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Characterization of Stress in the Leduc Formation over the Peace River Arch and Implications for Induced Seismicity

Amy D. Fox, Ph.D., P.Geo.
Enlighten Geoscience Ltd.

Introduction

Stress in the Leduc Formation over the Peace River Arch in Alberta was determined to assess induced seismicity risk from fluid injection into the formation since 2008. The specific focus for the induced seismicity assessment was the location of multiple seismic events of significant magnitude that occurred in November 2022 and March 2023. Although the 2022 events were originally stated by the Alberta Geological Survey (AGS, a branch of the Alberta Energy Regulator) to be natural, after the 2023 events the AGS concluded the events were caused by fluid disposal into the Leduc, and they identified a single well as being the cause. In the study presented here, not only was fault slip potential assessed at the location of the earthquakes, but stress was also determined over a broader area – the Leduc reef present east of range 21W5 from township 81 to 85 – in an attempt to identify either significant changes across the area and/or any unique stress conditions at the location of the earthquakes.

Study Approach

The orientations and magnitudes of in situ stresses in the Leduc formation in the study area were determined using widely accepted workflows and robust data sets from several wells. One key to building the Leduc geomechanical models was finding wells with adequate data for characterizing stress-induced wellbore failure. Another was finding measured rock properties in the Leduc and/or formations immediately above. In total, geomechanical models were developed for five wells, all but one of which was near the reef edge, similar to the well to which the AGS attributed the 2022 and 2023 earthquakes. The fifth well was on the interior of the reef.

Step-rate tests from area disposal well applications provided bounds on the minimum principal stress, density logs allowed for the calculation of vertical stress, and the models provided a range of estimates for the magnitude of the maximum horizontal stress.

Knowledge of the Leduc stress state allowed for the assessment of fault slip potential (FSP) using a Coulomb frictional failure approach to assess whether injection into the Leduc formation would be likely to have caused induced seismicity in the Leduc stress state, specifically at the location of the 2022 and 2023 earthquakes. Both a deterministic and a probabilistic assessment were performed, the latter to evaluate the effect of uncertainties in the geomechanical model parameters. A key input to the FSP analysis was the pore pressure in the Leduc at the time of the 2023 earthquakes, which was provided by a reservoir model and simulation developed by other members of the overall study team. Two pore pressures were examined – the pore pressure attributed to injection at only the well which AGS considered was the cause of the earthquakes, and the pore pressure attributed to cumulative injection into Leduc since 2008 by all injectors in the area. Nine different stress cases were run to address the range of results from the stress determination.

Study Results

All of the geomechanical models except the one from the interior of the Leduc reef produced consistent results indicating a strike-slip stress regime, where the vertical stress is the intermediate stress, in the Leduc. A strike-slip stress regime for this area is consistent with what is known about the basin in general (Bell et al., 1994) and the stress regime found in the nearby Devonian Duvernay formation (Shen et al., 2018; Shen et al., 2019a; Shen et al., 2019b).

Of the nine deterministic fault slip potential cases run, only two cases were critically stressed. Both of these cases included the influence of all area Leduc injectors on both the initial pressure at the location of the earthquakes (the pressure prior to the start of injection at the well to which the AGS attributed the earthquakes) and the pressure increase up to 2023. Neither the interpreted rupture plane determined from the high precision aftershocks recorded from the Peace River events (J. Verdon, pers. comm.) nor the planes from eleven published focal mechanism solutions from the November 2022 Peace River earthquakes (Schultz et al., 2023, orientations calculated by J. Verdon, pers. comm.) are critically stressed in the Leduc stress state, even in the most critically stressed of all cases and even considering the influence on pore pressure from all area Leduc injectors.

The probabilistic fault slip potential assessment found a very low probability that the Leduc is critically stressed at the location of the earthquakes. The two critically stressed cases from the deterministic approach have a less than 50% probability that any planes are critically stressed under modeled conditions given uncertainty in the model inputs (see example in Figure 1). Three

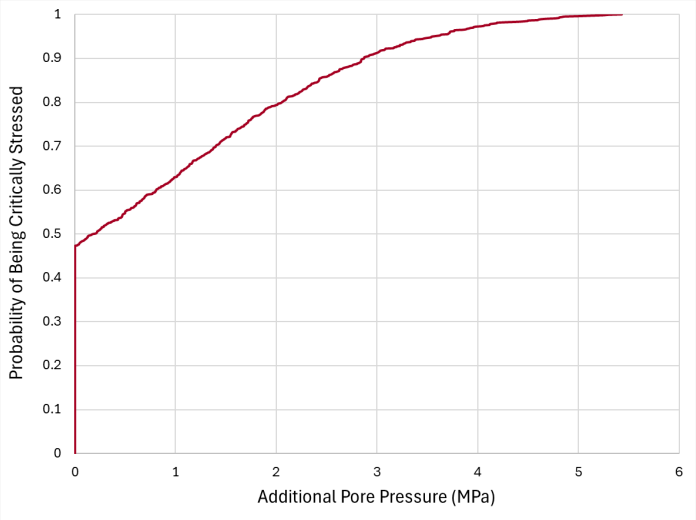

Figure 1. Results of the probabilistic fault slip potential assessment for an optimally oriented fault plane in one of the stress cases determined to be critically stressed in the deterministic analysis. The x-axis gives the *additional pore pressure* (above the modeled pressure) that would cause the fault to have a given probability (y-axis) of being critically stressed. The modeled pore pressure (0 on the x-axis) already includes the increased pore pressure attributed in Leduc due to contributions from all area injection wells.

of the cases have 0% probability, and the remaining cases all have between 13% and 24%. Under the probabilistic assessment in the most critically stressed case, the rupture plane has 1% probability of being critically stressed in modeled conditions and just one of the published 2022 fault planes has a non-zero probability, 16.5%, of being critically stressed under modeled conditions.

Implications

The results of the geomechanical analysis demonstrate that, although it is possible that the stress state in the Leduc is critically stressed in the study area, such a situation is unlikely. Even if the stress state is critically stressed, only a small set of fault orientations would be critically stressed. The probabilities of the interpreted rupture plane for the Peace River events or any of the fault planes associated with the published November 2022 seismic events being critically stressed in the Leduc stress state are extremely low. This suggests that these faults, which indeed hosted earthquakes, are likely under different stress and/or pore pressure conditions than the Leduc formation in the study area. The most recent seismic event locations indicate that the faults are in the Precambrian basement, and it has been previously documented (Lund Snee and Zoback, 2022) that the basement stress state in this area may be more compressive than in the sedimentary section above. The analysis results also suggest that, if injection into the Leduc or other formations is contributing to induced seismicity in the deeper basement, there must be a physical mechanism by which stress and/or pressure perturbations are reaching the faults from the well activity above.

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