Experimental investigation of chemically aided fracture growth in silicified fault rocks

Owen A. Callahan, Peter Eichhubl, Jon E. Olson, Nicholas C. Davatzes

Bureau of Economic Geology, The University of Texas at Austin, Austin, TX, United States
Hildebrand Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX, United States
Earth and Environmental Sciences, Temple University, Philadelphia, PA, United States

ABSTRACT

Using double-torsion load-relaxation tests, we evaluated the effect of chemical environment on fracture toughness and subcritical fracture growth index (SCI) in silicified fault rocks collected in the vicinity of the Dixie Valley, NV, geothermal system. Testing environments included: ambient air, deionized water, dilute HCl, NaOH, and NaCl solutions, and deionized water at elevated temperatures. We observed reductions in SCI in all aqueous environments, with > 60% reduction in alkaline solutions. These results suggest that physiochemical conditions in hydrothermal systems may facilitate fracture growth, with chemically aided fracture growth and flow conduit formation competing with precipitation and sealing in reactive systems.

1. Introduction

The location and lifecycle of hydrothermal systems are often considered through one of two lenses: either the mechanical properties or the chemical processes influencing permeability. Fault geometry commonly exerts a first-order control on hydrothermal flow, with thermal anomalies and mineral deposits localized in dilational fault jogs, stepovers, intersections, and tips (Curewitz and Karson, 1997; Cox et al., 2001; Faulds et al., 2006; Anderson and Fairley, 2008; Eichhubl et al., 2009; Micklethwaite, 2009). However, permeability in hydrothermal systems is modified by enhanced dissolution and precipitation and associated mineralogical and textural changes encountered in and around hydrothermal cells (e.g. Facca and Tonani, 1967; Browne, 1978; Summers et al., 1978; Lowell et al., 1993; Morrow et al., 2001; Nishimoto and Yoshida, 2010; Dempsey et al., 2012; Heap et al., 2017; Kamali-Asl et al., 2018). There is growing interest in the interaction between these two paradigms, with the observation that hydrothermal alteration changes the mechanical behavior of the host rock (e.g. del Potro and Hrlimann, 2009; Davatzes and Hickman, 2010; Julia et al., 2014; Pola et al., 2014; Siratovich et al., 2014; Wyering et al., 2014; Heap et al., 2015) and that mechanical processes may enhance chemical reactions (e.g. Gratier, 2011; Ameli et al., 2014).

Chemical-mechanical interactions may also manifest as specific changes in rock strength and elastic properties in response to different fluid environments. Deformation in the presence of water has a well-known weakening effect, particularly during slow loading and under sustained loads (Hadizadeh and Law, 1991; Lockner, 1993; Baud et al., 2000; Wong et al., 2016; Heap et al., 2019). In hydrothermal systems, which commonly contain spatially zoned fluid temperatures and compositions, as well as reactive and disequilibrium conditions (Henley and Ellis, 1983; Ord et al., 2012), the influence of physiochemical environment on deformation, and thus permeability, represents a possible feedback mechanism between chemical and mechanical processes and fluid flow. However, little is known about the impact that chemical environment has on the fracture mechanical properties of hydrothermally altered rocks encountered in hydrothermal systems.

The occurrence of opening-mode fractures in fault zones and fracture networks, and the evolution of these flow systems from single fractures to complex interconnected networks by fracture propagation, reactivation, and coalescence provides a fundamental control on the permeability evolution of fault-controlled hydrothermal and epithermal systems (Wong and Zhu, 1999; Crider and Peacock, 2004; Davatzes et al., 2005; Blenkinsop, 2008; Crider, 2015). Fracture mechanics testing isolates the fundamental processes of fracture initiation and growth and underlies more complex processes of fracture interaction and coalescence that lead to shear failure in triaxial experiments.

Linear elastic fracture mechanics describes the stress intensity at the tip of an opening-mode (mode-I) fracture, $K_I$, as a function of remote stress, $\sigma$, the radius of the fracture, $r$, and a fracture and loading geometry constant, $Y$ (Brown and Strawley, 1966):
The maximum $K_C$ that a material can sustain before critical failure and mechanical fracture propagation is known as fracture toughness, $K_{IC}$.

Fracture growth may occur below the critical threshold due to chemically aided failure of the loaded and stretched bonds at the fracture tip. The relationship between stress intensity at the fracture tip, physiochemical condition, and the velocity, $V$, of subcritical fracture growth is (Charles, 1958; Evans, 1972; Wiederhorn, 1974; Atkinson, 1979a):

$$V = V_0 \exp\left(-\frac{\Delta H}{RT}\right) K_{IC}^{SCI} \quad (2)$$

where $V_0$ is a pre-exponential constant, $\Delta H$ is the activation enthalpy, $R$ is the gas constant, $T$ is the absolute temperature, and SCI is the subcritical fracture growth or stress corrosion index. SCI describes the slope of the stress intensity versus velocity (K–V) relationship when fracture growth is governed by chemical reaction rates (Fig. 1) (Wiederhorn and Johnson, 1973), before fracture propagation velocity outpaces diffusion of reactive species to the fracture tip. Lower values of SCI imply fracture propagation at lower stress intensities or at greater velocity at the same stress intensity. Furthermore, variations in SCI may manifest as different fracture patterns, with lower SCI resulting in increased fracture abundance and reduced spacing and higher SCI leading to fracture clusters (Olson, 1993, 2004). Because subcritical fracture growth is sensitive to physiochemical environments and occurs at lower stress intensities than critical fracture failure, subcritical fracture growth may be an important but generally underappreciated mechanism of chemical-mechanical coupling in hydrothermal systems.

From Eq. 2, higher temperatures and changes in chemical fluid composition that reduce activation enthalpy both promote faster fracture propagation. However, fracture mechanics testing of various rock types has shown a complex dependence of this behavior on physiochemical environment, with mineralogic composition and rock texture influencing the fracture mechanical response to changing chemical environment in ways that are not always predictable *a priori* (Atkinson, 1979a; Waza et al., 1980; Meredith and Atkinson, 1985; Karfakis and Akram, 1993; Funatsu et al., 2004; Feng and Ding, 2007; Feng et al., 2009; Kumar, 2010; Nara et al., 2012, 2013, 2014; Rostom et al., 2012; Brantut et al., 2013; Chen et al., 2017). Mechanisms invoked to explain observed effects of chemical-mechanical interactions include changes in elastic parameters of the sample in the process zone of the propagating fracture (Balme et al., 2004; Funatsu et al., 2004; Nasser et al., 2009; Erarslan, 2016), localized stress-enhanced chemical corrosion (Anderson and Grew, 1977; Atkinson, 1979a; Atkinson and Meredith, 1981; Karfakis and Akram, 1993), fracture tip blunting or sharpening (Rostom et al., 2012), and cohesive or repulsive forces between the fracture walls (Karfakis and Akram, 1993; Rostom et al., 2012). These mechanisms are not mutually exclusive and may all be important in chemically reactive subsurface environments. Although there is substantial work describing fracture mechanical properties in sedimentary rocks of particular interest to oil and gas exploration and CO$_2$ sequestration (Schmidt, 1975; Atkinson, 1979b; Holder et al., 2001; Rijken, 2005; Nara et al., 2014; Chandler et al., 2016; Chen et al., 2017; Major et al., 2018) the impact of changing physiochemical conditions on fracture toughness and subcritical fracture growth in crystalline and hydrothermally altered rocks encountered in and around high temperature hydrothermal and engineered geothermal systems has not been evaluated in detail.

Fracture mechanical properties in hydrothermal systems may be influenced by 1) hydrothermal alteration changing rock composition and texture, and thus the rock mechanical properties, and 2) spatial and temporal variation in chemical environment and chemically aided deformation across hydrothermal systems. Here we focus on the latter scenario, by measuring fracture mechanical properties of silicified fault rocks in different physiochemical conditions. We used double-torsion load-relaxation (DT-LR) tests to quantify the peak stress intensity ($K_C$), a proxy for $K_{IC}$, and SCI in silicified rocks in different chemical environments. Samples were collected from the Dixie Comstock epithermal deposit, Dixie Valley, Nevada, USA (Fig. 2). Testing environments included room temperature ambient air conditions, room temperature aqueous conditions, including deionized (DI) water, hydrochloric acid, sodium hydroxide, sodium chloride, and DI water at elevated temperature. We discuss the impacts that chemical environments have on fracture growth and possible implications for feedback between fluid composition, fracture growth, and fluid flow in hydrothermal systems.

### 2. Sample materials

We tested multiple rock and fracture mechanics specimens of silicified fault rock obtained from the Dixie Comstock epithermal gold deposit in Dixie Valley, Nevada (Figs. 2 and 3). Several temporally distinct episodes of alteration are preserved in the Dixie Comstock area, including early widespread sodic and calcic alteration of the Jurassic Humboldt Igneous Complex (Dilek and Moores, 1995), and aureoles of quartz, albite, sericite, kaolinite, and iron oxide above and around apophyses of Cretaceous granite (Vikre, 1993). Alteration in the mine area is dominated by silicification along the range front fault (Fig. 3), with some silicified fault breccia exceeding 2 m in thickness. Intense silicification extends ~300 m north and south of the mine, with quartz veins and minor silicification of fault breccia occurring ~1.5 km along strike and > 600 m down dip (R. Zuza, personal communication).
Samples were obtained from the silicified fault core and represent the most intense phase of deformation, alteration, and silicification. Mineral composition, texture, and paragenesis were characterized by powder X-ray diffractometry (XRD) and transmitted-light thin section petrography. Total porosity, fracture porosity, and degree of fracture-filling by mineral cements were calculated by point counting standard petrographic thin sections with blue-dyed epoxy at 120X magnification. Total points counted per thin section ranged from 381 to 555. Ambient unconfined compressive strength (UCS) and static elastic parameters were measured with uniaxial compressive strength tests using a GCTS Testing Systems RTR-1000 triaxial rock mechanics rig at the Bureau of Economic Geology, Austin, TX. Plugs 25.4 mm in diameter were drilled from the samples, trimmed to ~53 mm length, and dried at ambient temperatures in vacuo > 48 h. Loading occurred at an axial strain rate of 0.055%/minute (~0.5 μm s⁻¹). UCS is reported from peak, area-corrected load. Elastic parameters were calculated from the middle section of the loading curve where the relationship between stress and strain was approximately linear.

All samples are dominated by fine-grained, intergrown microquartz and euhedral quartz-lined fractures, with minor chlorite, feldspar and plagioclase, calcite, and trace sercite, sulfides, and oxides (Fig. 4, Table 1). Calcite occurs as late fracture fill in the most silicified sample and as broken lathes in the least silicified sample. In all samples, porosity is < 1.6% and heterogeneous, hosted by quartz-lined vugs and partially quartz- or calcite-filled fractures (Table 1). All samples contain evidence for multiple generations of deformation and quartz cementation in the form of entrained and recrystallized silicified clasts and cross-cutting fractures. However, silicification in these samples appears to have reduced mechanical anisotropy at the scale of rock and fracture mechanics specimens. Mean UCS and Young’s modulus (E) of samples are high, up to 301.3 MPa and 62.8 GPa, respectively, and Poisson’s ratio (ν) is between 0.11-0.18 (Table 1).

3. Double-torsion load-relaxation testing

3.1. Double-torsion load-relaxation method

We used the DT-LR fracture mechanics testing configuration to measure $K_I$, $K_{IC}^*$, and SCI of 3 samples of silicified material in different chemical environments. The DT testing apparatus consists of a base plate, ball bearings that function as specimen supports, a loading ram with internal force sensor, and a linear variable displacement transducer to record displacement (Fig. 5a). $K_I$ is calculated from DT tests using the equation from Williams and Evans (1973):

$$K_I = \frac{P W_m}{3(1+\nu) \sqrt{W t_n t}}$$

where $P$ is load, $W_m$ is moment arm, $W$ is width of a pre-fractured specimen of sample material, $t$ is specimen thickness, and $t_n$ is the...
reduced thickness along the axial groove (Fig. 5b). Poisson’s ratio, $\nu$, was obtained from ambient UCS tests. The geometric correction factor, $\phi$, is based on individual specimen geometry and is derived from Fuller (1979):

$$\phi = 1 - 0.6302 \frac{2t}{W} + 1.2 \frac{2t}{W} \left(1 - \frac{2t}{W}\right)$$

Specimen thickness ($t$), width ($W$), and length ($L$) dimensions were approximately 1.8 mm $\times$ 30 mm $\times$ 75 mm, respectively, meeting dimensional requirements of $\sim 24t < 2W < L$ (Nara and Kaneko, 2005). Absolute specimen dimensions were similar to Atkinson (1979a); Sano and Kudo (1992), and Chen et al. (2017) and were influenced by sample size and load cell capacity. Specific specimen dimensions, loads, and derived SCI are included in Appendix C. A 0.5 mm deep axial guide groove was cut into the base of each specimen. Specimens were placed in the DT apparatus with the axial guide groove facing down (Evans, 1972; Pletka et al., 1979) and loaded from above. A starting fracture (“pre-fracture”) was introduced into the sample.

Table 1
Sample Identification, Composition, Physical, and Mechanical Properties.

<table>
<thead>
<tr>
<th>Paper ID$^d$</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field ID$^b$</td>
<td>090114-5B</td>
<td>061114-4B</td>
<td>052815-2</td>
</tr>
<tr>
<td>IGSN$^c$</td>
<td>IECAL002F</td>
<td>IECAL001K</td>
<td>IECAL001G</td>
</tr>
</tbody>
</table>

Normalized Composition (wt%$^d$)

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>88</td>
<td>91</td>
<td>97</td>
</tr>
<tr>
<td>feldspars</td>
<td>5</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>calcite</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>muscovite</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>sulfide/oxide minerals</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

XRD QC (wt%$^e$)

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>corundum, spike</td>
<td>2.60 ± 0.00</td>
<td>2.64</td>
<td>2.61 ± 0.01</td>
</tr>
<tr>
<td>corundum, analyzed</td>
<td>0.4</td>
<td>0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>density (g/cm$^3$)</td>
<td>8.3</td>
<td>6.9</td>
<td>12.6</td>
</tr>
<tr>
<td>porosity (%)</td>
<td>555</td>
<td>404</td>
<td>381</td>
</tr>
<tr>
<td>fractured area (%)</td>
<td>301.3, ± 38.4</td>
<td>187.8</td>
<td>286.5, ± 12.7</td>
</tr>
<tr>
<td>fracture porosity/fill (%)</td>
<td>51.1</td>
<td>22.6</td>
<td>28.3, ± 0.3</td>
</tr>
<tr>
<td>number of points</td>
<td>555</td>
<td>404</td>
<td>381</td>
</tr>
</tbody>
</table>

Mechanical Properties$^g$

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCS (MPa)</td>
<td>301.3, ± 38.4</td>
<td>187.8</td>
<td>286.5, ± 12.7</td>
</tr>
<tr>
<td>$E$ (GPa)</td>
<td>58.1, ± 0.8</td>
<td>51.1</td>
<td>62.8, ± 1.6</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.18, ± 0.1</td>
<td>0.13</td>
<td>0.11, ± 0.02</td>
</tr>
<tr>
<td>$G$ (GPa)</td>
<td>24.7, ± 0.4</td>
<td>22.6</td>
<td>28.3, ± 0.3</td>
</tr>
<tr>
<td>number of plugs</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

$^a$ Simplified sample nomenclature used in this manuscript. $^b$Identification number used in the field. “Sample 2” includes two adjacent blocks collect in different field seasons. $^c$Searchable catalog number with additional metadata (http://www.geosamples.org/). $^d$Mineralogical composition from XRD. Methods and spectra are included in Appendix A. $^e$Accounting of error in XRD analysis based on comparison between corundum spike and analyzed abundance. $^f$Density from UCS testing plugs, other properties from point counting. $^g$Individual plug measurements are included in Appendix B.

Fig. 4. Plain light (top row) and polarized light (bottom row) photomicrographs of sample material. Minor variation in texture (clast shape, microfractures, micro- vs euhedral quartz) and composition arise from variations in degree of silicification and composition of adjacent footwall material. Sample 1 (A, B) includes broken calcite lathes incorporated from calcite breccia in the adjacent footwall. Sample 2 (C, D) and 3 (E, F) reflect increasing amounts of silicification, but contain relict plagioclase and chlorite from the adjacent altered gabbroic rocks. All samples contain quartz-filled fractures, with some late calcite-filled fractures (F), and spatially heterogeneous open fractures and vugs.
using the DT apparatus under ambient conditions at low displacement rates (< 1 μm s\(^{-1}\)) until a distinct load drop indicated the formation of an edge-fracture. DT-LR tests were conducted by loading the pre-fractured specimen at a displacement rate between 1–2 μm s\(^{-1}\) until fracture propagation was indicated by a rapid drop in supported load. Displacement was stopped, and the load allowed to decay for ∼10 min. Load-cycles were repeated until the fracture propagated across the full length of the specimen (Fig. 5c). Load and displacement were recorded at 5 Hz.

Fracture toughness (K\(_{IC}\)) is calculated from peak load sustained by pre-fractured specimens under rapid loading. Low displacement rates used in our DT-LR tests allowed for controlled fracturing and multiple load-decay cycles per specimen (Fig. 6), improving the overall number of measurements without additional material expense. However, low displacement rates may underestimate intrinsic fracture toughness in some materials (see discussion in Atkinson and Meredith, 1987). We find no significant difference between peak load sustained under rapid versus slow displacement conditions in our tests and consider stress intensity during peak loads in slow displacement tests, K\(_{IC'}\), a reasonable proxy for K\(_{IC}\) (Callahan et al., 2019 and Appendix D). We use the K\(_{IC'}\) nomenclature for this measurement throughout.

Fracture propagation velocity, V, was calculated from the load relaxation curve after Evans (1972):

\[
V = -\psi \left( \frac{a_0 P_i}{P^2} \right) \frac{dP}{dT}
\]

where \(a_0\) is fracture length at the start of each load-decay cycle, \(P_i\) is initial load, and \(T\) is time. We used 0.2 for the fracture front geometry correction factor, \(\psi\) (Chen et al., 2017). Initial fracture length, \(a_0\), for the first load-decay cycle was measured along induced pre-fractures prior to submerging each specimen in testing fluid (Appendix C). Because fracture length was not observable once specimens were submerged, \(a_0\) for later cycles was estimated by adding 12.7 mm, a nominal value derived by dividing the average specimen length by the typical number of load-decay cycles per specimen, to the initial fracture length of the previous cycle. Variation of \(a_0\) does not affect the calculation of SCI and has limited impact on calculated fracture propagation velocity (Chen et al., 2017). SCI was calculated from stress intensity versus velocity (K–V) plots using smoothing and fitting functions using an in-house LabView script based in part on derivations described in Holder et al. (2001).

3.2. Testing conditions

We tested specimens in room temperature ambient air conditions, in room temperature aqueous conditions, including DI water (pH 6.3–7.5), 0.001 M HCl (pH = 3), 0.01 M NaOH (pH = 12), 0.1 wt% NaCl, and in DI water at elevated temperatures (60–65 °C). Aqueous conditions were selected to identify trends related to changes in fluid environment and do not represent specific hydrothermal fluids or subsurface conditions. The range of fluid pH is similar to that used in double-torsion tests of synthetic quartz crystal by Atkinson and Meredith (1981) and was selected to promote observable differences between short duration (∼10 min) load-decays. Conditions during elevated temperature tests were limited by poor signal to noise ratios at temperatures > 70 °C. Relative humidity during ambient tests was not controlled and typically varied from 63 to 79%. Aqueous conditions were controlled by placing the DT apparatus in an open stainless-steel basin filled with 3.5 liters of solution so that the specimen was submerged ∼7 mm below the surface (Fig. 5a). The pH of testing fluid was measured repeatedly during early tests. HCl and NaOH conditions showed no variation in pH, but the pH of DI fluids commonly dropped by < 0.5 pH units during individual tests, which we attribute to interaction with atmospheric CO\(_2\).
Temperature was recorded with two thermocouples. Elevated temperature tests were conducted with the basin and DT apparatus on a hotplate. To avoid problems resulting from transient thermal gradients in the sample, the solution containing the sample was heated from ambient to 60–65 °C at a rate of < 1 °C min⁻¹, consistent with the rate of temperature change reported in Meredith and Atkinson (1985) and Balme et al. (2004). Mean temperature during individual specimen tests varied by less than 0.3 °C. During elevated temperature tests a polycarbonate loading ram was used to reduce noise from thermal fluctuations. For all tests conducted in aqueous solution, specimens were first vacuum dried for > 48 h, then pre-fractured, and finally immersed in DI water for > 1 h before testing to avoid transient wetting effects. Reported durations and conditions for presoaking vary by author; some authors do not explicitly specify the duration of immersion (Atkinson, 1979a; Atkinson and Meredith, 1981; Karfakis and Akram, 1993), and others report samples were stored in testing fluids for hours to days (Waza et al., 1980; Nara and Kaneko, 2005; Nara et al., 2012, 2014; Rostom et al., 2012). We did not store specimens in testing fluids prior to testing because we wanted to isolate changes resulting from fluid interactions at the stressed fracture tip rather than changes resulting from more widespread dissolution or precipitation. Because specimens are thin (< 2 mm) and the pre-fractures are full thickness, we are confident that fluids accessed the fracture tip during testing; we found no consistent difference between dry samples tested immediately upon immersion and those soaked in DI water for > 24 h prior to testing.

4. Experimental results

4.1. SCI and \( Kc^* \) values in different testing environments

We tested specimens of silicified fault rock from three sample sites around the Dixie Comstock epithermal deposit in different chemical environments. Five to twelve specimens per sample site were tested in each chemical environment, with the total number of valid \( Kc^* \) and SCI measurements in each environment between 7–28 and 5–24, respectively. Tests that resulted in fractures that propagated out of the axial guide groove, exceeded load cell capacity, or failed on pre-fracturing were not included (Appendix C).

We observed high \( Kc^* \) and SCI in silicified fault rock in ambient conditions. Mean \( Kc^* \) in ambient conditions is 2.40–3.01 MPa \( \sqrt{\text{m}} \), and mean SCI in ambient conditions is 113.3–142.2 (Tables 2 and 3).

Testing environment had limited impact on \( Kc^* \) in these samples. Mean \( Kc^* \) is 2.13–2.73 MPa \( \sqrt{\text{m}} \) for all samples in aqueous conditions (Table 2, Fig. 7). The standard deviations of \( Kc^* \) overlap for the same sample tested in different environments, except sample 2, where \( Kc^* \) in NaOH tests are 29% lower than in ambient conditions. The largest relative standard deviations for \( Kc^* \) and SCI (22% and 60%, respectively) for any environment were observed in sample 2, suggesting inter-specimen heterogeneity in this sample may have negatively impacted the results. We calculated \( Kc^* \) in aqueous conditions using \( v \) derived from ambient UCS tests. Although mechanical degradation and changes in some elastic properties are reported in different fluid environments (e.g., Jeong et al., 2007; Heap et al., 2019), the impact of testing environment on \( v \), and therefore on miscalculations of \( Kc^* \), is expected to be small. First, Jeong et al. (2007) describe \( v \) as independent of environmental condition in their tests, and, second, a hypothetical doubling of \( v \) would result in < 5% increase in \( Kc^* \) (Eq. 3).

SCI was more sensitive to chemical environment. Mean SCI was reduced in aqueous environments compared to ambient conditions for all samples, with the degree of reduction dependent upon the environmental conditions (Table 3, Fig. 8). Reduction in SCI below ambient conditions was most pronounced in NaOH environments, where we saw a 46–66% reduction below mean ambient SCI (Fig. 8). P values from t-tests between SCI in ambient and NaOH conditions are < < 0.05 for all samples. In sample 1, SCI in NaOH was also significantly lower than DI and HCl tests, but not compared to NaCl test. In sample 3, SCI from NaOH tests was significantly lower than DI conditions, but not significantly different from HCl or NaCl conditions. Mean SCI values at elevated temperature were comparable to SCI in NaOH and NaCl conditions (Fig. 9). Despite some mineralogical, textural, and mechanical differences between samples, some elastic properties are reported in different fluid environments (e.g., Jeong et al., 2007; Heap et al., 2019), the impact of testing environment on \( v \), and therefore on miscalculations of \( Kc^* \), is expected to be small. First, Jeong et al. (2007) describe \( v \) as independent of environmental condition in their tests, and, second, a hypothetical doubling of \( v \) would result in < 5% increase in \( Kc^* \) (Eq. 3).

SCI was more sensitive to chemical environment. Mean SCI was reduced in aqueous environments compared to ambient conditions for all samples, with the degree of reduction dependent upon the environmental conditions (Table 3, Fig. 8). Reduction in SCI below ambient conditions was most pronounced in NaOH environments, where we saw a 46–66% reduction below mean ambient SCI (Fig. 8). P values from t-tests between SCI in ambient and NaOH conditions are < < 0.05 for all samples. In sample 1, SCI in NaOH was also significantly lower than DI and HCl tests, but not compared to NaCl test. In sample 3, SCI from NaOH tests was significantly lower than DI conditions, but not significantly different from HCl or NaCl conditions. Mean SCI values at elevated temperature were comparable to SCI in NaOH and NaCl conditions (Fig. 9). Despite some mineralogical, textural, and mechanical differences between samples, some elastic properties are reported in different fluid environments (e.g., Jeong et al., 2007; Heap et al., 2019), the impact of testing environment on \( v \), and therefore on miscalculations of \( Kc^* \), is expected to be small. First, Jeong et al. (2007) describe \( v \) as independent of environmental condition in their tests, and, second, a hypothetical doubling of \( v \) would result in < 5% increase in \( Kc^* \) (Eq. 3).

### Table 2

Mean Peak Stress Intensity (\( Kc^* \)) in Silicified Fault Rocks in Different Environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Temperature (°C)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean (^b)</td>
<td>n</td>
<td>mean (^b)</td>
</tr>
<tr>
<td>air</td>
<td>(RT)</td>
<td>2.40 ± 0.16</td>
<td>16</td>
<td>3.01 ± 0.18</td>
</tr>
<tr>
<td>DI water</td>
<td>(RT)</td>
<td>2.59 ± 0.27</td>
<td>16</td>
<td>2.61 ± 0.38</td>
</tr>
<tr>
<td>HCl (pH 3)</td>
<td>(RT)</td>
<td>2.33 ± 0.39</td>
<td>15</td>
<td>N.T. (^c)</td>
</tr>
<tr>
<td>NaOH (pH 12)</td>
<td>(RT)</td>
<td>2.51 ± 0.17</td>
<td>13</td>
<td>2.13 ± 0.45</td>
</tr>
<tr>
<td>0.1% NaCl</td>
<td>(RT)</td>
<td>2.51 ± 0.27</td>
<td>16</td>
<td>N.T. (^c)</td>
</tr>
<tr>
<td>DI water</td>
<td>60-65</td>
<td>N.T. (^c)</td>
<td>–</td>
<td>N.T. (^c)</td>
</tr>
</tbody>
</table>

\(^a\) RT = room temperature (22–23 °C). \(^b\)Mean and standard deviation of n tests. \(^c\)N.T. = not tested.

### Table 3

Mean Subcritical Fracture Growth Index (SCI) in Silicified Fault Rocks in Different Environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Temperature (°C)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean (^b)</td>
<td>n</td>
<td>mean (^b)</td>
</tr>
<tr>
<td>air</td>
<td>(RT)</td>
<td>113.3 ± 29.2</td>
<td>12</td>
<td>123.7 ± 31.9</td>
</tr>
<tr>
<td>DI water</td>
<td>(RT)</td>
<td>106.3 ± 20.2</td>
<td>7</td>
<td>86.6 ± 50.0</td>
</tr>
<tr>
<td>HCl (pH 3)</td>
<td>(RT)</td>
<td>89.8 ± 25.1</td>
<td>7</td>
<td>N.T. (^c)</td>
</tr>
<tr>
<td>NaOH (pH 12)</td>
<td>(RT)</td>
<td>61.4 ± 16.3</td>
<td>8</td>
<td>44.0 ± 21.7</td>
</tr>
<tr>
<td>0.1% NaCl</td>
<td>(RT)</td>
<td>63.6 ± 18.8</td>
<td>13</td>
<td>N.T. (^c)</td>
</tr>
<tr>
<td>DI water</td>
<td>60-65</td>
<td>N.T. (^c)</td>
<td>–</td>
<td>N.T. (^c)</td>
</tr>
</tbody>
</table>

\(^a\) RT = room temperature (22–23 °C). \(^b\)Mean and standard deviation of n tests. \(^c\)N.T. = not tested.
there is little difference in SCI between samples tested in the same environment; mean SCI measured in ambient, NaCl, HCl, and NaOH conditions are all statistically similar to mean values calculated from the same environmental condition in the other samples.

4.2. K–V curves and fracture propagation velocity

Calculated fracture propagation velocities are between $10^{-8}$ and $10^{-4}$ m/s (Fig. 9), which are consistent with reported subcritical fracture growth velocities for rocks derived from DT tests (Atkinson, 1979a; Nara et al., 2014; Chen et al., 2017). Due to the high SCI in these samples, individual fracture growth curves occur across a narrow range of high mode-I stress intensity ($K_I$). K–V curves for different environments overlap, reflecting scatter in $K_c^*$ and limited impact of chemical environment on toughness. However, in samples 2 and 3 a reduction in stress intensity in K–V curves from aqueous tests indicates subcritical fracture propagation at lower $K_I$ compared to ambient conditions. K–V curves normalized to peak fracture propagation velocity and stress intensity highlight the reduction in SCI (slope) in aqueous conditions, particularly NaOH, NaCl, and at elevated temperature (Fig. 9). We attribute noise in K–V curves from elevated temperature tests to thermal transients affecting the DT apparatus and/or load cell, even with mean temperature fluctuation during each decay period < 0.3 °C.

Fig. 7. Box plots showing $K_c^*$ results for different samples in different testing environments. Boxes show interquartile range, bars show standard deviations, and dots show outliers. Number of tests reported in Table 2. Testing conditions have limited impact on $K_c^*$, except for sample 2, which may reflect poor specimen quality in later tests.

Fig. 8. Box plots showing SCI results for different samples in different testing environments. Boxes show interquartile range, bars show standard deviations, and dots show outliers. Number of tests in Table 3. Aqueous conditions result in reduction in mean SCI compared to ambient tests for all samples. The largest reduction in mean SCI compared to ambient tests is observed in dilute NaOH conditions.
5. Discussion
5.1. Physiochemical effects and mechanisms

5.1.1. Water vs. Ambient air conditions
The water-weakening effect that we observe as reduced SCI is also described for glass and ceramics (Freiman et al., 2009), single synthetic quartz crystals (Atkinson, 1979a), and igneous, metamorphic, and sedimentary rocks (Nara et al., 2013, 2014, 2017; Chen et al., 2017). Chemical-mechanical interactions at the fracture tip are commonly invoked to describe the mechanics of water-weakening in silicates (Waza et al., 1980; Michalske and Freiman, 1982). In this model, mechanically stressed Si-O bonds enable penetration of H$_2$O molecules. The polar water molecular bonds with the Si-O-Si molecule, producing a weaker, short-lived OH bond that enables fracture propagation at lower stress intensity. Any condition that accelerates penetration of water molecules into the fracture tip region will favor increased subcritical growth. Particularly sensitive materials may exhibit a water-weakening effect with changing relative humidity (Wiederhorn, 1967; Nara et al., 2012). We did not control relative humidity in our experiments, which may have contributed to scatter in SCI in ambient conditions. However, the influence of changing humidity on SCI is more pronounced in clay-rich rocks (Nara et al., 2012).

5.1.2. Effect of changing pH
The 60% reduction in SCI we observed in silicified samples in strong base conditions under which quartz is more soluble, is consistent with other reported reductions in SCI in environments that enhance solubility or dissolution rate of material at the fracture tip. Reduced SCI is observed at high pH in glass (Wiederhorn and Johnson, 1973) and at high pH in single synthetic quartz crystals and silicate rocks (Atkinson and Meredith, 1981). However, there are exceptions to the positive correlation between increased dissolution and increased fracture growth. Rostom et al. (2012) described an increase in toughness of calcite in low pH conditions, conditions under which calcite is more soluble, which they attribute in part to fracture tip blunting. In silicates,
and in our samples, fracture growth is generally promoted in high pH conditions, due to the increased availability of OH⁻ facilitating the breaking of Si-O-Si bonds (Atkinson and Meredith, 1981; Karfakis and Akram, 1993).

SCI in our silicified samples in acidic conditions is statistically indistinguishable from DI water tests, whereas Atkinson and Meredith (1981) reported an increase in SCI in acidic environments relative to DI water for single synthetic quartz crystals. The difference between single synthetic quartz crystals and the behavior of the aggregate samples we tested may arise from the presence of minor amounts of calcite, which becomes more soluble at lower pH.

5.1.3. Effect of increased salinity

The effect of solution salinity on fracture propagation velocity in rocks varies widely. Clay-rich materials and some carbonates show non-linear relationships between toughness, SCI, and salinity, with both the concentration and type of cation influencing results (Rostom et al., 2012; Nara et al., 2014). Rostom et al. (2012) related increases in SCI in calcite at salt concentration below ~1 M NaCl to enhanced calcite solubility, whereas Nara et al. (2014) inferred that observed toughening in salt solutions was related to reduced clay-swelling ahead of the propagating fracture tip.

In our samples, dilute NaCl concentrations resulted in a reduction in SCI compared to DI water. We attribute this response to increased dissolution rates in silica with increased NaCl concentration at intermediate to elevated pH, as predicted by Dove (1995) for pure quartz. The behavior of the silicified material is best explained by the dissolution kinetics of the dominant mineral species in these samples, with an additive influence of minor components on behavior in different environments.

5.1.4. Effect of increased temperature

Temperature effects on KIC and SCI are typically attributed to mechanical changes (increased microstructural complexity due to damage caused by differential thermal expansion and fracturing in test environments) or chemical effects (increased activity of reactive agents or faster reaction kinetics at elevated temperature). The impact on KIC from increasing microstructural complexity by thermal treatments is commonly non-linear; Meredith and Atkinson (1985); Balme et al. (2004), and Nasseri et al. (2009) all reported initial toughening with increased temperature of thermally treated samples and then a decrease in material strength. They attribute initial toughening with the development of small misaligned thermal fractures that arrest induced fracture propagation, and the subsequent decrease in strength with the growth and coalescence of experimentally induced thermal microfractures throughout the sample. Physiochemical effects at higher temperatures include toughening in response to dehydra hydrothermal systems.

5.1.5. Summary of subcritical fracture growth behavior in silicified fault rocks

The influence of chemical environment on SCI is similar between samples: SCI is reduced in aqueous conditions relative to ambient conditions, with the most pronounced reductions in NaOH, at elevated temperature, and in dilute NaCl solutions. Synthetic K–V curves based on mean SCI in each environment and reduction below a nominal KIC (2.5 MPa √m) illustrate the relative change in subcritical fracture growth behavior in different environments (Fig. 10). On average, NaOH tests have the lowest slopes, representing fracture propagation at lower stress intensities or faster fracture propagation velocities at the same stress intensity when compared to fracture propagation velocities in other testing environments. Silica solubility increases with increasing pH (Fournier, 1985), but increased temperature and salinity also increase dissolution rate. The observation that environments that favor increased solubility and dissolution rate promote subcritical fracture growth in silicified materials is consistent with predictions by Dove (1995) based on single synthetic quartz crystals.

Although the trends that we observed are generally well described by quartz and silica kinetics, the impact of acidic condition on subcritical fracture growth index and the absolute fracture mechanical properties we measured in these naturally silicified fault zone samples differ from the fracture mechanical behavior of single synthetic quartz crystals as reported by Atkinson (1979a) and Atkinson and Meredith (1981) and as modeled by Dove (1995). In the silicified rocks we tested, the presence of minor amounts of plagioclase,feldspar, calcite, and sericite, which have different dissolution behavior, had negligible negative effect on bulk fracture mechanics compared to the dominant mineral phase, and instead appear to have an additive effect. Compared to the observed increase in SCI and reduction of fracture propagation velocity in single synthetic quartz crystals in acidic environments reported by Atkinson and Meredith (1981), we speculate that the presence of minor amounts of calcite may have reduced the contrast between SCI in neutral and acidic environments in our tests. The textural complexity found in silicified fault rocks (Fig. 4) may also contribute to the high toughness and SCI we observed in our samples, which are both approximately three times higher than the same parameters measured in single synthetic quartz crystals (Atkinson, 1979a; Atkinson and Meredith, 1981).

5.2. Feedback between physiochemical condition and fracture processes in hydrothermal systems

Permeability in many hydrothermal systems evolves through competition between dilatant damage and sealing. Negative feedback between hydrothermal alteration and reduction in permeability is well
Silicified bodies, low strain rates (2 × 10⁻¹⁶ s⁻¹) to minimize purely chemical conditions. We used model geometries representing 1 and 2 m thick rock bodies though not necessarily representative of any site-specific subsurface conditions and NaOH environments (i.e. least to most reactive), analogous to the SCI values we measured in silicified rocks in ambient, DI, and DI plus NaOH solutions. The SCI values from our measurements in silicified rocks range from 130 to 50, sensitive to changes in salinity at neutral to slightly alkaline pH. To- illustrate the possible impact of different physiochemical conditions on fracture growth, we conducted a limited set of boundary element models using JOINTS, a numerical fracture pattern growth simulator (Olson, 1993, 2004). The program leverages the power-law relationship between subcritical fracture propagation velocity and stress intensity (Fig. 1) to model fracture growth and fracture network development in response to loading (Segall, 1984; Olson, 1993). Fracture opening and shear displacements induced by far-field loading conditions and fracture to fracture interactions are computed numerically from a quasi-static two-dimensional displacement discontinuity solution (Crouch, 1976), where the fractures are divided into equal length boundary elements. The two-dimensional solution is augmented to incorporate the three-dimensional effects of layer-bounded fractures using a pseudo-3D correction factor derived in Olson (2004). Stress intensity factors are computed from fracture tip opening and shear displacement discontinuity solutions (Olson, 1991, 2007) and fracture propagation velocities are then determined using the K-V relationship. We modeled the effects of reducing SCI from 130 to 90 and to 50, similar to the SCI values we measured in silicified rocks in ambient, DI, and NaOH environments (i.e. least to most reactive), respectively, although not necessarily representative of any site-specific subsurface conditions. We used model geometries representing 1 and 2 m thick silicified bodies, low strain rates (2 × 10⁻¹⁶ s⁻¹) to minimize purely mechanical (critical) fracture propagation, average ambient elastic properties for these samples, and model run times ∼10 kyr. Model run times are nominally representative of interseseismic periods > 2.5 kyr in the fault segment hosting the Dixie Valley geothermal field and Dixie Comstock epithermal deposit (Bell et al., 2004). The direct application of these model results to fracture networks in the subsurface is limited by specific subsurface conditions and deformation history, rock and fracture mechanical properties, and fracture reactivation or inheritance in real systems. However, in these models, changing SCI resulted in measurable differences in fracture development: fracture growth was favored in models with lower SCI and suppressed in models with higher SCI (Fig. 11).

Based on our experimental results and illustrated in the JOINTS model, feedback between physiochemical condition, reduced SCI, enhanced subcritical fracture growth, and thus higher fracture intensity and permeability, may be found in quartz-rich rocks in parts of hydrothermal systems where the physiochemical conditions favor increased quartz dissolution rates, i.e., in higher temperature, higher pH, and higher salinity environments. Low pH conditions (pH < 2) are associated with near-surface acid sulfate environments in active geo thermal systems and epithermal and porphyry mineral deposits (Henley and Ellis, 1983; Henley, 1984; White and Hedengquist, 1990; Simmons et al., 2005; Tosdal et al., 2009). However, hydrothermal fluids in geothermal reservoirs are commonly composed of near neutral pH or slightly alkaline chloride and chloride bicarbonate fluids (Henley and Ellis, 1983; Henley, 1984; White and Hedengquist, 1990; Simmons et al., 2005), suggesting that pH at depth in geothermal reservoirs is more favorable for quartz dissolution, and thus more favorable for subcritical fracture growth, than in near surface portions of these systems. Mean temperatures encountered at depth in producing geothermal reservoirs (230–280 °C; Browne, 1978; Bertani, 2005) would likewise favor increasing rates of subcritical fracture growth relative to cooler conditions on the periphery of the system, up to the point of retrograde solubility ~340 °C (Fourier and Rowe, 1977). Salinity of hydrothermal fluids may exceed 30 wt% NaCl equivalent in some geothermal fields and analogous mineral deposits, but average terrestrial hydrothermal fluids are generally more dilute (Henley and Ellis, 1983; Simmons et al., 2005). Dove (1994, 1995) found that 1) changes in dissolution rate with salt concentration are more pronounced at low salt concentrations than at high concentrations, and 2) the dissolution rate of quartz is most sensitive to changes in salinity at neutral to slightly alkaline pH. Together, the pH, temperature, and salinity conditions in hydrothermal reservoirs favor increased subcritical fracture growth in silicic rocks relative to parts of hydrothermal systems influenced by cooler, more dilute meteoric fluids, in vapor-dominated or precipitation dominated
settings (e.g., boiling interfaces or shallow outflow zones), and in shallow, low pH, acid-sulfate environments. We further expect the effects of increased fracture propagation velocity at elevated pH and elevated temperature may be more pronounced in parts of hydrothermal systems containing more soluble phases of silica (e.g., amorphous silica or chalcedony (Fournier and Rowe, 1977; Fournier, 1985).

In addition to the potential spatial variation in subcritical fracture growth arising from different chemical environments encountered across hydrothermal systems, the relative importance of subcritical fracture growth may change through time. The role of subcritical fracture growth may evolve with changing chemical conditions as hydrothermal systems mature, or in relation to external forces, such as seismic cycles. Coseismic failure in hydrothermal systems, for instance, may be dominated by critical fracture failure and rapid post-seismic healing (Sheldon and Micklethwaite, 2007) with subcritical fracture growth gaining influence late in the interseismic period.

Our predictions of enhanced fracture growth at hydrothermal reservoir conditions diverge from other experimental results showing faster rates of fracture healing in quartz and quartz-rich fault gouge at elevated temperatures (Brantley et al., 1996; Brantley, 1992; Morrow et al., 2001; Beeler and Hickman, 2004). A critical difference between their analyses and ours, which predict enhanced fracture growth in hydrothermal conditions, is the introduction of concentrated tensile stress at the fracture tip, suggesting that fracture healing vs. fracture growth in hydrothermal reservoirs may be particularly sensitive to mismatches between load and fracture orientations.

5.3. Implications for operating geothermal fields

Production and injection in geothermal fields induce complex hydrologic, thermal, and mechanical interactions affecting overall productivity (e.g., Taron and Elsworth, 2009), which are the focus of extensive research and modeling efforts (e.g., Taron and Elsworth, 2010; Sonnenthal et al., 2012; Ameli et al., 2014; White et al., 2016 and references therein). Fault-fracture networks commonly dominate flow paths in commercial hydrothermal systems and are the fundamental components of engineered geothermal systems (e.g., Evans et al., 1999; Ghassemi, 2012; Olasolo et al., 2016; Amann et al., 2018; Lu, 2018). Therefore, correctly modeling fracture mechanical behavior in altered rock and at hydrothermal conditions may improve our understanding of the lifecycle of hydrothermal systems and promote better management of conventional and enhanced geothermal fields (Demarest, 1976; Evans et al., 1999; Ghassemi, 2012; Tomac and Sauter, 2018). Experimental fracture mechanics investigations using pristine rock samples, such as the work presented by Takahashi and Abé (1987), and reservoir models that include generic fracture mechanical parameters (e.g., McClure and Horne, 2014), may overestimate or underestimate the toughness of altered reservoir rock (Callahan et al., 2019), and tests conducted in ambient conditions cannot address coupled chemical-mechanical interactions. Our results help constrain fracture growth behavior in operating geothermal reservoirs by 1) measuring KIC and SCI in altered rocks commonly encountered in hydrothermal systems and 2) describing controls on chemically aided fracture growth that may be operating in hydrothermal reservoirs.

Improved understanding of fracture toughness, subcritical index, and chemically aided fracture growth may provide new approaches to reservoir management. Reducing fracture toughness through cyclic loading has been proposed as a way of reducing induced seismicity during hydraulic stimulation of geothermal wells (Zang et al., 2013). Chemical treatments, typically combinations of HCl and HF, are already successfully employed in conventional hydrothermal systems and in EGS projects to repair near wellbore damage caused by infiltration of drilling mud and cuttings into permeable formations and fractures, and to enhance permeability by dissolving mineral cements (e.g., Morris et al., 1984; Barrios et al., 2002; Jaimes-Maldonado and Sánchez-Velasco, 2003; Portier et al., 2009; Zimmermann et al., 2011). Chemical treatments designed to promote fracture growth are less common in geothermal well stimulations (Sutra et al., 2017). However, cyclic loading, coupled with the use of high pH chelating agents to reduce SCI in quartz-rich reservoir rocks (Rose et al., 2007), could be used during large volume injections to promote fracture growth at lower stress intensities, providing operators and reservoir engineers additional stimulation strategies.

6. Conclusions

The productivity of many hydrothermal systems is controlled by fluid flow in fault-fracture networks. Fracture mechanical properties, fracture toughness and subcritical fracture growth index, likely influence the hydro-mechanical evolution of these systems. However, little work has been done to measure these properties in damaged and altered rocks in hydrothermal systems or to quantify the effect that chemically aided fracture growth may have in common hydrothermal alteration products. We present results from double-torsion load-relaxation tests of silicified fault zone material conducted in various chemical environments. We find that the subcritical fracture growth index in this material is reduced by >60% in aqueous environments compared to tests conducted in ambient air conditions and that the largest reductions are associated with high pH NaOH, dilute NaCl solutions, and at elevated temperature. Peak stress intensity during slow loading, a proxy for fracture toughness, is less affected by chemical environment. In this end member material, with high strength, high resistance to fracture growth, and low chemical sensitivity, water-weakening and enhanced stress corrosion in favorable chemical environments produce measurable reductions in subcritical fracture growth index, indicating faster fracture propagation velocities at lower stress intensities. These results indicate that alkaline, higher temperature dilute brines encountered in hydrothermal upflow zones may promote subcritical fracture growth, providing a positive feedback mechanism that would contribute to localization of hydrothermal fluid flow and help sustain permeability.

Data availability

Appendices are public and archived at https://doi.org/10.17632/vbx72yb535.2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Xiaofeng Chen aided with fracture mechanics testing and data reduction. Donnie Brooks helped with UCS testing. Jeff Cullen and Ben Larson provided insight into silica solubility in high pH conditions. We also thank two anonymous reviewers for their comments. This work was supported by grants from The GDL Foundation, Geothermal Resources Council, and the AAPG Foundation. Additional support was provided by the Jackson School of Geosciences and the Fracture Research and Application Consortium (FRAC) at the Bureau of Economic Geology, Austin, Texas. Publication authorized by the Director, Bureau of Economic Geology.

References


