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Seismic and well log data as a source for the calculation of elastic properties of rock media – conditioning for successful exploration, well trajectory, completion and production design of unconventional reservoirs

Selected geomechanical parameters characterizing the reservoir and allowing recognition of the rock ability to generate the fracture system during well completion process known as hydraulic fracturing are commonly calculated based on seismic and well log data. Knowledge of ductile or brittle rock behavior enables engineers to select well location, design the most efficient trajectory of the borehole and well complection including selection of the best zones for the hydraulic fracturing.

Key words: unconventional reservoirs, hydraulic fracturing, geomechanical parameters, Poisson ratio, Young modulus.

Dane sejsmiczne oraz geofizyki otworowej jako źródło wiedzy na temat właściwości sprężystych ośrodka geologicznego – warunkujących sukces na etapie poszukiwania, projektowania i udostępniania złóż typu niekonwencjonalnego

Parametry geomechaniczne charakteryzujące ośrodek skalny pod kątem zdolności skał do generacji szczelin na drodze technologicznego udrażniania przepływu gazu zamkniętego w skale zbiornikowej (szczelinowanie) szacowane są na podstawie danych sejsmicznych oraz profilowań geofizyki otworowej. Wiedza na temat plastycznego lub sztywnego charakteru ośrodka geologicznego pozwala na poprawną lokalizację wiercenia oraz umożliwia zaprojektowanie najbardziej efektywnej trajektorii otworu wiertniczego i poziomów udostępnienia złóż na drodze hydraulicznego szczelinowania.

Słowa kluczowe: złoża niekonwencjonalne, szczelinowanie hydrauliczne, parametry geomechaniczne, współczynnik Poisson'a, moduł Young'a.

Introduction

Successful exploration and production of oil and natural gas is conditioned with an accurate geological model of the reservoir, including information about the petrophysical, geochemical and geomechanical properties of the reservoir and surrounding rocks. These last ones play a key role especially in the design and production stage of both unconventional shale gas formations and low-permeability tight sandstones.

A properly designed borehole trajectory and forecasted pressure of the drilling fluid acting on the borehole is of great importance as they enable to prevent many costly problems while drilling a well. They are mostly related to wellbore stability loss, which is the geomechanical response of poor selection of drilling fluid parameters. Another stage following the successfully drilled borehole is design of the reservoir development stage, especially challenging when we are dealing with unconventional oil and gas reservoirs, that are revealing very low flow parameters. Geomechanical investigation is essential during the reservoir production as it enables to recognize the ability of rocks to generate fractures during well completion process known as hydraulic fracturing. This technological process aims to create an artificial fracture network through which hydrocarbons can migrate to the wellbore [16, 17].

Elastic properties

Commonly used elastic properties characterizing mechanical strength and elasticity of rock mass are Young's modulus (E) and Poisson's ratio (ν).

Young's modulus is describing the relationship between relative linear deformations (ε) of the material under applied linear stress (σ) (1) [3, 18]. Its value is determined in a compressive test in a laboratory environment, but is also possible to estimate basing on shear (S) and compressive (P) wave velocity acquired within seismic survey and acoustic profiling [1, 7, 8, 9, 16].

$$E = \sigma/\varepsilon = \sigma/(\text{\% change of the sample length / initial sample length}) \quad (1)$$

E – Young's modulus,
σ – applied stress,
ε – relative linear strain.

Poisson's ratio (ν) expresses the ratio of lateral strain (ε_x) to the longitudinal strain (ε_z) for axial stress state (2), (fig. 1A):

$$\nu = -\varepsilon_x/\varepsilon_z = (\text{\% change of the sample width / initial sample width}) (\text{\% change of the sample length / inicial sample length})^{-1} \quad (2)$$

where:
ν – Poisson's ratio,
ε_x – relative lateral strain,
ε_z – relative longitudinal strain.

Other elastic parameters characterizing of the elastic properties of the geological media like Lamé's first parameter (λ), shear modulus (μ) and bulk modulus (K) can be distinguished. However their application in geomechanical modeling is limited to specific cases. Relationships between the following elastic parameters E, ν, λ, μ and compressive wave velocity (v_p) and shear wave velocity (v_s) are expressed by the presented equations (3), (4), (5):

$$v_p = \left[(\lambda + 2\mu)/\rho\right]^{1/2} = \left[E(1 - \nu/\rho(1 - 2\nu)(1 + \nu))\right]^{1/2} \quad (3)$$

$$v_s = (\mu/\rho)^{1/2} = \left[E/2\rho(1 + \nu)\right]^{1/2} \quad (4)$$

$$v_p/v_s = \left[(0.5 - \nu)/(1 - \nu)\right]^{1/2} \quad (5)$$

where:
v_p – compressive wave velocity,
v_s – shear wave velocity,
λ – Lamé parameter,
μ – shear modulus,
ρ – solid density,
E – Young's modulus,
ν – Poisson's ratio.

The elastic parameters that the author is referring to, allow to predict the relative brittle or ductile behavior of the rocks within the productive shale or tight sandstone formation (fig. 2).

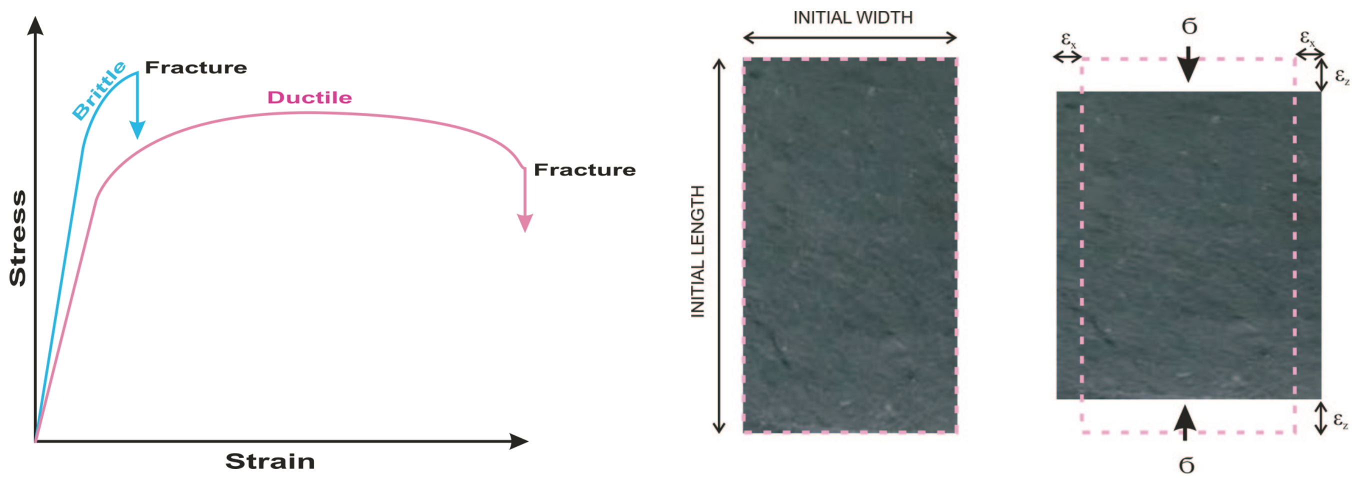

Fig. 1. A – Change of the rock sample dimensions under applied compressive stress.
B – Graph showing two types of deformation that rock undergoes under applied stress.
The blue curve is typical for brittle rocks while the pink one is typical for ductile rocks

For better understanding of complexity of the rock behavior during fracking, an investigation of parameters ε, γ and δ, describing anisotropy in transversely isotropic rocks with weak anisotropy, so called Thomsen's parameters, is strongly recommended [6]. They assume more a realistic approach namely, that the mass of rock is not perfectly isotropic and consists of anisotropy elements as preexisting surfaces of weakness like natural fractures, lineation, bedding [14] along which the artificial fractures are likely to propagate. Thomsen's parameters can be obtained from multi-component seismic data or well logging, allowing the velocity measurement in three dimensions.

Rock tending to have brittle body properties yield into elastic deformation under applied stress, and ruptures afterwards, when the applied stress exceeds the threshold strength value typical for the given rock type. Plastic rocks on the other hand undergo plastic deformation before breaking under applied stress [12] (fig. 1B).

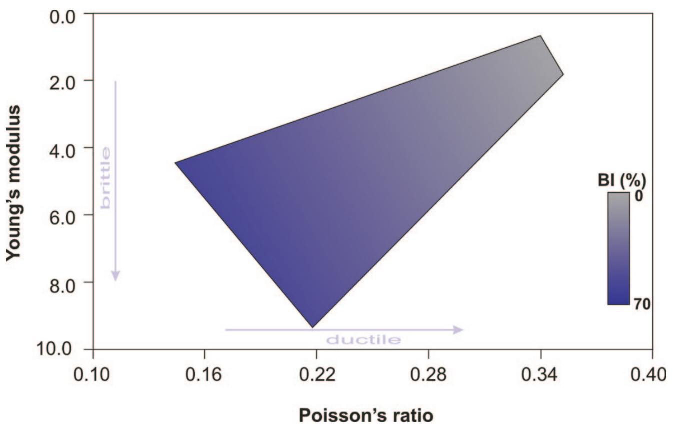

Fig. 2. Plot presenting the relationship between Young's modulus and Poisson's ratio for Brittleness Index (BI) estimation. The higher BI values the rock will be assumed to have, the more brittle and prone to generate artificial fractures network and therefore more efficient hydraulic fracturing will be [14] changed

The estimation of elastic parameters allows to perform a correct and effective design of the drilling process and reservoir development, especially hydraulic fracturing of recently investigated in large scale, unconventional oil and gas reservoirs [10].

Elastic parameter values obtained in laboratory through uniaxial test differ significantly from those calculated from well logs and seismic data. Multiple measurements of mechanical elastic parameters obtained in the laboratory environment reveal a difference in results from those obtained from the compressive and shear waves velocities record (fig. 3). Therefore there is a need to distinguish between dynamic (calculated from well logs or seismic waves velocity and density) and static (measured in the laboratory) elastic parameters. In general, we can observe that the values of elastic moduli measured in static (laboratory) conditions are lower than those obtained on the basis of the relationship with acoustic velocities record. This difference is more significant when we manage with low mechanical strength rocks and becomes smaller with the increase of the stress applied to the selected area of the tested rock. The reason for this variation may be due to the fluid saturation level difference during the measurement of rocks in static and dynamic conditions, as the sound waves velocity increases in the rocks saturated with fluid (typical under dynamic conditions) [6].

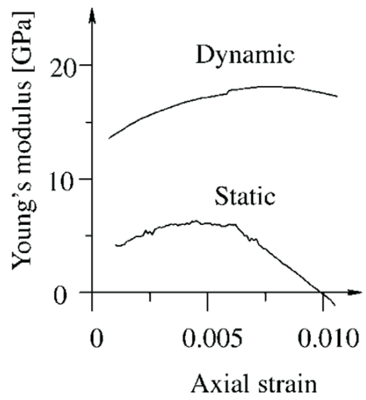

Fig. 3. Comparison of static and dynamic Young's modulus measured in triaxial tests of dry sandstones from the Red Wildmoor [6]

As mentioned above, the values of the elastic parameters is determined based on the velocity of the shear (*S*) and compressive (*P*) wave recorded during seismic or acoustic profiling [1, 5, 15]. Making the use of the relationships between v_p, v_s and density Young's modulus and Poisson's ratio can be calculated. Figure 4 presents the map of the Poisson's ratio distribution in the reservoir *Y*, which was obtained from the seismic data.

The v_p and v_s velocities derived from the 3D seismic data (fig. 4) and velocities recorded during the acoustic profiling in the borehole W-1 (fig. 5) differ slightly, and thus the calculated value of dynamic Poisson's ratio [13]. The difference is due to the small, reaching up to 5÷10% divergence in obtained through these two methods value of total time, within which the seismic wave travels through the geologic media, from the moment of its generation, through the reflection at a certain boundary between different geological layers, until its return to the receiver (so called two-way-traveltime). The variation in the resulting total time is mainly due to the difference in frequency ranges used during seismic and well logging measurements. Frequency spectrum during well logging is considerably wider, particularly towards higher frequencies. With the seismic method the presence of wave propagation effect, having influence on the recorded measurements can be also observed. Another factor contributing to the difference in the two-way-traveltime is scale effect [11]. To be more precise, estimation of the seismic wave is preceded with seismic data processing during so called stacking, which results in reduction of the amount of data to a single vertical profile of reflectivity. The input data for the procedure may include measurements of several thousand cubic kilometers of geological formation. So huge amount of information requires intensive statistical processing, which allows to obtain any single seismic trace. When we consider well logging measurements, the seismic waves velocity is recorded in the close environment of the borehole wall and refers to a volume much smaller than seismic profiling is dealing with. Thus, in each of the described measuring techniques we record velocity of seismic waves that traveled through a completely different volume of the rock, therefore we get a slightly different velocity [2, 4].

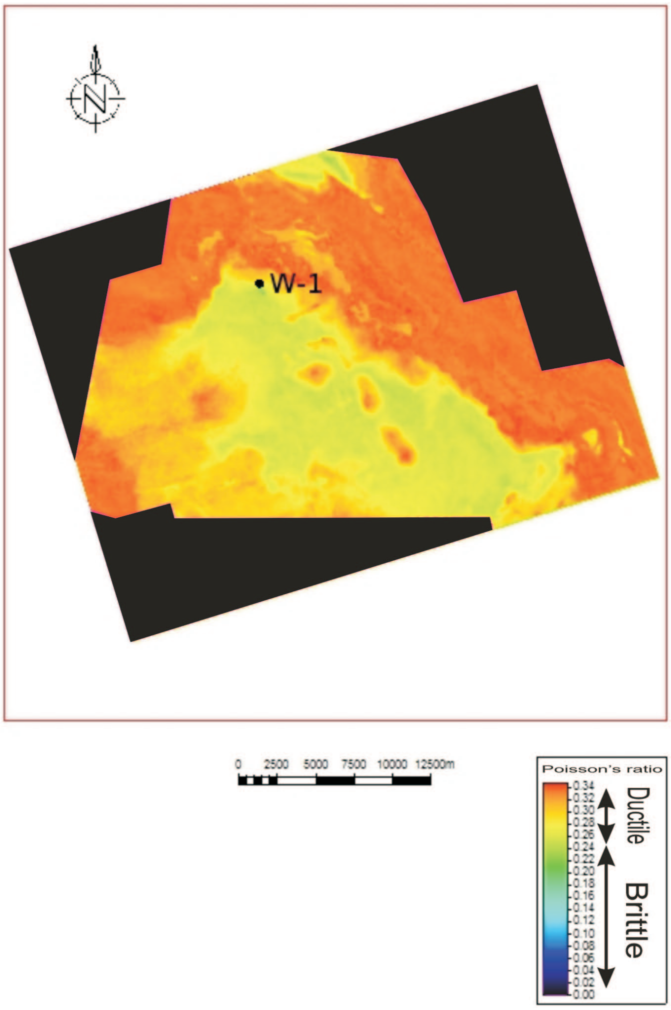

Fig. 4. Map of the distribution of mean value of Poisson's ratio in the reservoir A within zone A, calculated on the base of 3D seismic. For the well W-1 location, the arithmetic mean of the dynamic Poisson's ratio is equal to 0.280 for zone A. This low value of Poisson's ratio reflects plastic nature of the zone A, which suggests low susceptibility for artificial fractures development and therefore low efficiency of hydraulic fracturing itself. The change of the Poisson ratio values reflects the lithology change in the basin and even outlines its structure

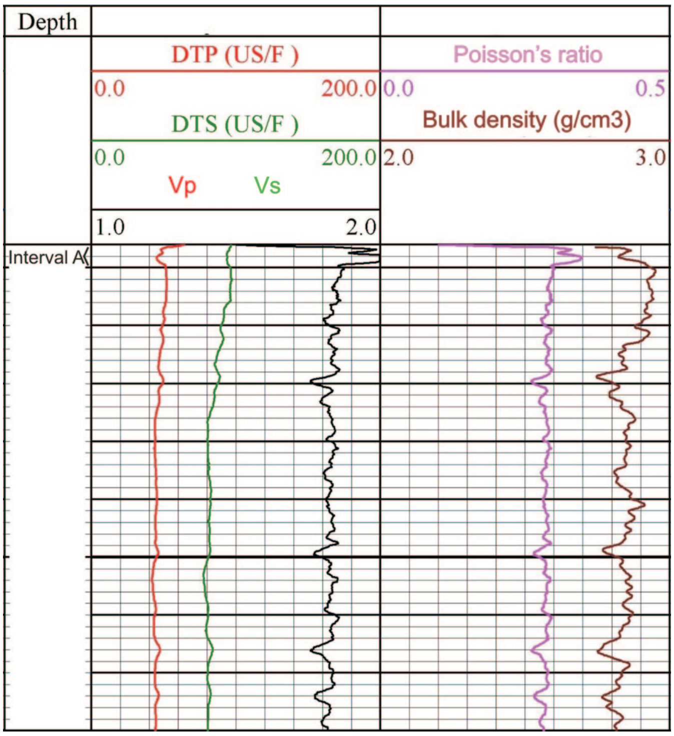

Fig. 5. Compressive (v_p) and shear (v_s) wave velocity curves, the v_p/v_s ratio curve, density (RHOB) curve and curve of dynamic Poisson's ratio calculated from logs from well W-1 with the arithmetic mean of the dynamic Poisson's ratio equal to 0.287 for interval A. This low value of Poisson's ratio confirms with seismic data and reflects plastic nature of the interval A, which suggests low susceptibility for artificial fractures development and therefore low efficiency of hydraulic fracturing

Summary

Proper selection of the well location, design of the most efficient trajectory of the borehole and well complection including selection of the best zones for hydraulic fracturing strongly relies on the mechanical properties of the penetrated rock media. The evaluation of the object of the interest is achieved by detailed analysis of the factors responsible for mechanical rock properties. This workflow significantly increases the chance for success at the reservoir development stage and can eliminate possible drilling problems, which directly reduce time and drilling costs.

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