Distinguishing Natural Reactivated Fractures from Hydraulic Induced Fractures using Microseimic Event Analysis

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Summary

Microseismicity induced during the stimulation treatment of a tight gas reservoir were mapped using a shallow buried array acquisition method. Though the events mapped from the monitoring project described in this study formed well-defined, distinct, parallel trends of microseismicity, the trends were not parallel to the regional maximum horizontal stress direction as indicated both by the source mechanisms and by a crossed-dipole sonic log interpretation. The linear event trends are interpreted to have formed from reactivation of natural fractures that strike at an angle to the maximum horizontal stress in the reservoir. Although the fractures were filled with calcite, they provided a plane of weakness along with failure occurred preferentially during the treatment. This result has important implications for interpretations of stress from source mechanisms and from in-situ reservoir stress interpreted from cross-dipole sonic logs, and illustrates the importance of being able to predict the impact of natural fractures on the stimulation treatment.

Introduction

Event locations are often interpreted to define the location and extent of induced fractures formed by mode I tensile failure in the reservoir, indicated by microseismic events forming linear trends parallel to the maximum horizontal stress direction. With the increased use of source mechanism analysis of microseismic events, a better understanding of the actual mode of failure of the rock during the stimulation treatment is being developed, and the results often indicate that failure occurs on pre-existing faults and fractures. Analyses of source mechanisms of microseismic events show that often the failure plane and the microseismicity trends are not parallel, or that multiple source mechanisms can occur during the same stimulation treatment (Williams-Stroud et al, 2010). Through stress inversion analysis of multiple failure planes, stress directions can be inferred from the microseismic event source mechanisms in the same way stress directions are inferred from focal mechanisms of naturally-occurring earthquakes (Aki & Richards, 2002).

Theory and/or Method

Microseismic monitoring was done using a shallow buried array to assess the effectiveness of the hydraulic fracture stimulation treatment with 13 hydraulic fracturing stages. A total of 98 stations using the GSR recording system were deployed at 300 feet below the surface above the monitoring area. Due partly to a very low background noise level the data quality was very high, making it possible to invert a large number of events for their source mechanisms. A total of 108 hours of data were recorded, with 39 hours of data processed over the 13 fracture treatments. Microseismic events induced by the hydraulic fracturing were located by a beam-forming process, which is essentially a one-way depth migration (Fig. 1). A layered velocity model was constructed using the sonic velocities logged in the well. Using the known locations of perforations, the velocity model was then calibrated to image the perforations at their correct position in X, Y and Z. This calibrated velocity model was then used to image the events produced by the hydraulic fracture treatments. The average locational error for the perforations and events was ±18 meters in X and Y, and ±27 meters in depth, with larger errors for smaller events and smaller errors for larger energy events.

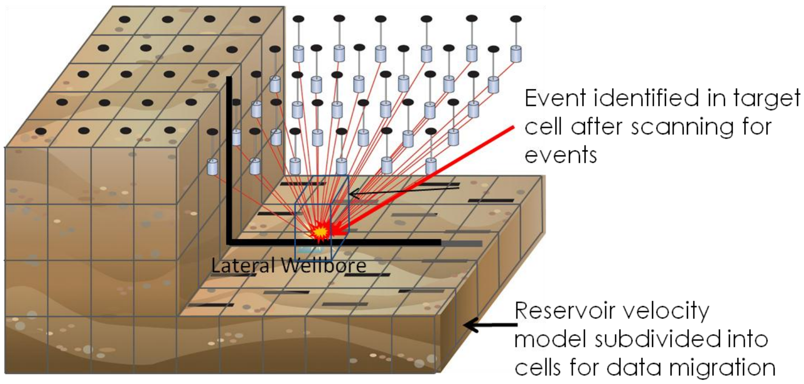

Figure 1: Buried array layout showing relative locations of microseismicity. Reservoir velocity model is scanned in space and time to detect and image induced microseismic events.

For tensile fracture formation, the direction of the maximum in-situ stress may be assumed to be parallel to the trends along which microseismicity forms, so wellbore laterals are often drilled perpendicular to the maximum horizontal stress direction. However, the additional information obtained from microseismic event source mechanisms provide a better understanding of the nature of rock failure that occurred during the stimulation treatment, and in the majority of monitored stimulation treatments double-couple, or shear, mechanisms dominate the source mechanism types inverted from microseismic events (Eisner et al, 2010). The dominance of shear events detected in the microseismicity suggests that in most cases, the source of microseismic activity is related to reactivation of existing features in the rock rather than to creation of new tensile fractures.

Examples

The well was drilled with a deviation perpendicular to the maximum horizontal stress presumed for the area in order to optimize expected fracture half-length from the stimulation treatment. Operators commonly refer to publically available stress data to determine the optimal wellbore deviation for hydraulic fracturing (Heidbach et al, 2008). Anisotropy measured in a crossed-dipole sonic log from a nearby well confirmed the presumed stress anisotropy with a northeast oriented fast shear wave polarization azimuth (Figure 2). Anisotropy in the well is less than 1%, but low anisotropy is not unexpected in over-pressured environments of the type found in this well. The dipole sonic log also indicates that the stress state in the reservoir and in the overlying rocks varies with depth so that the maximum horizontal stress changes orientation in different lithologies, rotating to an azimuth closer to the average regional stress with shallower depths away from the over-pressured interval. The dipole sonic log processing indicated only stress-induced anisotropy, where the fast shear wave azimuth is induced as a result of differential stress in the reservoir, rather than intrinsic anisotropy due to the rock fabric. An examination of drill core that was acquired from this well prior to the stimulation treatment shows calcite-filled fractures, along which the rock could have failed during the treatment.

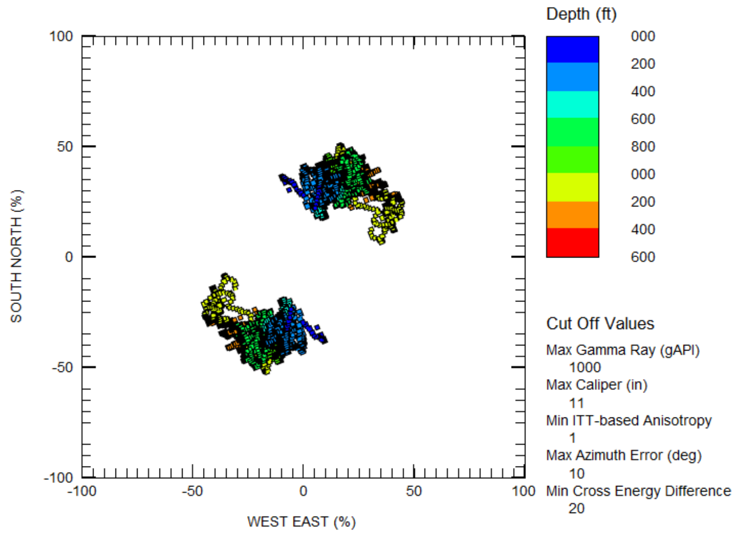

Figure 2: Plot of major tectonic axes with depth determined from crossed dipole sonic log. Shallower depths (above the reservoir) have a more northerly fast shear wave polarization direction, as do also the lithology just beneath the reservoir. The fast shear wave polarization direction in the depth range of the over-pressured reservoir (orange interval) is 40^o-50^o.

Well-defined trends of microseismicity formed as a result of the stimulation treatment with the failure planes of the source mechanisms parallel to the microseismicity trends, but neither are parallel to the maximum stress direction. We have interpreted the mode of failure to be reactivation of existing calcite-filled fractures in the reservoir, where the fractures have one strong preferred orientation that is approximately 30^o from the maximum horizontal stress.

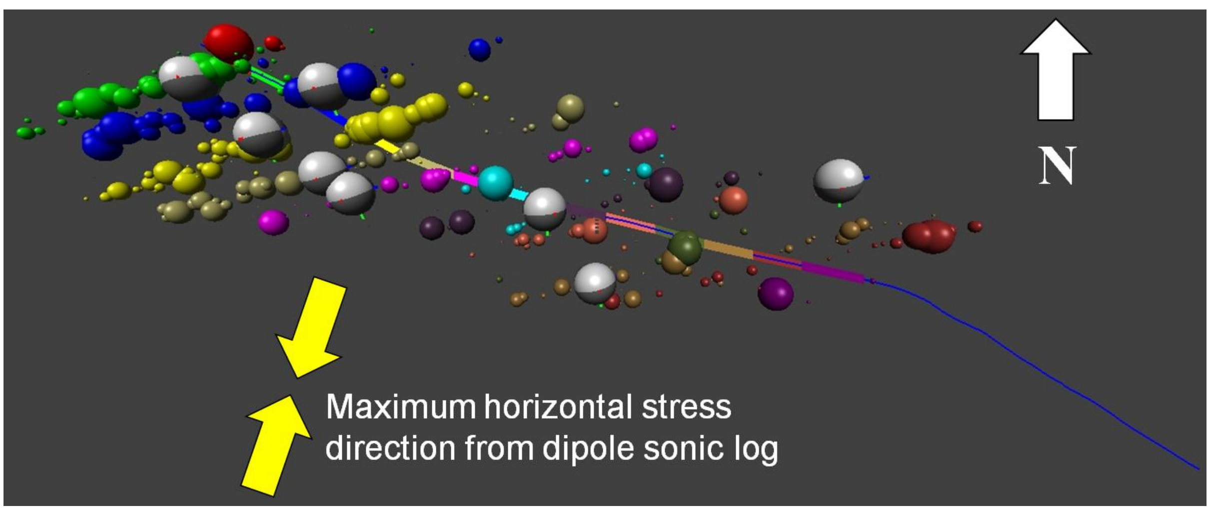

Figure 3: Microseismic monitoring result showing event trends parallel to failure planes of source mechanisms inverted from representative events. The spheres representing the events are sized by energy and colored by stage. The well was drilled with a deviation perpendicular to the maximum horizontal stress presumed for the area in order to optimize expected fracture half-length from the stimulation treatment. The angle of the event trends and the failure planes with respect to the maximum horizontal stress direction indicates reactivation of existing fractures in the reservoir.

Because these fractures were not open in the subsurface during acquisition of the sonic log, they were invisible to the anisotropy measurement and remained undetected. The calcite filling represents a plane of weakness in the shale reservoir, so that although it is cemented, the increased pressures of the stimulation treatment caused failure only along these failure planes. The source mechanisms are not pure-dip slip, but show a significant amount of oblique slip with most rakes between 20 and 30 degrees from 90. The conventional seismological interpretation for shear failure for strike slip mechanisms assumes the maximum stress orientation is 45^{o} from the P-axis (Aki & Richards, 2002). By analogy with natural earthquake focal mechanisms, oblique shear failure can be interpreted to be indicative of reactivation of existing fractures or faults.

Conclusions

The importance of understanding the influence of natural fractures on hydraulic fracture stimulations is becoming more and more recognized, and is being applied to fracturing methodologies that utilize natural fracture networks to optimize the stimulation treatment (Gale et al, 2007, Cipolla, 2010). In this paper we have illustrated the strong impact of natural fractures on the stimulation treatment of a tight gas reservoir. In this example, the maximum horizontal stress direction was presumed prior to drilling the well, based on already available stress data. The hydraulic fracturing behavior was not predicted by the regional stress state, and appears to have been controlled by the existence of the existing natural fractures in the rock. In addition, local perturbations in the stress field related to reservoir conditions such as overpressure, vertical lithologic variations, and subsurface structures make it difficult to accurately extrapolate the in-situ stress state to individual wells using publically available data. The source mechanism analysis provided additional information that showed shear failure along planes at an angle to the maximum horizontal stress direction determined from a crossed-dipole sonic log, with oblique dip-slip along those planes. Long, tightly constrained, linear trends in microseismicity developed away from the wellbore parallel to the source mechanism oblique slip failure planes, indicating significant fracture growth resulting from a shear failure mechanism. The existence of natural fractures was substantiated by fractures observed in drill cores from the well. This particular well is a strong producer, indicating that the shear failure on the existing fracture planes was effective in exposing surface area of the rock to allow flow of gas to the well.

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