Use of engineering data for microseismic event pattern analysis and determination of fracture height

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Summary

In multi-stage fracturing operations, each subsequent stage increases the minimum horizontal stress and reduces the stress anisotropy due to stress/strain perturbations in the vicinity of the clusters. This effect, known as the cumulative stress shadow, may cause a change in the microseismic event propagation pattern. ISIP analysis can capture the effect of mechanical stress interference, which contributes to both stress magnitude and orientation, causing fractures to curve either away or toward previously placed stages. The fracture height can be calculated along with the fracture spacing based on ISIP measurements and stress escalation. This study presents an approach based on the Stress Escalation Model to define horizontal stress anisotropy and fracture height dimension. These ISIP-based height predictions are then compared with microseismic observations to validate the method. Application on a field dataset produces comparable estimates for fracture heights.

Theory/ Method

The impact of a stress shadow is an increase in the minimum horizontal stress around the opened fracture, thereby gradually reducing the horizontal stress anisotropy (Figure 1). As the stress increases, fractures may not grow with the preferred orientation due to the diminished stress contrast; in addition, the frac height for different stages along the wellbore may be reduced (Dohmen et al., 2014). These phenomena will show as changes in the pattern of microseismic events per stage (Figure 1).

In multistage fracturing, the ISIP characterizes the pressure necessary to propagate fractures in the formation. As the opening stress escalates, ISIP will increase and reach a plateau (Figure 2). Specifically, the ISIP is correlated to the net fracture pressure (p_{net}) inside the fracture, the closure stress ($\sigma_{h\text{-}min}$), and the accumulated stress $\Delta\sigma$ shadow (Moradi, 2021) by

$$\mathrm{ISIP}(n) = p_{net} + \sigma_{h\text{-}min}, + \Delta\sigma_{shadow}\,(n-1). \quad (1)$$

To quantify the increase in ISIP due to mechanical stress interference, the stress increase is determined by the simplified Sneddon's equation for a semi-infinite fracture (Olson, 2004; Polard & Segall, 1987; their Equations 6 to 8):

$$\varphi_{semi-infinite} = \frac{\sigma_{shadow}}{\sigma_{load}} = 1 - \left(\frac{s_f}{h_f}\right)^3 \left[1 + \left(\frac{s_f}{h_f}\right)^2\right]^{-3/2} \quad (2)$$

The stress change, normalized by σ_{load}, represents the net pressure (p_{net}) in the hydraulic fractures of one stage just prior to another, which is the source of induced stress interference ($\Delta\sigma_{shadow}$). The change in the stress or in ISIP(n) is a direct result of the distance (s_f) along the well length and the fracture half-height (h_f) (Roussel, 2017).

The change in stress shadow can be described as escalation from one stage to another one and a total stress plateau reached at the end of the fracturing (Figure 3). Analysis of the observed, normalized ISIP data reveals the stress plateau and gradient (escalation) as a function of stage number, and escalation.

$$\Delta\sigma_{shadow}(n) = \Delta\sigma_{plateau}\left(1 - e^{\frac{1-n}{escalation}}\right) \quad (3)$$

The escalation is a direct result of stress around the fracture length and spacing of the fractures. This relation allows to back-calculate the fracture height using the known value of fracture spacing.

$$escalation = 1.928\left(\frac{s_f}{2h_f}\right)^{-1.36} \quad (4)$$

In this study, we investigate the effect the stress shadow has on fracture height and direction using both microseismic data and ISIP analysis to better understand fracture propagation characteristics in the study area, in particular the effect of cumulative stress shadows on observed patterns in microseismicity.

The microseismic analysis relies principally on the visualization of each stage. Height is simply determined by subtracting the shallowest event from the deepest event, to obtain a first-order magnitude.

Results

We used a microseismic dataset, including pumping information, acquired from a well drilled in the direction of the minimum horizontal stress. The stress regime in the area is normal faulting ($\sigma_V > \sigma_H > \sigma_h, \quad \sigma_H = 45.9 - 50.9\ MPa,\ \sigma_h = 35.5\ MPa$). Therefore, the microseismic events propagated predominantly perpendicular to the wellbore (Figure 3). Events tend to propagate unidirectionally toward the NE direction, although occasionally the cloud trends towards the SW, and there is a tendency for fracture length to decrease again after reaching a particular stage. These features could be caused by variations in the in situ cumulative stress shadow, as shown in figure 1. Therefore, we applied the ISIP analysis method to investigate the fracture propagation effect based on the engineering data. Results imply a fracture length based the stress data of 155.5m with a stress plateau of 4.25 MPa (Table 1). This stress perturbation is far inferior to the required minimum horizontal stress change to cause 90° degree flips in the orientation of microseismic clouds (Figure 1). Conversely, such a stress accumulation may force microseismicity to switch to the SW direction between certain stages (Figure 3).

Escalation	$\sigma_{Platueu}$ (Mpa)	s/2f	σ_{load} (MPa)	H_f	$p_{(net)@shut-n}$ (MPa)
3.5	4.25	0.63	1.4	155.5 m (+/- 20)	8.95

Table 1: Results based on ISIP Analysis

The average microseismic height from stage to stage is 175.5 m, which compares well with the value obtained from the engineering data (155.5m). As a further validation, Figure 4 displays anticipated stress changes due to a fracture with this height.

Conclusions

Patterns in the microseismic event propagation are directly affected by many factors, including injection rate, volume, and pressure, which in turn influence the cumulative stress shadow, which may locally change the in-situ stress regime for individual stages. ISIP analysis helps reveal the cumulative stress shadow and provides a first estimate of the average fracture height. These predictions can then be used as a constraint against observed microseismic patterns.

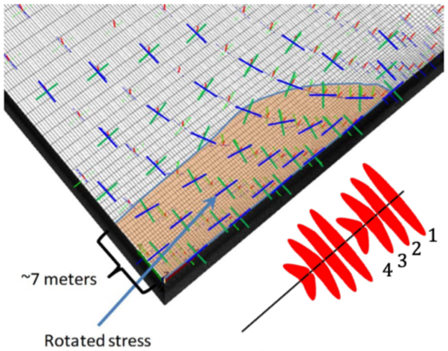

Figure 1: Change in propagation direction due to the stress reorientation. Green line represents maximum horizontal stress, while blue line represents minimum horizontal stress. Shadowed zone corresponds to the possibility of 90 degree flipped fracture propagation direction. (modified from Gorjian, M., Hendi, S., & Hawkes, C. D., 2021)

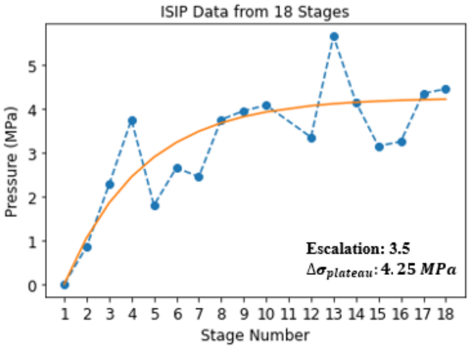

Figure 2: ISIP derived stress shadow change from stage to stage. The orange fitted line represents the stress shadow as a function of escalation (growth rate per stage) and its plateau.

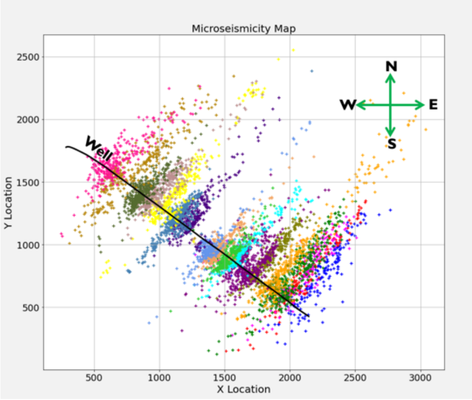

Figure 3: Microseismic events, with clouds mostly oriented perpendicular to the well. There is tendency in microseismic events to propagate unidirectionally toward the NE direction.

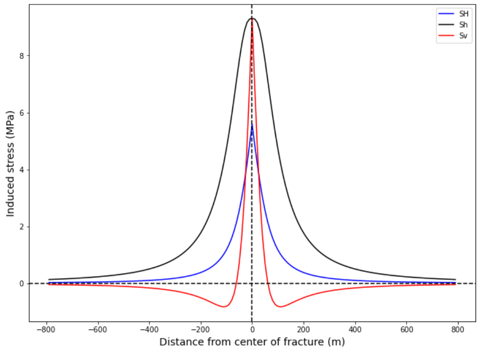

Figure 4: Induced stress change for a fracture height of 155.5 m. The horizontal line represents the spacing/ distance from the center of the fracture.

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