ВЕСТНИК ПНИПУ. ГЕОЛОГИЯ. НЕФТЕГАЗОВОЕ И ГОРНОЕ ДЕЛО
BULLETIN OF PNRPU. GEOLOGY. OIL & GAS ENGINEERING & MINING
ISSN 2224-9923
Volume / Том 15 №18 2016
http://vestnik.pstu.ru/geo/

УДК 552.086

Article / Статья

EXPERIENCE OF STUDY OF CORE FROM CARBONATE DEPOSITS BY X-RAY TOMOGRAPHY

A.A. Efimov, Ia.V. Savitckii, S.V. Galkin

Perm National Research Polytechnic University (29 Komsomolskii av., Perm, 614990, Russian Federation)

S. Shapiro

Free University of Berlin (74-100 Malteserstr., Building D, Berlin, 12249, Federal Republic of Germany)

ОПЫТ ИССЛЕДОВАНИЯ КЕРНА КАРБОНАТНЫХ ОТЛОЖЕНИЙ МЕТОДОМ РЕНТГЕНОВСКОЙ ТОМОГРАФИИ[1]

А.А. Ефимов, Я.В. Савицкий, С.В. Галкин

Пермский национальный исследовательский политехнический университет (614990, Россия, г. Пермь, Комсомольский проспект, 29)

С. Шапиро

Свободный университет Берлина (12249, Германия, г. Берлин, ул. Мальтезерштрассе, 74–100, стр. Д)

Received / Получена: 30.11.2015. Accepted / Принята: 10.03.2016. Published / Опубликована: 30.03.2016

Key words:
X-ray tomography, radiographic solutions, 2D-slices, 3D-models, core, carbonate deposits, reservoir, petrophysical studies, heterogeneity, voids, porosity, cavities, cracks, irreducible water saturation, oil saturation, capillary tests.

Relatively new direction for geological properties study in petroleum geology nowadays is the use of X-ray tomography. The basis of this method is X-ray rock density study. This paper shows the results of possible X-ray tomography applications while studying petrophysical properties of carbonate reservoir plugs on example of several oil fields in Perm region. The microfocus system of X-ray control with computer tomography Nikon Metrology XT H 225 and software AvizoFire 7.0 were used. The cylinder samples with diameters of 30 and 10 mm and cubic samples with a side length of 5 mm were used in the study. The results of X-ray tomography represent 2D-slices of lengthwise and crosswise sample cross-section, 3D-model of cavities, consolidation areas and initial oil saturation distribution as well as graphs of pore and irreducible water saturation versus sample height and histograms of pore diameters. The study of cavities and consolidation areas distribution in the samples allowed to type core depending on its cavity structure. Analysis of porosity evaluation of the samples with different diameters that were made from the one pies of core showed that correlation coefficient was 0.77. Such relatively low coefficient could be explained by significant heterogeneity of core even in one lithotype. During the irreducible water saturation determination four radiographic solutions were tested. It was noticed that irreducible water does not exist in the large voids (cavities, cracks, big pores). Best results were obtained for NaI and $LaCl_3 \cdot 3H_2O$ solutions. Presented in this paper results allow obtaining most authentic 3D distribution of pore space and fluid saturation during futhure X-ray tomography study of carbonate deposits.

Ключевые слова:
рентгеновская томография, рентгеноконтрастные растворы, 2D-срезы, 3D-модели, керн, карбонатные отложения, коллектор, петрофизические исследования, неоднородность, емкостное пространство, пористость, каверны, трещиноватость, остаточная водонасыщенность, нефтенасыщенность, капилляриметрия.

Относительно новым в нефтяной геологии направлением для исследования коллекторских свойств на сегодняшний день является применение метода рентгеновской томографии, в основе которого лежит изучение рентгеноплотностных характеристик горных пород. В данной работе на примере ряда нефтяных месторождений Пермского края представлены результаты изучения возможностей применения рентгеновской томографии при исследованиях петрофизических образцов керна карбонатных коллекторов. С этой целью применялись микрофокусная система рентгеновского контроля с функцией компьютерной томографии Nikon Metrology XT H 225 и программный продукт AvizoFire 7.0. Объектом изучения являлись образцы керна цилиндрической формы диаметром 30 и 10 мм, а также кубы со стороной 5 мм. Результаты исследований методом рентгеновской томографии представляют собой 2D-срезы продольного и поперечного сечения образцов; 3D-модели распределения пустот, уплотнений, начальной нефтенасыщенности; графики распределения пористости и остаточной водонасыщенности по высоте образца; гистограммы диаметров пор в образце. Изучение характера емкостного пространства и распределения уплотнений в образцах позволило провести типизацию керна в зависимости от структуры его емкостного пространства. При анализе результатов оценки пористости для образцов разного диаметра, изготовленных из одного куска керна, установлено, что коэффициент корреляции составляет 0,77 доли ед. Такой относительно невысокий коэффициент объясняется влиянием существенной неоднородности кернового материала даже в пределах одного литотипа. При определении остаточной водонасыщенности протестированы 4 рентгеноконтрастных раствора и установлено, что в крупных пустотах (каверны, трещины, крупные поры) остаточная вода отсутствует, а наилучшие результаты получены для составов NaI и $LaCl_3 \cdot 3H_2O$. Результаты, представленные в данной работе, позволят получать наиболее достоверные 3D-модели распределения емкостного пространства и флюидонасыщенности при последующих рентгентомографических исследованиях карбонатных отложений.

Artem A. Efimov (Author ID in Scopus: 10044885600) – PhD in Geological and Mineralogical Sciences, Associate Professor at the Department of Oil and Gas Geology (mob. tel.: +007 950 47 92 193, e-mail: lpfi@pstu.ru).
Ian V. Savitckii (Author ID in Scopus: 56613277900) – Assistant Lecturer at the Department of Oil and Gas Geology (tel.: +007 (342) 219 81 24, e-mail: yansavitsky@yandex.ru).
Sergei V. Galkin (Author ID in Scopus: 36711675500) – Doctor of Geological and Mineralogical Sciences, Professor at the Department of Oil and Gas Geology (tel.: +007 (342) 219 81 18, e-mail: gnfd@pstu.ru). The contact person for correspondence.
Serzh Shapiro (Author ID in Scopus: 7402734083) – Doctor of Engineering, Professor, Head of the Department of Geophysics (mob. tel.: +493 083 87 08 39, e-mail: shapiro@geophysik.fu-berlin.de).

Ефимов Артём Александрович – кандидат геолого-минералогических наук, доцент кафедры геологии нефти и газа (моб. тел.: +007 950 47 92 193, e-mail: lpfi@pstu.ru).
Савицкий Ян Владимирович – ассистент кафедры геологии нефти и газа (тел.: +007 (342) 219 81 24, e-mail: yansavitsky@yandex.ru).
Галкин Сергей Владиславович – доктор геолого-минералогических наук, профессор кафедры геологии нефти и газа (тел.: +007 (342) 219 81 18, e-mail: gnfd@pstu.ru). Контактное лицо для переписки.
Шапиро Серж – доктор технических наук, профессор, руководитель департамента геофизики (моб. тел.: +493 083 87 08 39, e-mail: shapiro@geophysik.fu-berlin.de).

[1] Исследование выполнено при финансовой поддержке РФФИ в рамках научного проекта № 13-05-96003 р_урал_а.

Introduction

X-ray tomography of core is a relatively new direction to investigate reservoir properties of oil deposits today. The method is based on study of X-ray specter characteristics of rocks. Theoretical basis of the method applied to the study of reservoir properties (porosity and permeability) is covered in detail in [1]. Analysis of the world experience shows that the method of X-ray tomography begins to be used not only in study of petrophysical characteristics of rocks [2-4], but also in evaluation of enhanced oil recovery methods [5, 6].

This paper shows the results of possible X-ray tomography applications while studying petrophysical properties of carbonate reservoir cores on example of several oil fields in Perm region. The microfocus system of X-ray control with computer tomography Nikon Metrology XT H 225 was used. To study the effect of sample size on the tomography results 25 pairs of same core samples were used. Each pair is a standard petrophysical sample 30 mm in diameter and smaller (5 and 10 mm). The aim of the research is to obtain the characteristics of X-ray specter heterogeneities, voids, fluid distribution in hollow core space.

The methods of detailed assessment of rock structures are most relevant during study of carbonate reservoirs with complex geology [7]. Heterogeneity of carbonate deposits and impact of facial conditions on its reservoir properties are proved in [8]. Accordingly, underestimation of heterogeneity of carbonate reservoirs reduces accuracy of final oil recovery assessment that is shown on the example of number of fields development [9, 10].

During the study following objectives were highlighted:

– lithological description and study of structure of reservoir voids;

– to build 3D-models of voids and calculate porosity coefficient (K_p);

– to select radiographic solutions and model ireducible water saturation in samples;

– to build 3D-models of fluid distribution, calculate initial oil saturation ($K_{i.o.}$) and irreducible water saturation ($K_{i.w.}$).

Lithological description came down to determination of mineral composition, structural and textural features, cement nature, cracks development. All of these data are used in the interpretation of core tomography results.

The results of X-ray tomography studies are as follows: 2D-slices of longitudinal and transverse cross-sections of samples; 3D-models of void distribution, seals, initial oil saturation; charts with distribution of porosity and irreducible water saturation along sample height; histograms of pore diameters in sample [11]. Computer modeling of objects and subsequent calculations were performed in the software package Avizo (Visualization Sciences Group, France).

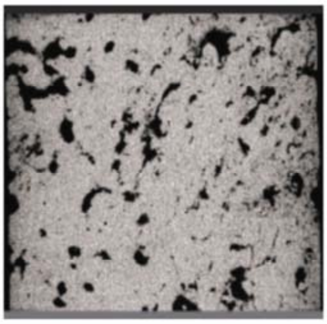
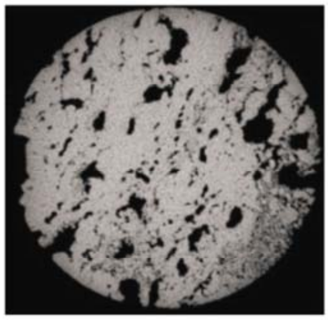
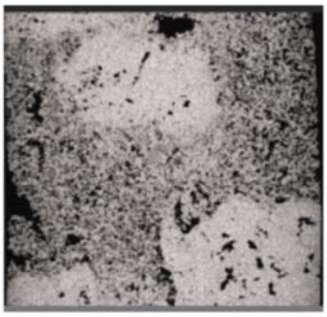
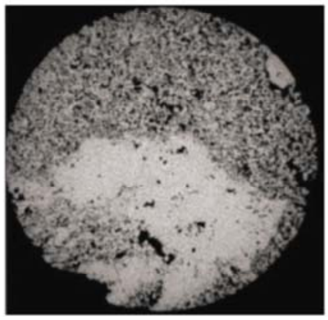
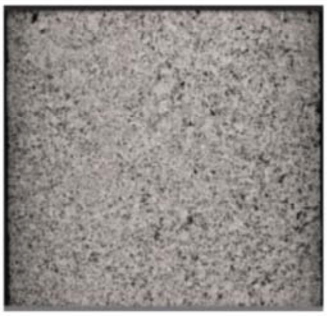
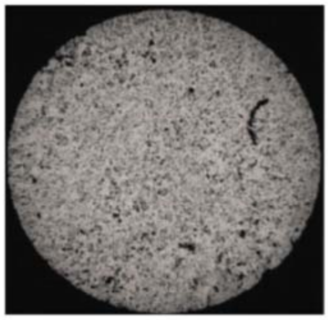
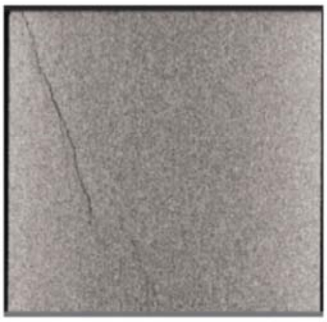
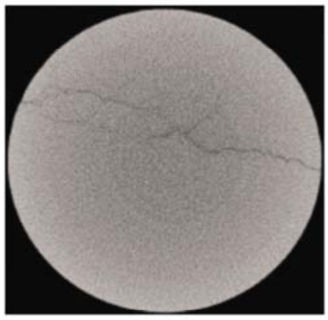
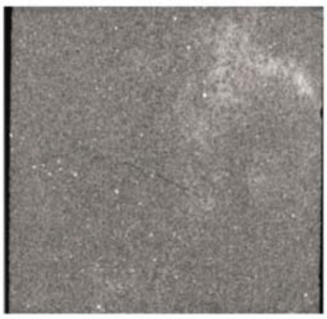
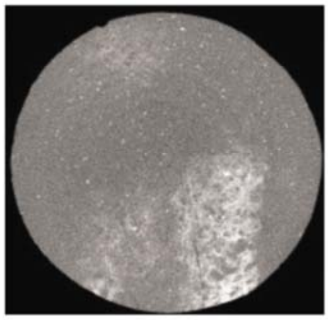
Study of void structure of carbonate deposits

Study of void nature and distribution of seals in the samples allowed to type core depending on its void structure. The results are shown in Table 1.

Table 1 shows that X-ray tomography allows you to select types of voids of different genesis. The porous type of structure is caused mainly by secondary inner voids. The method can determine primary (intergranular) and secondary (interparticle, intraparticle) voids. Secondary voids include cracks and cavities that were formed during leaching of fossils with carbonate composition.

Allocation of crack zones is one of the important areas of practical application of core tomography. According to [12] for a number of carbonate deposits there is a discrepancy between oil recovery and geological reserves, evaluated by standard methods. Integration of X-ray tomography analysis with well test for carbonate reservoirs in [13] allowed determining reservoir zones with pore-crack type along the interval with absence of granular reservoir. In [14] there are examples of fixation convergence (or absence) of cracks on X-ray tomograms and results of experiments during varying hydraulic compression of core samples.

Table 1

Photo of the sample	2D-Slices		Types
	longitudinal	transverse	
			Cavity
			Pore-cavity
			Pore
			Crack
			Dense

In the analysis of porosity evaluation results for samples of different diameters it is necessary to compare exactly that part of a larger sample, which smaller is made from. Conducted this way comparison showed a high convergence of K_p values ($r = 0.97$). During the comparison of average values over the entire volume of samples of 30 mm the correlation reduces significantly ($r = 0.77$) due to the influence of its heterogeneity.

Figure 1 shows an example of interpretation of tomography and distribution of pores according to identified void size for samples of 5 and 30 mm diameter. The sample of 5 mm was made from the bottom of the 30 mm sample. Comparison of the interpretation results shows their high convergence. The distribution of porosity along 30 mm sample height indicates that K_p value in its lower part is the closest to interpretation results of 5 mm sample.

In general, analysis of the results of core studies by X-ray tomography shows that for samples of smaller size the elements of voids and X-ray density heterogeneities are visualized in much detail. It is determined that for 30 mm diameter the minimal size of visible specter is 0.08 mm, for 10 mm diameter – 0.04 mm and for 5 mm diameter – 0.02 mm.

Discrepancy of visible pore size during the study of samples of different diameters leads to underestimated results for bigger samples. For instance, for dense difference in porosity of 5 % results of K_p evaluation in absolute values are underestimated by 1 %, for high dense differences of 10 % – 1.5 %. Thus, relative error of porosity determination for bigger samples decreases due to decreased share of pores with small diameter.

Study of fluid saturation of carbonate deposits

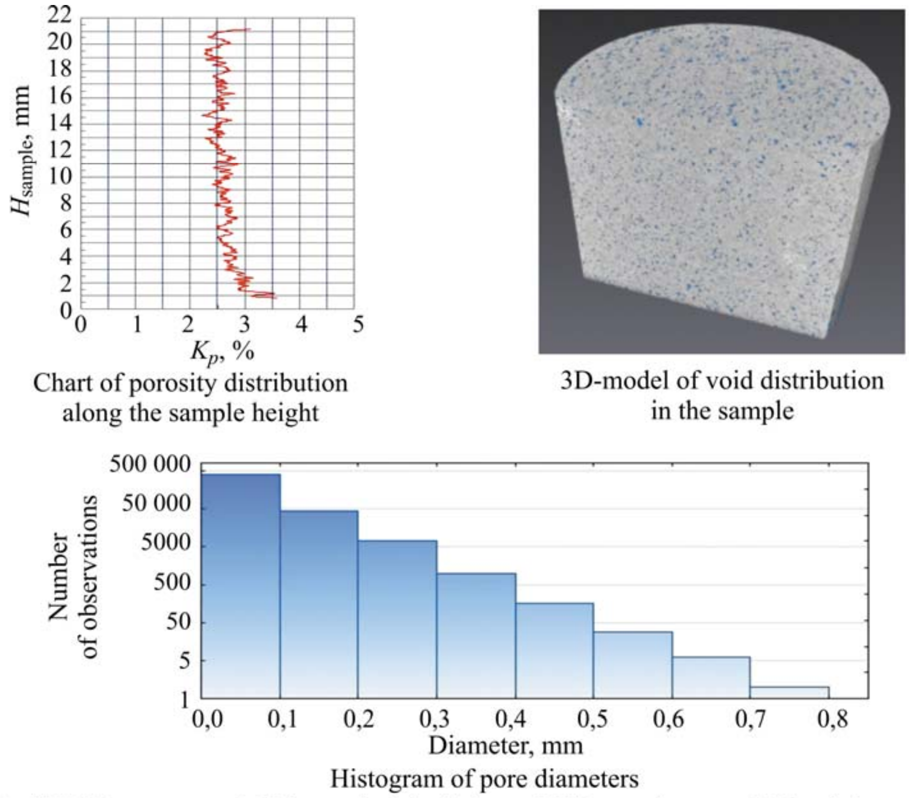
In order to determine nature of distribution and ratio of irreducible water and residual oil X-ray tomography was used on dry sample, sample with 100 % of water saturation and sample with ireducible water saturation. Irreducible water saturation was modeled by semi-permeable membrane under overpressure of 1.2 MPa. Radiographic solutions NaI (200 g/l), $CsNO_3$ (200 g/l), LiBr (1500 g/l), $LaCl_3 \cdot 3H_2O$ (100 g/l) were used as reservoir fluid models. Non-radiographic four-normal solution of NaCl usually used as reservoir fluid in petrochemical study is a reference sample in this research.

Determination of the volume occupied by irreducible water and residual oil, as well as nature of fluid distribution in voids of sample is carried out by binarization of 3D-model using Tresholding function of AvizoFire 7.0. In addition, $K_{i.w.}$ was determined by the difference between void space of dry sample and sample with irreducible water in case when irreducible water was not radiographic enough.

Results of fluid saturation study by X-ray tomography show that the most contrast in X-ray are water solutions of sodium iodide and lanthanum chloride. Figure 2 shows 2D-slices and 3D-models of core samples saturated by NaI (200 g/l) and $LaCl_3 \cdot 3H_2O$ (100 g/l). It is observed from the figures that in longitudinal and transverse 2D-slices saturating solutions appear as areas with higher X-ray density (filled white), equal density of the mineral skeleton or higher. It allowed creating 3D-model of initial oil saturation distribution (filled orange) and calculating behavior of $K_{i.w.}$ change along sample height. The results revealed that large pores, cracks and cavities are substantially free of irreducible water that always occupies fine pores (see Fig. 2).

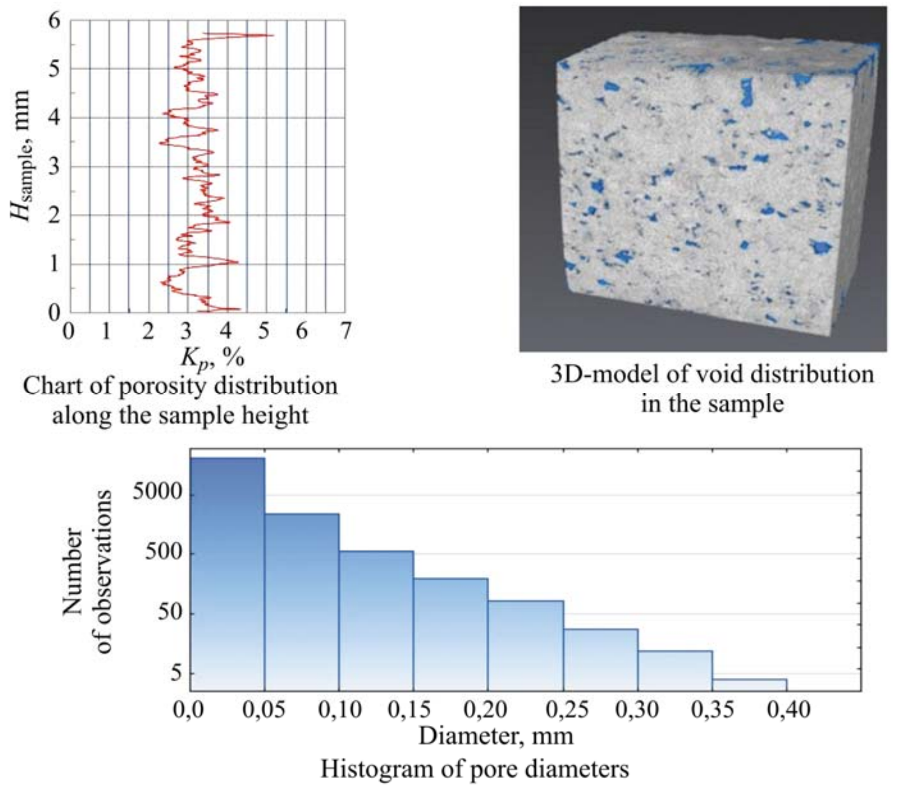
Due to X-ray density of NaI closed to the density of rock mineral matrix, allows to estimate the amount occupied by oil (see Fig. 2a). Thus, to assess $K_{i.w.}$ with use of NaI it is needed to apply results of scanning of dry sample and sample with irreducible water.

The solution of $AlCl_3 \cdot 3H_2O$, having X-ray density higher than mineral skeleton (see Fig. 2b), allow to allocate zones occupied by irreducible water without dry sample scanning.



N = 449787; average = 0.054; standard deviation = 0.043; maximum = 0.73; minimum = 0.08

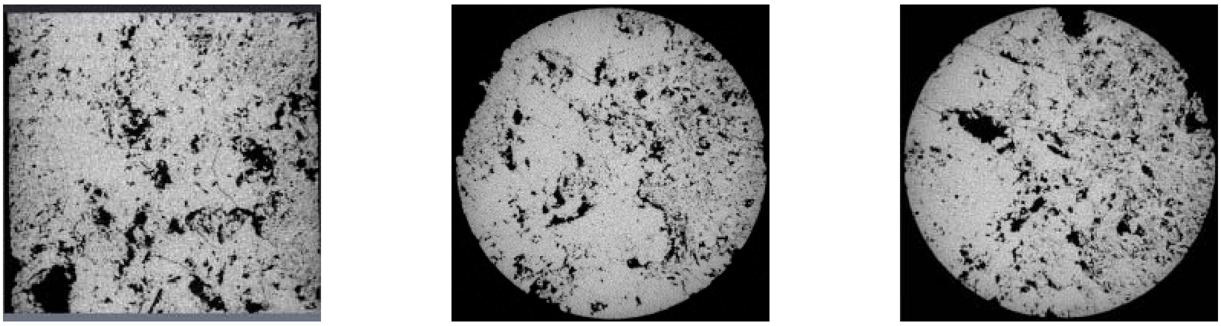
a



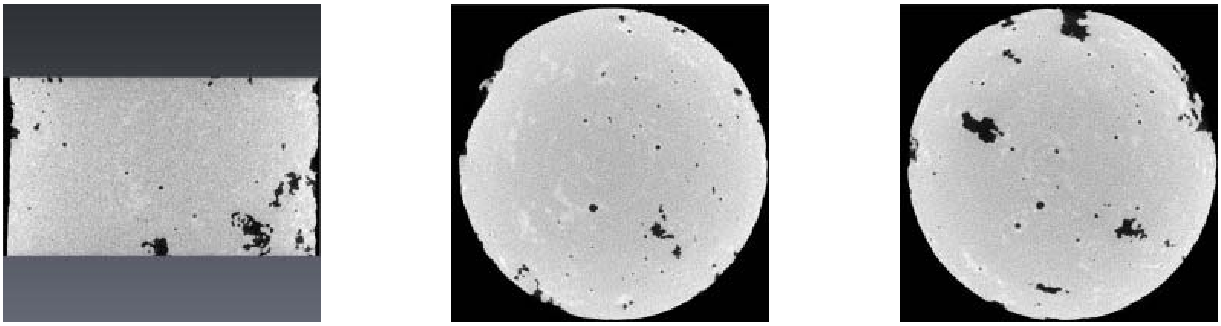
N = 24314; average = 0.035; standard deviation = 0.028; maximum = 0.39; minimum = 0.02

b

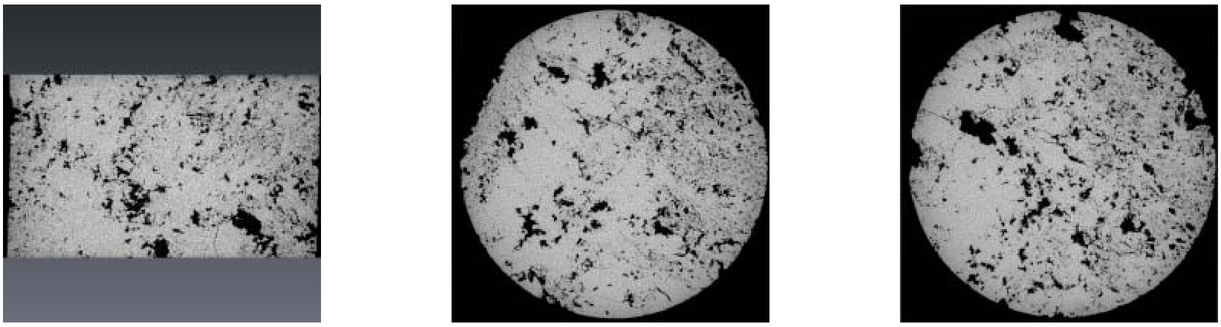
Fig. 1. Results of X-ray tomography of core sample pair:
a – diameter of 30 mm; *b* – cross-section of 5 mm



Before saturation



Saturation 100 %



With irreducible water

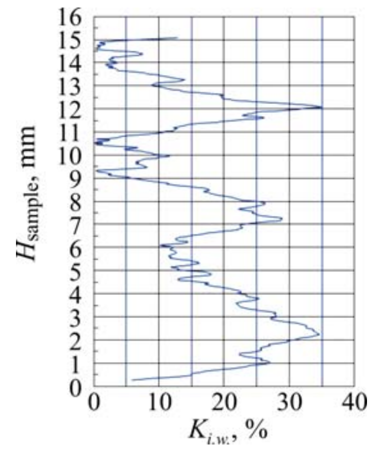
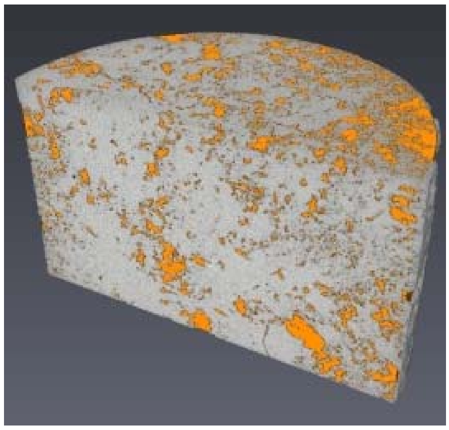


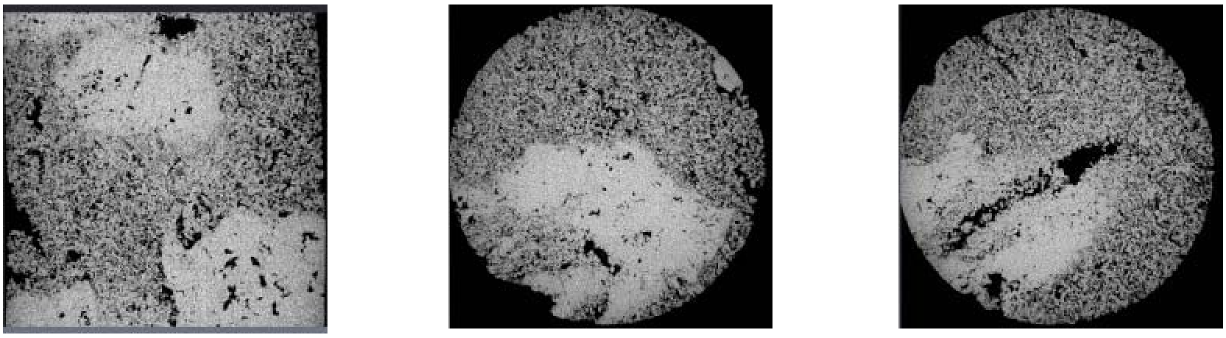
Chart of irreducible water saturation distribution along the sample height



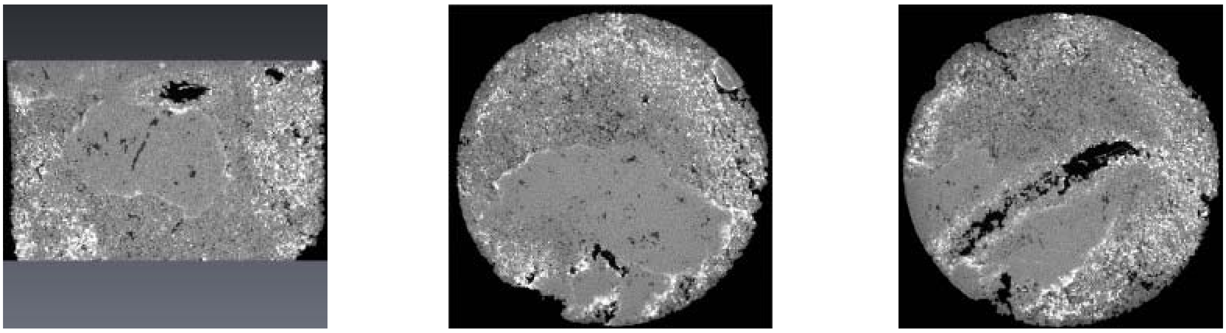
3D-model of initial oil saturation distribution

a

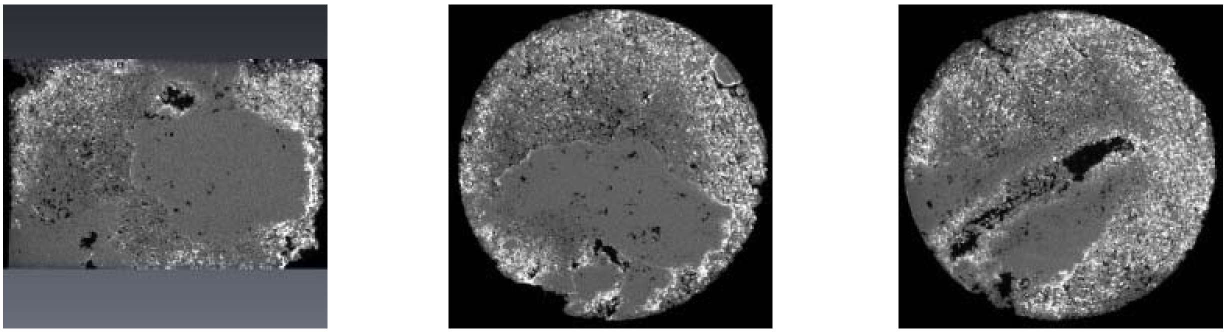
Fig. 2. Results of tomography of core samples with 30 mm in diameter saturated by radiographic solutions: *a* – NaI; *b* – $LaCl_3 \cdot 3H_2O$



Before saturation



Saturation 100 %



With irreducible water

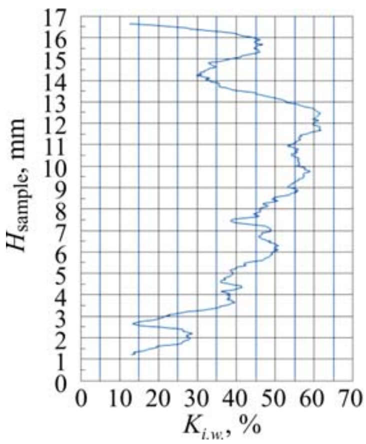


Chart of irreducible water saturation distribution along the sample height

3D-model of initial oil saturation distribution

b

Fig. 2. End of the figure

The values of $K_{i.w.}$ obtained from tomography were underestimated in comparison with $K_{i.w.}$ determined by semi-permeable membrane. The method allows visualizing voids higher than 0.021 mm for 5 mm samples and 0.075 mm for 30 mm samples. According to X-ray tomography big pores, crack and cavities do not have water. It is contained in the fine pores of diameter less than resolution of images obtained by tomography. Pores with inner fluid flow (as indicated by standard petrophysical studies) are in the range of 0.01-0.06 mm.

Conclusion

Based on the analysis of core of carbonate deposits by X-ray tomography following conclusions were obtained:

1. The method allows getting an idea of space distribution (visualization, 3D-models) of quantitative void reservoir properties of rocks (coefficients of porosity, irreducible water and residual oil saturation, crack opening, voids diameters) and determining reservoir type based on morphostructural features. It is easy to distinguish cavities, cracks, pores of large and medium size and determine its void.

2. The resolution of images obtained by X-ray scanning has minimal threshold depending on sample size. For samples of 30 mm in diameter, minimumal size of fixed object is 0.08 mm, for samples of 10 mm in diameter – 0.04 mm, for samples of 5 mm in diameter – 0.02 mm.

3. Determination of closed porosity is complex, since the estimation is made on the core with 100 % of water saturation. In case samples have large voids, then under the action of gravity saturating solution leaves voids in the first minutes of scanning. Therefore, voids that have no solution are erroneous referred to isolated. Moreover, if the solution is not sufficiently radiographic then it cannot be registered in large voids, even if they are filled. On the other hand it is registered as 100 % water saturation in the voids of smaller diameter. That leads to overestimation of open porosity.

4. Interpretation of X-ray heterogeneities without lithological description of the core is possible only while solving problems related to the establishment of their spatial distribution.

5. The test with 4 radiographic solutions showed that the best results in modeling of irreducible water were obtained for compositions with concentration of 200 g/l of NaI and 100 g/l of $LaCl_3 \cdot 3H_2O$ at.

6. During determination of irreducible water saturation it was found that large voids (cavities, cracks) have no irreducible water.

7. During evaluation of irreducible water saturation in the matrix it was determined that pore size has great influence on final results. It was noted that for reservoirs with predominance of small-diameter pores $K_{i.w.}$ value was underestimated (overestimation of $K_{i.o.}$).

It should be noted that the X-ray tomography of core have to be carried out in complex with standard petrophysical and petrographic studies, since the method has its limitations due to physics of scanning process and minimal sensitivity threshold depending on the size of scanned samples. In order to develop the method it is relevant to improve mathematical apparatus of software for tomography data processing by change from X-ray images to 3D digital model [15].

References

1. Arns C.H., Bauget F., Limaye A., Sakellariou A., Senden T.J., Sheppard A.P., Sok R.M., Pinczewski W.V., Bakke S., Berge L.I., Oren P.-E., Knackstedt M.A. Pore-scale characterization of carbonates using X-ray microtomography. *Society of Petroleum Engineers Journal*, 2005, vol. 10, no. 4, pp. 475-484. DOI: 10.2118/90368-PA.

2. Vinegar H.J. X-ray CT and NMR imaging of rocks. *Journal of Petroleum Technology*, 1986, 38, pp. 257-259. DOI: 10.2118/15277-PA.

Список литературы

1. Pore-scale characterization of carbonates using X-ray microtomography / C.H. Arns, F. Bauget, A. Limaye, A. Sakellariou, T.J. Senden, A.P. Sheppard, R.M. Sok, W.V. Pinczewski, S. Bakke, L.I. Berge, P.-E. Oren, M.A. Knackstedt // Society of Petroleum Engineers Journal. – 2005. – Vol. 10, № 4. – P. 475–484. DOI: 10.2118/90368-PA.

2. Vinegar H.J. X-ray CT and NMR imaging of rocks // Journal of Petroleum Technology. – 1986. – 38. – P. 257–259. DOI: 10.2118/15277-PA.

3. Eremenko N.M., Murav'eva Iu.A. Primenenie metodov rentgenovskoi mikrotomografii dlia opredeleniia poristosti v kerne skvazhin [Application of the X-ray microtomography methods for well plugs porosity determination]. *Petroleum Geology – Theoretical and Applied Studies*, 2012, vol. 7, no. 3, available at: http: //www.ngtp.ru/rub/2/35_2012.pdf.

4. Savitskii Ia.V. Sovremennye vozmozhnosti metoda rentgenovskoi tomografii pri issledovanii kerna neftianykh i gazovykh mestorozhdenii [Current features of X-ray tomography in examination of core samples from oil and gas deposits]. *Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining*, 2015, no. 15, pp. 28-37. DOI: 10.15593/2224-9923/2015.15.4.

5. Alemu B.L., Aker E., Soldal M., Johnsen O., Aagard P. Effect of sub-core scale heterogeneities on acoustic and electrical properties of a reservoir rock: a CO_2 flooding experiment of brine saturated sandstone in a computed tomography scanner. European Association of Geoscientists & Engineers. *Geophysical Prospecting*, 2012, 61, pp. 235-250. DOI: 10.1111/j.1365-2478.2012.01061.x.

6. Berg S., Armstrong R., Ott H., Georgiadis A., Klapp S.A., Schwing A., Neiteler R., Brussee N., Makurat A., Leu L., Enzmann F., Schwarz J.-O., Wolf M., Khan F., Kersten M., Irvine S., Stampanoni M. Multiphase flow in porous rock imaged under dynamic flow conditions with fast X-ray computed microtomography. *Petrophysics*, 2014, vol. 55, no. 4, pp. 304-312.

7. Galkin S.V., Efimov A.A. Zonal'nost' raspredeleniia viazkostei nefti, pronitsaemosti i koeffitsienta podvizhnosti dlia bashkirskikh zalezhei territorii Permskogo kraia [Zonal distribution of oil reservoir viscosity, permeability and mobility coefficient for Bashkir deposits of Perm krai]. *Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining*, 2013, no. 6, pp. 43-53.

8. Putilov I.S., Galkin V.I. Primenenie veroiatnostnogo statisticheskogo analiza dlia izucheniia fatsial'noi zonal'nosti turne-famenskogo karbonatnogo kompleksa Sibirskogo mestorozhdeniia [Application of statistical analysis for the study of facial zonation of Tournaisian-Famenian carbonate system of Sibirskoe field]. *Neftyanoe Khozyaistvo - Oil Industry*, 2007, no. 9, pp. 112-114.

9. Galkin V.I., Khizhniak G.P. O vliianii litologii na koeffitsient vytesneniia nefti vodoi [About the influence of lithology on the displacement of oil by water coefficient]. *Neftyanoe Khozyaistvo - Oil Industry*, 2012, no. 3, pp. 70-72.

10. Kochneva O.E., Moiseeva T.V. Vliianie geologicheskoi neodnorodnosti kollektorov bashkirskogo plasta na protsess izvlechenii nefti Sivinskogo mestorozhdeniia [Effect of reservoir heterogeneity Bashkir geological formation process for the extraction of Sivinsk oil field]. *Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining*, 2013, no. 8, pp. 28-34.

11. Galkin S.V., Efimov A.A., Krivoshchekov S.N., Savitskiy Ya.V., Cherepanov S.S. X-ray tomography in petrophysical studies of core samples from oil and gas fields. *Russian Geology and Geophysics*, 2015, no. 5, pp. 782-792. DOI: 10.1016/j.rgg. 2015.04.009.

12. Galkin S.V., Poplaukhina T.B., Raspopov A.V., Khizhniak G.P. Otsenka koeffitsientov izvlecheniia nefti dlia mestorozhdenii Permskogo kraia na osnove statisticheskikh modelei [Evaluation of oil recovery factors based on statistical models for the fields of Perm region]. *Neftyanoe Khozyaistvo - Oil Industry*, 2009, no. 4, pp. 38-39.

3. Еременко Н.М., Муравьева Ю.А. Применение методов рентгеновской микротомографии для определения пористости в керне скважин [Электронный ресурс] // Нефтегазовая геология. Теория и практика. – 2012. – Т. 7, № 3. – URL: http: //www.ngtp.ru/rub/2/35_2012.pdf (дата обращения: 19.07.2015).

4. Савицкий Я.В. Современные возможности метода рентгеновской томографии при исследовании керна нефтяных и газовых месторождений // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2015. – № 15. – С. 28–37. DOI: 10.15593/2224-9923/2015.15.4.

5. Effect of sub-core scale heterogeneities on acoustic and electrical properties of a reservoir rock: a CO_2 flooding experiment of brine saturated sandstone in a computed tomography scanner / B.L. Alemu, E. Aker, M. Soldal, O. Johnsen, P. Aagard; European Association of Geoscientists & Engineers // Geophysical Prospecting. – 2012. – 61. – P. 235–250. DOI: 10.1111/j.1365-2478.2012.01061.x.

6. Multiphase flow in porous rock imaged under dynamic flow conditions with fast X-ray computed microtomography / S. Berg, R. Armstrong, H. Ott, A. Georgiadis, S.A. Klapp, A. Schwing, R. Neiteler, N. Brussee, A. Makurat, L. Leu, F. Enzmann, J.-O. Schwarz, M. Wolf, F. Khan, M. Kersten, S. Irvine, M. Stampanoni // Petrophysics. – 2014. – Vol. 55, № 4. – P. 304–312.

7. Галкин С.В., Ефимов А.А. Зональность распределения вязкостей нефти, проницаемости и коэффициента подвижности для башкирских залежей территории Пермского края // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2013. – № 6. – С. 43–53.

8. Путилов И.С., Галкин В.И. Применение вероятностного статистического анализа для изучения фациальной зональности турне-фаменского карбонатного комплекса Сибирского месторождения // Нефтяное хозяйство. – 2007. – № 9. – С. 112–114.

9. Галкин В.И., Хижняк Г.П. О влиянии литологии на коэффициент вытеснения нефти водой // Нефтяное хозяйство. – 2012. – № 3. – С. 70–72.

10. Кочнева О.Е., Моисеева Т.В. Влияние геологической неоднородности коллекторов башкирского пласта на процесс извлечений нефти Сивинского месторождения // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2013. – № 8. – С. 28–34.

11. X-ray tomography in petrophysical studies of core samples from oil and gas fields / S.V. Galkin, A.A. Efimov, S.N. Krivoshchekov, Ya.V. Savitskiy, S.S. Cherepanov // Russian Geology and Geophysics. – 2015. – № 5. – С. 782–792. DOI: 10.1016/ j.rgg.2015.04.009.

12. Оценка коэффициентов извлечения нефти для месторождений Пермского края на основе статистических моделей / С.В. Галкин, Т.Б. Поплаухина, А.В. Распопов, Г.П. Хижняк // Нефтяное хозяйство. – 2009. – № 4. – С. 38–39.

13. Определение параметров трещиноватости пород на основе комплексного анализа данных изучения керна, гидродинамических и геофизических исследований скважин / С.С. Черепанов, И.Н. Пономарева, А.А. Ерофеев, С.В. Галкин // Нефтяное хозяйство. – 2014. – № 2. – С. 94–96.

13. Cherepanov S.S., Ponomareva I.N., Erofeev A.A., Galkin S.V. Opredelenie parametrov treshchinovatosti porod na osnove kompleksnogo analiza dannykh izucheniia kerna, gidrodinamicheskikh i geofizicheskikh issledovanii skvazhin [Determination of rock fracture parameters on the basis of a comprehensive analysis of the core study data, hydrodynamic and geophysical studies of wells]. *Neftyanoe Khozyaistvo - Oil Industry*, 2014, no. 2, pp. 94-96.

14. Shapiro S., Khizhniak G., Plotnikov V., Niemann R., Ilushin P., Galkin S. Permeability dependency on stiff and compliant porosities: a model and some experimental examples. *Journal of Geophysics and Engineering*, 2015, no. 12, pp. 376-385. DOI: 10.1088/1742-2132/12/3/376.

15. Denney D. Digital core laboratory: reservoir-core properties derived from 3D images. *Journal of Petroleum Technology*, 2004, vol. 56, is. 05, pp. 66-88. DOI: 10.2118/0504-0066-JPT.

14. Permeability dependency on stiff and compliant porosities: a model and some experimental examples / S. Shapiro, G. Khizhniak, V. Plotnikov, R. Niemann, P. Ilushin, S. Galkin // Journal of Geophysics and Engineering. – 2015. – № 12. – С. 376–385. DOI: 10.1088/1742-2132/12/3/376.

15. Denney D. Digital core laboratory: reservoir-core properties derived from 3D images // Journal of Petroleum Technology. – 2004. – Vol. 56, is. 05. – P. 66–88. DOI: 10.2118/0504-0066-JPT.

Please cite this article in English as:
Efimov A.A., Savitckii Ia.V., Galkin S.V., Shapiro S. Experience of study of core from carbonate deposits by X-ray tomography. *Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining*, 2016, vol.15, no.18, pp. 23-32. DOI: 10.15593/2224-9923/2016.18.3

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Опыт исследования керна карбонатных отложений методом рентгеновской томографии / А.А. Ефимов, Я.В. Савицкий, С.В. Галкин, С.А. Шапиро // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2016. – Т.15, №18. – С. 23–32. DOI: 10.15593/2224-9923/2016.18.3