Introduction

Microseismic monitoring has become essential to optimizing hydraulic fracture stimulation in unconventional resource plays. Among the most critical aspects to control fracture growth is a clear understanding of rock mechanics of the reservoir. We show a case study in which source mechanism analysis provides the information needed to discriminate between events generated by a pre-existing weakness in the rock, either a reactivated joint or reactivation of a tectonic fault (e.g. Maxwell et al., 2009). This process can be performed in real time during hydraulic fracture treatment to better inform completion engineers of the character of developing fracture networks.

An alternative method to differentiate between fracture and fault events exploits event statistics. Gutenberg and Richter (1954) first proposed that in a given region and for a given period of time, the number of seismic events of a certain magnitude can be represented by

$$log\ N = A - bM_s$$

where N is the number of earthquakes with magnitudes in a fixed interval around magnitude M_s, and A and b are constants. In general, b values are between 2/3 and 1 and do not show much regional variability (Lay and Wallace, 1995). Maxwell et al. (2009) and Downie et al. (2010) show that events recorded during hydraulic treatment have a b value of 2, while events associated with fault deformation have a b value of 1. Maxwell et al. (2009) also observed differences in the p- to s-wave amplitude ratios that were interpreted as differences in the failure mechanism where events after treatment are believed to have induced deformation on a fault proximal to the treatment well. Using b values is a valuable tool used to discriminate between types of fracture propagation, however it requires a large number of events and can only be performed after the fact. Source mechanism analysis is capable of providing this information, in real time for each event, and we show that the b values of the events are consistent with the inverted source mechanism differentiation between fracture and fault events.

We present microseismic events associated with 13 horizontal wells in the Barnett Shale in north Texas. Microseismic data were acquired using BuriedArray™ technology—a near surface permanent installation of 618 stations equipped with vertical component geophones distributed in an area of approximately 144 square kilometers (figure 1a). Bowker (2007) shows that the density of natural fractures is highest near faults in the Barnett shale, but they are healed with carbonate cements. He also mentions that this weakness, in turn, allows the energy and fluid from hydraulic-fracture stimulations to be diverted along the fault plane, thus resulting in the Barnett being under stimulated. In this paper we show how the use of source mechanism inversion can be used to identify and separate a reactivated joint from a reactivated tectonic fault to provide a critical piece of information for engineers making decisions during fracture treatments.

Methods

We derive the source mechanism, assuming a point source, with a least squares inversion of the observed P-wave amplitudes. The inversion algorithm inverts for full moment (i.e. including the volumetric part of the source mechanism), and double-couple (shear) mechanisms. The moment tensor can be inverted from a point source relationship between observed displacements on vertical component A and moment tensor components M_{jk}:

$$A = G_{3j,k} M_{jk} \ , \qquad (1)$$

where $G_{3j,k}$ are vertical components of the Green's function derivative and Einstein's summation rules apply (Aki and Richard, 1980). Equation (1) can be inverted by either least squares (Sipkin, 1982) or a grid search. The grid search option is possible only for a pure shear source as a non-shear source has an infinite number of possible combinations of M_{jk}.

We used only P-waves on vertical components for the inversion of the moment tensor, as the aperture and distribution of the array allows a robust solution. The Green's function derivatives of a homogeneous isotropic medium with correction for attenuation can be written as:

$$G_{3j,k} = \frac{M_0}{4\pi\rho r c^3}\gamma_3\gamma_j\gamma_k e^{-\frac{\pi r f}{cQ}} . \quad (2)$$

For further detail please refer to Williams-Stroud et al. (2010). Source mechanisms presented herein represent the solution that best approximates observed spatial trends of the microseismic events.

Case Study

This study focuses on a group of 13 horizontal wells in Montague County, TX. The wells are completed in the Lower Barnett Shale that lies unconformably above the Viola/Simpson Limestone and Ellenberger Limestone. The wells in this study lie 2-12 miles from the Muenster Arch and the recorded microseismic activity exhibits several different source mechanisms. Maximum horizontal stress is oriented approximately NE-SW, therefore we would expect induced fractures to grow in this direction. Healed natural fractures are oriented predominantly WNW-ESE (Waters et al., 2006) and, based on source mechanism inversion of microseismic events, natural fractures in this orientation are not significant sources of microseismic energy, whereas reactivated joint fracture growth releases adequate seismic energy to be observed from the surface.

All wells in this study produced microseismic events with source mechanisms aligned with maximum horizontal stress—oblique slip with left lateral strike slip and normal component down to the north on a vertical plane with a strike of 40-50° (figure 1b). However, some wells exhibited other additional source mechanisms, some of which are not easily explained by regional maximum horizontal stress.

The four wells featured in figure 1b exhibited only one mechanism of 40/90/-125 (strike/dip/rake in degrees, respectively). Microseismic events fall into a trend that generally agrees with predicted maximum horizontal stress. The four wells in figure 1c were only monitored for a portion of their respective treatments, however enough data was collected to identify clear trends in microseismic event distribution. Two mechanisms are present, 40/90/-125 in the NW, and 240/80/10 in the SE. Events with the 240/80/10 source mechanism are concentrated along the green line in figure 1c and were of greater magnitude than other events away from this zone. Proposed to be a pre-existing fault, treatment was diverted into this feature for several hundred feet along the wellbore. Similar to the events of figure 1b, the events of 1c exhibited the expected trend of microseismicity aligned with maximum horizontal stress.

The wells of figure 1d,e,f had much less observed seismicity in regard to total event count, but the range of event magnitudes is comparable to the other wells. Events from wells in 1d were of a single dip-slip mechanism (220/90/-70), however, similar to 1c, there is a zone of frac capture where much of the microseismic activity for several stages occurred in a single linear zone. Two source mechanisms are present in figure 1e, 49/71/175 throughout the well and 40/90/-125 to the SE. The linear event trend marked by a green line is associated with a suspected fault plane aligned with maximum stress. In figure 1f the events were generated by strike slip source mechanisms oriented nearly NS and EW on a near vertical plane, with strike, dip and rake of 357/87/5 and 267/85/177, respectively. The geophysical and geologic causes for the limited observed energy and abnormal event trends is unknown, however we suspect that there is a local change in maximum stress in this area due to the close proximity to the Muenster Arch located approximately 2 miles to the east.

Fault vs Fracture Source Mechanism

We also calculated magnitude values for the events in figure 1c (figure 2). The data set is comprised of over 10,000 events that occurred during approximately 3 weeks of treatment. The *b* values observed for the two different mechanisms support the findings of Downie et al. 2010, i.e. where events that occurred along the fault have a lower slope (*b* value of 1.0) than events caused by reactivation of joints (*b* value of 2.2). Downie et al. used fault events that occurred after the treatment to calculate *b* values while we present events recorded during and after the treatment. Our approach, which benefits from the wide azimuth coverage of the array, allows us to identify events by source mechanism and discriminate induced fracture events from fracture/fault reactivation events on an individual basis in real time. When this information is provided to the engineers directing the fracture treatment, decisions can be made to avoid or limit loss of water, proppant, time and money into a fault that will be detrimental to the production of the well.

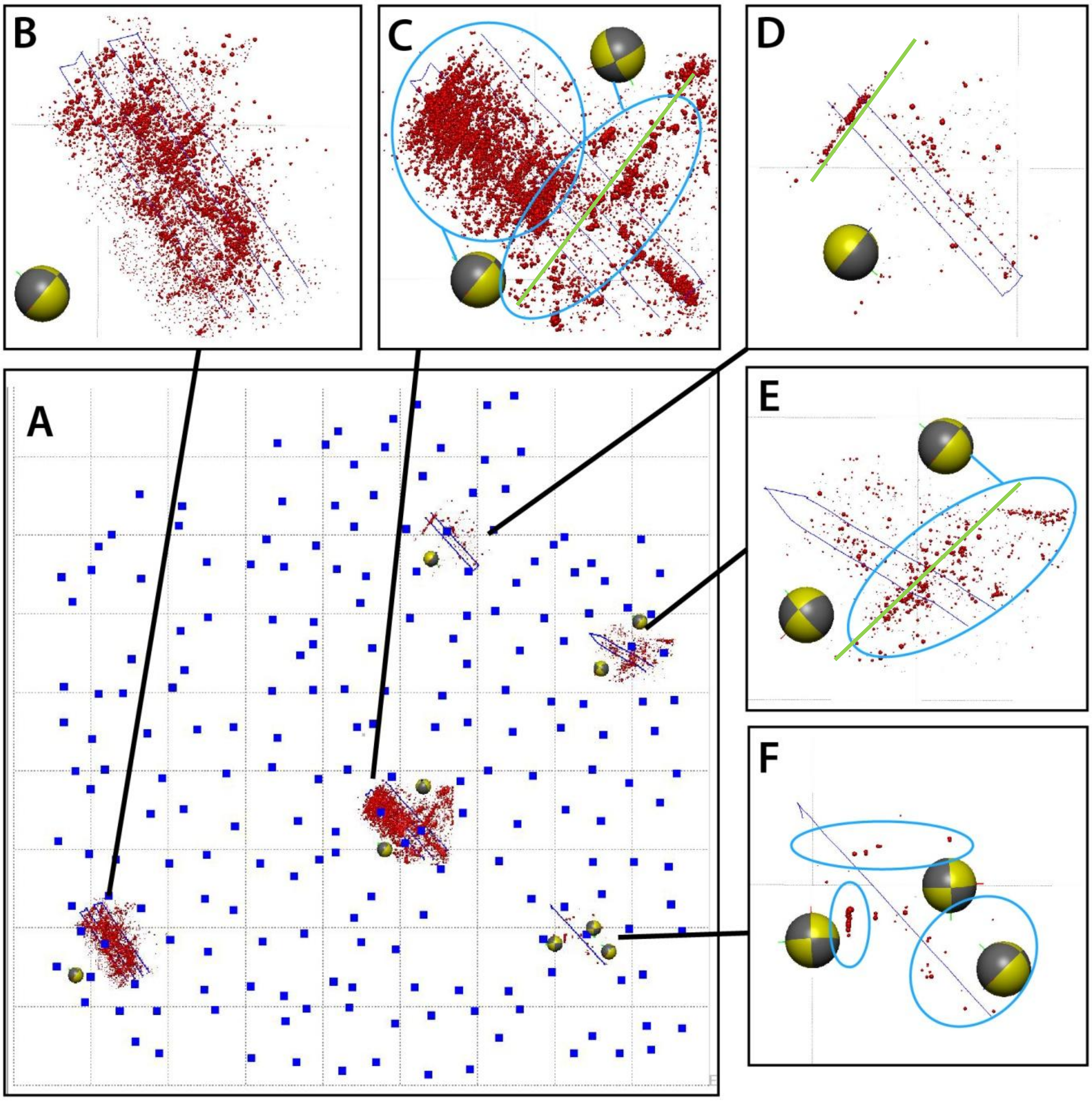

Figure 1 *(A) Map of observed wells and the near surface array with geophone stations marked by blue squares. Each station has an array of geophones at 3 levels. The Muenster Arch is located just outside the map area to the east. Each set of wells is shown in an inset with the observed source mechanisms included. Areas where a specific source mechanism is more prevalent are circled in blue; if no circle is present then the source mechanism was observed throughout the well. Green lines represent zones of frac capture where several fracture stages caused events along a single zone, sometimes several hundred feet from the treatment interval. Grid spacing is 1 mile. (B) Observed source mechanism with a strike/dip/rake of 40/90/-125. Events are distributed throughout the well horizontals and fracture trends are apparent. (C) Two source mechanism observed, 40/90/-125 in the NW, 240/80/10 in the SE. Only a portion of these wells were observed. (D) One source mechanism present, 220/90/-70. (E) Two source mechanisms, 49/71/175 throughout the well and 40/90/-125 to the SE. (F) Three observed source mechanisms, two of which do not align with predicted maximum horizontal stress; 357/87/5 in the central W, 267/85/177 in the N, and 45/90/-125 to the SE.*

Conclusions

Microseismic monitoring has become an important tool in the development of unconventional resources and a primary method to understand geomechanical properties of the reservoir. Engineers require reliable information during hydraulic treatment to make knowledgeable decisions and optimize resources. We have shown how source mechanism analysis of the microseismic events provides reliable discrimination of reactivated joints from a reactivation of tectonic faults. We have also shown that the negative effects of reactivating a fault can absorb or divert energy into fractures and faults in an undesirable way. Our *b* value result further supports our interpretation of the significance of differing source mechanisms. Finally the azimuth coverage of the acquisition allows us to differentiate between a reactivated joint and a tectonic fault during the fracture treatment to allow engineers to make informed decisions and control the hydraulic fracture treatment.

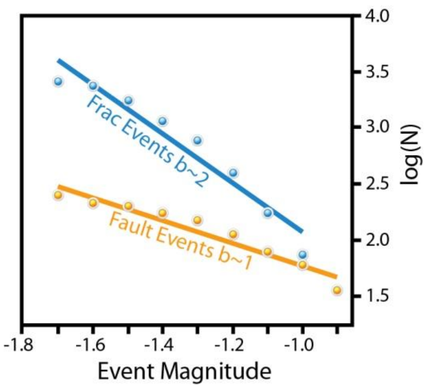

Figure 2 *Blue line with a slope of 2.2 represents the fracture induced events with 40/90/-125 strike, dip and rake (s-d-r) respectively. Orange line with a slope of 1.0 is the fault reactivation events with 240/80/10 s-d-r. Magnitude values are shown in the axis and number of events are shown in the y axis in hundreds.*

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