Fault Instability in a Geothermal Reservoir Facilitated by Low-grade Metamorphism

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Abstract

Occurrence of earthquakes related with geothermal reservoirs highlights the possibility that subsurface fluid injection may reactivate critically stressed faults and trigger seismicity. We report on laboratory experiments conducted at $T = 100\text{--}250\text{ }^{\circ}\text{C}$, $\sigma_c = 110\text{ MPa}$ and $P_f = 42\text{--}63\text{ MPa}$ and show that two prevalent minerals, epidote and chlorite, impact frictional properties and fault stability under conditions relevant to typical geothermal reservoirs. Numerous geothermal reservoirs worldwide exhibit metamorphic epidotization and chloritization. Shear experiments on simulated epidote-rich fault gouges indicate potentially unstable frictional behavior - more pronounced at elevated temperatures and pore pressures. Increased proportions of chlorite in fault gouges stabilize the faults, which indicates that gouge composition exerts significant control on fault stability. Our results imply a high potential for induced seismicity on faults containing epidote found in many geothermal reservoirs.

Introduction

High-pressure fluid injection at an enhanced geothermal system (EGS) site can reactivate critically stressed fractures and faults and trigger earthquakes (Deichmann & Ernst, 2009; Grigoli et al., 2018; Kim et al., 2018; Majer et al., 2007; Moeck et al., 2009). For a pre-existing mature fault, the fault movement and seismic potential are closely associated with the frictional response of fault gouge (Ikari et al., 2011; Niemeijer and Collettini, 2014). Therefore, a careful understanding of the deep fault or fracture properties and triggered earthquake physics is necessary for assessing and mitigating injection-induced seismic risks (Ellsworth, 2013; Lee, et al., 2019a). A direct and reliable way to evaluate deep fault or fracture properties is through experiments on materials at corresponding pressures and temperatures typically found in geothermal reservoirs (Boulton et al., 2014; Carpenter et al., 2009).

Natural fractures recovered from granodiorite cores prior to stimulation at a depth of 4.2 *km*-depth in the Pohang Geothermal reservoir show evidence of alteration and the native presence of both epidote and chlorite (Fig. 1 and Figure S1 in supporting information). Microstructural characterization (Fig. 1) and X-ray diffraction analyses (Figure S2) indicate the occurrence of epidotization and chloritization along the fracture surfaces. In addition, the borehole cuttings at depths between 3500 and 3800 *m* also contain up to 20 *wt.*% chlorite (Lee et al., 2019b), which is consistent with previous work showing that epidote and chlorite are common metamorphic minerals within geothermal systems (Bird & Spieler, 2004; Kwon et al., 2019). Outcrop samples of granite obtained from the Gonghe Geothermal site in China also show the presence of epidote and chlorite as shown in Fig. 1(c). The presence of both epidote and chlorite have been reported in numerous geothermal reservoirs including, but not limited to, Soultz (France), Newberry volcano (USA) and Coso (USA) (Kovac et al., 2005; Sonnenthal et al., 2012; Vidal & Genter, 2018). Thus, a key question arises as to how these minerals, which are produced as a result of significant alteration or metamorphism, influence fault strength and frictional stability.

To date, few laboratory studies have been carried out to explore the frictional properties of epidote and chlorite at hydrothermal conditions. Epidote is a nesosilicate mineral that is commonly found in active geothermal systems and volcanic rocks (Bird & Spieler, 2004). It is stable over a wide range of

temperatures and pressures, even in subduction zones (Hu et al., 2017; Poli & Schmidt, 2004). Previous research revealed that the metamorphism of feldspar minerals and water-rock interactions contribute to the formation of epidote in geothermal systems (Franz & Liebscher, 2004). Whether the frictional behavior of epidote is similar to its protolith of feldspar remains unknown. Chlorite is a phyllosilicate mineral found commonly in natural fault zones (Lacroix et al., 2012; Schleicher et al., 2012). Like most phyllosilicate minerals, the sheet structure of chlorite exhibits low frictional strength and promotes fault creep (Ikari et al., 2009; Kopf & Brown, 2003). Both epidote and chlorite are low-to-medium grade metamorphic minerals and they typically coexist in granodiorite-granite rocks (Poli & Schmidt, 2004). Furthermore, the interplay of the different responses of epidote and chlorite will further increase the complexity of fault frictional behavior. Here, we document the effects of temperature, pore fluid pressure and mineral composition on the frictional properties of simulated fault gouge containing these two metamorphic minerals (epidote and chlorite). We report results of laboratory shear experiments at conditions corresponding to up to the 4–5 km depth of a typical geothermal reservoir.

Results

A total of 11 experiments were conducted at varied gouge compositions, temperatures and pore fluid pressures (Table S1). The friction displacement curves are typical, with a linear increase initially followed by an inelastic yield point and slight slip hardening (Figures S7 and S8). The samples were deformed by stable shear in most cases. Stick-slips were found for epidote gouge at $T \geq 150$ °C and the stick-slip amplitude increased with increasing temperature. Epidote fault gouge exhibits consistent friction coefficients μ ranging from 0.73 to 0.75 at different temperatures and pore fluid pressures (Fig. 2a, Table S2). Friction of epidote gouges is insensitive to T and P_f in the studied range. Epidote/chlorite mixed gouges ($\mu = 0.35$ – 0.66) (Table S2) are frictionally weaker than the epidote gouge at $T = 150$ °C and $P_f = 42$ MPa, and values of μ decrease with increasing chlorite content (Fig. 2b). Pure chlorite gouge is the weakest in our experiments ($\mu = 0.35$), in agreement with previous work (e.g., Moore & Lockner, 2015).

Results of our velocity step tests to measure friction velocity dependence are summarized in Figs. 2c and 2d and Table S2. Epidote gouge exhibits a range of behaviors from velocity strengthening ($a - b = 0$ to 0.0022) at $T = 100$ °C, to velocity neutral ($a - b = -0.0021$ to 0.0001) at $T = 125$ °C and apparent velocity weakening ($a - b = -0.0073$ to -0.0034) at $T \geq 150$ °C (Fig. 2c), indicating the high seismic potential at higher temperatures for granodiorite faults or fractures lined with metamorphic epidote. At $T = 150$ °C, elevating P_f from 42 MPa ($a - b = -0.0062$ to -0.0039) to 63 MPa ($a - b = -0.0073$ to -0.0056) destabilizes the epidote gouge (Fig. 2c insert), implying that P_f also affects the stability of epidote gouge. Similar results on fault instability promoted by the elevation of P_f were reported by Sawai et al. (2016) on blueschist gouge. Epidote/chlorite mixed gouges show strong velocity strengthening ($a - b = 0.0010$ to 0.0057) with chlorite content ≥ 25 wt.% at $T = 150$ °C and $P_f = 42$ MPa, but exhibit slight velocity weakening ($a - b = -0.0019$ to 0.0007) when the chlorite content is below 25 wt.%.

The microstructural observations indicate that gouge samples characterized by velocity weakening develop a localized shear zone (LSZ) with particle size reduction and R_1 shears (Logan et al., 1992)

(Figures S9 and S10d). In contrast, no obvious localized shear zone can be found in the deformed gouge samples showing strong velocity strengthening (Figures S11a-S11c, Figure S12). For those samples, shear is homogeneously dispersed throughout the gouge zone with elongated lamellae of epidote and chlorite. For the 50% epidote + 50% chlorite mixed gouge with layered structure, we observe that the shear mainly develops within the chlorite (Figure S10e). Consequently, the value of μ of the layered gouge (50% epidote + 50% chlorite) ($\mu = 0.36$) is much lower than that of the homogeneously mixed gouge (50% epidote + 50% chlorite) ($\mu = 0.49$), but similar to that of pure chlorite ($\mu = 0.35$) (Figure S11, Table S2). This also supports the observation that the gouge fabric can have a significant effect on gouge friction and that the weak mineral (chlorite) dominates the frictional response of layered gouge (Niemeijer et al., 2010).

Discussion

Although both epidote and chlorite are low-to-medium grade metamorphic minerals, their frictional properties are vastly different. Under hydrothermal conditions, epidote gouge is frictionally strong ($\mu \sim 0.73$) and exhibits velocity weakening at $T \geq 125^\circ\text{C}$. These properties are similar to those of plagioclase (He et al., 2016), suggesting that metamorphic epidote maintains the frictional properties of its feldspar protolith. Conversely, chlorite gouge is frictionally weak ($\mu \sim 0.35$) and promotes strong velocity strengthening. These frictional characteristics are generally consistent with previous results and highlight the role played by mineral structure in fault friction (Bos & Spiers, 2002; Okamoto et al., 2019; Tesei et al., 2012) (Figure S12).

Our data indicate that epidote/chlorite mixed gouges exhibit velocity weakening with $< 25 \text{ wt.}\%$ chlorite at conditions expected for a geothermal reservoir at a depth of 4–5 km. We interpret this to indicate that the presence of epidote in fault gouge and along fracture surfaces promotes unstable slip and earthquakes. Where fractures and faults show the coexistence of epidote and chlorite (Figure S1), an important question remains as to whether the epidote or the chlorite dominates the mineralogical composition and how these relative proportions contribute to frictional instability. Although the X-ray diffraction results on natural granodiorite fractures (Figure S2) show a higher content of epidote, the exact mineral composition at the main fault where the M_w 5.5 Pohang earthquake occurred is unknown as it is a few hundred meters away from the sampling point – and unsampled. The proportions might transform under favorable hydrothermal conditions as chlorite + calcite $\leftrightarrow$ epidote + dolomite (Franz & Liebscher, 2004), however, the time scale of this transformation may be beyond the engineering scale of a few months or years. Thus, even if calcite in fault rocks (e.g., granite and granodiorite) or injected water (Westaway & Burnside, 2019) can promote this transformation from chlorite to epidote, which increases the possibility of fault instability and increases the seismic potential, whether this mechanism can explain the recent earthquake in Pohang merits further investigation.

Epidote and chlorite are likely to be heterogeneously distributed within a fault zone and along fracture planes because metamorphism results from interaction with heterogeneously distributed ground water (Spinelli & Wang, 2009). One expects that alteration or metamorphism would initially begin at the outermost minerals of a fault zone and progress inwards under the invasion of hydrothermal fluids within

a fault zone. For the layered gouge, the phyllosilicate content has a critical effect on gouge friction and previous lab or modelling results showed that ~ 5 wt.% layered phyllosilicates can lower the frictional strength and stabilize the faults (Niemeijer et al., 2010; Wang et al., 2017). Such geometric constraints will apply to chlorite/epidote mixtures when the layered chlorite gouge is distributed within the layered epidote gouge – defining strength and stability as a function of mixture proportions and structure.

Our experimental results have significant implications for the generation of both natural and induced earthquakes in a geothermal reservoir. In EGS wells drilled for fluid injection may intersect critically-stressed fractures and fault zones (Fig. 3). In such cases, weaker regions of fault gouge or fractures control fault slip (Choi et al., 2016). If epidote is natively present in such regions, as suggested by previous works (Majer et al., 2007; Olasolo et al., 2016) and temperatures are in the range 150–250 °C, our results suggest that friction will be velocity weakening and therefore potentially unstable. Considering geothermal reservoirs with high thermal gradients (40 °C/km or more) as representative, the estimated temperature at 4–5 km depth can reach up to 160–200 °C (Beckers et al., 2014; Olasolo et al., 2016) and the frictional properties of epidote gouge could promote unstable sliding at both hydrostatic and elevated pore fluid pressures. Conversely, for faults containing epidote/chlorite mixed gouges, even a low chlorite content can reduce fault frictional strength and promote failure (Zhang et al., 2017) and high proportions of epidote will maintain velocity weakening response and promote potentially unstable fault slip. Our results therefore imply that fault instability could be facilitated by the presence of epidote and such metamorphic transformations, allowing gouge composition to exert a subtle but significant control on fault stability.

Conclusions

Our shear experiments on epidote or epidote/chlorite mixed gouges highlight their effect of alteration and metamorphism on the stability of subsurface faults in a geothermal reservoir. The results show that chlorite-rich gouges exhibit much lower frictional strength than epidote-rich gouges at conditions typified by the typical geothermal reservoir, implying that faults filled with chlorite-rich gouges may be readily reactivated. However, the epidote-rich gouges show strong frictional weakening behavior at elevated temperatures and pore fluid pressures, promoting instability of subsurface faults and increasing their seismic potential. Our results demonstrate that the presence of epidote and its effect of alteration or metamorphism should be taken into consideration in mitigating both natural and injection-induced seismic risks in such geologic environments.

Methods

We collected epidote minerals from Handan, Hebei Province of China and chlorite minerals from Fanshi, Shanxi Province of China. After removing the impurities, both the epidote and chlorite minerals were crushed and sieved to particle sizes <75 μm to simulate the particles found in natural fault gouge. Laser particle size analyses identify median particle sizes of the epidote and chlorite gouges as 48.7 and 50.3 μm (Figure S3), respectively. X-ray diffraction analysis indicates that both the epidote and chlorite gouges

have >99 wt.% purity (Figure S4). Epidote/chlorite mixed gouges were prepared from the two minerals at different proportions by weight.

Shear experiments were performed using an argon gas confined triaxial shearing apparatus (Figure S5) (He et al., 2006). A 1-mm-thick layer of gouge was sandwiched between the 20-mm-diameter gabbro or porous ceramic cylindrical blocks along rough surfaces inclined at 35° to the principal loading axis. The surfaces of these simulated fault zones were roughened with 200-mesh silicon carbide polishing compound. We drilled boreholes into the upper gabbro driving block to apply pore fluid pressures to the fault zone. A brass filter was placed into the borehole at the edge of the fault zone to prevent gouge extrusion and maintain high permeability. The upper porous ceramic driving block was not drilled with a borehole due to its high permeability. In each case, the cylindrical samples and fault zones were inserted into a 0.35-mm-thick annealed copper jacket and discs of high-hardness corundum and tungsten carbide blocks were placed at the top and bottom of the cylinders within the copper jacket (Figure S5). At the initiation of the experiment, the confining pressure was applied by the argon gas through a servo-controlled intensifier. After that, the pore fluid (deionized water) pressure was elevated to the desired magnitude, followed by heating of a clamshell furnace to raise the temperature at a rate of 5 °C/min. The temperature was maintained constant within ±2 °C by an independent controller throughout each experiment.

A confining pressure (σ_c) of 110 MPa and pore fluid pressure (P_f) of 42 MPa were employed, corresponding to lithostatic pressure (with rock density of 2630 kg/m³) and hydrostatic pressure at 4.2-km depth. We explored the frictional properties of epidote gouge at $\sigma_c = 110$ MPa, $T = 100$ -250 °C (temperature) and $P_f = 42$ -63 MPa. For experiments with mixed epidote/chlorite gouges, we varied the chlorite content from 0 to 100 wt.% and gouge states from homogeneously mixed to layered at $\sigma_c = 110$ MPa, $T = 150$ °C and $P_f = 42$ MPa. Details are given in Table S1. Each experiment was initially sheared at a constant shear velocity of 1.22 $\mu\text{m/s}$ until the steady state friction regime was achieved. Then the shear velocity was stepped between 1.22, 0.244 and 0.0488 $\mu\text{m/s}$ to assess the velocity dependence of friction.

The coefficient of friction is calculated as $\mu = \tau / (\sigma_n - P_f)$, where τ and σ_n denote the shear stress and normal stress, respectively. The velocity dependence was evaluated based on the rate and state friction equation with the Dieterich evolution law (Dieterich, 1979; Rice, 1983; Ruina, 1983), expressed as,

$$\mu = \mu_0 + a \ln \left(\frac{V}{V_0} \right) + b \ln \left(\frac{V_0 \theta}{D_c} \right) \quad (1)$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c} \quad (2)$$

where μ is the coefficient of friction at the instantaneous shear velocity V , μ_0 denotes the coefficient of friction at the reference shear velocity V_0 ($V > V_0$), a and b are dimensionless constants, θ is a state variable that describes contact age and fault zone porosity (Marone, 1998), D_c represents the critical slip

distance, and t is time. At a steady state friction, the state variable θ does not change with time t and thus $d\theta/dt = 0$. Then, the frictional stability parameter ($a - b$) can be obtained from Equation (1),

$$a - b = \frac{\mu - \mu_0}{\ln(V/V_0)} = \frac{\Delta\mu}{\Delta\ln V} \quad (3)$$

Negative values of ($a - b$) reveal that the coefficient of friction decreases with an increase of shear velocity (velocity weakening), promoting potentially unstable frictional sliding. Conversely, positive values of ($a - b$) indicate velocity strengthening and result in inherently stable sliding. Examples of methods for determining the values of $\Delta\mu$ are shown in Figure S6.

After the shear experiments, the deformed gouge samples were first impregnated with resin in a vacuum chamber and then cut into thin sections along the shear direction for microstructural observation using scanning electron microscopy (SEM).

Declarations

Data availability

The experimental data are available at the supporting information.

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Competing interests

The authors declare no competing interests.

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Figures

Figure 1

(a) Epidote and chlorite occurrences on natural granodiorite fractures prior to stimulation from Pohang Geothermal site (backscattered electron SEM images) at 4.2-km depth. Native presence of epidote (Ep) and chlorite (Cl) on the granodiorite fractures. Other minerals include quartz (Qz) and microcline (Mc). (b) Chlorite forming at the microcracks of natural granodiorite cores in Pohang. Scale bars in (a) and (b), 50 μm . (c) Epidote and Chlorite observed in an outcrop sample from the Gonghe Geothermal site, China (optical thin section). Scale bar in (c), 500 μm .

Figure 2

Coefficient of friction μ and frictional stability ($a - b$) under varied conditions. (a) Values of μ versus temperature for epidote (Ep) gouge at $\sigma_c = 110$ MPa and $P_f = 42$ MPa. Insert shows μ of epidote gouge at $T = 150^{\circ}\text{C}$ and $P_f = 42$ and 63 MPa, respectively. Red dashed lines indicate $\mu = 0.73$. (b) Friction versus chlorite (Cl) content for epidote/chlorite mixed gouges at $\sigma_c = 110$ MPa, $T = 150^{\circ}\text{C}$ and $P_f = 42$ MPa. (c) Friction rate parameter ($a - b$) as a function of applied temperatures for epidote gouge at $\sigma_c = 110$ MPa and $P_f = 42$ MPa. Insert shows data for $T = 150^{\circ}\text{C}$ and $P_f = 42$ and 63 MPa, respectively. (d) Values of ($a - b$) as a function of the chlorite content for epidote/chlorite mixed gouges at $\sigma_c = 110$ MPa, $T = 150^{\circ}\text{C}$ and $P_f = 42$ MPa.

Figure 3

Interplay of the native presence of different metamorphic minerals on fault stability at a typical EGS site. (a) A drilled EGS well may transect the large-scale natural deep fault. Alteration minerals occur on the natural fault or fracture planes as a result of low-grade metamorphisms or interaction with injected water. (b) The temperature for an EGS reservoir generally spans the range from 150 to 250 °C (Majer et al., 2007; Olasolo et al., 2016). In this temperature range, fractures or faults altered or metamorphosed with pure epidote or epidote-rich gouge exhibit velocity weakening behavior and the potential for unstable reactivation. The areas surrounded by red lines or dashed lines indicate the potential unstable region of EGS reservoir metamorphosed by epidotization and chloritization.

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