Measurements and Observations of Fractured Height Growth

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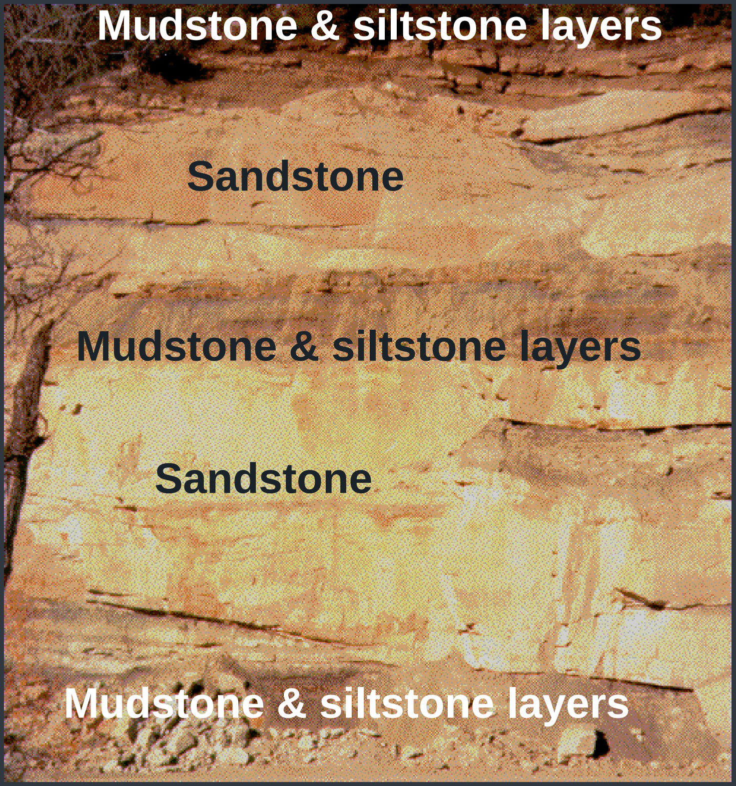
Fracture height growth in sedimentary rocks

- Clear understanding from minebacks, cores, lab tests, diagnostics, and numerical studies
  - Layered sedimentary sequences restrict vertical fracture growth
    - Reduced width in high stress & high modulus layers
    - Inefficient fracture growth vertically across layers and interfaces

Example Mesaverde section: sandstones interbedded with mudstones and stiltstones



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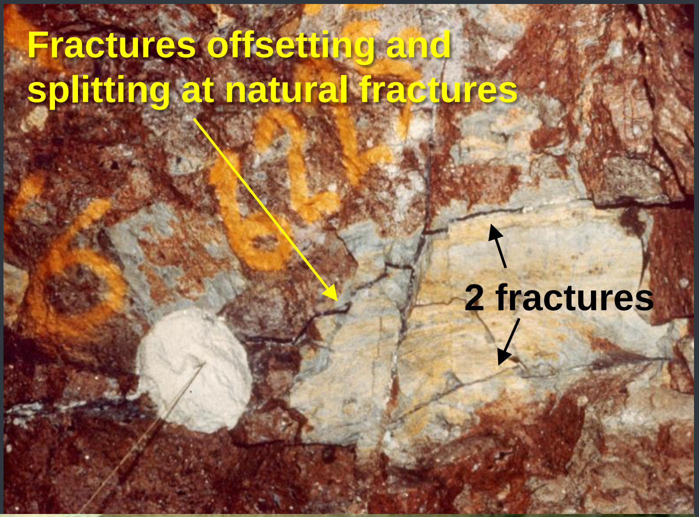
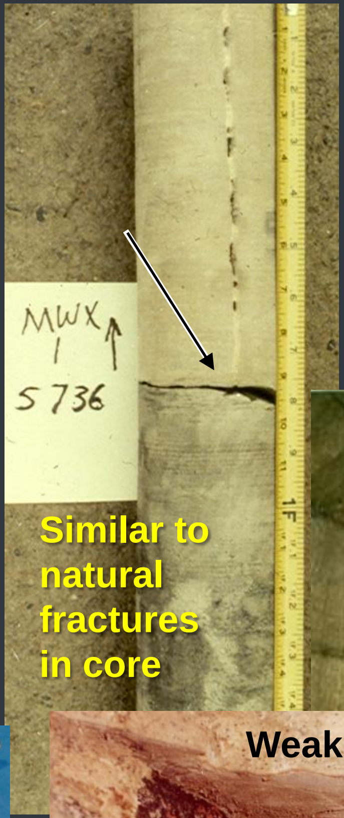
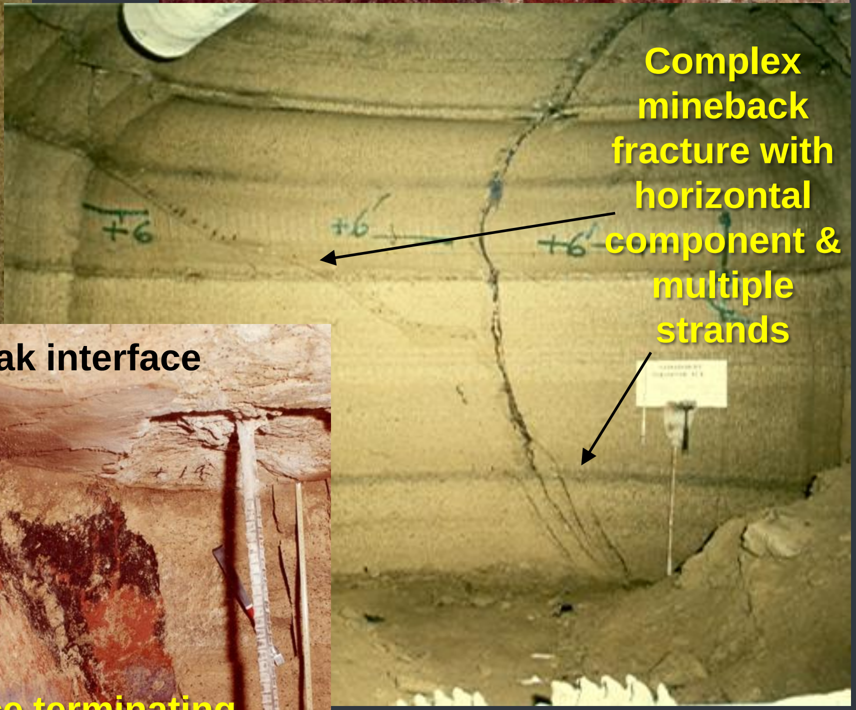
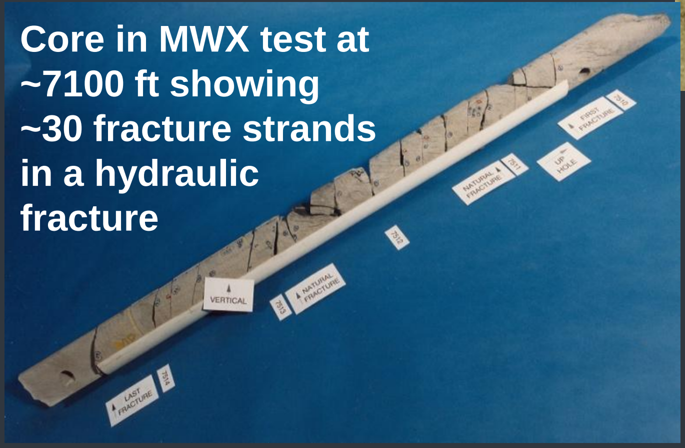
Observations: Minebacks & Core

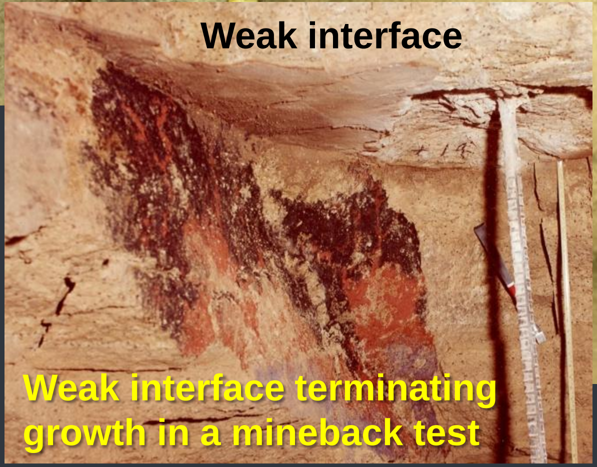
- DOE hydraulic fracture mineback experiments at the Nevada Test Site
  - Government funded research into hydraulic fracture behavior
- Cored fractures from the DOE Multiwell experiment & DOE/GRI M-Site
- Mineback tests in coal





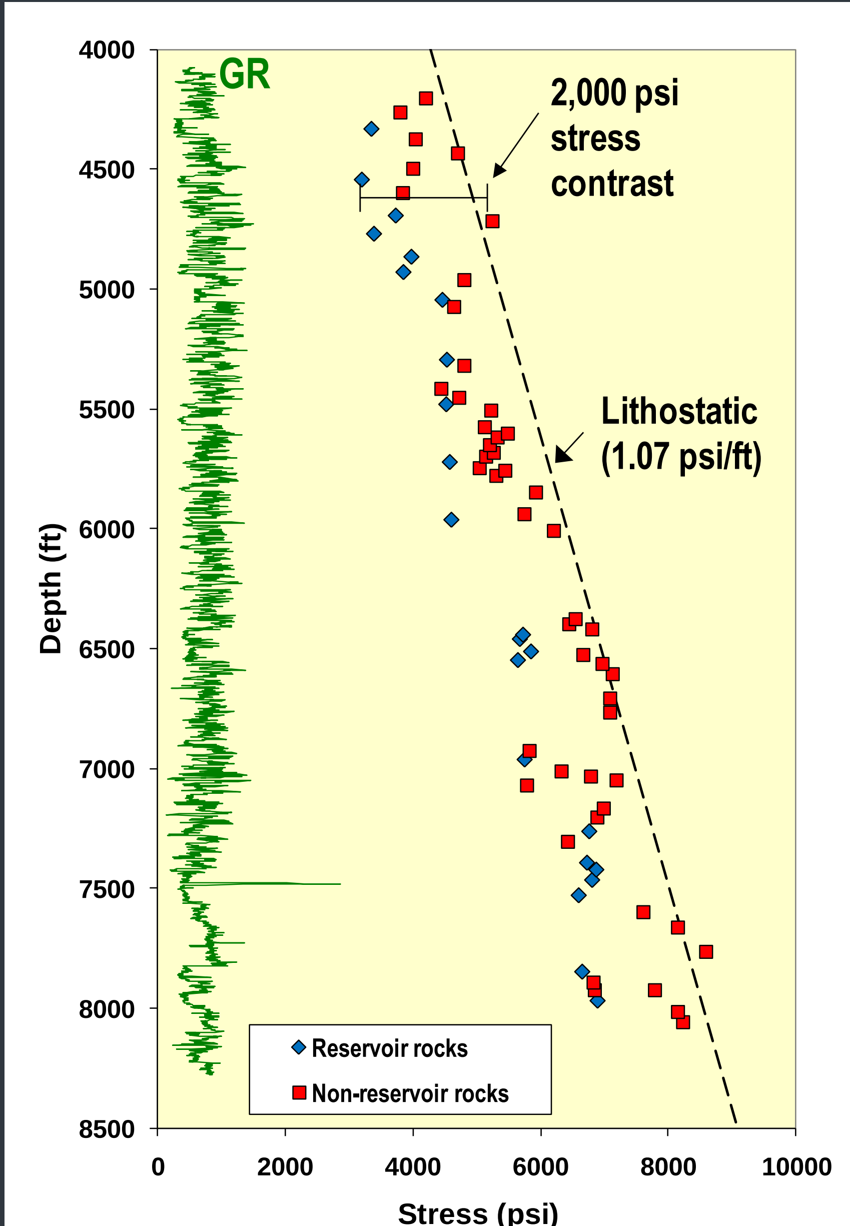






Stress contrasts

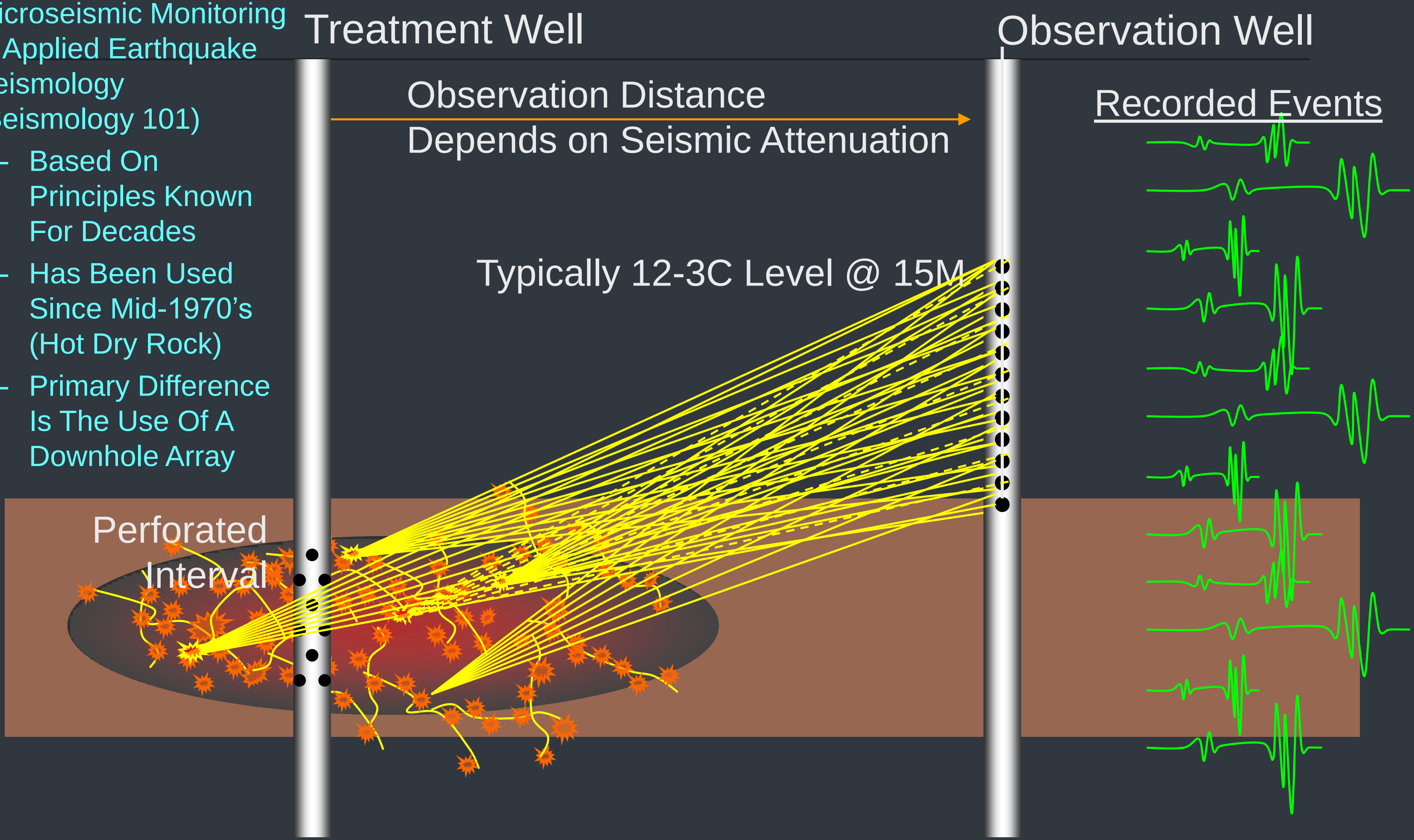
- Stress profile measured at DOE MWX test
  - Most comprehensive anywhere
    - Large variations in stress from layer to layer
    - Correlates well with lithology
- Stress contrasts restrict vertical growth
  - High stress may terminate fracture
  - Low stress zones "trap" fracture – extensive lateral growth



Source: DOE Multiwell experiment & DOE/GRI M-Site test

Offset -Well Microseismic Mapping

- Microseismic Monitoring Is Applied Earthquake Seismology (Seismology 101)
  - Based On Principles Known For Decades
  - Has Been Used Since Mid-1970's (Hot Dry Rock)
  - Primary Difference Is The Use Of A Downhole Array



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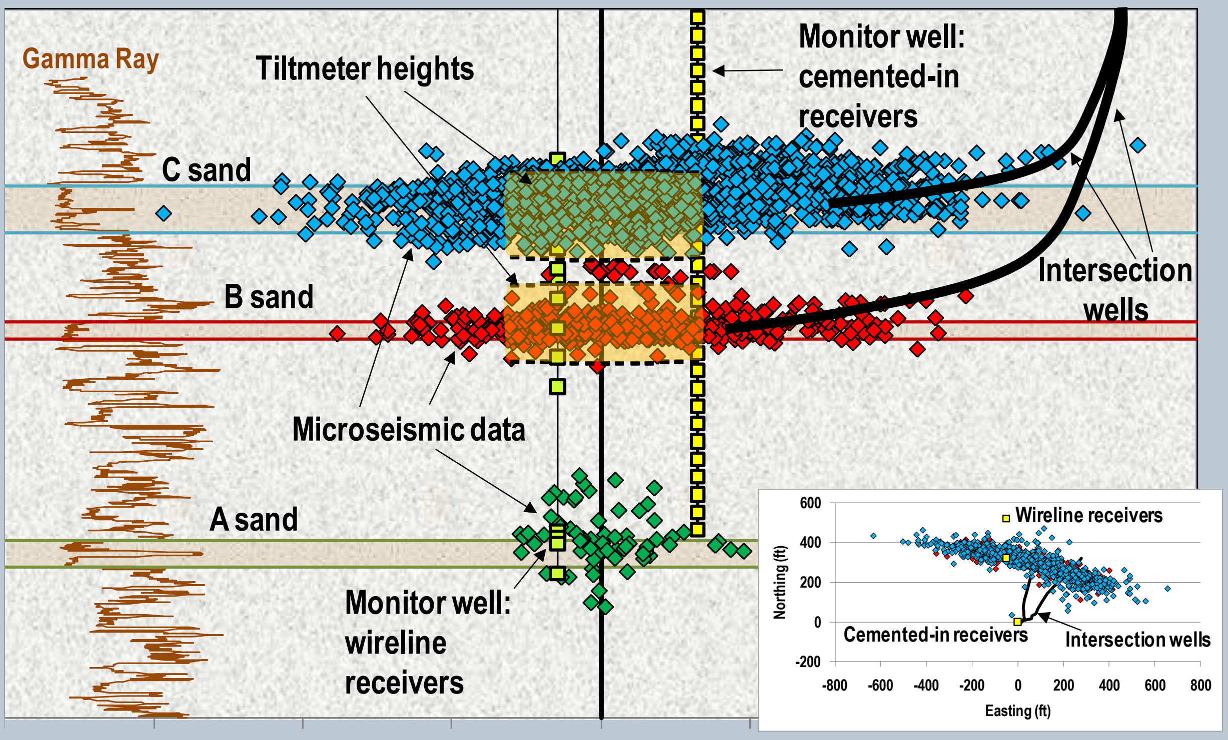
Microseismic validation: DOE/GRI M-Site

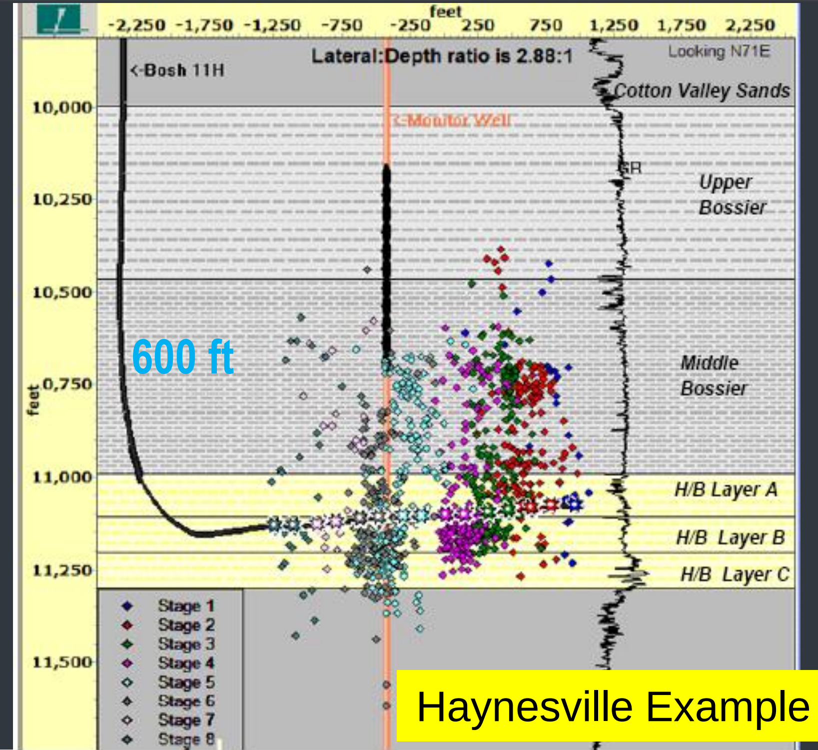
- M-Site diagnostics laboratory: validation of microseismic data using tiltmeters and intersection wells
- Azimuth
  - Wellbores
- Height
  - Tiltmeters
- Length
  - Wellbores

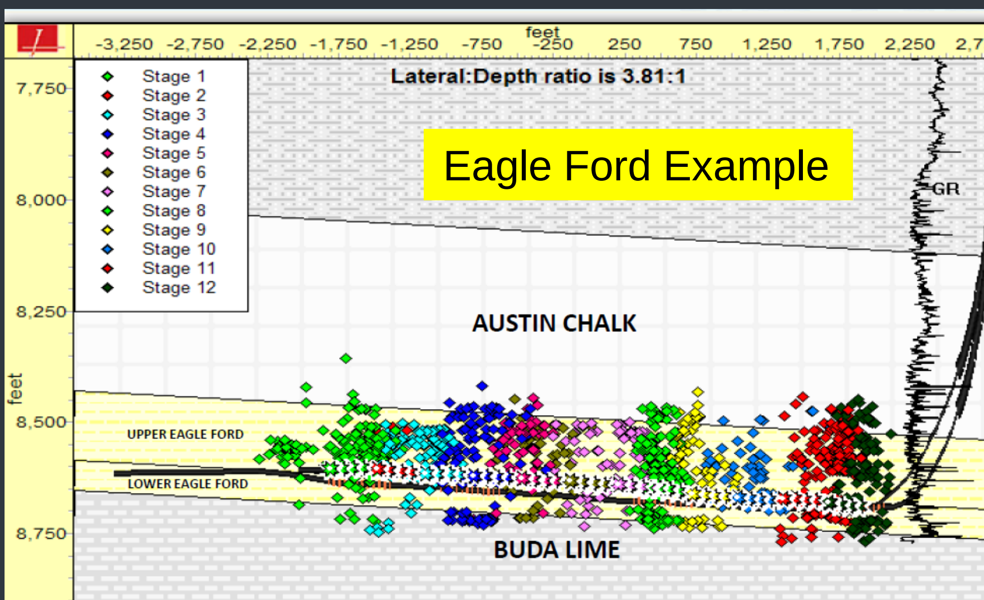


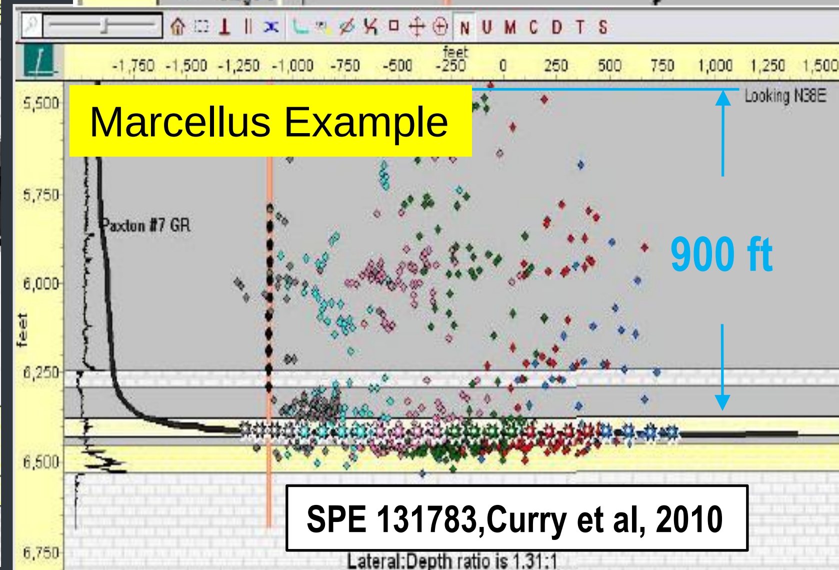
Source: DOE/GRI M-Site test

Fracture height growth

- Microseismic examples that show the extent of height growth in various formations
  - Haynesville
  - Marcellus
  - Eagle Ford







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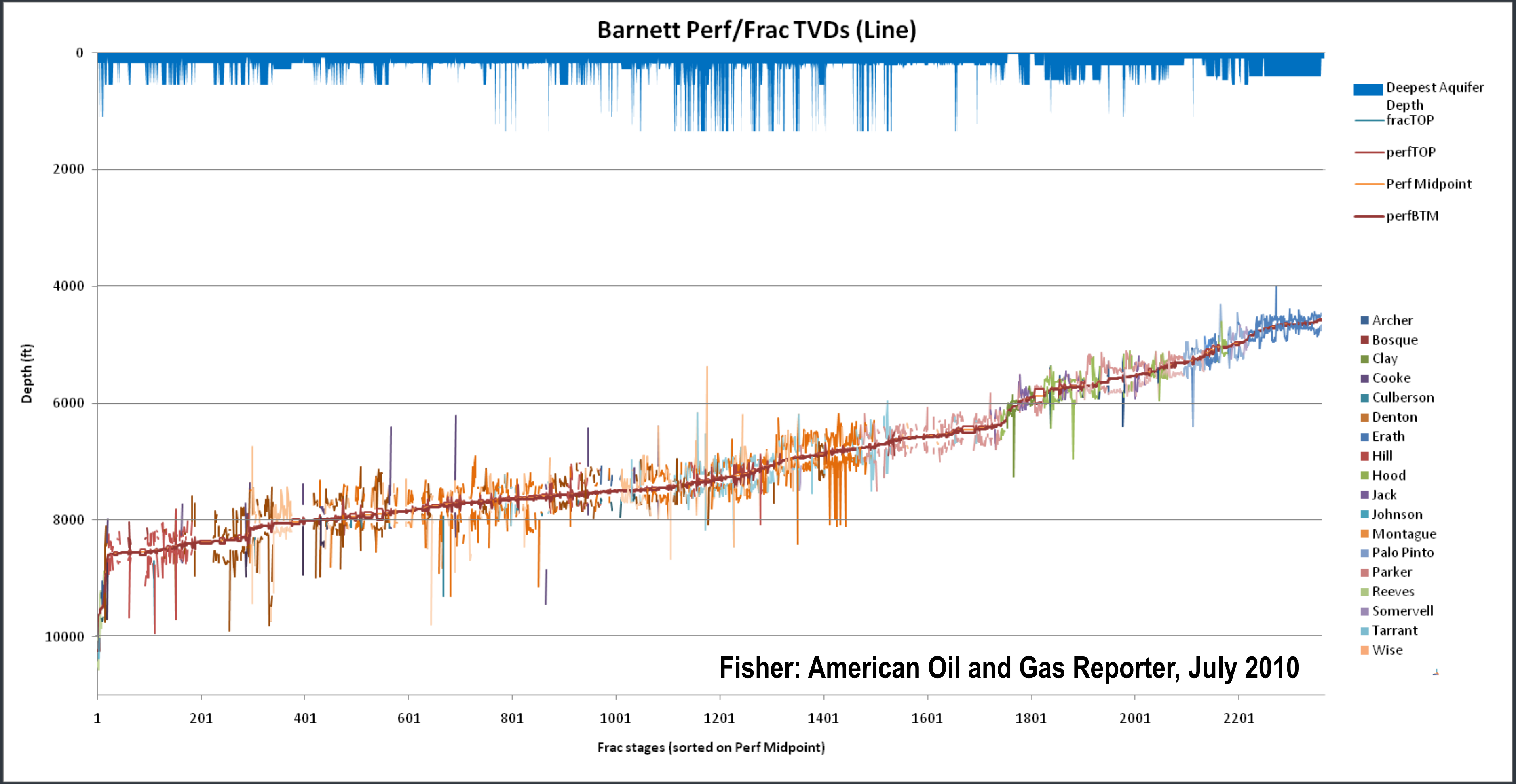
Mapped microseismic height for Barnett shale

- Top: shallowest microseism; Bottom: deepest microseism
- Aquifers: USGS deepest water wells by county



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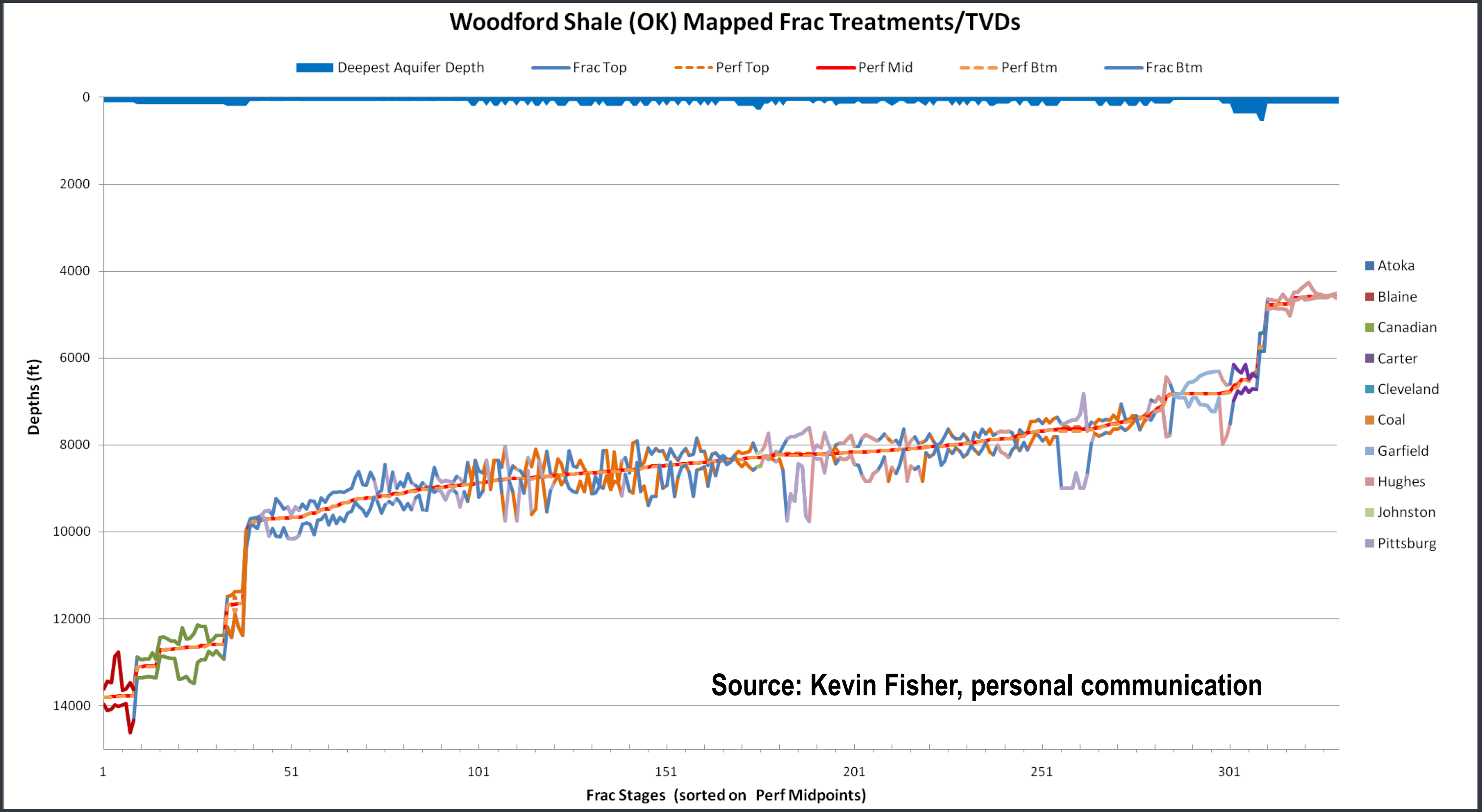
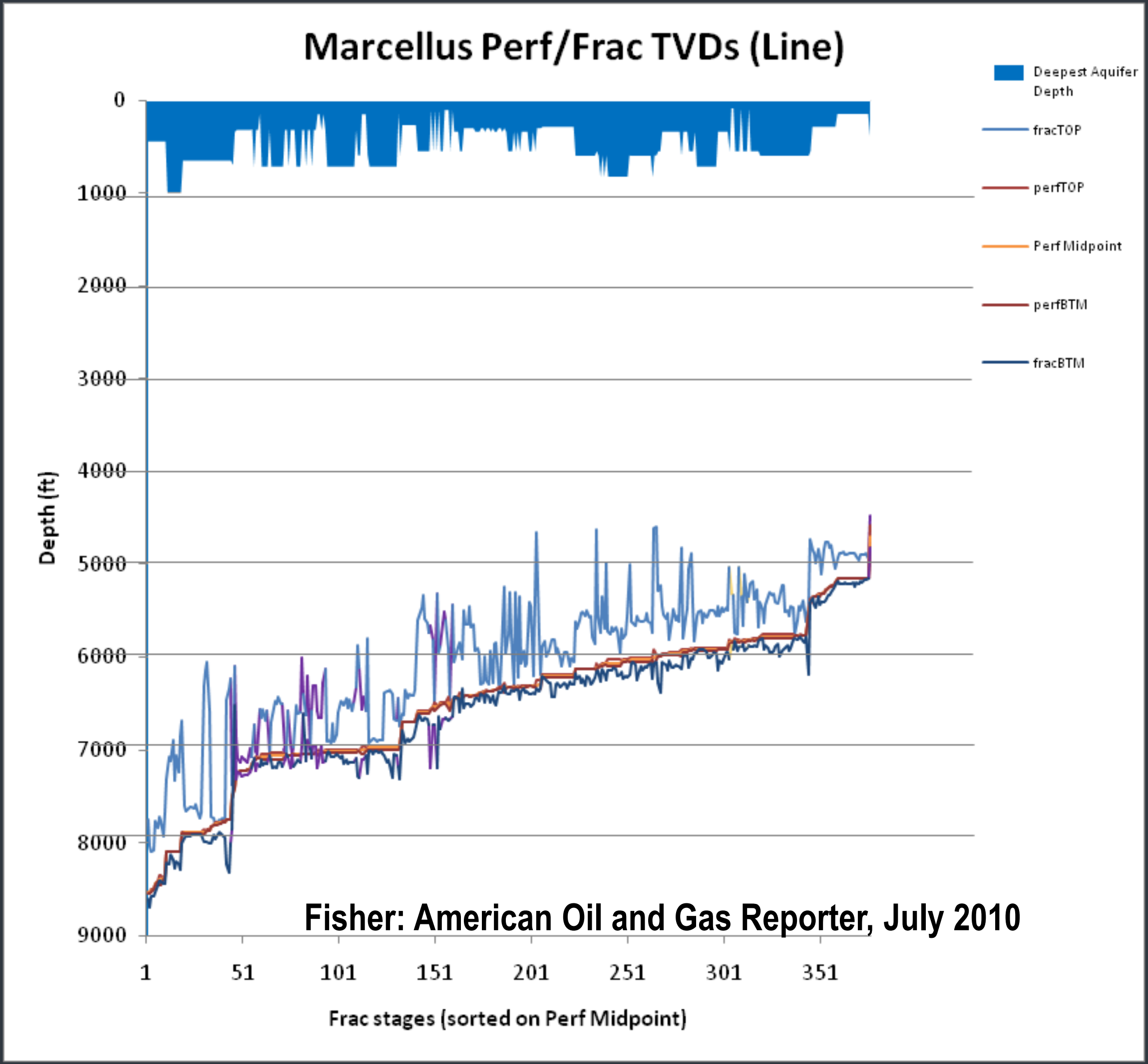
Mapped microseismic height for Woodford shale

- Top: shallowest microseism; Bottom: deepest microseism
- Aquifers: USGS deepest water wells by county



Mapped microseismic height for Marcellus shale

- Top: shallowest microseism
- Bottom: deepest microseism
- Aquifers: USGS deepest water wells by county
- Marcellus
  - Fractures far from mapped aquifers



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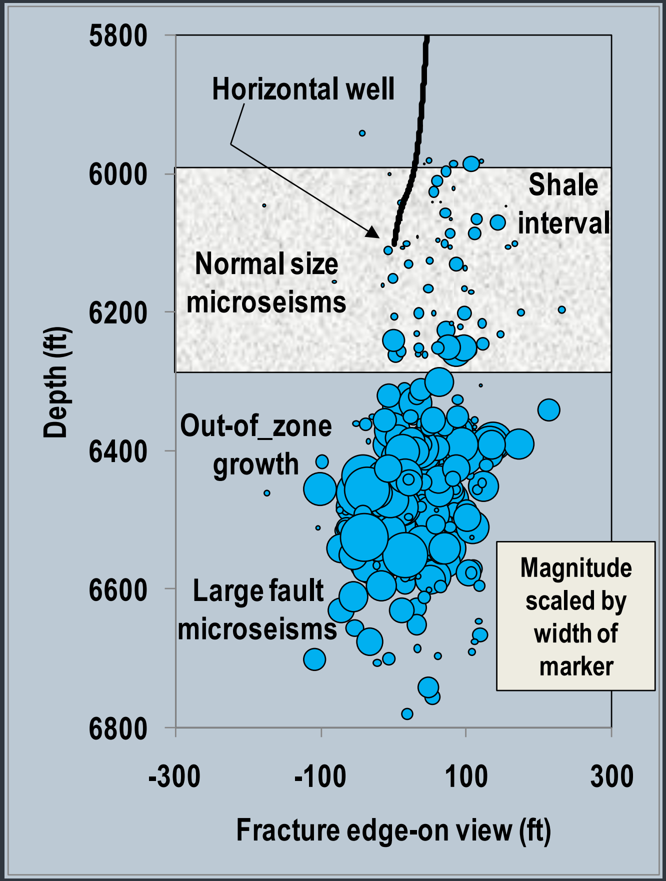
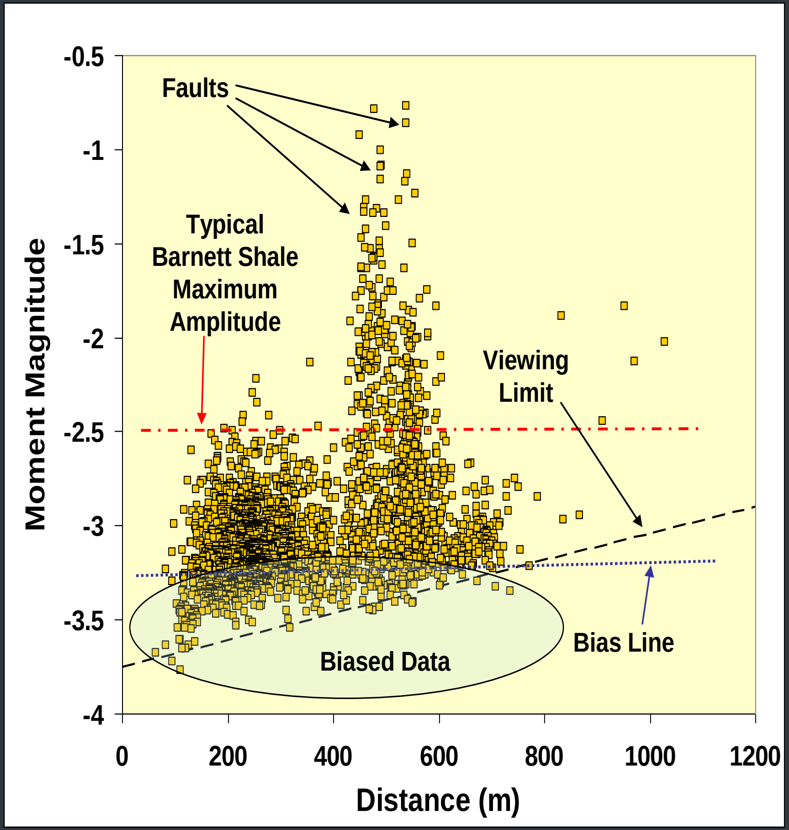
Intersection with faults

- Microseismicity is an excellent tool to monitor what happens when a fault is intersected by a hydraulic fracture





The magnitude-distance plot shown above is an important diagnostic tool for assessing data results, effects of noise, bias, and viewability. It is also useful for determining whether fault interactions have occurred.

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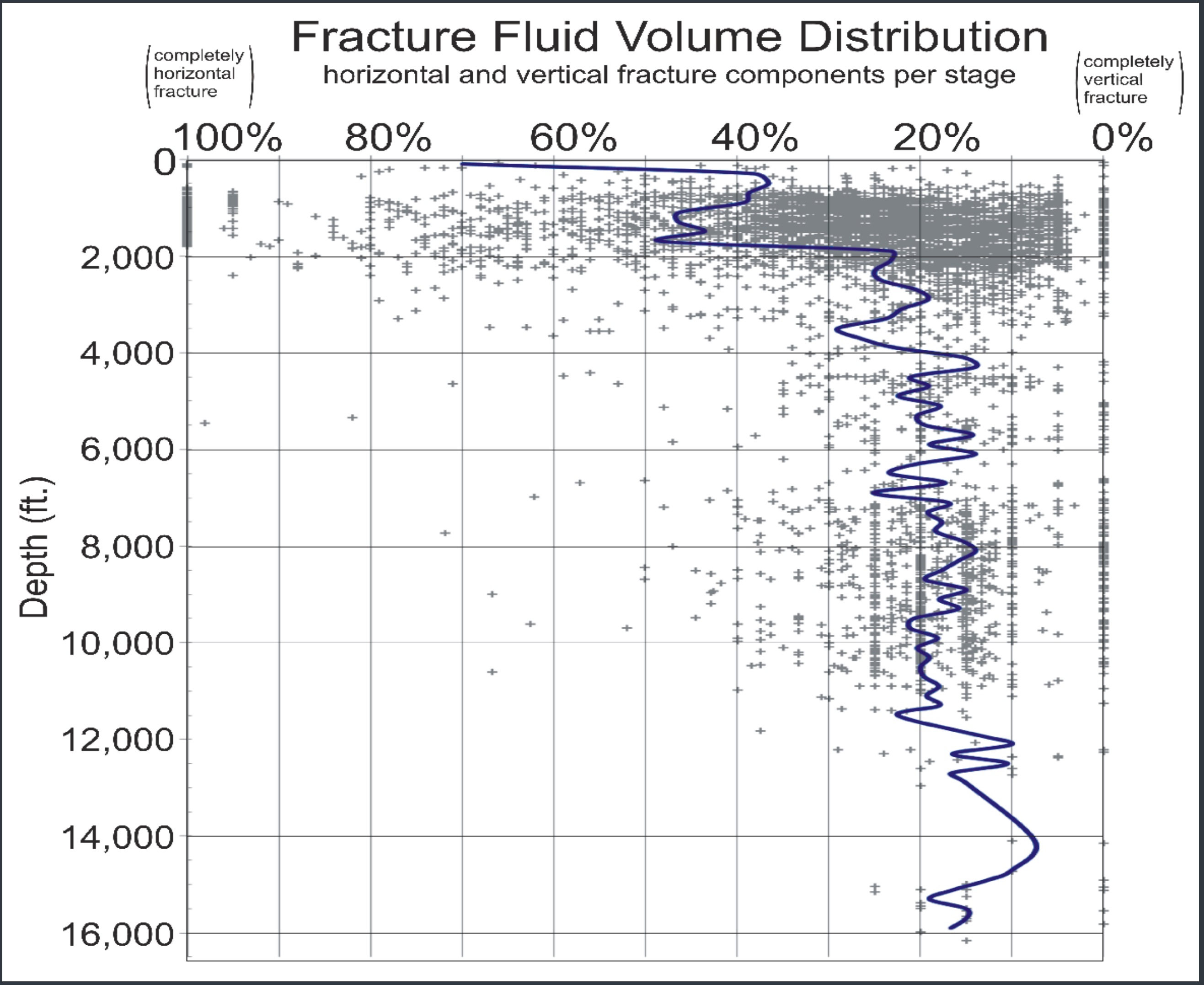
Tiltmeter Fracture Component Breakout versus Depth

- Tiltmeters readily identify fracture components
  - Horizontal
  - Vertical
  - Dipping
  - Combined
- Rapid increase in horizontal components at shallow depths preclude vertical growth



Source: Kevin Fisher, personal communication

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Summary

- Data from thousands of fractures show:
  - No extensive growth vertically
  - Increase in horizontal components at shallower depth (little vertical growth)
- Sedimentary features restrict vertical fracture growth
  - Very inefficient growth across layers
    - Alternating properties and stress
    - Interfacial properties

Measurements and Observations of Fracture Height Growth

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Hydraulic fracturing is a process that is necessary for economic extraction of natural gas and oil from unconventional resources such as tight gas sands and gas shales. It is a process that is well understood in its overall behavior and development, but is difficult to quantify in many of the details because of both geologic and mechanistic uncertainty. For example, fine details of the layering are impossible to resolve using the borehole tools available today, and features between wells are difficult, if not impossible, to distinguish unless their scale is extremely large. The mechanistic uncertainty follows from the poor description of the reservoir and the geologic features within, but also from the computational difficulties associated with a complex interaction problem in a heterogeneous material.

Nevertheless, thousands of papers have been written in the petroleum literature to study hydraulic fracturing, and these have provided a wealth of understanding about the behavior of fractures in different environments. These papers have provided field evidence, mineback and coring evidence, laboratory testing, analytical models, numerical models, and a host of other results that have guided the understanding, development and optimization of the fracturing process. What we may be missing in the fine details can be accounted for in overall generalized findings about the fracturing process.

Geology, Geology, Geology

It should be obvious from the literature that we only have a limited ability to direct fracture growth; Mother Nature does not let go easily. The best example is fracture azimuth (the direction a fracture propagates), which is dictated by the in situ stress that exists at the hydraulic fracture location and is very difficult to alter. Fractures will propagate in the same direction all across a field. A second general finding is that the layered earth sequence makes vertical fracture height growth difficult, thus generally promoting the growth of length over height. Height growth is inefficient due to the variable layer properties, the large number of interfaces, the rapidly varying stress that can

Figure 12. Mineback photograph of complex fracture

occur vertically, and the potential for a large number of energy-dissipative mechanisms that can occur in such an environment.

Figure 12, for example, shows a mineback photograph of a hydraulic fracture that has very complex behavior that is largely due to geologic factors, such as the stress state at this location and the interfacial properties. Fractures are not single planar features that extend long distances; they are a series of interconnected fracture segments that have many internal terminations and interactions with the local geologic conditions (Warpinski and Teufel 1987).

Figure 13 shows a second example of the complexity that can occur as hydraulic fractures intersect natural fractures and other geologic discontinuities (e.g., interfaces). There are many offsets and some splits that occur as part of this interaction process, the details of which are largely driven by the local stress state and the material properties in conjunction with the treatment conditions. In many instances, natural fractures, faults, and interfaces have been observed to terminate fracture growth, thus providing a complete containment feature.

Figure 13. Mineback photograph of offsets & splitting.

The in situ stress has a dominant role in all of these processes, but also directly affects vertical hydraulic fracture growth. Fractures are impeded from growing vertically by higher stress layers. This might appear to be an unusual case because stresses decrease as the depth becomes shallower, but measurements have shown that large stress contrasts exist in sedimentary basins at all depths.

Figure 14 shows an example of the results from a stress measurement program at the DOE funded multi-well experiment in the Mesaverde formation located in the Piceance basin (e.g., Warpinski and Teufel 1989). The stress measurements made in reservoir rocks (sandstones) are shown in blue, whereas the non reservoir shales, mudstones, and siltstones are shown in red. The stress contrasts are

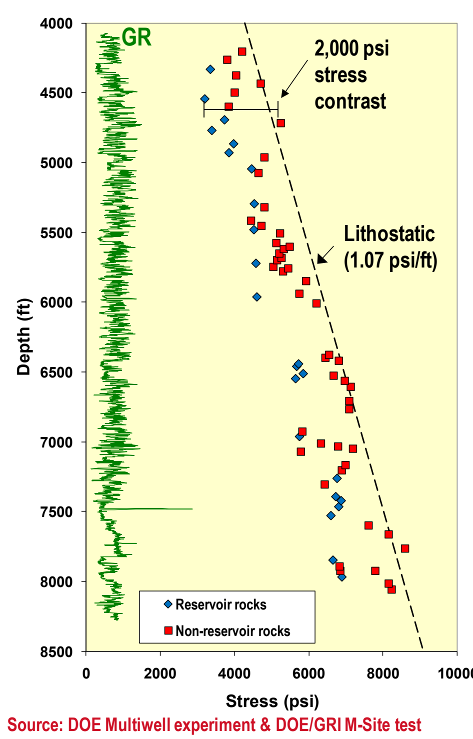

Figure 14. Measured stress profile in Mesaverde.

often in the range of 1,000 – 2,000 psi. While the overall trend is one of decreasing stress with shallower depth, the large variations make it unlikely that fractures would grow very far across such a section. Fractures that grow out of zone and propagate vertically upward would quickly hit another low stress layer and tend to grow laterally in it. Should the pressure overcome the next higher stress layer above it, then the fracture would grow and again hit a lower stress layer, and also result in preferential lateral growth. Repeated crossing of these layers is an inefficient process that soon uses up the fluid and energy.

All of these processes and mechanisms have been verified in laboratory testing and modeling. We now have the laboratory equipment to study layered and fracture rocks and the computational tools to study fracture behavior in a discontinuous medium. As noted above, the exact details may be difficult to determine because of the poor understanding of the geologic details, but the overall behavior is very clear.

Diagnostics Tell the Story

While all of the mechanisms discussed above provide the understanding of what is occurring as fractures propagate, it is the advent of far-field diagnostic technologies that have given us a full picture of the propensity of fractures to propagate laterally. Although tiltmeter deformation measurements have been applied more often and longer, it is microseismic technology that has been the most revealing.

Microseisms are small earth movements that occur in the vicinity of a hydraulic fracture due to inflation of that fracture and leakoff of high pressure fluid into the formation. These two mechanisms cause changes in both stress and pressure that can induce complex shear slippage processes. These microseisms emit seismic energy that can be detected at receiver arrays located in adjacent wells, and the waveform data, in conjunction with a velocity model, can be processed to extract microseismic locations. The sum of these locations yields a map of where the activity is occurring which describes the fracture.

One common question is that of validation. How can we be sure that the microseismic data is representative of the true fracture behavior? The answer to that question is in the results from several validation experiments, the most extensive of which was the DOE/GRI funded M-Site test in Colorado. (Warpinski et al. 1998) Figure 15 shows a side view representation of the testing results from M-Site, in which several approaches were taken to verify the microseismic data. There were two monitor wells with seismic receivers to capture microseismicity, but there were also tiltmeters cemented in place in one of the wells to measure the earth deformation and compare the mechanical behavior with the microseismic behavior to verify fracture height. In addition, intersection wells were drilled to verify fracture azimuth and examine the fractures in core or with imaging logs, but one of those intersection wells was drilled prior to fracturing and instrumented with pressure gages. During fracturing, the time at which the hydraulic fracture intercepted this well could be determined by an observed increase in pressure, thus providing a fracture length at that time which could be compared to the microseismic length. All parameters – length, height, and azimuth – exhibited close agreement between the microseismic results and the verification technologies.

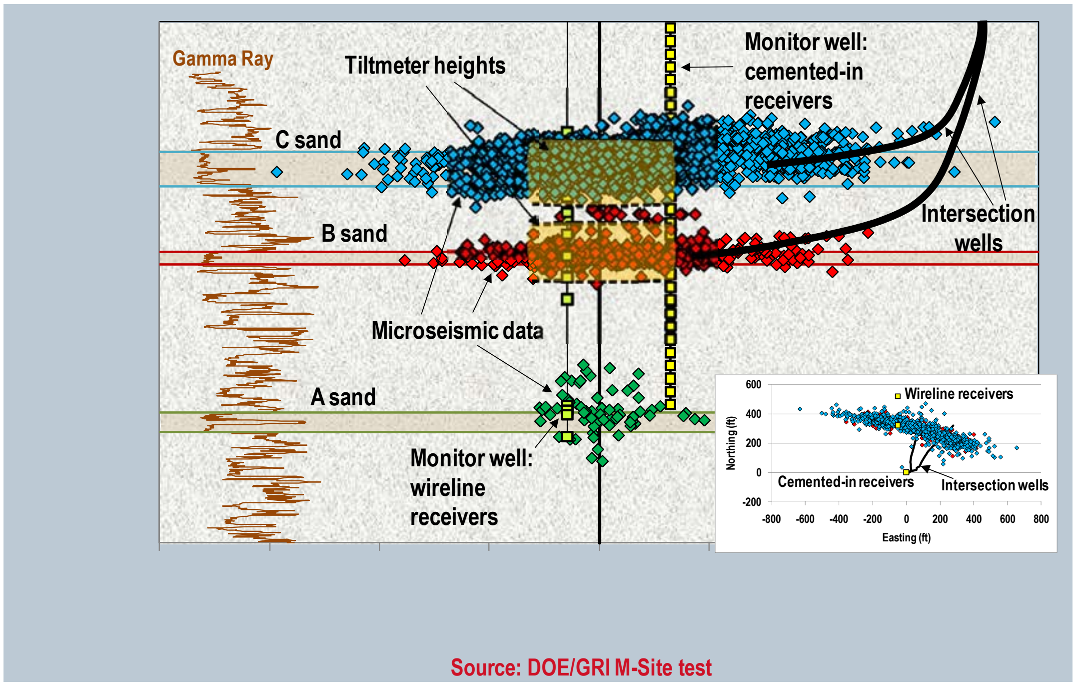

Figure 15. Overview of DOE/GRI M-Site hydraulic fracture diagnostics field test site.

While only a very limited number of industrial fracture monitoring projects have been published, there are many thousands that have already been done and these provide a comprehensive record of the behavior of fractures in these sedimentary environments. Figure 16 shows a case of a Haynesville shale fracture (Pope et al. 2009) where there is some extensive height growth – on the order of 600 ft. This degree of height growth does occur in some of these deep shale reservoirs and the monitoring provides information that can be used to optimize the process as much as is possible. Any amount of height growth out of zone is undesirable because it wastes fluid, horsepower, chemicals, and time. The point of hydraulic fracturing is to stimulate the reservoir, not the unproductive rocks around it. Monitoring provides information that can be used to figure out ways to minimize this behavior.

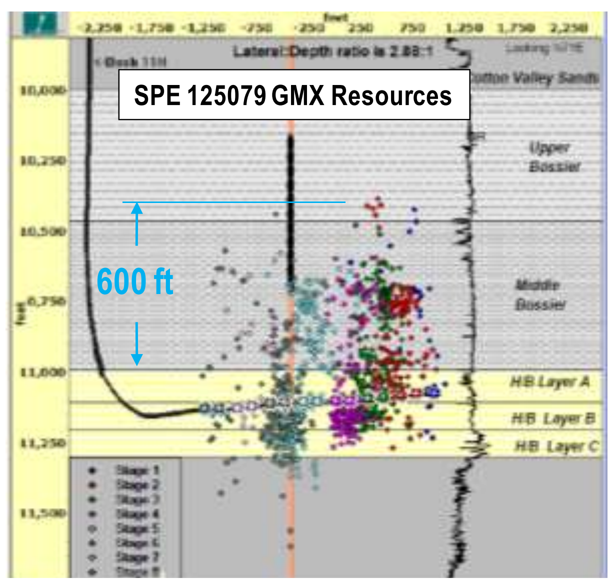

Figure 16. Example Haynesville shale microseismic data.

Since one monitoring test proves nothing and one can always use the best examples, a more compelling result can be demonstrated by showing all of the fracturing results in a basin in a correlated plot. Figure 17 shows the results of nearly 2400 fractures in the Barnett shale prior to mid-2010 – everything that was monitored up to that time (Fisher 2010). The plot has been sorted by depth, with deeper wells on the left. The perforation depth is shown, along with the top and bottom of the hydraulic fracture as measured by the microseismicity. Although difficult to see and read, the data are also colored by county. In addition to the fracturing results, the deepest water well in each county, as obtained from the USGS web site, is also plotted at the top.

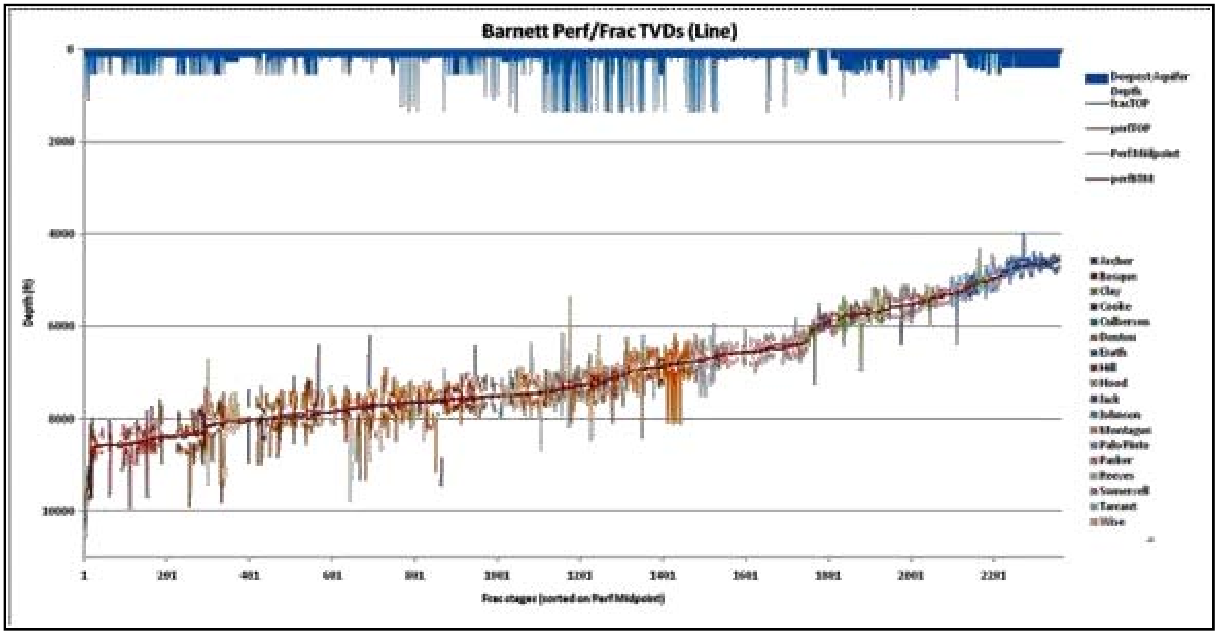

Figure 17. A compendium of microseismic fracture diagnostic results in the Barnett shale relative to known aquifers.

These results show that fracturing does not intrude on the aquifers. There is a limit to how much a fracture can grow vertically, even in the most advantageous conditions. There is considerable variability in fracture height in this plot, with much of it due to intersections of faults. However, even the most extreme cases do not extend vertically anywhere close to the aquifers. Similar results have been compiled for the Woodford and the Marcellus shale and those plots look similar.

The fractures that have been compiled in Figure 17 are for relatively deep injections, but there are many reservoirs that are much shallower. One might expect that fracturing to surface would be common in shallow reservoirs, but Mother Nature again conspires against vertical fracture growth by reversing the stress field at shallow depths. Hydraulic fractures at depths greater than ~2,000 ft are mostly vertical, but at depths less than ~1,500 ft, they are either horizontal or mostly horizontal (a vertical component in some layers) due to the overburden stress being generally greater than the horizontal stresses at shallow depths. There is a wealth of tiltmeter data on ~10,000 fractures that details how fractures have primarily vertical components at depth, but have a larger percentage of the fracture growing horizontally in shallow environments.

Summary

There are over seventy years of experience in conducting hydraulic fractures, a multitude of fracture models, thousands of petroleum engineering papers on the subject, many years of studying fractures using minebacks, corethroughs, laboratory experimentation and numerical analysis, and most recently the application of fracture diagnostic measurements in thousands of projects across North America. All of this knowledge and information has provided a sound understanding of the basic principles and general behavior of hydraulic fracturing.

Vertical propagation of a hydraulic fracture across layers is very inefficient and it is difficult to obtain extensive vertical growth. Fracture heights of several hundred feet are common, and they may occasionally exceed 1,000 ft in a few deep reservoirs. However, there has never been an observed case of a hydraulic fracture propagating thousands of feet vertically to intersect an aquifer. In shale projects where large fluid volumes are injected, the thousands of diagnostic measurements have consistently shown that fractures remain thousands of feet deeper than the aquifers.

Fractures do occasionally intersect faults, but the diagnostic information shows that vertical growth is also limited when this occurs. Some of the largest measured heights occur in cases where a fault has been intersected, but growth is equally likely to be downward as upward and it is typically only about twice the height of a normal fracture.

Shallow hydraulic fractures are not observed to grow vertically because of the changing stress state. Less than about 1500 ft, the overburden stress is the least principal stress and this causes fractures to be primarily horizontal at shallow depths. Some vertical components may occur, but they are typically very limited.

References

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