

# **A Workflow for Analysing Stress Shadows during Hydraulic Fracturing, With Application to the Bakken Formation, Southeast Saskatchewan**

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## **Summary**

This paper reviews methods for estimating changes to the in-situ stress field resulting from mechanical effects (fracture opening), poroelastic effects and thermoelastic effects associated with fluid injection for hydraulic fracturing. The application of these methods is illustrated for a multi-stage hydraulic fracturing operation in the Bakken Formation of southeast Saskatchewan.

## **Introduction**

The Bakken Formation is Upper Devonian to Lower Mississippian in age, and is found in Saskatchewan, Manitoba, North Dakota and Montana (see Figure 1). Oil production from the siltstones and silty sandstones of Unit A of the Middle Member of the Bakken Formation in the Viewfield area of southeast Saskatchewan relies on horizontal drilling and multi-stage hydraulic fracturing to achieve economic production rates. During fracturing operations, the stress changes induced in the reservoir during a given fracture stage may alter the conditions during subsequent stages, giving rise to the so-called “stress shadow” effect. Stress shadows can impact the effectiveness of fracturing operations by increasing the injection pressures required to create and propagate fractures, reducing fracture width, and potentially altering fracture trajectory. The design of effective fracture stimulation treatments in the Bakken Formation requires analysis of the geomechanical attributes of this reservoir and the prediction of stress shadow effects. Though numerical models can be used to simulate stress shadow effects (as illustrated in Figure 2), and basic capabilities exist for predicting stress shadows within some commercial fracture simulators (e.g., Barree et al., 2015), a goal of the work summarized here was to identify and implement stress shadow prediction tools that are more extensive than a commercial simulator’s built-in capabilities, yet which can be implemented without the need for numerical modeling.

## **Theory and Method**

Analytical solutions exist for modeling stress shadows under idealized conditions (e.g., homogeneous and isotropic rock properties; linear elastic material behaviour; 2-dimensional, plane strain geometry). Following is a summary of stress shadow mechanisms, and references for available analytical solutions:

- Mechanical stress shadow; i.e., the stress increase caused by a fracture as it “pushes” outwards on the rock mass on either side of the fracture plane. General expressions for the resulting induced stress field were presented by Pollard and Segall (1989), and can also be found in Ge and Ghassemi (2008).
- Poroelastic stress shadow; i.e., the stress increase caused by reservoir expansion associated with pore pressure increase in the rock mass surrounding a fracture. Equations for the resulting induced stress field were presented by Koning (1985) and Perkins and Gonzalez (1985).

- Thermoelastic stress shadow; i.e., the stress reduction caused by reservoir contraction associated with temperature drop due to the use of a fracturing fluid that is cooler than the native reservoir temperature. Equations for the resulting induced stress field were presented by Perkins and Gonzalez (1985), and can also be found in Ge and Ghassemi (2008).

Use of the afore-noted solutions for stress shadow prediction requires knowledge of the pressure within and the dimensions of the fracture that has induced the shadow. In this work, fracture dimensions and pressures were predicted using the commercial fracture simulator GOHFER (Barree and Associates, 2015). The workflow used to implement stress shadow prediction for a multi-stage fracture treatment is illustrated in Figure 3. The process begins by simulating the first fracture stage with GOHFER using the initial in-situ stress state as model input. The time interval simulated includes the injection period as well as the ensuing pressure falloff, up to the point in time when the second fracture stage is undertaken. At this point, key attributes of the fracture (length, average width, average pressure) are taken and used as inputs for the stress shadow equations. In turn, these equations provide estimates of stress changes induced at the location of the second fracturing stage, which are superimposed on the original in-situ stress state to yield a revised stress state. This revised stress state is used as input for a GOHFER simulation of the second fracture stage. This workflow is then repeated for each subsequent fracture stage, with the stress shadow effects of all preceding stages accounted for.

## Results

Figure 4 shows results of stress shadow modeling for a multi-stage fracture treatment that was undertaken for a Bakken reservoir in the Viewfield area of southeast Saskatchewan. Also shown on the figure are instantaneous shut-in pressures (ISIPs) recorded for each fracture stage during the treatment. ISIP is viewed as an approximate representation of minimum horizontal stress magnitude. The predicted trend of increasing minimum horizontal stress with increasing stage number compares favourably to the increase in ISIP observed during the treatment program. Specifically, both datasets suggest an increase in minimum horizontal stress of approximately 4 MPa. Further analysis of the data suggests that minor deviations from the trend may be explainable (in part, at least) by deviations in stage spacing and the time lag between stages.

Given that the full workflow presented in Figure 3 can be labour-intensive for a multi-stage fracture treatment, means of simplifying the process were explored. For this particular case, in which the injection volumes were relatively small (e.g., 27.5 m<sup>3</sup> of fluid per stage) and the formation permeability relatively low (<0.1 md), sensitivity analyses showed that poroelastic and thermoelastic stress shadow effects were negligible. As such, it was only necessary to account for the mechanical stress shadow. Also, the fracture simulations suggest that, approximately 40 minutes after shut-in, pressure fall-off and associated fracture closure progress to the point where the fracture faces are fully supported by the injected proppant. After such a time, fracture length and width remain constant, hence giving rise to a stress shadow distribution that is also constant. Given that 40 minutes is comparable to the typical time lag from one stage to the next, a simplified analysis was conducted in which mechanical stress shadows were predicted assuming that fracture length and average width instantaneously reach constant values (e.g., “propped length”) for each fracture stage. In such a case, the following equation can be used to predict the stress shadow for a given fracture stage (stage  $n$ ), accounting for all preceding stages:

$$\Delta\sigma_{Y,X=0} = \sum_{i=i_i}^{n-1} - \frac{E\varpi_i}{(1-\nu)\pi h_i} \left[ \frac{Y_i}{(Y_i^2 + \frac{L_i^2}{4})^{\frac{1}{2}}} - 1 + \frac{Y_i L_i^2}{4 * (Y_i^2 + \frac{L_i^2}{4})^{\frac{3}{2}}} \right]$$

Where  $\Delta\sigma_{Y,X=0}$  is the change in minimum horizontal stress magnitude at the fracture port (or perforation) for stage  $n$ ,  $i_i$  is the number of the first successful fracture stage (typically 1, unless stage 1 is aborted or fails),  $E$  is Young’s modulus,  $\nu$  is Poisson’s ratio,  $\varpi_i$  is average fracture width (aperture),  $h_i$  is fracture

height,  $L_i$  is the total (“tip-to-tip”) length of fracture, and  $Y_i$  is the spacing between stage  $i$  and stage  $n$ . As shown in Figure 4, the stress shadow predicted by this simplified model compares favourably to the more rigorous model predictions; exceeding the latter by magnitudes in the 0 to 1 MPa range.

## Conclusions

Analytical solutions exist for the estimation of mechanical, poroelastic and thermoelastic stress shadows under idealized conditions. These can be used in conjunction with a numerical fracture simulator to predict fracture behaviour during a multi-stage treatment. For the Bakken reservoir modeled in this work, sensitivity analyses demonstrated that a simplified modeling workflow could be implemented, thus significantly reducing the required effort. Predicted changes in the minimum horizontal stress magnitude compared favourably to changes in ISIP recorded during the Bakken treatment that was analyzed. Work is currently underway to assess if the trend observed for this well is repeatable across other wells, and to assess the potential consequences of fracture re-orientation resulting from stress shadow effects.

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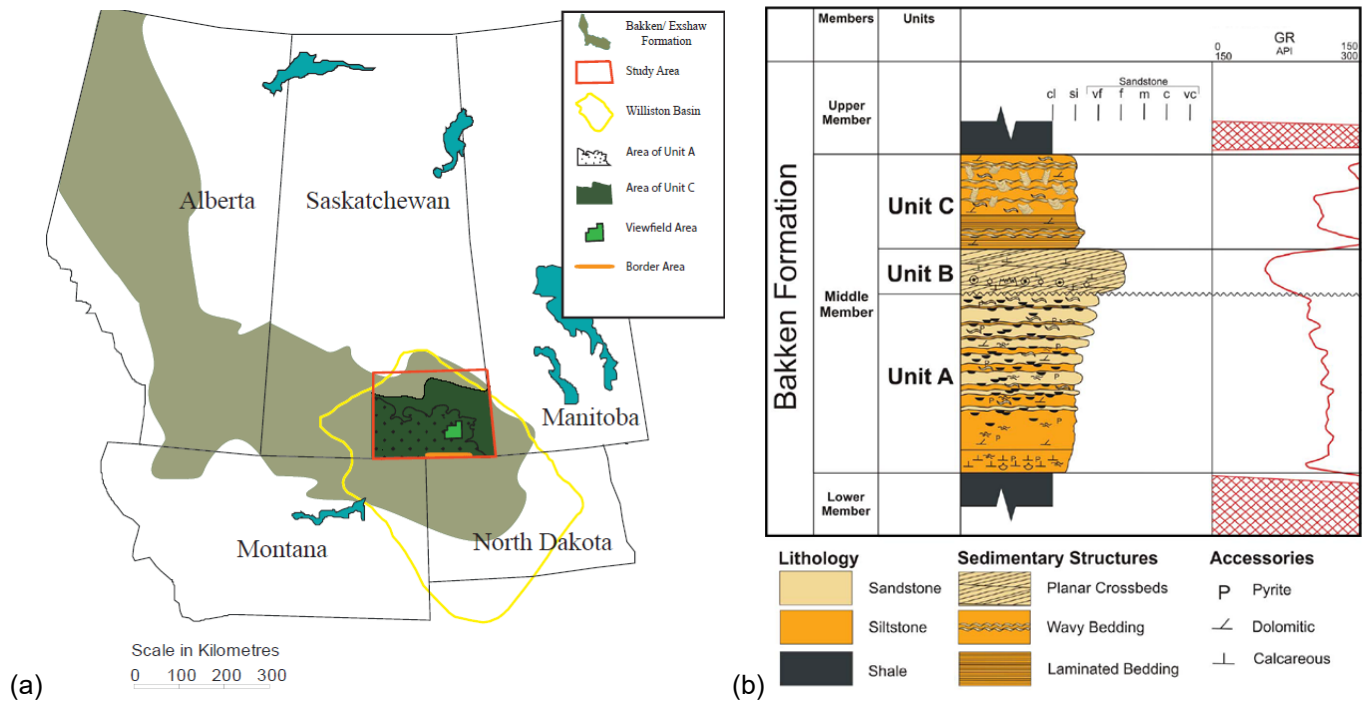


Figure 1: (a) Map showing extents of the Bakken Formation and location of the Viewfield area (N.E.B., 2015). (b) Stratigraphy of the Bakken Formation in southeast Saskatchewan (after Kohlruss and Nickel, 2013).

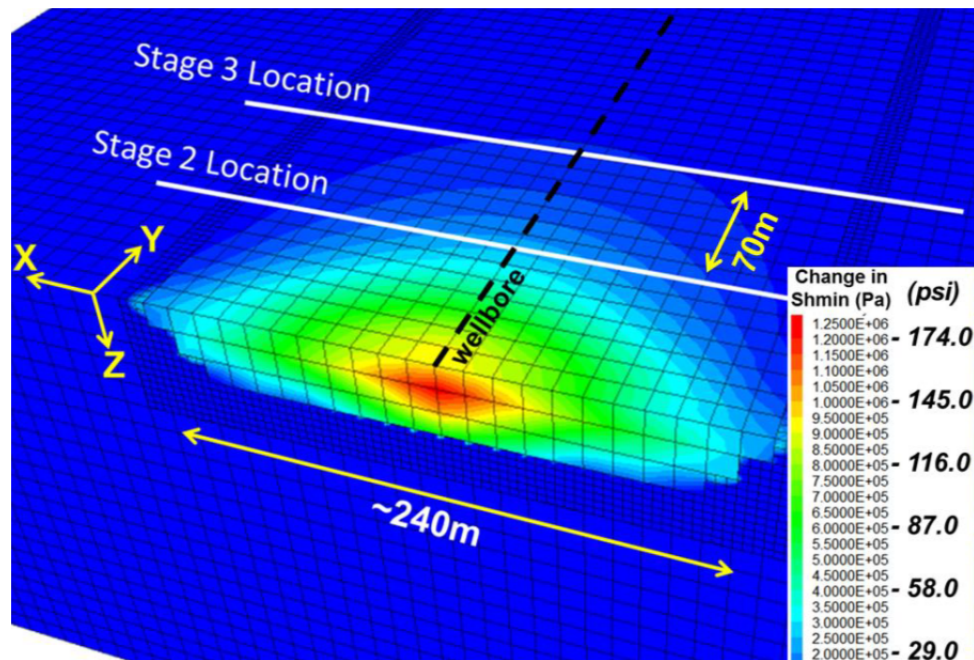


Figure 2: Example of stress shadow prediction undertaken with a numerical model (Oilfield Geomechanics, 2015).

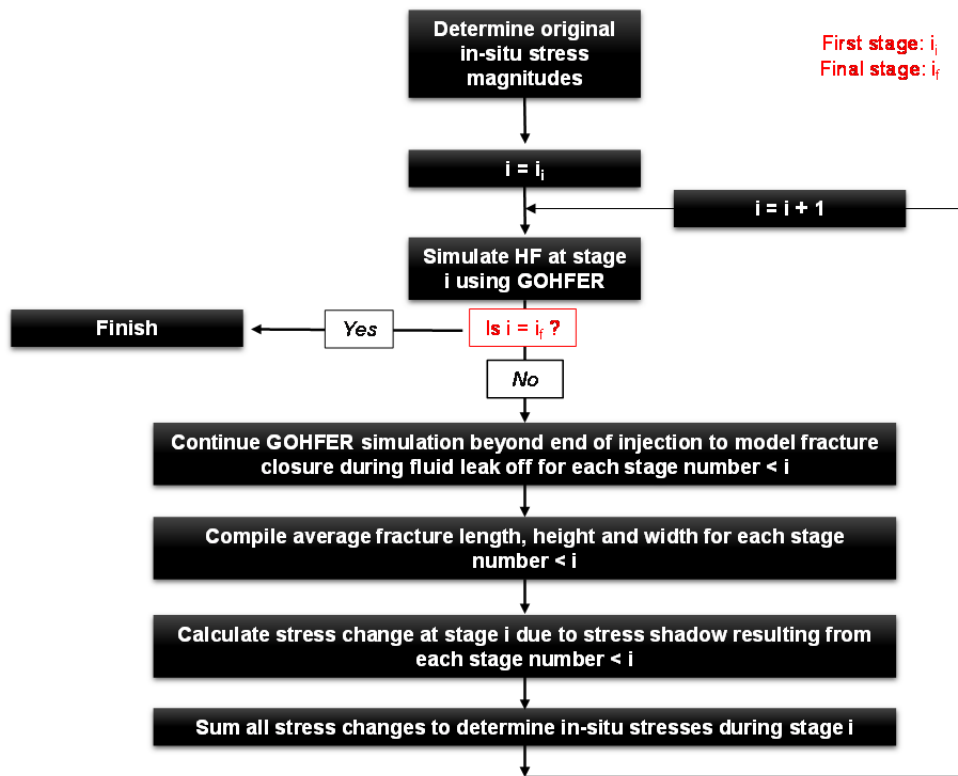


Figure 3: Workflow developed in this work for predicting stress shadow effects.

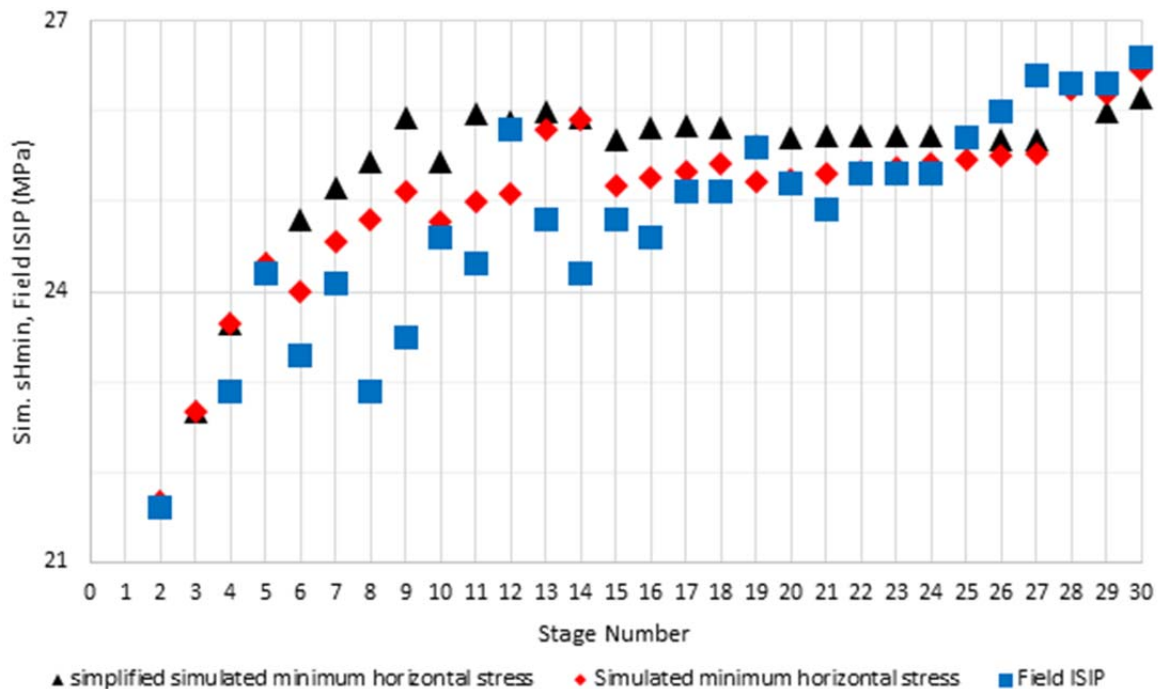


Figure 4: Assessment of stress shadow effects during multi-stage fracture treatment of a Viewfield-area Bakken oil reservoir. Blue squares show instantaneous shut-in pressures (ISIP) reported for each stage, red diamonds show minimum horizontal in-situ stress at each stage predicted ("simulated") using the general workflow presented in Figure 3, and the black triangles show minimum horizontal in-situ stress at each stage predicted using a simplified workflow.