Fracture Growth in Layered and Discontinuous Media

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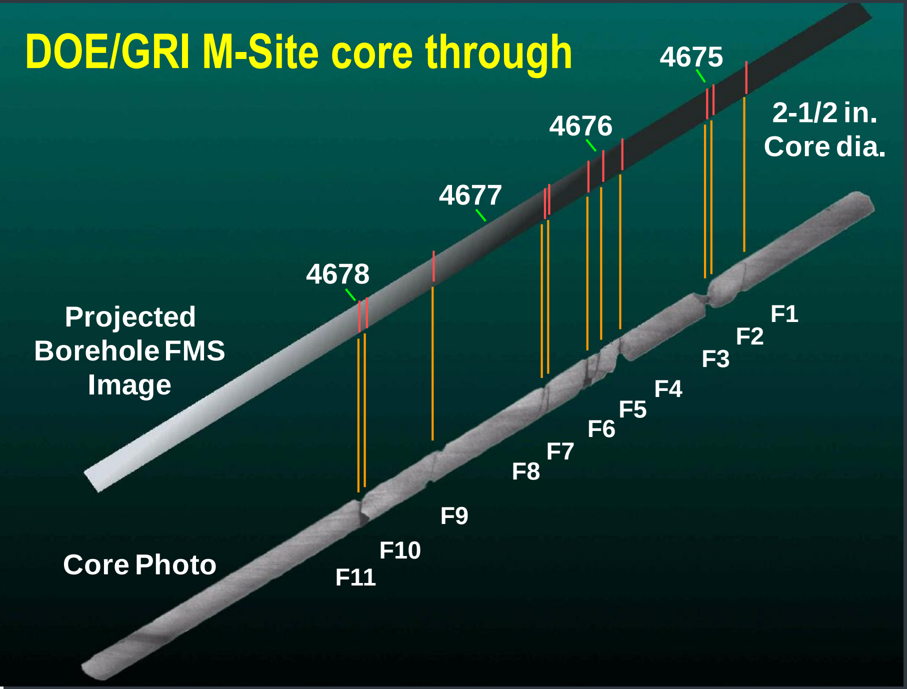
Norm Warpinski

Fracture growth in complex media

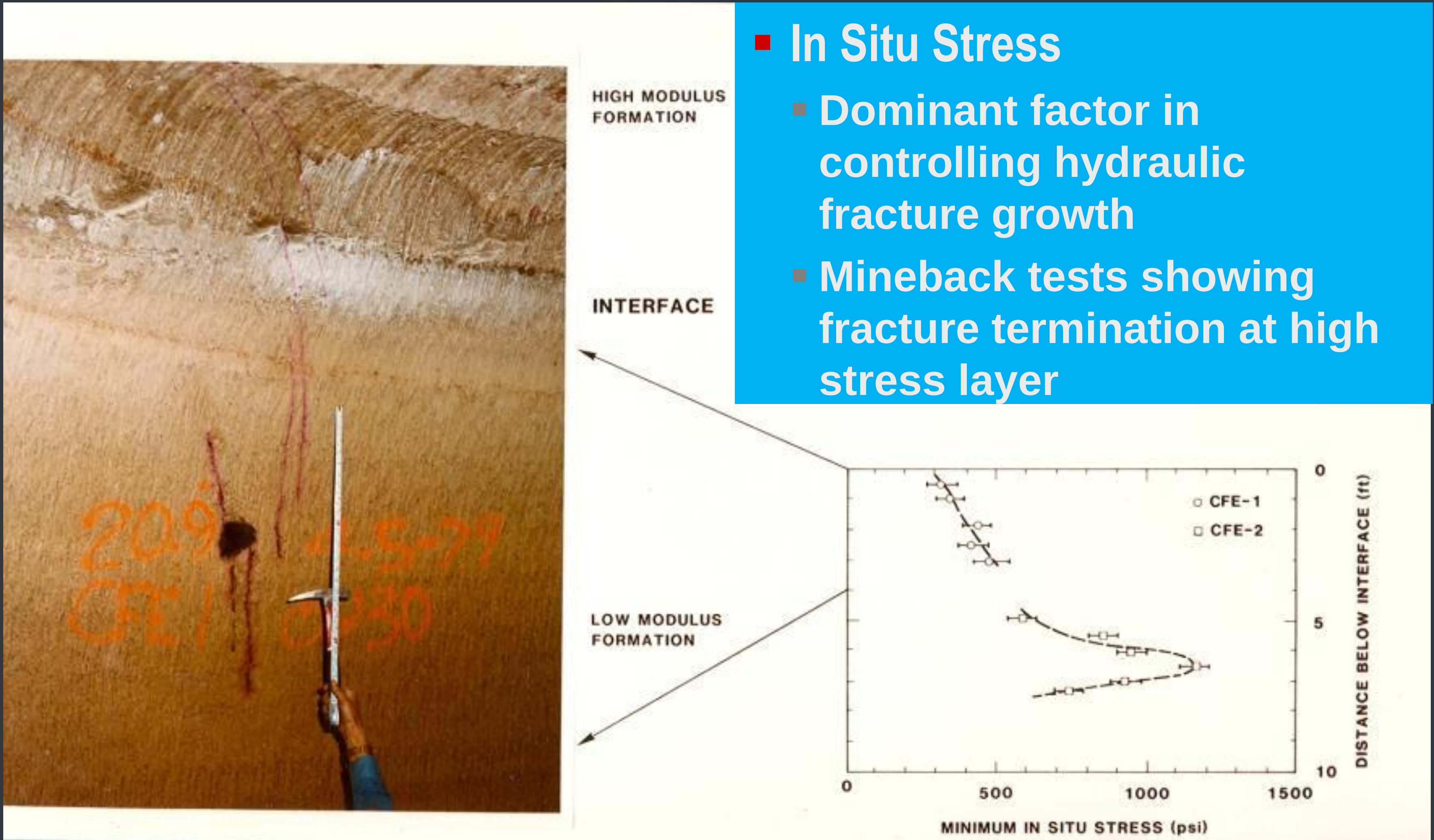
- Extensive research into affects of important parameters
  - In situ stresses
  - Material properties
  - Interfaces
  - Layering
  - Fracture toughness
  - Heterogeneities


DOE/GRI M-Site core through

Mounds Drill Cuttings Injection Experiment

Hydraulic Fracture Growth

DOE Mineback results showing effects of in situ stress contrasts



- In Situ Stress
  - Dominant factor in controlling hydraulic fracture growth
  - Mineback tests showing fracture termination at high stress layer

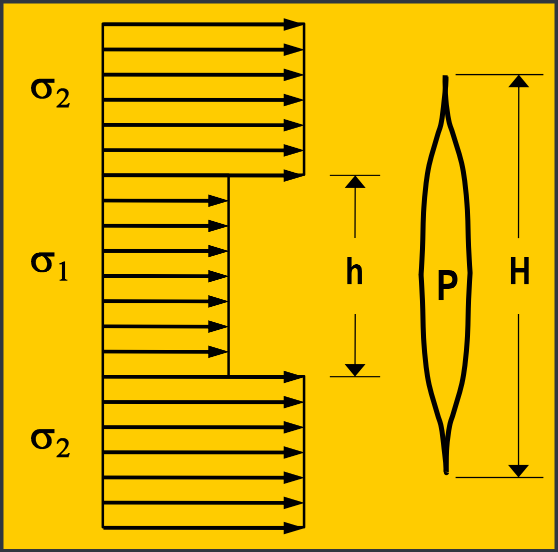
Fracture Height Growth

- In situ stress
- Example equilibrium calculation
  - Requires:
    - Stress
    - Pressure
    - Fracture toughness

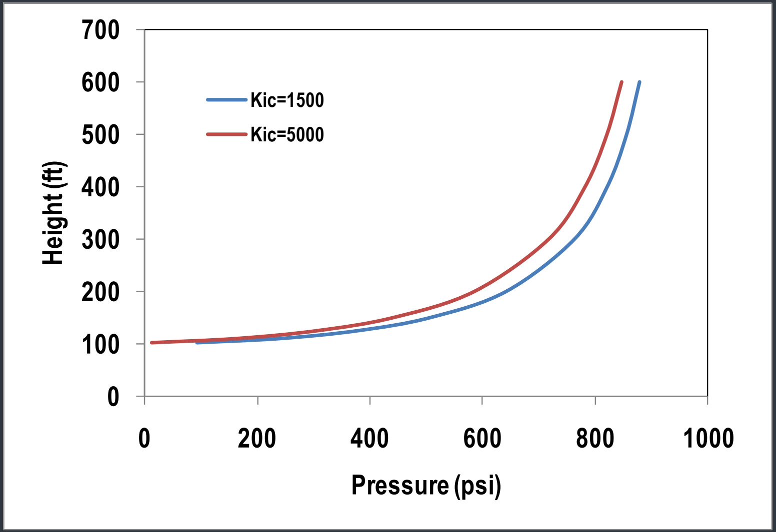
$$\sigma_2 - P = \frac{2}{\pi}\left[\sigma_2 - \sigma_1\right]\sin^{-1}\left(\frac{h}{H}\right) - \frac{K_{Ic}}{\sqrt{\pi H/2}}$$

Simonson et al., SPE, 1978

- In general, more complex equations are used
  - Modulus
  - Layers

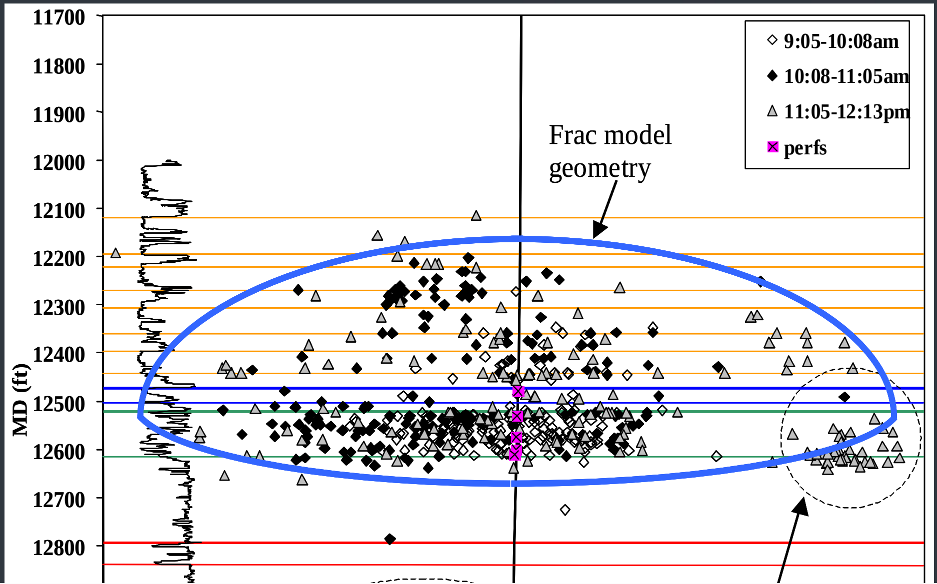


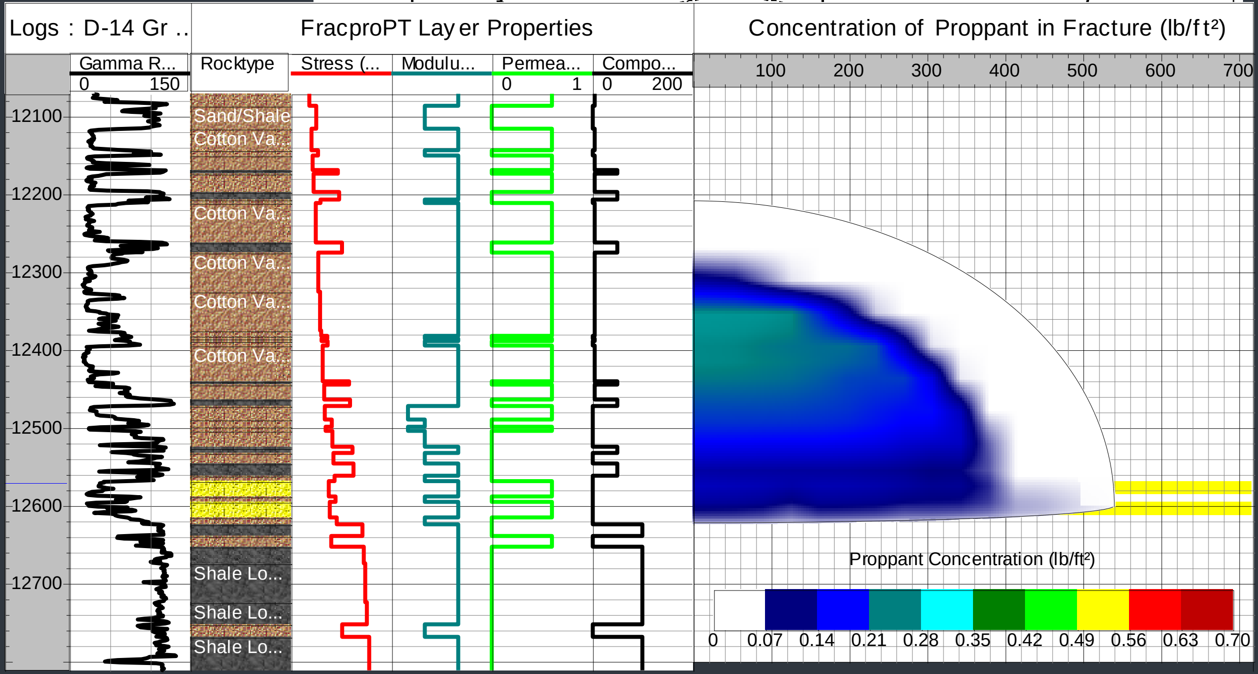
σ_1 – stress in reservoir
σ_2 – stress in bounding layers
P – pressure in fracture
H – fracture height



Modeling fracture growth

- Calibrated models using diagnostics
  - Verify data and behavior
  - Example in the Bossier sandstone in East Texas





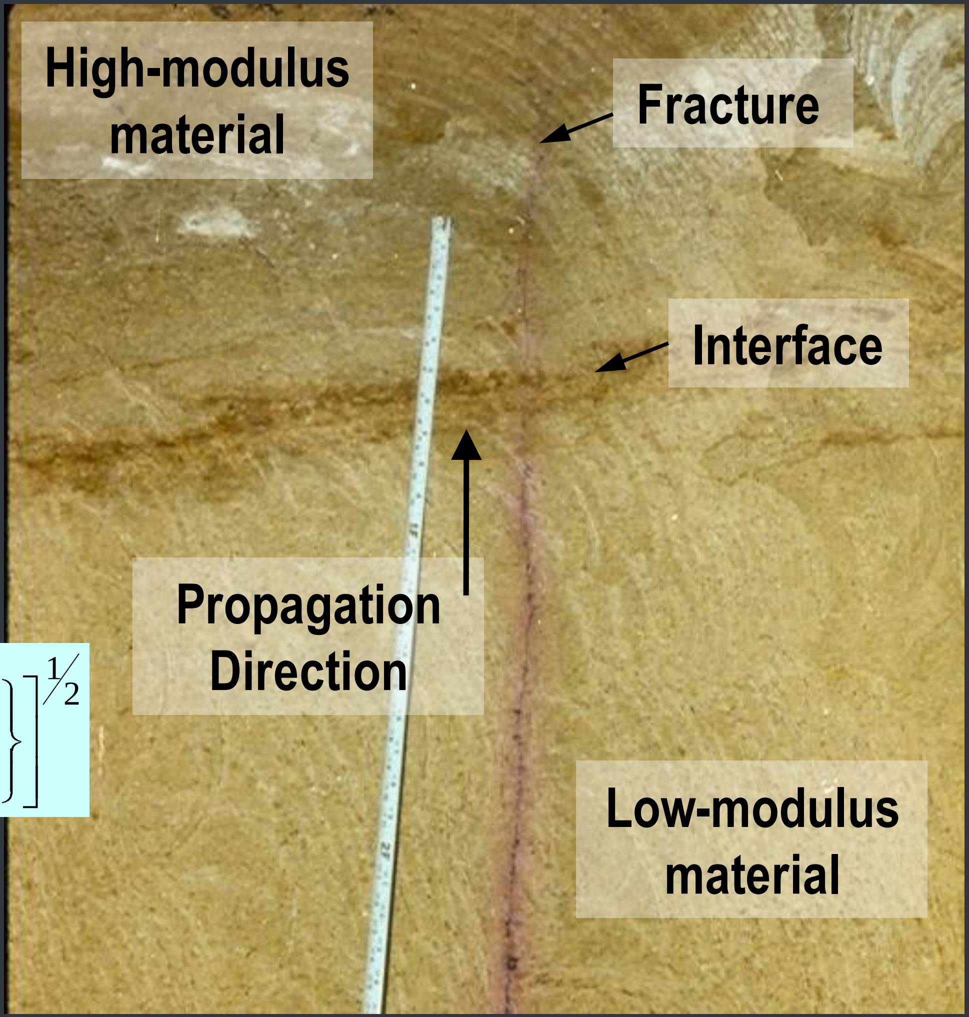
Griffen et al., SPE 84489

Fracture Height Growth

- Modulus variations
  - Limited effect due to influence on width
  - Van Eekelen formulation

$$L = \frac{H}{2}\left[1+\frac{12G_2}{19G_1}\left\{\log\left(\frac{H}{h}\right)+\frac{1}{4}\left(3+\frac{G_1}{G_2}\right)\left(\frac{H}{h}-1\right)\right\}\right]^{1/2}$$

  - Interfacial effect
    - Fracture toughness behavior at interfaces
    - Not observed in field

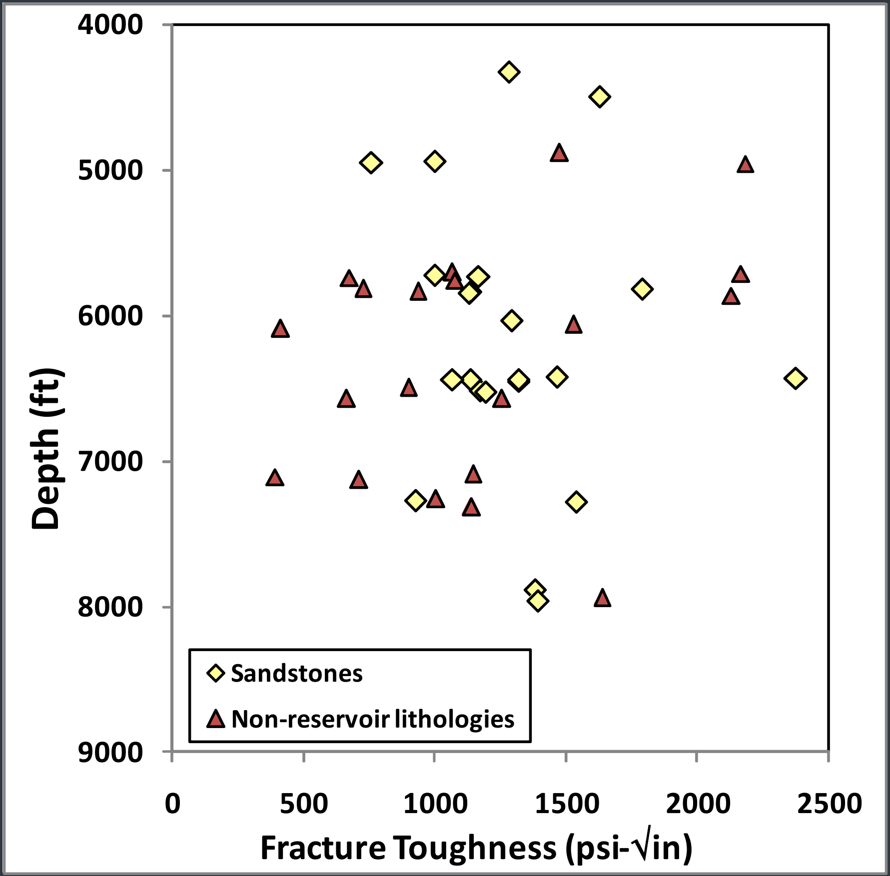


Mineback example showing behavior of fracture at a material property interface

Fracture Height Growth

- Fracture toughness
  - Generally assumed to have a small effect
  - Relatively low fracture toughness for rocks
  - Potential for scale effects that might constrain growth (Shlyapobersky)

Data from DOE Multiwell experiment in Piceance basin, Colorado

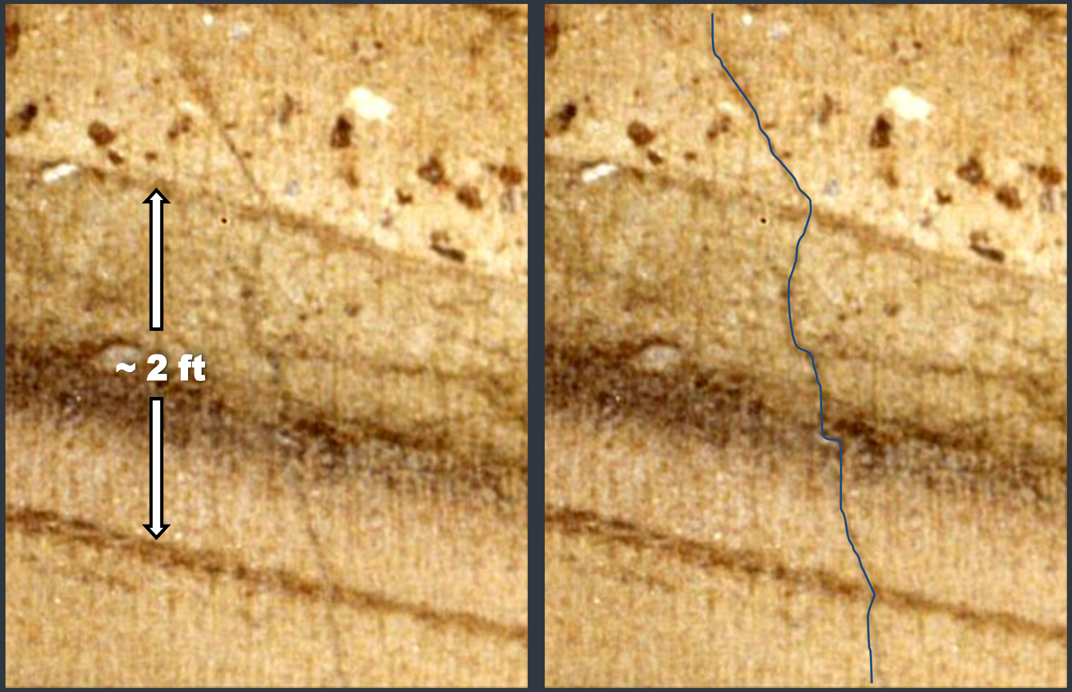


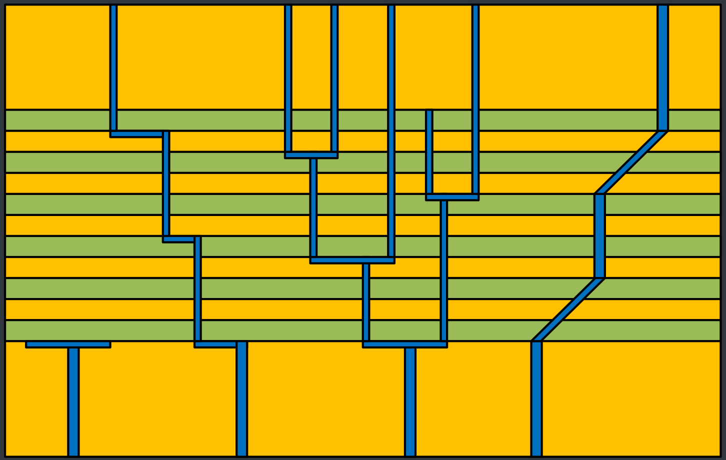
$$K_I = \frac{1}{\sqrt{\pi H/2}} \int_{-H/2}^{H/2} p(y) \sqrt{\frac{H/2+y}{H/2-y}}\, dy$$

Equation for calculating stress intensity factor, Rice (in *Fracture*, Liebowitz, 1968)

Fracture Height Growth

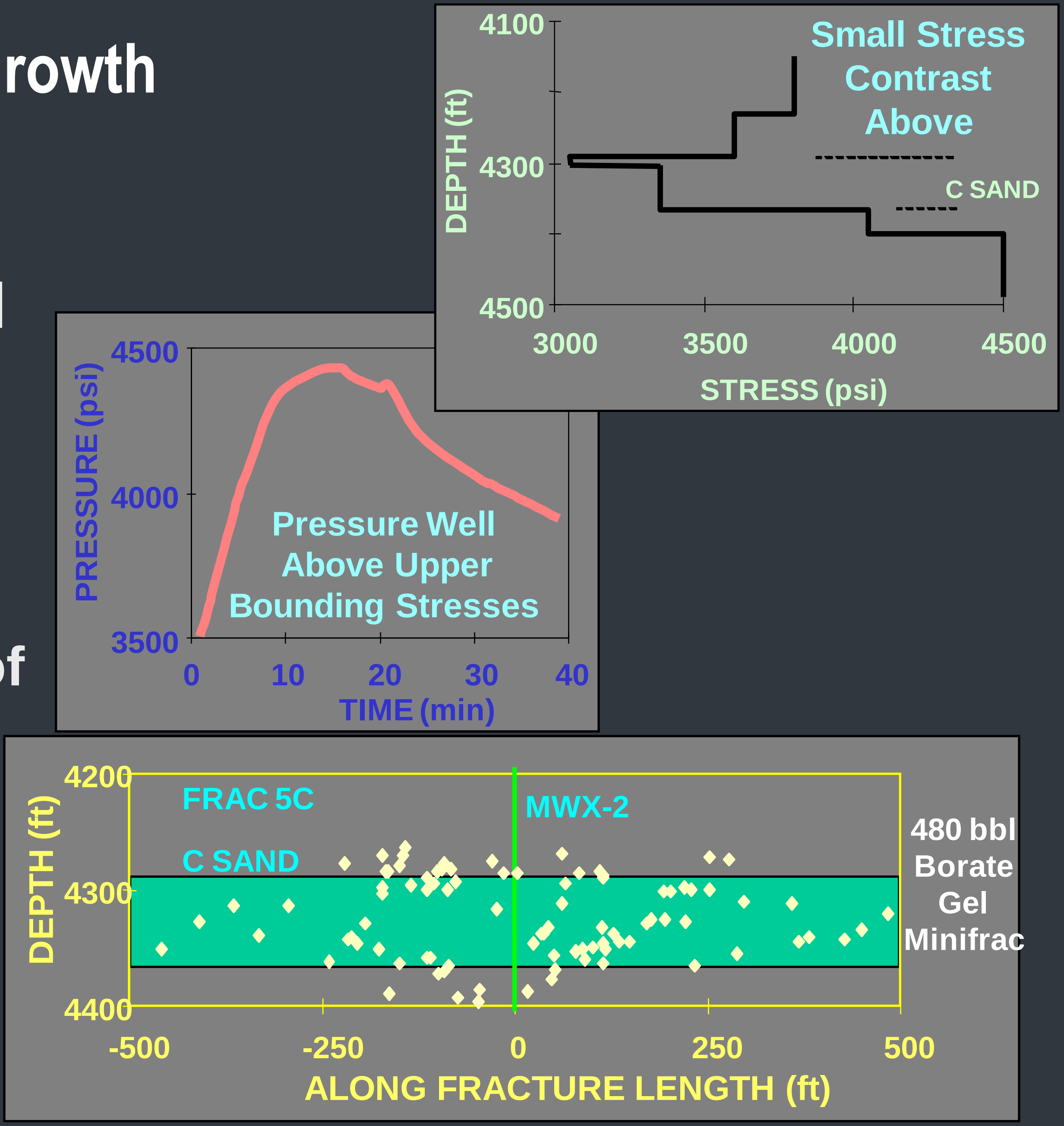
- Composite layering
- Mineback photos suggest a wide variety of mechanisms are interplaying
- Fracture diagnostics have shown the same behavior
  - Microseismic
  - Downhole tiltmeters





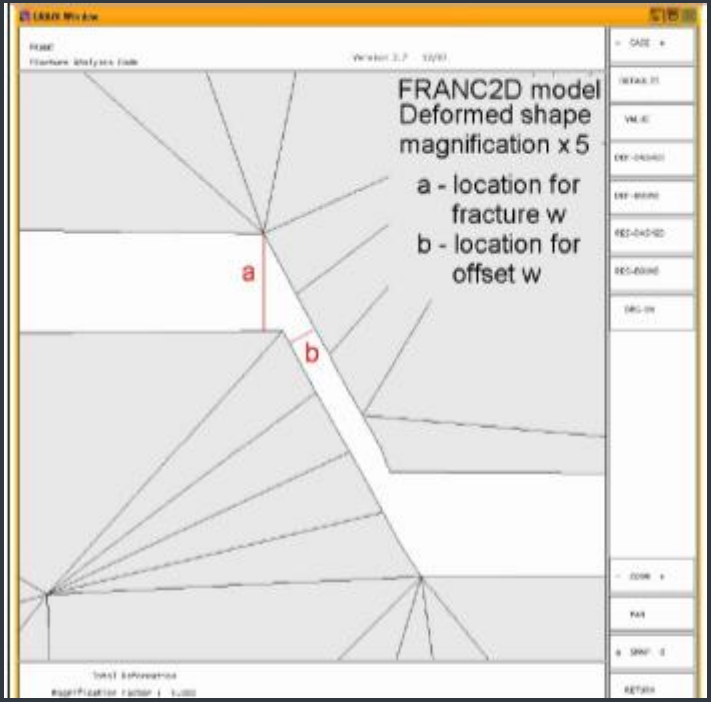
Fracture Height Growth

- Observed layering effects at DOE/GRI M-Site
  - Microseismic and downhole tiltmeter measurements of fracture height
  - In situ stress measurements
  - Treatment pressure



Discontinuities

- Fracture growth across discontinuities in the rock mass has been extensively studied
  - Depends upon
    - Stress
    - Material properties
    - Angle of approach
- Models
- Mineback
- Laborataory



FRANC2D model
Deformed shape
magnification x 5

a - location for
fracture w

b - location for
offset w

DOE mineback tests

Jeffrey & Zhang, 2009, SPE 119351

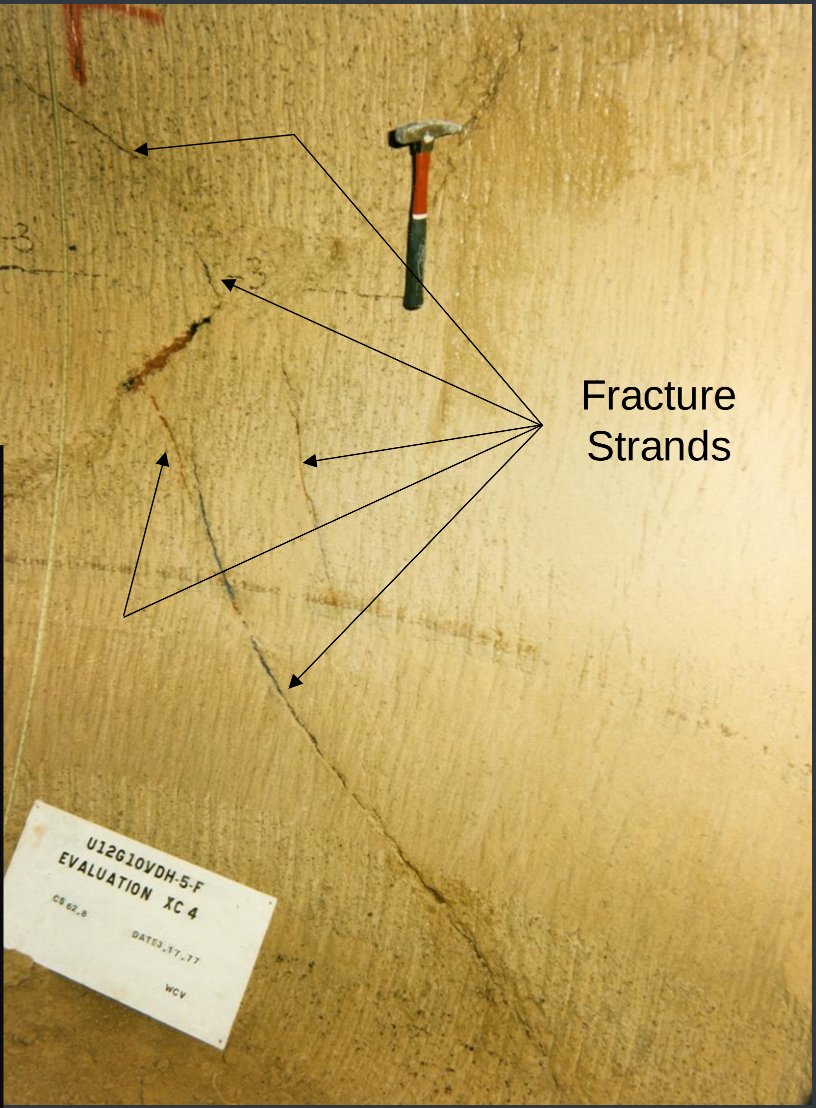
Discontinuities

- Fracture behavior as influenced by a wide range of discontinuities have been observed in minebacks and other tests
  - Faults
  - Cleats

Coal

Bureau of Mines Report 9083,
Diamond & Oyler, SPE 22395,
Diamond CBM Symposium 11/87,
Lambert SPE 15258

DOE mineback tests



Hydraulic Fracture Growth

- Summary
  - Hydraulic fractures influenced by heterogeneities within the reservoir
    - Any change in properties/uniformity
  - In situ stress is the dominant influence
    - Large stress contrasts contain fractures
  - Layering and interfaces result in inefficient growth
  - Models available to simulate/mimic behavior

Fracture Growth in Layered and Discontinuous Media

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Pinnacle – A Halliburton Service

Fracture behavior in the vicinity of layered and discontinuous rock masses has been the subject of numerous papers. The major factors that have been investigated are stress variations, modulus variations, fracture toughness variations, interface properties, high permeability zones, combined layering and interfacial behavior, and fluid pressure gradient changes. Of these, stress changes are clearly the largest influence on fracture growth across layers and stress bias is clearly the largest factor in the development of complexity in discontinuous media. Nevertheless, many of the other factors play a significant role in cases where the stress contrasts are not large and in the general development of complex fractures.

In Situ Stress

The in situ stress contrasts clearly have the most significant effect on fracture height growth. The importance of stress was recognized early on (e.g., Perkins and Kern 1961) and has been extensively studied in modeling (e.g., Simonson et al. 1978, Voegele et al. 1983, Palmer and Luiskutty 1985), mineback tests (Warpinski et al. 1982), and numerous laboratory experiments. Fracture height growth can be easily restricted if the layers above and below have higher stress than the reservoir rock, and this is a common occurrence in sedimentary basins.

An equilibrium (static) analysis of the Linear Elastic Fracture Mechanics behavior of a fracture surrounded by rocks with higher stress was first given by Simonson et al. (1978) for a symmetric case (stresses above and below are equal). Given the geometry in Figure 9, an equation can be written as

$$\sigma_2 - P = \frac{2}{\pi}[\sigma_2 - \sigma_1]\sin^{-1}\left(\frac{h}{H}\right) - \frac{K_{Ic}}{\sqrt{\pi H/2}}$$

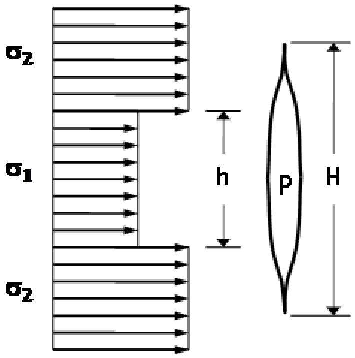

Figure 9. Geometry for stress effects.

where *P* is the net pressure in the fracture, σ_1 is the stress in the pay zone, σ_2 is the stress in the bounding layers, *h* is the thickness of the pay zone, *H* is the total fracture height, and K_{Ic} is the fracture toughness of the bounding layers. In this equation, the first term on the right is due to the stress contrasts, while the second term is due to fracture toughness. For standard laboratory values of fracture toughness, the term on the left is generally small (unless the fracture is very small) and the height of the fracture is mostly dependent on the stress contrasts. In general, this equation is conservative since there are other dynamic factors that affect the amount of height growth that will occur. Similar equations can be developed for non-symmetric stress contrasts, but more complete dynamic analyses are usually performed in fracture models.

Layer Material Property Differences

While Simonson et al. (1978) show that a material property interface in an ideal situation could blunt fracture growth, years of fracturing experience (Nolte and Smith 1979), fracture diagnostic monitoring (Warpinski et al. 1998, Wright et al. 1999), mineback testing (Warpinski et al. 1982), and other research (Smith et al. 1982; Teufel and Clark 1984; Palmer and Sparks 1990) have shown that this is not the case. Figure 10 shows an example of a dyed water fracture that has propagated through an interface from a low modulus material into a high modulus material (Warpinski et al. 1982). A more complete discussion of the role of the interface has been given by Cleary (1978), where the complexities of the interface, the micromechanics of the fracturing process, the potential for blunting and twisting (no longer only mode I fracture growth), and various other factors make the problem difficult to analyze with standard analysis tools. What is clear from these studies is that crossing interfaces requires additional energy and can hinder vertical growth.

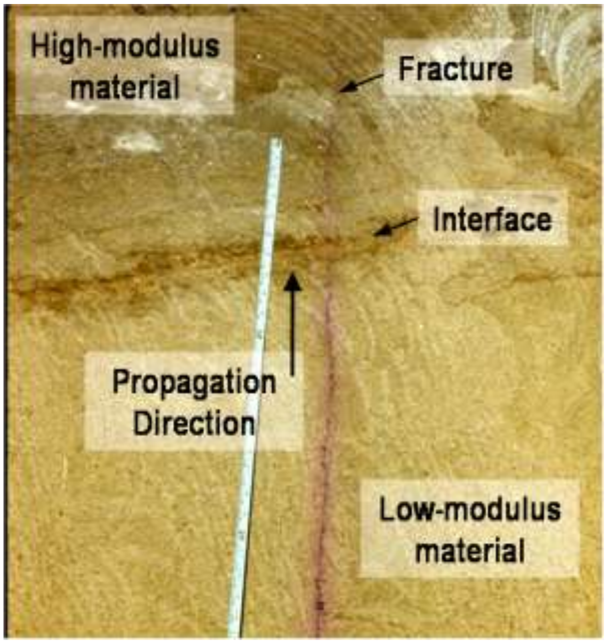

Figure 10. Mineback photo of fracture propagating across interface.

Modulus contrasts clearly have an effect on the width of the fracture and can be expected to enhance or restrict fluid flow appropriately. Cleary (1980) provided a time-constant analysis of the effect of modulus, while Van Eekelen (1980) developed a relationship based on relative height changes in the layers, given by

$$L = \frac{H}{2}\left[1 + \frac{12G_2}{19G_1}\left\{\log\left(\frac{H}{h}\right) + \frac{1}{4}\left(3 + \frac{G_1}{G_2}\right)\left(\frac{H}{h} - 1\right)\right\}\right]^{1/2}.$$

As discussed by Van Eekelen (1980) and Smith et al. (2001), these effects are generally small and cannot be expected to provide significant containment of fractures. Gu and Siebrits (2008) also show that low modulus layers surrounding a higher modulus pay zone can be restrictive due to a lowered stress intensity factor, but this also depends on the relative fracture toughness of the different materials.

Fracture Toughness

Fracture toughness can have a very significant impact on fracture growth, and a large value of K_{Ic} can either induce a high pressure, restrict the height, or both. For a homogeneous formation, the stress intensity factor at the top of the fracture can be computed if the net stress distribution is known by

$$K_I = \frac{1}{\sqrt{\pi H/2}} \int_{-H/2}^{H/2} p(y) \sqrt{\frac{H/2+y}{H/2-y}} dy \ ,$$

where p(y) is the net stress distribution vertically. If the stress intensity factor exceeds the fracture toughness of the material, the fracture will propagate. Obviously, the situation becomes more complex (and not analytic) for layered materials with different elastic properties, but the equation above gives a rough estimate of the fracture stability.

Laboratory experiments have generally shown that fracture toughness varies over only a limited range (e.g., Hsiao and El Rabaa 1987), which suggests that fracture toughness effects will be rather limited. Figure 11 shows a compendium of fracture toughness measurements made at the DOE MWX experiment that shows the relatively small range for both reservoir and non-reservoir rocks. However, the scale dependence of fracture toughness (or potentially other types of tip effects) is not well understood for large scale fractures, so there may be potential for fracture containment due to this mechanism (Shlyapobersky et al 1998).

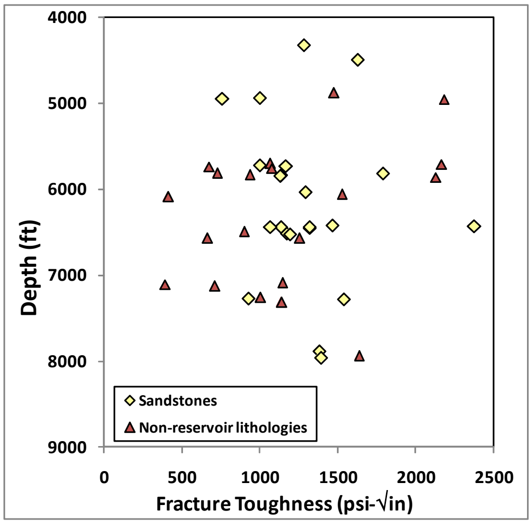

Figure 11. Fracture toughness data from MWX.

Interfaces

It is well known that weak interfaces can blunt fracture growth, and such a mechanism is often cited for the use of KGD (Khristianovich, Geertsma and De Klerk) models (Nierode 1985). Examples of blunting have been noted in mineback experiments (Warpinski et al 1982, Warpinski and Teufel 1987, Jeffrey et al. 1992, Zhang et al. 2007) and laboratory experiments (Anderson 1981, Teufel and Clark 1984). While it is generally expected that weak interfaces will be most important at shallow depths where friction due to the overburden stress is a minimum, other factors such as overpressuring or embedded particulates (equivalent to a fault gouge) can clearly minimize frictional effects even at great depths. Weak interfaces have the potential of totally stopping vertical fracture growth, initiating interface fractures, or causing offsets in the fracture. In addition to restricted growth effects, weak interfaces above and below the reservoir can decouple the fracture walls (Barree and Winterfeld 1998, Gu et al. 2008), resulting in poor coupling of the fracture pressure in the reservoir to the fracture outside of the weak interfaces. This reduced coupling would create narrower fractures in the layers across the interface and much wider fractures within the reservoir rock.

Many mechanism, such as those described above and others, can be bundled together to describe fracturing across a succession of interfaces. The possibility that such layered media could contain hydraulic fractures has been derived from fracture diagnostic information (Warpinski et al. 1998, Wright et al. 1999, Griffin et al. 1999). It is easy to conceive of multiple mechanisms serving to blunt, kink, offset, bifurcate, and restrict growth in various layers, much as a composite material hinders fracture growth across it. Various methods are now being used to model such behavior (Wright et al. 1999, Miskimmins and Barree 2003, Weijers et al. 2005).

Several of the mechanisms can be seen in Figure 12, which is a mineback photo of a fracture propagating upward across several interfaces. The left-hand side is the unaltered photograph, while the right-hand side has the fracture accentuated with a line drawn over it. There is kinking, offsetting, and bending occurring as the fracture makes its way through the layers. In other cases, additional fractures are initiated or some fractures are terminated.

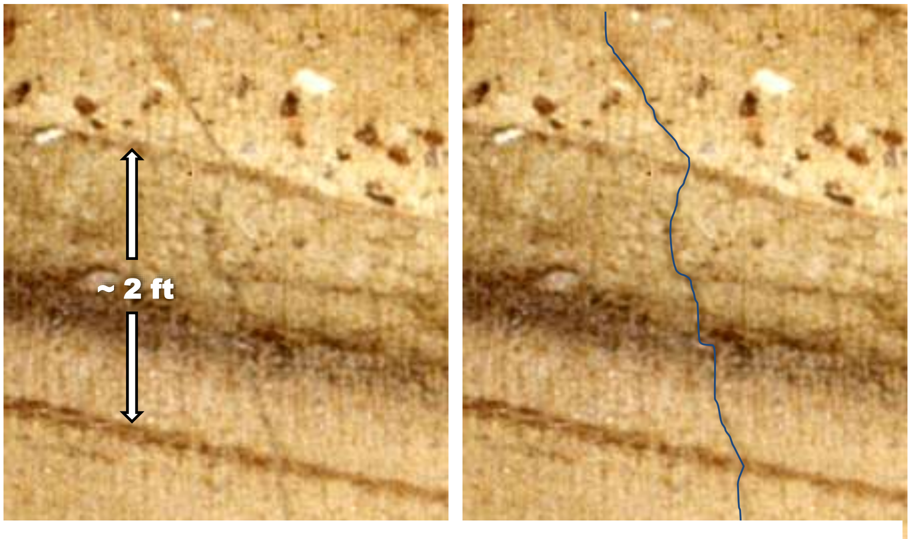

Figure 12. Photograph and line drawing of fracture behavior crossing interfaces.

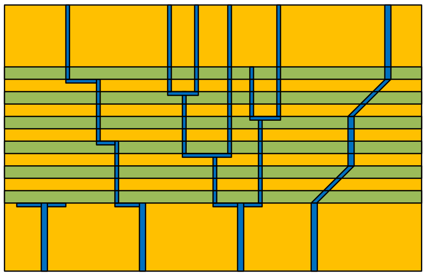

Figure 13. Schematic of types of observed fracture behavior crossing interfaces.

Figure 13 shows a schematic of several types of behavior that have been observed in minebacks or laboratory tests. The result of these behaviors could be any combination of complexity, restriction, or termination of the fracture as it propagates across the layered medium. Restrictions should be common if kinking or offsets occur, as the width in the kink or offset will necessarily be less than in the vertical part of the fracture due to both geometric and stress considerations.

Discontinuities

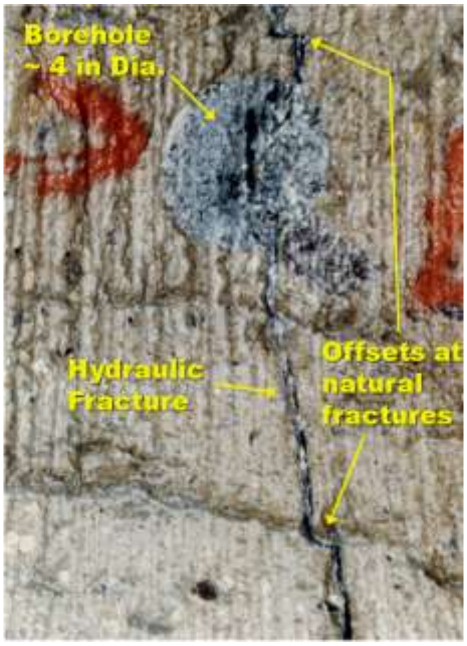

Figure 14. Fracture crossing discontinuities.

Any heterogeneities and discontinuities can modify the propagation behavior of fractures in a rock mass. Figure 14 shows an example of a fracture that is crossing unhealed natural fractures (Warpinski et al. 1981), which is also equivalent to the case of a weak interface with some permeability along the interface. This example shows offsets of the fractures at a location that is very close to the wellbore. Cement was used as the fracturing fluid for this test in order to preserve the width of the fracture. Such offsets would clearly restrict fracture growth because of the narrower width of the fracture in the offset and the possibility of sand bridging.

There have been many studies of the factors that influence fracture growth across discontinuities (e.g., Teufel 1979). These studies have demonstrated the effects of stress, angle of approach, and various material properties in blunting or offsetting fractures. These types of offsets are likely responsible for much of the complexity observed in hydraulic fractures in cores (Warpinski et al. 1993, Branagan et al 1996) and mineback tests. They prevent fractures from propagating as a single planar feature and instead force it into multiple, variably connected, intersecting components. This complexity makes it difficult for fractures to grow large distances as planar features.

High permeability interval

High permeability zones can also terminate vertical fracture growth by dehydrating the slurry through high leakoff. Coals are excellent examples of zones where fracture growth might be terminated by this mechanism.

Summary

Hydraulic fracture growth is influenced by a multiplicity of factors that are common in any reservoir. Of most importance is the in situ stress distribution, but interfaces, natural fractures, and other heterogeneities may also significantly affect behavior.

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