Investigation of the impact of depleted zones and completion sequence on hydraulic fracturing performance using microseismic collective behaviour analysis

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Summary

Through an example in the Midland Basin, we demonstrate how dynamic parameters characterize a complex reservoir response to hydraulically-stimulated stacked wells where the completion of the investigated stages on one well (A-well) proceed the treatment of the second well (B-well). These two stacked wells target two different siliciclastic formations within 400 ft, separated by a carbonate formation that acts as a hydraulic fracture barrier. Dynamic parameter characterization indicates that the A-well stages generate high anelastic deformation (PI) associated with fluid-driven deformation around the injection interval at early stages of completion where stress is more gradually released through a series of relatively low stress events in a spatially contained target zone (Low SI and DI). The stress-triggered seismicity plays a role for the later event-clusters for these stages. In contrast with this observation, the B-well stages, which are completed after the A-well stages, demonstrate low deformation (Low PI) in the highly stressed rockmass (high SI) where the energy release is more episodic. The presence of the previously stimulated vertical well (depleted zone) in the vicinity of the completed stages can be tracked by the temporal evolution of deformation where high diffusion (high DI) is observed.

Introduction

Throughout the hydraulic fracturing process, high pressure fluid and proppant injection generates stress gradients within a reservoir. The rockmass responds to this change by means of energy, momentum and mass transport to reduce and transfer stresses. Previous activities in the reservoir and variations in the completion program in addition to the structural and lithological properties of the target formations play critical roles in the adjustment of the rockmass the stress-induced disturbance and consequently the performance of the completion.

One way to track the changes in the seismic strain and stress regime and rheological properties of the rockmass is through the use of cluster-based microseismic data analysis. The concept of cluster-based analysis to describe the deformation processes in the reservoir by using windows of seismicity in time and space to localize descriptions in terms of time-dependent fields of deformation was first introduced by Kostrov and Das (1988). More recently this concept has been applied to the microseismic data acquired during the hydraulic fracturing process under the “Dynamic Parameter Analysis” expression by Urbancic et al. (2015; 2017), Baig et al. (2017), and Ardakani et al. (2018). The cluster-based attributes to describe the collective behaviour consist of Plasticity Index (PI), Diffusion Index (DI), and Stress Index (SI). These individual parameters are computed using the source characteristics (seismic energy release, stress release, seismic moment) and the inter-event times and distances between events within each cluster. These parameters are elaborated in detail under the methodology section.

In this work, we present a case study to discuss the use of the microseismic cluster-based analysis to arrive at collective behaviour observations and interpretations of processes occurring during the hydraulic fracturing, with a main focus on the influence of the depleted zones and completion sequence on the fluid- vs stress-driven and spatial distribution of the deformed rock volumes.

Cluster-based microseismic attributes

Microseismicity is essentially a dissipative process that radiates seismic waves that contains information about the in-situ deformation. The amplitude and frequency of seismic waves radiated from seismic events depend on the strength and state of stress of the rock, the size of the source of seismic radiation, the magnitude, and the rate at which the rock is deformed during the fracturing process. Although each microseismic event contains all these valuable information, investigation of the behaviour of a single event attributed to a single rupture on a crack surface is not adequate to assess the entire fracturing and deformation process. Therefore clustering of a substantial number of events associated with multiple ruptures and slips on several fracture surfaces within a spatio-temporal context is recognized as a solution which allows for description of the rockmass response to hydraulic fracturing. The clusters of seismic events are formed using two approaches: static and dynamic sampling of a number of events and time differences between these events, as selected based on the characteristic space or spatio-temporal scales (Figure 1).

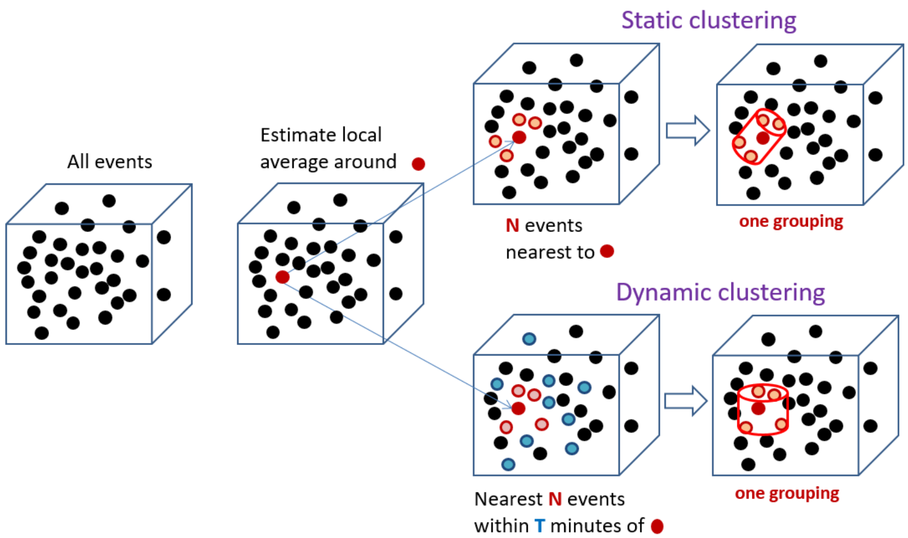

Figure 1. Schematic illustration of the microseismic data clustering. The clustering is called dynamic or static based on whether a time scale is imposed on event-clustering or not.

To measure the variations on the macroscopic properties of the system, several attributes are estimated for each cluster of microseismic events, such as the statistical properties of coseismic deformation and associated changes in the strain rate, the stress and rheology of the process such as the time between event occurrence, distance between events, time span, volume encompassing these events, radiated energy, seismic moment, and density.

Using these attributes, three indices of Plasticity Index (PI), Diffusion Index (DI), and Stress Index (SI) are defined and can be calculated if the statistics of the recorded microseismic data is in place. PI, infers the total co-seismic deformation associated with the cluster. As such, a low PI means the rock volume has a dominant elastic behaviour and has not suffered large anelastic deformation whereas the high PI clusters define rock that is easily deformable, generally related to an increase in crack complexity or changes in material rock properties (Figure 2a). SI combines different source parameter information with the inter-event-times and distances to characterize how stress is released in the reservoir for the volume encompassing the events. A lower SI indicates that the transfer of stress is more unstable and localized whereas a higher SI would indicate a less complex and further reaching stress transfer mechanism (Figure 2b). DI uses the relationships between the inter-event time and inter-event distances to define the effectiveness of the reservoir in transferring or loading stress via seismicity. Low DI would represent seismic activity that occur close together in space, with large inter-event times whereas high DI would be related to events that occur in space over large inter-event distances and/or over short inter-event time intervals (Figure 2c).

Each one of these parameters is inversely proportional to the other two, so it is natural to plot the deformation state of the medium in terms of a ternary plot, as shown in Figure 2d. This plot is a great tool for behavioral interpretation of the rockmass throughout the completion process in such a way that the combination of PI, SI and DI can be used to categorize fluid-driven versus stress-driven processes. Where PI is high, and SI and DI are low, as illustrated conceptually by the blue clusters in Figure 2d, the seismicity is categorized as fluid-driven whereas the red clusters with high SI, moderately high DI, and low PI have the characteristics of a stress-driven seismicity.

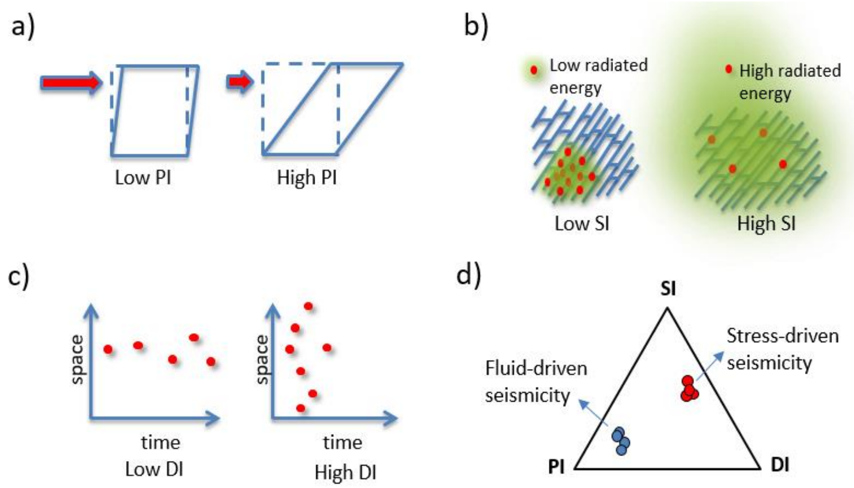

Figure 2. Contrast of behavior of a) low and high PI, b) low and high SI, c) low and high DI, d) the ternary plot composed of these three parameters with two datasets categorized as fluid- and stress driven seismicity.

Case study- Reservoir response to completion sequence and depleted zones

In a case study conducted in Midland Basin, we use dynamic parameters to characterize the complex reservoir response to hydraulically-stimulated stacked wells where the completion of the investigated stages on one well (A-well) proceed the treatment of the second well (B-well). These two stacked wells target two different siliciclastic formations within 400 ft, separated by a carbonate formation that acts as a hydraulic fracture barrier. A previously stimulated vertical well is located about 500 ft away from the investigated stages. Figure 3 shows the computed Dynamic Parameters over five stages under investigation.

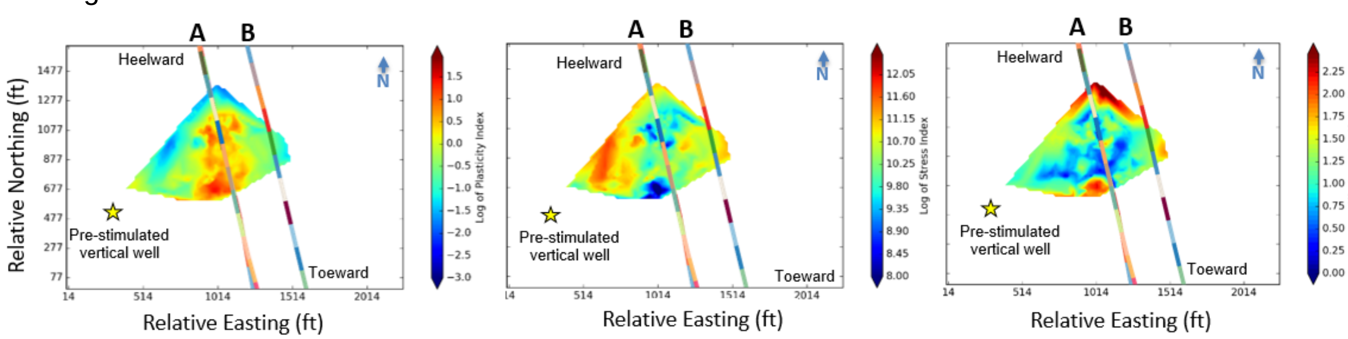

Figure 3. From left to right, computed PI, SI, and DI for the stages under investigation.

Dynamic parameter characterization indicates that the A-well stages generate high anelastic deformation (PI) associated with fluid-driven deformation around the injection interval at early stages of completion where stress is more gradually released through a series of relatively low stress events in a spatially contained target zone (Low SI and DI). The stress-triggered seismicity plays a role for the later event-clusters for these stages. In contrast with this observation, the B-well stages, which are completed after the A-well stages, demonstrate low deformation (Low PI) in the highly stressed rockmass (high SI) where the energy release is more episodic. As the pore pressure increases and stress builds up around the B-well, the seismicity encounters a quick migration to the readily deformed zone around the A-Well and surrounding depleted zones. Therefore, the later event-clusters of B-well stages are identified with ease of deformation and diffusivity (high PI and DI) (Figure 4). This complex response for the B-well stages is due to the completion sequence and adjacent depleted zone.

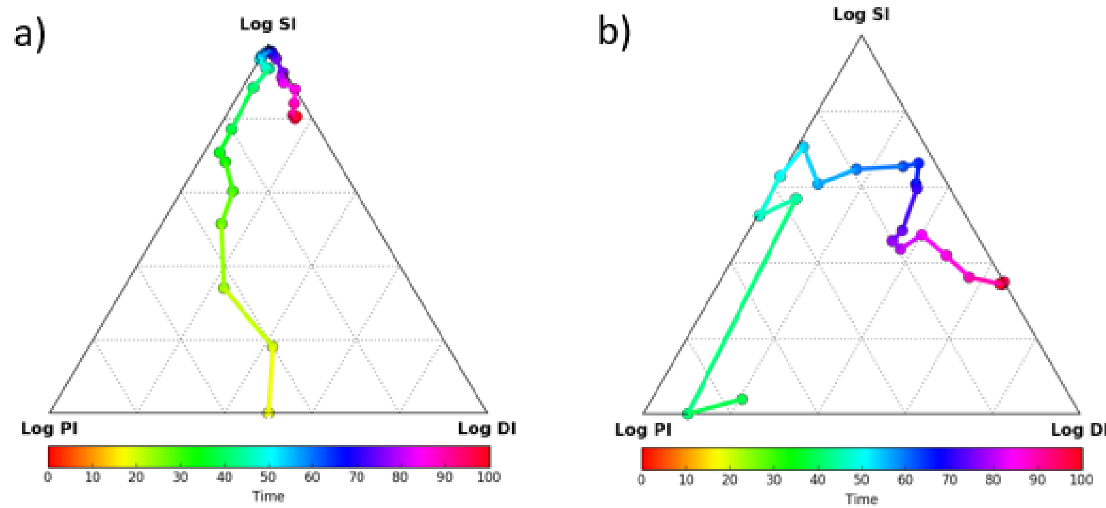

Figure 4. Deformation path throughout treatment time for two stages on a) "A" well and b) "b" well near the pre-stimulated vertical well.

Conclusions

This approach offers valuable insight for operators on the deformation and stress state evolution across pads particularly where hydraulically fractured wells exhibit seismicity interactions. In such conditions the completion sequence and depleted zones near the treatment well have a significant influence in the rock response to the hydraulic stimulation that can be tracked through microseismic collective behaviour analysis (i.e., Dynamic Parameters).

References

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