow 83\text{Bi}^{210}(\beta, \tau=5,01\text{days}) \rightarrow 84\text{Po}^{210}(\alpha, \tau=138,4\text{days}) \rightarrow 82\text{Pb}^{210} \text{(stable)}. \\
\end{align*}
\]

2. Uranium-Actinium Series:

\[
\begin{align*}
92\text{U}^{235}(\alpha, \tau=7,10^{6}\text{years}) \rightarrow & 90\text{Th}^{231}(\beta, \tau=25,52\text{hours}) \rightarrow 91\text{Pa}^{231}(\alpha, \tau=3,2810^{4}\text{years}) \rightarrow 89\text{Ac}^{227}(\beta, \tau=21,77\text{years}) \rightarrow 90\text{Th}^{227}(\alpha, \tau=18,72\text{days}) \rightarrow 88\text{Ra}^{223}(\alpha, \tau=11,435\text{years}) \rightarrow 86\text{Rn}^{219}(\alpha, \tau=3,96\text{c}) \\
& \rightarrow 84\text{Po}^{215}(\alpha, \tau=1,7810^{-3}\text{ s}) \rightarrow 82\text{Pb}^{211}(\beta, \tau=36,1\text{min}) \rightarrow 83\text{Bi}^{211}(\alpha, \tau=2,15\text{min}) \rightarrow 81\text{Th}^{207}(\beta, \tau=4,77\text{min}) \rightarrow 82\text{Pb}^{207} \text{(stable)}. \\
\end{align*}
\]

3. Thorium Series:

\[
\begin{align*}
90\text{Th}^{232}(\alpha, \tau=1,4110^{10}\text{years}) \rightarrow & 88\text{Ra}^{228}(\beta, \tau=5,76\text{years}) \rightarrow 89\text{Ac}^{228}(\beta, \tau=5,13\text{hours}) \rightarrow 90\text{Th}^{228}(\alpha, \tau=1,91\text{years}) \rightarrow 88\text{Ra}^{224}(\alpha, \tau=3,65\text{days}) \rightarrow 86\text{Rn}^{220}(\alpha, \tau=55,5\text{ s}) \rightarrow 84\text{Po}^{216}(\alpha, \tau=0,15\text{s}) \rightarrow 82\text{Pb}^{212}(\beta, \tau=10,64\text{days}) \rightarrow 83\text{Bi}^{212}(\beta, \tau=50,6\text{min}) \rightarrow 84\text{Po}^{212}(\alpha, \tau=3,10^{-7}\text{ s}) \rightarrow 82\text{Pb}^{208} \text{(stable)}. \\
\end{align*}
\]

4. Neptunium Series:

\[
\begin{align*}
93\text{Np}^{237}(\alpha, \tau=2,1410^{6}\text{years}) \rightarrow & 91\text{Pa}^{237}(\beta, \tau=27\text{days}) \rightarrow 92\text{U}^{233}(\alpha, \tau=1,5910^{5}\text{years}) \rightarrow 90\text{Th}^{229}(\alpha, \tau=7,310^{3}\text{years}) \rightarrow 88\text{Ra}^{229}(\beta, \tau=14,8\text{days}) \rightarrow 89\text{Ac}^{229}(\alpha, \tau=10\text{days}) \rightarrow 85\text{Fr}^{225}(\alpha, \tau=4,8\text{min}) \rightarrow 85\text{At}^{217}(\alpha, \tau=0,0323\text{ s}) \rightarrow 83\text{Bi}^{213}(\beta, \tau=45,6\text{min}) \rightarrow 84\text{Po}^{213}(\alpha, \tau=4,210^{-5}\text{ s}) \rightarrow 82\text{Pb}^{209}(\beta, \tau=3,25\text{hours}) \rightarrow 83\text{Bi}^{209} \text{(stable)}. \\
\end{align*}
\]

What is characteristic of each of these radioactive series (rows)?

In the first uranium-radium decay series (the initial isotope of uranium with an atomic mass of 238), radium, through alpha decay, forms radioactive gas radon (isotope with an atomic mass of 222 – 86Rn222) with a half-life of 3.82 days. This half-life is small but sufficient for the formation of a certain amount of gas in a specific place, sufficient to create an abnormal pressure rupturing individual packets of clay particles with the formation of cracks. Moreover, radium is a precursor to the appearance of radon in this chain.

The second uranium-actinium series is also resulted from the decay of uranium with an atomic mass of 235 (92U235). The radon gas that appears during the decay of radium (an isotope with an atomic mass of 219 – 86Rn219) has a very short half-life of only 3.96 s, that is, it will appear and decay instantly without time to create concentrations sufficient to cause pressure and rupture of individual packages of clay particles.
The third thorium series of radioactive decay resulted from thorium with a very long half-life at \( \tau = 1.41 \cdot 10^{10} \) years, compared with which the half-lives of radium at \( \tau = 5.76 \) years and even more at \( \tau = 3.65 \) days are negligible, and they cannot leave any tangible amounts of radium by now. The radon gas (an isotope with an atomic mass of \( 220 - ^{86}\text{Rn}^{220} \)), which appears in the middle of this radioactive chain, decays quickly with a half-life of \( \tau = 55.5 \) s and, therefore, as well as in the second row, should not create the necessary pressure to form clay breaks packages, that is, it should not form fracture in clay rock.

The fourth neptunium series with a long half-life of neptunium at \( \tau = 2.14 \cdot 10^{6} \) years by stage decay forms the appearance of uranium and thorium with sufficiently large half-lives, respectively, \( \tau = 1.59 \cdot 10^{5} \) years and \( \tau = 7.3 \cdot 10^{3} \) years but with a very short half-life of the radium isotope (\( \tau = 14.8 \) days). Therefore, it forms a certain concentration of thorium, and the concentration of radium will be negligible. Besides, this series of successive decays generally does not result in the formation of a radon gas, and therefore, with the initial deposition of a radioactive isotope of neptunium in the rock, radon gas will not form in the rock, that will lead to the lack of a condition for the formation of fractures in the clay mass.

Therefore, the decay of the radioactive elements of the thorium and uranium-actinium series, although it results in the formation of different isotopes of radon gas. The lifetime of these gaseous radon atoms is calculated in seconds, and therefore there are no conditions for the formation of high pressure of this gas. The presence in the rock of radioactive elements of the uranium-radium series formed from uranium with a mass of 238 (\( ^{92}\text{U}^{238} \)), can lead to the appearance of an increased concentration of gaseous radon (with a half-life of 3.82 days) in individual rock microdistricts and break it due to the created abnormal pressure.

5. Conclusion

Thus, we can draw the following conclusions:

1. The periodic epochs' manifestation of accumulation of radioactive elements on the Earth indicates their cyclic outflow from the mantle into the ocean and the probability of concentration of radioactive elements in the mantle at great depths with the formation of powerful deposits of radioactive materials.

2. The cyclic introduction of radioactive elements into the waters of the oceans resulted in the intensive development of the simplest microscopic and planktonic algae. These algae represented the basis for the future classic oil source formations with a high content of organic matter and high radioactivity.

3. Those rock strata that mainly had deposits of isotopes of radioactive uranium with an atomic mass of 238 (\( ^{92}\text{U}^{238} \)) during the successive decay of the radioactive elements of the uranium-radium series led to the formation of a radon gas isotope with a maximum half-life of 3.82 days, sufficient for the formation of abnormally high pressure in the microvolume of the rock. This resulted in the rock breaking in this microvolume and the creation of a fractured medium.

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