Vertical Anisotropy of the Lower Jurassic Gordondale Shales (Alberta) and Geomechanical Modeling for Optimization of Hydraulic Fracturing

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Summary

The organic-rich Lower Jurassic Gordondale shales of the Western Canada Sedimentary Basin are characterized by vertical anisotropy related to the extensive horizontal laminated fabric common in shales. The laminae result in differences in rock mechanical properties measured in directions orthogonal and parallel to the bedding planes, which strongly influences the hydraulic fracture height. To accurately generate a horizontal stress profile and predict stress barriers and fracturing heights from logs in unconventional shale reservoirs, vertical anisotropy of organic shales must be taken into consideration. These parameters are essential for predicting the optimal landing point of a horizontal well and hydrocarbon productivity.

Analysis of core-test and well log data in 28 wells has been carried out for the Gordondale shales in a study area of 100 km x 90 km in west-central Alberta to characterize mechanical rock properties and estimate the orientation and magnitude of present-day in-situ pressure and stresses. We show that the mechanical properties across the study area display a NW-SE trend, where the Gordondale shales have higher brittleness (BI) and lower anisotropy (K_0) in the SE than the NW. The best interval for hydraulic fracturing in the Gordondale shales is characterized by high BI (~65.4), low K_0 (~0.3) and low minimum horizontal stress (S_{hmin}) gradient (~1.44 g/cm^3) and is bounded by layers having lower BI (~50.2%), higher K_0 (~0.41) and higher S_{hmin} gradient (~1.57 g/m^3). The bounding units may represent good stress barriers providing fracture containment zones. The orientation of present-day maximum horizontal stress was determined to be N28°E in the study area from caliper data in 8 wells. This value differs from the regional stress orientation of N47°E and it may reflect local stress rotation influenced by tectonic structures, which is essential for optimizing horizontal well trajectory.

Introduction

The Lower Jurassic Gordondale Member is an organic-rich mudrock that is the basinal equivalent of the more carbonate-rich Nordegg Member of the Fernie Formation in the Western Canada Sedimentary Basin (WCSB). With a total organic content (TOC) of up to 12% and thickness ranging from 24 to 30 meters, the Gordondale member is a potential shale gas or shale oil reservoir (Ross and Bustin, 2007), although commercial production has not yet been established. To better understand the parameters that are important for optimizing hydraulic fracturing, we analyze mechanical properties of the Gordondale shales from core-test data and estimate the orientation and magnitude of present-day in-situ pressure and stresses in a study area of 100km x 90km in West-Central Alberta.

The mechanical rock properties of the organic-rich Lower Jurassic Gordondale shales of the Western Canada Sedimentary Basin are typically characterized by a Vertical Transverse Isotropy (VTI). This dependence of mechanical rock properties on the direction of measurement is caused by the extensive horizontal laminations found in shales. The VTI analysis and geomechanical modeling were carried out for the Gordondale shales in 28 wells to accurately generate a minimum horizontal stress (S_{hmin}) profile distribution across the reservoir, predict the stress barriers and the height of expected hydraulic fractures.

Analysis of present-day horizontal stress orientation and local stress rotation that may be influenced by tectonic structures was completed to optimize horizontal well trajectory for hydraulic fracturing.

Theory and Methods

Core-test and well log data, available for a calibration well from the Alberta Energy Regulator database, were used to characterize the mechanical and petrophysical properties of the Gordondale shales and obtain correlations between dynamic and static elastic parameters (Young modulus and Poisson's ratio). By applying these correlations, continuous profiles of static-elastic parameters (for both horizontal and vertical components), brittleness (BI) and anisotropy indices (K_0) were estimated from well logs in 28 wells across the study area. The obtained brittleness profile was compared to the hardness profile obtained by direct measurements from the calibration core using an Equotip Bambino 2 hardness tester. By integrating the modeled profiles of vertical stress, pore pressure and static-elastic parameters, continuous profiles of anisotropic minimum horizontal stress were obtained for 28 wells and calibrated by mini-frac test data. Mechanical properties of the Gordondale shales have been propagated in a 3D model by applying blind well tests, which helped characterize the distribution of brittleness and minimum horizontal stress gradient within the study area. The orientation of minimum horizontal stress was determined from borehole breakouts by studying 4-arm caliper data in 8 wells.

The obtained results were compared to the orientations and magnitudes of principle stresses, summarized in the Geological Atlas of the WCSB (Bell et al., 1990; Bell and Grasby, 2012, AGS dataset) and World Stress Map Project (WSM).

Results

Based on 4-arm caliper data from 8 wells, the maximum horizontal stress orientation (S_{Hmax}) in the study area was determined to be N28°E (Fig. 1). This value is different from the regional stress orientation of N47°E reported by the World Stress Map and the Alberta Geological Survey for 181 wells; the deviation may be caused by a local stress rotation influenced by tectonic structures.

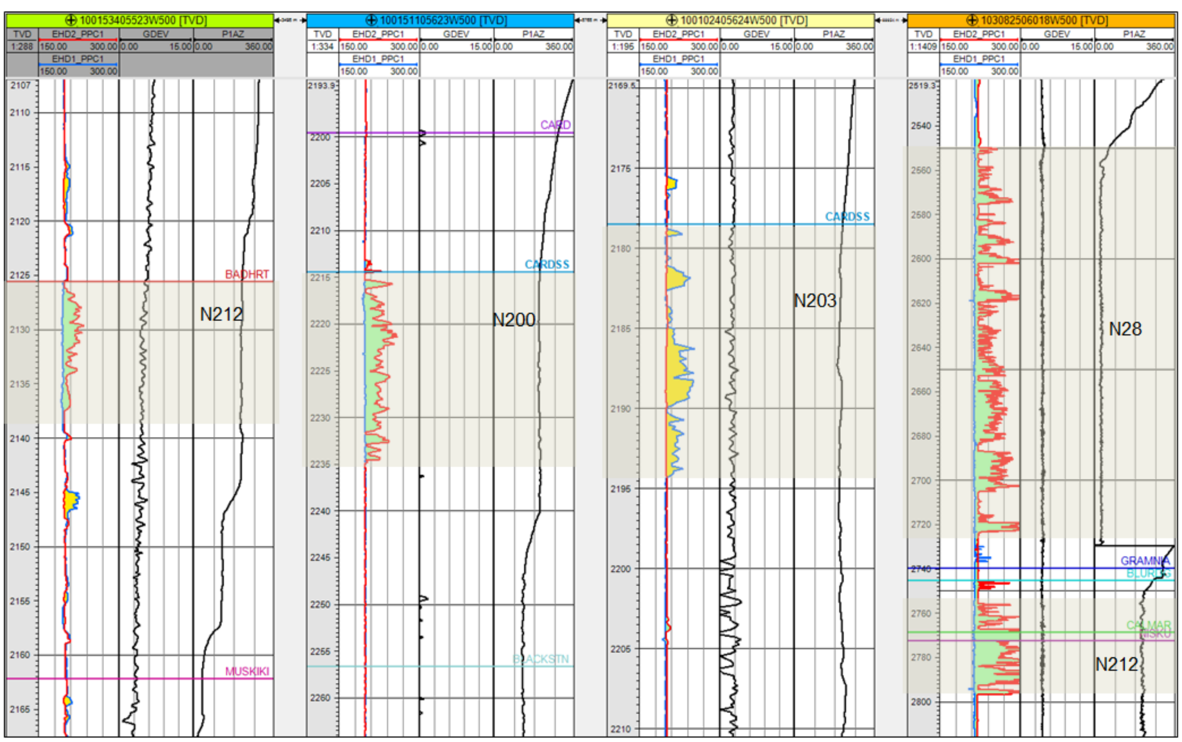

Fig. 1. Orientation of S_{hmin} from borehole breakouts (shaded intervals) in 4 wells in the study area.

Dynamic Young modulus (YM) and Poisson's ratio (PR) in the Gordondale shales were estimated from well logs in a calibration well. The static value of Young modulus was converted from the acoustically measured dynamic value using a correlation deived from core-test data in a calibration well. The dynamic Poisson's ratio was not converted.

The maximum vertical and horizontal static Young modulus in Gordondale is 5.98x10^6 psi and 7.3x10^6 psi, respectively, whereas the minimum values are 2.72x10^6 psi and 3.04x10^6 psi. PR is varying from 0.22 to 0.34 with an average value of 0.25.

Brittleness index (BI) was estimated from the static elastic moduli (Young modulus and Poisson's ratio). BI is used to predict a rock's tendency to fail and maintain an open facture (Grieser and Bray, 2007; Rickman, 2008). The average BI in Gordondale is 45% with a standard deviation of 9.7%. Hardness values measured on the calibration core range from 456 to 848 with an average of 634, characterized by trends similar to the BI profile.

An anisotropy coefficient (K_0) was estimated from the horizontal and vertical components of static Young modulus and Poisson's ratio (Glover et al., 2015, Waters et al., 2011). The anisotropy coefficient K_0 in the Gordondale was estimated to range between 0.64 and 0.34 with an average of around 0.42.

The minimum horizontal stress has shown to be sensitive to the VTI of rocks and the anisotropy coefficient. The S_{hmin} magnitude was estimated by considering vertical transverse isotropy (Thiercelin and Plumb, 1994), with S_{hmin} being directly proportional K_0. The estimated gradient of anisotropic S_{hmin} in Gordondale is about 16.2 KPa/m, while the isotropic S_{hmin}, 5.11 KPa/m.

The mechanical properties across the study area display a NW-SE trend, where the Gordondale shales have higher brittleness and lower anisotropy in the SE than the NW (Fig. 2). The best zone for hydraulic fracturing in the Gordondale shales (Fig. 2, red rectangle) is characterized by a high BI (~65.4), low K_0 (~0.3) and a low S_{hmin} gradient (~1.44 g/cm^3) and a thickness of 4.5 – 5.3 m. This interval is bounded by layers with lower BI (~50.2%), higher K_0 (~0.41) and higher S_{hmin} gradient (~1.57 g/m^3). These bounding unit properties may represent good stress barriers providing fracture containment zones.

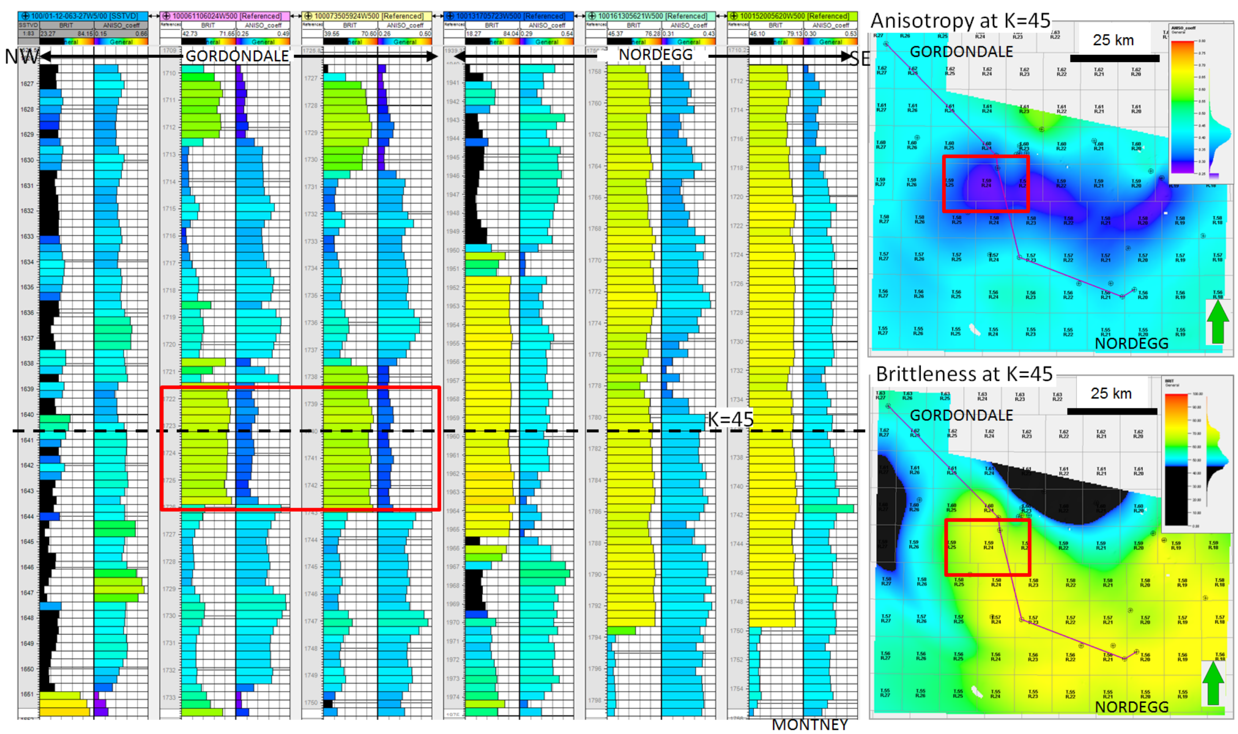

Fig. 2. Estimated profiles (left) and maps (right) of brittleness (BRIT, or BI) and anisotropy indices (ANISO_coeff, or K_0) in Gordondale-Nordegg in 5 wells. Maps are shown for layer K=45 in 3D model. Ductile zones (BI<45%) are shown in black, brittle zones (BI>45%) are colored. Depth scale is SSTVD. Red rectangles show targeted interval (left) and area (right) in Gordondale.

The estimated brittleness and anisotropy coefficient are characterized by an inverse relationship, which was used to identify the optimal targeting interval in Gordondale (Fig. 2, red rectangle on cross-section) with contrasting high BI and low K_0 (and low S_{hmin}), identified in an area of about 15 km by 20 km (Fig. 2, red rectangle on maps). The presence of bounding stress-barrier units is essential for defining the targeted interval as the optimal landing point of a horizontal well for hydraulic fracturing.

It was suggested that clay content could be one of the main factors controlling rock brittleness (Rickman, 2008; Dong et al., 2017). However, no clear relationship between BI or K_0 versus clay content was identified in the calibration well for Gordondale. Glover et al. (2015) also previously reported a high anisotropy coefficient K_0 in Nordegg in rocks with low clay volume. Further studies of the Gordondale shales are planned to analyse the relationship between lithological and mineralogical composition and mechanical properties of rocks that may help relate depositional environment, burial and diagenesis to mechanical properties, brittleness and vertical anisotropy of shales.

Standard practice consists of drilling horizontal wells parallel to the orientation of S_{hmin} to maximize hydrocarbon production. However, it was noted that, in the WCSB, horizontal wells are frequently drilled in an oblique direction, i.e. in N-S and W-E directions to the NE-SW S_{Hmax} which results in much higher cumulative production from the Montney, Bakken and Cardium formations (Cui et al., 2013). This is likely caused by oblique fractures induced around wellbores, which interfere with existing fractures, parallel to the far-field NE-SW S_{Hmax}. However, this approach requires smaller well spacing to drain all the reservoir area.

The obtained S_{Hmax} orientation (N28E) in the study area differs from the regional horizontal stress orientation (N47°E) that should be taken into account for planning horizontal wells for optimizing hydraulic fracturing. A detailed structural interpretation of the subsurface tectonic structures is required to understand the local rotation of the horizontal stress orientation with respect to the regional stress orientations.

Conclusions

The geomechanical study of the Gordondale shales in West-Central Alberta has shown that an accurate estimate of the minimum horizontal stress profile in organic-rich shales requires a detailed analysis of vertical anisotropy and brittleness of rocks. The 1D and 3D modeling of the distribution of mechanical properties in the Gordondale Member was essential for identifying an optimal interval for targeting, which is characterized by contrasting high brittleness and low vertical anisotropy (and low minimum horizontal stress), bounded by stress-barrier units over an area of about 15 km by 20 km. The targeted interval was recommended as the optimal landing point of horizontal well for hydraulic fracturing. The obtained orientation of maximum horizontal stress (N28E) in the study area differs from the regional horizontal stress orientation of N47°E, and this should be taken into account for planning horizontal wells to optimize hydraulic fracturing.

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