

Principal stress estimation in shale plays using 3D seismic

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Summary

The principal stresses, vertical, maximum horizontal and minimum horizontal, and rock strength parameters can be estimated from wide-angle, wide-azimuth seismic data. This is demonstrated using a small 3D seismic survey over the Colorado Shale Gas play of Alberta, Canada. It is demonstrated that this information can be used to optimize the placement and direction of horizontal wells and hydraulic fracture stimulations.

Introduction

A simplification of Hooke's Law, using Linear Slip Theory, by Schoenberg and Sayers (1995), allows the estimation of principle stresses from wide-angle, wide-azimuth seismic data. The rock properties required in its implementation are derived from wide-angle seismic data, e.g. Gray (2002). The method is demonstrated by estimating the principle stresses and rock properties for the Second White Speckled Shale (2WS) using seismic data acquired in central Alberta in Canada. The results show that only about $\frac{1}{4}$ of the 2WS in the survey area will fracture as a network, while most of the rest of it will fracture linearly, which implies that this information should be extremely important in well planning for this shale gas reservoir.

Method

Hooke's Law is a fundamental elastic relationship relating strain to stress. Therefore, it represents the fundamentals of hydraulic fracturing, i.e. the deformation (strain) and fracturing of rock is caused by stressing it with hydraulic pressure in the borehole. The relationship between stress and strain is controlled by the elastic properties of the rock. Simplifications of Hooke's Law, such as Schoenberg and Sayers (1995) development from Linear Slip Theory, allow us to estimate these properties from a seismic experiment. Estimates such as these have been made for many years (e.g. Lefeuvre et al. 1992, Varela et al. 2009) for fracture detection. Iverson (1995) demonstrated that the use of anisotropic elastic properties significantly reduces the "order-of-magnitude errors" that had previously been observed in stress calibration studies. Schoenberg and Sayers' (1995) parameters can be substituted into Iverson's (1995) equations

to solve for the vertical and two horizontal principle stresses, σ_v , σ_{Hmax} , and σ_{hmin} , respectively, assuming that these are the principle stresses. The use of Schoenberg and Sayers' (1995) formulation allows for a more simple extraction from the seismic data as well as a better understanding of these anisotropic elastic parameters.

The parameters in Schoenberg and Sayers (1995) approximation of Hooke's Law can be estimated using either birefringence or azimuthal analysis of multi-component seismic data, or from azimuthal velocity and AVO analysis of conventional 3D seismic data. Once these parameters are estimated, values for all three principal stresses can be predicted, provided that the assumptions of elasticity and Linear Slip Theory are met. These should be calibrated to information on the stress state of the reservoir derived from wells, microseismic data and regional knowledge. Furthermore, using this theory, an important parameter for prediction of hydraulic fractures, the Differential Horizontal Stress Ratio, $DHSR = (\sigma_{Hmax} - \sigma_{hmin}) / \sigma_{Hmax}$, can be estimated from the seismic parameters alone, without any knowledge of the stress state of the reservoir.

Example

A small, 10 km², conventional, wide-azimuth, 3D seismic survey shot SE of Red Deer, Alberta, Canada is used to demonstrate the method. Additional examples will be described in the presentation. Figure 1 shows the DHSR shown as plates displayed over estimates of Young's Modulus for the entire 3D volume. The direction of the plates indicates the estimated direction of maximum horizontal stress, σ_{Hmax} , and shows significant variations over this very small area. This is due either to different lithologies being stressed differently as they drape over underlying pinnacle reefs of the Leduc Formation (Gray, 2005) or to the presence of open fractures in this formation. The horizontal slice in Figure 1 shows 100% variations in Young's Modulus ranging from 12 – 24 MPa. Variations in Young's Modulus and Poisson's Ratio should be expected due to variations in lithology, porosity, fluid content and cement in any sedimentary rock. Furthermore, there are significant variations in the DHSR ranging from 0 – 50%. Both of these parameters have significant impact on how and if the rock will fracture: higher values of Young's Modulus indicate rocks that are more brittle and lower values of the DHSR indicate areas where the rock will have a greater tendency to fracture into a network. Clearly, we want to find areas where both these properties occur in order to find the best areas for hydraulic fracturing.

This suggests that a crossplot of these values will indicate areas that are preferable for the creation of fracture networks. Figure 2 is a demonstration of such a crossplot using the seismic data for the Colorado Group consisting primarily of Late Cretaceous shales. The result of applying this crossplot to the Second White Speckled Shale Formation of the Colorado Group is shown in Figure 3. The cutoffs in the crossplot should be optimized through well control as the field is developed. Areas where the DHSR is small and Young's Modulus is large (green in the Figure) are confined to small areas of this already small survey. These results indicate that most of the Second White Speckled Shale will fracture with parallel fractures implying that it will be very important to direct the horizontal wells to be fractured as nearly perpendicular to the σ_{Hmax} stress direction as is reasonable. Therefore, knowledge of the rapid variation in the direction of σ_{Hmax} , shown in Figure 1, is important information for optimal fracturing of this reservoir.

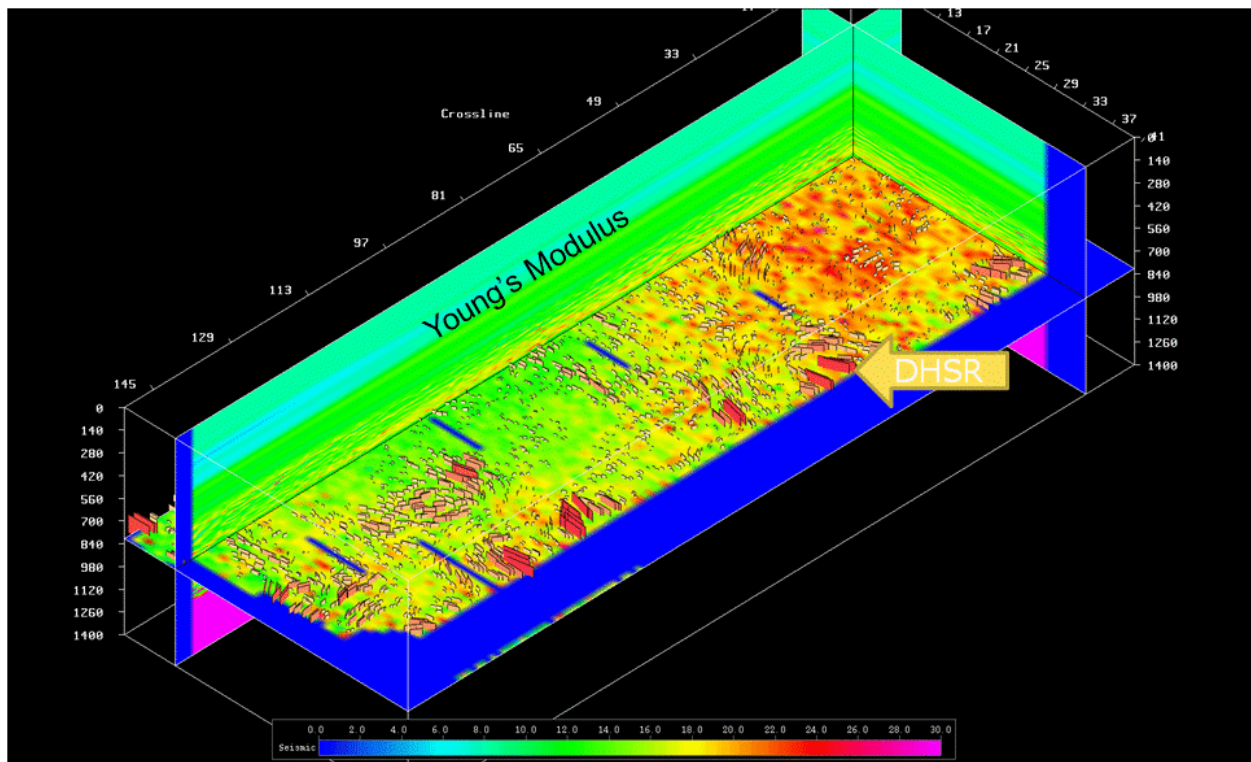


Figure 1: Colour background shows dynamic Young's Modulus estimated by our method, with its scale in MPa at the bottom of the Figure on this 10 km², 3D seismic volume. "Plates" (indicated by the arrow) show the Differential Horizontal Stress Ratio (DHSR). The size of the plate is proportional to the magnitude of the DHSR and the direction of the plate shows the direction of the local maximum horizontal stress. The long axis of the survey is E-W and survey area is 10 km².

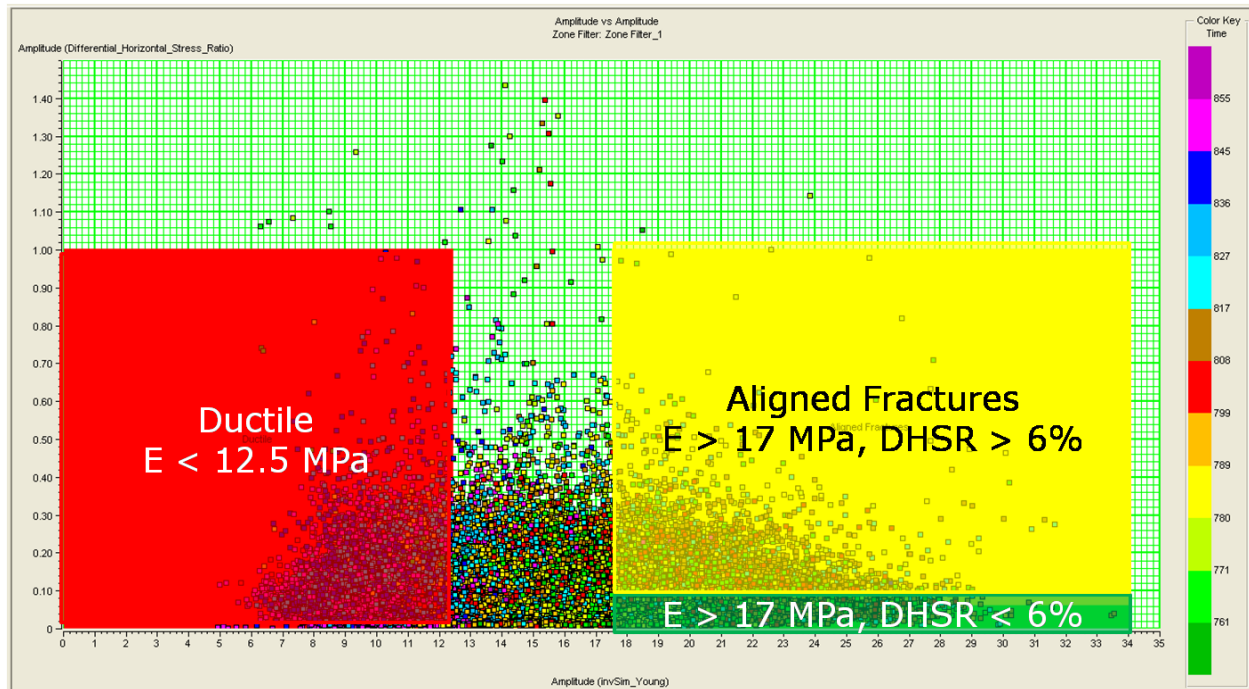


Figure 2: Crossplot of DHSR ratio versus Young's Modulus. Preferred areas for hydraulic fracturing are indicated in green, less desirable areas in yellow and poor areas in red.

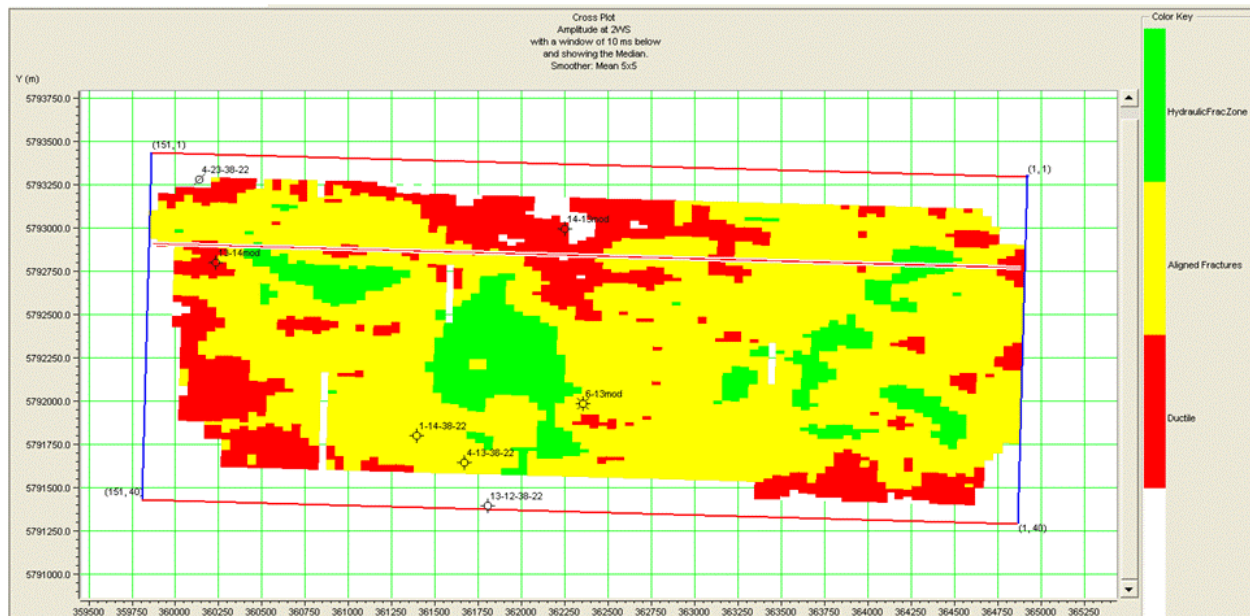


Figure 3: Map of 2nd White Speckled Shale showing zones highlighted in the crossplot in Figure 2. Green suggests where fracture swarms will form, red suggests the rocks are more ductile and thus less likely to fracture and yellow suggests where aligned fractures are likely to occur. Considerable variations are noted in the North-Central part of the survey, where the data suggests areas good and bad for hydraulic fracturing within about 100 m of each other.

Conclusions

We have demonstrated that the principle stresses – the vertical, maximum and minimum horizontal stresses - and rock strength parameters can be estimated from anisotropic analysis of wide-angle, wide-azimuth, 3D seismic data. These results should be validated with well data, which will be shown in the presentation. The results indicate that these values can vary considerably over very short distances (~100 m) in a shale gas reservoir. This has significant implications for where and how such reservoirs should be produced. Without a doubt, information such as this, once validated, must be used to optimize hydraulic fracture jobs in these reservoirs.

Acknowledgements

We would like to thank CGGVeritas, EnCana, Apache, Talisman Energy, Magnitude, Fairborne Energy, Doug Anderson, Bill Goodway, Ron Larson, Mark Houston, Jonathan Miller, Louis Chabot, Eric Andersen, Jared Atkinson, Ron Schmid, Tobin Marchand, Dominique Holy, Colin Wright, Wayne Nowry, Jessie Arthur, Philip Janse, Christophe Maison, Dragana Todorovic-Marinic, Christian Abaco, Lee Hunt, Scott Reynolds and Jon Downton.

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