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Editors Note

A RMA Letters is pleased to present this Special Issue on Permeability of Fracture Systems. This issue is one of a series of Letters dedicated to a specific subject, with submissions from a range of authors. The issue was organized by Bill Carey of Los Angeles National Laboratory. We are grateful to him for his work in coordinating this collection of papers.

We would also note that this issue will be designated as the 2020 Spring Issue, Number 29. Because of scheduling issues, and external events, there is no Winter Issue.

Bezalel Haimson
Chair, Publications Committee

Introduction to Special Issue on Permeability of Fracture Systems

Submitted by J. William Carey, Earth & Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM USA.

Fracture permeability is an important problem that lies at the intersection of several disciplines, involving at least geomechanics, hydrology, and geochemistry. Recently, there has been significant interest among researchers and funding agencies to push forward our understanding of the factors that control the permeability of fracture systems, with the ultimate aim of controlling and manipulating these systems. This interest has been driven by ubiquitous findings that fractures profoundly influence the movement of fluids in the crust, with important implications for many engineering applications. In contrast to the more mature field of porous media flow, methods of predicting, investigating, characterizing, and modeling fluid flow in fracture systems are more complex, leading to significantly greater uncertainty in predictive models or risk analysis of fractured rock systems.

In this Special Issue, we have collected six contributions from researchers examining fracture permeability problems from different perspectives. Interestingly, three primary themes emerge from the collection: (1) The origin and character of permeability anisotropy in fractures; (2) a distinction between the behavior of individual fractures and fracture

networks; and (3) that permeability is a dynamic and evolving property that is sensitive to its environment. As explored in both experimental and numerical work in this issue, permeability anisotropy arises in both space and time. Spatial anisotropy relative to the direction of shear is developed in experimental studies discussed by Carey et al. and in numerical work of Morris and of Wang and Pyrak-Nolte, and relative to principal stress directions by Paluszny and Zimmerman. Temporal evolution is emphasized in the contribution of Elsworth et al., where episodic fracture activation is followed by fracture healing, creating cycles of permeability increase and decline.

A distinction is drawn between the behavior of individual fractures and fracture networks in the experimental work described by Carey et al., and in the fracture network modeling of Sweeney et al. In experiments, flow moving from fracture segment to segment encounters varying fracture apertures and permeabilities, with connections between the fractures forming relatively open or closed pathways. As fracture segments and connections form in response to fracture mechanisms (also see Wang and Pyrak-Nolte), flow structure develops with enhanced permeability perpendicular to displacement. In models of fracture networks, flow may be focused on pathways involving a relatively small subset of the network forming a flow backbone. Such pathways may be relatively insensitive to in-fracture variability, but sensitive to fracture-to-fracture permeability differences.

The Special Issue on the permeability of fractures consists of a review, two papers focusing on experiments, and four papers focusing on numerical simulations. The issue is organized beginning with a review:

1. *Permeability of Shear Fractures in the Subsurface* by Carey, Frash and Welch. This paper combines a review of fracture permeability in lab, field, and theory with a discussion of experimental work. The experiments involve shear fracturing of intact specimens and characterizing permeability/aperture relations with x-ray radiography/tomography. Multi-segmented en échelon fracture structures create permeability anisotropy and are strongly sensitive to stress conditions at fracture formation.
2. *Fluid Flow through Fractures with Corrugated*

Surface Roughness by Wang and Pyrak-Nolte. This paper presents numerical studies of the impact of corrugated fracture surfaces, as found in nature, on creating permeability anisotropy. The authors find that corrugated structures arise during tensile fractures due to a combination of layering and heterogeneous bonding, creating mineral fabrics. Enhanced flow parallel to corrugations is observed, which is further amplified by shear displacement perpendicular to the corrugations.

3. *The Effect of the Intermediate Principal Stress on the Permeability Tensor of a Fractured Rock Mass* by Paluszny and Zimmerman. These authors present numerical simulations of the relationship of fracture permeability and confining stress, in 3D systems. They find that anisotropic permeability develops consistently throughout various realizations, with the maximum permeability aligning with the intermediate principal stress.
4. *Channels in Rough Fractures Under Stress: A Potential Link Between Fracture Conductivity and Seismic Properties* by Morris. In numerical simulations, the author examines how stress impacts the structure of flow through a fracture, where the formation of channels creates strong flow anisotropy. He further correlates anisotropy in fracture compliance with permeability, suggesting potential acoustic/seismic methods of characterizing subsurface fracture flow properties.
5. *Seismicity-Permeability Coupling in the Breaching and Sealing of Reservoirs and Caprocks* by Elsworth, Fang, Im, Wang, Ishibashi, Jia, Li, Yildirim, and Zhang. These authors use experimental and computational methods to investigate how permeability changes with fault slip -- contrasting seismic and aseismic slip and exploring the role of mineralogy, roughness, and healing processes in permeability changes. Healing occurs rapidly in experiments and is necessary for seismic recurrence.
6. *Advances in Discrete Fracture Network Modeling: A Review* by Sweeney, Hyman, Karra, Make-donska, O'Malley, Srinivasan, and Viswanathan. This review describes discrete fracture network (DFN) models of flow and transport in fracture systems, using both high-fidelity physics-based approaches, and graph-theory reduced-order representations. They explore the effects of in-fracture variability, injection boundary con-

ditions, and fracture-matrix interaction in physics-based models, and examine the fidelity of graph-based methods to physics-based models.

Permeability of Shear Fractures in the Subsurface

Submitted by J. William Carey, Luke P. Frash and Nathan J. Welch; Earth and Environmental Sciences Division; Los Alamos National Laboratory; Los Alamos, NM, USA

1. Introduction

Fracture systems in rocks have received a great deal of attention in recent years spurred by developments in hydraulic fracturing (e.g., Detournay, 2016), concerns about induced seismicity (e.g., Ellsworth, 2013), and ongoing challenges in the extraction, storage and disposal of energy and its byproducts (e.g., geothermal energy and CO₂ storage reservoirs; Tester et al., 2006; Rutqvist, 2012) as reflected in a Department of Energy Basic Research Needs report (Pyrak-Nolte et al., 2015). Natural and induced fractures can act as fluid conduits enabling orders of magnitude faster flow than through the adjacent rock matrix. For many applications, understanding fracture permeability is a key objective including the transmissivity of unpropped fractures in a hydraulically stimulated reservoir volume (geothermal and unconventional oil and gas); potential leakage through fractures in caprock (storage security in CO₂ sequestration); transport processes of radionuclide species in fractures (nuclear waste repositories); and induced seismicity where permeation of fractures leads to earthquakes far from the injection point (underground fluid disposal, geothermal energy and hydraulic fracturing).

Our lack of knowledge is due to two things: first, the difficulty of making measurements or inferring permeability of fractures in the subsurface and second, the challenge of reproducing subsurface fracture conditions in the laboratory. In subsurface environments, it is difficult to isolate flow and pressure measurements to a single fracture or to a well-defined set of fractures. It is even more challenging to explore the full 3D permeability field associated with a fracture system. In the lab, it is difficult to create, characterize, and measure

permeability of realistic fractures formed at subsurface conditions. Typically fracture formation and fracture permeability are studied separately. For example, triaxial compression experiments may be used to study shear-fracture formation but the geometry of the apparatus makes permeability characterization challenging. Fracture permeability studies are typically conducted on idealized fractures (saw-cut, Brazilian split, re-assembled natural features) with the aim of understanding the impact of roughness, displacement, or normal stress on permeability. While highly informative, it is challenging to translate these results to the hydraulic properties of an as-formed fracture system. In particular, the aperture and aperture distributions in such experiments have an unknown relationship to those present in the subsurface, making predictions of permeability in the subsurface quite uncertain.

There is renewed interest in fracture permeability research spurred in part by growing appreciation of the multiple applications that would benefit but also by the recent advances in experimental and field observations. In this letter, we review developments in understanding of fracture permeability with the aim to stimulate interest and ideas for innovative theory, experiment, field and computational approaches to improved understanding of fracture permeability in the subsurface.

2. Structure of Fault Zones and Impact on Permeability

Faults and shear fractures are observed to consist of discontinuous structures at all scales of observations with structures and linkages evolving with increasing deformation (Ben-Zion and Sammis, 2003; Faulkner et al., 2010; Scholz, 2018). Although a number of mechanisms can lead to non-planar fault systems, including material heterogeneity, stress heterogeneity, or subsequent deformation (e.g., Martel, 1999), in this study we emphasize that nonplanarity is intrinsic to shear fractures as they develop by coalescence of microcracks and because maximum stresses at crack tips are not aligned with the shear plane frustrating propagation within a simple plane (Scholz, 2018). The resulting multi-segmented character of fractures indicates that fracture permeability can't be viewed as the property of a singular planar feature but is inherently scale-dependent on the extent and complexity of communicating segments.

The initial stages of deformation, as characterized in triaxial compression laboratory studies, show the formation of distributed, but unconnected microcracks (Einstein and Dershowitz, 1990; Lockner et al., 1991; Renard et al., 2019). With increasing strain, these features coalesce, eventually forming a dominant shear zone. While the shear zone corresponds to a Mohr-Coulomb “failure plane”, in detail it is built from the linkage of structures having both tensile and shear characteristics and is not a simple geometric plane.

The non-planar character of fractures can be readily observed even in experimental systems that might be expected to produce simple planar shear, i.e., direct-shear devices (e.g., Tchalenko, 1970). We have used a triaxial direct-shear core-flood system coupled with simultaneous x-ray radiography and tomography to observe shear fracture development without disturbing the specimens from subsurface conditions (Carey et al., 2015; Frash et al., 2016, 2017, 2019a). The direct-shear assembly is shown in Figure 1 (top) and consists of two opposing semi-circular platens that should force a simple plane of shear through the specimen. However, as illustrated in Figure 1 (bottom), segmented features emerge as soon as fracturing begins and appear in both layered and relatively homogeneous and fine-grained materials. Importantly, with respect to permeability, the segments consist of tight, shear-dominated regions and open, tensile-dominated regions creating a distinct anisotropy in physical aperture. This pattern may develop in a manner similar to the formation of tensile wing cracks found during coalescence of shear-oriented fractures in compression experiments.

These experimental observations are reinforced by numerous field observations. Segall and Pollard (1980) find that “Discontinuities are, indeed, a fundamental feature of faults”. They find that fault segments are commonly arrayed in en échelon segments at all scales, from outcrop to regional tectonics (e.g., the Dead Sea transform), and found in both strike-slip and dip-slip faults. The connections between en échelon segments form distinct features that may be compressive or tensile in character depending on the sense of slip and offset. As in the experiments, the individual segments and connections form a strongly anisotropic system. Numerical and theoretical studies of fracture coalescence show that individual segments interact strongly and form connec-

tions outside the dominant shear fracture plane (Segall and Pollard, 1980) and that non-planar, segmented en échelon structures form at lower stress than simple planar structures (Frash et al., 2019a).

Dynamic rupture processes (i.e., earthquakes) also increase fault complexity. For example, off-shear plane stresses increase with rupture velocity creating potential for fault bends and fault jumping (Kame et al., 2003; Poliakov et

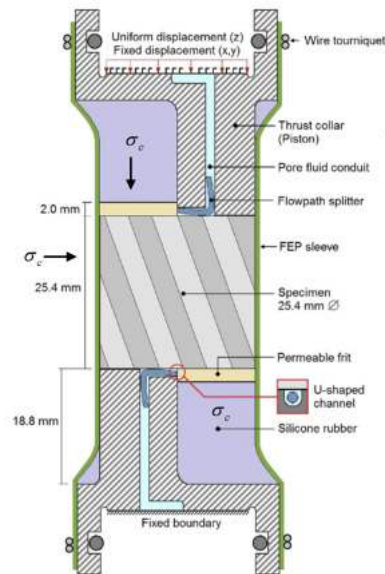
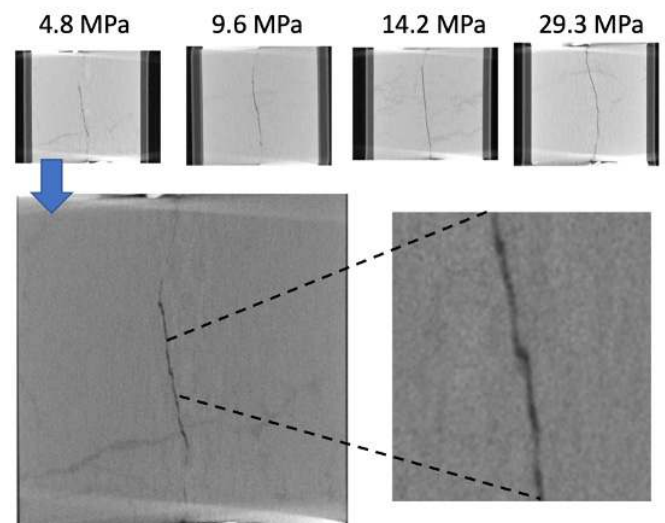


Figure 1: (top) : Schematic diagram of a direct-shear collar used in a triaxial coreflood system to induce shear fractures and permit measurement of shear fracture permeability. Shear is developed by two opposing, semi-circular thrust collars. Well-defined stress boundary conditions are imposed by the confining fluid on the side of the specimen and the silicone rubber (which is also at the confining pressure) on the top and bottom semi-circular regions of the sample that do not face the thrust collar. (After Frash et al. (2017)).

Figure 1 (bottom) Series of x-ray tomograms collected during fracturing of Marcellus shale at four different confining pressures. Details are shown for the lowest stress fracture showing nested en échelon fractures. (Cf., Frash et al. (2017)).



al., 2002). Fliss et al. (2005) considered cases where the fault propagation appears to reverse direction and Hamling et al. (2017) describe just how complicated fault processes can be in the case of the 2016 Kaikōra earthquake in New Zealand with surface ruptures expressed on at least 12 different faults. Indeed, rupture processes do not involve the sudden release of a single sliding surface but are characterized by nucleation on patches and complex propagation involving a number of fault segments.

With increasing deformation, fault systems evolve toward a mature state in which slip is increasingly localized (Ben-Zion and Sammis, 2003). The idealized structure of mature fault systems consists of a fault core that accommodates much of the slip within a matrix of gouge and cataclastite and which is surrounded by a region of damaged rock. (Caine et al., 1996; Faulkner et al., 2003). The damage zone consists of fractures with comparably minor displacement that were developed at early stages of deformation and later abandoned, that developed from stresses formed at fault segment step-overs or bends, or as a result of dynamic rupture processes (Faulkner et al., 2010). The extent of damage decreases exponentially with distance from the fault core and the width of the damage zone increases with overall slip on the fault system. Many fault systems are more complex with multiple fault “cores” within a region of rock damage (Faulkner et al., 2010).

An interesting characteristic of the mature fault system is that high permeability corresponds not to high displacement in the core but to regions of lesser deformation in the damage zone. The very fine-grained character of material in the fault core renders it relatively impermeable. The core acts as a fluid barrier to both flow across the fault zone or to flow parallel within the fault core. In contrast, the low-displacement fractures of the damage zone are permeable and accommodate fluid flow that is parallel to but may not allow fluid to easily cross the fault plane. Damage zone permeability generally increases with fracture density toward the fault core. As discussed in more detail below, damage zone permeability is likely to rise suddenly once fracture density reaches a percolation threshold and may have an anisotropic permeability such that permeability is enhanced perpendicular to the shear direction.

Within the damage zone, there are a hierarchy of

structures that govern permeability. There are individual fracture segments where flow is controlled by asperities and roughness. There are the linkages between fractures that may either restrict or enhance flow. And there is the fracture network as a whole that establishes percolation thresholds and forms a dominant pathway for fluid movement.

The fact that permeability is carried primarily by low-displacement fractures in the damage zone suggests that laboratory experiments can be useful in understanding fracture permeability in the subsurface. Typical compression and direct-shear experiments also have relatively low displacement and the properties of the fractures created in these systems may therefore reflect features that control fluid flow in the crust.

3. Permeability of individual fracture segments and the cubic law

Starting with a simple segment or a patch within a complex fracture, we can imagine a feature that is approximately planar with some form of surface roughness. Here, the concepts of parallel plate flow may be applicable (Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996). The 2D aperture of the system modified by surface roughness characterizes the (potentially) anisotropic permeability of the fracture:

$$k_{frac} = \frac{b^2}{12f} \quad (1)$$

where b is the fracture aperture and f is a correction for roughness. Witherspoon et al. (1980) were the first to show that this “parallel plate” model was applicable to real fractures where the two sides of the fracture are in contact as a function of normal stress. This model captures the role of asperities in creating both obstacles to flow and the mechanism for propping the fractures open. Significant experimental work has been conducted characterizing the behavior of this idealized system in terms of roughness, normal stress, and displacement on fracture aperture and fluid flow (e.g., Huo and Benson, 2015; Lee and Cho, 2002; Pyrak-Nolte and Morris, 2000; Vogler et al., 2016; Witherspoon et al., 1980). Although there are limitations to the fidelity of the cubic-law and experimental data, the basic conceptual model relating aperture to flow is a useful framework for thinking about permeability controls of individual segments (Pyrak-Nolte and Morris, 2000).

However, application of roughness to permeability is complex because roughness is neither scale-invariant or a simple, stochastic feature. Measurements of roughness increase with the scale of observation (Power et al., 1988). Detailed field measurements show that roughness parallel to slip decreases with increasing slip while roughness perpendicular to slip remains relatively constant -- indicating anisotropic fracture permeability (Sagy et al., 2007; Brodsky et al., 2011). Moreover, fault surfaces can have larger scale structures superimposed on the fault surface as shown by elliptical mullions that are elongated parallel to the slip direction (Sagy et al., 2007; Sagy and Brodsky, 2009; Edwards et al., 2018).

Laboratory studies indicate potential mechanisms for creating non-stochastic roughness on fracture surfaces. Direct shear experiments described by Frash et al. (2019a), Sagy et al. (2017) and Crandall et al. (2017) show the formation of stepped surfaces perpendicular to the shear direction during fracturing of intact, saw-cut and natural-fracture bearing specimens. In the triaxial direct-shear experiments shown in Figure 1, steps occur at a variety of scales and impose a form of roughness on the fracture surface. Analysis of the stress conditions leading to the formation of these features showed that propagation of en échelon sets of fractures connected by steps developed at lower shear stress than a (smooth) through-going planar fracture (Frash et al., 2019a). A phase diagram for the en échelon system showed that the preferred angles of fracture segments departs from the direct line of shear by 5-20° (similar to Riedel shears) and that these features can form at multiple scales (Frash et al., 2019a). Sagy et al. (2017) observed similar step features developing in elongated deformation zones (termed tool marks) on sliding limestone surfaces that may be similar to comb fractures described in the field by Stewart and Hancock (1991). Analysis of roughness of the tool-marked surfaces showed power-law relationships between surface height and profile length. Aperture profiles presented by Crandall et al. (2017) show similar development of perpendicular-to-shear steps in a natural fracture occurring in shale.

Owing to the complexity of single fracture elements, fracture permeability is often characterized by an effective hydraulic aperture (b_{eff}) reflecting a lack of knowledge of roughness and the

true fracture opening. The latter, where known, is termed the mechanical aperture (b_m), representing the average opening of the fracture. The distinction between b_{eff} and b_m is important where transient fluid flow and the total volume of fluid in the fractures is important. A further useful concept is the more generally available measurement of the volumetric change or dilational aperture (bd) of a rock unit during fracture deformation. The development of statistical relationships among the three apertures as a function of fracture length and displacement is needed for applications such as discrete fracture network modeling (e.g., Frash et al., 2019a).

4. Permeability of Fracture Networks

Ultimately, fluid flow through the crust occurs not through individual fractures but through a fracture network. Connections between the fractures and the geometry of the fracture network create additional constraints on flow. Connections form through fracture coalescence that can be either compressional or tensile in character. Stress analyses show compression-dominated connections in right-lateral shear systems with left-stepping fracture segments and tensile-dominated connections in right-lateral shear systems with right-stepping fracture segments (Segall and Pollard, 1980). Intuitively, compressional connections should impose flow restrictions in comparison with tensile connections. Sibson (1987) provides field evidence for enhanced fluid flow and mineralizing hydrothermal systems at tensile connections at cm to km scales. Experimental examples are evident in direct-shear experiments where tensile openings connect shear segments (See Figure 1; Frash et al., 2017, 2019a).

These connections create strong permeability anisotropy in the fracture system. In addition to spatially varying permeability among alternating shear, compressional, and tensile segments, flow parallel and perpendicular to the shear direction is likely to differ. Tensile openings create transmissive channels perpendicular to shear while shear and compressional segments in the direction of shear create relative restrictions for flow parallel to the shear direction.

Fracture networks make clear that a critical threshold exists where sufficient damage accumulates to allow a connected path for fluid flow (Hyman et al., 2018b). In mature fault systems,

this implies that the damage zone is not characterized by a continuous increase in permeability toward the fault core, but that a sudden increase in permeability occurs as the damage threshold is crossed moving toward the fault core (Figure 2). Fracture network studies also demonstrate that the bulk of fluid flow is carried by a fracture “backbone” wherein a limited set of high permeability fractures and connections dominate transmissivity (Hyman et al., 2018a). An analogous process occurs within individual fracture segments where asperities and restrictions limit sheet-like flow resulting in flow channeling (Tsang and Neretnieks, 1998; Gentier et al., 2000).

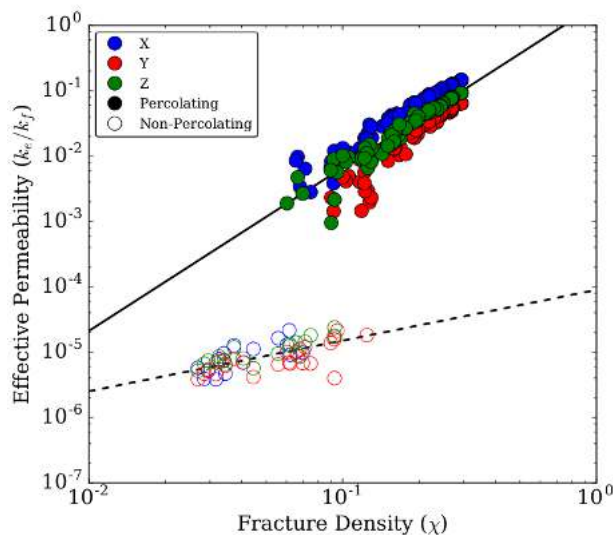


Figure 2: Discrete fracture network simulation of percolation threshold as a function of increasing fracture density in a 3D randomly placed fracture system. The fractures are six orders of magnitude more permeable than the matrix. (After Hyman et al. (2018b)).

5. Laboratory measurements of complex fracture permeability under stress

Most experimental studies of fracture permeability have used either artificial fractures (saw-cut), reassembled laboratory-produced tensile fractures or reassembled natural fractures. A wide variety of materials have been studied including epoxy (Fang et al., 2018; Yeo et al., 1998), glass (Detwiler, 2010), mortar (Gentier et al., 1997), granite (Esaki et al., 1999; Lee and Cho, 2002; Witherspoon et al., 1980), basalt (Witherspoon et al., 1980) and shale (Fang et al., 2017; Gutierrez et al., 2000). We have already noted that measurements of permeability values on single fractures correspond to elements of a fracture network and so do not capture the impacts of fracture connections and network geometry. However, the relationship between the properties

of these “simple” fractures and those of shear fractures in the subsurface is unclear. Planar, saw-cut fractures are clearly idealized representations. Laboratory-induced tensile fractures are likely different than tensile fractures formed in a predominantly compressional subsurface environment and have initial apertures governed by specimen reassembly. Natural fracture aperture distributions are modified by stress cycling during exhumation from the subsurface and, where separated prior to experiments, require reassembly.

In order to avoid these ambiguities, a more limited set of studies of fracture permeability has been conducted on initially intact specimens at subsurface conditions. These experiments are challenging because of the requirements of simultaneously inducing fractures and measuring fluid production. For example, conventional triaxial compression experiments develop fractures that do not connect with shear platens, making permeability measurements difficult.

Nonetheless, triaxial compression experiments with permeability measurements include work on shale (Nygård et al., 2006; Zhang and Rothfuchs, 2008), sandstone (Shukla et al., 2012), granite (Mitchell and Faulkner, 2008) and coal (Cai et al., 2014). Direct shear methods provide a more ready means of connecting fractures and injection fluid hardware and include a study on tuff (Park et al., 2013) and studies we have conducted using a triaxial version of the direct-shear system (Carey et al., 2015; Frash et al., 2016, 2017). Although not directly relevant to shear, a number of hydraulic fracturing experiments have been conducted at elevated stress conditions generally involving injection into a hollow cylinder or notch including studies on shale (Chandler et al., 2019; Frash et al., 2019b; Gehne and Benson, 2019; Li and Einstein, 2019; Li et al., 2016b,a; Menaceur et al., 2015), sandstone (Chandler et al., 2019), and granite (Frash et al., 2019b; Goncalves da Silva and Einstein, 2018; Li and Einstein, 2019).

In order to make a connection between experimental measurements of permeability and fracture geometry, some form of fracture imaging is required. Various methods have been used including post-experiment serial sectioning, x-ray tomography, laser profilometry and direct visualization. Most such observations have been

conducted post-experiment at room (unstressed) conditions (e.g., Cai et al., 2014; Elkhoury et al., 2015; Renard, 2012), but these leave ambiguity as to potential changes in fracture extent and aperture occurring during depressurization. Recently, there has been significant progress toward direct observations of fracture formation, distribution, and aperture at subsurface conditions. Particularly noteworthy are dynamic measurements in which full x-ray CT data have been recorded as a function of strain (Lenoir et al., 2007; Renard et al., 2019; Zhao et al., 2018).

Here we briefly describe experiments conducted in our laboratory aimed at developing relationships among stress, displacement, aperture and permeability by combining x-ray observations with

(which occurs at about 30 MPa) and stabilization of the shear fracture at a direct-shear stress of about 9 MPa, a series of three shear activation events with peak stress about 10 MPa, reduction of direct-shear stress to near zero (i.e., near hydrostatic conditions at 3 MPa), and then a series of step-increases in the confining pressure. The middle panel shows a log plot of permeability. The initial permeability of the intact specimen was less than 1 μD , the limit of our system measurement. The initial fracture event resulted in a 3-order of magnitude increase to about 5 mD; shear reactivation resulted in a 2-order of magnitude increase; and subsequent shear reactivation resulted in continued increases in permeability. The system was then brought to hydrostatic conditions where increasing confining pressure

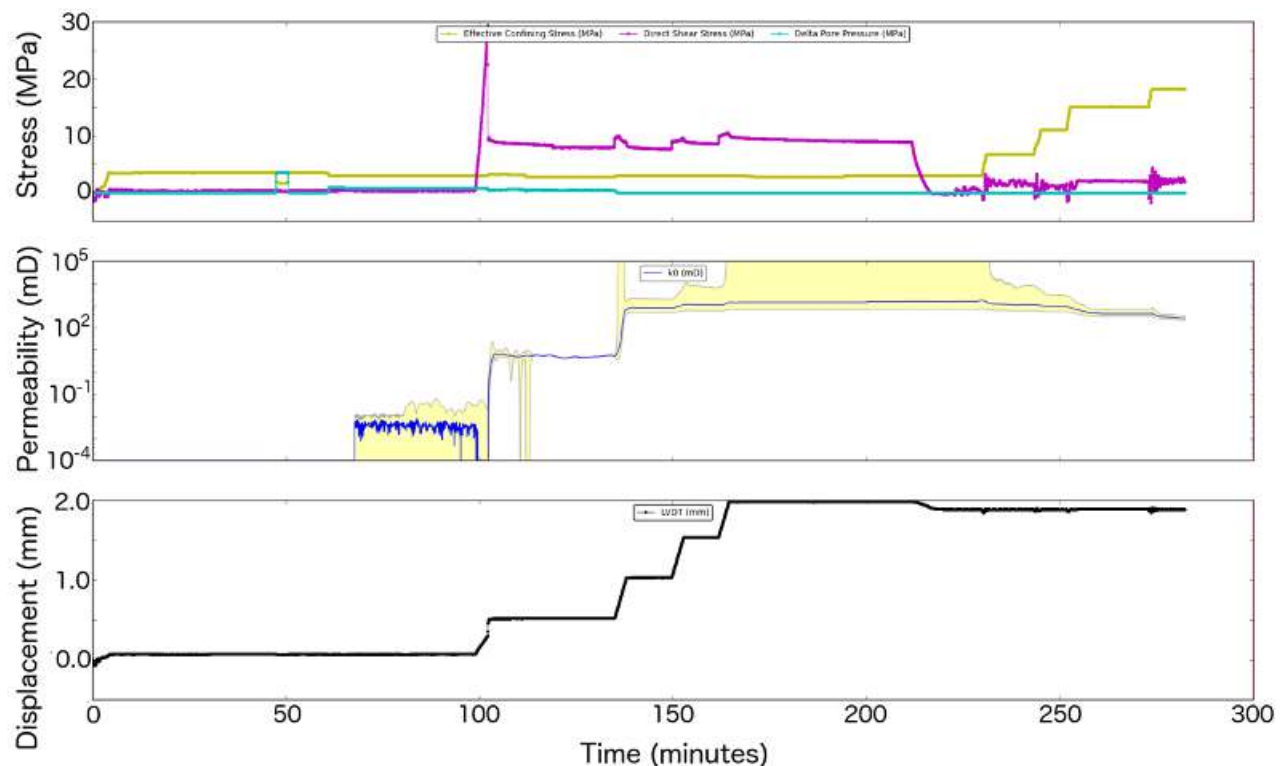


Figure 3: Experimental data for Marcellus shale. Top panel: Purple line = direct-shear stress; dark yellow line = confining stress; cyan line = pore pressure all in MPa. Middle panel: blue line is nominal permeability in mD with yellow-shaded region representing uncertainty, primarily due to differences between upstream and downstream pumps. Bottom panel: black line is displacement measured by LVDT on the piston.

triaxial coreflood methods (Carey et al., 2015; Frash et al., 2016, 2017, 2019a). We used a triaxial direct-shear coreflood system with an aluminum coreholder that allows simultaneous x-ray radiography and tomography (Figure 1). Figure 3 illustrates a typical experimental run as a function of time. The top panel shows system stress and pressure which includes an initial period of equilibration at the initial confining pressure (3 MPa), application of direct-shear stress until fracture

resulted in declining permeability spanning about an order of magnitude. Shear displacement shown in the bottom panel was measured by an LVDT connected to the upper shear platen and jumped during the initial fracture event. The shear platen was driven approximately 0.5 mm of displacement during each of the subsequent fracture events. Relaxation of the system to hydrostatic conditions resulted in a slight decrease in displacement.

Experimental results from Figure 3 are summarized at each of the primary fracture and stress changes in Figures 4 and 5. At each stage, we show direct comparisons between permeability, specimen dilation, and fracture geometry (shown as radiographs) as a function of stress conditions. Figure 4 shows the first half of the experiment containing the initial fracture event and subsequent fracture reactivation events. The radiographs show a progression from the intact spec-

geometry are more subtle than changes due to fracture reactivation but are apparent in the dilation measurements: permeability and dilation decrease with applied stress.

Analysis of permeability and dilation relations are approximately linearly correlated as a function of shear reactivation or changes in confining stress (Figure 6). Note that linear relations are not consistent with cubic law behavior. As is ev-

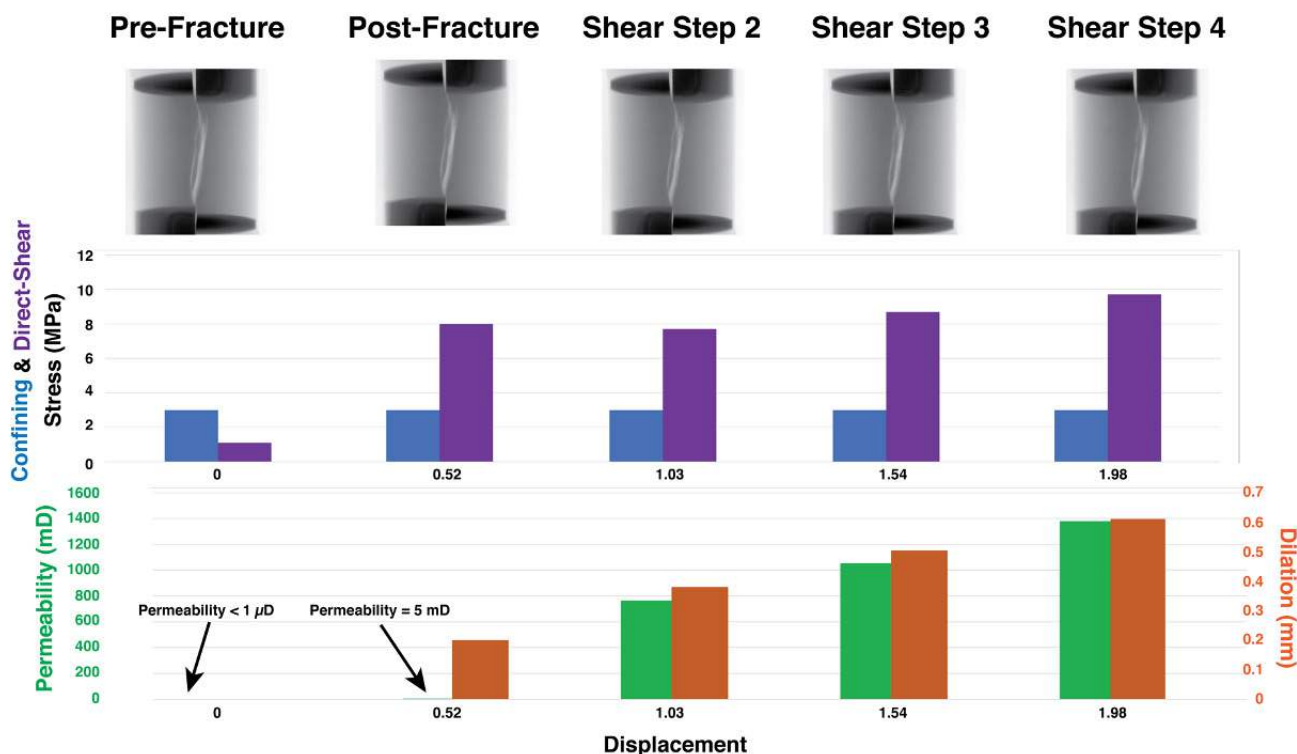


Figure 4: Radiographs (collected without disturbing experimental conditions), stress, permeability, and dilation for each of the primary fracture events shown in Fig. 3.

imen to formation of a multi-stranded non-planar fracture system. The aperture and fracture porosity vary along the length of the fracture, with tighter regions prominent at the fracture ends. Fracture reactivation greatly increases porosity, aperture and permeability, with the first reactivation having a particularly dramatic effect. Dilation of the specimen was measured as the average change in diameter obtained directly from the radiographs and provides a measure of the net aperture porosity. The dilation increases steadily with each fracture reactivation event.

Figure 5 shows the second half of the experiment where stress conditions were returned u\\ to isotropic conditions at 3 MPa (first panel), followed by subsequent increases in the isotropic stress to 18 MPa (panels 2-5). The changes in fracture

ident in the radiographs, the permeability in the direction of shear is not controlled by average fracture porosity (dilation) but is governed by shear segments of the fracture system that are relatively tight (low porosity) which have little effect on net dilation. The difference in slope between the curves is important for some applications. Fracture reactivation has a stronger influence on fracture permeability than changes in effective stress on the fracture. As a result, permeability gains from fracture reactivation may be preserved despite pressure drawdown effects during production of hydrocarbon.

The results shown here combined with additional experiments not shown have a number of implications as further discussed in Frash et al. (2016, 2017, 2019a):

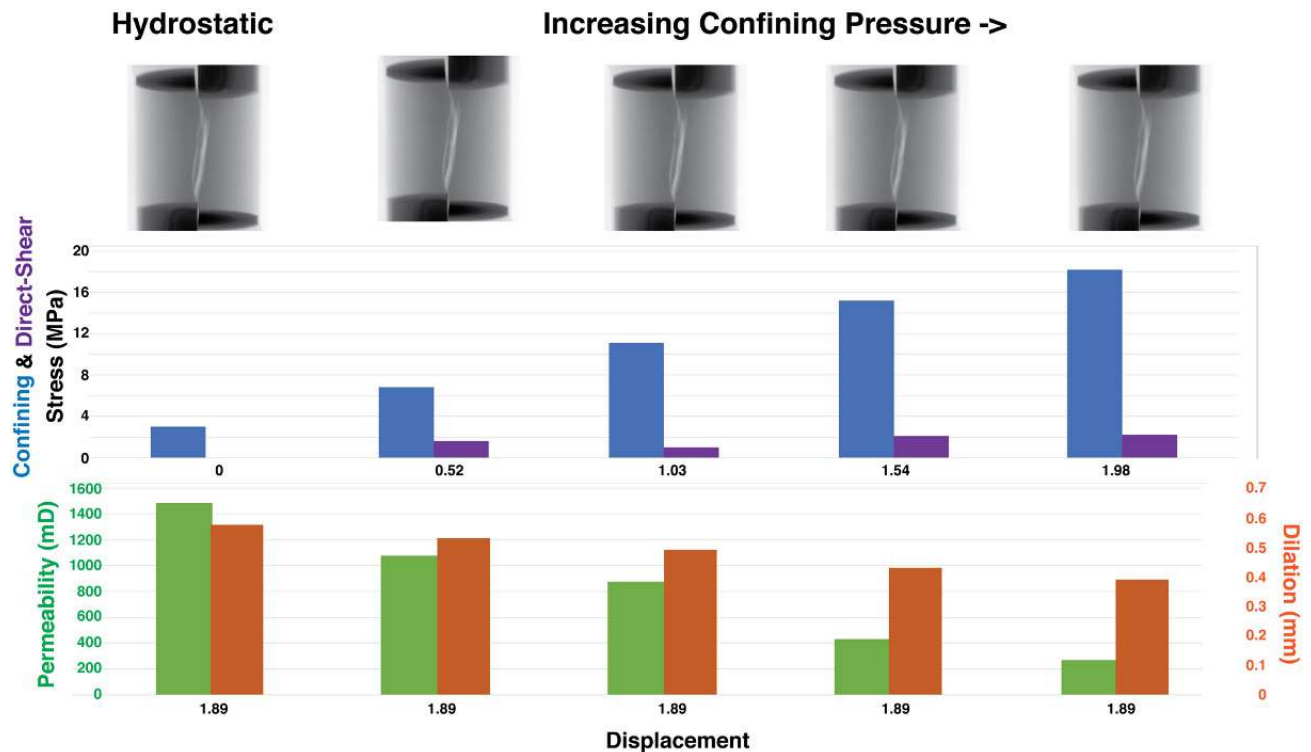


Figure 5: Radiographs, stress, permeability, and dilation for each of the changes in confining pressure shown in Fig. 3.

1. Initial fracture permeability depends on the confining stress at time of formation. Permeability decreases by 2-3 orders of magnitude when confining stress increases from 3 to 30 MPa.
2. Fracture reactivation improves permeability but is most dramatic at low stress conditions (Figure 4). At high stress conditions, permeability changes are smaller and may either increase or decrease.
3. Permeability is not controlled by average fracture porosity or system dilation but by pinch-points formed along shear segments and at connections between fracture segments.
4. Fractures have strong anisotropy within the fracture plane. Permeability parallel to shear is governed by pinch-points. Permeability perpendicular to shear is governed by open, tensile regions that flow as a network of open channels.
5. Shear fractures form not as planar features but as multi-stranded, en échelon structures. These structures create permeability anisotropy and give rise to specimen dilation with increasing fracture displacement at stress conditions of the experiments.

6. Field Observations

Recognition of fractures as conduits for fluid flow has long been appreciated beginning with observations in mines and the association of ore deposits with fracture systems (as reviewed by Hickman et al., 1995). Further understanding of fracture

and flow has been developed through a combination of reservoir-scale observations of pressure and fluid movement; wellbore observations; field experiments on single faults; and measurements of the permeability of fractures in recovered core. Early on, flow in fractures was understood to be episodic and tied to fault movement. Field studies showed the importance of reactivation

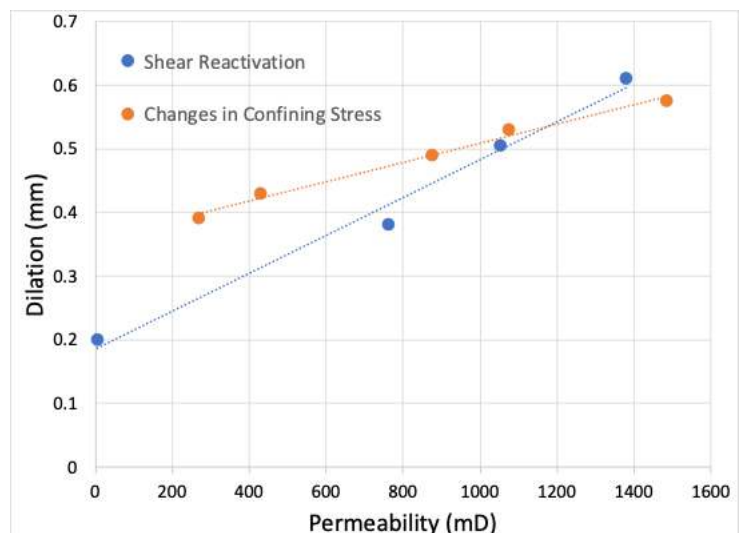


Figure 6: Summary of permeability and dilation relations shown in Figures 4 (= "shear reactivation") and 5 (= "Changes in confining pressure"). The data for shear reactivation show the progressive increase in permeability (starting at < 0.001 mD for dilation = 0) for the initial fracture (dilation = 0.2) and subsequent reactivation events. The data for changes in confining pressure reflect application of isotropic stress conditions at 3 MPa (highest permeability value associated with a slight drop in dilation) and subsequent increases in confining pressure resulting in decreased fracture dilation and decreased permeability.

of fractures in (re)establishing fracture permeability with feedback between the resulting fluid flow and development of fluid pressure impacting renewed failure (Gratier, 2011; Sibson, 1992). This was formalized in a conceptual framework presented by Faulkner et al. (2010) showing the interconnections among fault rock composition, fracture structure, fracture mechanics, and fluid flow.

Key observations have been developed by considering the dynamics of oil and gas movement in relation to faulting. Losh and Haney (2006) found episodic increases in fault permeability tied to seismic activity in the Gulf of Mexico. Understanding of such behavior was developed in the concept of “fault-valve action” by Sibson (1981, 1992). While faults can act as fluid pathways, they can also act as seals either by juxtaposing low-permeability rocks against high-permeability rocks or because of intrinsic low permeability character (Downey, 1984). Fisher and Knipe (1998, 2001) review detailed observations at the core-scale of fracture permeability from North Sea and Norwegian Continental Shelf clastic reservoirs. In many cases, fracturing results in significant reduction in permeability due to compaction, grain fracturing and clay entrainment with time driving post-fracturing cementation and healing. This behavior is reflected in observations of compartmentalization of fault-bounded reservoirs as found, for example, in the North Sea (Fisher and Knipe, 2001; Jeanne et al., 2013).

The relationship between fracture activation and fracture permeability is further illustrated by work of Barton et al. (1995). Using borehole observations of fault-rich regions, they found that faults optimally oriented for activation in the current stress field (and presumably more recently activated) were much more permeable than non-optimally oriented faults. This indicates that continued movement of faults is necessary for faults to maintain relatively higher permeability. Townsend and Zoback (2000) used a similar approach and found that such critically stressed faults provide an explanation for the unexpectedly high-permeability (0.1-0.01 mD) of the upper crust.

Field data on the permeability of faults have been obtained by measurement of hydraulic diffusivity (i.e., the rate of propagation of a pressure disturbance). For example, Xue et al. (2013, 2016) derived fracture permeability from measurements

of tidal-forcing of water levels in wells in or adjacent to the Wenchuan and San Andreas fault systems. At the Wenchuan fault, they found that permeability decreased from 1.6 mD by about a factor of 60% over the course of a year of monitoring. At the San Andreas fault, they found a permeability of 10 mD near the fault that fell to 1 mD further from the fault.

These are larger scale observations and the measured permeability may correspond to a rather complex system of fault core(s) and damage zones (e.g., Fig 10 of Faulkner et al., 2010). Measurements at the scale of a fault were obtained in a series of field experiments by Guglielmi and others (Guglielmi et al., 2015a,b, 2020; Jeanne et al., 2018). They used a straddle packer in a borehole drilled through a fault system. They isolated a 2-3 m region of the fault system and injected fluid to activate the fault and measure fault permeability. Fracture activation was accompanied by aseismic and seismic deformation with permeability increases of 20X in a fault in carbonate that was originally 7D (Guglielmi et al., 2015a); with a two-order of magnitude increase in permeability in a fault in shale at Tournemire (Guglielmi et al., 2015b); and with complex, spatially varying (up to 3 orders of magnitude) increases and decreases in permeability in a fault in shale at Mont Terri (Jeanne et al., 2018).

7. Conclusions

There is renewed interest in developing predictive models of fracture permeability, driven in part by applications in the energy sector. In this paper, we combine a review of the literature and discussion of our own laboratory experiments to shed light on some of the complexities involved in understanding flow through fracture systems. A wide range of observations in nature and the lab show that faults develop not as simple planar features but as individual segments that coalesce with increasing deformation.

To shed light on the impact of these structures on permeability, we describe integrated triaxial direct-shear and x-ray radiography/tomography experiments performed on initially intact rock specimens. As in nature, we find that shear systems develop in segments arranged in en échelon patterns such that flow must pass through both shear and tensile segments. Flow in the direction of shear encounters a series of alternating segments that are relatively closed and

open such that the net permeability is governed by the tightest features and is not directly related to the average fracture aperture or porosity. In contrast, flow perpendicular to the direction of shear can follow tensile channels and avoid flow restrictions. The result is strong anisotropy in fracture permeability.

Our experiments reveal that fracture permeability is highly sensitive to conditions at the time of fracture creation with increasing confining stress leading to reduced permeability. We find a similar but less sensitive response of fractures to post-fracture changes in confining stress. Field studies also reveal the strong anisotropy of fracture flow; properly accounting for this is critical to determining whether faults are acting as seals or conduits for flow in a given direction.

Laboratory measurements and field studies show that flow in fault systems is episodic in character with fault reactivation necessary to maintain fracture permeability and fault quiescence allowing fracture healing to occur over relatively short periods of time due to a combination of processes including creep and chemical reactions. Additional resources on the subject of fracture permeability can be found in reviews by Bense et al. (2013); Caine et al. (1996); Faulkner et al. (2010); Hickman et al. (1995); Wibberly et al. (2008).

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Fluid Flow through Fractures with Corrugated Surface Roughness

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Abstract

Recent studies have shown that the generation and suppression of corrugated fracture surfaces depend on the relative orientation between mineral fabric and layering. Corrugated fractures result in an inherent anisotropy in fluid flow. In this short note, we describe recent work to explore, numerically, the relative bonding strength among components in a layered medium that give rise to corrugated fracture surfaces and the resultant anisotropy in fluid flow field. These initial simulations demonstrate (1) that corrugated fractures form when layering and mineral fabric provide resistance to fracturing in the same direction during tensile failure, and (2) that highly conductive flow paths form parallel to ridges and valleys of the corrugations, even after shear displacement; flow rates parallel to the ridges can be 1.14 to 20 times higher than flow rates perpendicular to the ridges. Improved understanding of the role of layering and in-plane mineral fabric on the generation of corrugated surfaces can aid in the design of fracturing strategies to maximize fluid production potential from layered rock.

1. Introduction

Fluid flow through fractures in rock is well-known to be controlled by fracture surface roughness that forms the voids and regions of contacts in a fracture¹⁻⁷. In nature, fractures can emerge with corrugated surfaces (Figure 1), with flow paths parallel to the ridges largely unobstructed compared to the more tortuous path perpendicular to the ridge. The amplitude of the corrugations can vary (Figure 1) with the variation often attributed to failure mode, structural features, mineralogy, stress orientation, as well as geochemical interactions that can alter mineral bond strength^{3,8-10}. Recent work by Jiang et al.¹¹ demonstrated that corrugated fracture surfaces (Figures 1a & 2a) arise in tensile fractures in layered media, and that the degree (amplitude) of the corrugations

is affected by the relative orientation between layering and in-plane mineral fabric. In their study, the ridges of the corrugations always ran parallel to the in-layer mineral lineation. They observed that large amplitude corrugations were formed when the resistance to fracturing from the mineral fabric and layer orientations were aligned, while small amplitude corrugations were produced when a fracture propagated parallel to layering but deviated around oriented mineral fabric. Here, we present the results of a new numerical study currently underway to examine the effect of mineral fabric and layering on the generation of corrugations and how these corrugations affect flow anisotropy in a fracture. Understanding the links among layering, mineral fabric

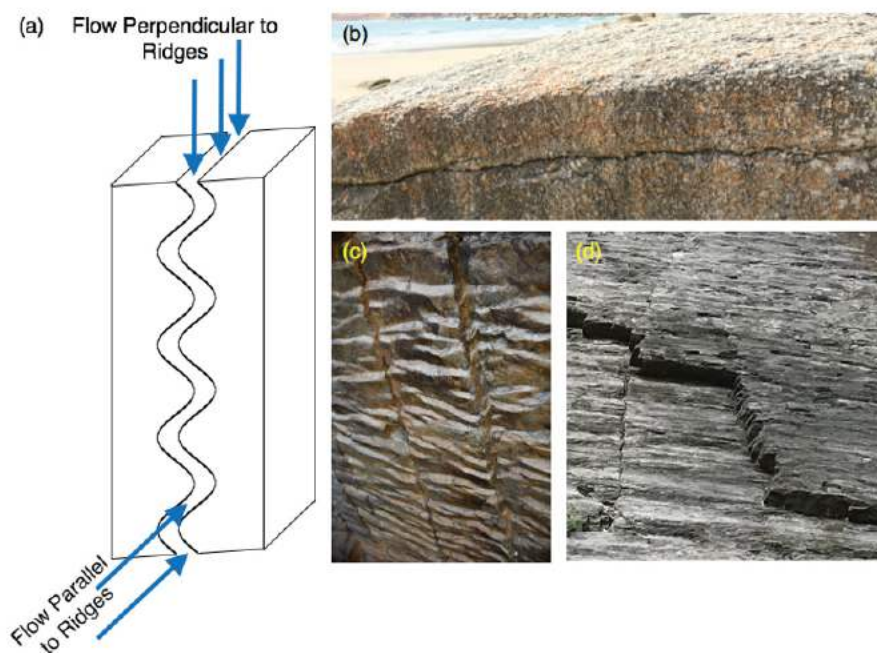


Figure 1. (a) Schematic of a corrugated fracture. Fractures exhibiting different degrees of corrugation in (b) granitic rock, Wilson's Promontory, Australia, (c) & (d) sedimentary rock, Lederberg State Park, Australia. (Courtesy of Pyrak-Nolte).

and corrugations will aid in the design of induced fractures in layered rock to maximize production potential in fractures.

2. Tensile Fractures in Layered Media

Quantitative understanding of the presence and orientation of the ridges and valleys formed by

corrugated surfaces is required to enable identification of anisotropic fracture flow paths that will enable next-level subsurface flow engineering. Mineral layering and fabric orientation have been shown to produce corrugated fractures when both provide resistance in the same direc-

tion during tensile failure¹¹ (Figure 2a). Both the in-layer mineral bonding and bonding between layers cause a fracture to deviate during crack propagation, creating anisotropic corrugated surface roughness.

Here, simulations of three-point bending test using a discrete element method (DEM¹²) were per-

formed to simulate induced tensile fracturing in a specimen with a central notch (Figure 2b inset, established *via* Particle Flow Code, Itasca Consulting Group, Inc.). The simulated rock sample in the DEM simulations had dimensions of 7.62 cm in width, 2.54 cm in height with a thickness

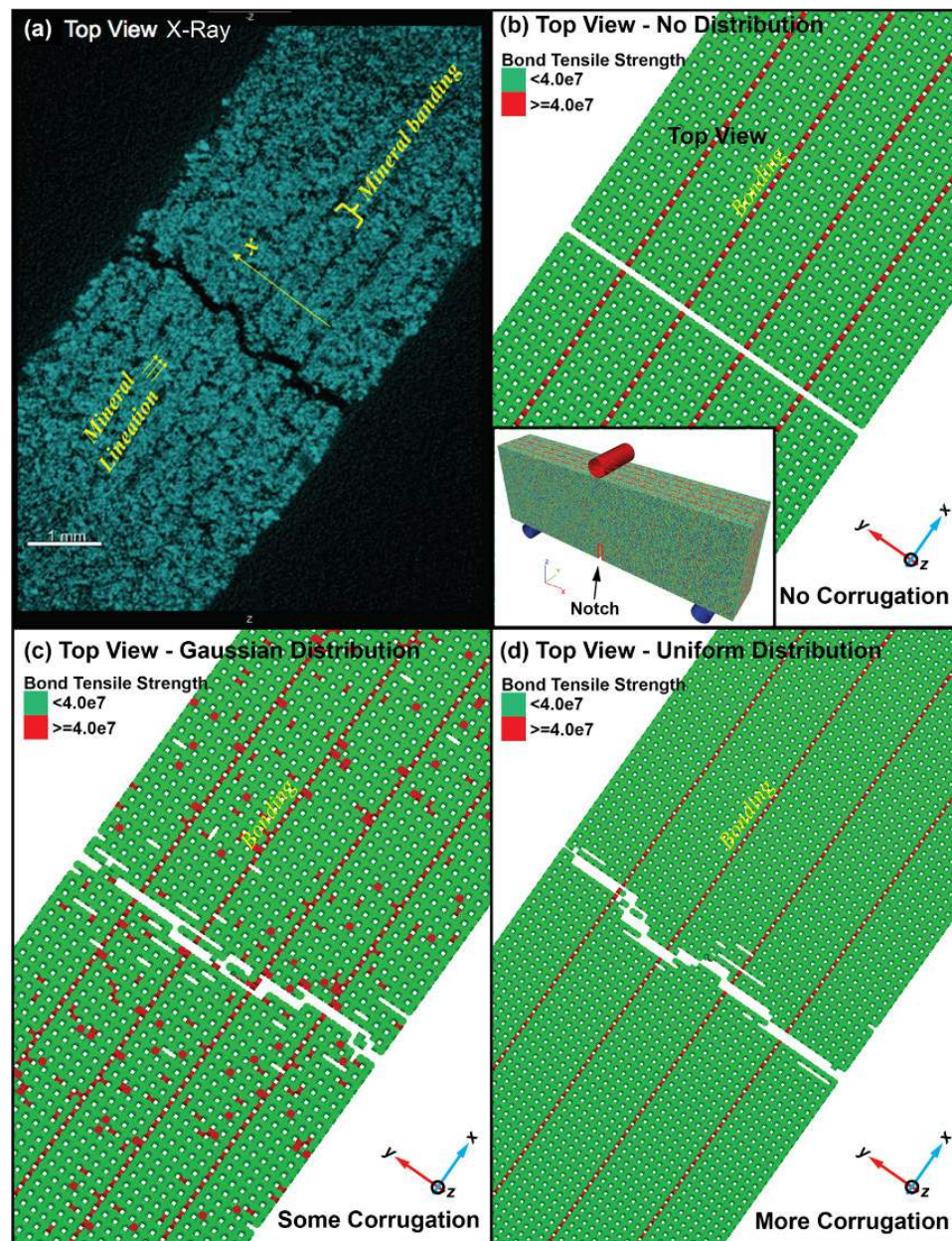


Figure 2. (a) X-ray image of fracture corrugation in additive manufactured rock analogs¹¹. (b) Simulated fracture geometry (white region between the two green blocks, with other small white areas representing pores) with isotropic contact tensile strength in mineral layers. (c) Simulated fracture geometry if a Gaussian distribution is applied to contact tensile strength in mineral layers. (d) Simulated fracture geometry if a random distribution is applied to contact tensile strength in mineral layers.

Figure 2, while mineral layers are shown in green. The sample shown in Figure 2b contains $180 \times 60 \times 30 = 324000$ particles with identical diameters of $\sim 423 \mu\text{m}$ and with an isotropic bonding strength. In Figure 2c, the sample contains $180 \times 60 \times 30 = 324000$ total particles with identical diameters of $\sim 423 \mu\text{m}$ but with a Gaussian distribution of bonding strengths. Finally, the sample shown in Figure 2d contains $240 \times 80 \times 40 = 768,000$ total particles with identical diameter of $\sim 318 \mu\text{m}$ and a random distribution of bonding strengths. Note that the divider mineral bonding is stronger than the mean value of other contacts in terms of tensile strength by a factor of 10.0. The top slice views of the simulated tensile fractures with corresponding contact tensile strength distributions are shown in Figure 2b, 2c, 2d. Detailed model and bonding strength distribution parameters are listed in Table 1.

In the isotropic case, a difference in bonding strength between the layers (red particles in Figure 2b) and within the layer (green particles) was

to anisotropic flow with the degree of anisotropy dependent on the aperture and contact area spatial and probabilistic distributions^{3,14-17}. In this new study, a suite of numerical simulations was performed to determine the effect of the amplitude of corrugation on flow anisotropy. Fracture corrugation was simulated by two sinusoidal surfaces with ten cycles with a fixed wavelength ($\lambda = 10 \text{ mm}$) with an offset in the vertical direction of 0.2λ (Figures 1a and 3). The amplitude of the sine wave that defined the surfaces was varied from 0.05λ , 0.1λ , 0.2λ , 0.4λ , 0.8λ , to 1.2λ for the corrugated fractures (Figure 3). The simulated fractures were defined as 10.0λ in length in the direction of flow and 1.0λ in width perpendicular to the flow direction to maximize computational efficiency. The volumetric flow rate was calculated (using Abaqus CAE) for a constant head at the inlet of 5 kPa and 0 kPa at the outlet, first in a direction parallel to the ridges, and then in the direction perpendicular to the ridges (Figure 1a). The flow through a non-corrugated uniform aperture fracture was

Table 1. Model Parameters

Parameter	Value
Linear Effective Modulus (MPa)	850
Normal to Shear Stiffness Ratio	1
Parallel Bond Effective Modulus (MPa)	850
Parallel Bond Stiffness Ratio	1
Friction Coefficient	0.3
Parallel Bond Tensile Strength (MPa)	4.0
Parallel Bond Cohesion (MPa)	8.0
Mineral Bonding Strength Multiplier	10.0
Gaussian Distribution	Mean, 1.0; Variance, 5.0
Random Distribution	Range, 0.0~5.0

not sufficient to produce corrugated fracture surfaces. The generation of corrugations required a high degree of in-layer mineral heterogeneity such as in the random distribution of in-layer bounding strengths (Figure 2d). This initial study suggests that micro-structural distribution of bonding strengths plays a key role in the generation of corrugations. Additional studies are underway to explore the controls on the amplitude and wavelength of the corrugations.

3. Flow Anisotropy in Corrugated Fractures

Anisotropy in fracture surface roughness can lead

also determined to act as an isotropic reference. In addition, simulations were performed with a phase shift between the surfaces to mimic shear displacement (Figure 4). The lower fracture was phase-shifted by 0.05λ and 0.1λ perpendicular to the ridges after the universal 0.2λ vertical offset was applied.

4. Flow Perpendicular vs. Flow Parallel to the Ridges

The resultant flow rates, Q_N , were normalized by the flow rate from the non-corrugated fracture. Q_N at the outlet for cases with different normal-

ized amplitudes, A_N , (amplitudes are normalized by the sinusoidal wavelength) are shown in Figure 3, noting that flow rates are normalized against the parallel plate case, i.e., $A_N = 0.0$. For a constant vertical offset, the degree of anisotropy in flow through corrugated fracture surfaces depends on the amplitude of the corrugation. For flow perpendicular to the ridges, Q_{Nper} , even for values of A_N that are relatively small (0.05λ , 0.1λ , and 0.2λ), the flow differs between the two orthogonal directions as compared to the non-corrugated case (Figure 3). Q_{Nper} decreases sharply to less than half the value of non-corrugated case when A_N exceeds 0.5λ , and as small as one fiftieth for 1.2λ . Additional increases in amplitude will inevitably result in a minimal hydraulic conductivity. On the other hand, parallel to the ridges, Q_{Npar} is less affected by increases in the corrugation amplitude. Specifically, Q_{Npar} is slightly enhanced for small corrugation amplitudes while a noticeable reduction occurs at $A_N = 0.4\lambda$. For $A_N > 0.4\lambda$, Q_{Npar} decreases slightly but the flow rate reduction is significantly less than that observed

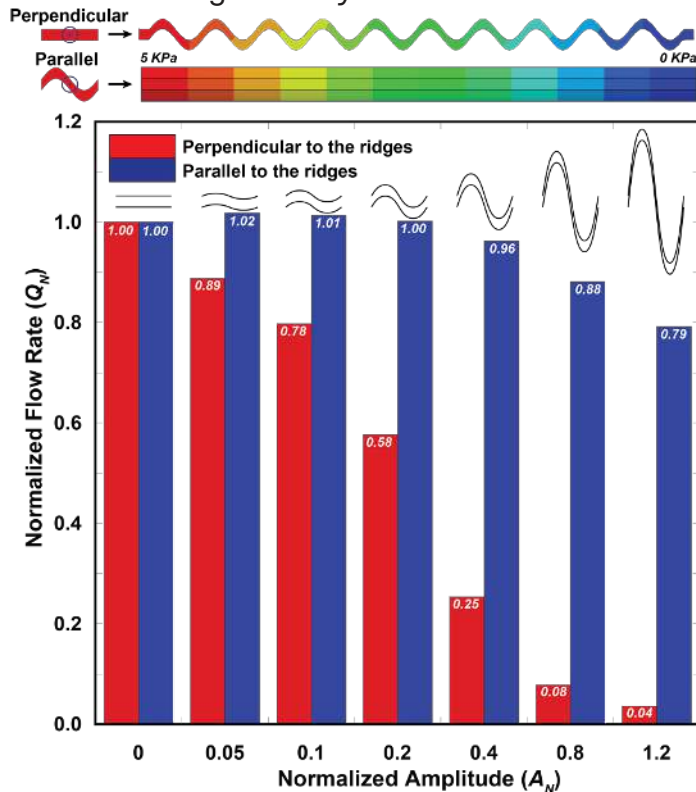


Figure 3. Normalized flow rate (Q_N) vs. normalized corrugation amplitude (A_N). The side and left projections of the representative flow geometries perpendicular and parallel to the corrugation ridges are shown on the top two rows with the pressure gradient profile. The cross-sections of different corrugation amplitudes are shown as inset schematics.

for Q_{Nper} . For the $A_N = 1.2\lambda$, $Q_{Npar} \sim 20Q_{Nper}$. For all cases, $Q_{Npar} > Q_{Nper}$, which demonstrates the importance of identifying when corrugations

may occur from layering and/or mineral texture.

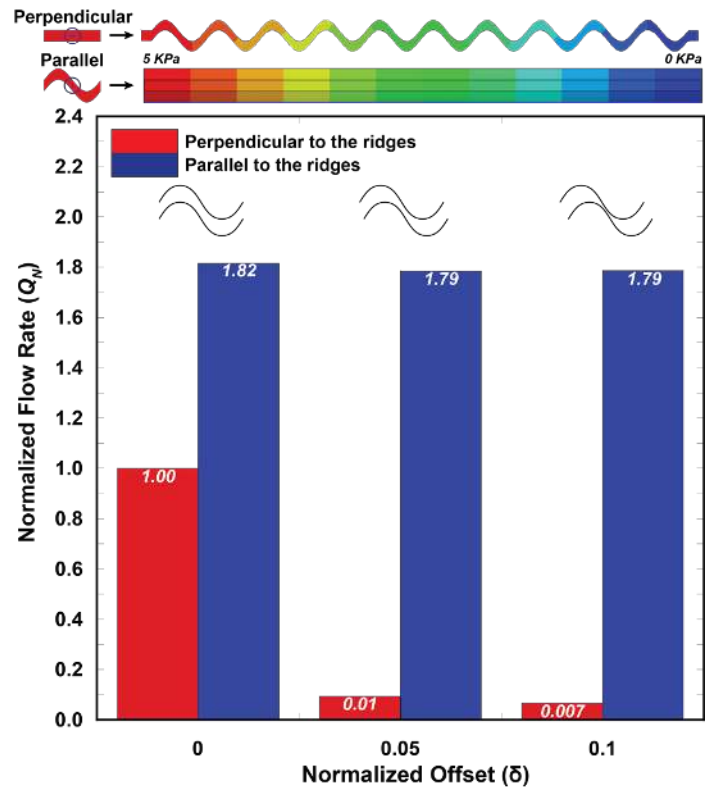


Figure 4. Normalized flow rate (Q_N) vs. normalized offset (δ). The side and left projections of the representative flow geometries perpendicular and parallel to the corrugation ridges are shown on the top two rows with the pressure gradient profile. The cross-sections of corrugations with shear displacement offset of 0.05λ and 0.1λ are shown as inset schematics.

5. Effect of Shear Displacement on Flow Anisotropy

Fractures in rocks are often subjected to physical and chemical processes that alter the fracture void geometry^{8,10}. Here, the effect of shear displacement on flow anisotropy in corrugated fractures is examined. Two simulations were performed using fractures with $A_N = 0.2\lambda$ and phase shifts of $\delta = 0.05\lambda$ and 0.1λ . The results are shown in Figure 4. Note that the flow rates are normalized by the values from $A_N = 0.2\lambda$ (Figure 3) with the flow direction perpendicular to the ridges. Shear displacements significantly affect Q_{Nper} but not Q_{Npar} . A two-order of magnitude reduction in Q_{Nper} is observed at $\delta = 0.05\lambda$, and further reduction is observed $\delta = 0.1\lambda$. When contact is made with a large enough offset, flow perpendicular to the ridges ceases, resulting in zero hydraulic conductivity. However, the transverse flow paths are much less sensitive to the offset alteration, showing little or no change in Q_{Npar} .

6. Conclusions

This work is part of an ongoing study to elucidate the role of mineralogy and microstructure on induced tensile fracture geometry, and on the resulting fluid flow behavior within induced fractures in rock. As presented here and in the experimental work of Jiang et al.¹¹, corrugations in fracture surfaces can arise from a competition among bonding strengths within a layer and between layers. In-layer preferentially oriented minerals are observed in natural materials such as in shale and in igneous and metamorphic rocks where foliation and compositional layering orientations do not align. Future studies will examine how the probability and spatial distribution of bonding strength and of layer spacing control corrugations amplitudes and wavelengths, and what controls the generation of corrugations with two or more co-existing wavelengths as observed in the outcrop in Figure 1d.

As shown, the presence of surface corrugations leads to preferential flow paths. Specifically, corrugation amplitude strongly affects flow anisotropy with flow parallel to the corrugation ridges ranging from 1.14 to 20 times that perpendicular to the ridges. A corrugation amplitude greater than half of the corrugation wavelength produces a significant reduction in hydraulic conductivity (one tenth of non-corrugated case). More importantly, a relatively small amount of shear offset can significantly reduce the hydraulic conductivity perpendicular to the corrugation ridges while those through parallel paths to the ridges are only slightly affected. Future studies will continue to explore the role of corrugations on anisotropic flow with both short and long wavelengths, and the role of shear displacements on these flow fields.

This study highlights the importance of understanding microstructural controls on the formation of fracture geometry in layered rock and on the resultant macroscopic flow field. When possible, mineralogical studies should be performed to determine if in-layer mineral fabric exhibits a preferred mineral orientation or preferred direction of mineral-bonding strengths. The potential exists to exploit these microstructural controls on fracturing to engineer enhanced induced-fracture hydraulic conductivity in the Earth's subsurface.

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The Effect of the Intermediate Principal Stress on the Permeability Tensor of a Fractured Rock Mass

Submitted by Adriana Paluszny and Robert Zimmerman, Department of Earth Science and Engineering, Imperial College London, London, UK.

The permeability of subsurface fractured rock masses is strongly influenced by highly permeable fractures, and in some cases also compartmentalized by impermeable faults. The state of stress at any point in the Earth’s crust is almost always anisotropic, with a significant deviatoric component. Fracture networks that form under these conditions will be geometrically anisotropic (Zoback et al., 1989) and will display highly directional

patterns that often record the deformation history of the rock (Laubach et al., 2018). Depending on their individual orientations, fractures will experience different magnitudes of compression and shear displacement, both of which have a strong influence on hydraulic transmissivity. Observations indicate that fractures subjected to significant shear displacement will accrue higher permeability in the direction perpendicular to the

shear direction than in the direction parallel to it (Auradou et al., 2005).

Remote stresses preferentially activate specific fractures with a favourable orientation to the far-field stress. These fractures can form high-conductivity pathways that span the entire domain and dominate the macroscopic permeability. Two-dimensional studies (Baghbanan & Jing, 2008; Jing et al., 2013) have found that the direction of maximum permeability of a fractured rock mass is aligned with the orientation of the maximum principal stress. However, these models assume isotropic transmissivity of individual fractures and, being two-dimensional models, cannot account for the effects of the intermediate principal stress. Most numerical studies of the mechanical deformation of fractured rocks have been two-dimensional, whilst most three-dimensional studies of permeability have been restricted to fluid flow, and have not included mechanical effects. Some recent models have been extended to three dimensions, but ignore shear-induced dilation, or implement constitutive models that account for shear-induced dilation in an isotropic manner. Further details of previous work in this area has been reviewed by Lang et al. (2018).

This letter summarizes the findings of a paper published in *Water Resources Research*, entitled “Relationship between the Orientation of Maximum Permeability and Intermediate Principal Stress in Fractured Rocks” (Lang et al., 2018). That paper investigated the permeability of three-dimensional fractured rocks as a function of network geometry and remote compressive stresses. Fractures were assumed to be stochastically generated disks, and focus was placed on investigating the

effect of assumptions regarding individual fracture permeability on the overall properties of the fracture network. This three-dimensional analysis includes the coupled direct simulation of individual fracture transmissivities as a result of shear deformation.

The simulations capture processes both at the meso-scale (meters) and at the small-scale (millimeters). Fractures are represented discretely at the meso-scale using a finite element-based continuum mechanics approach, which resolves the compressive stresses, while taking into account friction along fracture surfaces (Nejati et al., 2016). This computation uses an Augmented-Lagrangian gap-based approach that assumes linear elastic constitutive behavior of the rock. This approach was specifically developed for the accurate computation of contact stresses in fracture networks using the finite element method, and does not rely on arbitrarily imposed penalties, but instead relies on three material properties: Young’s modulus, Poisson’s ratio, and macroscopic friction coefficient of the rock. Using this approach, the volume of the rock is represented by isoparametric tetrahedral elements and the fracture surfaces are represented using isoparametric triangular elements. This methodology is implemented as part of the Imperial College Geomechanics Toolkit (Paluszny & Zimmerman, 2013).

Compression of the 3D fractured rock mass results in a distribution of stresses along the triangular elements of the fracture surfaces (Figure 1). Subsequently, a small-scale model computes the resulting fracture stiffness and anisotropic fracture transmissivities locally for each individu-

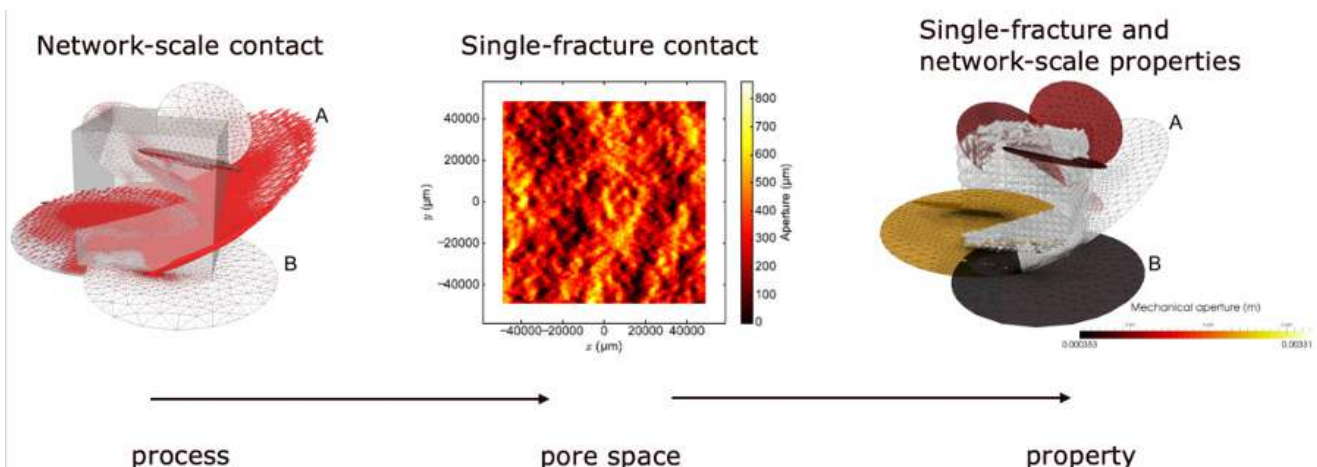


Figure 1. Two-scale approach to model stress-dependent permeability that evolves during the deformation of a fracture embedded in a fractured rock mass.

al fracture, as a function of contact stresses. The stiffness and transmissivity result from numerically modelling local shear-induced dilation and elastic compression. These mechanical and flow fracture properties are then used to populate the mechanical and flow properties of the fractures at the meso-scale in order to evaluate the meso-scale permeability tensor of the fractured rock mass (Lang et al., 2014).

This approach is novel in that fracture permeability is not prescribed as a uniform value, nor is it only a result of hydro-mechanical interaction of fractures and matrix. Instead, it incorporates the changes that fractures undergo during compres-

gate fractures, and 256 different eight-fracture datasets, so as to develop a comprehensive understanding of the relationship between confining stresses and fractured rock permeability. Some results are shown in Figure 2.

As part of the network scale study, 2120 fractures having different (initial) random rough surfaces were deformed, resulting in a consistent mechanical response, as shown in Figure 2C. Fracture aperture distribution and permeability were found to be consistently anisotropic, as a result of progressive deformation of the initially random small-scale fracture roughness. The method assumes that the fracture is a self-affine

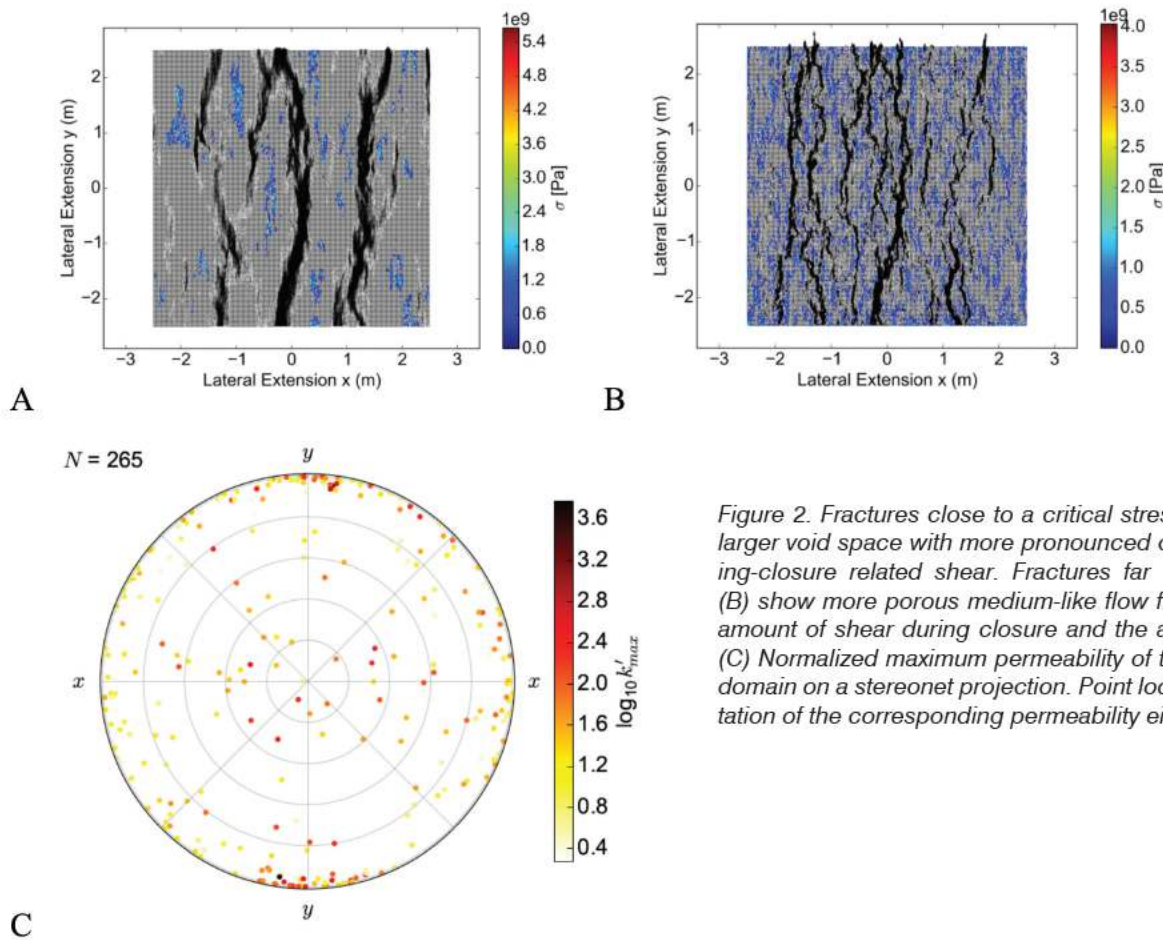


Figure 2. Fractures close to a critical stress state (A) possess a larger void space with more pronounced channels due to opening-closure related shear. Fractures far from this stress state (B) show more porous medium-like flow fields. This reflects the amount of shear during closure and the acting normal traction. (C) Normalized maximum permeability of the fracture rock mass domain on a stereonet projection. Point locations mark the orientation of the corresponding permeability eigenvectors.

sion at the small scale, which in turn influence their macroscopic properties. This results in a comprehensive investigation of the effects of the small-scale deformation of the fracture surface on fracture permeability, and its subsequent effect on network-scale properties. In particular, it allows the estimation of the permeability tensor of a complex fracture-matrix system. The paper contains an application of this methodology to a single fracture, a set of rotating pairs of conju-

composite surface that acts as an elastic body under confining pressure. Therefore, the method explicitly models changes to fracture roughness, using small-scale methods originally developed for the study of compaction and dissolution and precipitation effects on fracture permeability (Lang et al., 2015). Simulations consistently yield anisotropic permeability of individual fractures, which influence the resulting macroscopic maximum permeability direction, which is found

to be aligned with the remote intermediate principle compressive stress.

When assuming isotropic fracture transmissivities, this model can reproduce commonly reported values of maximum permeability parallel to the maximum remote compressive stresses (Min et al., 2004; Baghbanan & Jing, 2008; Jing et al. 2013), because there is a preferential mechanical activation of fractures aligned with the maximum compressive stress. In contrast, when fracture permeability is modelled mechanically at the small scale, numerical experiments indicate shear-displacement induced anisotropic transmissivity of fractures. This causes the fracture network's maximum permeability to be consistently aligned in the direction of the intermediate remote compressive stress. Thus, in these experiments, the direction of maximum permeability of the network is aligned with the direction of the intermediate principal stress applied on this network. These results highlight the importance of accounting for anisotropic fracture permeability, and its potential effect on the macroscopic permeability of sub-surface fractured rock masses. It also highlights the importance of the characterization of the intermediate principal stresses, as this parameter may strongly influence the permeability tensor of the subsurface fractured rock mass.

Over the past decade, we have developed capabilities to computationally model geomechanically realistic three-dimensional discrete fracture deformation, including small-scale deformation as presented in this paper, as well as fracture growth. We have developed these models in order to understand the relationship between chemical, thermal, hydraulic, and mechanical changes on the local and regional properties of fracture networks. Results presented in this Letter show that in geometrically isotropic fracture networks that consider anisotropic local fracture permeabilities, the direction of maximum permeability of a fractured rock mass tends to be aligned with the direction of the intermediate principal stress, as opposed the maximum principal stress. This subtle distinction may influence how future storage sites for nuclear waste disposal, fracturing of deep geothermal systems, and CO₂ sequestration are designed and managed. This is one of many examples of how emerging properties, which are tied to the process-based evolution of fractures and fracture patterns, including small scale de-

formation and growth, may dominate the flow properties of the system at larger scales.

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Channels in Rough Fractures Under Stress: A Potential Link Between Fracture Conductivity and Seismic Properties

Submitted by Joseph P. Morris, Computational Geosciences Group; Lawrence Livermore National Laboratory, Livermore, California.

Seismic and acoustic measurements are the most readily available methods for inferring the geometric and mechanical properties of fractures and faults in situ. In turn, if it were possible to accurately characterize the in-situ geometry of fractures remotely, it would be possible to estimate their conductivity. Therefore, many have sought to develop approaches that can relate the

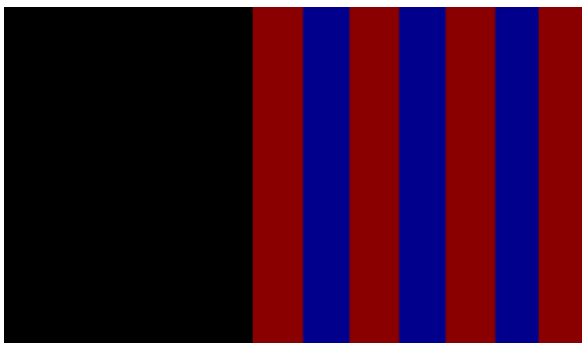


Figure 1: A simple spatial distribution of aperture within a fracture where red indicates aperture and blue indicates contact. (Margetan and Thomsen (1998)).

geometric properties of a fracture to its seismic or acoustic signature. In particular, the ratio of shear compliance to the normal compliance has

been pursued as an indicator of the microstructure within a fracture (Kachanov, 1992). A simple example, due to Margetan and Thomsen (1988), considers a periodic set of thin strips separating two surfaces (see Figure 1).

Margetan and Thomsen (1988) determined that for this geometry, the ratio of normal to shear compliance in the direction parallel to the long axis of the cracks is:

$$C_{zz}/C_{yy} = 1 - \nu$$

where C_{zz} is the normal compliance (i.e.: compliance in the z-direction) and C_{yy} is the shear compliance in the direction parallel to the cracks (i.e.: compliance in the y-direction). In contrast, the ratio with the shear traction perpendicular to the long axis of the cracks is:

$$C_{zz}/C_{xx} = 1$$

where C_{xx} is the shear compliance in the direction perpendicular to the cracks (i.e.: compliance in the x-direction). Of particular interest here is that the fracture geometry in Figure 1 will clearly

have anisotropic conductivity, with zero flow in the x-direction and conductivity in the y-direction. This raises the question: Is it possible that similar effects might be observed in more realistic fracture geometries? Specifically, we might expect that the direction of highest conductivity (aligned with the channels in this case) will be correlated with the direction of lowest normal to shear compliance ratio (the y-direction in this example) in real fractures.

Relatively simple, efficient numerical solutions for the detailed deformation of fractures can be obtained by approximating a fracture with two parallel half-spaces separated by a spatial distribution of contacting points. Early approaches for normal (Greenwood and Williamson, 1966; Brown and Scholz, 1985) and shear deformation (Yoshioka and Scholz, 1989) did not include interaction terms or over-simplified the geometric representation of the fracture. A more general, related class of approaches was developed by including the interaction between contact points by allowing each of the half-spaces to deform about the asperities in addition to the deformation response of the asperities themselves (Hopkins, 1990). The method of Hopkins (1990) was made more efficient by considering a regular grid

of asperity locations (Pyrak-Nolte and Morris, 2000). The method developed by Pyrak-Nolte and Morris (2000) resembles a combination of boundary elements to simulate the rock matrix deformation with an asperity-based mechanical model to capture the details of the spatial distribution of aperture within the fracture and the appropriate model for deformation of the asperities themselves. While their approach applied only to fractures under normal stress, the method was subsequently extended to consider shear deformation within a deformable fracture (Morris, 2015), making it possible to infer the stress-dependent relationship between acoustic and hydraulic fracture properties.

Morris (2015) explored numerically how different spatial distributions of aperture within a fracture influence the relationship between anisotropy in acoustic and conductive properties. Figure 2 shows examples of numerically-generated self-affine fractures, comparing results for short-range and long-range correlations in spatial distribution of aperture. To quantify the degree of anisotropy in compliance and fluid conductivity/transmissivity we calculate:

$$\Delta C = \frac{C_{xx} - C_{yy}}{C_{xx} + C_{yy}} \text{ and } \Delta T = \frac{T_{xx} - T_{yy}}{T_{xx} + T_{yy}}$$

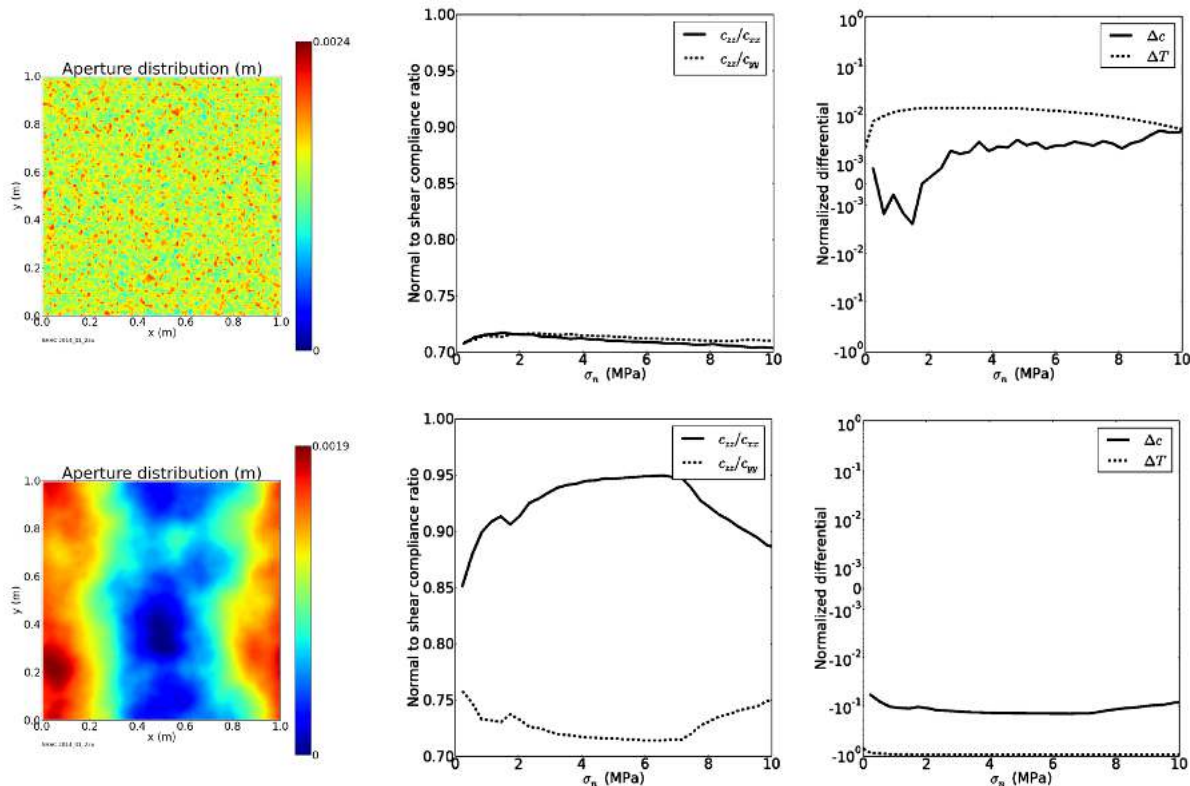


Figure 2: Left: Initial, stress-free aperture distribution for a numerically-generated fracture. Middle: Evolution of normal to shear compliances ratios with increasing stress. Right: Evolution of compliance and hydraulic conductivity anisotropy with increasing stress (plotted as a symmetric log plot to allow for positive and negative values). Upper row: Self-affine fracture with very short-range correlations. Lower row: Self-affine fracture with longer-range correlations

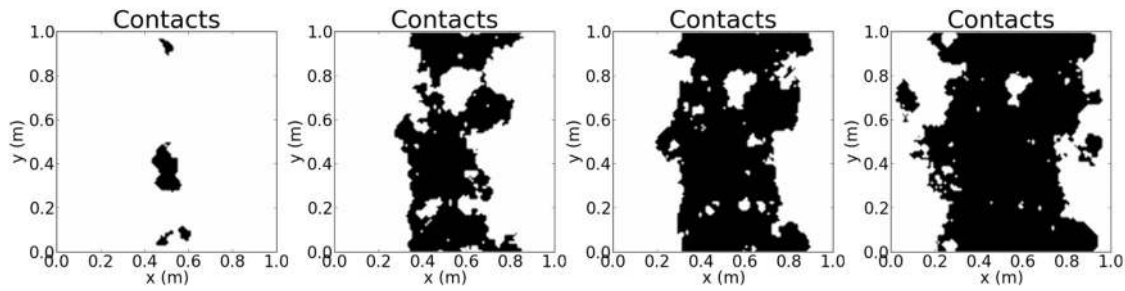


Figure 3: Contact area shown in black for the fracture with long-range aperture correlations for (a) 0.2 MPa, (b) 3.5 MPa, (c) 6.5 MPa and (d) 10.0 MPa. Contact area changes from isolated contact at low stress, to channels at higher stress, to closed channels at highest stress.

We observe that the fracture with short-range correlations shows very little variation in shear/normal compliance ratio with stress. In fact, the fracture is essentially isotropic with respect to both acoustic and acoustic properties. In contrast, the fracture with long-range spatial correlations exhibits significant anisotropy in both shear and conductivity properties over a wide stress range. The results do indicate, however, that the anisotropy is most profound at intermediate stresses. Figure 3 displays the corresponding evolution in contact area with increasing stress. We observe that the contact evolves from isolated islands of contact, to very strong channeling, and ultimately towards isolated islands of aperture. The channels in this instance are oriented in the y-direction so, consistent with the results of Margetan and Thomsen (1988), the normal to shear compliance ratio is smallest in the y-direction. In addition, the results indicate the anisotropy is strongest under stress conditions when the channelization of contact in the fracture is most evident.

The results discussed here suggest that there may be correlations between anisotropy in shear wave speeds and anisotropy in conductivity in individual, rough fractures. As long hypothesized, this dependence is tightly related to the details of the aperture distribution within the fracture; however, being able to quantify the shear compliances appears key. In the examples discussed here, that connection is driven by the predominant orientation of channeling within the fracture.

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Seismicity-Permeability Coupling in the Breaching and Sealing of Reservoirs and Caprocks

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1. Summary

Contemporary methods of energy conversion that reduce carbon intensity include sequestering CO₂, fuel switching to lower-carbon sources (such as from gas shales), and recovering deep geothermal energy via EGS. In all of these a crucial requirement is to control the evolution of permeability -- either to increase it to recover fluids or to retain low permeability to safely enable geological isolation. In all cases, the operation of such projects typically results in significant changes in effective stress, driven by direct fluid injection or recovery or as a result of related thermal or chemical stresses. Where the reach of these fluids or their effects is extensive, the reactivation of pre-existing faults may result in aseismic or seismic rupture with changes in permeability that are indexed to these end-member modes of deformation -- and indeed the spectrum of modes in-between. Understanding controls on this spectrum of deformation modes and their link to permeability evolution is key to controlling transport properties in the subsurface and thereby safely recovering or interring fuels, energy or wastes therein.

2. Introduction

The presence of pre-existing faults and fractures in the upper crust contributes to induced seismicity as a result of fluid injection in hydraulic fracturing, deep storage of CO₂, and stimulation of EGS reservoirs (Ellsworth, 2013; Im et al., 2017; Guglielmi et al., 2015; Majer et al., 2007; McGarr et al., 2002; Shapiro et al., 2006; Walsh and Zo-

back, 2015; Elsworth et al., 2016). In all of these, either maintaining the low permeability and integrity of caprocks or in controlling the growth of permeability in initially very low-permeability shales and geothermal reservoirs are key desires. Hence, it is of particular interest to understand the seismicity-permeability interaction in caprocks and unconventional reservoirs. Permeability is known to change during shear deformation (Elsworth and Goodman, 1986). It has been widely observed that failure may occur stably (aseismically) at slow creep rates of long duration (order of 1~100 mm/yr) or unstably (seismically) at fast frictional sliding rates of short duration (order of 1 m/s) (Anderson et al., 1996; Brune, 1968; Peng and Gomberg, 2010; Schmidt et al., 2005). The stability of sliding is governed by the frictional properties of faults and can be described with rate-and-state friction laws (Dieterich, 1979; Marone, 1998; Ruina, 1983; Scholz, 1998). These studies provide potential insights into the rheological response of caprocks and unconventional reservoirs with regard to the mode and timing of induced earthquakes. However, it is still unclear whether different styles of permeability evolve from unstable fast sliding of seismic events versus slow-slip aseismic events. We integrate both experimental and computational methods to explore how fracture permeability changes in response to fracture/fault reactivation and investigate the roles of (1) mineralogy and (2) fracture roughness in conditioning response, together with (3) intrinsic controls of healing on the earthquake cycle and permeability evolution.

3. Frictional Stability and Permeability Evolution

Seismic displacement on faults is predicated on three principal requirements. First, the applied stress must exceed the strength to enable failure to occur. Second, the strength must reduce as failure occurs (velocity-weakening or strain-softening), enabling shear displacement to accelerate. These two requirements allow a sustained failure but do not define how fast the failure will radiate seismic energy. For the rupture to be seismic, the physical stiffness of the fault material must be larger than the geometric stiffness of the fault itself, enabling the dissipation of the stored strain energy in a runaway failure.

This final necessary-and-sufficient requirement enables the indexing of potential modes of failure – aseismic versus seismic – to be recovered from straightforward friction-permeability experiments that concurrently measure the evolution of friction and permeability with shear displacement of laboratory faults and fractures. Thus measurements may characterize the response of both materials that control cross fault flows, via the fault core and that control along-fault flows in the fault damage zone. The focus here is on along-fault flows in the damage zone that may transect caprocks and promote fugitive flows for reservoirs and aquifers.

4. Mineralogical Controls on Friction and Permeability Evolution

Understanding the component response of individual fractures comprising the fault damage zone is the key constraint in constraining along-fault fugitive emissions. Deformation on such fractures may be velocity-weakening or -strengthening, with these styles of deformation potentially conditioning permeability evolution. The stability response is conditioned by the velocity-weakening/strengthening behavior through the parameter $(a-b)$ for a finite step in shear velocity, V , applied to a (laboratory) fault as (Dietrich, 1979; Ruina, 1983),

$$(a-b) = \Delta\mu / \Delta \ln V.$$

Thus the μ (friction) value defines the propensity for failure, while $(a-b)$ values define the mode of slip, as stable, aseismically (i.e. $a-b > 0$), or unstable, seismically ($a-b < 0$) (Kohli and Zoback, 2013; Samuelson and Spiers, 2012).

Thus, the anticipated seismic versus aseismic

reactivation response may be probed by exploring the stability characteristics observed during shear, for the resulting magnitude of the instability parameter, $(a-b)$, and used to project the observed evolution of permeability as related to this propensity towards seismic or aseismic deformation. We conducted velocity stepping shear experiments on laboratory faults/fractures to explore this response. Shearing velocities were stepped-up then -down between 1 and 10 $\mu\text{m/s}$. Figure 1(a) shows the results of one sample as an example of the net friction and permeability evolution with displacement. The calculated net fracture permeability monotonically decreases with displacement, consistent with previous observations (Fang et al., 2017). Local frictional change and permeability evolution in response to shear velocity change are shown in Figures 1(b) and 1(c). The permeability change in each velocity step is normalized against the reference permeability in the state immediately before the velocity-step induced change. These responses are examined for a full range of compositional minerals of rocks binned into the groups of silicates, carbonates, and clays with a typical result for Green River Shale shown in Figure 1 (Fang et al., 2018a).

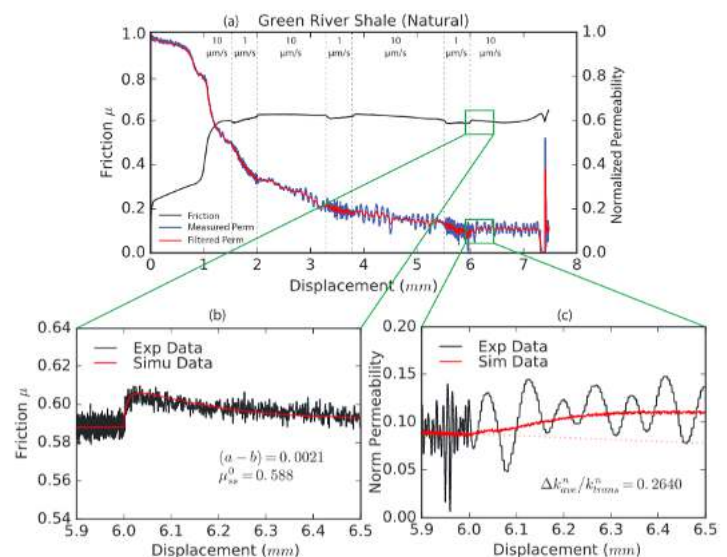


Figure 1. (a) Concurrent measurements of friction and permeability evolution on laboratory faults in Green River Shale. Insets show zoom-in of friction (b) and permeability (c) with shear offset for an upstep in shearing velocity.

Outputs from the experiments are magnitudes of friction, stability (i.e. evolution of friction via $(a-b)$) and change in permeability Δk resulting from the shear. Frictional parameters and transient permeability change in response to velocity change for a broad sequence of rocks are shown

in Figure 2. As surface contact state, which determines the flow path, is reflected in the frictional strength and stability, we directly correlate the permeability change with friction (Figure 2). The permeability change Δk has a positive correlation with concurrently measured frictional strength μ but a negative correlation with the corresponding frictional stability (a-b). This intrinsic linkage of friction and permeability change is directly determined by the asperity contact state and the material properties (e.g., mechanical and swelling) that control the mechanical behaviors of fracture asperities. However, it is worth noting that the magnitude of permeability change in the natural samples is much larger than that of the artificial samples (shown as the solid black symbols in Figure 2); this is due to the difference in the surface textures.

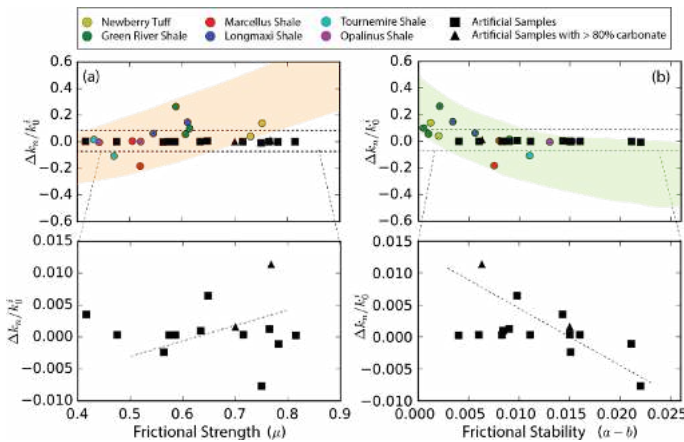


Figure 2. Trends in normalized permeability with (a) frictional strength and with (b) frictional stability parameter (a-b).

In summary, with known mineralogical compositions comprising the fracture, the frictional strength and stability of fractures can be estimated. Shear failure is less likely to occur for fractures with a higher content of tectosilicates. However, once failure initiates, the fracture is more likely to slip unstably. This process is opposite that for fractures with higher clay content -- where the fracture is easier to reactivate and will slip stably. When an unstable fracture slides at an accelerating rate, the transient change in fracture permeability can be speculated -- those richer in tectosilicates exhibit larger permeability enhancement.

5. Upscaling Permeability Evolution for Fracture Roughness

With permeability evolution and stability characteristics defined by rate-state response and linked via stability, the roles of roughness, asper-

ity breakage and the generation of wear products may then be explored (e.g., Fang et al., 2018b). Analog virtual fractures with calibrated roughness may be fabricated (Figure 3) to evaluate the role of shearing on the evolution of friction, stability and permeability, as an ensemble linked behavior (Wang et al., 2020). In this, strain-weakening or -strengthening response is applied to the individual particle contacts (Wang et al., 2017; 2019). This enables the frictional (Figure 4(a)), stability and permeability evolution (Figure 4(b)) response to be followed when

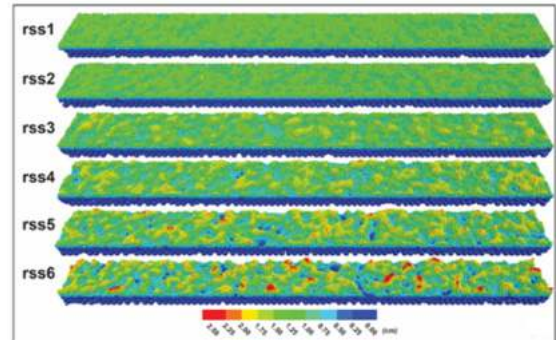


Figure 3. Lower fracture surfaces of rss1 through rss6 before shear with colored contours illustrating the topography of the surfaces (asperities).

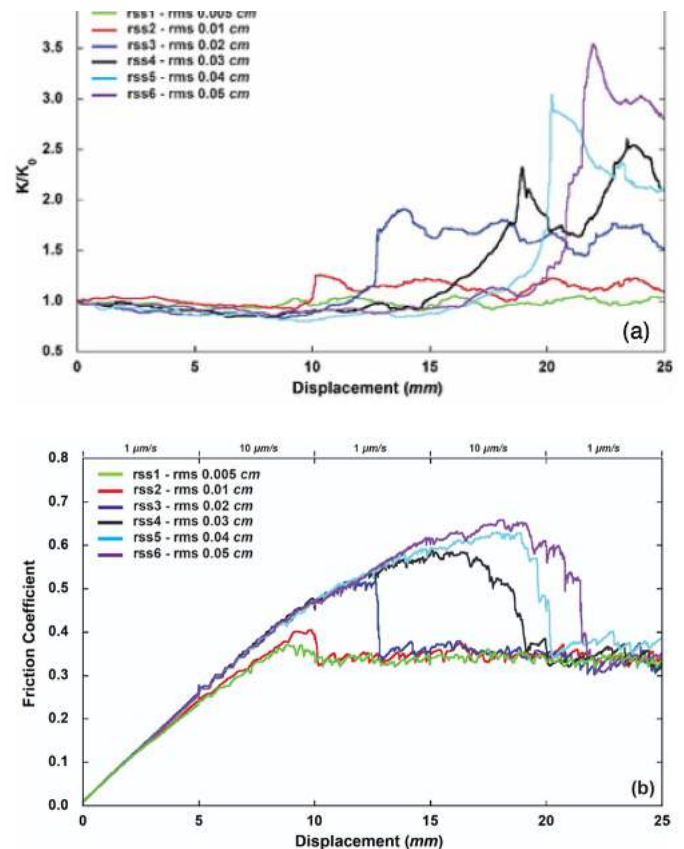


Figure 4. (a) Evolution of fracture permeability (k/k_0) for tests rss1 through rss6. (b) Evolution of shear strength interpreted as friction (τ/σ) for rss1 through rss6 (RMS asperity heights ranging from 0.005cm to 0.05cm).

these “virtual” fractures are then sheared. The evolution of shear strength interpreted as friction (τ/σ) for rss1 through rss6 (RMS asperity heights ranging from 0.005cm to 0.05cm) is shown in Figure 4(a). The shear strength of the specimens generally builds until reaching peak strength, followed by a stress drop post-peak, sometimes comprising several successive stress drops. Specimens with rougher fractures exhibit a higher peak shear strength and larger threshold shear displacement to peak strength. All specimens show similar residual shear strength after failure.

The evolution of fracture permeability (k/k_0) for tests rss1 through rss6 is shown in Figure 4(b). Permeability decreases slightly with compaction during early shear. Permeability increases rapidly upon a threshold shear displacement and continues to increase until reaching a peak, after which plateau (rss1- rss3) is observed. Fracture in rss4 shows unstable permeability evolution after reaching the peak. Fractures with large RMS asperity heights (rss5 and rss6) exhibit permeability reduction after reaching peak values.

The ensemble of the responses for both mineralogy and geometric components is important in defining the overall response of behavior, both seismic and aseismic and the corresponding implications for the evolution of permeability for deformation in these two modes.

6. Role of Healing and Sealing in Permeability Evolution

As previously noted, the demarcation between seismic and aseismic response is defined by three conditions: that the fracture fails, that it weakens as it fails, and that the geometric shear stiffness of the embedded fault is smaller than that of the physical fault material or interface. The latter enables the stored strain energy to be unstably ejected -- i.e. seismically. However, there is a fourth requirement for seismic response -- and that is that the fault heals and strengthens after rupture. Otherwise only a single rupture event can occur -- all others being stable sliding. Thus the role of healing (strengthening) is important in defining the recurrence time of individual slip events (seismic or aseismic) with this healing (strengthening) potentially influencing the mode of reactivation (seismic or aseismic) and thereby the style and magnitude of permeability evolution

-- reduction or enhancement -- as noted earlier, is related to the style of deformation (Im et al., 2018; 2019).

The response during interseismic periods (repose) may be represented in experiments where the shear displacement is held, prior to reactivation in shear, as illustrated in Figure 5. Such “slide-hold-slide” experiments enable the evolution of healing (strengthening) to be followed; reactivation following a hold (Figure

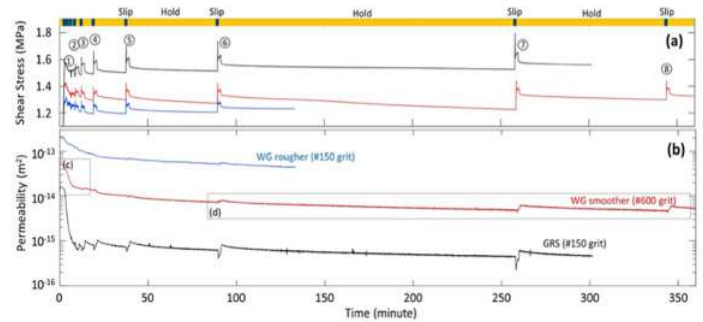


Figure 5. Friction (a) and permeability (b) response during slide and hold experiments. Each color denotes rock and surface roughness: blue: westerly granite (WG) rougher sample (#150 grit), red: WG smoother (#600 grit), and black: Green River shale (#150 grit). (a) Shear stress and (b) permeability response during the overall experiment, respectively. Slip and hold periods are denoted on the top of Figure 5(a) by blue and orange bars, respectively. Circled numbers denote event numbers.

5(a)) results in a gain in strength as a result of various processes of welding, cementation, pressure solution and others. During the hold, any initial gain in permeability engendered in the prior reactivation is reset as a power-law decline by sealing (Figure 5(b)). Rates and magnitudes are broadly consistent with mechanisms involving interpenetration of compacting asperities driven by creep or pressure solution. These responses are repeatable in multiple cycles of repose then reactivation. Similarly, the permeability response that results upon reactivation is typically conditioned by the duration of the prior repose -- longer repose times result in greater healing and strengthening, and increased strengthening results in a greater increase in permeability that occurs with reactivation (Figure 6). For all reactivation events collocated at time zero in Figure 6, short duration repeses result in compactive reactivations (Figure 6①) and long-duration repeses in dilative reactivations (Figure 6⑦). The magnitude of the dilative reactivation scales broadly with repose time (Figure 6).

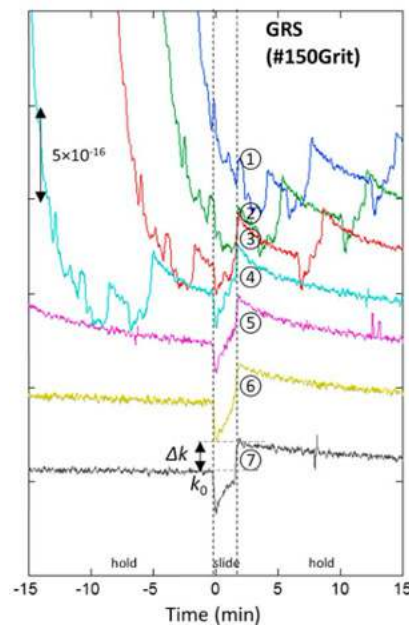


Figure 6. Evolution of permeability post reactivation for a variety of different repose times. Shortest holds for hold-period #1 (10 s) and increasingly longer holds through #7 (10,000 s) return largest increase in post-reactivation permeability for the longest-duration holds.

7. Conclusions

We have posited that the style of deformation, seismic versus aseismic, exerts systematic control on the mode and style of permeability evolution in faults and fractures. Frictional strength and stability may be used as appropriate indices to follow this relation and to define both mineralogical and geometric controls on behavior -- each linked to the stability characteristics of fractures and faults. These define not only the short-term response of fractures but also, by extension through healing, the long-term response. This linkage between both seismic and interseismic behaviors is mechanistically-based on the formalism of rate-state friction, defining the various characteristics of the complex first- and second-order deformation processes over a full range of timescales.

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Advances in Discrete Fracture Network Modeling: A Review

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1. Introduction

Discrete fracture network (DFN) models incorporate the important effects of fracture structure and network topology to better characterize their influence on flow and transport through fractured systems (Viswanathan et al. 2018). In a typical DFN model, each fracture in the network is assigned a shape, location, aperture, and orientation by sampling distributions whose parameters are based on site characterization. While recent advances in high performance computing have opened the door for flow and transport simulations in large explicit three-dimensional discrete fracture networks, there is still a huge computational cost associated with DFN models because of the large number of mesh elements required to represent thousands of fractures. Up until recently it could be argued that high-fidelity DFN models were a sort of albatross due to inherent uncertainties associated with actual field site characterizations -- for instance, it is nearly impossible to have exact knowledge of every fracture's location, orientation, and physical properties. As a result, this would require many realizations to bound uncertainty in flow and transport in the systems. However, detailed datasets are now available at field sites, such as the SKB Laboratory in Sweden and the Marcellus Shale Energy and Environment Laboratory in West Virginia, USA. They provide excellent opportunities for validation of physics-based DFN simulations. That said, these sites are certainly the exception, not the norm, so data-driven reduced order models must be considered in conjunction with high-fidelity DFN models.

Advances in machine learning and graph-based algorithms have transformed how we approach the development of reduced order models of fractured systems (Viswanathan et al. 2018). Due to the prohibitive cost of DFN models and sparsity of data, it is often advantageous to reduce the DFN to a graph-based representation. Model reduction is especially appropriate if the quantity of interest is an averaged quantity, such as a breakthrough curve, because this can smooth out the differences between high-fidelity DFN models and

reduced order graph models. Reducing a DFN to a graph can be done in various ways but one common method is to have the vertices of the graph represent the fractures and the edges of the graph represent intersections of fractures. This formulation preserves the connectivity information of the fractures, and is thus topologically equivalent to the full DFN. While this approach is computationally cheap, there are limitations to the physics that can be simulated directly on the graph itself. However, given the speed at which graph-based simulations can be completed--- $O(10^4)$ faster than DFN simulations -- they are ideal for incorporating uncertainty quantification methods (Karra et al. 2018).

In this letter, we review some of the important contributions from our group related to discrete fracture network modeling, which includes both high-fidelity physics-based models and graph-based reduced order models. This two-pronged strategy is exploited not only to improve our understanding of physics, but also to figure out how to accelerate models with goals such as robust uncertainty quantification and real-time forecasting. Establishing a direct link between high-fidelity physics-based models and reduced order models is critical to take full advantage of both approaches.

2. Discrete fracture network modeling

2.1. Physics-based modeling

While there are countless physical aspects of fracture networks that can be studied quantitatively using DFN models, we will briefly review three here. These include: (1) in-fracture variability, (2) injection mode, and (3) matrix effects. We choose these because they are each active topics of research and have long-standing open questions. With regards to in-fracture variability, there is a persistent debate as to the importance of variability within a fracture and its effect on the overall network behavior. This presents an interesting opportunity to study the difference between single fracture and net-

work scale phenomena. Injection mode refers to boundary conditions for transport calculations on DFNs. We review the two typical boundary conditions used for transport that can significantly affect quantities of interest like breakthrough curves. Lastly, we review some recent advances in including matrix effects in fracture-informed continuum models.

Many physical processes can result in apertures that vary within an individual fracture. These include geological stress and strain, as well as chemical dissolution, precipitation, and erosion. While it has long been known that internal fracture variability can have strong effects on flow and transport in single fractures (such as increasing flow channeling), characterizing how individu-

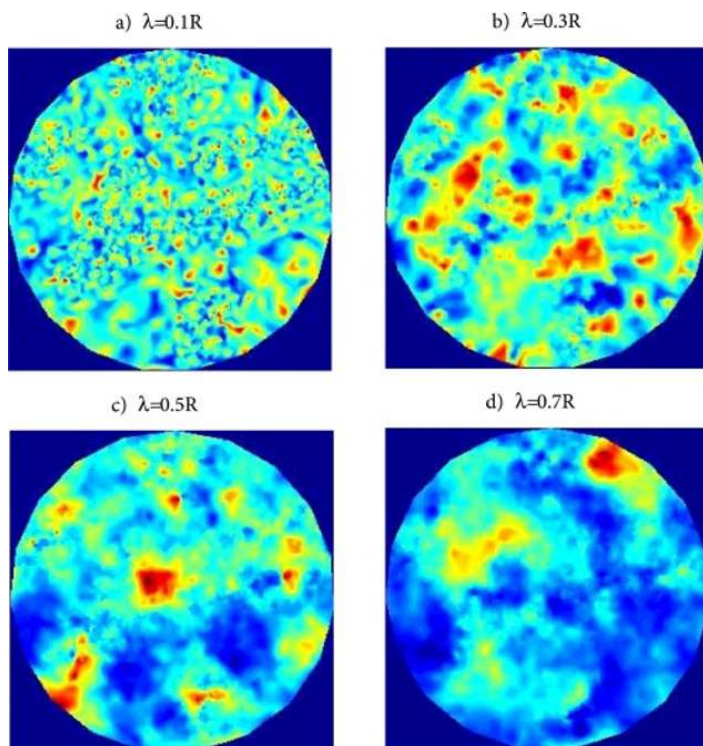


Figure 1. An example of a single circular fracture with aperture variability. The applied different spatial correlation lengths are: (a) $0.1R$, (b) $0.3R$, (c) $0.5R$, and (d) $0.7R$, where R is the radius of the fracture. As the spatial correlation length increases, the areas of high and low aperture zones expand. (Taken from Makedonska et al. (2016)).

al fracture aperture variability influences flow and transport through an entire fracture network is a key question in a variety of energy, defense, and hydrology applications.

Makedonska et al. (2016) incorporated internal aperture heterogeneity of individual fractures into flow simulations within kilometer scale three-dimensional DFNs generated by dfnWorks (Hyman

et al. 2015a). They represented in-fracture aperture variability by a stationary log-normal stochastic field with various correlation lengths and variances (Figure 1), which could then be applied to each fracture in the DFNs. Interestingly, the internal heterogeneity of aperture effects, which greatly influence transport on single fractures, showed no significant difference in large DFNs consisting of thousands of individual fractures. This work adds a critical contribution to the debate of whether it is important to include internal fracture variability in DFN simulations, as well as illustrating key differences between studies of single fracture phenomena and network scale phenomena. It is interesting to point out, however, that since there is no correlation in apertures between individual fractures, we could be missing phenomena that persist over the scale of the entire network. For instance, one might expect some sort of fast flow paths across the network due to physical and chemical processes such as weathering or dissolution. This is an active area of research we plan to address in the future.

In general, the initial distribution of mass transport in fractured rock can be modeled using one of two injection methods. The first method, flux-weighted injection, mimics a solute that is released in proportion to the flux at the location of insertion. The second method, resident-based injection, is designed to mimic a source that introduces a solute uniformly throughout the input zone. It has been hypothesized that solute plumes injected under resident conditions evolve to behave similarly to solutes injected under flux-weighted conditions. Hyman et al. (2015b) tested this using dfnWorks by simulating flow in kilometer-scale three-dimensional DFNs based on fractured granite at the Forsmark site in Sweden, and used a Lagrangian approach to simulate transport in the networks. Their results show that after traveling through a pre-equilibrium region, both injection methods exhibit linear scaling of the first moment of travel time and power law scaling of the breakthrough curve with similar exponents. The physical mechanisms behind this evolution appear to be the combination of in-network channeling of mass into larger fractures, which offer reduced resistance to flow, and in-fracture channeling, which results from the topology of the DFN (Figure 2). So, early time behavior can differ substantially between the two injection modes, but the long-term behavior is quite similar. However, these results are

dependent on the network characteristics. For instance, in simulations where not enough fractures are sampled from injection to collection, the travel time distribution could be significantly impacted by injection mode. A more systematic analysis of the effects of injection mode on networks with different densities and size distributions could be warranted in the future.

The key aspect that sets DFN modeling apart from

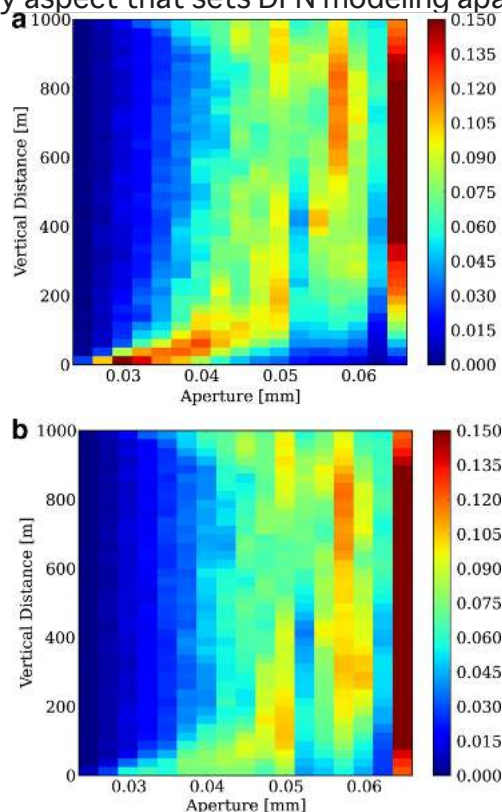


Figure 2. Heat map of mass distribution plotted as a function of fracture apertures (abscissa) and vertical distance traveled (ordinate) where colors indicate percent of particles for all realizations. The primary direction of flow is from bottom, vertical distance equal to 0, to top. (a) Resident injection. (b) Flux-weighted injection. (Taken from Hyman et al. (2015b)).

typical continuum frameworks is the recognition that fracture geometry and network topology play a critical role in determining flow and transport properties within fractured media (Viswanathan et al. 2018). However, DFN models do not include matrix effects and are thus limited to ultra-low permeability systems, such as crystalline rock. While transfer functions have shown some utility in describing first order matrix effects, their use in complex fractured systems with high fracture density and variable orientations is not valid because the possibility of transport between fractures via matrix is not captured. As a result, we would argue that for systems where accurately predicting the tailing behavior is important

(e.g., environmental remediation, long-term production of hydrocarbons, and enhanced geothermal systems), moving beyond transfer functions is necessary.

These facts motivated the development of a novel continuum approach that preserves the underlying fracture topology by exploiting novel computational geometry algorithms (Sweeney et al. 2020). In this approach, named the Upscaled Discrete Fracture Matrix (UDFM) model, fracture attributes (orientations and apertures) are upscaled and combined with matrix attributes (permeability and porosity) into properties of a spatially variable Delaunay tetrahedral continuum mesh. The resolution of the mesh depends on the proximity to the fractures to preserve the geometric and topological integrity of the underlying fracture network as well as increasing the accuracy of gradients in the dynamics between the fractures and matrix (Figure 3). The UDFM was verified against analytical and numerical benchmarks for various flow, transport, and coupled heat-mass flow problems and was found to be accurate in every case tested, including reproducing the underlying DFN behavior when matrix permeability is low (Sweeney et al. 2020). The UDFM is thus capable of handling much larger scale problems than previous continuum models because key features are not over-smoothed.

2.2. Graph-based models

DFN models are the most accurate way to simulate high-fidelity physics in fracture networks. However, they are not easily amenable to statistical and machine learning analyses because of their computational cost. In contrast, graph-based models are reduced-order equivalent representations of DFNs and their simplicity offers the opportunity for data-driven analyses, which is critical when data are sparse.

One of the primary reasons to choose a high-fidelity model over a reduced order model is to accurately simulate the physical phenomena when given reliable data. In theory, the more mechanistic a model, the more predictive it will be even when parameters change that drive said model. However, in the presence of uncertainty it is permissible to solve governing equations directly on graphs, alleviating the need for physics-based models altogether. Karra et al. (2018) developed a workflow to reduce a full DFN to a

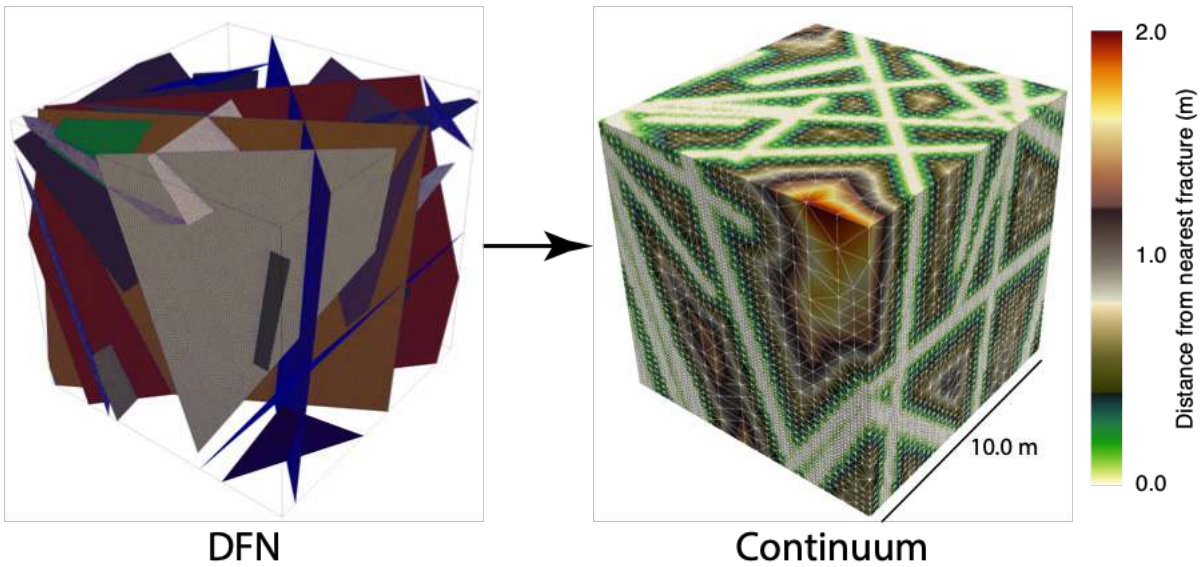


Figure 3. DFN and corresponding UDFM continuum mesh with 28 fractures with exponentially distributed lengths. The colors in the continuum mesh show how the refinement depends on distance from nearest fracture. (Taken from Sweeney et al. (2020)).

graph-based representation and then solve flow and transport directly on the graph. Their initial results showed a systematic bias between the breakthrough curves of the full DFN and the graph, which is due to the graph algorithm's underprediction of the pressure gradients across intersections on a given fracture, and leading to

slower tracer particle speeds between intersections and longer travel time. However, they were able to correct the bias using a correction factor that requires the realization of only a single high-fidelity DFN simulation. Their results show excellent agreement between breakthrough on the graph versus breakthrough on the full DFN,

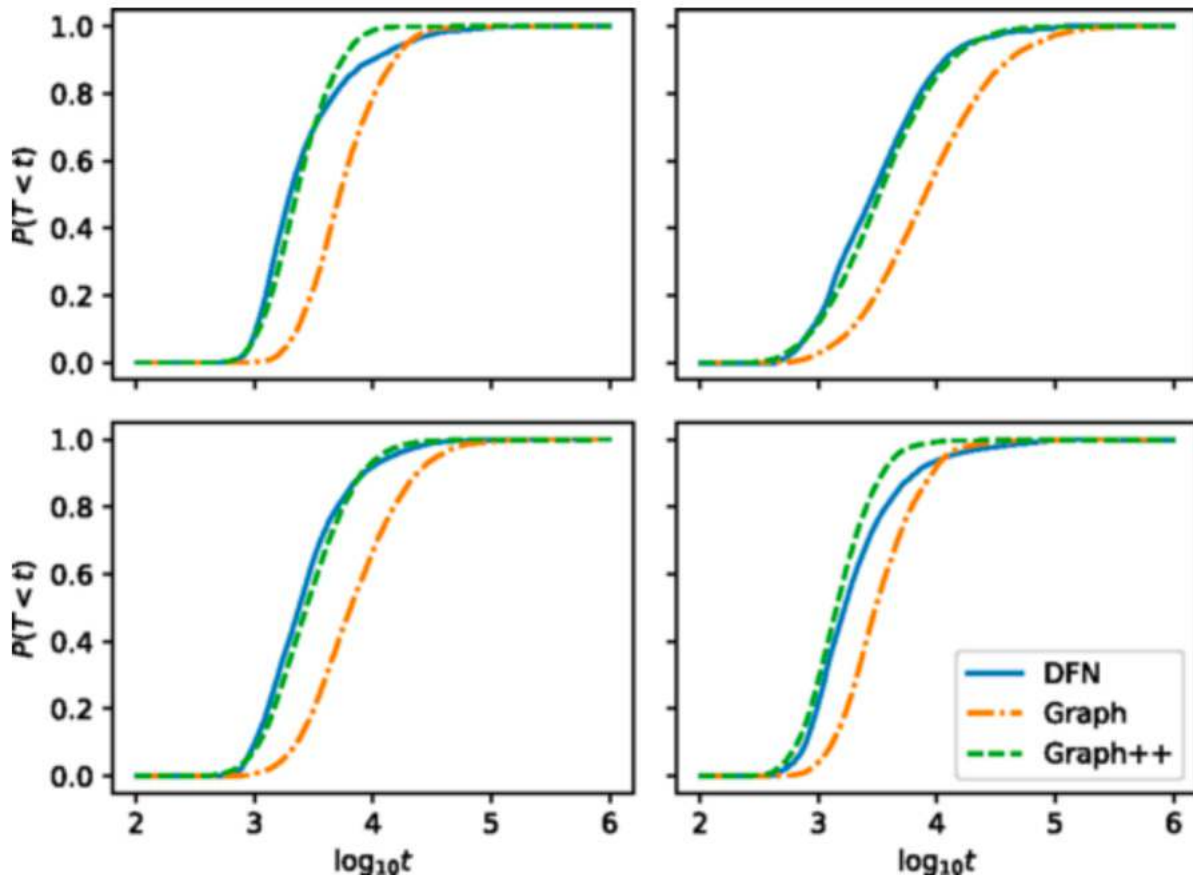


Figure 4. Breakthrough curves for four realizations of 500 fracture networks with heterogeneous permeability. Blue curves are for the DFN, orange is for the graph, and green is the graph utilizing the bias correction procedure (called “Graph++” in the legend). (Taken from Karra et al. (2018))

while achieving four orders of magnitude speed-up using the graph algorithm (Figure 4).

Viswanathan et al. (2018) developed a complete DFN model reduction framework, which provides an efficient means for DFN modeling through both system reduction of the DFN using graph-based properties and combining DFN and graph-based flow and transport simulations (Figure 5). The framework consists of several steps. First, a DFN is reduced to a graph representation. Following that, the framework splits into two sub frameworks. In one, the primary flow paths of the network are identified on the graph, and those fractures are then explicitly represented in a new DFN, which can be used for high-fidelity simulations. In the other, simulations are performed directly on the graph using the methods developed by Karra et al. (2018). The results of each sub workflow can then be combined into a single suite of results for analysis, such as uncertainty quantification. This framework increases computational efficiency while retaining accuracy of key quantities of interest. Furthermore, they also showed how the choice of a graph representation, namely, which attributes of the DFN are to be represented as nodes and which ones as edges connecting those nodes, depends on the relevant scientific questions. For instance, when only the

first arrival times are of interest, a mapping that is based solely on topology can be used to determine shortest paths through a fractures network. On the other hand, using a mapping that allows graph edges to inherit hydrological properties such as permeability and in-plane geometry can be used to simulate flow and transport in a computationally efficient manner. Overall, the DFN model reduction framework is an efficient way to bound system behavior and quantify uncertainty by combining DFN and graph-based flow and transport simulations.

3. Outlook and future research directions

In this review, we have highlighted some of our group's contributions to high-fidelity physics-based DFN modeling, graph-based reduced order models, and the important connections between them. In general terms, DFN models are unmatched in their accuracy and representation of the true system and allow for detailed analyses, such as those shown here. However, we often do not know where all the fractures in a system are, so reduced order models can be equally useful, and be used with greater efficiency. To this end, we believe a direct link between high-fidelity physics-based models and reduced order models needs to exist to be able to switch from one to the other. Such a framework should be based on: (1) available site characterization data, (2) whether the model is being applied to sites similar to where it has been trained, and (3) the quantity of interest.

Representing the full network is necessary to accurately describe physical processes, whereas considering single fracture phenomena is likely to lead to incorrect predictions at the network scale. However, the accuracy of DFN models comes at an enormous cost. Fracture-aware continuum models alleviate some of the burden and can capture important matrix effects DFN models cannot, but even they fall short for fast, real-time predictions. In contrast, graph-based models are capable of rapid simulations and are thus easily exploited for uncertainty quantification and machine learning analyses. However, current graph algorithms are limited to relatively simple flow and transport problems and cannot be used for more complex processes such as multiphase flow, nonlinear reactions, or matrix effects.

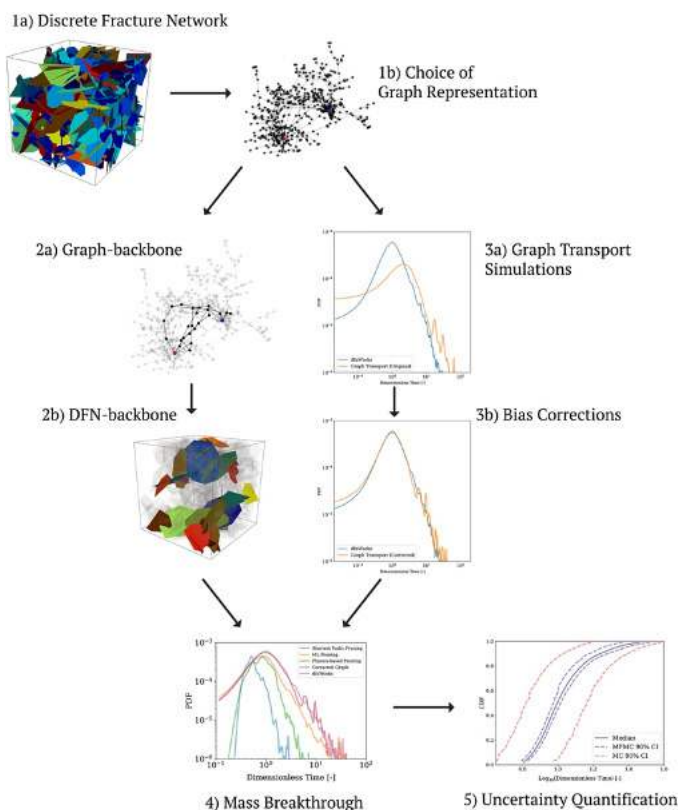


Figure 5. Schematic of discrete fracture network model reduction framework. (taken from Viswanathan et al. (2018)).

Ultimately, the goal of DFN modeling and their reduced order counterparts is to move towards real-time predictions of phenomena with fully integrated physics. To accomplish this, neither high-fidelity models nor reduced order models can be considered in isolation. To this end, future research efforts will be directed toward combining them into a single physics-informed machine learning framework, which could then be portable to any fracture network analysis.

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