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Bridging the Gap Between Microseismic and Hydraulic Fracturing Using the Horizontal Slip Mechanism

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Abstract

Introduction

Microseismic data has been widely acquired for the monitoring of hydraulic fracturing in the unconventional plays. Most service companies use either P/S arrival times or the stacking based method to locate the microseismic events. Current research of the microseismic community focuses on the location uncertainty and source mechanism inversion from surface and downhole measurements. Some researchers tried to derive mechanical information by further inversion of the microseismic moment tensor inversion results. It remains challenging to understand the connection between microseismic pattern and the stimulated reservoir volume. Furthermore, another challenge is the use of microseismic events to improve hydraulic fracturing design. Key questions include: Are the microseismic events caused by hydraulic fracturing or triggered by stress transfer (wet or dry)? Can microseismic events help determine where the proppants are distributed? Why do some shales have more microseismic events than others?

In this paper we try to use a refined interpretation of the mechanisms of microseismicity to answer these questions. Also we attempt to provide an insight to help understand the magnitude and event rate of microseismic events based on horizontal slip on bedding planes.

Horizontal slip mechanism

In Southwest PA the larger microseismic events produced overwhelming focal plane solutions with vertical/horizontal nodal planes (dip slip or horizontal slip due to the ambiguity of focal mechanism). A new mechanism proposed recently provides a bridge between microseismic monitoring and hydraulic fracturing. This mechanism for horizontal bedding slip has been proposed by several people at almost the same time. Published sources include Jim Rutledge (Rutledge et al., 2013) and Leo Eisner (Stanek and Eisner, 2013).

This mechanism states that the microseismic events happen as a result of the slip on bedding planes at the tip of vertical hydraulic fractures.

The criterion for producing horizontal slip during hydraulic fracturing

Using the interpretation of the mechanism mentioned above, we can establish the criterion for a hydraulic fracture driven microseismic event: In order to have bedding slip, hydraulic fracture opening must overcome friction and cohesion along the bedding. If the fracture overcomes the friction and cohesion of the bedding interface, it does not break through the layer above or below.

The criterion of whether a fracture will propagate through a frictional interface has been investigated by structural geologists (Cooke and Underwood, 2001; Renshaw and Pollard, 1995). We apply similar method to derive the criterion of microseismic bedding slip quantitatively (Figure 1):

$$\sigma_{xy} > \mu(\sigma_{yy} - p) + c_0 \qquad (1)$$

μ: friction coefficient; p: pore pressure; σ: in-situ stress near the crack tip; c_0 is the cohesion of the interface.

The magnitude range of microseismic event

The magnitude of this horizontal slip also makes sense. Using some simple numbers, we can do a quick calculation of the magnitude of the microseismic events caused by this mechanism (Figure 2). The seismic moment of a shear event is:

$$M=uDA \qquad (2)$$

Here M: moment, u: shear modulus; D: displacement of the slip; A: slip area.

Using reasonable range of numbers, we can get: u is between 0.5-2 GPa; D is about 2-20 mm; A is between 1-10 m^2. Using these calculations with the simple relationship between moment and magnitude, we get:

$$M_w=2/3(\log M-9.1) \qquad (3)$$

The range of this calculation is between -2 and -0.5, which is typical of the microseismic events observed during hydraulic fracturing.

On the other hand, if the microseismic magnitude exceeds 0, from the calculation above, we know that one of the parameters must have increased to a large number. However, even with the largest reasonable slip, we cannot have a microseismic event exceed M=1. Therefore, for the decision making of induced seismicity, M=1 should be a criterion for triggering the alarm of traffic light system.

Quiet vs. loud

People have observed different numbers of microseismic events per stage associated with hydraulic fracturing from different plays. Here we call shale with lots of microseismic events “loud” and vice versa “quiet”. For example, Eagle ford shale is known to be very loud. The microseismic monitoring is generally successful from either surface or downhole. With similar depth, microseismic monitoring in the Permian Basin has more challenges in finding microseismic events. Similar things happen at different regions of the same play. For example, based on a very limited dataset, the Marcellus play of the Southwest PA sweet spot shows many microseismic events whereas in Northeast sweet spot it does not. Despite successful production from both areas, microseismic responses look dramatically different.

We try to explain this difference using this horizontal slip mechanism model. Geologically, the difference between the two Marcellus regions is dramatic: in the SW region, Marcellus is only 100 ft thick while in the NE region it is over 300 ft thick. The carbonates (Tully, Cherry Valley, Onondaga) within and around Marcellus are known as a high stress fracture barrier.

Because there is relative low stress contrast between the shale layers in the Marcellus itself, the hydraulic fracture breaks through the formation vertically up or down with ease. If the hydraulic fracture tip does reach a carbonate or carbonaceous shale, it will cause significant horizontal slip. Magnitudes of these microseismic events increase.

Interpretation of hydraulic fracturing using microseismic event rate

Looking at the microseismic event rate within each frac stage, most of the events happen at two periods: at the breakdown or at the high sand concentration pumping time. Sometimes microseismic events keep popping up even after shut down. However, these phenomena are not observed in every dataset. Therefore we will not focus on post-shut in events.

The two periods of peak microseismic event rate are consistent with the opening of the hydraulic fracture. At breakdown, the fracture width increases from zero to a small number. During the pumping of high concentration sand, the fracture keeps widening if the previous width is not large enough to contain all the sand that is being pumped down.

This creates an interesting question: what is the response of microseismic event rate at different stress levels? At lower stress level, it is easier to open fractures with a significant width. Therefore, the majority of the microseismic events should happen during the breakdown stage. The placing of sand in these fractures should be easy because the crack volume is large enough. On the other hand, when the stress level in the rock is high, it is much harder to open the fracture. Even after breakdown, with a similar amount of pressure, the width of the fracture is much smaller than the fracture opened under lower stress level. Therefore, not many microseismic events will be induced at this period. However, during the pumping of high concentration sand, the higher sand volume will force the walls of the hydraulic fractures move. During this stage, a lot of microseismic events will be generated.

In most cases, if the stress is neither too high nor too low, we should see two peaks of microseismic event rates. The first event peak corresponds to the initial opening of the hydraulic fracture. This will tell us where is fluid is. The second peak corresponds to the second widening of the hydraulic fracture. This will tell us where the proppants are.

Conclusion

1. The horizontal slip mechanism explains most the microseismic events observed during hydraulic fracturing.
2. The criterion for horizontal slip events is established

3. Using the horizontal slip mechanism, we can explain the magnitude range, quiet vs loud shale and the event timing during one hydraulic fracturing stage.

References

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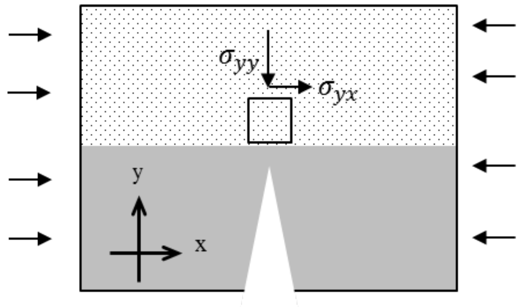

Figure 1. Illustration of the stress state near the fracture tip (modified from Renshaw and Pollard 1995).

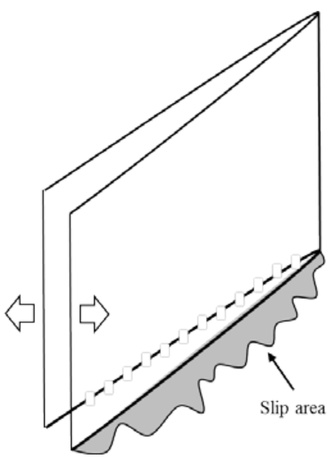

Figure 2. Illustration of the horizontal slip at the interface as a result of the widening of the hydraulic fracture.