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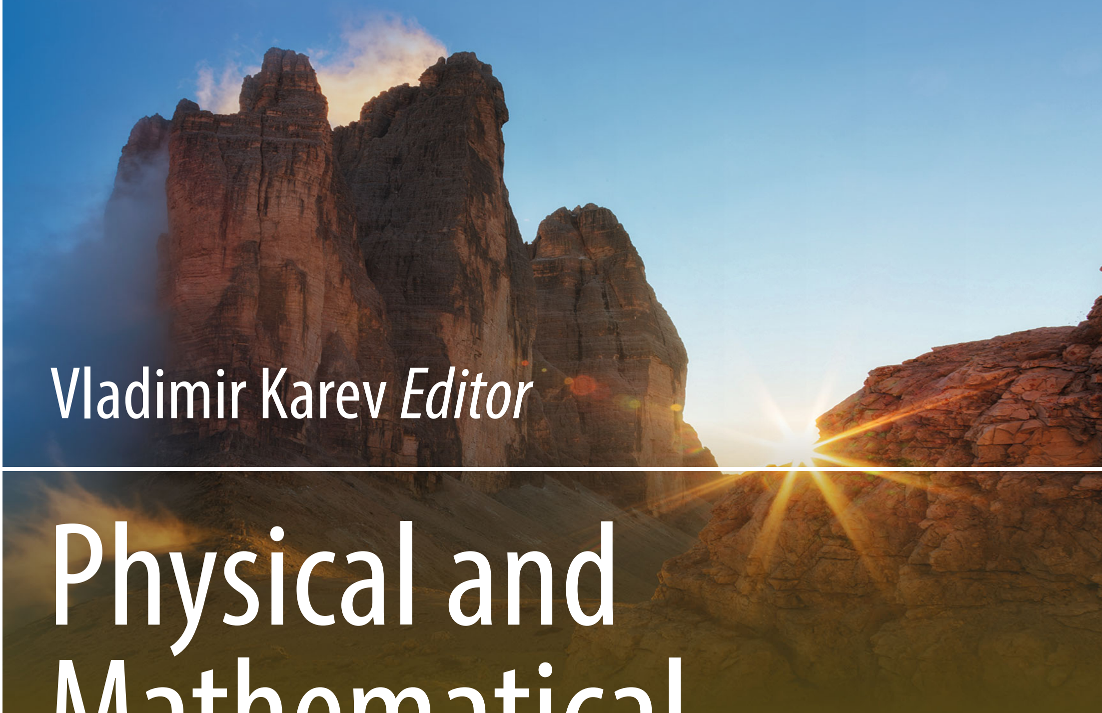

Vladimir Karev *Editor*

Physical and Mathematical Modeling of Earth and Environment Processes

Proceedings of the 10th International Scientific School for Young Scientists, Moscow, October 23–25, 2024

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Applications of 3D Digital Methods of CT Image Processing to Study Macrocracks in Low-Permeability Rocks Formed When Modeling on Specimens the Method of Directed Unloading of the Reservoir

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Abstract. The paper presents a methodology for obtaining high-quality 3D models of macrocracks from X-ray computed tomography images on the example of rocks from low-permeability when modeling on specimens the method of directed unloading of the reservoir. Traditionally, a very small representative volume of rock is selected during rock micro-CT studies. However, when analyzing macrocracks, this approach is not possible due to the need to scan, process and create models of large volumes. Thus, it becomes necessary to search for efficient and resource-saving methods of working with large images, which will allow to carry out fast, high-quality image processing, create accurate models and optimize them for further calculations. The described approach includes works on obtaining, reconstruction, processing, segmentation and optimization of the created models in order to obtain the most realistic and suitable for analyzing the structures of the internal space of rocks. The work describes the results of analysis of fractures formed in the rock specimens after physical modeling of the increase well productivity method application - the directional unloading reservoir method. All stages of work with tomography images are described, and 3D models of the specimens under study are created. The orientation of fractures and their openness are analyzed, as well as the modeling of particle movement in the rock is performed to determine the characteristics of new percolation paths in the rock. The proposed methodology is designed to simplify the acquisition of high-quality 3D models of the internal space of dense geomaterials based on full-scale CT images.

Keywords: method of directed unloading of a reservoir · CT image processing · macrocracks system analysis · GeoDict software · percolation paths · 3D reservoir models · low-permeability rocks

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1 Introduction

The study of low-permeability reservoirs containing hard-to-recover (HTR) reserves is of significant importance in today's energy context. As conventional oil and gas reserves become scarcer, these unconventional resources represent a crucial component of meeting the world's energy demands. Unlocking the vast potential of HTR reservoirs is essential for ensuring a sustainable energy future. Developing new approaches to harness these reserves is pivotal because the conventional methods used in high-permeability reservoirs are often inadequate for tight low-permeability ones. The development of such deposits with low permeability and porosity necessitates innovative drilling, stimulation, and extraction techniques. In addition, the environmentally sensitive nature of many HTR reservoir development techniques, such as hydraulic fracturing, reinforces the importance of developing cleaner and more sustainable energy extraction methods.

The development of an geomechanical approach to improving well productivity and oil and gas recovery of low-permeability reservoirs allowed scientists at the Institute for Problems in Mechanics of the Russian Academy of Sciences to create a highly efficient and economically beneficial technology - the method of directed unloading of the reservoir (DUR) [1]. This innovative technique stands out as a unique and environmentally friendly solution with no global counterparts. It is based on the phenomenon of a significant increase in permeability in the bottomhole reservoir zone with a corresponding change in its stress-strain state. The approach involves establishing an artificial network of micro - and macrocracks, new filtration channels system near the well. This is accomplished by reducing well pressure to a certain level, combined with a specific bottomhole design. The required drawdown level and bottomhole geometry are determined through rigorous testing of core materials using TILTS – unique Triaxial Independent Load Test System [2]. This facility enables the recreation on rock specimens of real stress states encountered in the reservoir during any technological operations. Unlike hydraulic fracturing methods, which require significant energy inputs to create fractures and overcome rock pressure, this technology utilizes the significant amount of elastic energy available in the rock mass itself to create a network of fractures that form a new system of filtration channels with high permeability.

Through laboratory research, scientists can assess the geomechanical properties of low permeability rocks and determine the optimal methods of affecting them in order to increase production efficiency and reduce the negative impact on the environment.

X-ray computed tomography (CT) holds significant importance as a non-destructive technique for examining the internal structure of rocks, complementing direct laboratory investigations effectively. This method entails the reconstruction of the spatial distribution of X-ray linear attenuation coefficients through computer processing of acquired during the radiation scan projections. The result of a CT examination is presented as a series of grayscale images, collectively forming a three-dimensional representation of X-ray absorption within the studied specimen [3]. To extract valuable information, specialized software is employed to ascertain attributes such as linear dimensions, quantity, sphericity, and anisotropy of structural elements within the specimen [4]. For quantitative material stucture analysis and the application of tomography results in numerical process modeling, image segmentation becomes essential [5]. Segmentation involves the analysis of images and the transition from X-ray absorption pattern to the spatial distribution of constituent components within the specimen space, and it can be either binary (two-phase) or multiphase. Pore imaging experiments, coupled with modeling, serve as valuable tools for predicting geological and physical properties [6], including porosity and permeability [7], with calculations primarily focused on the segmented image's of macropore space or cracks.

Complex laboratory studies of the processes in the studied reservoirs include physical modeling of deformation and filtration processes under real three-dimensional stresses occurring near the well during the application of the DUR method. For detailed analysis of macrocracks that appear in the rock after application of the DUR method, a digital analysis based on computed tomography images is the most effective way of investigation To create a high-quality 3D model of the rock for further analysis and numerical modeling, a special approach to scanning and processing of CT images is required.

This paper presents a methodology for obtaining high-quality 3D models of macrocracks from X-ray computed tomography images on the example of a low-permeability reservoir rock. Traditionally, a very small representative volume of rock is selected during rock micro-CT studies. However, when analyzing macrocracks, this approach is not possible due to the need to scan, process and create models of large volumes. Thus, it becomes necessary to search for efficient and resource-saving methods of working with large images, which will allow to carry out high-quality image processing. Such techniques should also make it possible to create accurate and lightweight models upon which numerical modeling and digital analysis will be possible. The described approach includes works on obtaining, reconstruction, processing, segmentation and optimization of the created models in order to obtain the most realistic and suitable for analyzing the structures of the internal space of rocks. The connectivity of the investigated crack system is shown, and the percolation paths in the rock are calculated.

2 Research Methodology and Results

The studied core material was low-permeable terrigenous rocks with pronounced layering. Specimens for the studies were made in the form of a cube with a 40 mm edge. Tests of specimen were carried out using the Triaxial Independent Load Test System (TILTS) created at the Institute for Problems in Mechanics of the Russian Academy of Sciences [1, 2]. TILTS is a unique facility that allows one to study the strain, strength and filtration properties of rocks by testing cubic rock specimens. TILTS allows to recreate any stress states that occur in rock mass during technological operations, and to study the deformation, fracture and filtration processes in rocks. As a result of physical modeling of application of DUR method on specimens of the reservoir under study, a crack system was formed.

During physical modeling, the real stress states occurring at specific points of the borehole during the implementation of the DUR method are recreated. In the described studies, the stresses occurring in the upper and sidewall points on the contour of the horizontal well were recreated in specimens. The process of creating loading programs and analysis of stress state near a well is presented in more detail in [1].

The initial permeability of the specimens was very low and was less than 10 mD. After the tests, a clearly distinguishable crack system was formed in the specimens.

Figure 1 shows photos of two specimens with typical crack distribution. The specimen in Fig. 1a was tested using a loading program for a upper point of the well, and the specimen in Fig. 1b was tested using a loading program for a sidewall point on the well.

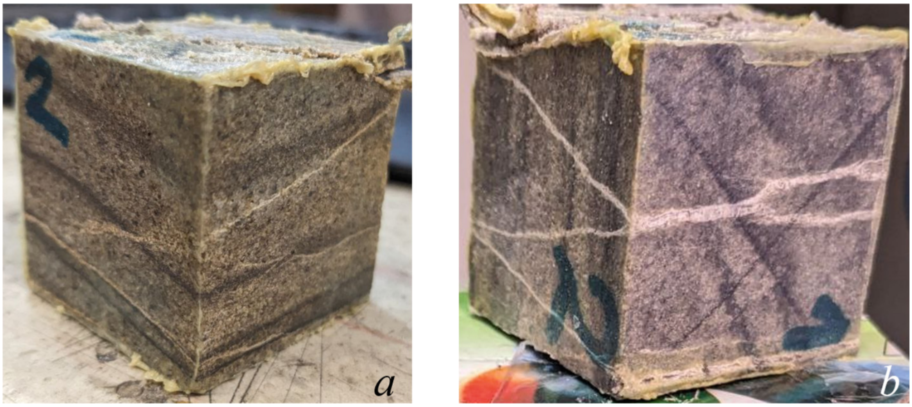

Fig. 1. a, b – the specimens of low-permeability rocks with macrocracks formed

Layering is visually distinguishable on the specimens: horizontal dark lines in Fig. 1a and vertical lines in Fig. 1b. Depending on the points on the contour of the horizontal well, for which the modeling of the implementation of the DUR method is carried out - sidewall or upper, the stress distribution changes. Consequently, the loading program are different and the orientation of the formed macrocracks is also different. In Fig. 1a, the stresses acting at the top point on te contour of the borehole were modeled, so that the minimum pricipal stress acted along the core axis and macrocrack formation occurred in the direction close to layering. In Fig. 2b, the specimen is shown on which the stresses at the lateral point on the contour of a horizontal well were modeled. And cracks occurs in perpendicular direction.

At the same time, it should be noted that the orientation of the obtained crack system agrees well with the theory of conjugate fractures by M. V. Gzovsky [8], which is used in studying the structure of deposits [9].

To obtain a detailed three-dimensional picture of the cracks formed [10], tomographic studies of specimens were carried out. The ProCon X-Ray CT-MINI high-resolution micro-CT scanner was utilized for the computed tomography procedure and image acquisition of the specimens [11]. This device exhibits dimensions of 1300x850x600 mm and is built upon a robust base composed of a monolithic granite slab. This design choice effectively eliminates temperature-induced drift and ensures precise alignment of the X-ray optical and other system components within the device, thereby guaranteeing measurement accuracy and stability across its entire operational range.

The scanner adopts a vertical core placement configuration for research purposes, accommodating specimens with a maximum height and diameter of 200 mm. It can handle loaded specimens weighing up to 5 kg. To enable precise measurements, the design integrates a precision positioning system (manipulator), offering a distance of 335 mm from the tube to the object. Furthermore, the detector can move perpendicular to the primary system axis within a range of ±25 mm. The manipulator facilitates a 360-degree rotation of the specimen around its axis, achieving an angular position reproducibility accuracy of 1.5 angular seconds. The microfocus X-ray tube, known for its high resolution and closed-loop operation, provides an adjustable output voltage range from 20 kV to 90 kV and an adjustable current range from 10 μA to 160 μA. The tube's maximum output power reaches 8 W, featuring the smallest focal spot size measuring 5 μm. The X-ray detector exhibits high sensitivity and low noise, with a pixel count of 2940 × 2304 and a pixel size of 49.5 μm. The active (sensitive) area of the detector spans 146 × 114 mm.

I. Acquisition and Reconstruction of CT Images. Full-scale images of the cubic specimens were taken. Scanning parameters for cube specimens were next: source voltage was 90 kV, amperage was 89 μA, exposition time was 0.52 s, rotation step was 0.25 degree and the voxel size was 21.048 μm. As a result of reconstruction of the projections obtained on tomography, a 3D image in grayscale is created. Figure 2a shows one of the projections of the obtained image of one of the specimens: black indicates air (cracks, pores, defects), and gray indicates rock material.

To create a three-dimensional model of the fracture system, it is necessary to perform special image processing, followed by a segmentation procedure [12], i.e., assigning a label of a specific substance to each voxel (in our case, dividing the image into fractures and material). The initial image has higher granularity, noise and gray shade scatter. This is due to the peculiarities of the tomography methodology, the heterogeneity of the studied rock, the presence of bedding with different material densities, as well as the absorption of radiation as it passes through the materials [13]. Images of dense rocks with strong cementation, high strength and density, and apparent anisotropy due to bedding are particularly inhomogeneous [14]. When trying to segment a raw image, a large amount of noise and traces of bedding and impurities will be extracted along with the fractures. As a consequence, the model will be unsuitable for analysis and further modeling. Therefore, for low-permeability dense rocks it becomes especially important to select appropriate image processing parameters and methods of image cleaning from unnecessary noise.

Application of primary correction methods when working with images of large specimens of dense rocks is necessary already at the stage of imaging and reconstruction. The physical basis of micro-CT is that material attenuates the X-ray passing through it. The attenuation rate depends on X-ray energy and composition of the object. The mass attenuation coefficient relies on factors such as the incident X-ray photon energy, material density, and composition [15]. However, Beer's law holds true only under the condition of imaging with a monochromatic X-ray beam (single energy). In practical laboratory X-ray systems, a polychromatic X-ray beam (a spectrum of energies) is typically employed. When such a beam passes through an object, its various energy components do not attenuate uniformly. The lower-energy component of the X-ray spectrum is more susceptible to attenuation and may even be completely absorbed when passing through denser regions of the object. If we reconstruct the image assuming linear beam attenuation, the edges of the object in the reconstructed volume will appear brighter, even if the object consists of homogeneous material. This phenomenon is known as beam-hardening or cupping artifact [16]. Beam hardening poses several significant issues. Firstly, it provides inaccurate information about the sample's composition and density. Additionally, it adversely affects results when attempting to distinguish materials based on intensity differences (e.g., through global thresholding). Consequently, various methods have been developed to mitigate or correct beam hardening in micro-CT scans: pre-harden the beam with metal plate placed between the X-ray source and the object, filter at the sample (tubing or liquid bath surrounding the part), post correction and advanced computation/simulation methods. In this study, the algorithm of high beam hardening reduction during image reconstruction was used. In this way, dark shades of gray in the depth of the cubic specimen and lightened areas at the edges of the specimen are equalized. The image after reconstruction becomes more uniform throughout the entire volume.

II. Image Processing. After successful reconstruction, it is necessary to turn the object according to its geometric shapes, aligning the program axes with the specimen axes. After that, for further processing it is necessary to crop the outdoor areas (Fig. 2a). Usually, when analyzing the internal structure of rocks, a small representative volume inside the specimen is taken. In such cases, a homogeneous area of the image is selected, so most of the algorithms described in this paper become unnecessary. When describing macrocracks, it is necessary to consider the entire specimen volume, which significantly complicates processing and requires significant CPU and RAM resources. Without rotating the image, it will be impossible to crop the outer air space. It cannot be kept, because during further processing the outer air will not allow grayscale correction and will make it difficult to visualize the results.

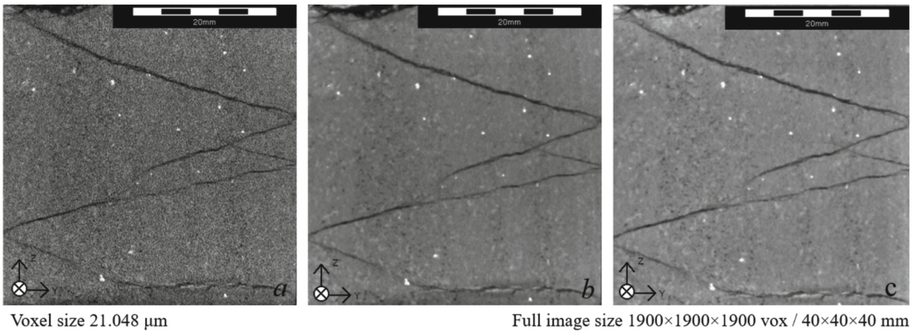

Fig. 2. a – slice of high-resolution 3D image after reconstruction; b – same slice after NLM filtering; c – same slice after Gaussian brightness correction (gray and white – matrix material, black – air)

One of the primary methods of processing a reconstructed image is brightness correction [17]. Such methods allow to make the shade distribution more uniform over the volume, complementing the previous method. Gradient Brightness Correction and Gaussian Brightness Correction methods were used for the rocks described in the article. The first of them allows to equalize shades on the edges and in the center of the specimen, the second allows to equalize bright/dark areas on all projections depending on the selected radius of the sphere. The radius of the sphere should be chosen depending on the bedding and pore space structure of the rock. It may be comparable to the characteristic size of the noise, or it may be substantially larger than the noise and pore size, if it is necessary to leave them for consideration. Depending on the homogeneity of the rock, these methods can give the best result either together or separately.

The next, and one of the most important steps, is to apply algorithms in image processing for image denoising. One of the most common ones is Non-local means filter [18]. The non-local means algorithm substitutes the pixel's value with an average calculated from a set of other pixel values. It achieves this by comparing small patches centered on these other pixels to the patch centered on the pixel of interest. The averaging process includes only those pixels whose patches closely match the current patch. The image is thus blurred, but the crack boundaries are still clearly visible. At the same time, noise and small inhomogeneities merge with the material shades. Figure 2b shows the result of image processing with Gradient Brightness Correction and Non-local means filter. In this projection, the air in the cracks, which is clearly visible after the applied methods, is represented in black. Separate vertical stripes now more clearly show the traces of bedding in the rock. Bedding may further interfere with correct fracture segmentation. Figure 2c shows the result of further application of Gaussian Brightness Correction. It can be seen that the vertical stripes have become slightly less visible, but are still prominent in the image. Further processing procedures can reduce the brightness of these stripes, but it will also affect the crack boundary, so it was decided to proceed to the segmentation procedure.

III. Segmentation Procedure. The segmentation procedure can be performed by various methods, including automatic K-means or Otsu methods [19], manual Global thresholding or using learning AI. With sufficient processing and grayscale equalization, automatic methods like Otsu show good results for homogeneous dense rocks. However, manual methods often have to be used for more accurate segmentation. Image segmentation is the most important factor for further analysis and modeling. Due to the non-ideal gray-scale distribution, the segmentation procedure will inevitably be accompanied by noise and rock inhomogeneities. When trying to cover the fracture boundaries in the best possible way, the resulting structure will have a high amount of noise along with the fractures, making the model unsuitable for analysis. If the segmentation is done focusing on the minimum amount of noise, the size of cracks may decrease and not correspond to the real size of the fracture.

Figure 3a shows the result of segmentation by the global method with minimal noise and bedding traces. As can be seen, the crack opening width and contour are compromised, which will not reflect the real picture of crack distribution on the created 3D model. Figure 3c shows the result of crack segmentation with the clearest edge, but covering a large number of noise and bedding, which will make the model unsuitable for analysis. Figure 3b shows an intermediate segmentation result that retains the most convincing fracture contour while highlighting the minimum amount of noise. However, even with this segmentation, the final model may be too noisy, so a methodology for simplifying the model will be proposed.

The final segmentation version for the described image is shown in Fig. 4. At the same time, Fig. 4a shows the grayscale projection, and Fig. 4bc shows the segmentation

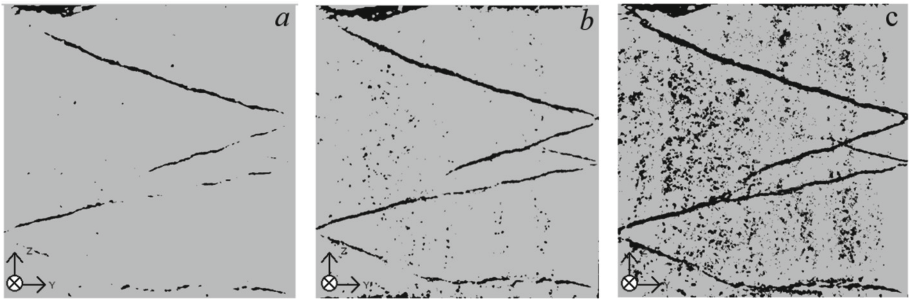

Fig. 3. Three possible characteristic types of macrocrack segmentation (black is air, gray is rock material)

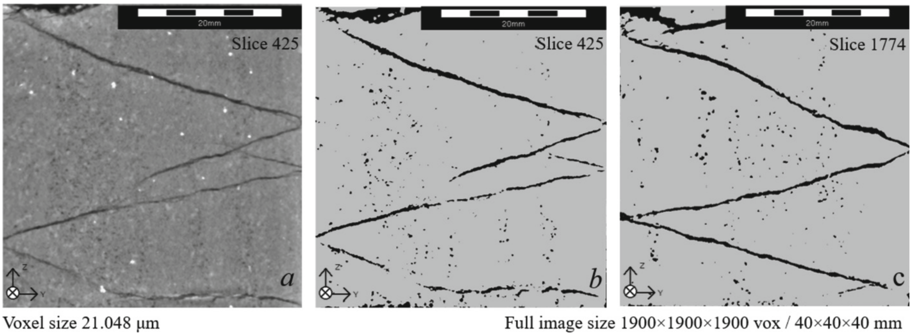

Fig. 4. a – slice of high-resolution 3D image after processing; b – same slice after segmentation, c – another slice of the image after segmentation (black is air, gray is rock material)

results for two projections of the image. As can be seen, the outline of the macrocracks is clearly visible, and bedding and noise are particularly noticeable in the vertical direction across the cracks. The shape, orientation and crack size of the obtained model correspond very well to the real specimen. However, analysis and modeling on such a structure can be difficult if only cracks without rock material are considered.

IV. Optimization of Obtained Structures. Figure 6a shows a 3D visualization of the created specimen model with visible fractures and air space (in black), while the rock material itself is transparent. As can be seen, bedding traces, pores, noise and inhomogeneities make it difficult to further work with the model. For a better understanding of the airspace pattern, Fig. 5b shows the same model with increased transparency of noises and cracks. Here it becomes clear that the crack planes are clearly visible but are mixed with small inclusions. When trying to model the filtration flow across cracks, these inclusions may not have a significant impact on the final result because many of them are closed. But these noises significantly complicate the 3D model, requiring much more computer resources in computation, and will also make visualization of the flow impossible.

One way to eliminate isolated noise is to apply closed and dead-end pore extraction algorithms. For example, the PoroDict module [20] of the GeoDict package allows to

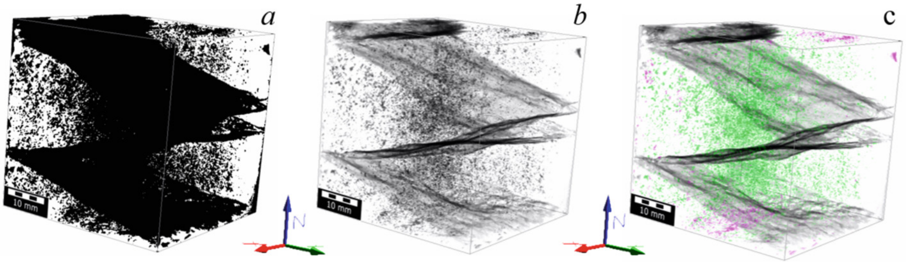

Fig. 5. a – air visualization (cracks, pores and noises) after segmentation; b – air visualization using transparency (for better visibility); c – result of closed (green) and dead-end (pink) pores determination

analyze specific components of a 3D model and identify isolated parts of the structure. Figure 5c shows the result of airspace separation by this module into closed, dead-end and connected components. The green color indicates areas that are completely isolated from others, while the pink color indicates areas that have only one exit, i.e. dead-ends. After separation, such zones can be completely removed from the model (Fig. 6ab). At the same time, empty zones may remain on the fracture surface; however, if the total fracture surface is wide, their influence on the modeling results is not significant. Figure 6ab shows the final structure of the macrocrack system formed in the specimen.

If segmentation has been performed with a very large amount of noise, as in Fig. 3c, a lot of noise and bedding traces may have extensive fracture contact surfaces and may also be well connected. In such a case, extraction of isolated areas by this method will not yield proper results, as part of the space not belonging to the actual fractures will remain available for flow. In this case it is necessary to return to the steps of image smoothing or selection of the correct segmentation model.

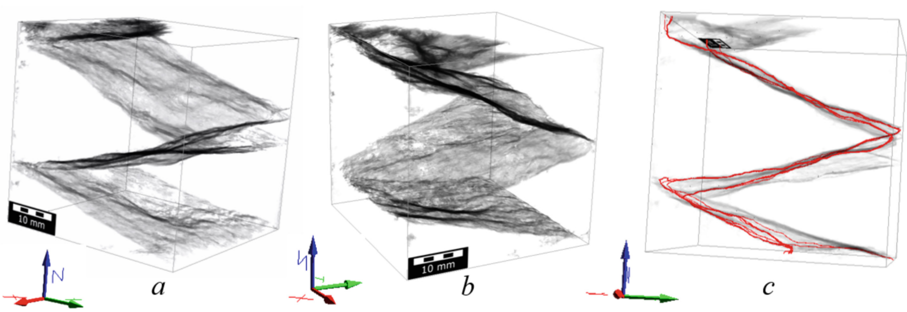

Fig. 6. A, b – macrocracks after separation of noises and closed pores; c – part of percolation paths (red lines) in fractures

The described methodology allows successful analysis of fracture formation and numerical modeling of filtration flow along fractures based on X-ray computed tomography images of specimens of dense heterogeneous low-permeability reservoirs. The obtained models make it possible to measure the surface area of fractures, their volume openness, orientation, branching, curvature, as well as to perform numerical modeling of various processes. For the structure described in the paper, the analysis of percolation paths through cracks was performed. It includes calculation of the maximum diameters of particles that can pass all the way through the specimen volume. That is, the effective crack openness is estimated in this way. The length of percolation paths was also calculated using the PoroDict module. Figure 6c shows some percolation paths inside macrocracks. For ten calculated percolation paths, the lengths were 115–137.6 mm. Thus, the minimum fluid path through the specimen in the filtration direction is 2.8 times longer than the specimen itself, and the maximum is 3.44 times longer. The maximum particle size able to pass through the whole fracture system was from 84 to 157 μm. Obviously, the average crack opening under atmospheric scanning conditions is much higher than the quoted particle sizes. However, for successful passage of a fixed size particle through the entire fracture system, it is necessary to consider the tightest regions, which are described by these sizes.

Numerical simulations of fluid filtration flow were also performed at different stages of 3D rock model creation and optimization with different mathematical approaches to compare results and evaluate the applicability and feasibility of the methods used. For different filtration patterns, the new fracture permeability was more than 3 Darcies. Thus, the confirmation of the possibility of successful realization of the method for the conditions of the studied field was obtained.

The proposed methods of working with images have been successfully applied to reservoir rocks of different fields with hard-to-recover reserves, and the modeling results on the obtained structures are in good agreement with physical laboratory measurements [10, 21]. The described technique can be extended, if necessary, by other methods of working with images, depending on the complexity and noisiness of the original image. The paper presents the general techniques and algorithms on the basis of which basic work with dense fractured materials can be carried out.

3 Conclusion

The paper presents the findings of an analysis of cracks formation that occurs in rocks in the result the physical modeling on specimens of DUR method application. The confirmation of the possibility of successful realization of the method for the conditions of the studied field was obtained.

The paper outlines a methodology for generating precise 3D models of macrocracks using X-ray computed tomography (CT) images on the example the examination of low-permeability reservoir rocks. The analysis concerns fracture orientations, their extent of openness, and the modeling of particle movement within the rock, new percolation pathways. Each step in working with tomography images and the creation of 3D models of the specimens under study is described comprehensively. Several stages are presented, including data acquisition, reconstruction, image processing, segmentation, and optimization of the resultant models, all aimed at achieving realistic representations suitable for analyzing the internal structures of rocks. Usually, when analyzing the internal structure of rocks, a small representative volume within the specimen is taken. In such cases, a homogeneous image area is selected, so the application of a wide range of processing methods may be unnecessary. When describing macrocracks, it is necessary to consider the entire volume of a large specimen, which significantly complicates processing and requires significant CPU and RAM resources. Without the use of special methods of image smoothing and alignment, as well as simplification and optimization of the resulting models, detailed digital analysis and numerical simulation becomes impossible.

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