Seismic Evidence of Formation Damage in the Lower Colorado Group Shales

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Summary

Recently drilled wells in the area of the Foster Creek Thermal Project in northeastern Alberta have encountered an increased risk of open hole collapse while drilling in a localized area above the reservoir zone. The anomalous zone crosses formations in the Lower Colorado Group and is most visible on shear velocity measurements. The areal extent of the anomaly was clearly delineated using 3D converted wave seismic. We believe that the observed anomaly's high Vp/Vs values are due to the presence of weak planes or fluid filled fractures in the shales, possibly caused by local stresses prior to reservoir development.

Introduction

Foster Creek is a SAGD (Steam Assisted Gravity Drainage) operation that has been producing since 1998. The reservoir is located in the Lower Cretaceous McMurray Formation at approximately 500m depth. The overlying Lower Colorado Group shales are located at shallower (200-300m) depths.

Recent drilling of new wells in the area of the original SAGD pilot has encountered increased sloughing of shale into the borehole while passing through the Lower Colorado interval and a program of delineation wells was employed to diagnose the problem. Dipole shear logs were found to contain significantly slower velocities across several members of the Lower Colorado Group when compared to the background trend from the area, while compressional velocities and porosities were comparable to their respective trend values.

The slow shear velocity anomaly has been mapped areally from several converted wave surveys shot from 2000 to 2009. By comparing horizons on the PP and PS volumes, a map of Vp/Vs for the lower Colorado Group interval clearly delineates the region of slow shear velocities (Figure 1).

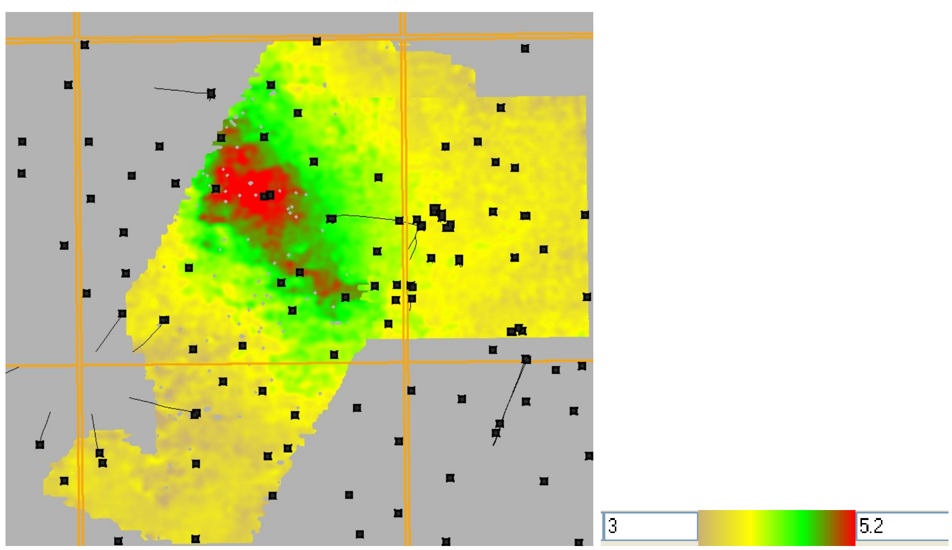

Figure 1: Colour represents Vp/Vs anomaly through the Lower Colorado Group. Section boundaries (1 mile interval) are shown.

The slow velocity region can be thus be avoided by future drilling programs by calibrating the Vp/Vs anomaly with the thickness of the disturbed zone.

Analysis

It is important to investigate the origin and implications of the Vp/Vs anomaly to help with planning future development. As such we shall examine the rock physics associated with the low shear velocities and speculate as to their possible cause.

The observed anomalies indicate a reduction in shear wave velocity from the background trend from ~650m/s to ~350m/s. The compressional velocity was not significantly reduced. This type of high Vp/Vs ratio is common in the near surface and can possibly occur in overpressure conditions (Dutta et. al, 2009). Shale density and Vp/Vs data from 7 wells at Foster Creek are plotted in Figure 2 for depths up to 500m. The scatter among the blue data is due to mineralogy and grain sorting. Also shown is with the shale Vp/Vs trend from Vernik et. al. (2002). Wells that are from the shear anomaly region are plotted in red.

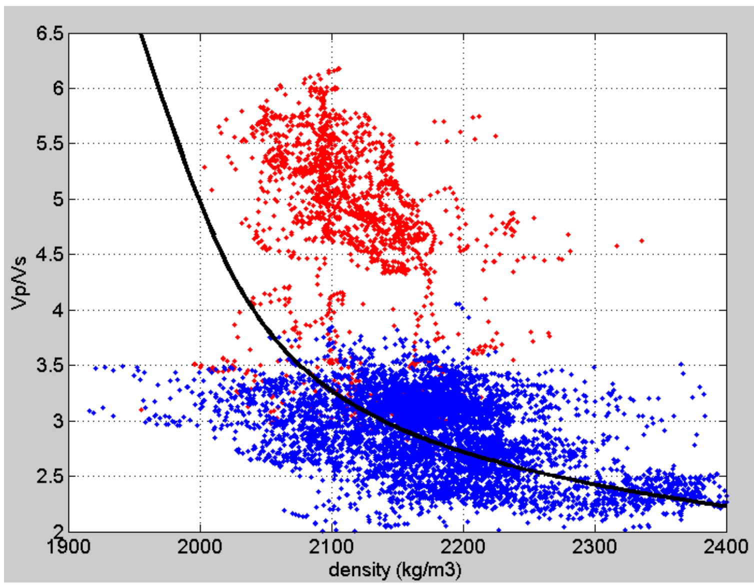

Figure 2: Vp/Vs trend for shales at Foster Creek. The trend line is from Vernik et. al. (2002). Red data correspond to wells in a region of anomalously low shear wave velocities.

We see that the data line up along the deeper (denser) measurements, while the shallow data corresponding to the wells in the shear anomaly deviate from the line. This suggests that the anomaly is not due to a natural overpressure, although it does not rule out pore pressure elevation after compaction. This is because trend line is most likely calibrated for virgin compaction in the Gulf of Mexico, and trends should be different in precompacted sediments subjected to overpressure, especially if they are shales (Zimmer et. al., 2002).

Another explanation for the observed anomalies is the presence of fractures in the formation. There are several ways of modeling the effect of cracks, each with its own assumptions. We first look at the simple model of a medium with a single set of horizontal parallel weakness planes inserted into the background shales. We employ the linear slip model of Schoenberg and Douma (1988) for rotationally invariant cracks, which implies non-interaction between the cracks. It can be shown (eg. Gurevich, 2003) that the fracture weaknesses for low aspect ratio , isolated, liquid filled cracks can be approximated by

$$\Delta_N << \Delta_T \approx \frac{16e}{3(3-2g)} \tag{1}$$

where Vp and Vsv represent the background medium P- and SV- wave velocities, $g = Vs^2 / Vp^2$, e is the crack density and Δ_N, Δ_T are the normal and tangential fracture weaknesses. The last term comes from relating the excess compliances to a dilute concentration of penny shaped cracks, which aids interpretation. In Figure 3 below we use a normal fracture weakness of 0.1 and a tangential weakness of 0.75 and plot the compressional and shear velocity surfaces if the fractures are horizontal (TI medium). This illustrates the well known result that inserting isolated fluid filled cracks into an isotropic medium can affect the shear wave velocity dramatically, while leaving the compressional velocity relatively unchanged from its native state.

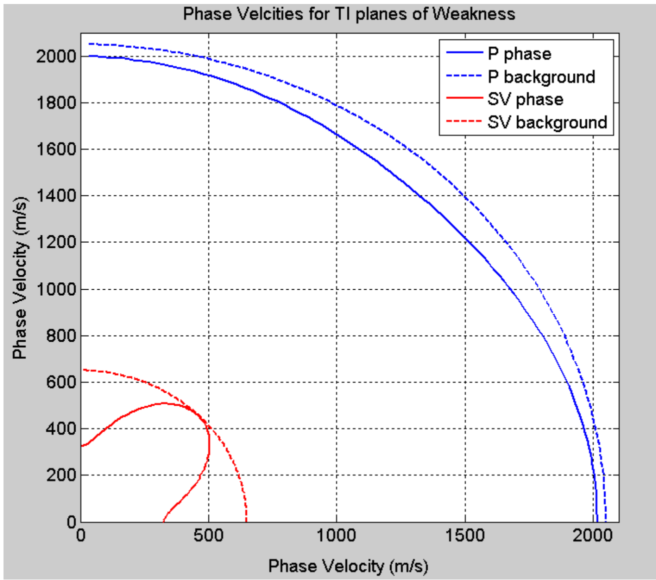

Figure 3: Phase velocities as a function of the angle from vertical for a series of horizontal planes of weakness described in the text. Dashed lines are isotropic velocities without cracks.

The velocities for the set of parallel weakness planes depends heavily on the orientation of the planes for the shear wave, and often the assumption of vertical or horizontal fractures are used. However, if fractures have been caused by shear failure, then according to Mohr-Coulomb theory, they would occur at an acute angle to the maximum stress direction, which is horizontal in our area. Thus the planes of weakness would be inclined.

To model average velocities without prior knowledge of the orientation, we can use the DEM formulation (Mavko et. al., 1998). This method iteratively inserts randomly oriented cracks into the background medium, which leads to an isotropic formulation that also takes into account crack interaction. The results of this are plotted in Figure 4, where we see that again, with little increase in porosity of the formation we can have the Vp/Vs ratio climb rapidly.

The origin of localized fractures is a topic currently being explored through finite element geomechanical modeling. This will include stresses from previous geologic events, as well as current thermal development. One factor considered was a steam injector whose casing failed in the Lower Colorado Group. However, there are indications that the Vp/Vs anomaly pre-dates the injector failure, as it was partially mapped by a 2000 survey, whereas the steam injector in question was not drilled until 2001. The geomechanical implication of the region with high Vp/Vs is that open hole failure while drilling will be more common in these zones. Failure around a borehole can be modeled approximately by Mohr-Coulomb theory, and the presence of inclined fractures would constitute a weak plane along which slip can occur more readily than in other regions. In addition, they represent a conduit for fluid pressure to enter the shales from the borehole, leading to accelerated time-delayed failure mechanism.

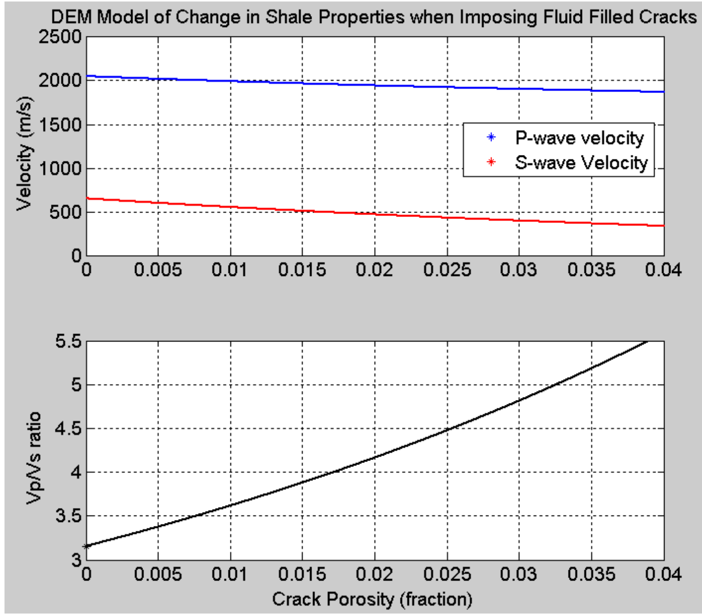

Figure 4: DEM modeling velocities for an increasing density of isolated and randomly oriented fluid filled cracks.

Conclusions

Very slow shear wave velocities have been encountered in a localized area of the Lower Colorado Group at Foster Creek. This region is the only one of its type discovered to date, and is characterized by increased risk of open-hole borehole collapse. The velocities are consistent with the presence of fluid filled cracks, inserted into the background formations. Geomechanical modeling is currently underway to determine possible causes of the fractures. As shear velocities are the only clear diagnostic of this drilling hazard, converted wave imaging was key in mapping the extent of the damaged zone.

Acknowledgements

I would like to thank Peter Cary and Gulia Popov from Sensor Geophysical for careful processing of the converted wave surveys. Also, I would like to thank Shauna Wilson, Harry Schaepsmeyer, Doug Walsh, Simon Gittins and Steve Raffa from Cenovus and Yanguang Yuan from BitCan Inc. for many valuable discussions, and Cenovus Energy for permission to publish the data.

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