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The mechanism of fractured porosity formation in heterogeneous rocks under irreversible volume-stress deformation

Mechanizm tworzenia porowatości spękaniowej w skałach niejednorodnych pod wpływem nieodwracalnego odkształcenia naprężeniowo-objętościowego

Halyna Bondar, Mykola Yevdoschuk

Institute of Geological Sciences of NAS of Ukraine

ABSTRACT: The paper deals with the study of the deformation, strength, and reservoir properties of rocks under various stress conditions, typical of great depths. The effect of all-round compression causes a change in the elastic, plastic, and strength characteristics of rocks. Some features of fracture formation and development in inhomogeneous solids under tension and compression were determined. The irreversible deformation mechanism of rocks under an uneven volume stress was considered. The irreversible deformation of rocks combines two types of deformation–intergranular slip, which produces the development of micro-fracturing, and intracrystalline slip, which mainly develops only at high pressure. The typical types of rock damage for uneven triaxial compression (transcrystalline and intercrystalline damage) were investigated. The phenomenon of loosening and increasing the volume as a result of irreversible deformations is mainly caused by the simultaneous formation of intergranular micro-cracks and micro-shifts along grain boundaries. As a result of these micro-dislocation combinations, macroscopic shift planes are formed, followed by irreversible deformation. On the surfaces of deformed samples, slip lines often appear; these are the traces of these macroscopic shift planes. Rock samples deformed due to high pressure are presented. The slip plane traces are clearly visible on the samples' surfaces. It has been stated that under conditions typical of 8–10 km depths, irreversible deformation occurs with decompaction of their structure, increasing the coefficients of porosity and permeability. The effect of rocks deconsolidation caused by stress can be so significant, that in some cases may even increase the volume of voids by 1.5–2 times. The processes of dissolution and leaching of chemically unstable elements are of great importance in determining the filtration capacity and reservoir properties of deep-lying rocks, affected by irreversible deformation changes. Different dependences of volume growth, decompaction intensity coefficient, and permeability coefficient on the overall compression under uneven triaxial stress–which was based on the data of sandstone and marble–have been illustrated. The volume growth is quantitatively determined with the help of the decompaction intensity coefficient, and it is correlated with the collector and filtration capacity of rocks.

Key words: filtration capacity and reservoir properties, irreversible deformation, uneven triaxial compression and tension, cracks, loosening, decompaction.

STRESZCZENIE: Artykuł dotyczy badań odkształcenia, wytrzymałości oraz właściwości zbiornikowych skał w różnych warunkach naprężenia typowych dla znacznych głębokości. Wpływ ściskania obwodowego powoduje zmianę właściwości sprężystych, plastycznych i wytrzymałościowych skał. Określono niektóre cechy tworzenia i rozwoju pęknięć w niejednorodnych ciałach stałych pod wpływem rozciągania i ściskania. Rozważano mechanizm nieodwracalnego odkształcenia skał pod wpływem niejednolitego naprężenia objętościowego. Nieodwracalne odkształcenie skał łączy dwa rodzaje odkształcenia: poślizg międzyziarnowy, powodujący rozwój mikropękania, oraz poślizg międzykrystaliczny, który rozwija się tylko przy wysokim ciśnieniu. Badano rodzaje zniszczenia skał typowe dla niejednolitego trójosiowego ściskania (zniszczenie śródkrystaliczne i międzykrystaliczne). Zjawisko rozluźniania i zwiększenia objętości w wyniku odkształceń nieodwracalnych jest powodowane przez jednoczesne tworzenie mikropęknięć międzyziarnowych oraz mikroprzesunięcia wzdłuż granic ziaren. W wyniku tych kombinacji mikrodyslokacji tworzone są makroskopowe płaszczyzny przemieszczenia, a następnie odkształcenie nieodwracalne. Na powierzchni próbek odkształconych często pojawiają się linie poślizgu, które są śladami tych makroskopowych płaszczyzn poślizgu. Zaprezentowano próbki skalne odkształcone z powodu wysokiego ciśnienia. Na powierzchni próbek widoczne są wyraźnie ślady płaszczyzn poślizgu. Stwierdzono, że w warunkach typowych dla głębokości 8–10 km występuje odkształcenie nieodwracalne z rozgęszczeniem ich struktury, zwiększeniem współczynników porowatości i przepuszczalności. Wpływ dekonsolidacji skał powodowany przez naprężenie może być tak istotny, że całkowicie usuwa konsolidację skał, powodowaną przez naprężenia efektywne, a w niektórych przypadkach może zwiększyć objętość pustek nawet 1,5–2 razy. Procesy rozpuszczania i ługowania elementów niestabilnych chemicznie mają duże znaczenie dla określenia zdolności filtracji oraz właściwości

Correspondig author: Halyna Bondar, e-mail: *galyna-bondar@i.ua*

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zbiornikowych skał zalegających głęboko pod wpływem nieodwracalnych zmian odkształcenia. Zilustrowano różne zależności wzrostu objętości, współczynnika intensywności dekompakcji i współczynnika przepuszczalności od całkowitego ściskania pod wpływem niejednolitego naprężenia trójosiowego, oparte na danych dla piaskowca i marmuru. Wzrost objętości jest ilościowo określony za pomocą współczynnika intensywności dekompakcji i jest skorelowany z właściwościami filtracyjnymi skał.

Słowa kluczowe: zdolność filtracji i właściwości zbiornikowe, odkształcenie nieodwracalne, niejednolite ściskanie i rozciąganie trójosiowe, pęknięcia, rozluźnienie, dekompakcja.

Introduction

The study of deformation and the strength properties of rocks under conditions of uneven triaxial compression and tension was started by Bridgeman (1935), Adams and Coker (1910), and Boker (1915). Extensive development of this research has been done in recent years by studying the structure of the Earth's deep zones, prospecting and exploring mineral resources at great depths, and making progress in the technology of experimentation at high pressure.

Studies carried out under conditions of high pressure and different stresses (longitudinal compression and tension, shearing, bending, and torsion) revealed that the effect of all-round compression causes a change in the elastic, plastic, and strength properties of rocks (Pavlova, 1975). Studies of the rocks' deformation and strength properties can be found in a number of publications (Griggs and Handin, 1960; Baidyuk, 1963; Handin, 1966; Schreiner et al., 1968).

Most of the metamorphic and igneous rocks, as well as the minerals that make them up, within the range of stresses and temperatures typical of depths up to 15 km, show significantly less ability for plastic deformation than sedimentary rocks.

Methods

The paper by T. Jokobori (1965) considers the process of damage to solids in terms of microstructural differences. The types of rock damage typical of uneven triaxial compression are chipping and cutting, while common damage fractures intersect grains of a polycrystalline body – called transcrystalline damage; this differs from intercrystalline damage, which occurs only along the grain boundaries. The latter type of damage is typical of the stage of irreversible deformation in most rocks, preceding the process of general disintegration (Pavlova, 1975).

In most cases, the irreversible deformation of rocks combines two types of deformation–intergranular slip, producing the development of micro-fracturing, and intracrystalline slip, which mainly develops only at high pressure. An analysis of sandstone fracturing (Pavlova, 1975) showed that the irreversible deformation of sandstone is due to the development of intergranular fractures and displacements along grain contact points, while reorientation of clay minerals of cement and detrital material occurs, resulting from the turning – and sometimes flection – of separate mica pieces. Reorientation contributes to the formation and growth of intergranular fractures, which separate grains and cementing mass, and open and break them.

The irreversible deformation of sandstone begins with the twinning of the calcite crystals that make the cement of these rocks and the development of intracrystalline fractures. Channels, pores, and discontinuities of calcite grains are formed as a result of cement grains twinning. Grains of quartzite save its integrity. Thus, the deformation process in this case affects the weakest structures, which here are the grains of calcite and the grains' boundaries.

The loosening and increasing of the volume as a result of irreversible deformation is mainly caused by the simultaneous formation of intergranular micro-cracks and micro-shifts along the grain boundaries. As a result of these micro-dislocation combinations, macroscopic shift planes are formed, followed by irreversible deformation. Slip lines often appear on the deformed samples' surfaces, which are traces of these macroscopic shift planes. Two systems of intersecting slip lines can be observed, the orientation angles and density of lines per surface unit of which depend on the stress type.

When critical-state conditions lead to a horizontal position (pure shear zone), the slip lines are located at an angle of 45°. In the stressed zone between pure shear and uniaxial compression, the angle of the slip plane inclination varies from 45° to about 18–20°. In the tensile stress zone, the angle of damage plane inclination varies from about 18° under uniaxial compression to 0° under uniaxial tension. Figure 1 shows rock samples deformed due to high pressures. The slip plane traces are clearly visible on the surfaces of the samples.

All rocks can be divided into two large groups according to their deformation behavior, characterized by the magnitude of relative deformation—for total damage, $\varepsilon_i = \Delta L/L_0$ (where L_0 is the initial sample length and ΔL is its decrease), and for irreversible damage (plastic), $\varepsilon_{in} = \varepsilon_i - \varepsilon_{iy}$, (where ε_{iy} is the elastic component of deformation):

1) elastobrittle rocks, which are not resistant to plastic deformation ($\varepsilon_i \leq 1\%–2\%$; $\varepsilon_{in} \approx 0$) and
2) plastic rocks, among which there are subgroups,
   a) limited plastic rocks that can be damaged with a small irreversible deformation ($\varepsilon_i \leq 2–10\%$; $\varepsilon_n = 1–8\%$) and
   b) plastic and highly plastic ($\varepsilon_i > 10–15\%$; $\varepsilon_{in} > 8–10\%$).

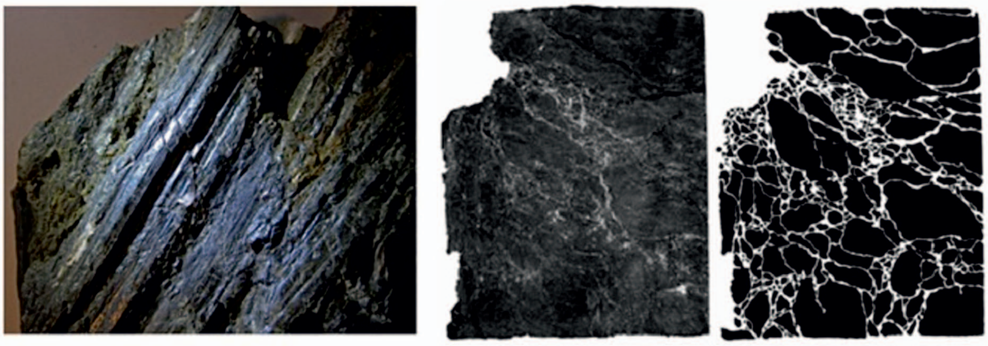

Fig. 1. Photos of rock samples with clear traces of slip planes (Flickr; Research Gate)

Rys. 1. Zdjęcia próbek skał z wyraźnymi śladami płaszczyzn poślizgu (Flickr; Research Gate)

As most rocks in the process of plastic deformation are characterized by the ability to deconsolidate (with predominantly developed deformation of the intergranular mechanism) under conditions of uneven all-round compression, an analysis of changes in their collector properties is of some interest.

As a result of previous research (Baidyuk, 1963), it was found that additional voids, formed in rocks under uneven stress, were caused by deformation.

The effect of rock deconsolidation ($+\varepsilon_{v\sigma i}$) caused by stress can be so significant that it completely undoes the rock consolidation, resulting from the effective stresses $\sigma_{e\phi}$ ($-\varepsilon_{v\sigma e\phi}$), and in some cases may even increase the volume of voids by 1.5–2 times. The process of void formation under natural conditions is greatly influenced by the processes of dissolution and leaching of chemically unstable elements. For example, the highest values of deformation void increases have been noted in organogenic limestones (Bridgeman, 1935).

Various carbonate rocks have demonstrated a development of more fractured reservoirs. As a rule, small fluid deposits in fracture-type reservoirs occur in sandy-aleurite, metamorphic, and igneous rocks.

These regularities have been confirmed by the analysis of the structural features and collector properties of fractured reservoirs (Smekhov, 1968, 1969).

Decompaction of the rock structure in the process of irreversible deformation should also contribute to the growth of rock permeability. In fractured-type collectors, the main influence on the filtration rocks' properties is created by fractures that increase at a certain level of stress and which should be larger than the size of the grains, according to studies by Smekhov (1968, 1969). In pore-type collectors under low tectonic stresses, deformation decompaction can develop without fracturing.

The relationship between the permeability coefficient (PC) and the absolute value of the rocks' growth in volume may vary. In Figure 2, based on data for sandstone (Pavlova, 1975) and marble (Stavrogin, 1968), various dependences are shown between the volume growth (ε_v) and the PC on overall compression under uneven triaxial stress (σ). If ε_v first increases in a rather complicated way to a certain maximum value and then decreases, then the PC decreases continuously from the very beginning. Therefore, it is impossible to determine the value of the PC according to the value of ε_v.

In explaining this phenomenon, it should be taken into account that an increase in both ε and σ_3 is connected with increased deformation (ε_i), resulting in damage, i.e., with the rock's growth in plasticity. This complicated phenomenon can be neglected if the magnitude of volume growth ε_v is not the basis, but a parameter of critical decompaction C_{vic}.

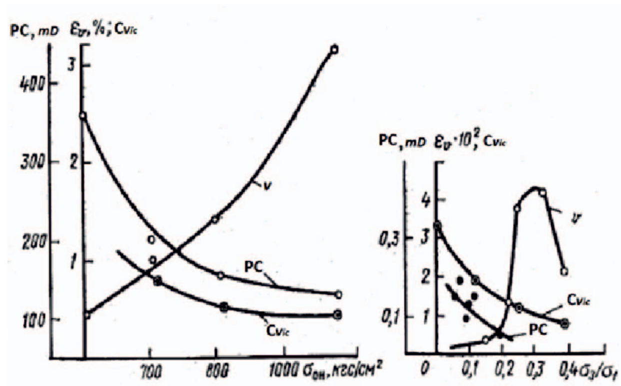

Fig. 2. Dependences of volume growth (ε_v), the decompaction intensity coefficient (C_{vic}), and the permeability coefficient (*PC*) on overall compression under uneven triaxial stress (σ) Note. "a" is sandstone, sample 731К; "b" is marble (Pavlova, 1975)

Rys. 2. Zależności wzrostu objętości (ε_v), współczynnika intensywności dekompakcji (C_{vic}) oraz współczynnika przepuszczalności (*PC*) od całkowitej kompresji przy niejednolitym natężeniu trójosiowym (σ): gdzie „a" piaskowiec, próbka 731К; „b" marmur (Pavlova, 1975)

In Figure 2, the dependences of C_{vic} and the PC on $\sigma_{он}$ are shown (on σ_3/σ_1 in Stavrogin [1968]). As you can see, the dependences of a change in C_{vic} on the overall compression is similar to a change in the PC. As it follows, PC = ηC_{vic}, where η is the coefficient of proportionality. As Figure 2 shows, with an increase in rock plasticity (caused by σ_3 growth) and where ε_v at first increases, PC decreases. Therefore, we can assume that the ε_v growth is related to the number (N) of developing micro-faults, the length of which (less than the grain size) decreases with σ_3 growth.

Since the volume growth under deformation is proportional to the product of the number of micro-cracks, we can assume that $C_{vic} = \varepsilon_v/\varepsilon_{in}$, which chiefly characterizes the length (and, therefore, the openness) of deformation micro-faults (micro-cracks).

Conclusions

Some general features of the process of rock deformation in conditions which are typical of large depths were determined. The most important features are the likeness of the irreversible deformation mechanism and the growth in volume of the rocks, which are determined by the lithological and petrographic features and the nature of deformation and damage to the rocks. The volume growth is quantitatively determined with the help of the decompaction intensity coefficient and it is correlated with the reservoir and filtration capacity of the rocks.

The process of deformation, resulting in the development of fracturing and mutual displacement of the structural elements, occurs along the weakest parts of the structure, namely, the contacts between grains and the weakest mineral grains in polymineral rocks. Despite the strong stresses and deformations, the material retains its structural basis; the grains do not lose their integrity as structural elements, but are subjected to different kinds of faults.

The processes of dissolution and leaching of chemically unstable elements are of great importance in determining the filtration capacity and reservoir properties of deep-lying rocks, which are affected by irreversible deformation changes, including decompaction under plastic deformation.

Some mechanism features for the formation and development of cracks in inhomogeneous solids under tension and compression were determined, based on the considered research results (Stavrogin and Tarasov, 2001).

1. The sites of crack formation are related to different heterogeneities in the material: defects, micro-cracks, pores, grain boundaries, etc.
2. The reason for the formation of cracks is the concentration of stresses on these defects as a result of heterogeneous elastic or plastic deformation.
3. Under compression conditions, cracks increase in the direction of the strongest main compressive stress, and – under tension – in the direction perpendicular to the tensile stresses.
4. The most favorable orientation angles of initial cracks to tearing cracks (with respect to the acting stress) are 30–45° under compression (depending on the initial crack configuration) and 90–45° under tension.
5. In volumetric stress-state conditions, side compressive stress prevents the formation and development of tearing cracks, which leads to increased material strength and reduced tearing cracks under equal stresses.

The study of the strength and deformation properties of rocks under stresses and temperatures which are typical of depths up to 10–15 km can be used to solve various problems of petroleum geology and mining.

Investigation of the influence of deformation on the filtration capacity of deep-lying reservoir rocks should be carried out in view of their oil and gas prospects, which will enable the design of criteria for evaluating oil and gas accumulations and a better understanding of the mechanisms of influence on these reservoirs in further industrial development.

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H.M. BONDAR
PhD student
Institute of Geological Sciences of NAS of Ukraine
st. O. Goncharа 55-b
01054 Kyiv, Ukraine
E-mail: *galyna-bondar@i.ua*

M.I. YEVDOSCHUK
Doctor of geological sciences, head of the department
Institute of Geological Sciences of NAS of Ukraine
st. O. Goncharа 55-b
01054 Kyiv, Ukraine
E-mail: myevdoshchuk@rambler.ru