# Structural Controls on the Vertical Growth of Microseismicity Revealed Through Moment Tensor Inversion

Adam M. Baig*, Ted I. Urbancic and Shoshana B. Goldstein ESG Solutions, Kingston, ON, Canada
AdamBaig@esgsolutions.com

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## Summary

Vertical growth of hydraulic fractures in shale plays is a phenomenon that requires more understanding as certain completion designs seek to both exploit a tendency in a formation for events to grow in a certain direction while not breaking into undesirable formations, for example salt-water aquifers. Using seismic moment tensor inversion, we show for an example in the Marcellus Shale that stages exhibiting vertical growth are activating moderately dipping joint sets while vertical confinement is characterized by a preference of horizontal fracture planes. These two behaviours can occur in close proximity, but the amount of growth could be related to the local structure of the lithological layers. In this case, the vertical growth is postulated to be associated with the stress induced by the buckling of an anticline.

## Introduction

Microseismic data generated from hydraulic fracturing are frequently used to infer the stimulated volumes of reservoir in tight gas and shale formations. Growth characteristics between different stages of these treatments can show some very different characteristics. For the example of the Barnett Shale, Urbancic et al. (2002) show that the variability that can exist within a single formation undergoing similar treatments: event distribution show a variety of behaviours from the tight symmetric linear clusters that are consistent with models of bi-wing fracture growth to (more commonly) very complex and asymmetric clusters that grow in a more irregular fashion. The existence of the natural fracture system in the reservoir was invoked to explain these differences in behavior.

We examine the treatments of two wells from the same pad in the Marcellus Shale in Pennsylvania. The spatial distribution of the microseismic event hypocentres for the stages on one of the wells featured vertical containment while the other cluster featured a large amount of growth vertically. Further understanding on the interaction between the events is gained by considering the seismic moment tensors determined from the data. These data reveal that vertical confinement is associated with the activations of a sub-horizontal fracture planes while vertical growth tends to activate the joint sets noted by Engelder et al. (2009). We explore the why one of the joints would be activate for one well but horizontal fracture planes be more prevalent in other fracture sets.

## Data

Figure 1 shows the stages examined in the dataset comprising the vertically confined dataset in the one well and the less-confined dataset in the other well. Both stages occur near the heels of their respective treatment wells and were pumped after clusters of perforations were shot. The cross-sectional views of the hypocentres include the surfaces representing the top and the bottom of the Marcellus and show the differences in the vertical confinement between the Well A and Well B stages.

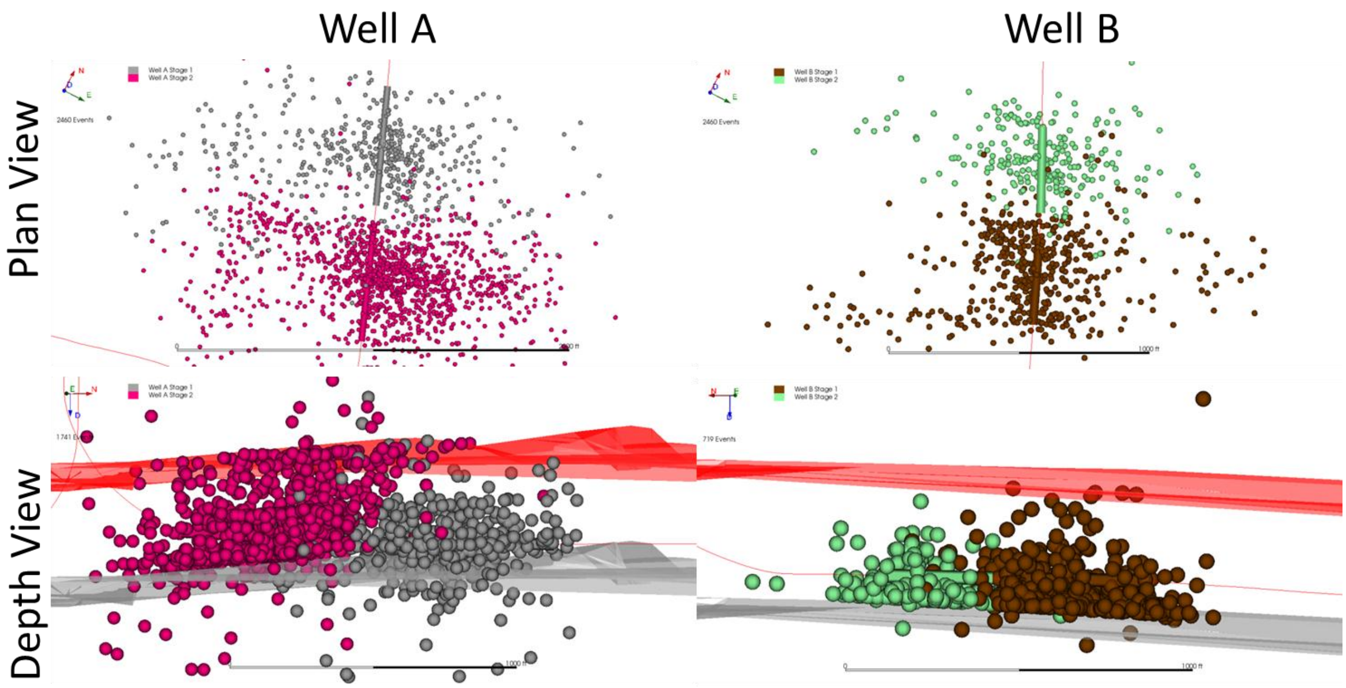


Figure 1: Events from 4 stages (2 in each well) shown in plan and cross-sectional view. The events are colour-coded by stage and shown for well A to the left and well B to the right. Also depicted is the top and bottom of the Marcellus as the red and grey surfaces.

## Seismic Moment Tensor Inversion and the Discrete Fracture Network

The moment tensor is a representation of the failure mechanism that controls the amplitudes and polarities of the waveforms of *P*, *SV*, and *SH* waves that propagate outwards from the event hypocenter. The process of seismic moment tensor inversion (SMTI), as described by Baig and Urbancic (2010), involves observing these waveforms and projecting the amplitudes back to the hypocenter to determine the mechanism. In order to get a stable solution, it is essential that the sensors recording the waveforms be deployed in a three-dimensional network around the events. For downhole deployments of geophone arrays around hydraulic fractures, this means that at least two or preferably more arrays need to be deployed to record the data.

The mechanism is usually described as a failure on a fracture plane, where the types of failures are usually considered to be opening of cracks, crack-closure, or slip on a fracture plane. As the moment tensor itself is proportional to the instantaneous strain rate imposed on the medium by the event, it has both a tensional axis (greatest outward strain) and a compressional axis (greatest inward strain). If the event has a mechanism that is consistent with the opening of a crack, the fracture plane is well-approximated by the plane normal to the tensional axis. Conversely, for closure mechanisms, this plane is taken as normal to the compressional axis. Double-couple events, representing shear on a fracture plane, present a more complicated scenario. The fracture planes in these cases will be 45° to both of these axes; as two such planes exist, disambiguating this plane is a challenging task. Gephart and Forsyth (1984) presented an algorithm that determines the orientation of the best-fitting stress axes given a set of moment tensors. With a best-fitting stress orientation for a group of mechanisms, one of the potential fracture planes will be more likely than the other, and this plane is assigned as the fracture plane for the moment tensor.

## Relation to Structural Trends

The Marcellus Shale is cross cut with two of different joint sets, $J_1$ and $J_2$ ,as observed by Engelder et al. (2009) in outcrop, core and borehole images. The earlier joints, $J_1$, strike ENE and are more closely spaces and crosscut the other set, $J_2$, which strikes NW. Co-incidentally, $J_1$, strikes nearly parallel to the regional $S_{Hmax}$ so that wells drilled perpendicular to the maximum horizontal compressive stress are thought to activate the second set preferentially.

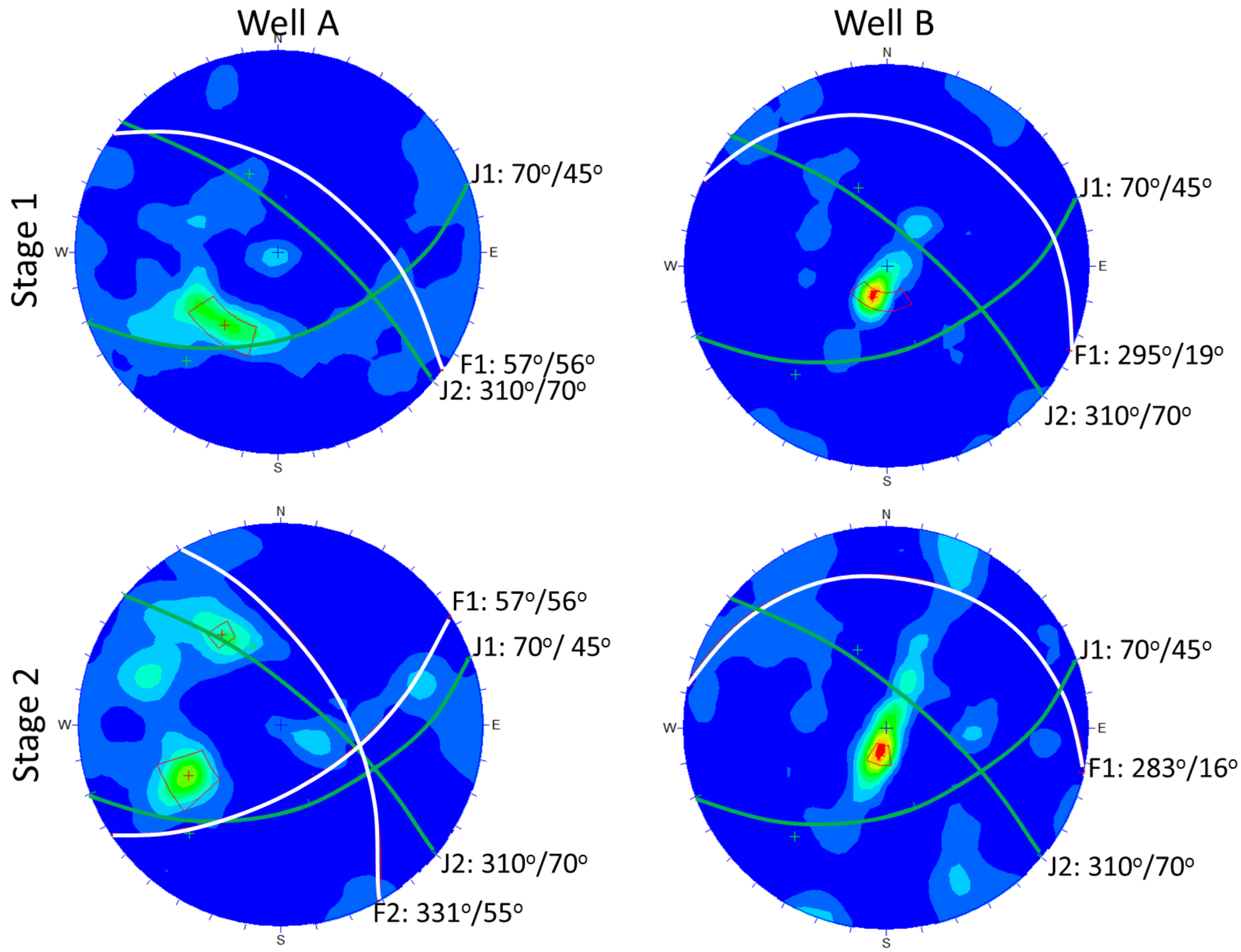


Figure 2 Lower stereographic projections of the poles to the SMTI-derived fracture planes in Stages 1 and 2 for both Wells A and B. These fracture planes are compared against the orientations of the dominant joint sets in the Marcellus described by Engelder et al. (2009).

In figure 2, we show the orientations of the poles to the fracture planes as determined from SMTI, contoured by density on a lower stereographic projection, for each of the stages that we show in Figure 1. Notably, for the stages in well A, the dominant fracture set in Stage 1 seems to agree within error to the orientation of $J_2$. For Stage 2 in this well, there appear to be two dominant fracture sets, corresponding to $J_1$ and $J_2$. Although well B is just on the other side of the same pad, the situation is very different. In this well, the dominant fracture set is observed to be sub-horizontal, striking WNW and dipping around 15-20°. These orientations suggest that the dominant failure mechanisms in these stages involves the fissile delamination of bedding planes.

## Conclusions

Comparing the dominant fracture plane orientations, shown in figure 2, with the depth distribution of events in the Marcellus, as shown in figure 1, it is notable that the stages activating the system of joints show much larger vertical growth than the stages where the dominant failure mechanism appears to be controlled by bedding planes. The implication is that there is a very local control on the stress conditions that promotes the jointed fracture network in Well A, but prefers to activate bedding planes in Well B. One suggestion is apparent on examining the local structural trends is that for the stages in well B, both the Marcellus appears to be uniformly oriented whereas there is a subtle anticline around stages 1 and 2 in well A. This anticline could indicate that the is a locally different stress regime promoting the failures on the joints rather than on the bedding planes, as in the less disturbed region around well B.

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