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Hydraulic fracturing of the Upper Devonian Duvernay Formation and induced strike-slip fault reactivation in the Fox Creek area: insight from 3D geomechanical and reservoir modeling

Elena Konstantinovskaya, University of Alberta; Qiuquo Li, Freelance consulting; Alexey Zhmodik, Freelance consulting; Charles Ibelegbu, Resourcesfusion Ltd.; Ryan Schultz, Stanford University; Todd Shipman, Alberta Energy Regulator

Summary

Hydraulic fracturing of the Upper Devonian Duvernay Formation of the Western Canada Sedimentary Basin (WCSB) can trigger felt induced seismicity as it was shown in the Fox Creek and Red Deer areas (Bao and Eaton, 2016; Wang et al., 2020). We investigate how fluid pressure buildup around lateral treatment wells located to the south of Fox Creek can propagate across the low permeability reservoir in presence of natural fractures and quantify the potential of shear slip reactivation along neighboring strike-slip fault zone.

Methods

Interpretation of 3D seismic reflection data and ant-tracking attribute analysis are used to identify high-angle strike-slip fault zones that affect the Devonian sedimentary succession in the subsurface. Hydraulic Fracture Modeling and High Resolution Reservoir Pressure Simulation modeling are carried out to analyze interaction of natural fractures (NFs) represented by Discrete Fracture Network (DFN) and hydraulic fractures (HFs) and evaluate lateral fluid pressure propagation during treatment of lateral wells. 3D poroelastic reservoir geomechanical modeling is applied to quantify shear slip along a high-angle fault zone located at about 500 m away from the treatment wells. Petrophysical and geomechanical core testing data, DST and DFIT tests results and microseismic clouds are used to calibrate simulation results.

Results

Seismic interpretation of the study area helped to highlight the presence of linear discontinuities (Fig. 1a). Some of the zones correlate with structural heterogeneity in the structure of carbonate rocks of the underlying Swan Hill Formation and can be interpreted as pre-existing high angle strike slip faults in the Devonian sedimentary succession. One of the fault zones is aligned with the linear N-S zone of induced earthquakes (up to 3.9 Mw) occurred in May-June 2015 during hydraulic fracturing of the Duvernay Formation. The interpreted N-S fault is about 1.4 km long along the strike and extends vertically from the Precambrian basement to the top of the Ireton Formation. Strike-slip fault zones of similar orientation and geometry were previously interpreted from seismic reflection data and earthquake mechanisms in the areas of Fox Creek (Weir et al. 2018; Eyre et al. 2019, Zhang et al., 2019) and Red Deer (Wang et al., 2020). It appears that high-angle strike-slip faults inferred in sedimentary succession of the WCSB are located at a distance of about 120-150 km to the east of the deformation front of the Canadian Rockies. The eastward propagation of tectonic deformation in the subsurface is supported by structural studies of mudstone cores from Devonian to Cretaceous units of the WCSB (Davies et al. 2016, Konstantinovskaya & Bahramiyarahmadi 2020). The inferred pre-existing high-angle strike-slip faults can likely be correlated with the phase of post-Eocene transpressional deformation that resulted in dextral strike-slip kinematics of subvertical faults mapped in the southeastern Canadian Cordillera (Finley, 2020).

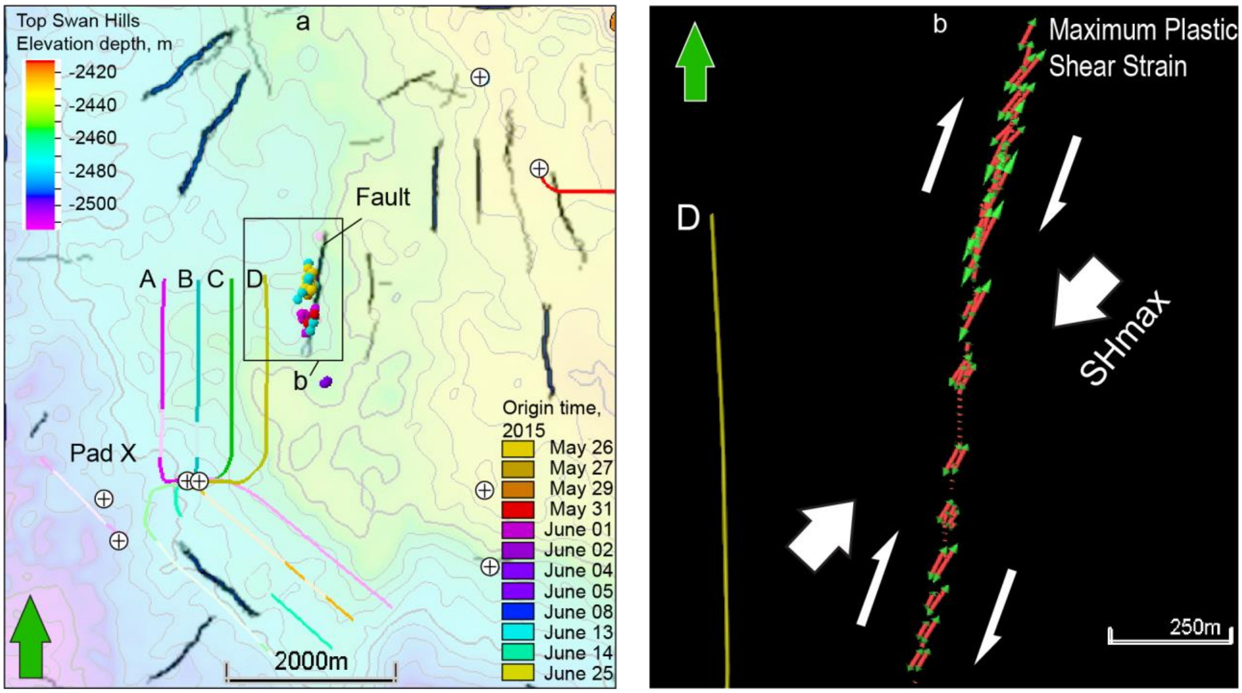

Fig. 1. (a) Zones of discontinuity interpreted as faults highlighted by ant tracking attribute (dark blue color) at depth slice at elevation depth Z of 2425 m bsl within the Duvernay Formation, after Konstantinovskaya et al. (2021). Structural map in depth domain of the underlying Swan Hill Formation top is shown as a background. The induced earthquakes are colored according to the time of origin. Circles with crosses indicate location of analyzed wells; (b) Orientation of the vector of maximum plastic shear strain along the fault simulated by FEM in 3D coupled reservoir geomechanical modeling, after Konstantinovskaya et al. (2021).

The DFN was modeled in the Duvernay Formation by generating two sets of vertical natural fractures (Fig. 2) oriented parallel and orthogonal to the orientation of present-day maximum horizontal stress. This approach was inspired by the study of natural fractures based on the analysis of image logs in the Duvernay Formation in two horizontal wells in the Kaybob area (Fothergill et al. 2016).

The simulated complex HFs in the Duvernay Formation are vertical and generally propagate parallel to the orientation of present-day maximum horizontal stress (N43°E) interacting with NFs represented by DFN (Fig. 2). The HFs are arrested by orthogonal NFs or branching and redirected along NFs. Half-length of the HFs ranges from 30-80 m to 705 m with mean value 250-350 m. Most of simulated HFs are vertically contained within the Duvernay Formation that is about 50 m thick in the treatment zone. This is consistent with modeled stress contrast at the upper and lower boundaries of the formation. The geometry of simulated HFs is supported by the microseismic point clouds used in this study and by previous observations (McKean et al., 2019).

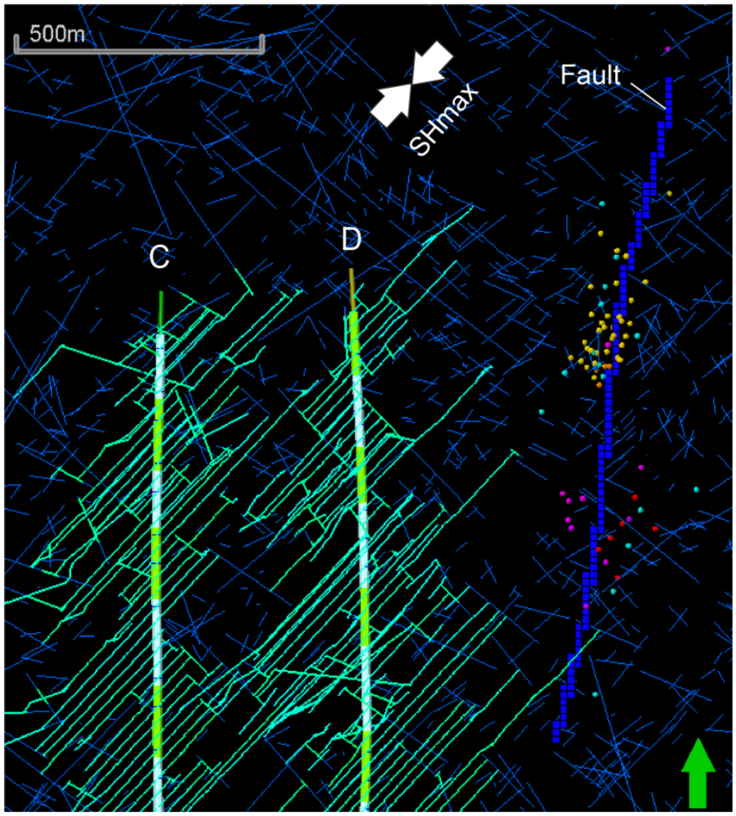

Fig. 2. Simulated *HFs (green color) and NFs (blue color) interaction during zipper fracturing of the Duvernay Formation in lateral wells C and D, after Konstantinovskaya et al. (2021). Fault is identified based on ant tracking attribute (Fig. 1a). The induced earthquakes are shown by time of occurrence on May 26 to June 14, 2015 (Fig. 1a).*

Our results suggest that the initiation of shear failure along the fault occurs at additional fluid pressure of 5 MPa to 10 MPa in the fault zone (Konstantinovskaya et al., 2021). The increase of bottomhole pressure by 20 MPa recorded during stimulation operations in horizontal wells C and D can be transmitted through the system of hydraulic (and probably natural) fractures over 500 m to the neighboring vertical fault prompting dextral shear slip along the fault in the interval of the Duvernay Formation and overlying Ireton Formation. Maximum plastic shear strain orientation (Fig. 1b) modeled in the fault zone is consistent with dextral shear displacement along the fault, which is also supported by the observed focal mechanism (Schultz et al. 2017). The simulated maximum plastic shear displacement in fault elements is 3.08 cm. The moment release associated with the simulated shear fault reactivation is 7.76e14 Nm that can be estimated as a product of slipped fault area (1.4 km x 0.6 km), maximum plastic shear displacement (0.0308 m) and shear modulus (30 GPa) of fault material. It is close to the estimation of moment release (Mo 7.9e14 Nm; Mw 3.9) from the radial seismic energy.

The combined results of DFN and hydraulic fracture modeling, reservoir simulations and poroelastic geomechanical modeling allowed us to explain the occurrence of a linear N-S zone of induced earthquakes with magnitude up to 3.9 Mw recorded in May-June 2015 during hydraulic fracturing of the analyzed horizontal wells. The estimated additional minimum fluid pressure of 5 MPa to 10 MPa associated with hydraulic fracturing operations, if transmitted to the neighboring pre-existing faults, may result in shear fault reactivation. Interpretation of 3D seismic data and reservoir geomechanical modeling may help to minimize the risks of induced seismicity.

Novel/Additive Information

The reservoir simulation results indicate that 6 days are required to transmit fluid pressure buildup over the distance of 600 m along the complex HFs from the treatment zone to interpreted fault through the system of hydraulic fractures. These results are close to the field observations of induced seismicity that occurred 4 days after the beginning of treatment of the lateral wells in the study area. More precise simulation results can be obtained by including natural fractures in fluid transmission and with better calibration of orientation, length and density of natural fractures represented by DFN. The time required for lateral pressure transfer depends on fracture permeability and connectivity. Similar time delay of 90-100 h was obtained by alternative technique for simulated pore pressure transfer along 1 km-long fracture corridors with permeability of fracture corridors of 150-230 mD (Igonin et al., 2021).

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