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Physical simulation aspects of structural changes in rock samples under thermobaric conditions at great depths

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Abstract

When designing the parameters for the development of oil and gas field at significant depths, crucial to comprehend how certain factors affect the behavior of reservoir rocks and host rocks. These factors include the high level of rock stress, the ambient temperature field, and the hydro- and gas-dynamic processes within the mass. The impact of one or a combination of these factors can result in alterations to the construction, structure, composition, and properties of the rock mass and, ultimately leading to a mismatch between the design solutions and the actual conditions.

The purpose of the research is to establish a methodology for conducting laboratory studies that investigate the impact of the mode of occurrence of oil and gas field reservoirs at great depths on the properties of rock samples.

The research objectives encompass a theoretical analysis and the identification of the principal factors influencing rock behavior and changes in internal structure. Additionally, the objectives include developing laboratory research methods that comprehensively simulate these factors and conducting trial experiments to assess their effects.

As part of the project, tests were conducted on sandstone samples collected from depth ranging from 3.5 to 4 km within the hydrocarbon field. These studies were performed while simulating thermobaric reservoir conditions, which include temperature, rock pressure, and reservoir pressure.

The results of these experiments, aimed at examining the behavior of rock samples as closely as possible to their natural reservoir occurrence at depth of 3.5–4 km, are presented.

It has been observed that rock samples of the same lithology, collected from nearly identical depths, can exhibit significant differences in deformation characteristics, both in the pre- and off-limit regions of loading. The findings from these studies provide the initial data for the development and refinement of geomechanical model behavior for materials that take into account not only fracture strength criteria but also dilatancy processes at various stages of rock deformation.

Increasing lateral pressure within the range of 0 to to 55 MPa causes relatively minor change in ultrasonic vibration velocities, typically ranging from 1 to 10%. This makes it challenging to determine the necessity of utilizing these results for indirectly assessing changes in rock properties within the mass. Nevertheless, within the context of geophysical studies, considering variations in velocity values enhances the quality of result interpretation, especially given the substantial geometric dimensions of the rock masses under investigation.

Research into the acoustic emissions of rocks in a complex stressed state enables the monitoring of spatial micro- and macrofracturing processes throughout the entire loading phase of samples. This provides a more comprehensive understanding of changes in their internal structure.

The article delves into the factors that impact structural changes in oil and gas field rocks, particularly as their development extends to greater depths. The study outlines methodological approaches that facilitate the investigation of physical and mechanical properties of rock samples, while accurately modeling complex thermobaric conditions. Additionally, the it describes the technical specifications of the testing equipment, ensuring the closest possible replication of the actual conditions of reservoir rock occurrences. Lastly, the study reveals key features related to the deformation and fracture of rock samples during testing under lateral pressures of 55 MPa and pore pressures of 30 MPa, along with the creation of temperature fields up to 100 °C.

Keywords

rock, sample, stress, pore pressure, temperature, structure, acoustic emission, field, structural changes

For citation

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Аспекты физического моделирования процессов структурных изменений образцов горных пород при термобарических условиях больших глубин

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Аннотация

При проектировании параметров разработки нефтяных и газовых месторождений на больших глубинах необходимо иметь представление о влиянии на поведение пород-коллекторов и вмещающих их пород таких факторов, как высокий уровень напряженного состояния пород, температурное поле окружающей среды, гидро- и газодинамические процессы в массиве. Воздействие как одного, так и комбинации данных факторов могут привести к изменениям в строении, структуре, составе и свойствах породного массива и, как следствие, несоответствию реальным условиям принятых проектных решений.

Целью исследований является разработка методики лабораторных исследований влияния условий залегания коллекторов нефтяных и газовых месторождений на больших глубинах при изучении свойств образцов горных пород.

Задачи исследования: теоретический анализ и выявление основных факторов, влияющих на поведение и изменение внутренней структуры пород, разработка методики лабораторных исследований с комплексным моделированием данных факторов и проведение пробных экспериментов по оценке их влияния.

В рамках работы были выполнены испытания образцов песчаников, отобранных с глубин от 3,5 до 4 км месторождения углеводородов. Исследования проводились с моделированием термобарических пластовых условий залегания: температуры, горного и пластового давлений.

Представлены результаты экспериментов по исследованию поведения образцов горных пород с максимальным приближением к естественным условиям залегания пород коллекторов 3,5–4 км.

Установлено, что образцы пород одной литологической разности и отобранные практически с одинаковых глубин могут иметь существенные отличия в характере деформирования как в до-, так и запредельной области нагружения.

Результаты данных исследований служат исходными данными при разработке и уточнении геомеханических моделей поведения материалов, которые учитывают не только прочностные критерии разрушения, но и дилатансионные процессы на различных этапах деформирования пород.

Увеличение бокового давления в интервалах от 0 до 55 МПа приводит к относительно незначительному изменению скоростей ультразвуковых колебаний (от 1 до 10 %), что не позволяет судить о необходимости использования данных результатов при косвенной оценке изменения свойств горных пород в массиве. Однако в рамках геофизических исследований учет изменения численных значений скоростей позволит повысить качество интерпретации результатов, что связано с большими геометрическим размерами изучаемых массивов.

Исследования акустической эмиссии пород в сложнонапряженном состоянии позволяют отслеживать процессы пространственного образования и развития микро- и макротрещиноватости на всей стадии нагружения образцов и дают более полное представление об изменении их внутренней структуры.

В статье рассмотрены факторы, влияющие на процессы структурного изменения горных пород нефтяных и газовых месторождений, связанных с увеличением глубины их разработки. Разработаны методические подходы, позволяющие производить исследования физико-механических свойств образцов горных пород с моделированием сложных термобарических условий. Описаны технические характеристики испытательного оборудования, обеспечивающие максимальное воспроизведение реальных условий залегания пород-коллекторов. Выявлены особенности деформирования и разрушения образцов горных пород при их испытаниях в условиях бокового давления 55 МПа, порового 30 МПа с созданием температурного поля до 100 °С.

Ключевые слова

горная порода, образец, напряжение, поровое давление, температура, структура, акустическая эмиссия, месторождение, структурные изменения

Для цитирования

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Introduction

When designing the parameters for the development of oil and gas fields at significant depths, it's essential to understand the impact on the behavior of both reservoir and host rocks. These factors encompass a high level of rock stress, the ambient temperature field, and hydro- and gas-dynamic processes within the mass [1–3]. The influence of any single factor or a combination of these can lead to alterations in the construction, structure, composition and properties of the rock mass [4–6] and, ultimately resulting in a divergence from the design solutions intended for the actual conditions.

Currently, there are two prominent and contrasting theories regarding the origins of hydrocarbons: biogenic (organic) and abiogenic (inorganic) [7–9].

According to the biogenic (organic) theory, the formation of hydrocarbon fields involves several key stages. Initially, a layer of organic residues (oil source rocks) develops at the bottom of a water body. Subsequently, due to the Earth's crust movement and sedimentation, there's a gradual subsidence of this layer to greater depths, leading to increased temperature and pressure. This, in turn, results in the creation of bitumoids (diffusion-dispersed oil) from organic matter. Over time, under the influence of gravity and tectonic forces, oil migrates from the source rocks through the reservoir rocks to the areas where fields form (Fig. 1) [10].

The most common types of reservoirs where oil accumulates are vaulted and tectonically shielded anticlinal traps [11, 12]. Vaulted traps form due to the combined horizontal and vertical deformation of strata without breaks (Fig. 2, *a*). Tectonically shielded traps develop when discontinuities such as downthrows, upcasts, or overthrusts occur, leading to impermeable formations overlapping the reservoir along the tectonic fault line due to formation displacement (Fig. 2, *b*).

The theory of abiogenic origin suggests that hydrocarbons form in mantle sources through inorganic synthesis at great depths, involving colossal pressures and high temperatures, using inorganic

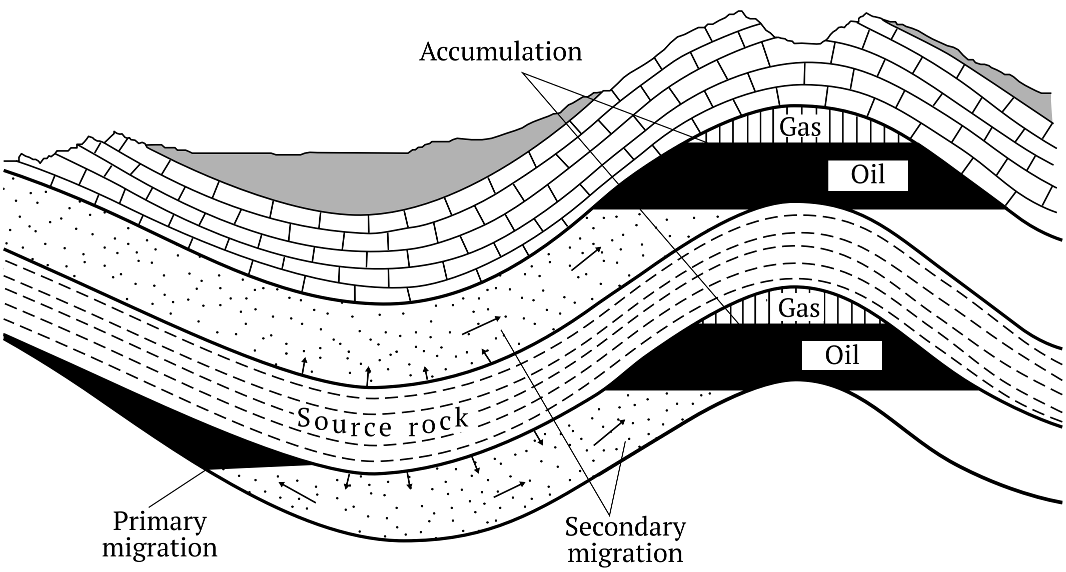


Fig. 1. Basic diagram of formation of oil deposits according to the biogenic theory [10]

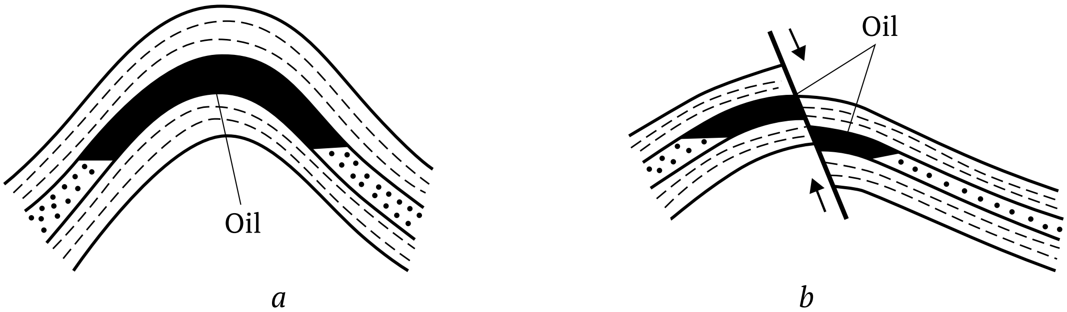


Fig. 2. Diagrams of formation of oil deposits:
a – vaulted trap; *b* – tectonically shielded trap

carbon and hydrogen. According to this concept, these hydrocarbons are generated deep within the Earth's mantle and subsequently migrate along deep faults into the Earth's crust, accumulating in hydrocarbon fields [13–15].

If we set aside the fundamental differences in the genesis of hydrocarbon formation and focus solely on evaluating thermobaric and filtration processes, we can observe their qualitative similarity in both theories. In both cases, the formation of hydrocarbons and their migration through rocks occur under conditions of elevated rock pressure and temperature [16–18]. The divergence lies only in the numerical values of these indicators [19].

The influence of thermobaric conditions on the physical and mechanical properties of rocks is typically assessed through experimental methods involving the simulation of the real mode of occurrence, often utilizing testing equipment. In recent times, with advancements in software and computer technology, laboratory research results have been complemented with mathematical simulations based on various numerical methods [20–22]. These methods permit a more detailed examination of rock deformation and fracture processes, with the accuracy of their results hinging directly on the chosen geomechanical model and reasonable material behavior parameters. Consequently, identifying experimental patterns and dependencies that reflect the impact of specific factors on the behavior of rock samples serves as fundamental initial data for the subsequent evaluation of the behavior of both rocks and reservoir rocks within the mass [23, 24].

The purpose of this work is to develop a methodology for conducting laboratory studies to examine the impact of the mode of occurrence of oil and gas field reservoirs at great depths on the properties of rock samples. To accomplish this, the following objectives were established: conducting theoretical analyses to identify the primary factors affecting the behavior and structural changes in rocks, developing laboratory research methods that comprehensively simulate these factors, and conducting preliminary experiments to evaluate their influence.

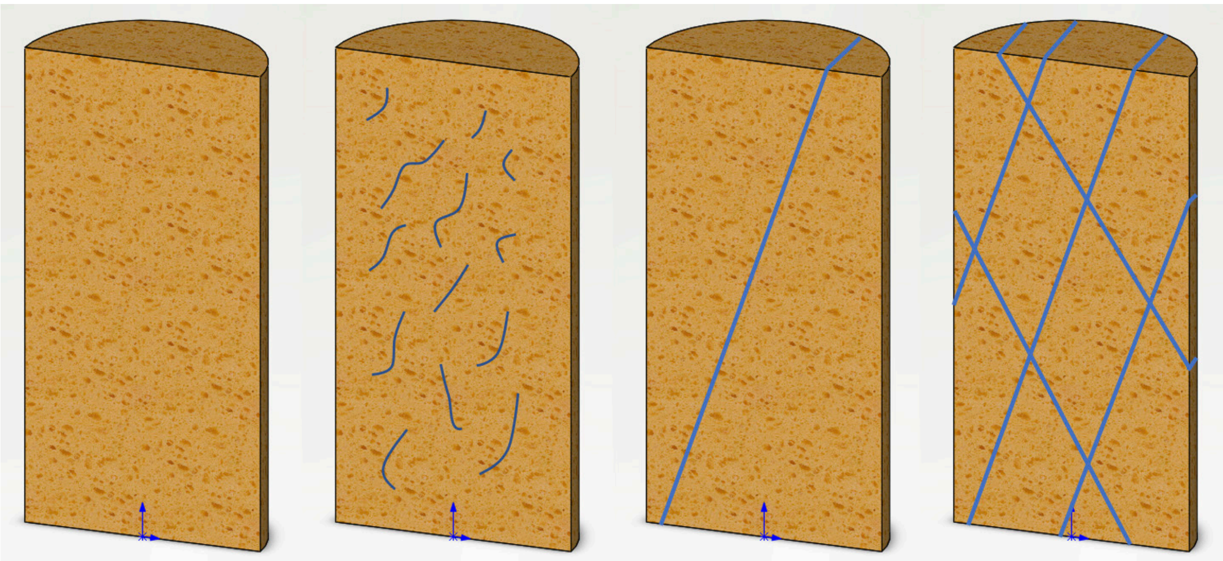
Methods and techniques

The laboratory studies of rocks aim to fully mirror the structural influences that naturally occur within the mass during the formation of a hydrocarbon field [25–27]. As previously mentioned, porous and fractured reservoirs exhibit distinct types of voids. Pore voids develop due to rock compaction resulting from the pressure exerted on the rocks. Fracture voids, on the other hand, are associated tectonic plicative or disjunctive dislocations within the Earth's crust [28, 29].

In light of this, laboratory studies will be conducted on three types of samples:

– the first type comprises rock samples with pore-type voids (Fig. 3, *a*) without any additional external mechanical influences;

– the second type consists of rock samples with pore-type voids and the presence of natural or artificial micro- and macrofractures (Fig. 3, *b*), formed due to plastic deformations during the creation of the anticlinal folded structure of the reservoir;



a *b* *c* *d*

Fig. 3. Types of laboratory samples for research:
a – first type; *b* – second type; *c* and *d* – third type

– the third type encompasses rock samples with the presence of both individual and systems of disjunctive faults, positioned at various angles to the sample (Fig. 3, *c d*), simulating the existence of tectonic faults in the rock formation.

The primary criterion for selecting samples for research within one lithotype of rocks is the high degree of homogeneity of the original core material.

When preparing the side and end surfaces of samples, it is imperative to adhere to the requirements outlined in regulatory documents for the preparation of rock samples intended for volumetric compression testing [30–32].

The boundary conditions set during the testing process should correspond to the depth at which reservoir rocks are typically found, which ranges from 6 to 10 km. These conditions should also account for a degree of variation, considering the heterogeneous nature of the Earth's crust structure. It has been determined that at these depths, the stress levels can range from 250 to 280 MPa, pore (reservoir) pressures can vary from 200 to 220 MPa, and rock temperatures can reach up to 300°C [33–35]. The process of fluid filtration through the sample body must be taken into account. In order to assess the factors influencing the changes in the internal structure and deformation under the conditions of volumetric stress in rock samples, a test chart is proposed (Fig. 4).

In order to achieve these specific boundary conditions, the use of advanced testing press systems is essential. Most press systems are typically designed for standard testing methods outlined in GOST (State Standards). To address this, the servohydraulic testing system MTS 815, equipped with a 4600 kN force load frame and a triaxial compression chamber that allows the generation of lateral pressures up to 80 MPa, was retrofitted. This system also includes controllers and software designed for the automatic control of loading modes, as well as data collection from force and strain sensors in its basic configuration. In addition, thermal heaters with temperature control ranging from 20 to 200 °C were integrated into the triaxial compression chamber. Pumping units were added to facilitate the simulation of pore pressure at the inlet and outlet of the sample (P1 and P2, Fig. 5, *a*) within the range of 0 to 80 MPa. In this particular setup, the testing system is capable of investigating deformation and fracture characteristics of samples under the influence of mechanical loading. It also enables the determination of static deformation properties of rock samples, including elasticity and strain moduli, Poisson's and lateral strain ratios, as well as the assessment of volume changes (dilatancy) at various loading stages. Importantly, this configuration with the utilization of modern sensors provides higher signal accuracy from the measuring channels (accuracy class 0.2), consequently enhancing the overall reliability of the test results.

Another significant aspect of laboratory research involves the study of acoustic emission from rock samples during the testing process [36–38]. This

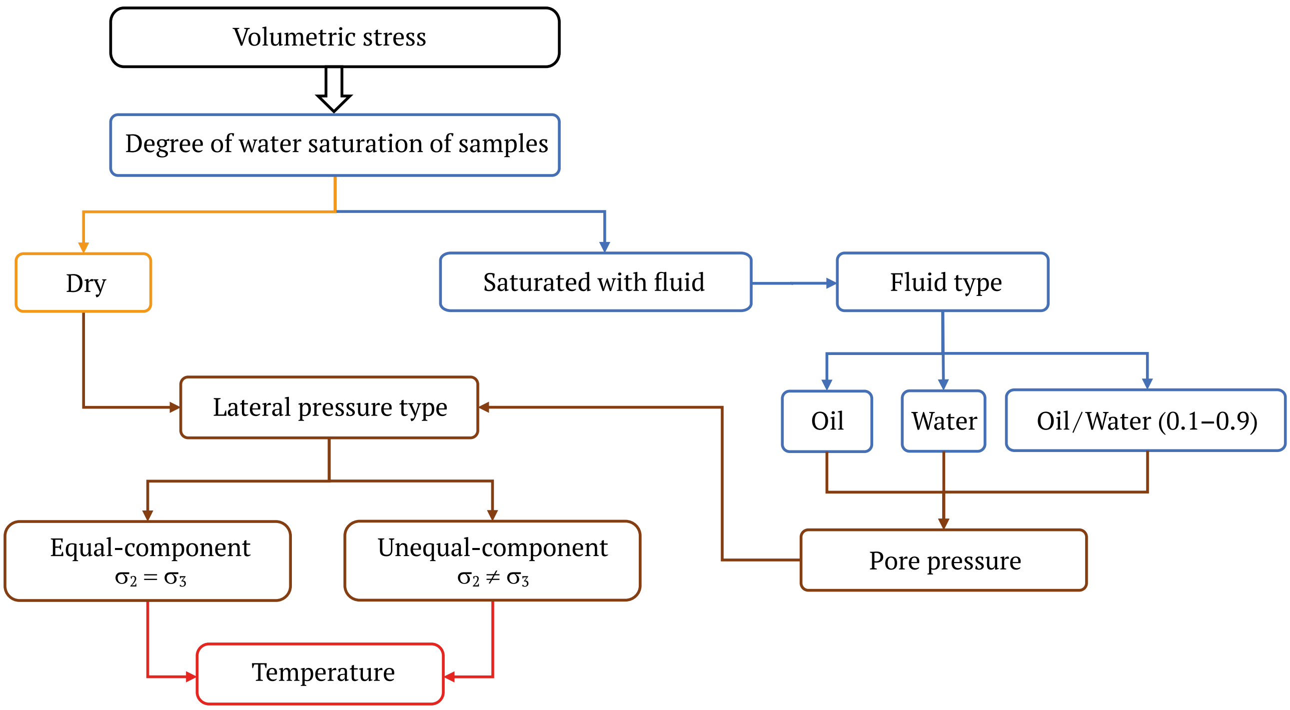


Fig. 4. Algorithm for creating boundary conditions when testing rock samples under volumetric stress

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practice aims to enhance the level of detail in geophysical results obtained during field exploration by establishing correlations between the acoustic properties of rocks and their internal structure. From a theoretical standpoint, it allows for the acquisition of a comprehensive representation of the formation and development of micro- and macrofractures within the sample body during the loading process. To fulfill this purpose, the ErgoTech acoustic emission system was seamlessly integrated into the MTS 815 testing system, which facilitates the recording of acoustic emissions from rock samples within a triaxial compression chamber. The ErgoTech system comprises the following key components:

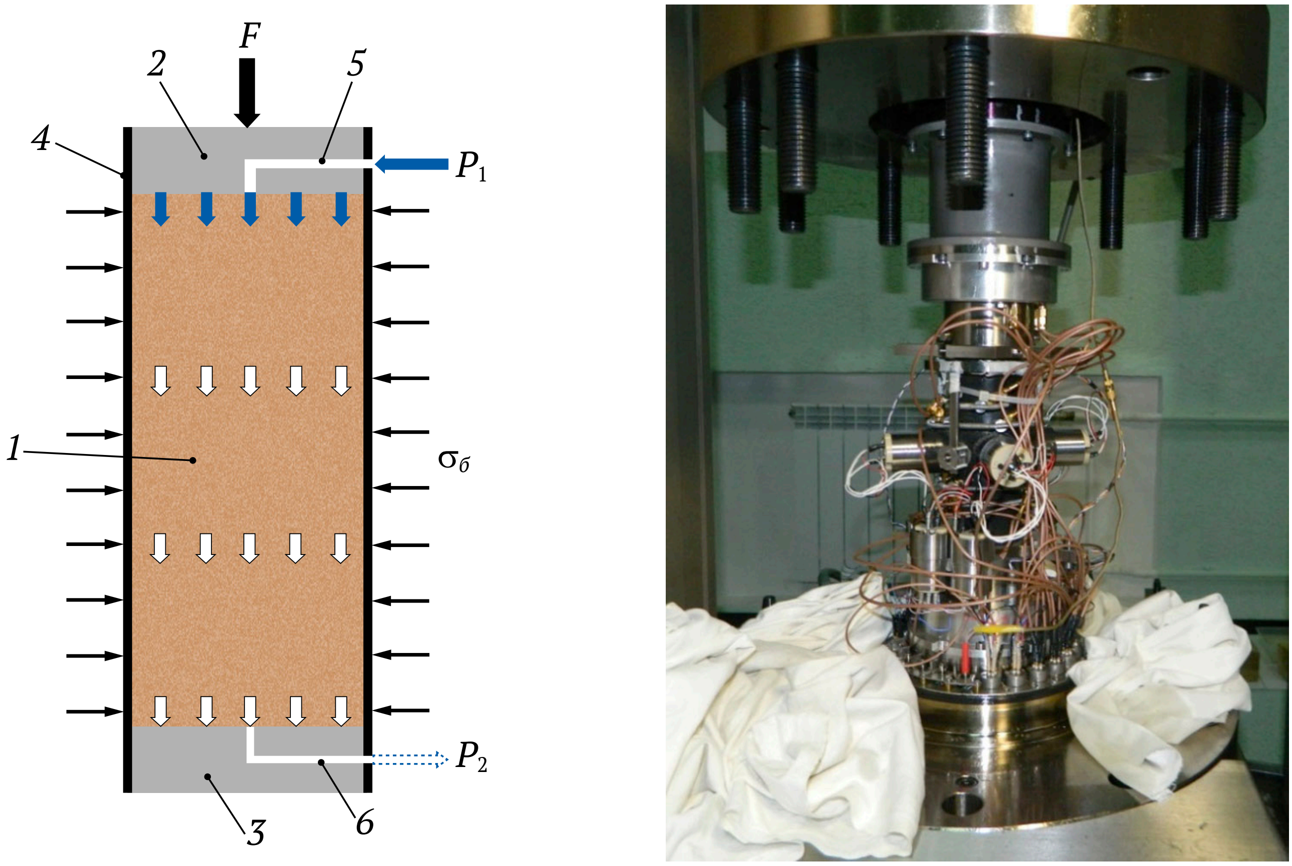
– a measuring unit that fully integrated into the triaxial compression chamber of the MTS 815 system, equipped with 6 ultrasonic sensors and 18 acoustic emission (AE) sensors (Fig. 5, *b*);

– a set of acoustic signal preamplifiers used for signal amplification and transmission to the information acquisition system;

– a unit dedicated to generating, collecting, and processing ultrasonic pulses, which is designed to determine wave velocities at various stages of the experiment.

The processing of test results is carried out using specialized software, namely PicoScope 6 and ASC InSite. PicoScope 6 was employed to ascertain the P- and S-wave velocities at different stages of sample loading. Meanwhile, the ASC InSite software was used to process signals from acoustic sensors and construct volumetric models depicting changes in signal locations and acoustic emission activity at different stages of sample testing.

In the laboratory studies, tests were conducted on sandstone samples collected from depths of 3.5 to 4 km within the hydrocarbon field. These studies were carried out while simulating thermobaric reservoir conditions, encompassing temperature, rock pressures, and reservoir pressures. The fundamental diagram illustrating the simulation of reservoir conditions during testing is depicted in Fig. 5, *a*.



a *b*

Fig. 5. Basic diagram of the experiment (*a*) and sample prepared for tests in the triaxial compression chamber (*b*) with installed acoustic emission sensors:
1 – sample; *2* – upper end lining; *3* – lower end lining; *4* – lateral waterproofing shell of the sample;
5 – channel in the upper end lining for water supply to the sample end; *6* – channel in the lower end lining for outflow of water filtered through the sample; *F* – differential axial load on the sample;
σ_1 – lateral pressure on the sample; P_1, P_2 – porous fluid pressure at the inlet and outlet of the sample

The testing process was as follows.

Samples with a diameter of 100 mm and a height of 200 mm, were crafted from "full-size" core material. These samples, prepared in accordance with GOST 21153.8 "Rocks. Method for determination of triaxial compressive strength", were placed inside the triaxial compression chamber. Lateral pressure was incrementally increased at a rate of 1 MPa/min until reaching 55 MPa, and pore pressure was raised to 30 MPa. Then, the triaxial compression chamber was heated to 100 °C for two hours. Once the formation conditions for potential creep deformations were met, the sample was held until readings from longitudinal and transverse strain sensors had stabilized. The samples were then subjected to an axial load until they failed, with a strain rate of 1 mm/min. The specified boundary conditions remained constant throughout the entirety of the sample testing process. This approach ensured that laboratory tests, which included complex simulation of the rock mode of occurrence, closely approximated the real conditions of rock behavior within the mass, in stark contrast to conventional methods for determining strength and strain properties.

Results

The results of the tests showed that samples of the same lithotype, collected from approximately the same depth of occurrence, have different properties. They can be broadly categorized into three groups. A description of the behaviors observed in these sample groups is presented below.

During the phase of reaching the formation conditions, measurements were taken for P- and S-wave velocities. Fig. 6 illustrates the dependences of changes in acoustic parameters of rocks on the lateral pressure value. The upper set of curves pertains to P-wave velocities, while the lower set relates to S-wave velocities. It's noteworthy that an increase in lateral pressure does not lead to a significant rise in the velocities of ultrasonic vibrations. Specifically, for P-waves within the range of lateral pressures from 0 to 55 MPa, there is an increase of 5–10% in velocity, and for S-waves, the increase is even smaller, around 1–5%. Since the velocity of ultrasonic oscillation is an indirect indicator of the material's (rock) density, we can infer that the formation conditions do not have a significant influence on the processes of compaction within the interior of the samples compared to normal atmospheric conditions.

Fig. 7, *a* illustrates the relationships between relative longitudinal and transverse strains and differential stress when testing these groups of sandstone samples under volumetric compression conditions. Samples in Group 3, which exhibit higher ultrasonic wave velocities, also demonstrate superior strength properties. The obtained variation in strength values, ranging from 80 to 220 MPa, under nearly identical testing conditions, indicates a significant discrepancy in the internal structure of the samples. This observation is further supported by the analysis of changes in volumetric deformations during sample loading (Fig. 7, *b*). For samples in Group 1, characterized by the lowest strength, both during the pre-limit deformation stage and the initial phase of off-limit deformation, a characteristic feature is the volume change in the negative region. This can be attributed to the processes of compaction and

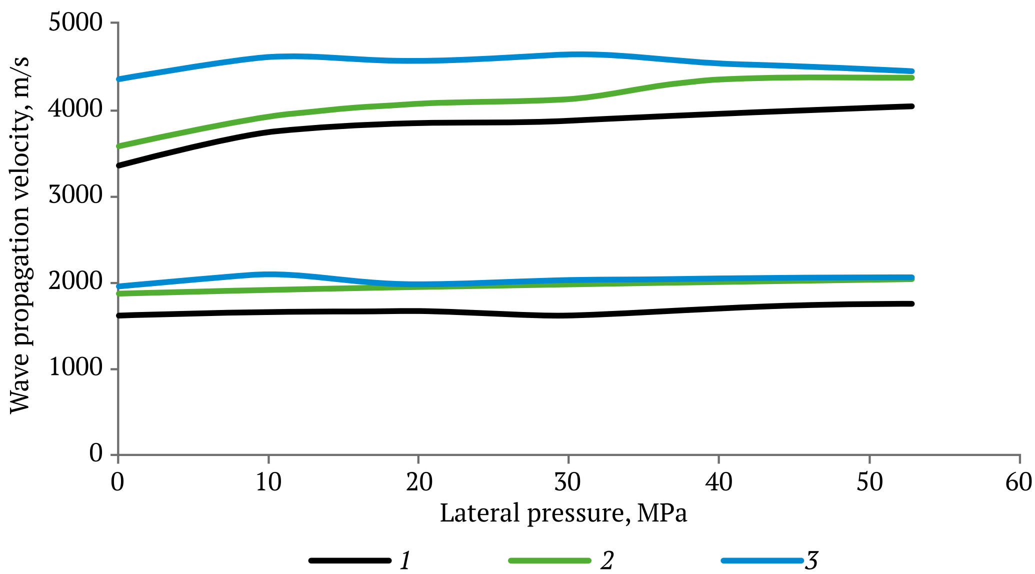


Fig. 6. Dependences of change in propagation velocities of P- and S-waves on the lateral pressure value: *1*, *2*, *3* – groups of sandstone samples

plastic yielding, which involve the closure of internal pore space without fracturing the rock skeleton. Samples in Groups 2 and 3 lack this negative volume change feature, with the transition from the negative to the positive region of volume change occurring prior to fracture. However, distinctions can still be observed, particularly concerning the intensity of volume increase in samples at stress levels close to the strength limit. Group 2 samples display a gradual increase in the rate of volumetric deformations throughout the entire loading range. On the other hand, Group 3 samples exhibit an intensified increase in intensity as they approach the strength limit, with fracture marked by a sudden spike in volumetric deformation values. These findings indicate the presence of structural differences among the sample groups, stemming not from differences in constituent minerals but from variations in textural, structural features, and historical conditions during the rock stratum's formation. Based on this, it can be inferred that the samples in Group 3 likely possessed a more homogenous initial internal structure. The process of plastic yielding and eventual fracture in these samples primarily developed due to the accumulation of stresses within the sample's body exceeding the forces of internal bonds between particles. In contrast, the deformation and fracture of samples in Groups 1 and 2 were influenced to a greater extent by the presence of internal defects, layering, and other structural characteristics.

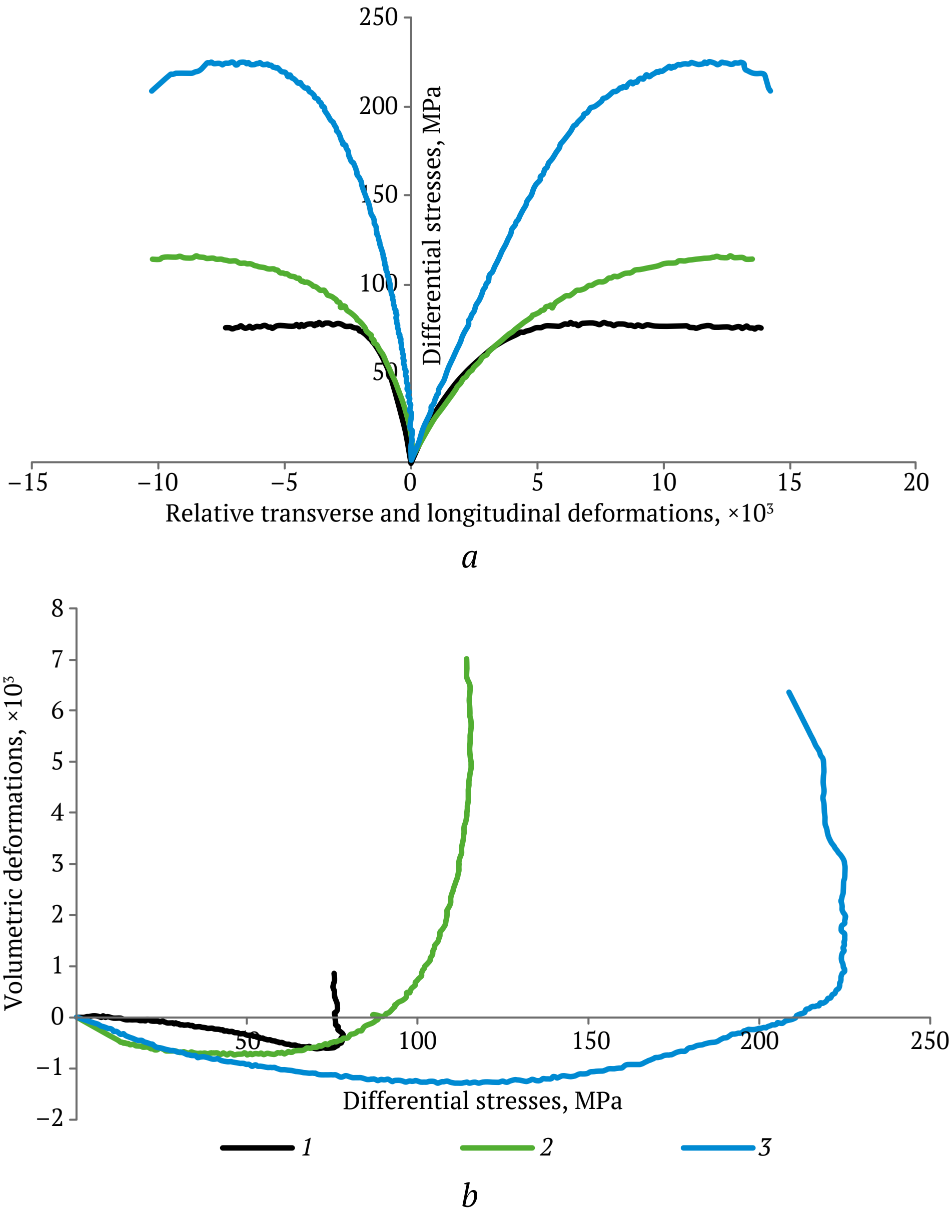


Fig. 7. Curves of dependences of changes in relative longitudinal and transverse deformations (*a*) and volumetric deformations (*b*) on the value of differential stress during volumetric compression testing of samples: *1*, *2*, *3* – groups of sandstone samples

The experiments conducted previously [39] demonstrated the fundamental viability of using the acoustic emission method to investigate the mechanisms of nucleation and subsequent development of micro- and macrofractures during the volumetric compression of rock samples. The results highlighted that the ErgoTech acoustic emission system for rocks allows us to ascertain the spatial and temporal distribution of hypocenters for acoustic emission events while recording amplitude and frequency parameters of signals. Fig. 8 presents the relationship between the intensity of acoustic emission signals and differential stress for rock samples of the same lithotype, tested at a lateral pressure of 40 MPa. In both cases, the maximum signal intensity is concentrated within the region of stress values closely approaching the breaking stress. This is attributed to the formation of a diagonal shear surface, along which the subsequent fracture of the samples occurs. However, there are differences between the two samples. For the second sample, there is a systematic increase in signal intensity throughout the loading process. In contrast, the first sample, with a value of around 50% of its tensile strength, experiences a significant surge in signal intensity, nearly reaching the maximum value. An analysis of the signal locations at this loading stage revealed that in the first sample, there was the initiation and development of a weakening surface (fracture). However, after reaching certain stress values, the further growth of this surface halted, and failure occurred through a different shear surface. Additionally, there are some disparities in the location of acoustic signals at the time of sample fracture (as indicated in the right part of Fig. 8).

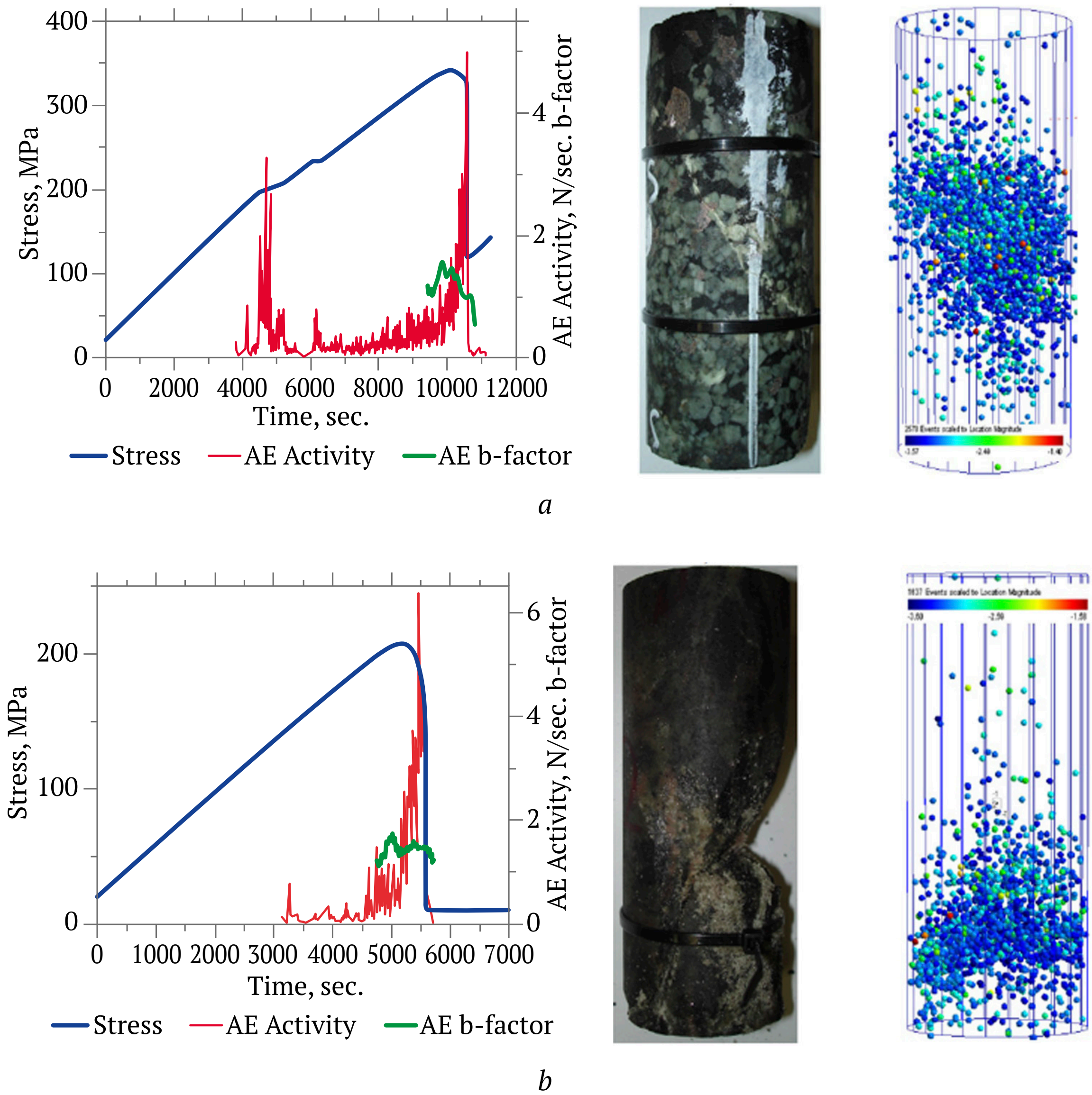


Fig. 8. Test results of two rock samples (*a*, *b*) under the conditions of volumetric stress with acoustic emission fixation [14]

Discussion of results

Methodological approaches to complex laboratory study of the factors influencing changes in the rock structure and including the type of the stress state, the values of principal stresses, and the values of pore pressure and temperature are presented. Existing regulatory documentation for testing rock samples under conditions of volumetric compression does not encompass the reproduction of the complex interplay of these factors during testing. This necessitates the introduction of additional requirements in the development of technical specifications for laboratory studies. Only under these conditions can the results accurately describe the behavior of reservoir rocks in their natural occurrences.

The research presents the results of experiments aimed at studying the behavior of rock samples with the highest possible approximation to the natural conditions of reservoir rock occurrence at depths of 3.5–4 km. It has been established that rock samples of the same lithology, collected from nearly identical depths, can exhibit significant differences in deformation characteristics, both in the pre- and off-limit regions of loading. These research findings serve as essential input data for the development and refinement of geomechanical models governing material behavior, including Coulomb–Mohr, Drucker–Prager, Hoek-Brown models, etc. These models consider not only strength criteria for fracture but also dilatancy processes at various stages of rock deformation, as described by the dilatancy angle formula [40]:

$$\psi = \arcsin\left(\frac{\dot{\varepsilon}_v^p}{-2\dot{\varepsilon}_l^p + \dot{\varepsilon}_v^p}\right),$$

where $\dot{\varepsilon}_v^p$ is the velocity of plastic volumetric deformations, and $\dot{\varepsilon}_l^p$ is the velocity of plastic principal maximum normal (longitudinal) deformations.

An increase in lateral pressure in the range from 0 to 55 MPa results in a relatively minor alteration in ultrasonic vibration velocities, typically ranging from 1 to 10%. This implies that the practical utility of these results for indirectly assessing changes in rock properties within the mass may be limited. However, in the context of geophysical studies, where variations in numerical velocity values are considered, the interpretation of results is substantially enhanced. This is particularly relevant given the substantial geometric dimensions of the studied masses.

Investigations into acoustic emissions from rocks under complex stress conditions provide valuable insights into the spatial formation and development of micro- and macrofracturing processes throughout the entire sample loading stage. These findings contribute to a more comprehensive understanding of changes in the internal structure of the rock samples.

Conclusion

The study analyzes the factors that influence structural changes in rock samples under thermobaric conditions typical of great depths. This represents a pertinent area of scientific inquiry aimed at acquiring fresh insights into the existing structural condition of rocks and how it evolves in tandem with the geological history of the field.

The paper presents the results of comprehensive laboratory studies, highlighting the necessity for further, more extensive laboratory research to establish quantitative relationships that account for the impact of both individual factors and their cumulative influence on the nature of deformation and changes in the internal structure of rocks. Conducting such studies demands the involvement of highly qualified specialists, specialized press equipment, and a dedicated timeframe for experimentation.

Furthermore, the paper introduces approaches and a methodology for laboratory studies, which can be subsequently used in the revision and development of new regulatory documents within the realm of research on the physical and mechanical properties of reservoir rocks. The author team envisions continuing research endeavors aimed at broadening the scope of temperature and pressure effects on the behavior of reservoir rocks using different types of fluids.

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