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

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**Key Points:**

* Fracture growth in sandstone occurs through shear and tensile microcracking; shear microcrack fraction increases with confining pressure
* Fracture growth in granite occurs through tensile microcracking; microcrack abundance increases with confining pressure
* Fracture energy accounts for 10-47% of input energy; frictional deformation is the largest component of the energy budget of fracture growth

**Abstract**

We employ the Discrete Element Method to analyze the dynamic micromechanical response of sandstone and granite to unstable failure. Calibrated granular models of sandstone and granite are subjected to biaxial experiments under confining pressures of 0 – 50 MPa, leading to the development of shear fractures through interactions of microcracks occurring in shear and tensile modes. We document the mode and energy associated with emergent microcracks to analyze fracture growth patterns and quantify energy release during rock fracture. Our models document that the growth of shear fractures in sandstone occurs through cooperative interaction between shear and tensile microcracks, with shear microcracks accounting 4-44% of total microcracks and 31-92% of fracture energy. Shear microcracking fraction increases with confining pressure, resulting in an increase in fracture energy and a transition from dilatant to compactant fracture zones in sandstones. The growth of shear fractures in granite occurs primarily through coalescence of tensile microcracks, which account for 96-98% of total microcracks and 87 -93% of fracture energy. Tensile microcracking increases with confining pressure, resulting in an increase in fracture energy and formation of dilatant fracture zones in granite. Fracture energy increases with confining pressure, accounting for 10-15% of the total input mechanical energy in sandstone vs. 16-47% in granite. We estimate that the work done against friction from intergranular sliding and fracture accounts for 69-86% of total input energy in sandstone and 46-81% in granite. Our results indicate that frictional deformation is a significant term in the energy budget during biaxial deformation.

1. **Introduction**

The mechanical loading of rocks results in local inelastic processes that produce microcracks, and their cooperative interaction leads to formation of macroscopic fractures (Kranz, 1983). 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. The deformational energy put into a rock is partitioned into recoverable strain energy and non-recoverable fracture energy and frictional energy (Cooke and Murphy, 2004; Wong, 1982), and this partitioning determines how the rock responds to applied external stresses. Observations from the field and laboratory indicate a wide range of fracture growth mechanisms (Mitchell and Faulkner, 2009; Stanchits et al., 2006; Baud et al., 2004), but their effect on the energy budget of rock remains poorly constrained. The quantification of fracture growth and associated energy for different lithologies and confining pressures 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 understand the control of lithology and confining pressure on fracture growth mechanisms and associated fracture energy release.

The formation 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; Baud et al., 2004; 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 (Fortin et al., 2009; Gallagher et al., 1974), 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). Although 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.

Acoustic emissions (AEs) have been employed to understand the influence of microcrack mode on fracture growth and energy. The spatial and temporal distribution of microcracks identified by AEs has helped identify distinct stages of fracture coalescence and provide a quantitative dependence between microcracking mechanisms and fracture energy (Lockner et al, 1991). However, AE source mechanisms and calculations of fracture energy show significant variation with lithology and confining pressure on rock (Baud et al. 2004; Stanchits et al., 2006; Lei et al., 2004). As a result, fracture energy estimates exhibit a range of over six orders of magnitude from fault area calculations (Wong, 1982; Chester et al., 2005) and AE energy estimation (Lockner et al, 1991; Goodfellow et al, 2015; Warpinski et al., 2012). Additionally, AE’s only account for a small fraction of the total elastic energy release during fracture growth and nucleation (Cooke and Murphy, 2004; Chester et al., 2005); and their correlation with fracture energy may be complicated due to difficulty in recognizing microcrack mode (Modiriasari et al., 2017; Jalali et al., 2017). Thus, there is need for a micromechanical study to complement laboratory AE studies to analyze fracture growth mechanisms and associated energy release. The accurate quantification of fracture energy is a key factor in balancing the energy budget during rock deformation.

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; Barr and Dahlen, 1989). 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 in various studies (Wong, 1982; Dempsey et al., 2012), the association between fracture growth mechanism and energy partitioning remain poorly constrained. Laboratory and field experiments provide estimates that brittle fracture growth consumes anywhere between 10% and 90% of input deformation energy (Chester et al., 2005; Pittarello et al., 2008; Madden et al., 2017; Goodfellow et al., 2015), leaving open the question of how lithology and confining pressure influence partitioning of input 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) is used to create and examine the behavior of sandstone and granite models in which cracks and fractures form spontaneously and release elastic energy. 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 the influence of lithology and confining pressure on fracture nucleation mechanisms and associated energy release.

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, 2005), 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. The interparticle mechanics of RICEBAL are described in supporting Text S1 and supporting Fig. S1.

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. We employ the calibrated samples of sandstone and granite to study the growth of shear fractures and evolution of fracture energy during biaxial deformation.

* 1. **Biaxial Experiments using RICEBAL**

We simulate samples as granular assemblage of ~6,000 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 0.0775 m x 0.038 m (Fig. 1a). We assume plane strain conditions, and out of plane stresses are zero. Following preconsolidation, we reset the particles along horizontal walls 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. Bulk porosity (*φ*) is calculated using total volume within the membranes and total volume of all the spheres within the sample as (Longjohn et al., 2018):

(Eq. 1)

Porosity of all samples after preconsolidation is 17.6%. Porosity is relatively uniform across the domain of the sample at the onset but exhibits local changes during a biaxial test.

Axial compression is conducted by moving vertical platens inward at a constant velocity. As the lateral platens move inwards, local differential stresses increase, which causes failure of interparticle bonds, generating microcracks and yielding local changes in porosity (Fig. 1b-e). With increasing deformation, the induced asperities coalesce to form one or more shear fractures, ultimately resulting in the failure of the sample (Fig. 1). The mechanisms of microcrack formation and coalescence result 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**

In our study, we simulate two rock types – Berea Sandstone and Lac du Bonnet Granite, which are defined by the micromechanical properties of the discrete particles and bonds 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 supporting Text S2 and supporting Fig. S2 and Fig. S3. 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. 2)

Where *Linitial* is the initial sample length (0.0775 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. 3)

where *Z* is the constant thickness of the particles (0.008 m) and *Wp* is the width of the platens (0.038 m). Total energy input (*WS1* (Joules)) from axial stress (*S1* (Pa)) is calculated using the area under the axial stress-strain curve (*QS1*):

(Eq. 4)

(Eq. 5)

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

(Eq. 6)

Where *Dinitial* is the initial sample diameter (0.038 m). Confining stress is applied over the length sectional area of the sample (*AS3*)

(Eq. 7)

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. 8)

(Eq. 9)

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

**3.4. 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. 2). 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.

**3.4.1.** **Mode of Microcracks**

Interparticle bonds can fail in either tension or shear, as defined in supporting Eq. S13-S14. 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. 2a), along with the failure stress at the time of bond breakage.

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

We document the location of each bond breakage event, representing microcracks, during biaxial tests. The documented bond breakages are plotted as a function of their mode and applied axial strain during formation (Fig. 2b). By tracking the development of individual microcracks, we implement a visual tool to analyze the progressive localization of damage. The spatial distributions of microcracks are referenced back to their initial position at the onset of the biaxial test to maintain a consistent framework across biaxial experiments of varying confining pressures and lithologies.

**3.4.3. 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 elastic signal analogous to seismic energy. The fracture energy associated with each microcracking event is calculated using the following equation (Tang and Kaiser, 1998; Jaeger et al., 2009):

(Eq. 10)  
Where *Wfrac* 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 the energy released with applied axial stress (Fig. 2c). 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%.

**3.5. 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. 1). 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 and its conjugate fractures, porosity changes during deformation are indicative of the fracture zone character (Renaud et al., 2017; Longjohn et al., 2018). Thus, the evolution of the bulk sample porosity is representative of the volumetric changes in the fracture gouge during nucleation and rupture.

We employ Eq. 1 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. 11)

where *φi* is the porosity of the sample before the onset of the biaxial experiment. The Damage Index provides a simple, 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. 3).

1. **Results**

**4.1. Progressive Localization of Fractures: 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. 2a). 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. 2b). 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. 1a).

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%. 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 during the biaxial experiment exhibits an exponential trend (Fig. 2c). Fracture energy release from microcracking activity during Stage 1 is small, contributing to 5% of the fracture 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 fracture. 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. Similarly, while only 19% of all the total microcracking in Stage 3 occurs in shear mode they contribute to 75% of fracture energy released. Frictional sliding in Stage 4 results in a small amount of fracture energy release. 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 eventual shear fracture and associated conjugate fractures (Fig. 1b). 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. 3). The abundance of shear microcracks in the fracture gouge (Fig. 2b) 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. The nature of the fracture zone is controlled by the interplay between competing dilatant character of tensile microcracks and the compactant character of shear microcracks and imposed pressure.

**4.2. Progressive Localization of Fractures: 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. 4a). 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. 4b). 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%. We calculate a total fracture energy (*Wfrac*) of 730 J released during the biaxial experiment, corresponding to 15.1% of the input mechanical energy. The release of fracture energy during the biaxial experiment exhibits an exponential trend (Fig. 4c). Through the entirety of the experiment, tensile microcracking is the dominant mode of energy release, contributing to 93% of the total fracture 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. The release of fracture energy in Stages 1-4 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. 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 calculate a decline in the sample, indicated by negative values of *DI* (Fig. 3). However, 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. 3). The abundance of tensile microcracks in the fracture gouge (Fig. 4b) 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.

**4.3. Effect of Confining Pressure on Fracture Growth and Energy**

To examine the influence of confining pressure on fracture growth mechanisms, we carry out identical biaxial 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. 5a). 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. 5b). 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. 5c). 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 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. 5d). The increase in fracture energy with confining pressure is due to increase in fraction of shear microcracking, which is associated with a larger stress release as cracks must overcome both tensile and compressive forces during formation. Thus, the increase in shear microcracking with confining pressure results in an increase in fracture energy in sandstone.

Visual representation of microcrack locations in sandstone show an increase in microcrack distribution and fracture gouge thickness with confining pressure (Fig. 5e). At low confining pressures, we observe thin fracture gouges dominated by tensile microcracking. As confining pressure on rock increases, we observe thicker fracture gouge regions dominated by shear microcracking. In general, an increase in confining pressure also correlates with increase in number of conjugate fractures. Thus, as confining pressure on sandstone increases we calculate increasing shear microcracking, especially in the fracture zone, and declining values of *DI*. The transition from tensile-dominated micromechanics at low confining pressure to shear-dominated micromechanics at high confining pressure results indicates a transition from dilatant to compactant fracture zones with increasing confining pressure.

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. 6a), 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. 6b). While number of shear microcracks increases from 2.0% to 3.4%, the growth of the fracture is facilitated by a significant increase in tensile microcracking with confining pressure, indicating dilatant deformation. 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. 6c). 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. Thus, we calculate a decline in values of the Damage Index with confining pressure.

Total fracture energy released 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. 6d). 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. 6e). 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 fracture energy, and the formation of dilatant fracture zones.

1. **Discussions**

**5.1. Fracture Growth Mechanisms in Berea Sandstone and Lac du Bonnet Granite**

Based on our simulations, we can infer that different mechanisms of fracture nucleation occur in sandstone and granite. In sandstone, the growth of fractures occurs through the progressive coalescence of shear and tensile microcracks (Fig. 7a). 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, and we calculate a positive value of *DI* indicating the formation of dilatant fracture zones. At high confining pressures, shear microcracking replaces tensile microcracking in the fracture gouge, and we calculate a negative value of *DI* indicating the formation of compactant fracture zones. In granite, the growth of fractures occurs predominantly through coalescence of tensile microcracks, and we calculate positive values of *DI* at failure indicating the formation of dilatant fracture zones (Fig. 7b). As confining pressure increases, the increased resistance to fracture coalescence is countered by an increase in microcracking activity. The nature of the fracture zone is an interplay between the competing dilatancy of tensile microcracking and compactant tendency of imposed confining pressure on rock.

The different mechanisms of fracture growth observed from our models of these two lithologies are consistent with experimentally observed deformation in granites and sandstones. Shear fractures in sandstones have been shown to occur through coalescence of tensile and shear microcracks using AE source mechanisms (Fortin et al., 2009) and microstructural analyses (Menendez et al., 1996), with the fraction of shear microcracking increasing with confining pressure (Baud et al., 2004). This decline in tensile microcracking results in a transition from dilatant to compactant fracture zones with increasing confining pressure in sandstones (Menendez et al., 1996; Besuelle, 2001). In contrast, 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). The modeled decline in dilatancy of fracture zones in granite has also been experimentally observed by Escartin et al., 1997. Thus, our models replicate experimentally observed behavior in sandstones and granites, providing new insights into the spatial and temporal growth of microcracks and associated fracture energy.

Stage 1 (initiation), is characterized by low microcracking activity in both sandstone (Fig. 2) and granite (Fig 4). 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, resulting in emergent shear fractures and conjugate fractures. Fracture nucleation in sandstone involves both shear and tensile microcracking, whereas 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, in granite, tensile microcracks coalesce to define the through-going shear fracture and conjugate fractures. As the fractures develop, microcracking declines in both sandstone and granite. Stage 4 (frictional sliding) is characterized by an increase in gouge production and 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.

Our results show that fracture energy is a function of lithology and confining pressure on rock and is also strongly dependent on microcracking mode. Fracture energy associated with deformation in sandstone and granite increases with confining pressure. In sandstone, total fracture energy increases from 173.6 J at confining pressure of 0 MPa to 797.6 J at confining pressure of 50 MPa. The increase in fracture energy with confining pressure in sandstone is due to increase in shear microcracking activity, which accounts for 31% of total fracture energy at confining pressure of 0 MPa to 92% at confining pressure of 50 MPa (Fig. 5d). In granite, total fracture energy released increases from 586.9 J at confining pressure of 0 MPa to 967.5 J at confining pressure of 50 MPa. The increase in fracture energy with confining pressure in granite is due to the increase in the number of tensile microcracks each releasing accumulated elastic stress upon formation (Fig. 6b). Since Lac du Bonnet granite is stronger than Berea sandstone, the fracture energy associated with individual microcracks is greater. Despite greater occurrence of microcracks in sandstone when compared to granite (Fig 5b, Fig 6b), we calculate greater fracture energy associated with deformation in granite than in sandstone. Thus, our numerical analysis shows that fracture energy is strongly influenced by abundance and mode of microcracks, which is in-turn controlled by lithology and confining pressure on rock. The quantification of fracture energy as a function of lithology and confining pressure is essential to develop an understanding of balanced energy budgets during rock deformation.

**5.2. Energy Budget during Biaxial Experiments**

Our analyses of different contributions of fracture energy depending on lithology and confining pressure, raises the question of its contribution to the energy budget during deformation. The complete deformational work budget consists of five components (Herbert et al., 2015; Cooke and Murphy, 2004): 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. 12)

During biaxial deformation experiments, the potential recoverable energy is stored in the system as work against gravity (*Wgrav*) and strain energy within the host rock (*Wint*). In our study, samples remain in place during biaxial experiments, and no work is done against gravity (*Wgrav* = 0). External stresses on rock perform recoverable work in the form of volumetric changes within the rock surrounding the shear fracture referred to as the internal strain energy of rock (Timoshenko and Goodier, 1951). The work done by external stresses resulting in elastic volumetric changes within the rock is the quantitative measure of the strain energy (*Wint*). We adapt the methodology presented by Cooke and Murphy, 2004 to calculate *Wint* for each biaxial experiment, detailed in supporting Text S3.

The input energy is also dissipated in the rock through irreversible processes such as frictional work (*Wfric*), seismic energy (*Wseis*) and energy to initiate and propagate fractures (*Wprop*). In this study, *Wfric* represents the summation of all work done against frictional forces during a biaxial experiment. Thus, *Wfric* accounts the for energy dissipated during frictional sliding along the shear fracture and conjugate fractures; and the frictional sliding of grains in the unfractured regions. *Wseis* and *Wprop* represent the elastic energy released during brittle deformation. The cumulative fracture energy (*Wfrac*) calculated using the micro-scale stress changes accompanying microcrack formation is representative of fracture propagation and associated seismic energy (*Wfrac* =*Wseis* + *Wprop*) (Tang and Kaiser, 1998). Thus, for our study, Eq. 12 can be simplified to

(Eq. 13)

We employ the calculations of *Wext*, *Wint* and *Wfrac* using Eq. 5, 9, 10 and S21 to infer *Wfric* and understand the partitioning of input energy between elastic deformation (*Wint*), inelastic deformation from fracture growth (*Wfrac*) and inelastic deformation from frictional sliding (*Wfric*).

The total 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. 8a). 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 only 3.1 % of the input energy at 50 MPa. Simultaneously, the total 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. This implies 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. 8B). 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. *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 (*Wfrac*) accounts for 10-15% of total input energy in sandstone and 16-47% in granite, over the confining pressures we tested here. While fracture energy increases with confining pressure, *Wfrac*/*Wext* declines, indicating greater dissipation of input energy through other mechanisms. Elastic strain energy (*Wint*) stored in rock accounts for 3-16% of total input energy in sandstone and 2-6% in granite. While internal strain energy increases with increasing confining pressure, *Wint*/*Wext* declines, indicating that frictional energy dominates with confining pressure. The increase in resistance to elastic volumetric changes provided by confining pressure results in a decline in *Wint*. 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 frictional deformation is a significant term in the energy budget during rock deformation, with its share of total input energy increasing with confining pressure.

Thus, our results show that fracture energy (*Wfrac*) accounts for a small fraction of input energy, similar to energy budget estimations from field, laboratory observations and numerical studies (Pittarello et al., 2008; Goodfellow et al., 2015 and Herbert et al., 2015). Additionally, we show that the fraction of input energy partitioned into fracture growth is a function of lithology and confining pressure influenced by microscale processes. Our results show that the largest fraction of input energy is partitioned into frictional energy, similar to results of experimental (Yoshioka, 1986) and numerical studies (Barr and Dahlen, 1989). The input energy partitioned into *Wfric* accounts for the work done in the gouge during frictional sliding of the fractured blocks, and off-fault frictional movement between grains. In natural fault systems, *Wfric* accounts for frictional deformation of the rock in the gouge and off-fault regions and associated frictional heating. Frictional deformation and associated heating have been shown to account for 24 - 80 % of the total energy budget during fault rupture (Yoshioka, 1986; Dahlen and Barr, 1989; Madden et al., 2017; Kanamori and Rivera, 2006), showing general agreement with our estimates of *Wfric*. by abundance and mode of microcracks, which is in-turn controlled by lithology and confining pressure on rock. Thus, through our modeling approach, we develop ability to accurately quantify the energy budget during rock deformation, while accounting for the influence of lithology and confining pressure on rock.

1. **Conclusions**

In this study, we employ the Discrete Element Method to capture key attributes of shear fracture growth and associated energy release in sandstone and granite. We characterize the mode and fracture energy associated with emergent microcracks during simulated biaxial experiments to infer fracture growth mechanisms and balance energy budget during rock deformation. 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. As confining pressure is increased upon sandstone, the 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, which account for 96-98% of total microcracks and 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.

Our results show that fracture growth in granite releases greater energy than sandstone due to larger stress drops associated with each microcrack in the former rock. Fracture energy (*Wfrac*) increases with confining pressure, accounting for 10-15% of total input energy (*Wext*) in sandstone and 16-47% in granite, with the fracture energy increasing with confining pressure. However, *Wfrac*/*Wext* declines with confining pressure indicating greater dissipation of input energy frictional mechanisms. We infer that the work done against friction (*Wfric*) 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 micromechanical insights into the fracturing process and associated energy budget in sandstone and granite.

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**Tables**

Table 1: Microparameters used in DEM modeling of Berea Sandstone and Lac Du Bonnet Granite

|  |  |  |
| --- | --- | --- |
| Micromechanical Parameter | Berea Sandstone | Lac du Bonnet Granite |
| Young’s Modulus of Bonds (*Eb*)  *GPa* | 5,000 | 50,000 |
| Shear Modulus of Bonds (G*b*)  *GPa* | 5,000 | 50,000 |
| *σc/σt* | 10 | 20 |
| Tensile Strength of Bonds (T*b*)  *MPa* | 9 | 600 |
| Cohesion of Bonds (*Cb*)  *MPa* | 90 | 12,000 |
| Shear Modulus of Particles (*Gp*)  *GPa* | 29 | 2000 |
| Poisson’s Ratio of Particles (*νp*) | 0.33 | 0.26 |
| Interparticle friction (*µp*) | 0.4 | 0.7 |

Table 2: Macromechanical behavior of models calibrated to Berea Sandstone and Lac du Bonnet Granite

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Macromechanical Property | Model Values for Berea Sandstone | Experimental Values for Berea Sandstone | Model Values for Lac du Bonnet Granite | Experimental Values for Lac du Bonnet Granite |
| Unconfined Compressive Strength (UCS)  *MPa* | 85.05 | 95.00 | 233.79 | 224.00 |
| Young’s Modulus (*E*)  *GPa* | 5.28 | 8.00 | 42.47 | 50.00 |
| Mohr-Coulomb Cohesion (*C*)  *MPa* | 29.35 | 26.10 | 54.60 | 46.00 |
| Mohr Coulomb Slope (*µ*) | 0.55 | 0.49 | 0.83 | 1.05 |

**Figure Captions**

Figure 1: Progressive evolution of porosity in Berea Sandstone from microcracking during biaxial compression tests under confining pressure of 15 MPa, at axial strain of (a) 0.000, (b) 0.0206, (c) 0.0371, (d) 0.0618 and (e) 0.0927 respectively.

Figure 2: 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 in shear and tensile modes as a function of axial strain: 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 in shear and tensile modes with axial strain.

Figure 3: 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, signified by negative values of *DI*. Failure (*σ*/*σfailure*) is preceded by dilation, indicated by increase in values of *DI*. Berea Sandstone exhibits compactant character upon failure, whereas Lac du Bonnet granite exhibits dilatant character upon failure.

Figure 4: 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 in shear and tensile modes as a function of axial strain: Deformation stages 1-4 correspond to axial strain of 0.0103, 0.0228, 0.0371 and 0.0927 (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 in shear and tensile modes with axial strain.

Figure 5: 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 174 J at 0 MPa to 798 J at 50 MPa with fraction of energy released in shear increasing from 31% to 92%. (e) Spatio-temporal distribution of tensile and shear microcracks at axial strain of 0.103 shows increase in concentration of shear microcracks in fracture zone of primary shear fracture and conjugate fractures with confining pressure, indicating a transition from dilatant deformation processes to compactant deformation processes.

Figure 6: Effect of Confining Pressure from 0 to 50 MPa on microcracking in Lac du Bonnet granite 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) Positive values of Damage Index prior to failure indicates formation of dilatant fracture zones. The decline in *DI* with increasing confining pressure indicates decline in dilatant character of fracture zone. (d) Fracture energy released during fracture formation increases from 978 J at 0 MPa to 1612 J at 50 MPa with fraction of energy released in shear increasing from 6% to 13%. (e) Spatio-temporal distribution of tensile and shear microcracks at axial strain of 0.103 shows increase in number of tensile microcracking, indicating dilatant deformation processes to overcome the effect of increasing confining pressure.

Figure 7: Fracture nucleation mechanisms in sandstone and granite. Stages 1,2 and 3 correspond to the localized microcracking 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. (b) Growth of tensile shear fracture in Lac du Bonnet granite through cooperative coalescence of tensile microcracks, with number of tensile microcracks increasing with confining pressure.

Figure 8: Energy partitioning into fracture energy, internal strain energy and frictional energy during confined biaxial experiments on (a) Berea sandstone and (b) Lac du Bonnet granite.