Subcritical stress controls on rock stability

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1. Introduction

Stress in rocks can affect their damage, fracture, and erosion processes. It is a common notion that increased stress leads to increased crack propagation and fracture, which in turn causes increased damage and erosion rates. As rocks are uplifted and exhumed from the crust, the conditions change from a critically stressed and confined state to low confinement, and lower stress magnitudes, and the direction of the principle stress can even revert (Zang and Stephansson, 2010; Leith et al., 2014). At the Earth's surface, the stresses that act on rocks are typically sub-critical. Topographic perturbation can cause stress concentrations and create barriers to stress transmission (Miller and Dunne, 1996). Yet, due to reduced confinement, fractures can open, exposing fresh rock to be weathered (St. Clair et al., 2015). Weathering depends on temperature and environmental conditions of the rock, which are driven by and interact with atmospheric processes. The exposure to atmosphere, hydrosphere and biosphere results in lower, ambient temperature ranges than in deep crustal rock. In addition, water is ubiquitous available. Its effect fluctuates over time with avaialbility, and may include phase changes (freeze, evaporation) as well as chemical and mechanical effects due to biota and human activities (Anderson, 2019).

The rheology of rocks under these conditions are less explored. Near-surface stress fields and conditions have been investigated on short time-scales in the context of natural hazards and infrastructure. The importance of rock physics and fracture mechanics near the Earth's surface have recently been more and more recognized on timescales of e.g. land-scape evolution, weathering, erosion and long-term waste storage. The acting mechanisms for progressive rock failure at and near the Earth's surface are subcritical both in rate and magnitude.

In the subcritical range, applied stress not only leads to cracking and fatigue, but also to toughening, frictional interlocking and strengthening. The observed mechanism depends on the mode, magnitude and orientation of the stresses. We use three sets of laboratory experiments to explore mechanisms controlled by the subcritical stress and provide interpretations and explanations.

In the first set of experiments the focus is on opening mode I fracture propagation at subcritical load while water is present at the crack. The second set, highlights stepped indirect tensile tests, which show a compaction prior to the onset of fracture. In the third set we show how stress transmission, friction and interlocking results into an erosional strengthening of the material. Determining the conditions for weakening and strengthening mechanisms at subcritical stress magnitudes and rates will allow for more reliable temporal and spatial predictions of progressive rock failure at and near the Earth's surface.

2. Experiments

2.1. Experiment I: Water and fracture localization

Propagating a fracture subject to tensile stresses is easily done in rock, especially if stresses can concentrate at a notch. The rate at which the fracture nucleates and starts to grow can be related to the stress intensity at the crack tip. In a set of three-point bending experiments Voigtländer et al. (2018) showed that a localized fracture more readily grew in mode I if water was present at the crack tip, than if the sample was kept dry. Elastic residual strain measurements using neutron diffraction of the same samples showed that in the wet-tested samples, stress was relieved where the fracture formed, while the dry samples retained elastic stress at the notch (Voigtländer et al., 2020). While in general, any increase in stress concentration in mode I is expected to lead to an increase in subcritical crack growth, non-linear effects can alter the response if water is present or introduced. Water not only enhances fracture growth by chemo-mechanical mechanisms, including stress corrosion and surface energy changes, but seems to enhance localization of the fracture. Highly localized damage by the presence of water in the crack has also been observed in other experiments (King et al., 2008). Thus, if water is present, a lower stress corrosion rate or subcritical cracking bound likely does not exist, as all stress would concentrate and no stresses be transmitted to other parts or grains.

2.2. *Experiment II: Strengthening and stable crack growth*

Fracture mechanics are conceptualized for crustal conditions with triaxial stress states or over short timescales in engineering applications, which are difficult to relate to long-term near surface conditions. The inherent expectation of these concepts is a direct proportionality of applied stress to deformation, quantified by constant material properties like the Poisson ratio. At ambient conditions and without confining pressure like in axial splitting or indirect tensile experiments, though with a stress stepping protocol, Voigtländer et al. (2016) observed with neutron diffraction techniques that prior to microcrack nucleation, propagation and consequent rupture of the samples, compressive stress builds up as the sample compacts in the first loading steps. At increased applied stress extensional strains prevail and are even retained in intermittent unloading steps. Only at higher applied stress steps, a proportionality of compression to resulting indirect tension develops. The compaction also has an effect on the growth of mode I cracks. First, it creates an internal confinement which suppresses fractures to open in mode I. Due to the experimental set-up probably both intergranular and geometrical confinement are present. Second, due to the confinement of the material/grains amongst each other, damage is localized and aligned, and thus can also lead to stable crack growth before rupture. The threshold where the confinement and thus strengthening/toughening transits to extension can likely be explained by the elastic constants, the change in rheology has, to our knowledge, not been quantified so far. The path from an initial closing of microcracks to an opening of fractures has been inferred by Acoustic Emission (AE) and other techniques in unconfined and uniaxial compression experiments (UCS) as well (e.g. Diederichs, 2003). The transition from confining (crack closure) to indirect tension (opening of microcracks), and the stress range at which this happens, would determine a lower bound to progressive fracture at subcritical compressive conditions, e.g. the foot of a rock wall.

2.3. *Experiment III: Stress transmission and local controls*

The third set of experiments differs from the first two, which were adaptations of classical rock mechanics experiments. The aim was to constrain the relationship between stress and erosion rate. Locked-sand has been used as an analogue material for rock mass, which has little to no tensile strength but relatively high compressive strength. Particles can readily be detached or eroded by any geomorphic agent, like flowing water, rain impact or wind (Bruthans et al., 2014). The samples were placed under uniaxial confinement with a constant load. Artificial rain on the sample was used as erosive driver, which was switched on and kept constant for each erosion interval. As the sample eroded, the cross-sectional area of the sample decreased. This decrease in contact area led to an increase in the stress within the sample. With the increase in stress we observed a decrease in erosion rates.

With increasing normal stress, the sand grains compact and transfer stresses to one another, like in a Roman arch. This results in increased rigidity and strength of the bulk material. The path of the stress through the material has a specific geometry. Grains that are not part of the confinement can be readily detached and eroded. The transfer of stresses is depicted in granular physics as metastable local force chains, which strengthen the material until they buckle and shear (Abed Zadeh et al., 2019). The concept relies on the transmission of stress. Buckling of force chains and thus the interception of stress transmission is only possible at or near a free interface. Within the sample, where stress transmission causes confinement, stresses concentrate and can cause macroscopic tensile and shear planes (Diederichs, 2003). Thus the bulk behavior might be rather controlled by friction. If we turn to friction as an explanation to the observed behavior, Murrell & Digby (1970) identified surface traction as the mechanism to alter the rheological response of shear stress under increased normal stress. Friction at low confinement is controlled by interface properties (grains/crystal/failure plane) (Barton, 1976; Byerlee, 1978). If we assume traction to be the controlling mechanism in our experiments, it seems to scale with normal stress, and leads to strain hardening and a general toughening. This causes a decrease of damage or, in our case, of the erosion rate as stress increases.

3. Conclusion

For direct tension, like in the first set of experiments, the prediction of the more stress concentration the more failure, though highly localized is likely. That there is a stress intensity below which no fracture propagation occurs needs further exploration, and might not exist if water and other environmental conditions are taken into account. Near the Earth's surface, we can expect that damage accumulation is more localized than when formed in the crust, where damage under high confinement is more dispersed and distributed.

The second set of experiments showed that when considering indirect tension due to compression, like at the foot of a rock wall, we also need to include the effect of the resulting confinement. The confinement due to non-critical indirect tension strengthens the rock and enables stable crack growth parallel to the principle stress (spalling).

The third set of experiments, where an increase in normal stress made the material more rigid, highlights stress transfer. Especially at low confinement (low normal stress) the stress transmission depends on the microscale where grains and crystals interlock. At increased confinement, traction and friction strengthen the material as well.

The three experiments represent a suite of normal stress condition, likely to be found at and near the Earth's surface. While little to no confining stresses are experienced in direct tension, an increase in compressive stresses, leads to confinement, that can suppress, or hamper mode I fractures hitherto to open and propagate. The effect compression in the indirect tension experiment offsets the expected proportionality of applied compression to resulting indirect tension. If confinement is further increased local mechanisms like force chains, but also traction and friction strengthen the material until the conditions at the local scale become critical. The bulk (macroscopic) rheology of the samples at subcritical loads depend on the conditions at the local or microscale and their criticality. The rheology of rocks at low confinement, subcritical stress magnitudes, and exposure to atmospheric processes, those conditions at and near surface, need further attention, as the general expectation of more stress leading to more damage might not hold at subcritical conditions at and near Earth's surface.

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5. Reference list

Abed Zadeh, A. et al., 2019, Enlightening force chains: a review of photoelasticimetry in granular matter: Granular Matter, v. 21, p. 1–12, doi:10.1007/s10035-019-0942-2.

Anderson, S.P., 2019, Breaking it Down: Mechanical Processes in the Weathering Engine: Elements, v. 15, p. 247–252, doi:10.2138/gselements.15.4.247.

Barton, N., 1976, The shear strength of rock and rock joints: International Journal Rock Mechanics, v. 13, p. 255–279.

Bruthans, J., Soukup, J., Vaculikova, J., Filippi, M., Schweigstillova, J., Mayo, A.L., Masin, D., Kletetschka, G., and Rihosek, J., 2014, Sandstone landforms shaped by negative feedback between stress and erosion: Nature Geoscience, v. 7, p. 597–601, doi:10.1038/ngeo2209.

Byerlee, J.D., 1978, Friction of rocks: Pageoph, v. 116, p. 615–626, doi:10.1007/BF00876528.

St. Clair, J., Moon, S., Holbrook, W.S., Perron, J.T., Riebe, C.S., Martel, S.J., Carr, B., Harman, C., Singha, K., and Richter, D. deB, 2015, Geophysical imaging reveals topographic stress control of bedrock weathering: Science, v. 350, p. 534–538, doi:10.1126/science.aab2210.

Diederichs, M.S., 2003, Rock fracture and collapse under low confinement conditions: Rock Mechanics and Rock Engineering, v. 36, p. 339–381, doi:10.1007/s00603-003-0015-y.

King, A., Johnson, G., Engelberg, D., Ludwig, W., and Marrow, J., 2008, Observations of intergranular stress corrosion cracking in a grain-mapped polycrystal: Science, v. 321, p. 382–385, doi:10.1126/science.1156211.

Leith, K., Moore, J.R., Amann, F., and Loew, S., 2014, In situ stress control on microcrack generation and macroscopic extensional fracture in exhuming bedrock: Journal of Geophysical Research: Solid Earth, v. 119, p. 594–615, doi:10.1002/2012JB009801.

Miller, D.J., and Dunne, T., 1996, Topographic perturbations of regional stresses and consequent bedrock fracturing: Journal of Geophysical Research, v. 101, p. 25523, doi:10.1029/96JB02531.

Murrell, S.A.F., and Digby, P.J., 1970, The Theory of Brittle Fracture Initiation under Triaxial Stress Conditions—II: Geophysical Journal of the Royal Astronomical Society, v. 19, p. 499, doi:10.1111/j.1365-246X.1970.tb06050.x.

Voigtländer, A., Leith, K., and Krautblatter, M., 2018, Subcritical crack growth and progressive failure in Carrara marble under wet and dry conditions: Journal of Geophysical Research: Solid Earth, v. 123, p. 3780–3798, doi:10.1029/2017JB014956.

Voigtländer, A., Leith, K., Müller, B.I.R., Scheffzük, C., Schilling, F.R., and Krautblatter, M., 2016, Control of Induced and Residual Crystal-Scale Strains on Tensile Failure in Pure Quartzite and Marble, *in* AGU Fall Meeting 2016, p. MR41A-2675.

Voigtländer, A., Leith, K., Walter, J.M., and Krautblatter, M., 2020, Constraining internal states in progressive rock failure of Carrara marble by measuring residual strains with neutron diffraction: Journal of Geophysical Research: Solid Earth, v. 125, p. e2020JB019917, doi:10.1029/2020jb019917.

Zang, A., and Stephansson, O., 2010, Stress field of earth's crust: Berlin, Heidelberg, New York, Springer, 324 p., doi:10.1007/978-1-4020-8444-7.