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Characteristics of serial fractures distribution in mechanically stratified shale complexes based on borehole data analysis from the Baltic Basin, Poland

Abstract

Geometry and statistical parameters of fracture networks have been studied for years concerning their influence on rock permeability, fluid migration, or reservoir response to hydraulic fracturing operations. Joints are critical in this context because of their common occurrence and characteristic relationship to lithostratigraphic units. Petroleum analysts often ignore joint fractures in basin models due to their small sizes and thus neglect their impact on the triggering of microseismic events and permeability stimulation. Therefore, the primary justification for undertaking the research was to include the joint fracture system and to characterize it as accurately as possible by developing and implementing new analytical methods that provide more reliable values for its statistical parameters and stratigraphic distribution. The methods that have been developed, their application to borehole data, and the use of the results in basin analyses have been described in four scientific articles that make up the thesis:

1. **Bobek K.**, & M. Jarosiński, 2021. Modifications of methods for the fracture analysis from borehole data in application to shale formations. *Geological Quarterly*, 65: 23, doi: 10.7306/gq.1591
2. **Bobek K.**, & M. Jarosiński, 2018. Parallel structural interpretation of drill cores and microresistivity scanner images from gas-bearing shale (Baltic Basin, Poland). *Interpretation*, 6, 1-14, doi: 10.1190/INT-2017-0211.1
3. Olkowicz M., **K. Bobek**, M. Jarosiński, R. Pachytel, 2021. Comparison of joint sets orientation in the Lower Paleozoic shales exposed in Scania (SW Sweden) and concealed in N Poland: a multi-methodological approach. *Geological Quarterly*, 65: 63, doi: 10.7306/gq.1632
4. M. Jarosiński, **K. Bobek**, A. Głuszyński, K. Sowiżdżał, T. Słoczyński, in press. Fracture stratigraphy, stress and strain evolution in shale succession of the Lower Paleozoic Baltic Basin (Poland). *AAPG Bulletin,* doi: 10.1306/10112221140

The first article describes methods for fracture network analysis developed by the authors. These methods are applied to analyze joints in shale formations based on borehole data. Analytical code packages were developed in MatLab and Python programming languages. The first code package contains a new algorithm to represent the orientation of fractures at a weighted rose diagram, taking into account the measurement error. In the standard projection of rose diagrams, each fracture is treated as a single record, regardless of its actual size. However, due to the nature of joints, most of which are strata-bound, and therefore their actual height can be measured even in the borehole, the new algorithm takes this parameter into account for projecting their orientation. In this approach, the values obtained for each angular class of the selected azimuthal intervals do not represent the number of fractures, but their total height. In addition, knowing the fractures' orientation collected from the oriented core, the algorithm was designed to blur the strike records into adjacent angular classes depending on the measurement error. The second method presented in this article is a new algorithm for the calculation of the fracture intensity, which is expressed as the total area of the fractures per

cubic meter of rock, including the true height of the joints. The basic idea of the algorithm is to calculate the fracture intensity in the borehole profile using a modified version of the moving average method. To determine the fracture area, the measured height of each fracture falling within a given sampling window was multiplied by the expected value of the borehole chord. The averaged fracture area within the rock volume of a given height is then assigned the depth corresponding to the center of the selected window.

The second paper describes the results of structural profiling of borehole cores from five wells with a total length of 1299 m and the interpretation of the corresponding microresistivity images of the borehole walls acquired with the X-tended Range Micro-Imager (XRMI) and the Formation Micro-Imager (FMI) tools. In profiling the core, fracture parameters such as depth to the upper termination of a fracture, height constraint by layers (none, one-sided or two-sided), dip angle, mineral vein opening, degree and type of vein cracking (through the central suture of mineralization or along the boundary between rock and mineral infill) were taken into account. Such precise structural analyses were developed to be used in designing and interpreting hydraulic fracturing treatments. Analysis of the fractures visible in the microresistivity images was done using TechLog software (Schlumberger). As part of the interpretation of the geophysical data, the following parameters were collected: depth to the top of the fracture, azimuth of the dip direction, dip angle, and height (actual or within the observation space), along with determining the subjective evaluation of the quality of the interpretation. The collected parameters have been used for the determination of fracture orientation and intensity using the developed algorithms. The calculated fracture intensity profiles obtained from the drill cores were compared with those obtained from the interpretation of the microresistivity scanner images. The analysis revealed several discrepancies between the results within the same depth intervals. The first reason for these differences is fracture termination by bedding planes, which results in the possibility of their detection only in microresistivity images due to the larger observation space available. Since the diameter of the borehole is usually more than twice longer than the diameter of the borehole core, a novel method has been developed to predict which fractures that are visible in the scanner images are likely to be present also in the borehole core. The method determines the angular range of fractures visible in scanner images (the critical angle) at which the fractures do not penetrate the core. The effectiveness of this method was verified and its usefulness in correlating core depth with the scanner image was demonstrated. Another reason for the differences in fracture intensity between the core and the scanner image is the calcite filling of the veins, which makes them poorly visible in the bright marly core. The differences are also due to the presence of tuff interbeds, which cause instability of the borehole walls and blur the fractures in the geophysical record, and the occurrence of drill-induced fractures that mimic natural fractures. In reservoir intervals, the presence of natural gas, which increases the electrical resistivity of both the rock matrix and the fractures, obscures fractures causing them not to be visible in the scanner image.

A third of the papers present the results of fracture network analyses performed on eight boreholes in the Baltic Basin and 13 outcrops in southern Sweden (Skåne). As part of the fieldwork carried out on the outcrops in Sweden, data such as the strike azimuth, height, spacing, and length of the fractures visible in the walls of the outcrops were collected using a geological compass. For inaccessible exposures, joints were also photogrammetrically measured and analyzed using Google Maps satellite imagery. Statistical processing of the results showed a high degree of convergence of the measured joint orientation for the different measurement methods and the areas of northern Poland and southern Sweden. Both, the analysis of the borehole data and the measurements at the outcrops indicated the existence of three sets of joints: the dominant J1 set striking NNE, the subordinate J2 striking WNW, and the minor J3 set striking NW. The strike of the joint sets identified in Skåne differs from that of the joint sets identified in the Pomerania by 5 to 10 degrees on average. This indicates that the analyzed joint network was formed as a result of the same basin-scale tectonic events, and there was no significant variation in the directions of tectonic stresses at the time. The lack of a clear influence of the Teisseyrea-Tornquist zone on the distribution of the major joint sets in Skåne is an indication that they were formed before the latest Carboniferous-Permian reactivation of this zone. It was the first overview of the joint system in the sedimentary sequence of the Baltic Basin.

The final paper describes the potential use of precise fracture profiles in the analysis of the evolution of petroleum basins. Constructed fracture intensity profiles, in combination with profiles of serial structures such as horizontal veins and small-scale slickensides, reveal a typical distribution of the fracture stratigraphy. We identified two reasons for this phenomenon: the variability of pore pressure determined by hydrocarbon generation, and the mechanical stratigraphy of the shale sequence. By integrating a structural and mechanical analysis, subsidence of the complex, hydrocarbon generation, and geotectonic evolution of the basin within the model, the structural evolution of the Baltic Basin was quantitatively reconstructed. It includes three phases of natural hydraulic fracturing in the Late Carboniferous: (1) the episode of horizontal vein opening after maximum burial and heating, (2) the J1 joint set fracture formation after the main phase of the Variscan collision, and (3) the J2 joint set formation due to final relaxation of collision forces at the Carboniferous-Permian transition. For these episodes, an evolution of the tectonic stress regime was determined and changes in pore pressure, stress, and elastic strain were calculated. Finally, the contribution of the different components of the pore pressure and stress changes related to the exhumation of the studied shale complex has been evaluated. Finally, the pure tectonic factor, characteristic for the analyzed part of the basin has been extracted from them.

In general, the conducted research has shown that standard methods for analyzing fractures in rock complexes where bedding fractures predominate need to be modified. The proposed methods of analysis concern: (1) inclusion of the height of joints terminated by bedding planes in fracture intensity profiles; (2) calculation of fracture orientation diagrams with weighting by fracture height and, if necessary, vein aperture; (3) inclusion of fracture orientation measurement error in the construction of rose diagrams; (4) need for a compilation of fracture interpretation based on core and scanner images; (5) possibility of using both sets of data to correlate core and image log depths. The need to analyze how mineral veins crack in core from shale reservoir was pointed out, which is important for understanding the effects of hydraulic fracturing. Reasons for the differences in the fracture profiles based on the analysis of the core samples and the scanner images were also pointed out. The accuracy of fracture intensity profiles, which allow the detection of the distribution of fracture stratigraphy, was improved by the application of new methods. It was shown how accurate borehole structural analysis can be used to correlate connections between distant parts of sedimentary basins and to interpret stress, strain, and pore pressure evolution in analyzed formations. Implementation of the developed analytical methods to hydrocarbon reservoirs will allow a better characterization of the natural fracture network and, consequently, the identification of its role in the hydraulic fracturing treatment and the migration and production of hydrocarbons.