**Microscale Characterization of Fracture Nucleation and Energy in Granite and Sandstone: Insights using the Discrete Element Method**

Harsh Biren Vora and Julia K. Morgan

Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX

**Abstract**

We develop micromechanical models of sandstone and granite to analyze fracture nucleation and propagation, causing fracture energy release during unstable failure. Calibrated models of rock are subjected to biaxial experiments leading to the development of a shear fracture through the progressive interaction of microcracks occurring in shear and tensile modes. Our models document a range of fracture growth patterns, providing insights into the source mechanisms of fracture energy release and volumetric changes in fracture gouge. Our models document that the growth of shear fractures in sandstone occurs through cooperative interaction between shear and tensile microcracks, with shear microcracks accounting for the majority of fracture energy release. The fraction of shear microcracking and associated energy increases with confining pressure on sandstone, resulting in a transition from dilatant to compactant fracture zones in sandstones. The growth of shear fractures in granite occurs primarily through coalescence of tensile microcracks, with minimal shearing microcracking in the fracture zone. Increase in confining pressure on granite results in increased microcracking activity, dominantly in tensile mode. The increase in tensile microcracking with confining pressure results in larger fracture energy release and formation of dilatant fracture zones in granite. Fracture energy accounts for 10-15% of total input energy in sandstone and 16-47% in granite, with the fracture energy increasing with confining pressure. We estimate that the work done against friction accounts for a majority of the input mechanical energy during biaxial tests, accounting for 69-86% of total input energy in sandstone and from 46-81% of input energy in granite.

1. **Introduction**

The mechanical loading of rocks results in local inelastic processes that produce microcracks [Kranz, 1983], and their cooperative interaction leads to formation of macroscopic fractures [Wong et al., 1997]. The growth of fractures results in the loss of cohesion and a reduction in rock strength, imparting permanent changes to the material. In addition, the introduction of fractures within a rock volume can modify porosity and permeability, affecting the transport properties of these materials. Finally, fracture energy is a major component of the work budget during rock deformation [Lockner et al., 1991; Wong, 1982]. The input deformational energy into a rock is partitioned into recoverable strain energy and non-recoverable fracture energy and frictional energy [Herbert et al., 2015; Cooke and Murphy, 2004]. The quantification of fracture energy is of relevance to industrial applications such as geothermal recovery, hydrocarbon extraction, safe design of nuclear repositories, as well as natural processes that accompany volcanism and earthquake generation. Thus, it is important to quantify the mechanisms of fracture growth and associated energy release.

The evolution of microcracks during rock deformation, and their evolution into macrofractures is a complex process influenced by lithology and associated rock strength [Menendez et al, 1996; Horii and Nemat-Nasser, 1985], porosity [Sulem and Ouffroukh, 2006] and confining pressure [Wong, 1997]. Microstructural analyses of rock fracture indicate that while fracture growth in crystalline rocks such as granite occurs largely through the coalescence of tensile microcracks [Brace et al., 1966; Moore and Lockner, 1995], resulting in the formation of dilatant shear bands [Walsh and Brace, 1984]. In weaker sedimentary rocks such as sandstone, pore collapse and shear microcracking have been shown to be the dominating mechanisms [Gallagher et al., 1974; Zhang et al, 1990], often resulting in the formation of compactant shear bands [Sulem and Ouffroukh, 2006]. The process of fracture growth is further influenced by the effect of confining pressure, which impedes dilatant deformation and favors non-dilatant processes. In granite, shear microcracking is observed to increase with confining pressure [Velde et al., 1993; Escartin et al., 1997], whereas a transition from dilating shear bands to compacting shear bands occurs in sandstone [Menendez et al, 1996; Besuelle, 2001]. While microstructural analyses help us build qualitative, observation-based models of fracture growth, they do not quantify the relative abundance of tensile and shear microcracks, and their influence on fracture energy, geometry and volumetric evolution of the shear fracture zone.

Recently, acoustic emissions have been employed to understand the influence of microcrack mode on fracture growth and energy. Acoustic Emissions (AEs) are broadly defined as high-frequency transient elastic waves generated by a sudden release of stored strain energy during fracturing of a rock [Lockner, 1993]. Unlike traditional rock damage indicators that rely on bulk changes in rock strength, moduli and density of rock, the AE method offers the ability to detect individual fracture events, which contribute progressively to the deformation. The spatial and temporal microcrack distribution identified by AE’s has helped identify distinct stages of fracture initiation and coalescence, corresponding to the interplay between tensile and shear microcracks [Lei et al., 2007]. AEs also provide a quantitative measure of the work budget during rock deformation, and suggest that ~10-90% of input energy is released during growth of fracture in rock [Lockner et al, 1991; Goodfellow et al, 2015]. However, correlation between fracture energy and associated microcrack modes in laboratory studies may be complicated, for example, due to shear to compressional wave conversions [Modiriasari et al., 2017], difficulty in inverting AE’s for double-couple mechanisms [Jalali et al., 2018], and seismic attenuation [Ni and Iwamoto, 2002]. Distinguishing between tensile and shear microcracks is integral to balancing the fracture work budget, quantifying mechanisms of shear fracture growth, and determining how they affect volumetric changes in fracture zones.

The concept of a balanced energy budget has been widely applied to study geologic deformation from processes observed in laboratory samples [Herbert et al., 2015; Wong, 1982] to earthquakes in the crust [Cooke and Murphy, 2004]. For a balanced energy budget, the sum of recoverable strain energy and irrecoverable fracture energy will equal the external mechanical work applied to the system [Jaeger et al., 2009]. While the different components of work budget during deformation have been quantified [Wong, 1982; Dempsey et al., 2012], the control of lithology and confining pressure over fracture energy remain elusive. Laboratory and field experiments estimate that brittle fracture growth consumes anywhere between 10% and 90% of input deformation energy [Chester et al., 2005; De Paola et al., 2015; Madden et al., 2017; Goodfellow et al., 2015]. The quantification of fracture energy from emergent deformation can help resolve the partitioning of energy between recoverable strain energy and non-recoverable fracture energy.

Numerical methods provide the ability to monitor stresses and displacement of grains on a micro-scale, complementing the macromechanical behavior observed from microstructural and AE analyses. Discrete numerical methods are attractive to study brittle fracturing because, much like real rocks, the numerical materials are composed of assemblages of grains. Grain interactions yield emergent behaviors and heterogeneities form and evolve in response to changing stress conditions and material properties [Morgan 2015; Longjohn et al., 2018]. The grains are bonded to impart cohesion and simulate rock properties. Bond breakage, in response to applied boundary conditions, simulates microcracking allowing us to study the distribution and mode of individual microcracks and the bulk evolution of fracture and associated porosity. In this study, we use the Discrete Element Method [Cundall and Strack, 1979] to create and examine the behavior of sandstone and granite models in which cracks and fractures form spontaneously and release energy in the form of seismic waves. This choice of rock types will help us to compare the fracture growth mechanisms between weak, sedimentary rock (sandstone) and strong, crystalline rock (granite) of widespread interest. By monitoring microcracking activity, we seek to constrain fracture nucleation mechanisms, seismic energy release and volumetric changes in the fracture gouge during biaxial deformation experiments.

1. **The Discrete Element Method**

The discrete element method [Cundall and Strack, 1979] is a particle-based numerical technique that employs a time stepping, finite difference approach to solve Newton’s equations of motion for every particle in a system. The method first solves for forces imposed on the surfaces of each particle by neighboring particles or boundaries and then calculates a displacement based on the acceleration caused by sum of the forces. Particle motions are induced by external forces prescribed by stress or strain rate boundary conditions, and by forces resolved at interparticle contacts. The disequilibrium of forces drives particle displacements.

The Discrete Element Method (DEM) has been employed to simulate rock deformation from laboratory scale experiments to large scale geodynamic processes, including formation of deformation bands in sandstones [Wang et al.,2008], analyze changes in porosity and stress during biaxial experiments [Longjohn et al., 2018], evolution of fault gouges [Guo and Morgan, 2007], evolution of slope failure and landslide processes [Amitrano, 2006], and deformation of fold and thrust belts [Morgan and Boettcher, 1999]. The numerical code used is RICEBAL, based on open-source code TRUBAL [Cundall and Strack, 1979]. RICEBAL resembles a numerical sandbox but offers added value by allowing material properties and mechanical states to be monitored throughout simulations and be correlated with deformation behavior and structure.

**2.1. Interparticle Contact Forces and Bonding**

Morgan, 2015 provides a detailed description of the mechanics of RICEBAL, which is summarized here. The force-displacement caused by particle interaction is characterized by normal and shear forces along elastic, frictional contacts, calculated using the following equations respectively [Fig. 1a]:

(Eq. 1)

(Eq. 2)

where *fn* is the repulsive normal force, *kn* is the normal interparticle stiffness, *δn* is the amount of overlap between particles in contact, *fs* is the shear force, *ks* is the shear stiffness, *δs* is the shear offset of particle centers. We implement the non-linear Hertz-Mindlin theory [Johnson, 1985] to calculate *kn* and *ks*, which are related to the elasticity of the particles the contact area of overlapping particles:

(Eq. 3)

(Eq. 4)

Where *Ep* is the Young’s Modulus of the particles, *Gp* is the Shear Modulus of the particles, and *Ra* and *Rb* are the radii of the respective discrete elements. In RICEBAL, *Gp* is an input parameter, which is related to *Ep* through the equation:

(Eq. 5)

Where *νp* is the Poisson’s ratio of particles. Shear forces at interparticle contacts are also limited by friction along particle surfaces (*µp*), as

(Eq. 6)

Where *fsmax* is the threshold force for particles to slide past each other. We implement interparticle bonding to impart cohesion into the material assemblage. The bonds have four key mechanical properties – *Eb*, the Young’s Modulus of the bond, *Gb*, the Shear Modulus of the bond, *Tb*, the tensile strength of the bonds, and *Cb*, the bond cohesion (unconfined shear strength of bonds at *fn*=0). The bonds connect the centers of particles in contact, and bond forces are at zero when particles are not displaced relative to each other (*δn*=*δs*=0). When particles are displaced in tension, the bonds support tensile and shear forces below predefined tensile strength and shear strength. When particles are displaced in compression, the bonds support the shear forces below the predefined shear strength. Normal and shear forces are related through the following equations [Fig.1b]:

In compression (*δn*>0): (Eq. 7)

In tension (*δn*<0): (Eq. 8)

Where *fnmin* is the minimum normal force required to break the bond. Bond-induced interparticle forces are calculated as

(Eq. 9)

(Eq. 10)

where *Ab* is the cross-sectional area of the elastic bond, assumed to be a circle with the radius equal to the smallest particle in contact. When particles are separated in tension (*δn*<0), bond tensile forces are limited by tensile strength and bond area

*fb = Tb*\**Ab*. (Eq. 11)

Shear forces are limited by

In tension (*fn*<0): (Eq. 12)

In compression (*fn*>0): (Eq. 13)

**2.2. Particle Motions**

For each time step, net force, displacement, and moment are calculated by summing components of all contact forces acting on a particle. Net force (*Fp*) and net moment (*Mp*) are calculated for each particle by

(Eq. 14)

(Eq. 15)

Where *mp* and *Ip* are mass and moment inertia and *ẍp* and *Ӫp* are the linear and angular accelerations respectively. The particle displacements and roataions are calculated by inverting twice and integrating Eq. 14 and Eq. 15 over each time step for the new particle positions and orientations. At each time step, new particle configurations and contact forces are calculated. At each time step, particle motions are partially damped to dissipate energy in the system, to recreate the inelastic deformation in rocks [Cundall, 1987; Hazzard et al., 2000].

**2.3. Quantification of Stress, Strain and Porosity**

Sample volume, boundary stresses and particle positions through time are used to calculate bulk scale properties during biaxial experiments. The quantification of stress tensors during biaxial experiments using RICEBAL are explained in detail by Morgan, 2015. Membrane and platen boundary stresses correspond to the minimum and maximum principal stress (*σ3* and *σ1*). Membrane stresses are maintained constant at a specified confining pressure; the platen stresses are calculated by summing the net forces of the particles at each platen and dividing that sum by the platen area. Stress associated with bond breakage is recorded by dividing force at failure (fs or fn) by the area of the bond, which is equal to the area of the smallest particle in contact. The displacement of the platens is used to calculate axial strain (*εa*).

The quantification of bulk porosity during biaxial experiments using RICEBAL are explained in detail by Longjohn et al., 2018. Bulk porosity (*φ*) is calculated using total volume within the membranes and total volume of all the spheres within the sample as:

(Eq. 16)

1. **Methods**

In this study, we develop numerical analogs for Berea Sandstone and Lac du Bonnet Granite, representing two widely studied rock types ranging from weaker non-crystalline rocks to strong crystalline rock. We simulate biaxial experiments for both rock types to calibrate bulk behavior of numerical samples to experimental datasets under confined and unconfined conditions.

* 1. **Biaxial Experiments using the Discrete Element Method.**

We simulate samples as granular assemblage of ~60,000 particles with particle radii of 10-40 µm within an initial spatial domain of 0.04 m x 0.03 m. To prepare cohesive samples for biaxial experiments, we preconsolidate our samples to a confining pressure of 10 MPa. The two horizontal confining walls, constructed of rows of particles, are moved inward between rigid vertical walls of particles until preconsolidation stress of 10 MPa is achieved. After consolidation, sample dimensions are 0.019 m x 0.03 m. Porosity of all samples after preconsolidation is 17.6%. Following preconsolidation, we reset the particles along horizontal platens to move independently in the vertical direction, while maintaining their constant confining stress, thus acting as a “membrane” that confines the sample during biaxial experiments. At this stage, we introduce interparticle bonds to simulate cohesive rock material. Axial compression is conducted by moving lateral platens inward at a constant velocity. As the vertical platens move inwards, local differential stresses increase, which causes failure of interparticle bonds, generating microcracks and yielding local changes in porosity. With increasing deformation, the induced microcracks coalesce to form one or more shear fractures, ultimately resulting in the failure of the sample [Fig. 2]. The mechanism of microcrack formation and coalescence results in local changes in porosity, concentrated in the gouge region of the shear fracture and its conjugate fractures. Biaxial experiments are run under confining pressures of 0, 2, 5,10,15,20,25,30,40 and 50 MPa. Macromechanical properties of the sample are collected at increments of 2000 cycles, associated with axial strain increments of 0.001 corresponding to incremental platen displacements of 0.008 mm.

* 1. **Calibration of Samples**

we simulate two rock types – Berea Sandstone and Lac du Bonnet Granite, which are defined by the propertiesthe within the assemblage.The micromechanical model properties are adjusted and the bulk behavior of our model materials is calibrated to replicate experimental laboratory data for Berea Sandstone [Bobich, 2005; Schellart, 2000] and Lac du Bonnet Granite [Martin and Chandler, 1994]. To capture the range of geomechanical rock behavior under both unconfined and confined conditions, we sought to reproduce to experimental datasets for Unconfined Compressive Strength (*UCS*), Young’s modulus (*E*), Mohr-Coulomb cohesion (*C*), and internal friction coefficient (*µ*),. The pertinent input microparameters include (1) mechanical properties of the particles - Shear modulus of particles (*Gp*), Poisson’s ratio of particles (*νp*), (2) mechanical properties of interparticle bonds - Young’s and shear moduli of bonds (*Eb* and *Gb*), tensile strength and cohesion of bonds (*Tb* and *Cb*), and (3) interparticle friction (*µp*). The selected values of input microparameters that best reproduce the bulk properties of the two rock types are presented in Table 1. The calibration of numerical samples to experimental datasets is explained in detail in supplemental information, S1, and figures FS1 and FS2. The bulk behavior of numerical samples under confined and unconfined conditions is shown in Table 2, replicating the experimental geomechanical character of Berea Sandstone and Lac du Bonnet granite.

**3.3. Input Energy during Biaxial Experiments**

We modify the methodology presented by Wong, 1982 for our numerical samples to calculate input energy for each biaxial experiment. We measure the sample length (*L*) during the biaxial experiment to calculate axial strain (*ξ1*) as

(Eq. 17)

Where *Linitial* is the initial sample length (0.3 m). All simulations of biaxial experiments are conducted up to axial strain of 10.3%. Axial stress is applied over the cross-sectional area of platens (*AS1*):

(Eq. 18)

where *Z* is the constant thickness of the particles (0.008 m) and *Wp* is the width of the platens (0.019 m). Total energy input (WS1 (Joules)) from axial stress (S1 (Pa)) is calculated using the area under the axial stress-strain curve (*QS1*):

(Eq. 19)

(Eq. 20)

Similarly, we measure the sample radius (*D*) during the biaxial experiment to calculate transverse strain (*ξ3*) as

(Eq. 21)

Where *Dinitial* is the initial sample diameter (0.019 m). Confining stress is applied over the length sectional area of the sample (*AS3*)

(Eq. 22)

where *Z* is the constant thickness of the particles (0.008 m) and *L* is the varying length of the sample. The total energy input (*Ws3* (Joules)) from confining stress (S3 (Pa)) is calculated using the area under the radial stress-strain curve (*QS3*):

(Eq. 23)

(Eq. 24)

The total external work input (*Wext*) for a biaxial experiment is calculated as (*WS1* + *WS3*).

**3.4. Strain Energy during Biaxial Experiments**

External stresses on rock perform work in the form of internal strain within the rock surrounding the shear fracture referred to as the internal strain energy of rock [Timoshenko and Goodier, 1934]. The work done by external stresses resulting in elastic and inelastic volumetric changes within the rock is the quantitative measure of the strain energy. We implement the methodology presented by Murphy and Cooke, 2004 to calculate the strain energy stored within rock during each biaxial test using the strain energy density function (V0):

(Eq. 25)

Where *E* is the bulk Young’s Modulus of the material, *υ* is the Poisson’s ratio of the material calculated as

(Eq. 26)

and *S13* is the differential stress approximated by

(Eq. 27)

The total work (*Wint*) is calculated by summing the calculated energy density over the area of sample

(Eq. 28)

**3.5. Characterizing Microcracks and Fracture Energy**

To characterize the progression of fracture growth and associated material damage, we document several quantities and derive characteristic relationships that can be compared among experiments. Each bond breakage event is assumed to be a microcrack in the modeled rock samples. As axial stress is applied to the platens during the numerical biaxial experiments, fractures grow by the coalescence of emergent microcracks [Fig. 3]. During each simulated biaxial experiment, we track the spatial and temporal evolution of microcracks and their mode of failure, and calculate the energy associated with each microcrack.

**3.5.1.** **Mode of Microcracks**

Interparticle bonds can fail in either tension or shear, as defined in Eq. 12-13. A tensile microcrack forms when interparticle normal stress exceeds the tensile strength of the bond, resulting in a mode 1 microcrack. Similarly, a shear microcrack results when local shear stress exceeds the shear strength of the bond in compression, resulting in a mode 2 microcrack. During our biaxial tests, we document the mode of each microcrack generated in association with the applied axial stress [Fig. 3a], along with the failure stress at the time of bond breakage.

**3.5.2. Spatial and Temporal Evolution of Microcracks**

We document the location of each bond breakage during biaxial tests. The document bond breakages are plotted as a function of their mode and applied axial strain during formation [Fig. 3b]. By tracking the development of individual microcracks, we implement a visual tool to analyze the progressive localization of damage.

**3.5.3. Fracture Energy from Microcracking**

As axial stress is applied to the platens, interparticle bonds become distorted prior to failure, accumulating elastic strain energy. Bond failure that accompanies microcrack formation releases this energy instantly, emitting an acoustic signal analogous to an earthquake. The fracture energy associated with each microcracking event is calculated using the following equation [Tang and Kaiser, 1998; Jaeger et al., 2009]:

(Eq. 29)  
Where *Efrac* is the energy associated with an individual micro-fracture, *Cf* is the elastic modulus of the bond broken, *σcf* is the peak strength of the failed element and *vf* is the volume of microcrack. RICEBAL provides us with the ability to monitor stress associated with each broken bond *σcf*. Volume of a microcrack (*vf*) is taken as the sum of the areas of the two particles bounding the broken bond. If the microcrack fails in shear, *Cf* takes the value of shear modulus of the bond (*Gb*); if the microcrack fails in tension, *Cf* takes the value of Young’s modulus of the bond (*Eb*). During our biaxial tests, we calculate the energy released during formation of each microcrack and document changes in acoustic association with the applied axial stress [Fig. 3c]. Total fracture energy is calculated as the sum of energy from all microcracking events during a biaxial experiment, up to an axial strain of 10.3%. Fracture energy (*Wfrac*) (Joules/m2) associated with each microcrack is calculated by dividing the calculated microcrack energy by the area of the bond (*Ef*/*Ab*).

**3.6. Porosity and Damage Index**

Another measure of sample deformation is change in porosity induced by the growth of microcracks. During biaxial experiments, the changes in porosity are largely confined to the gouge of the shear fracture and its conjugate fractures [Fig. 2]. We define the fracture gouge as the region around a fracture influenced by the stress changes during fracture initiation and nucleation, resulting in microcracking and porosity changes. In general, tensile microcracks are associated with dilation and increase in local porosity, whereas shear microcracks are associated with compaction and decline in local porosity. Since deformation during biaxial experiments becomes concentrated in the gouge zone of a shear fracture, porosity changes during deformation are indicative of the fracture zone character [Renaud et al., 2017; Longjohn et al., 2018]. The evolution of the bulk sample porosity is representative of the volumetric changes in the fracture gouge during nucleation and rupture.

We employ Eq. 16 to measure changes in bulk sample porosity compared to the initial porosity of samples using the Damage Index (*DI*). For each biaxial simulation, we use the measured porosity (*φ*) at each increment of axial strain to calculate the Damage Index (*DI*) defined by Renaud et al., 2017 as:

(Eq. 30)

where *φi* is the porosity of the sample before the onset of the biaxial experiment. After preconsolidation to 10 MPa, the initial porosity of all samples in this study is 0.176. The Damage Index provide a quantitative characterization of volumetric changes in the fracture gouge while eliminating the influence of the initial porosity of the sample. A positive value for *DI* at peak stress (*σ/σfailure*=1) indicates the growth of a dilatant fracture zone, whereas a negative value of *DI* indicates a compactant fracture zone [Fig. 4].

1. **Results**

**4.1. Progressive Localization of Damage: Berea Sandstone**

As a first demonstration of our simulation results, we examine the growth of fractures in Berea Sandstone under a confining pressure of 15 MPa. We identify four stages in the mechanical behavior as observed by the stress-strain behavior of the sample, and prescribed by experimental [Amitrano, 2003] and numerical studies [Longjohn et al., 2018]. Stage 1 (initiation), corresponding to an axial strain range from 0 to 0.023, is characterized by increasing rock strength and a linear stress-strain curve [Fig. 3a]. This initial stage of the biaxial experiment is characterized by low microcracking activity, 97% of which are generated in tensile mode. Microcracking activity during Stage 1 increases as axial strain on sample increases. Stage 2 (nucleation), corresponding to an axial strain range from 0.024 to 0.038, begins with the introduction of non-linearity in the stress-strain behavior of the sample until peak stress of 143.5 MPa is attained. Stage 2 is characterized by increasing rock strength and decreasing slope of the stress-strain curve, corresponding to strain hardening behavior of the sample. Stage 2 of the biaxial experiment is characterized by very high microcracking activity, generated in both shear (25%) and tensile (75%) modes. Microcrack growth increases as we approach peak stress of rock, marking the end of Stage 2. Stage 3 (rupture localization), corresponding to an axial strain range from 0.039 to 0.062, defines the post-peak stress-strain behavior of rock until residual strength of rock is attained. Stage 3 (localization) is characterized by decreasing rock strength corresponding to strain softening behavior of the sample. Stage 3 is characterized by high microcracking activity, generated in both shear (19%) and tensile (81%) modes. Microcrack growth, especially in shear mode, declines as we approach the post-fracture residual strength of rock. Stage 4, corresponding to an axial strain range from 0.063 to 0.103, defines the frictional sliding behavior of the rock sample. Stage 4 (sliding) is characterized by nearly constant rock strength of 132.2 MPa, corresponding to the residual strength of rock. Stage 4 is characterized by very low microcracking activity, 94% of which are generated dominantly in tensile mode. Microcracking activity declines gradually as we approach the end of the experiment at an axial strain of 0.103. A total of 5442 microcracks developed in the sandstone sample deformed at a confining pressure of 15 MPa, with only 18% of them occurring in shear mode, generated mostly during Stage 2 and Stage 3 of the biaxial experiment.

The spatial distribution of microcracks generated during the four stages of the biaxial experiment show significant variation. Stage 1 is characterized by distributed tensile microcracking through the rock sample, indicating onset of dilatancy in the fracturing process [Fig. 3b]. Stage 2 is characterized by growth of shear and tensile microcracks, arising from the tensile asperities created in Stage 1. Shear microcracks generated in Stage 2 frequently occur as clusters, enveloped by tensile microcracks. During this nucleation stage, deformation is progressively localized as shear and tensile microcracks coalesce to form small fractures through the sample. Stage 3 is characterized by the coalescence of pre-existing microcracks and smaller fractures into a through-going shear rupture, assisted by newly generated shear and tensile microcracks. Microcracking activity during Stage 3 is very localized, with new asperities largely confined to the process zone of the developed shear fracture. Shear and tensile microcracks also coalesce to form smaller conjugate fractures, originating from the primary shear rupture. Stage 4 is characterized by shearing along the macrofracture surface. Microcracks are generated by the rupture of surface asperities and gouge fracturing, caused by plucking of grains along the shear fracture and associated conjugate fractures from sliding of fractured blocks of the rock. Thus, the nucleation and localization of fracture in sandstone is controlled by the cooperative interaction of tensile and shear microcracks. This indicates interplay between competing processes –dilatation from tensile microcracking and compaction from shear microcracking. Thus, the volumetric changes in the fracture zone in sandstone is dependent on the variation in local porosity induced by tensile and shear microcracking [Fig. 2a].

We calculate a total input mechanical energy (*Wext*) of 3487 J for the biaxial experiment on Berea sandstone under a confining pressure of 15 MPa to an axial strain of 10.3%. The calculated elastic strain energy (*Wint*) stored in the system is 203 J, corresponding to 5.8% of the input external work. We calculate a total fracture energy (*Wfrac*) of 355 J released as fracture energy during the biaxial experiment, corresponding to 10.3% of the input mechanical energy. The release of fracture energy as AE during the biaxial experiment exhibits an exponential trend [Fig. 3c]. AE energy release from microcracking activity during Stage 1 is small, contributing to 5% of the AE energy release. Stage 2 of the experiment, corresponding to the highest microcracking activity, is also associated with the highest release in fracture energy, with 49% of the total energy released as AE. Although, only 25% of the total microcracking from Stage 2 occur in shear mode, they contribute to 76% of the fracture energy released. Stage 3 of the biaxial experiment, corresponding to the coalescence of the shear fracture, is associated with release of 38% of the total fracture energy. While only 19% of all the total microcracking in Stage 3 occurs in shear mode but contribute to 75% of fracture energy released. Frictional sliding in Stage 4 results in a small amount of fracture energy release as AE. Stage 4 is associated with 7% a release of total fracture energy, with 39% released by microcracks occurring in shear mode.

As fracture growth progresses from initiation to rupture, we observe a decline in porosity in the gouge of the shear fracture and associated conjugate fractures [Fig. 2a]. At *σ/σfailure*=1, we calculate a negative value of the Damage Index (*DI*), indicating a net decrease in volume of the sample during rupture [Fig. 4]. The abundance of shear microcracks in the fracture gouge and associated decline in porosity [Fig. 3], coupled with a calculated negative value of the Damage Index at failure indicates the formation of a compactant fracture zone. Thus, the growth of shear fracture in Berea sandstone occurs through the cooperative coalescence of tensile and shear microcracks. While the abundance of shear microcracks is less than tensile ones, shear microcracking is localized in the fracture gouge and is the dominant mode of fracture energy release as AE. The nature of the fracture zone is controlled by the interplay between dilatant character of tensile microcracks and the compressive character of shear microcracks and imposed pressure.

**4.2. Progressive Localization of Damage: Lac du Bonnet Granite**

A comparison simulation to that described above is carried out on the numerical analog to the Lac du Bonnet Granite. The biaxial experiment, also conducted at 15 MPa confining pressure, results in some similar deformation trends as Berea Sandstone, but also some distinct differences, which are highlighted here. The growth of macrofractures in Lac du Bonnet Granite is dominated by tensile microcracking in four distinct stages [Fig. 5a]. Stage 1, corresponding to an axial strain from 0 to 0.007, is characterized by a linear stress-strain curve and rapid increase in rock strength attributed to the high Young’s Modulus of granite. Stage 2, corresponding to an axial strain range from 0.008 to 0.015, is the strain hardening phase of the experiment and is characterized by very high tensile microcracking activity as we attain peak strength of rock. Stage 3, corresponding to an axial strain range from 0.016 to 0.036, defines the post-peak strain-weakening behavior of rock, and is characterized by high tensile microcracking activity. Microcrack growth declines as we approach residual strength of rock. Stage 4, corresponding to an axial strain range from 0.037 to 0.103, defines the frictional sliding behavior of the granite sample and is characterized by residual strength of rock and low microcracking activity. A total of 2598 microcracks developed in the granite sample at a confining pressure of 15 MPa, with ~98% of them occurring in tensile mode generated largely during Stage 2 and Stage 3 of the biaxial experiment.

Stage 1 is characterized by distributed tensile microcracking through the rock sample, indicating onset of dilatant deformation in the sample [Fig. 5b]. Stage 2 is characterized by growth of shear and tensile microcracks, predominantly around asperities created in Stage 1. Shear microcracking during Stage 2 dominantly occurs in the gouge of the nucleating fracture, enveloped by tensile microcracks. As deformation begins to concentrate, coalescence of tensile microcracks results in emergent localized fractures, indicating the nucleation of the shear and conjugate fractures. Stage 3 is characterized by the coalescence of pre-existing and newly generated microcracks and smaller fractures into a through-going shear rupture. Conjugate fractures, originating from the primary shear rupture are fully developed at this stage, originating from coalescence of tensile microcracks in the gouge of the primary shear fracture. Stage 4 is characterized by increased microcracking in the fracture zone of the developed shear fracture. Frictional sliding of the fractured blocks results in gouge damage by plucking of grains from the faulted blocks of the sample. Thus, new microcracks are generated by microcracking in the fracture gouge. Thus, the nucleation and localization of fractures in granite occurs through the coalescence of microcracks, predominantly generated in tensile mode.

We calculate a total input mechanical energy (*Wext*) of 4830 J for the biaxial experiment on Lac du Bonnet granite under a confining pressure of 15 MPa to an axial strain of 10.3%. The calculated elastic strain energy (*Wint*) stored in the system is 141 J, corresponding to 2.9% of the input external work. We calculate a total fracture energy (*Wfrac*) of 730 J released as AE during the biaxial experiment, corresponding to 15.1% of the input mechanical energy. The release of fracture energy as AE during the biaxial experiment exhibits an exponential trend [Fig. 5c].The release of fracture energy in the four sequential stages of the biaxial experiment are 15%, 43%, 31% and 11% respectively. Stage 2 and 3 have the highest contribution to released fracture energy due to the high number of tensile microcracks initiated during the nucleation and rupture of the shear fracture. Through the entirety of the experiment, tensile microcracking is the dominant mode of energy release, contributing to 93% of the total AE energy. However, the small number of microcracks generated in shear mode (2% of total microcracks), correspond to events of high energy, contributing to 7% of total energy released. Thus, the growth of shear fracture in Lac du Bonnet granite occurs through the cooperative coalescence of microcracks predominantly generated in tensile mode. Fracture energy is largely released by microcracking in tensile mode. Since tensile microcracking is the primary mode of deformation, they compete with the imposed confining pressure to form dilatant fracture zones.

As fracture growth progresses from initiation to rupture, we observe an increase in porosity in the gouge of the shear fracture and associated conjugate fractures [Fig. 2b]. At *σ/σfailure*=1, we calculate a positive value of the Damage Index (*DI*), indicating a net increase in volume of the sample during rupture [Fig. 4]. The abundance of tensile microcracks [Fig. 5] in the fracture gouge and associated increase in porosity, coupled with a calculated positive value of the Damage Index indicates the formation of a dilatant fracture zone. Thus, the growth of shear fracture in Lac du Bonnet granite occurs dominantly through the cooperative coalescence of tensile microcracks. Abundant tensile microcracking results in the formation of a dilatant fracture zone and is the dominant mode of fracture energy release as AE.

**4.3. Effect of Confining Pressure**

To examine the influence of confining pressure on fracture growth mechanisms, we carry out identical experiments on Berea Sandstone and Lac du Bonnet Granite models over a range of confining pressures. As we increase confining pressure from 0 MPa to 50 MPa on samples of Berea Sandstone, we observe an increase in peak strength of rock from 85.05 MPa to 238.82 MPa [Fig. 6a]. As confining pressure increases, rock strength increases, providing greater resistance to the formation of a shear fracture during biaxial deformation experiments. This increased resistance to fracture formation with confining pressure results in an increase in shear microcracks and a decline in tensile microcracks [Fig. 6b]. While the total number of microcracks created during biaxial deformation of sandstone does not vary significantly with confining pressure, microcracking in shear increases from 4% of total events at 0 MPa to 45% of total events at 50 MPa. The increase in shear microcracking and simultaneous decline in tensile microcracking indicates transition from dilatant fracture formation at low confining pressures to compactant fracture formation at high confining pressure. This observation is supported by the declining values of calculated Damage Index at *σ*/*σfailure* =1 with confining pressure [Fig. 6c]. At low confining pressures (0-10 MPa), we calculate positive values of the Damage Index at peak strength of rock, indicating formation of a dilatant fracture zone. At higher confining pressures (15-50 MPa), we calculate negative values of the Damage Index at peak strength of rock, indicating formation of a fracture zone dominated by compaction and shear.

Total fracture energy released as AE increases from 173.6 J at confining pressure of 0 MPa (corresponding to 14.9% of the input mechanical energy) to 797.6 J at confining pressure of 50 MPa (corresponding to 10.1% of the input mechanical energy). The contribution of shear microcracking to total fracture energy released increases from 31% at confining pressure of 0 MPa to 92% at confining pressure of 50 MPa [Fig. 6d]. The increase in fracture energy with confining pressure is due to increase in fraction of shear microcracking, which are associated with a larger stress release as they overcome both tensile and compressive forces during formation. Thus, the increase in shear microcracking with confining pressure results in an increase in AE energy in sandstone.

Visual representation of microcrack locations in sandstone show an increase in microcrack distribution and fracture gouge thickness with confining pressure [Fig. 6e]. At low confining pressures, shear microcracks are concentrated in the fracture zone of the primary shear fracture and conjugate fractures. However, the distribution of shear microcracks increases with confining pressure as shearing becomes increasingly dominant mode of microcracking. In general, an increase in confining pressure also correlates with increase in number of conjugate fractures. The increase in confining pressure results in slower fracture coalescence and increase in events of shear microcracks, which are associated with high energy release. Thus, the increase in confining pressure on sandstone during deformation results in an increase in shear microcracking and associated AE energy, and the formation of compactant fracture zones.

As we increase confining pressure from 0 MPa to 50 MPa on samples of Lac du Bonnet granite, we observe an increase in peak strength of rock from 233.79 MPa to 433.63 MPa [Fig. 7a], indicating greater resistance to the formation of shear fracture during biaxial experiments. The formation of a fracture under increasing confining pressure is facilitated by an increase in total number of microcracks created during biaxial tests increases from 2110 at a confining pressure of 0 MPa to 3204 at a confining pressure of 50 MPa [Fig. 7b]. While number of shear microcracks increases slightly, the growth of the fracture is facilitated by a significant increase in tensile microcracking with confining pressure, indicating dilatant fracture zones in granite. Over a range of confining pressures from 0 to 50 MPa, we calculate positive values of Damage Index at *σ*/*σfailure* =1, indicating formation of dilatant fracture zones [Fig. 7c]. However, the dilatant tendencies of tensile microcracks are countered by the imposed confining pressure on rock resulting in a decline in rock volume with confining pressure. We calculate a decline in values of the Damage Index with confining pressure.

Total fracture energy released as AE increases from 586.9 J at confining pressure of 0 MPa (corresponding to 28% of the input mechanical energy) to 967.5 J at confining pressure of 50 MPa (corresponding to 10% of the input mechanical energy). The contribution of shear microcracking to total fracture energy released increases from 7% at confining pressure of 0 MPa to 13% at confining pressure of 50 MPa [Fig. 7d]. The increase in fracture energy with confining pressure is due to the rapid increase in number of tensile microcracks to form the shear fracture.

Visual representations of microcrack locations in granite show an increase in fracture gouge thickness with confining pressure [Fig. 7e]. The increase in resistance to fracturing from confining pressure is countered by increase in tensile microcracking activity in the gouge region of granite, resulting in nucleation of dilatant shear fractures. The increase in confining pressure on granite results in slower fracture growth due to coalescence of larger number of tensile microcracks. Thus, the increase in confining pressure on granite during deformation results in an increase in number of tensile microcracks and associated AE energy, and the formation of dilatant fracture zones,

1. **Discussions**

**5.1. Comparison of Fracture growth in Berea Sandstone and Lac du Bonnet Granite**

We test the validity of our model results by comparing them to experimental datasets and highlight how our study can add to the current understanding of fracture nucleation in sandstone and granite. The formation of shear fractures in simulated sandstone and granite has similarities, but also some important differences that inform us about the mechanics of fracturing in these contrasting materials. Stage 1 (initiation), is characterized by low microcracking activity in both sandstone [Fig. 3] and granite [Fig 5]. Initial deformation in both rock types is characterized by distributed tensile microcracking, marking the onset of inelastic deformation. Stage 2 (nucleation), is characterized by high microcracking activity in both sandstone and granite. Microcracking becomes increasingly localized in the gouge regions of the emergent shear fracture and conjugate fractures. While fracture nucleation in sandstone is characterized by both shear and tensile microcracking, tensile microcracking is the dominant nucleation mechanism in granite. Stage 3 (rupture) is characterized by localized microcracking in both sandstone and granite. In sandstones, the shear fractures and conjugate fractures localize through the progressive coalescence of tensile and shear microcracks. However, tensile microcracks coalesce to localize the shear fracture and conjugate fractures in granite. As the shear fracture localizes microcracking declines in both sandstone and granite. Stage 4 (frictional sliding) is characterized by an increase in gouge damage in both sandstone and granite. The sliding of faulted blocks results in localized tensile microcracking in the gouge region of the developed shear fracture due to frictional plucking of grains.

The growth of shear fractures in sandstones has been shown to occur through coalescence of tensile and shear microcracks using AE source mechanism [Fortin et al., 2009] and microstructural analyses [Menendez et al., 1996], with fraction of microcracking occurring in shear increasing with confining pressure [Baud et al., 2004]. Similarly, the growth of fractures during biaxial experiments in granites has been shown to occur through coalescence of tensile microcracks using AE source mechanism [Lockner et al., 1991] and microstructural analyses [Peng and Johnson, 1972]. Thus, our model results replicate the experimentally observed deformation in granites and sandstones, adding knowledge of spatial and temporal growth of microcracks and associated fracture energy.

In sandstone, the increase in confining pressure results in an increase in shear microcracking. The increase in shear microcracking results in the formation of compactant shear fracture zones [Fig. 6]. Experimental deformation experiments on sandstone show a transition from dilating to compacting fracture zones with increasing confining pressure [Menendez et al., 1996; Besuelle, 2001]. Our simulation results exhibit that the fracture zone is an interplay between the competing shear and tensile microcracks in the fracture zone. At low confining pressures, we observe dilatant fracture zones as tensile microcracks dominate the fracture and gouge region. At high confining pressures, the dominant damage mechanism is compactant, resulting in abundant shear microcracks in the fracture and gouge region. As a result, we observe compactant fracture zones in sandstones under high confining pressure conditions.

In granite, the increase in confining pressure results in an increase in tensile microcracking. The increase in tensile microcracking in granite results in the formation of dilatant shear fracture zones [Fig. 7]. Our model results show that the number of tensile microcracks generated during biaxial experiments in granite increases in response to the increased resistance provided by confining pressure. Escartin et al., 1997 show a decline in dilatant nature of fractures in granite with increase in confining pressure. Our results reproduce this behavior, exhibiting a declining trend bulk dilation trend with confining pressure.

Our results show that fracture energy is a function of lithology and confining pressure on rock. Since Lac du Bonnet granite is stronger than Berea sandstone, the energy required to initiate microcracks is greater. Thus, despite greater occurrence of microcracks in sandstone when compared to granite [Fig 6b, Fig 7b], we calculate greater fracture energy associated with shear fracture formation in the latter rock. Fracture energy associated with deformation in sandstone and granite increases with confining pressure. The increase in fracture energy with confining pressure in sandstone is due to increase in shear microcracking activity [Fig. 6d], which are associated with greater stress release upon microcrack formation than tensile microcracks. The increase in fracture energy with confining pressure in granite is due to the increase in number of tensile microcracking activity [Fig. 7d], each releasing accumulated elastic stress upon formation.

We infer different mechanisms of fracture nucleation in sandstone and granite. In sandstone, the growh of the fracture occurs through the progressive coalescence of shear and tensile microcracks [Fig. 8a]. The damage in the fracture zone is characterized by the interplay of dilatant and compactant tendencies of tensile and shear microcracks respectively. At low confining pressures, tensile microcracks dominate the fracture zone, resulting in the formation of a dilatant fracture zone. At high confining pressures, shear microcracking replaces tensile microcracking, resulting in the formation of a fracture zone dominated by compaction and shear. AE energy associated with fracture formation increases with confining pressure due to increase in shear microcracking. In strong rocks such as granite, the growth of fracture occurs predominantly through coalescence of tensile microcracks, resulting in formation of dilatant fracture zones [Fig. 8b]. As confining pressure increases, the increased resistance to fracture coalescence is countered by an increase in microcracking activity. The nature of fracture zone is an interplay between the competing dilatancy of tensile microcracking and compactant tendency of imposed confining pressure on rock. Fracture energy increases with confining pressure on rock as number of tensile microcracks increases.

**5.2. Energy Budget during Biaxial Experiments**

The complete deformational work budget consists of five components [Herbert et al., 2015; Cooke and Madden, 2014]: internal work (*Wint*), work against gravity (*Wgrav*), work against friction (*Wfric*), seismic radiated energy (*Wseis*), and the work of fault propagation (*Wprop*). These components sum to the total external work (*Wext*) applied to the system:

(Eq. 31)

During fracture growth, the potential recoverable energy is stored in the system as work against gravity (*Wgrav*) and strain energy within the host rock (*Wint*). The input energy is also dissipated in the rock through irreversible processes such as frictional heating (*Wfric*), seismic energy (*Wseis*) and energy to initiate and propagate fractures (*Wprop*). In our study, samples remain in place during biaxial experiments, and no work is done against gravity (*Wgrav* = 0). *Wseis* and *Wprop* are energy changes due to formation of brittle fractures. Fracture energy (*Wfrac*) captured through micro-scale stress changes accompanying microcracks is indicative of fracture propagation and associated seismic energy (*Wfrac* =*Wseis* + *Wprop*). For this study, Eq. 31 can be simplified to

(Eq. 32)

We employ the calculations of *Wext*, *Wint* and *Wfrac* using Eq. 20, 24, 28 and 29 to infer *Wfric* and understand the energy balance during growth of shear fractures in biaxial experiments.

Input mechanical energy (*Wext*) increases from 1163 J at 0 MPa to 7355 J at 50 MPa during biaxial experiments on Berea sandstone. The internal strain energy (*Wint*) increases from 186.2 J at 0 MPa to 227.1 J at 50 MPa [Fig. 9A]. The relative contribution of the internal strain energy to the energy budget declines with confining pressure, accounting for 16% of the input energy at 0 MPa to 3.1 % of the input energy at 50 MPa. Simultaneously, the accompanying fracture energy (*Wfrac*) increases from 173.7 J at 0 MPa to 797.6 J at 50 MPa. The partitioning of input energy into fracture energy declines from 14.9% at 0 MPa to 10.8% at 50 MPa in Berea sandstone. We calculate an increase in frictional energy from 803.1 J at 0 MPa to 6330 J at 50 MPa. Thus, as confining pressure on sandstone increases, increasing amount of input energy is used for frictional work and associated heating, with *Wfric* accounting for 69% at 0 MPa to 86% at 50 MPa.

*Wext* increases from 2062 J at 0 MPa to 9659 J at 50 MPa during biaxial experiments on Lac du Bonnet granite. *Wint* increases from 128.7 J at 0 MPa to 154.9 J at 50 MPa [Fig. 9B]. The relative contribution of the internal strain energy to the energy budget declines with confining pressure, accounting for 6.2% of the input energy at 0 MPa to 1.6 % of the input energy at 50 MPa. Simultaneously, *Wfrac* increases from 978.3 J at 0 MPa to 1612.5 J at 50 MPa. The partitioning of input energy into fracture energy declines from 47.4% at 0 MPa to 16.6% at 50 MPa in Lac du Bonnet granite. We calculate an increase in frictional energy from 954.9 J at 0 MPa to 7891.3 J at 50 MPa. Thus, as confining pressure on granite increases, increasing amount of input energy is used for frictional work and associated heating, with *Wfric* accounting for 46% at 0 MPa to 81% at 50 MPa.

Thus, fracture energy accounts for 10-15% of total input energy in sandstone and 16-47% in granite. While fracture energy increases with confining pressure, *Wfrac*/*Wext* declines indicating greater dissipation of input energy through other mechanisms. Elastic strain energy stored in rock accounts for 3-16% of total input energy in sandstone and 2-6% in granite. While internal strain energy energy increases with confining pressure, *Wint*/*Wext* declines indicating dominance of frictional energy with confining pressure. Thus, we calculate that *Wfric* accounts for 69-86% of total input energy in sandstone and from 46-81% of input energy in granite, with the energy partitioned into frictional work increasing with confining pressure. Our results indicate that aseismic deformation is a significant term in the energy budget during rock deformation, as observed by other experimental [Goodfellow et al., 2015] and numerical studies [Madden et al., 2017].

1. **Conclusions**

In this study, we employ the Discrete Element Method to capture key attributes of damage evolution associated with growth of shear fractures in sandstone and granite. We characterize the mode and fracture energy associated with emergent microcracks during biaxial experiments to understand the mechanism of shear fracture evolution in sandstone and granite. In sandstone, the growth of shear fractures occurs through the progressive coalescence of tensile and shear microcracks. While shear microcracking accounts for 4-44% of the total microcracks, they contribute 31-91% of the total fracture energy released. At low confining pressures, tensile microcracks dominate the fracture gouge resulting in the formation of dilatant fracture zones. While the number of microcracks in sandstone does not show much variation as we increase confining pressure, fraction of shear microcracking increases, resulting in the formation of compactant fracture zones. In granite, the growth of shear fractures occurs dominantly through the progressive localization of tensile microcracks, releasing 88-93% of the total fracture energy. Since the fracture zone in granites is dominated by tensile microcracks, the fracture zone is dilatant in nature. As confining pressure on granite increases, the number of tensile microcracks increases and the nature of the fracture zone is an interplay between the competing dilatant tensile microcracks and the compactant nature of confining pressure.

Fracture energy accounts for 10-15% of total input energy in sandstone and 16-47% in granite, with the fracture energy increasing with confining pressure. Simultaneously, elastic strain energy stored in rock increases with confining pressure, accounting for 3-16% of total input energy in sandstone and 2-6% in granite. Finally, we calculate that the work done against friction increases with confining pressure on rock, accounting for 69-86% of total input energy in sandstone and from 46-81% of input energy in granite. Thus, using the discrete element method we develop a methodology to micromechanical insights into the fracturing process and associated energy balance in sandstone and granite.

**Figure Captions**

Figure 1: Mechanics of the Discrete Element Modeling implemented in this study.

Figure 2: Progressive evolution of porosity due to microcracking in during biaxial compression tests under confining pressure of 15 MPa. (a) Evolution of porosity in Berea sandstone at axial strain of 0.0206, 0.0371, 0.0618 and 0.0927 respectively (b) Evolution of porosity in Lac du Bonnet granite at axial strain of 0.0061, 0.0144, 0.0371 and 0.0927 respectively

Figure 3: Evolution of microcracking and fracture energy in Berea sandstone during biaxial compression test under confining pressure of 15 MPa. (a) Applied axial stress and microcracking events as a function of axial strain: four distinct stages of deformation are identified Deformation stages 1-4 correspond to axial strain of 0.0206, 0.0371, 0.0618 and 0.0927, complementing the porosity distributions in Fig. 2a. (b) Spatial distribution of shear and tensile microcracks corresponding to Stages 1-4 highlighted in the biaxial experiment. (c) Evolution of fracture energy from microcrack formation with axial strain.

Figure 4: Evolution of calculated Damage Index prior to onset of failure in Berea sandstone and Lac du Bonnet granite during biaxial compression tests under confining pressure of 15 MPa. Deformation is characterized by compaction as differential stress is increased, followed by dilation when approaching failure. Berea Sandstone exhibits compactant character upon failure, whereas Lac du Bonnet granite exhibits dilatant character upon failure.

Figure 5: Evolution of microcracking and fracture energy in Lac du Bonnet granite during biaxial compression test under confining pressure of 15 MPa. (a) Applied axial stress and microcracking events as a function of axial strain: four distinct stages of deformation are identified Deformation stages 1-4 correspond to axial strain of 0.0103, 0.0228, 0.0371 and 0.0927, complementing the porosity distributions in Fig. 2b. (b) Spatial distribution of shear and tensile microcracks corresponding to Stages 1-4 highlighted in the biaxial experiment. (c) Evolution of fracture energy from microcrack formation with axial strain.

Figure 6: Effect of Confining Pressure from 0 to 50 MPa on microcracking in Berea Sandstone during biaxial experiments to a final axial strain of 0.103. (a) Stress-Strain curves during biaxial tests show an increase in rock strength from 85 MPa to 235 MPa. (b) Total number of microcracks generated during biaxial tests does not show significant variation but the fraction of shear microcracks increases from 4% at 0 MPa to 45% at 50 MPa of confining pressure. (c) Evolution of Damage Index prior to failure indicates formation of dilatant fracture zones at low confining pressures (0-2 MPa) and compactant fracture zones at higher confining pressures (5-50 MPa). (d) Fracture energy released during fracture formation increases from 1.7 J at 0 MPa to 7.8 J at 50 MPa with fraction of energy released in shear increasing from 31% to 92%. (e) Spatial distribution of tensile and shear microcracks shows increase in concentration of shear microcracks with confining pressure, indicating a transition from dilatant deformation processes to compactant deformation processes.

Figure 7: Effect of Confining Pressure from 0 to 50 MPa on microcracking in Berea Sandstone during biaxial experiments to a final axial strain of 0.103. (a) Stress-Strain curves during biaxial tests show an increase in rock strength from 234 MPa to 434 MPa. (b) Total number of microcracks generated during biaxial increases from 2110 at 0 MPa to 3204 at 50 MPa, facilitated by a rapid increase in number of tensile microcracks (c) Evolution of Damage Index prior to failure indicates formation of dilatant fracture zones at low confining pressures (0-2 MPa) and compactant fracture zones at higher confining pressures (5-50 MPa). (d) Fracture energy released during fracture formation increases from 17.5 J at 0 MPa to 29.0 J at 50 MPa with fraction of energy released in shear increasing from 6% to 12%. (e) Spatial distribution of tensile and shear microcracks shows increase in number of tensile microcracks confining pressure, indicating dilatant deformation processes to overcome the effect of increasing confining pressure.

Figure 8: Fracture nucleation mechanisms in sandstone and granite. Stages 1,2 and 3 correspond to the localized damage at the onset of yielding, localization and rupture respectively. (a) Growth of shear fracture in Berea sandstone through cooperative coalescence of shear and tensile microcracks, with fraction of shear microcracks increasing with confining pressure. Dilatant fracture zones are calculated for low confining pressures (0-2 MPa) and compactant fracture zones are calculated for higher confining pressures (5-50 MPa). (b) Growth of tensile shear fracture in Lac du Bonnet granite through cooperative coalescence of primarily tensile microcracks. Dilatant fracture zones are calculated for confining pressures from 0-50 MPa due to abundance of tensile microcracking.

Figure 9: Energy partitioning into fracture energy, internal strain energy and frictional energy during biaxial experiments on (a) Berea sandstone and (b) Lac du Bonnet granite.

Supplementary Figure 1: Unconfined macromechanical properties of calibrated DEM materials used in this study. Berea Sandstone model has a Young’s Modulus of 4.28 GPa and unconfined compressive strength of 85 MPa. Lac du Bonnet granite model has a Young’s Modulus of 42.47 GPa and unconfined compressive strength of 234 MPa.

Supplementary Figure 2: Mohr-Coulomb properties of calibrated DEM materials used in this study. Berea Sandstone model has a cohesion of 29.3 MPa and an angle of internal friction of 29 degrees. Lac du Bonnet model has a cohesion of 54.6 MPa and an angle of internal friction of 40 degrees.

**References**

Amitrano, D., 2003, Brittle-ductile transition and associated seismicity: Experimental and numerical studies and relationship with the *b* value: Journal of Geophysical Research: Solid Earth, v. 108, p. 1–15, doi: 10.1029/2001JB000680.

Amitrano, D., Grasso, J.R., and Senfaute, G., 2005, Seismic precursory patterns before a cliff collapse and critical point phenomena: Geophysical Research Letters, v. 32, p. 1–5, doi: 10.1029/2004GL022270.

Baud, P., Klein, E., and Wong, T. Fong, 2004, Compaction localization in porous sandstones: Spatial evolution of damage and acoustic emission activity: Journal of Structural Geology, v. 26, p. 603–624, doi: 10.1016/j.jsg.2003.09.002.

Bésuelle, P., 2001. Compacting and dilating shear bands in porous rock: Theoretical and experimental conditions. Journal of Geophysical Research: Solid Earth, 106(B7), pp.13435-13442.

Bobich, J.K., 2005, Experimental analysis of the extension to shear fracture transition in Berea sandstone: Texas A&M University, p. 52.

Brace, W.F., Paulding, B.W., and Scholz, C., 1966, Dilatancy in the fracture of crystalline rocks: Journal of Geophysical Research, v. 71, p. 3939–3953, doi: 10.1029/JZ071i016p03939.

Brown, E.T., 1977, Fundamentals of rock mechanics: Tectonophysics, v. 38, p. 367–368, doi: 10.1016/0040-1951(77)90223-2.

Chester, J.S., Chester, F.M., and Kronenberg, A.K., 2005, Fracture surface energy of the Punchbowl fault, San Andreas system: Nature, v. 437, p. 133–136, doi: 10.1038/nature03942.

Cooke, M.L., and Murphy, S., 2004, Assessing the work budget and efficiency of fault systems using mechanical models: Journal of Geophysical Research: Solid Earth, v. 109, p. 1–13, doi: 10.1029/2004JB002968.

Cundall, P.A., and Strack, O.D.L., 1979, A discrete numerical model for granular assemblies: Géotechnique, v. 29, p. 47–65, doi: 10.1680/geot.1979.29.1.47.

De Paola, N., Holdsworth, R.E., Viti, C., Collettini, C., and Bullock, R., 2015, Can grain size sensitive flow lubricate faults during the initial stages of earthquake propagation? Earth and Planetary Science Letters, v. 431, p. 48–58, doi: 10.1016/j.epsl.2015.09.002.

Dempsey, D., Ellis, S., Archer, R., and Rowland, J., 2012, Energetics of normal earthquakes on dip-slip faults: Geology, v. 40, p. 279–282, doi: 10.1130/G32643.1.

Escartín, J., Hirth, G., and Evans, B., 1997, Nondilatant brittle deformation of serpentinites: Implications for Mohr-Coulomb theory and the strength of faults: Journal of Geophysical Research: Solid Earth, v. 102, p. 2897–2913, doi: 10.1029/96JB02792.

Fortin, J., Stanchits, S., Dresen, G., and Gueguen, Y., 2009, Acoustic emissions monitoring during inelastic deformation of porous sandstone: Comparison of three modes of deformation: Pure and Applied Geophysics, v. 166, p. 823–841, doi: 10.1007/s00024-009-0479-0.

Gallagher Jr, J.J., Friedman, M., Handin, J. and Sowers, G.M., 1974. Experimental studies relating to microfracture in sandstone. Tectonophysics, 21(3), pp.203-247.

Geology, J., Ndez, B.M., Zhu, W., and Wong, T., 1996, Pergamon Micromechanics of brittle faulting and cataclastic flow in Berea sandstone: Science, v. 18, doi: 10.1016/0191-8141(95)00076-P.

Goodfellow, S.D., Nasseri, M.H.B., Maxwell, S.C., and Young, R.P., 2015, Hydraulic fracture energy budget: Insights from the laboratory: Geophysical Research Letters, v. 42, p. 3179–3187, doi: 10.1002/2015GL063093.

Guo, Y., and Morgan, J.K., 2007, Fault gouge evolution and its dependence on normal stress and rock strength—Results of discrete element simulations: Gouge zone properties: Journal of Geophysical Research, v. 112, p. B10403, doi: 10.1029/2006JB004524.

Hazzard, J.F., Young, R.P., and Maxwell, S.C., 2000, Micromechanical modeling of cracking and failure in brittle rocks: Journal of Geophysical Research: Solid Earth, v. 105, p. 16683–16697, doi: 10.1029/2000JB900085.

Herbert, J.W., Cooke, M.L., Souloumiac, P., Madden, E.H., Mary, B.C.L., and Maillot, B., 2015, The work of fault growth in laboratory sandbox experiments: Earth and Planetary Science Letters, v. 432, p. 95–102, doi: 10.1016/j.epsl.2015.09.046.

Horii, H., and Nemat-Nasser, S., 1985, Compression-induced microcrack growth in brittle solids: Axial splitting and shear failure: Journal of Geophysical Research, v. 90, p. 3105, doi: 10.1029/JB090iB04p03105.

Jalali, M., Gischig, V., Doetsch, J., Näf, R., Krietsch, H., Klepikova, M., Amann, F., and Giardini, D., 2018, Transmissivity Changes and Microseismicity Induced by Small-scale Hydraulic Fracturing Tests in Crystalline Rock: Geophysical Research Letters, p. 2265–2273, doi: 10.1002/2017GL076781.

Kranz, R.L., 1983, Microcracks in rocks: A review: Tectonophysics, v. 100, p. 449–480, doi: 10.1016/0040-1951(83)90198-1.

Lei, X., and Satoh, T., 2007, Indicators of critical point behavior prior to rock failure inferred from pre-failure damage: Tectonophysics, v. 431, p. 97–111, doi: 10.1016/j.tecto.2006.04.023.

Lockner, D., 1993, The Role of Acoustic Emission in the Study of Rock Fracture: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 30, p. 883–899.

LongJohn, T., Morgan, J.K., and Dugan, B., 2018, Microstructural Evolution of Porosity and Stress During the Formation of Brittle Shear Fractures: A Discrete Element Model Study: Journal of Geophysical Research: Solid Earth, v. 123, p. 2228–2245, doi: 10.1002/2017JB014842.

Madden, E.H., Cooke, M.L., and McBeck, J., 2017, Energy budget and propagation of faults via shearing and opening using work optimization: Journal of Geophysical Research: Solid Earth, v. 122, p. 6757–6772, doi: 10.1002/2017JB014237.

Martin, C.D., and Chandler, N.A., 1994, The progressive fracture of Lac du Bonnet granite: International Journal of Rock Mechanics and Mining Sciences and, v. 31, p. 643–659, doi: 10.1016/0148-9062(94)90005-1.

Modiriasari, A., Bobet, A., and Pyrak-Nolte, L.J., 2017, Use of seismic wave conversions (S-to-P wave) to monitor shear crack growth: 51st US Rock Mechanics / Geomechanics Symposium 2017, v. 3.

Moore, D.E. and Lockner, D.A., 1995. The role of microcracking in shear-fracture propagation in granite. Journal of Structural Geology, 17(1), pp.95-114.

Morgan, J.K., 2015, Journal of Geophysical Research: Solid Earth wedges: Discrete element simulations: p. 3870–3896, doi: 10.1002/2014JB011455.Received.

Morgan, J.K., and Boettcher, M.S., 1999, Numerical simulations of granular shear zones using the distinct element method: 1. Shear zone kinematics and the micromechanics of localization: Journal of Geophysical Research: Solid Earth, v. 104, p. 2703–2719, doi: 10.1029/1998JB900056.

Ni, Q.Q., and Iwamoto, M., 2002, Wavelet transform of acoustic emission signals in failure of model composites: Engineering Fracture Mechanics, v. 69, p. 717–728, doi: 10.1016/S0013-7944(01)00105-9.

Peng, S. and Johnson, A.M., 1972, January. Crack growth and faulting in cylindrical specimens of Chelmsford granite. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 9, No. 1, pp. 37-86). Pergamon.

Renard, F., Cordonnier, B., Kobchenko, M., Kandula, N., Weiss, J., and Zhu, W., 2017, Microscale characterization of rupture nucleation unravels precursors to faulting in rocks: Earth and Planetary Science Letters, v. 476, p. 69–78, doi: 10.1016/j.epsl.2017.08.002.

Schellart, W.P., 2000, Shear test results for cohesion and friction coefficients for different granular materials: Scaling implications for their usage in analogue modelling: Tectonophysics, v. 324, p. 1–16, doi: 10.1016/S0040-1951(00)00111-6.

Sulem, J., and Ouffroukh, H., 2006, Shear banding in drained and undrained triaxial tests on a saturated sandstone: Porosity and permeability evolution: International Journal of Rock Mechanics and Mining Sciences, v. 43, p. 292–310, doi: 10.1016/j.ijrmms.2005.07.001.

Tang, C.., and Kaiser, P.., 1998, Numerical Simulation of Cumulative Damage and Seismic Energy Release During Brittle Rock Failure—Part I: Fundamentals: International Journal of Rock Mechanics and Mining Sciences, v. 35, p. 113–121, doi: 10.1016/S0148-9062(97)00009-0.

Velde, B., Moore, D., Badri, A., and Ledesert, B., 1993, Fractal and length analysis of fractures during brittle to ductile changes: J Geophys Res, v. 98, p. 11935–11940.

Walsh, J.B., and Brace, W.F., 1984, The effect of pressure on porosity and the transport properties of rock.: Journal of Geophysical Research, v. 89, p. 9425–9431, doi: 10.1016/j.vascn.2012.03.003.

Wang, B., Chen, Y., and Wong, T.F., 2008, A discrete element model for the development of compaction localization in granular rock: Journal of Geophysical Research: Solid Earth, v. 113, p. 1–17, doi: 10.1029/2006JB004501.

Wong, T.F., 1982. Shear fracture energy of Westerly granite from post‐failure behavior. Journal of Geophysical Research: Solid Earth, 87(B2), pp.990-1000.

Wong, T.-F., David, C., and Zhu, W., 1997, The transition from brittle faulting to cataclasic flow in porous sandstones: Mechanical deformation: Journal of Geophysical Research, v. 102, p. 3009–3025, doi: 10.1029/96JB03282.

Zhang, J., Wong, T.F. and Davis, D.M., 1990. Micromechanics of pressure‐induced grain crushing in porous rocks. Journal of Geophysical Research: Solid Earth, 95(B1), pp.341-352.