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LLNL-TR-594292

Creating the link between micro-seismic observations and hydro-mechanical changes in the reservoir

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October 23, 2012

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Creating the link between micro-seismic observations and hydro-mechanical changes in the reservoir

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Overview

The goal of this document is to highlight the current state of knowledge governing different aspects of the hydraulic fracture propagation process characteristic of many stimulation operations. Specific emphasis is placed on how observations of seismic sources can be used to infer the production behavior of the reservoir.

Failure of Rock and Rock Interfaces

For the case of a propagating fracture due to hydraulic fracture stimulation, micro-seismic data collected from a number of projects indicate bulk fracture propagation of O(10^1) m/s << O(10^3) m/s for the sound speed in intact rock. This is counter-intuitive when considering fracture mechanics, where fractures in tension (Mode I) generally propagate near the Rayleigh wave speed. If we resort to theoretical consideration of fluid-driven fractures in an elastic medium, the anecdotally observed propagation velocity noted above is recovered [1]

$$\lambda = 4\mu E'^2 v\, \sigma_0{}^{-3},$$

where μ is the viscosity, v is the mean fluid velocity into the fracture, E is the modulus of the fluid, and σ_0 is the confining pressure. For typical rock properties at confining pressures of 10-100MPa, the tip velocity is O(1-10) m/s.

In general, this suggests stress equilibrium in the far field for bulk fracture propagation, such that there exists a temporal scale separation between the resolution of stress in the local region of a fracture and that at larger scales. This region, referred to in the literature as the "process zone", can often be decoupled from the solution of the mechanics in the rest of the domain (referred to as the "far field"). For instance, numerical, multi-scale research [2–4] has suggested that scale-separation, when implemented in numerical models in practice, can predict crack fronts in mixed mode fracture situations where the forcing term is constant. For the case of a hydraulically-induced fracture, where fluid forcing controls the crack front propagation, the time constant is separated by an even greater scale, suggesting that this may be a viable path to multi-scale coupling. In addition, a number of experimental studies in brittle, homogeneous polymers are available for validation [5] of such multi-scale approaches.

For the case of failures either along the developed fracture network or in regions where the stress field has been rotated enough to effect failure in pre-existing fractures, the failures are

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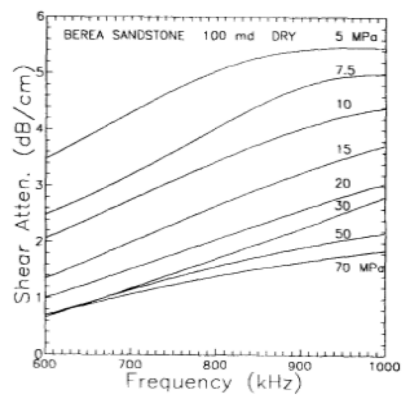
often Mode II (strike-slip) events, as they are predominantly for laboratory hydraulic fracture experiments [6–8]. A number of joint models can capture this effect [9–15], and for clayey interfaces, a more in-depth discussion is given later.

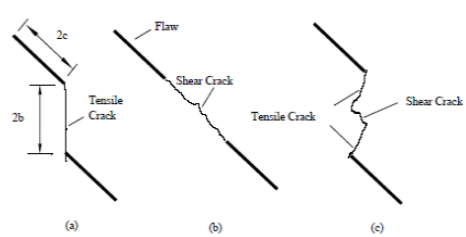
Near-source Signal Propagation



From experimental studies of shear attenuation in fractures in Berea sandstone [16], it is clear that a rough fracture can interrupt and attenuate a pressure pulse traveling through a fluid-saturated, rough fracture in characteristic geologic material. The 1dB/cm lower range would suggest the pulse magnitude would drop by an order of magnitude within 10cm. The impedance mismatch between the fluid and the fracture walls also causes the roughened fracture to act as a wave guide to trap the energy of the pulse along the fracture length. This suggests that the mechanisms being restricted to a finite (short) length of the fracture near the pulse initiation point and also restricted mainly to the discontinuity itself with separable components traveling away from the discontinuity into the far field continuum. However, caution must also be exercised, as it is also clear that energy loss is dependent on confining pressure, with higher confining pressures causing better mechanical coupling (i.e., reduced impendence mismatch) across the fracture interface.

For the near source response, the material models must resolve a variety of effects, including bulk plasticity, damage at different scales and through different mechanisms, wave propagation in discontinuous materials, and wave dispersion and interaction. This topic is too detailed to cover even cursorily here, and the reader is referred to a number of works on dynamic loading of geomaterials [11], [17–25].

Multiple Fractures



Finally, there are issues with interactions between discontinuities as the fracture system grows. Interacting stress fields have a drastic effect on fractures as they approach, indicating that the individual fractures cannot necessarily be addressed separately, as is commonly assumed for most traditional fracture mechanics work. Analytical studies have sought to characterize this interaction [26], [27]. Several experimental studies have also been performed to elucidate crack coalescence behavior in rock, including studies by Wong [28] to investigate Mode I, Mode II, and mixed Mode I/II fractures in brittle materials with multiple discontinuities.

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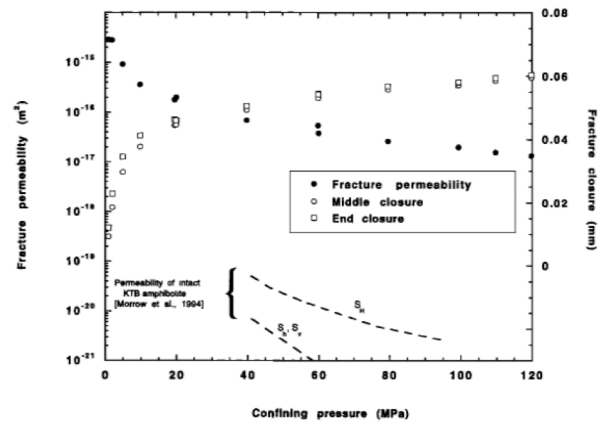
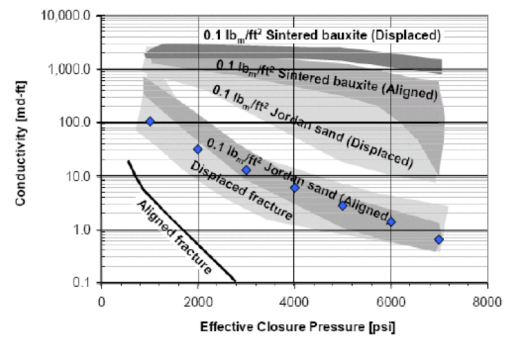
Fracture maintenance (hydro-mechanical)

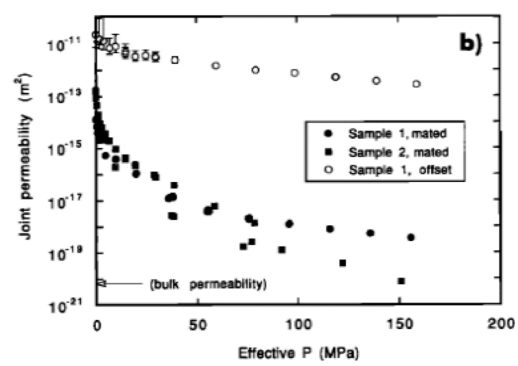
Maintaining fractures and determining their response to changes in the stress tensor is a major concern for establishing the behavior of a reservoir and the response of the system. For simple changes in the confining pressure, there are well-established relationships between fracture closure and confining pressure for a number of geologic materials. An example for the KTB pilot hole project at LLNL is shown at right [29]. There is, however, a significant degree of scatter in the data.



As shown by the work of Cipolla [30] in the graph at the right, the data for offset (displaced) versus mated (aligned) fractures exhibits a different functional form dependent on the geologic material.



For a number of systems of engineering interest (e.g., where injection of fluids alters the stress tensor orientation), changes in the shear stress components can lead to other effects on permeability. Shearing of a fracture by a fraction of a millimeter can lead to many orders of magnitude change in the permeability, which is a first-order effect in determining the hydrologic response of the system. This is demonstrated by Durham and Bonner [31] for Westerly granite under 160 MPa confinement, as shown to the right.



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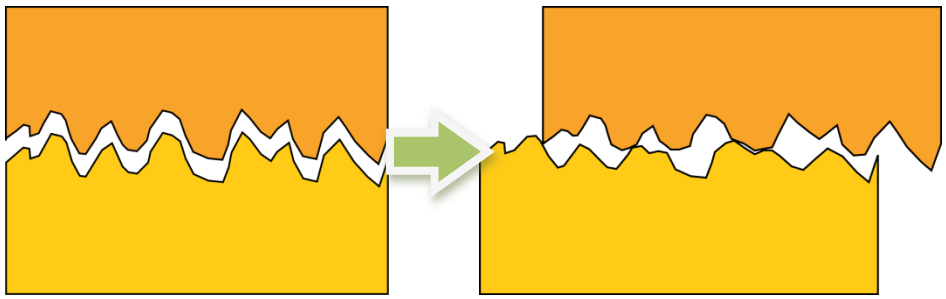
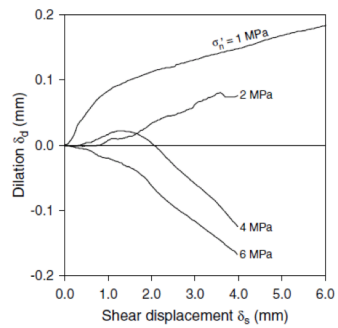
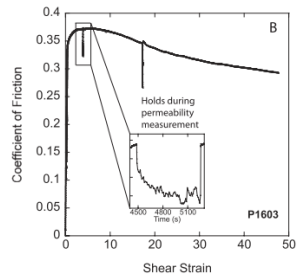


Illustration of shear-induced dilation

Shearing, however, is not *guaranteed* to cause permeability enhancement, and the trend has been seen to reverse for some geologic materials under high confinement. Shear-induced compaction (versus dilation) for a relatively weak Kimmeridge shale has been characterized by Gutierrez [32], and is shown in the figure to the right. Note, below 3 MPa confining pressure, the fracture dilates; whereas, above this, the fracture shears the asperities into gouge material that plugs the fracture and reduces permeability.



If we expand the consideration of materials to those that are unconsolidated (or become unconsolidated as gouge through shear displacement along the fault face) and have high clay content, we can appeal to the extensive literature on seismogenic gouge. Generally, lab experiments and behavior extrapolated from field observations of seismic events agree in terms of qualitatively similar functional forms of strain-friction response (e.g., 2 inflection points, a local maximum at strains below 10%, etc.). Functional relationships of the type proposed by Dieterich [33], [34] and others [35–39] provide a reasonable form for capturing this behavior; recently, Zoback [40] has suggested using such models for capturing slow slip events in stimulated reservoirs. An example of laboratory data recording the behavior of sheared clayey materials is shown at left from Fig. 3 of Ikari [41]; many other experiments exist [42–45]. Shear-induced permeability decrease is consistently observed in clayey materials, indicating that though one may accomplish plastically, aseismically, slow-slip regions in such materials [40], the accompanying permeability changes would be deleterious to production goals. Specific hydro-mechanical properties of shales, specifically, can be found found in a number of references, e.g., [46–48].



The effects of loading on permeability demonstrate the coupling effects from mechanical to hydrologic. There are also effects coupled from hydrologic to mechanical in terms of effective

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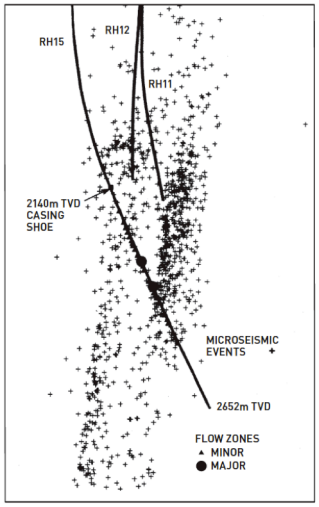
stress changes due to elevation of pore pressure, which can lead to failure and shearing of pre-existing fractures and faults. This illustrates the bi-directional coupling between hydrology and mechanics.

Fracture morphology changes, which can be caused by a number of mechanisms, including shear-induced compaction, changes in normal compressive stress (which can reduce the mean aperture or cause permeability increases from fracture offset), precipitation and dissolution, and thermally-induced cracking and spall in the fracture walls, may also cause large magnitude changes in the permeability. Along with basic permeability alteration comes the possibility of local flow transitions between laminar to turbulent. Even in nominally low flow rate situations, as fractures change geometry, the flow profile can transition from laminar to turbulent within the discontinuities with consequent reduction in the flow within the reservoir [49], which can function to reduce production. To add an additional mechanism, the introduction of non-Newtonian fluids, as are common in colloidal working fluids and proppant entrained fluids employed in industry, can also introduce new sensitivities, including an enhancement of the effects of path tortuosity in the fractures [50].

Fracture monitoring (dynamic mechanical)

Two of the most difficult behaviors to predict in subsurface systems are the generation of a seismic source term and the associated wave propagation and dispersion of that term as it travels through the rock. Though a number of models exist for characterizing the effective continuum response [51] and the explicit response of rock joints [12], the ability to upscale these models to be useful in large scale wave propagation continues to be a challenge, though methods have been successfully verified and validated for some systems.



Field measurement methods, such as microseismic arrays, also provide a data component to match calculations and include information on extent, orientation, and rate of fracture propagation for stimulation operations. An example of microseismic characterization of fracture propagation at Rosemanowes, UK, is shown at the right. For computational methods to be effective, there must be a way of handling the aleatoric errors inherent in determining material properties, initial conditions, and boundary conditions, but given such a method, field measurements of seismicity can offer a way of completing the loop to relate subsurface changes to observations and to use such observations to improve models.

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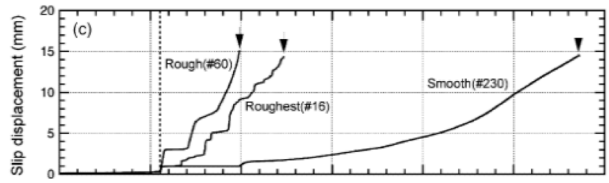
For the source term, the determination of seismic versus aseismic (creep) displacement is related both to the flow into the fracture as well as the fracture roughness. Experiments performed by Nemoto [52] show how a wet joint can transition between the modes depending on the roughness of the joint, as shown in the figure to the right. Thus, gouge formation [40] is not the only mechanism for inducing slow slip events. Determining the roughness, though, in a practical application is non-trivial, since diagnostics are limited to small patches and often acquired through quasi-one-dimensional cross-sections via well logs. A significant amount of aleatoric error is associated with the characterization of the joints; however, there is promise in inverting these properties, in a stochastic sense, from historical data for a particular site. Another note on the data from Nemoto is that the characteristic time scale for a complete slip event (i.e., source term generation) is $O(10^2)$ seconds for a displacement of $O(10^{-2})$ m, or $O(10^{-4})$ m/s (for the low frequency components) << wave speed in the material. This also suggests the possibility for temporal and spatial scale decoupling to resolve the source term event.



Precipitation and dissolution (hydro-thermo-chemical)

The total time for a typical hydraulic fracture stage rarely exceeds a typical work day [53]. The precipitation and dissolution of material is often considered to occur at rates where permeability alteration effects are noted after no less than a day, suggesting that geochemical effects can be neglected when considering the initial fracture network stimulation. A somewhat separate issue, however, is the formation of a “filter cake” on the fracture surfaces, which causes the well-known reduction of permeability between a fracture and the matrix rock that it interfaces as a function of time [53–55]. The flow of fluid from the fracture conduits into the surrounding matrix rock is often referred to as “leak-off”. The leak-off has competing processes that can either reduce (as through the filter cake formation) or enhance (as through thermally induced cracking) the permeability through the fracture interface. These effects, though complex at a microscopic scale, are often treated effectively with empirical relations at larger scales [56].

Conclusions

There are a number of important attributes of the subsurface that can be inferred from microseismic wave propagation. To achieve this more effectively will require appropriate treatment of the joint model (a rate- and state- dependent friction model with appropriate inclusion of saturation and calibrated to the specific geology), inclusion of poroelastic effects away from the fracture, and treatment of the pre-existing joints in a stochastic manner.

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