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Key Points:

- Frictional strength loss in amphibole-rich gouge may provide an additional weakening mechanism for detachment faults
- Crystallographic-preferred orientation development in amphibole tentatively linked to negative frictional healing
- Phyllosilicates enable water to cause frictional strength reduction, more velocity-strengthening behavior, and reduced frictional healing

Supporting Information:

Supporting Information may be found in the online version of this article.

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Negative Frictional Healing in Icelandic Geothermal (IDDP-2) Core Samples: Potential Implications for Detachment-Fault Mechanics

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Abstract Detachment faults in mid-ocean ridge settings accommodate tectonic extension. These faults are potentially weakened by alteration through phyllosilicate- and amphibole-mineral formation. Seven core samples taken from the Krafla and Reykjanes geothermal fields in Iceland allow for the study of the effect of mineral alteration on the frictional behavior of basic rocks in the context of high-enthalpy geothermal fields and slow-spreading mid-ocean ridges. Gouge samples were prepared from the core samples and tested in a biaxial apparatus. In the core samples from Krafla, the presence of phyllosilicate minerals, which are generally stable at low (<400°C) temperatures, enables water to cause frictional weakening, increased stability, and reduced frictional healing. The core samples from Reykjanes, however, offer a unique opportunity to study the effect of high-temperature alteration, as they are from a spreading center at 4,600 m depth and >600°C and have not been overprinted by low-temperature alteration. Although these samples appear frictionally strong and more velocity-weakening than the Krafla samples, they also exhibit negative frictional healing. This might be associated with a developing crystallographic-preferred orientation of the amphibole minerals during inter-seismic periods, potentially implying a new weakening mechanism that may operate along oceanic detachment faults at intermediate temperatures (approximately 400–600°C) in conditions too hot for serpentinization and too cold for the crystal plastic deformation of peridotite. This progressive frictional strength loss along detachment faults may influence detachment-fault morphology, but further investigation is required to both conclusively link crystallographic-preferred orientation to negative healing and extrapolate its relevance to crustal conditions.

Plain Language Summary The reorientation of amphibole minerals in fault material may lead to weakening and could be important in the development of faults along mid-ocean ridges. Rock samples have been collected from geothermal fields in Iceland, an active mid-ocean ridge spreading center. The primary minerals composing these rocks have been altered through interaction with water. Samples are ground into powder and friction tests are performed. In samples from lower-temperature settings, alteration resulted in phyllosilicate minerals, which are shown to be frictionally weak yet stable. Rocks from higher-temperature zones have experienced alteration resulting in the presence of amphibole minerals and have not been overprinted with phyllosilicates. These rocks are frictionally strong, but extended periods of fault locking result in a reorientation of the minerals potentially weakening the gouge material. This weakening mechanism may be particularly relevant for detachment faults along mid-ocean ridges, where numerical models generally consider plastic weakening mechanisms at large depths and temperatures and phyllosilicate-induced weakness at low temperatures. These models have been unable to entirely explain the characteristics of detachment faults, but the weakening shown here in amphibole-rich rocks, relevant for intermediate depths, may provide a solution.

1. Introduction

Mid-ocean ridges are an integral part of the plate-tectonic cycle. They extend some 50,000 km throughout the world's oceans, are the site of oceanic crust creation, host large mineral deposits (e.g., Coumou et al., 2008), and are the conduit through which a significant proportion of the Earth's total heat flux either conducts or advects. Magmatic accretion (i.e., dike injection, lava extrusion, and gabbroic intrusions) and extensional processes (i.e., localized faulting and ductile deformation) taking place at mid-ocean ridges are responsible for the structure of the

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oceanic crust as well as seafloor morphology (Escartín et al., 1999; Tucholke et al., 2008). Indeed, abyssal hills, the most widespread topographical feature on Earth, are thought to be a product of extensional faulting related to plate spreading (e.g., Buck & Poliakov, 1998; Shaw, 1992). However, at slow-spreading centers ($12\text{--}50\text{ mm} \cdot \text{a}^{-1}$), the controls on normal-fault offset and spacing (Buck & Poliakov, 1998), as well as the weakening mechanisms behind detachment fault formation (Bickert et al., 2020), remain unresolved.

It has been suggested that the nature of fault deformation along mid-ocean ridges might depend on a number of potentially interrelated parameters such as the lithospheric thickness (e.g., Escartín et al., 2008; Shaw, 1992), the rheology of the deforming crust (e.g., Escartín & Hirth, 1997; Harper, 1985), magma supply (e.g., Buck et al., 2005; Laughton et al., 1979), and spreading rate (e.g., Buck et al., 2005; Cowie et al., 1993). It is thought that the strain localization along detachment faults, which form an integral part of the structure of mid-ocean ridges, may be at least in part related to alteration fronts within the brittle lithosphere (Cann et al., 1997; Escartín et al., 1997a, 1997b, 2003; MacLeod et al., 2002).

Alteration products such as phyllosilicates, which have long been recognized in oceanic and geothermal systems worldwide (e.g., Browne, 1978; Kristmannsdóttir, 1975, 1979), have also been linked to the relatively aseismic nature of brittle deformation at fast spreading centers (Cowie et al., 1993; Reinen et al., 1991). Certainly, phyllosilicate minerals are often frictionally stable and weak (e.g., Escartín et al., 1997a, 1997b; Giorgetti et al., 2015; Ikari et al., 2020; Tesei et al., 2018). As such, the rheology of the oceanic lithosphere is dependent to a first order on not just its thermal state (e.g., Harper, 1985), but also its composition and the mechanical and frictional properties of its components; to the point that even phases which are not necessarily abundant, such as alteration products, may have a significant influence on the strength of the lithosphere and the mode of localization of the deformation (e.g., Cannat, 1993; Searle & Escartín, 2004). For example, oceanic detachment faults may act as conduits for fluid flow, encouraging the localized alteration of the host rock. This may lead to the serpentinization of (partially) exhumed mantle material, resulting in phyllosilicate mineral formation which weakens (in the case of lizardite) and further localizes deformation along the detachment fault (e.g., Bickert et al., 2020; Escartín & Hirth, 1997; Escartín et al., 1997a, 1997b; Escartín et al., 2003, 2008; Tesei et al., 2018). Further weakening may occur if other phyllosilicate minerals such as chlorite and talc, which are common in these contexts, have also formed from alteration.

Yet, this weakening mechanism, in combination with grain size reduction in the ductile upper mantle, is thought to be insufficient to explain the structure and form of detachment faults along ultraslow-spreading ($<12\text{ mm} \cdot \text{a}^{-1}$) ridges because neither mechanism is expected at intermediate temperatures ($\approx 400^\circ\text{C}$) (Bickert et al., 2020). Other alteration products, such as amphibole, are also present in oceanic crust. Unlike phyllosilicates, amphiboles have traditionally been considered frictionally strong, though their occurrence in altered gabbros and peridotites at mid-ocean ridges makes them a potentially important factor in controlling fault mechanics and deformation localization. In general, measurements of the frictional properties of basalt, gabbro, and olivine-, amphibole-, chlorite-, serpentine-, and talc-rich rocks have not yet been able to uncover a mechanism which would be able to explain the predicted frictional weakness of detachment faults at intermediate ($400^\circ\text{C}\text{--}600^\circ\text{C}$) temperatures.

Understanding mid-ocean ridges has implications beyond plate tectonics, however. It is thought that the largest and most abundant high-temperature systems on Earth occur along submarine rifts and transform boundaries (Jolie et al., 2021; Stimac et al., 2015). While the industrial development of these systems is currently prohibitively expensive, in the context of global climate change and technological development, these systems may become attractive global targets for geothermal energy exploitation in the near future. A number of subaerial rift zones, such as in Iceland and Kenya, are already sites of commercial developments (e.g., Stimac et al., 2015).

The frictional properties of relevant reservoir rocks and their dependence on mineral alteration are important considerations in the development and sustainable exploitation of these resources. These reservoirs generally require a clay cap to act as a reservoir seal, and these clay caps are formed by mineral alteration (e.g., Ármannsson et al., 1987; Gasperikova et al., 2015; Kristmannsdóttir, 1979). An understanding of the frictional properties as a function of alteration allows for the stress field of the reservoir to be more accurately constrained, for the identification of potentially active faults, and for improved induced-seismicity hazard analyses. This is especially true for fields which may one day be hosted in low-angle detachment faults, which have already been shown to act as conduits in the context of off-axis blacksmoker vents at slow- and ultraslow-spreading ridges (McCaig et al., 2007).

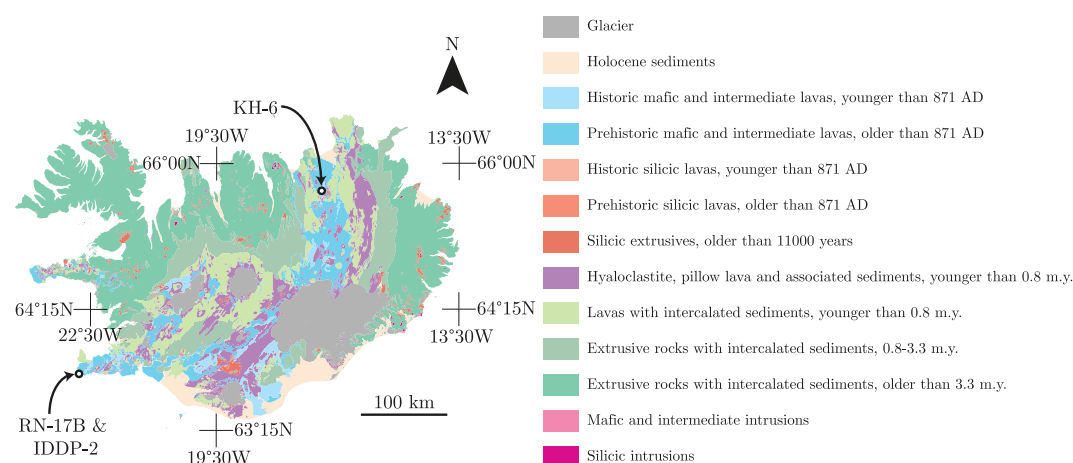


Figure 1. A geological map of the bedrock of Iceland, modified from Náttúrufræðistofnun Islands (2022). Also noted are the emplacements of the three relevant wells for this study, KH-6, RN-17B, and IDDP-2, which can be seen to be located in the regions of Iceland with the youngest bedrock. Well locations based on Weaver et al. (2020), Zierenberg et al. (2021).

In this study, seven cores are taken from the Reykjanes and Krafla reservoirs in Iceland which together are considered to represent altered hyaloclastites, pillow lavas, and sheeted dike complexes from the oceanic crust. Gouge samples from these cores are prepared and then tested in a biaxial apparatus, allowing for the constraint of their frictional properties. The frictional tests on samples taken in situ from an active spreading center and devoid of significant low-temperature overprinting allow for the characterization of the expected strength and seismogenic profiles of the oceanic crust along mid-ocean ridges. These results are then used to better understand the rheology of the oceanic lithosphere in order to provide insight into the structure and deformation occurring in the oceanic crust along mid-ocean ridges.

2. Sample Context

Iceland is located along an oceanic spreading center, spanning the Mid-Atlantic Ridge, Figure 1, and is also the surface expression of a mantle hotspot (Friðleifsson et al., 2020). Because of these tectonics, areas in Iceland often have very high geothermal gradients (in many instances above $100^{\circ}\text{C} \cdot \text{km}^{-1}$), and currently the total installed geothermal generation capacity is over 700 MWe. Moreover, due to its high geothermal gradient, operators in the last few decades have begun considering the possibility of drilling wells deeper, into higher temperatures and pressures, where seawater would exist as a supercritical fluid (Bischoff & Rosenbauer, 1984; Friðleifsson et al., 2014), allowing for greatly increased power output.

Because of its tectonic setting, Iceland also represents a unique opportunity to study mid-ocean ridges. The challenges and expense associated with ocean drilling have meant that deep sea drilling programs are limited in the number of deep ($>1,000$ m) wells they drill (Alt et al., 1986, 2010; Anderson et al., 1982; Bach et al., 2001; Drouin et al., 2009; Godard et al., 2009). Yet, wells to these kinds of depths have been regularly drilled in the Krafla geothermal field in Iceland since the 1970s (Ármannsson et al., 1987). Additionally, as Iceland is located precisely on a spreading axis, its subsurface is composed of fresh oceanic crust. Indeed, while deep sea drilling programs have been able to recover core samples from pillow lavas and sheeted dike complexes (and in certain instances even gabbro samples from Layer 3), these samples are invariably recovered from areas at a significant distance from the spreading center at low temperature, such that the alteration phases present in the samples may represent low-temperature overprinting (Alt et al., 1986, 2010; Anderson et al., 1982; Bach et al., 2001). The spreading center which runs SW-NE through Iceland means that wells in Iceland can be drilled from the surface into young high-temperature rock which has experienced relatively little or no low-temperature overprinting, making any core samples collected in this region ideal for the study of mid-ocean ridges.

Yet, spreading axes along mid-ocean ridges exist with a wide range of spreading rates. Different spreading rates are associated with different structures, meaning the inferences made regarding one spreading center are not necessarily applicable to another. Iceland is unique amongst mid-ocean ridges not only in that it stands above sea level over a potential hotspot, it also spreads faster than submerged parts of the ridge and contains multiple rifts in

Table 1
A Summary of the Samples Used for This Study

Sample	Location (well)	Rock type	Depth (m)	Temp. (°C)
K665	Krafla (KH-6)	Basaltic Dike	665	133 ^a
K708	Krafla (KH-6)	Dolerite Dike	708.5	128 ^a
K731	Krafla (KH-6)	Hyaloclastite	731	125 ^a
R2806	Reykjanes (RN-17B)	Hyaloclastite	2,806	322 ^b
R4641	Reykjanes (IDDP-2)	Dolerite Dike	4,641	426 ^c
R4648	Reykjanes (IDDP-2)	Dolerite Dike	4,648	426 ^c
R4654	Reykjanes (IDDP-2)	Dolerite Dike	4,654	426 ^c

Note. The rock types are taken from Escobedo et al. (2021) for KH-6, Fowler et al. (2015) for RN-17B, and Gibert et al. (2020), Scott et al. (2023) for IDDP-2. ^aTemperatures of 145 and 125°C were measured at 556 and 732 m, respectively (Weaver et al., 2020). The listed temperatures are linear interpolations. ^bResult based on the last temperature log (Friðleifsson & Richter, 2010). ^cA temperature of 426°C was measured at 4,560 m after drilling (Friðleifsson et al., 2017), but due to ongoing thermal recovery the likely temperature is approximately 600°C (Zierenberg et al., 2021).

its southern section (Walker, 1975). Iceland offers a unique opportunity to study mid-ocean ridges for its relative ease of access, but its uniqueness highlights that mid-ocean ridges exist in wide varieties. Its spreading rate of approximately $18 \text{ mm} \cdot \text{a}^{-1}$ (Sigmundsson et al., 2020) means Iceland rifts at a rate which can be considered “slow,” as the transition to an “intermediate” spreading rate along a mid-ocean ridge is approximately $50 \text{ mm} \cdot \text{a}^{-1}$ (Tucholke et al., 2008) and the transition to “ultra-slow” is approximately $12 \text{ mm} \cdot \text{a}^{-1}$ (Dick et al., 2003). However, even fast-spreading ridges ($>100 \text{ mm} \cdot \text{a}^{-1}$) such as the East Pacific Rise (Cowie et al., 1993), exhibit many of the alteration phases encountered in Icelandic drill cores, such as smectite, chlorite, and amphibole (Alt et al., 2010). Icelandic drill core samples may therefore have potential to be interpreted in the context of intermediate- and fast-spreading ridges.

Due both to excellent geothermal potential and the scientific relevance of deep drilling in Iceland, the Iceland Deep Drilling Program (IDDP) was established in 2000 as a consortium of three Icelandic energy companies (Friðleifsson et al., 2014). IDDP drilling has been centered in the Reykjanes and Krafla geothermal fields and has resulted in core recovery from over 4,500 m depth at temperatures greater than 600°C (Zierenberg et al., 2021),

achieving its primary goal of demonstrating deep drilling into active supercritical geothermal conditions (Friðleifsson et al., 2017). Considering the location and in situ temperatures of the coring, these samples are considered to be either void of or only marginally over-printed by low-temperature alteration, making them ideal for the study of fresh mid-ocean ridge deposits.

2.1. Krafla

The Krafla geothermal field is located inside the Krafla caldera in the Neovolcanic zone in northeast Iceland and is one of the main geothermal fields in Iceland. An exploratory well, KH-6, was drilled in Krafla in 2007 to a depth of approximately 732 m, reaching a bottom-hole temperature of 125°C, with a maximum temperature of 200°C at 345 m (Eggertsson et al., 2020). Numerous core samples were taken in this well and many of these have been the subject of previous studies (Eggertsson et al., 2020; Escobedo et al., 2021; Lévy et al., 2018, 2020; Weaver et al., 2020). Three core samples from this well are additionally used here, Table 1. Samples from 665, 708.5, and 731 m depth will be referred to as K665, K708, and K731, respectively. Selected samples consist of a basaltic dike, dolerite, and hyaloclastite, respectively. These basaltic rocks and dolerites are dominated by plagioclases and clinopyroxene (augite/diopside) as phenocrysts and in microlithic matrix. Vesicles are mainly filled by quartz, zeolites, calcite, and clay minerals such as chlorite-corrensite. Glass (in hyaloclastic rocks or in dikittaxitic cavities) is mainly replaced by trioctahedral smectite ($\pm$ zeolite, calcite).

2.2. Reykjanes

The Reykjanes geothermal system, situated at the onshore extension of the Mid-Atlantic Ridge in southwest Iceland, represents one of the few onshore sites where supercritical conditions have been accessed through deep drilling. In this study, four core samples are analyzed from two boreholes within the field. Sample R2806 was recovered from 2,806 m measured depth in RN-17B, a high-enthalpy well with in situ temperatures exceeding 320°C (Friðleifsson & Richter, 2010). R2806 is characteristic of a hyaloclastite deposit formed during submarine volcanic and then epiclastic events which has then been hydrothermally altered with a significant presence of amphibole (Fowler et al., 2015). Indeed, pyroxenes have been altered to chlorite and green hornblende in this sample. Samples R4641, R4648, and R4654 originate from IDDP-2, a deepened borehole reaching over 4,600 m depth, with estimated equilibrium temperatures approaching 600°C (Zierenberg et al., 2021). R4641, R4648, and R4654 are interpreted as dolerites from sheeted dike complexes and have been described as showing primary assemblages of plagioclase, augite, and titanomagnetite with low porosity and non-mineralized microcracks that cross-cut minerals and grain boundaries (Gibert et al., 2020; Scott et al., 2023). IDDP-2 samples show significant uraltization, in this case specifically alteration of igneous clinopyroxene to hornblende (amphibole); this alteration resembles that of hydrothermally altered oceanic crust (Friðleifsson et al., 2017, 2020). Biotite was locally

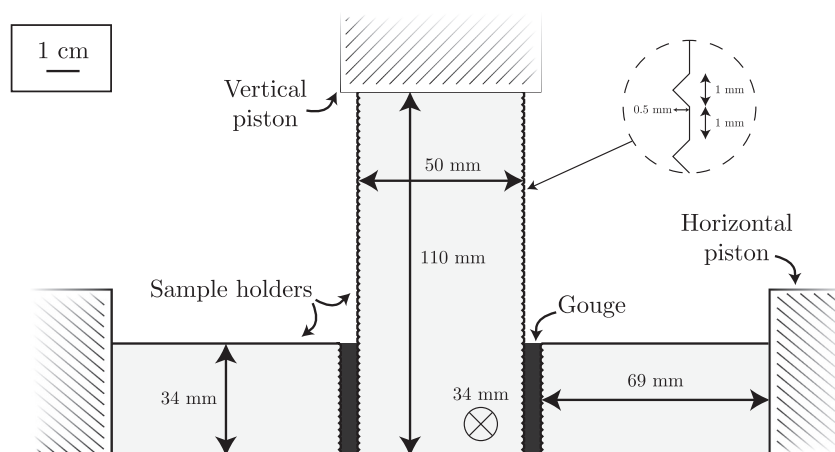


Figure 2. Schematic of the double-direct shear apparatus used for the experiments. A gouge sample is placed in between one vertical- and two horizontal-driving blocks. A horizontal piston on the right-hand side of the image applies a normal force. A vertical piston applies a vertical shearing force. The left-hand side is supported by the wall of the apparatus. The driving blocks are composed of stainless steel.

observed in R4641 and R4648. According to Zierenberg et al. (2021), augite in these levels is completely replaced by hornblende intimately intergrown with orthopyroxene, clinopyroxene, and biotite. According to the same authors, the deeper dyke is richer in feldspars and shows similar alteration to the overlying rocks, except for the absence of biotite. The alteration mineralogy and textures in samples from IDDP-2 are consistent with those observed in high-temperature, mid-ocean ridge hydrothermal systems, but without the effects of retrograde overprinting characteristic of older, submarine cores.

3. Methods

3.1. Sample Preparation and Characterization

The core samples were ground by hand into gouge, ensuring a particle size of less than 125 μm , confirmed by granulometry, Table S1 in Supporting Information S1. Samples were dried at room temperature. Oven drying was not employed as this can alter the clays present in the samples (Summers & Byerlee, 1977). Prior to sample crushing, a piece of intact sample was used to prepare a thin section which was then analyzed using a scanning electron microscope (SEM). Quantitative phase analysis was performed using X-ray powder diffraction (XRD) based on Rietveld quantitative analysis (Doebelin & Kleeberg, 2015) in conjunction with the SEM analyses. In particular, phyllosilicates were grouped by families (micas, chlorite, and 2:1 trioctahedral expandable clays). Note that 2:1 trioctahedral expandable clay minerals include both discrete smectite and smectite-containing interstratifications. Details on the Quantitative phase analysis and XRD can be found in Supporting Information S1.

Additionally, on select post-mortem samples Electron Backscatter Diffraction (EBSD) analyses were performed. These analyses were performed with a Camscan X500FE Crystal Probe SEM, equipped with the Oxford instruments Symmetry EBSD detector at Geosciences Montpellier. The operating conditions were a working distance of 25 mm, an acceleration voltage of 20 kV and a probe current of around 5 nA. Low vacuum conditions (2 Pa) were used to avoid electron charging. Data were acquired with AZtec software. EBSD maps were acquired with a step size of 0.3 μm .

3.2. Apparatus and Experimental Procedure

Double-direct shear experiments were performed in a biaxial apparatus on the seven core samples (Dieterich, 1972; Violay et al., 2021). A compacted gouge layer ($4.86 \times 34 \times 34$ mm) held by a grooved steel block was placed on either side of a driving block, Figure 2. An initial normal stress of 1 MPa was applied to the sample. When the experiment was performed under nominally wet conditions, the sample (contained within an impermeable membrane) was submerged in deionized water at this stage, and the stress held constant for 40 min. When the experiment was performed under nominally dry conditions, this 40-min hold was skipped. The normal stress was then increased to either 10, 30, or 50 MPa, depending on the test conditions. These stresses correspond to

approximately 650, 2,000, and 3,300 m considering an effective lithostatic stress gradient of $15 \text{ MPa} \cdot \text{km}^{-1}$. These depths are relevant for geothermal energy exploration in these settings. Next, the applied normal stress was held constant for 20 min at which point a run-in was performed. The run-in allows for the development of the shear fabric (e.g., Noël et al., 2023) and was performed at $10 \mu\text{m} \cdot \text{sec}^{-1}$ for 11 mm. Following this, velocity steps were performed at up-step velocities of 3, 10, 30, 100, and $300 \mu\text{m} \cdot \text{sec}^{-1}$ across 500 μm . Next, slide-hold-slides were performed with hold times of 1, 3, 10, 30, 100, 300, 1,000, and 3,000 s; in between holds the sample was sheared at $10 \mu\text{m} \cdot \text{sec}^{-1}$ for 500 μm . After the last slide-hold-slide, the sample was unloaded. A recording frequency of 10 Hz was used, except during the velocity steps where 2 kHz was employed. Each sample was tested six times: at 10, 30, and 50 MPa normal stress under both nominally wet and nominally dry conditions, or 42 total experiments. Experiments were performed at approximately 23°C (room temperature). In the following sections, experiments will be simply referred to as wet (immersed in deionized water but not certainly saturated) or dry (room humidity, approximately 40%).

3.3. Data Treatment

The vertical and horizontal forces recorded by the load cells are converted to stress considering the nominal dimensions of the sample. Slip and horizontal displacement are calculated based on the optical encoders on the pistons and are corrected for the stiffness of the machine. The data are not filtered. The error in the vertical and horizontal forces was taken as 0.3 kN, and the error in the vertical and horizontal displacements was taken as 250 nm. Both of these values are based on the standard noise levels recorded. These errors propagate and are considered for all derived quantities.

3.3.1. Friction Coefficients

An apparent friction, μ^* , is calculated considering the ratio between shear, τ , and normal, σ , stresses. An apparent coefficient of frictional yield, μ_y^* , is determined for each experiment based on when the loading during the run-in phase breaks from linear elastic behavior, Figure 3a. This point is analogous to the yield point of the material and is also known as the proportionality limit. An apparent dynamic coefficient of friction, μ_d^* , is found for each experiment as the average value of μ^* during the last 1.5 mm of the run-in, Figure 3a. Considering that the samples are tested at three different normal stresses, the values μ_y^* and μ_d^* are used to perform a least-squares estimate of the coefficients of frictional yield and dynamic friction coefficients, μ_y and μ_d , under both wet and dry conditions, Figure S1 in Supporting Information S1.

3.3.2. Velocity Steps

Using the rate-and-state friction constitutive law (Dieterich, 1979),

$$\mu^* = \mu_0^* + a \ln\left(\frac{v}{v_0}\right) + b \ln\left(\frac{v_0 \theta}{D_c}\right), \quad (1)$$

the velocity dependence of friction was investigated. Here, the apparent friction prior to a velocity step from v_0 to v is given by μ_0^* . The direct effect is given by a , the evolution effect by b , and the critical slip distance by D_c (not to be confused with the slip-weakening distance, δ_c). θ is a state variable given by the slip law (Ruina, 1983),

$$\frac{d\theta}{dt} = -\frac{v\theta}{D_c} \ln\left(\frac{v\theta}{D_c}\right), \quad (2)$$

employed here over the aging law for its increased relevance to rock samples (Bhattacharya et al., 2022). The velocity steps are de-trended prior to fitting, Figure 3b. This framework allows for an assessment of whether or not a given sample is velocity weakening ($a - b < 0$) or velocity strengthening ($a - b > 0$); one of the necessary conditions for the nucleation of dynamic rupture under the assumption of small perturbations (Ruina, 1983; Rice & Ruina, 1983).

A normalized dilatancy parameter α is defined for each velocity step (Giacometti et al., 2021; Ikari et al., 2009; Marone & Kilgore, 1993),

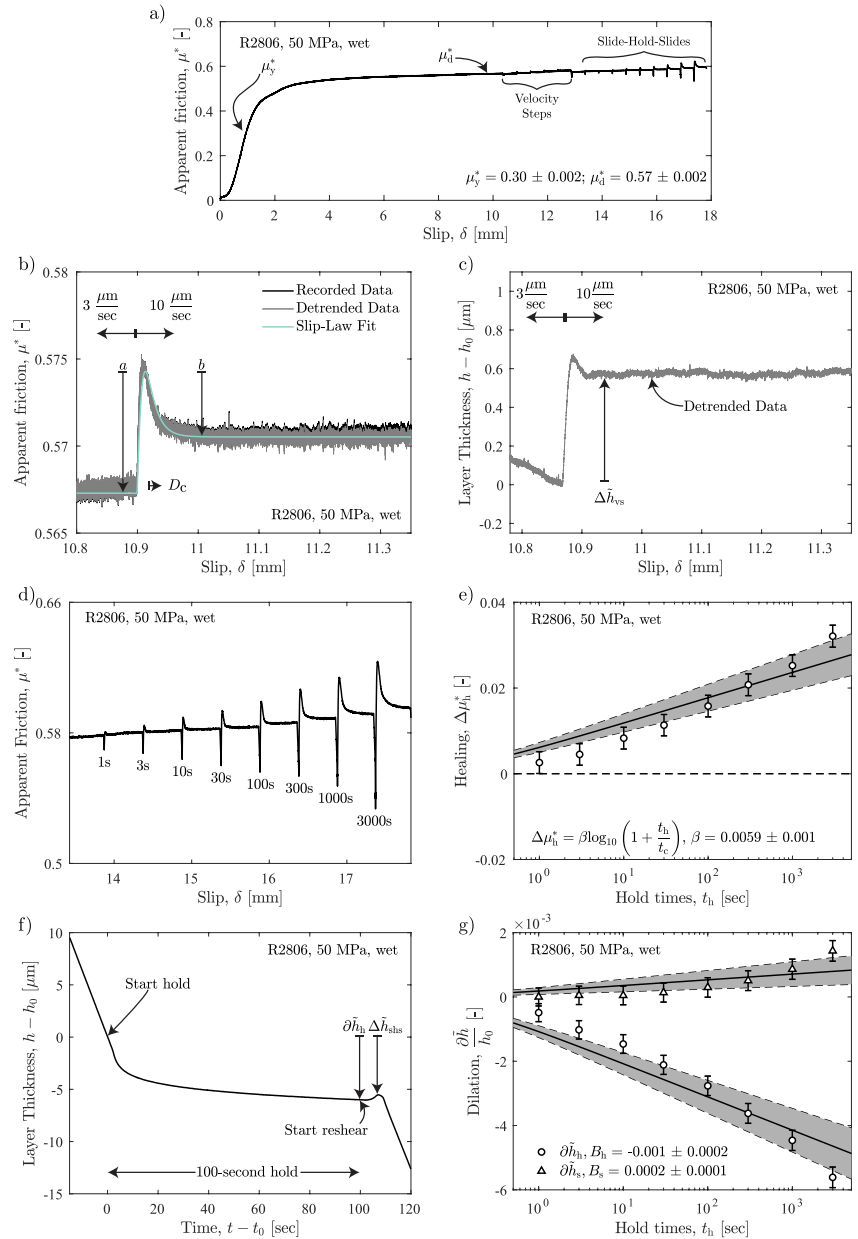


Figure 3. An example experiment, R2806 performed at 50 MPa under wet conditions. (a) A full overview of the experiment. An initial run-in period initiates shearing and prepares the shear fabric; a break from elasticity corresponds to the onset of sliding, μ_y^* . Continued sliding results in a near steady-state friction, albeit with slight strain hardening, allowing for the selection of μ_d^* . Then, five velocity steps ($3, 10, 30, 100$, and $300 \mu\text{m} \cdot \text{sec}^{-1}$) are performed across $500 \mu\text{m}$ each. This is followed by eight slide-hold-slides ($1, 3, 10, 30, 100, 300, 1,000, 3,000 \text{ s}$) with $500 \mu\text{m}$ slides. (b) An example velocity step showing how a , b , and D_c are fit using detrended data. (c) An illustration of the way the dilation during the step, Δh_{vs} , is found. (d) An example series of slide-hold-slides. (e) The picked values of healing for each hold, which then result in a fit value of β . (f) An example slide-hold-slide showing how δh_s and Δh_{shs} are found. (g) The dilation parameters for each series of slide-hold-slides are fit yielding B_h , B_s , and B_{shs} . The data are not filtered.

$$\frac{\Delta \tilde{h}_{vs}}{h_0} = \alpha \ln \left(\frac{v}{v_0} \right), \quad (3)$$

which attempts to capture the dilatant response of the sample to velocity changes. Here, the change in layer thickness that occurs when the velocity changes from v_0 to v is given as $\Delta \tilde{h}_{vs}$, and the layer thickness prior to the step is given as h_0 . The layer thickness is detrended prior to this calculation, Figure 3c.

3.3.3. Slide-Hold-Slides

In order to assess the inter-seismic healing of the samples, slide-hold-slides were used (Dieterich, 1972). The healing resulting from a given hold, $\Delta \mu_h^*$, is taken as the difference in apparent friction between the peak reached after re-shearing and the steady-state value prior to the hold, Figure 3d. The healing rate, β , is then found based on a weighted-least-squares fit based on the logarithm of hold time (Dieterich, 1972; Paterson & Wong, 2005),

$$\Delta \mu_h^* = \beta \log_{10} \left(1 + \frac{t_h}{t_c} \right), \quad (4)$$

Figure 3e. Here, t_h is the hold time and t_c is one divided by the recording frequency of 10 Hz. The change in layer thickness that occurs during a slide-hold-slide, $\Delta \tilde{h}_{shs}$, can be calculated as (Giacomet et al., 2021),

$$\Delta \tilde{h}_{shs} = \partial \tilde{h}_h + \partial \tilde{h}_s, \quad (5)$$

with $\partial \tilde{h}_h$ being the dilation occurring during the hold phase and $\partial \tilde{h}_s$ the dilation occurring during re-shearing, Figure 3f. In a similar fashion to β , this allows for the definition of three dilation rates: B_h , B_s , B_{shs} , for the hold periods, re-shearing events, and overall slide-hold-slide sequence, respectively. These quantities are the best-fit slopes of,

$$\frac{\partial \tilde{h}_h}{h_0} = B_h \log_{10} \left(1 + \frac{t_h}{t_c} \right), \quad \frac{\partial \tilde{h}_s}{h_0} = B_s \log_{10} \left(1 + \frac{t_h}{t_c} \right), \quad \frac{\Delta \tilde{h}_{shs}}{h_0} = B_{shs} \log_{10} \left(1 + \frac{t_h}{t_c} \right). \quad (6)$$

This process is illustrated in Figure 3g. Generally, only B_h and B_s will be considered here.

4. Results

4.1. Sample Compositions

SEM analyses showed differences in sample mineralogy. Figures 4a–4c shows samples from Krafla and Figures 4d–4g shows samples from Reykjanes. The presence of amphibole ($\pm$ biotite) can be seen in the Reykjanes samples while being absent in samples from Krafla. Conversely, phyllosilicates are largely absent from Reykjanes samples excluding some chlorite in R2806, whereas they are present in samples from Krafla. This is indicative of the lack of overprinting with low-temperature alteration in the Reykjanes samples.

The results of the XRD analysis are presented in Table 2 and generally agree with the SEM observations and literature data. All samples show the major presence of plagioclase. In addition, the samples from Krafla are characterized by the presence of clinopyroxene, 2:1 expandable trioctahedral clay minerals, and chlorite. The samples from Reykjanes, on the other hand, have almost no phyllosilicates (with the exception of R2806) and instead show significant amounts of amphibole. SEM and Energy-Dispersive X-ray spectroscopy (EDX) analyses show that amphiboles present in the Reykjanes samples are generally characterized by more than 1.5 Ca atom per formula unit, Table S2 in Supporting Information S1, and around 0.5 Na or K atoms per formula unit, or less. These amphiboles are further richer in Fe than in Mg. Therefore, they can be classified as an iron-rich hornblende-edenite series. The plagioclase minerals present in both Reykjanes and Krafla samples compositionally belong to bytownite-labradorite-andesine members, although K731 may present some oligoclase, Table S3 in Supporting Information S1 (e.g., Deer et al., 2013). Clinopyroxenes from Reykjanes and Krafla can be classified as pigeonite,

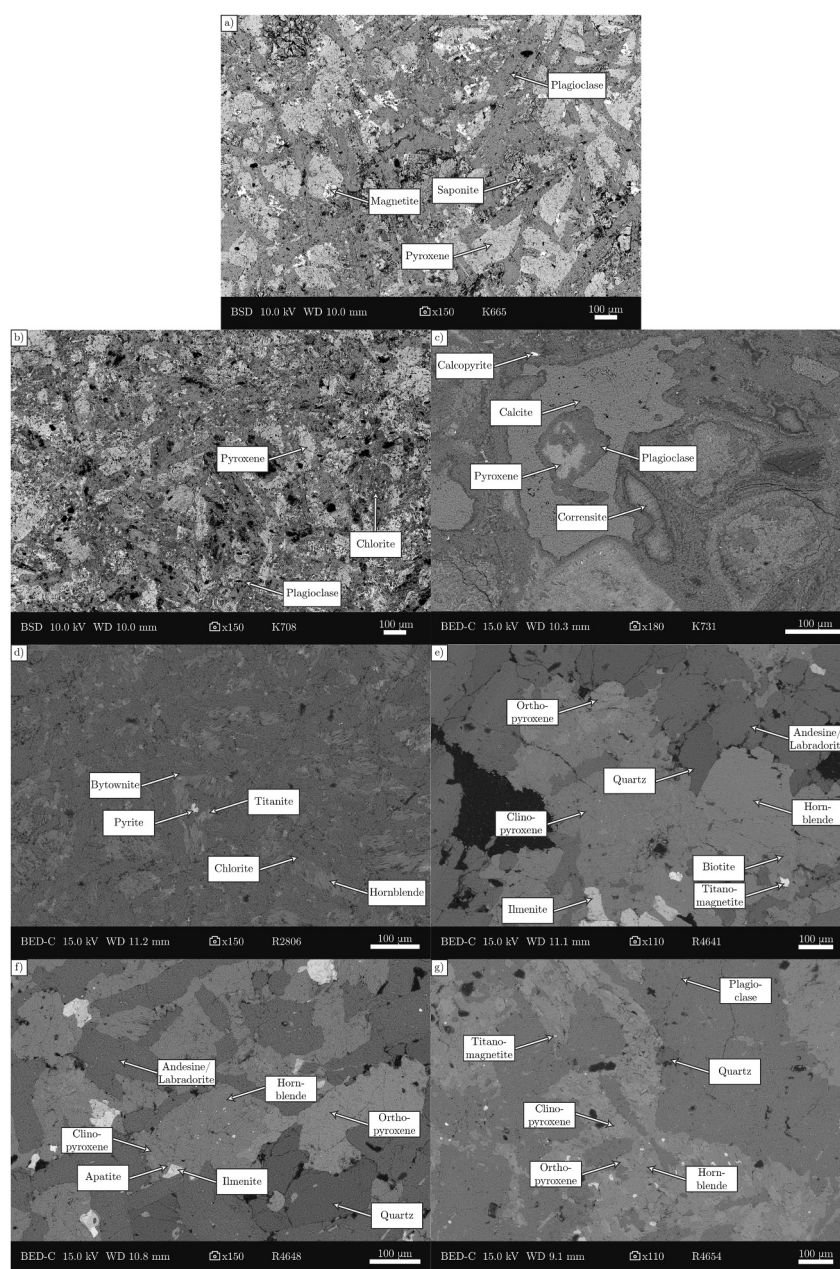


Figure 4. Images of intact samples taken during scanning electron microscope analysis with backscattered electrons, illustrating electron density contrast. Identification of minerals was made using Energy-Dispersive X-ray spectroscopy analysis. (a–c) Shows samples from Krafla and (d–g) shows samples from Reykjanes; specifically, (a) K665, (b) K708, (c) K731, (d) R2806, (e) R4641, (f) R4648, and (g) R4654.

although some diopside may be present for Krafla samples, Table S4 in Supporting Information S1. Finally, orthopyroxenes from Reykjanes are classified as ferrosilite, Table S5 in Supporting Information S1.

4.2. Krafla

4.2.1. Friction Coefficients

All three samples tested from Krafla (K665, K708, K731) have dynamic coefficients ranging from 0.56 to 0.63 in dry conditions. In wet conditions these samples all display water weakening (with water weakening referring here to a water-induced frictional-strength reduction). K665 experiences a reduction of 0.07 and K708 a reduction of

Table 2

A Summary of the Mineral Compositions of Each Sample, Found From X-Ray Powder Diffraction, in Conjunction With Chemical Analyses Performed During Micro Structure Analysis Using Scanning Electron Microscope

Mineral	K665	K708	K731	R2806	R4641	R4648	R4654
Quartz	0.4 ± 0.1	11.3 ± 0.2	1.1 ± 0.2	—	4.1 ± 0.1	4.7 ± 0.1	3.3 ± 0.1
Plagioclase	43.8 ± 1.2	33.8 ± 1.0	23.9 ± 1.1	31.2 ± 1.1	37.2 ± 1.8	40.1 ± 1.3	45.7 ± 2.0
K-spar	3.1 ± 0.2	3.7 ± 0.2	4.1 ± 0.2	—	—	—	—
Amphibole	—	—	1.4 ± 0.1	42.1 ± 0.3	22.9 ± 0.3	32.8 ± 0.4	20.2 ± 0.8
Clinopyroxene	29.3 ± 0.3	17.4 ± 0.4	9.8 ± 0.4	—	11.5 ± 0.4	11.3 ± 0.5	15.3 ± 0.3
Orthopyroxene	—	—	—	—	4.7 ± 0.6	5.0 ± 0.8	10.9 ± 0.7
Clinoptilolite	—	—	1.3 ± 0.2	—	—	—	—
Wairakite	—	—	4.9 ± 0.1	—	—	—	—
Apatite	0.7 ± 0.1	0.4 ± 0.1	—	—	0.7 ± 0.1	1.1 ± 0.2	—
Cristobalite	2.6 ± 0.1	—	—	—	—	—	—
Calcite	0.5 ± 0.1	2.0 ± 0.2	5.1 ± 0.2	—	—	—	—
Hydromagnesite	—	1.2 ± 0.2	—	—	—	—	—
Ilmenite	—	—	—	—	2.8 ± 0.1	3.3 ± 0.1	2.1 ± 0.1
Titanite	—	3.4 ± 0.2	5.3 ± 0.2	3.0 ± 0.2	—	—	—
Titanomagnetite	—	—	—	0.3 ± 0.1	3.0 ± 0.1	0.3 ± 0.1	2.4 ± 0.1
Rutile	—	0.6 ± 0.1	—	—	—	—	—
Magnetite	3.9 ± 0.1	—	0.5 ± 0.1	—	—	—	—
Pyrrhotite	—	0.8 ± 0.1	—	—	—	—	—
Pyrite	—	—	—	0.5 ± 0.1	—	—	—
Mica Diact.	1.1 ± 0.2	—	—	—	—	—	—
Mica Triact.	—	—	—	—	1.2 ± 0.1	1.5 ± 0.5	—
Chlorite	—	13.9 ± 0.7	17.9 ± 1.1	14.1 ± 1.3	—	—	—
2:1 Exp. Triact.	14.5 ± 0.2	11.4 ± 1.4	24.8 ± 1.0	—	—	—	—
Amorphous	<5	<5	—	8.7	11.9	<5	<5

Note. Values are given as weight percentage. Estimated standard deviations provided account only for the covariance of the Rietveld refinement procedure. Absolute errors on phase estimates are ≈ 0.5 wt.% for non-clay phases and ≈ 1 wt.% for clay phases. K-spar, potassium feldspars; diact., dioctahedral; triact., trioctahedral. Note that 2:1 Expandable Trioctahedral (Mg rich) includes discrete smectite, smectite-chlorite interstratifications, and corrensite.

0.11, resulting in wet dynamic friction coefficients between 0.52 and 0.54. K731 experiences significant water weakening, with a reduction of 0.21, resulting in a μ_d^w of 0.35. The coefficients of frictional yield of K665 and K708 exhibit almost no water weakening, with values of 0.26 and 0.32 in dry conditions and 0.24 and 0.29 in wet conditions. K731 has a similar dry coefficient of frictional yield of 0.28, with this value reduced in the presence of water, dropping to 0.21. These data can be found in Table 3.

4.2.2. Velocity Dependence

For Krafla samples, a has median values of 0.0109, 0.0107, and 0.0118 for K665, K708, and K731, respectively. b has median values of 0.0083, 0.0073, and 0.0059 for K665, K708, and K731, respectively. Finally, $a - b$ has median values of 0.0026, 0.0039, and 0.0058 for K665, K708, and K731, respectively.

a is larger in wet conditions when compared to dry conditions for K708, but not for K665 and K731. The value of b is smaller in wet conditions than in dry conditions for all samples; $a - b$ is larger in wet conditions than in dry conditions. Often, a and b both decrease with increasing normal stress. There is frequently no trend in $a - b$ with normal stress. D_c generally increases slightly with increasing normal stress, Figure S2 in Supporting Information S1. For some samples, α increases with increasing normal stress. The values for a and b generally increase with upstep velocity. This is also true for $a - b$ in wet experiments. These data can be seen in Figure 5 and Tables A1, A2, and A3.

Table 3
A Summary of the Friction Coefficients

Rock	μ_y^d (–)	μ_y^w (–)	μ_d^d (–)	μ_d^w (–)
K665	0.26 ± 0.04	0.24 ± 0.03	0.61 ± 0.02	0.54 ± 0.03
K708	0.32 ± 0.03	0.29 ± 0.06	0.63 ± 0.02	0.52 ± 0.02
K731	0.28 ± 0.04	0.21 ± 0.05	0.56 ± 0.06	0.35 ± 0.02
R2806	0.26 ± 0.05	0.32 ± 0.03	0.61 ± 0.01	0.57 ± 0.02
R4641	0.29 ± 0.03	0.21 ± 0.01	0.60 ± 0.01	0.60 ± 0.02
R4648	0.26 ± 0.05	0.27 ± 0.05	0.60 ± 0.01	0.60 ± 0.03
R4654	0.28 ± 0.06	0.22 ± 0.10	0.60 ± 0.01	0.61 ± 0.00

Note. The coefficients of frictional yield for dry and wet conditions are given by μ_y^d and μ_y^w , respectively. The dynamic coefficients of friction for dry and wet conditions are given by μ_d^d and μ_d^w , respectively. Each friction coefficient is based on three separate experiments, each at a given normal stress of either 10, 30, or 50 MPa.

4.2.3. Frictional Healing

Dry Krafla samples exhibit some of the highest healing rates of the rocks tested, with, for example, an average healing rate among the three samples of 0.0094 at 10 MPa. In wet conditions these high healing rates are only slightly reduced for samples K665 and K708. The frictional healing for samples K665 and K708 is generally quite similar; however, K731 shows lower frictional healing, particularly in wet conditions. For example, the difference in healing rate between dry and wet healing rates for samples K665 and K708 is 0.0011 at 10 MPa. Conversely, K731's dry healing rate at 10 MPa is 0.0095; in wet conditions this healing rate is 0.0050, a difference of 0.0045. All samples show a decreasing healing rate with increasing normal stress in both wet and dry conditions. No negative healing rates were observed for any Krafla samples.

The dilation-during-hold rate is generally greater in wet conditions than in dry conditions. In dry conditions it ranges from -0.00084 to -0.00136 , with a median of -0.00100 . In wet conditions it ranges from -0.00084 to -0.00161 , with a median of -0.00116 . The dilation-upon-reshear is approximately the

same in both dry and wet conditions, albeit lower in wet conditions for K731. It ranges from 0.00011 to 0.00035, with a median of 0.00023, in dry conditions and from 0.00005 to 0.00042, with a median of 0.00020, in wet conditions. Additionally, samples generally show greater dilation rates for larger normal stresses in wet conditions; for example, the greatest (most negative) value for B_h at 10 MPa in wet conditions is -0.00107 , while the smallest (least negative) value for B_h at 50 MPa in wet conditions is -0.00144 . A similar trend can be seen for B_s . This trend is also present for dry experiments in B_h . These data can be found in Figures 6a, 6b, 7a, and 7b as well as in Table B1 and Figures S3–S5 in Supporting Information S1.

4.3. Reykjanes

4.3.1. Friction Coefficients

All four samples tested from Reykjanes (R2806, R4641, R4648, and R4654) present dynamic friction coefficients of approximately 0.6 in both dry and wet conditions, implying no water weakening (omitting slight water weakening in R2806). Coefficients of frictional yield range between 0.21 and 0.32, with no clear evidence of water weakening. These data can be found in Table 3.

4.3.2. Velocity Dependence

For Reykjanes samples, a has median values of 0.0071, 0.0078, 0.0077, and 0.0079 for R2806, R4641, R4648, and R4654, respectively. b has median values of 0.0054, 0.0055, 0.0058, and 0.0071 for R2806, R4641, R4648, and R4654, respectively. Finally, $a - b$ has median values of 0.0017, 0.0018, 0.0018, and 0.0009 for R2806, R4641, R4648, and R4654, respectively.

Values of a , b , and $a - b$ are generally larger in wet conditions when compared to dry conditions. D_c increases slightly for wet samples compared to dry samples. a is larger in wet conditions than in dry ones for all samples. Generally, a and b both decrease with increasing normal stress, but $a - b$ increases with increasing normal stress. D_c generally decreases slightly with increasing normal stress, Figure S2 in Supporting Information S1. Commonly, a does not trend with normal stress. The values for a and b generally increase with upstep velocity; however, $a - b$ is fairly independent of this parameter. These data can be seen in Figure 8 and Tables A4–A7.

4.3.3. Frictional Healing

The frictional healing of samples from Reykjanes is generally quite similar between samples. The frictional healing rate, β , observed for samples from Reykjanes is generally higher in wet conditions than in dry conditions, ranging from between 0.0027 and 0.0061 in dry conditions, with a median value of 0.0034, and between 0.0058 and 0.0073 in wet conditions, with a median value of 0.0065. Additionally, the dilation-during-hold, B_h , and the dilation-upon-reshear, B_s rates are also both generally greater in wet conditions than in dry conditions. B_h ranges from between -0.00065 and -0.00108 in dry conditions, with a median value of -0.00083 , and -0.00065 to

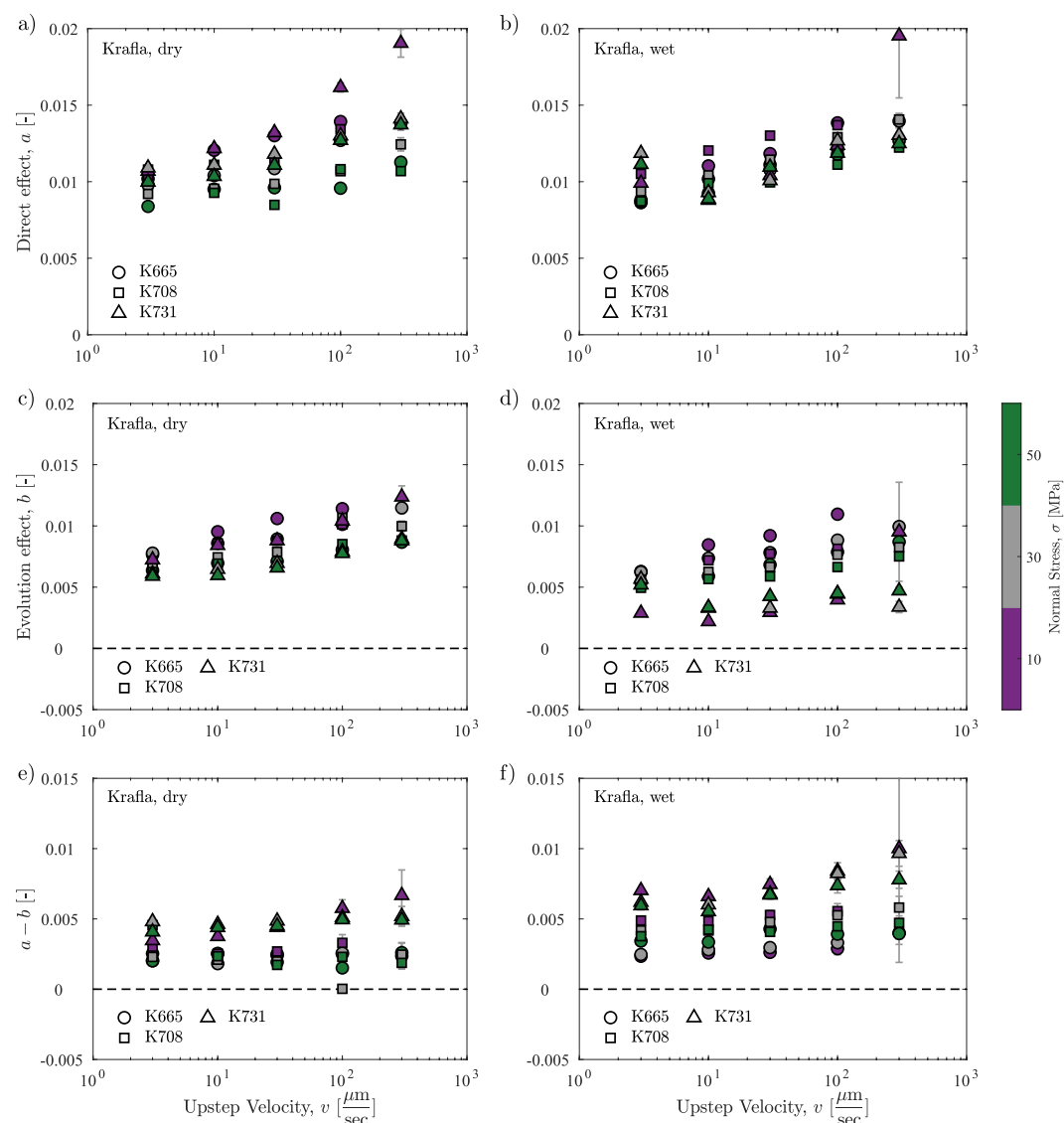


Figure 5. A summary of the velocity steps recorded for samples from Krafla. (a, b) The direct effect, a , (c, d) evolution effect, b , and (e, f) $a - b$ recorded for each experiment for dry (a, c, e) and wet (b, d, f) conditions. Velocity steps where either a or b was found to be above 0.02 were excluded because they were considered to be anomalous values related to difficulties in keeping a constant normal stress at high velocities.

−0.00117 in wet conditions, with a median value of −0.00102. B_s ranges from between 0.00006 and 0.00024 in dry conditions, with a median value of 0.00010, and 0.00012 to 0.00033 in wet conditions, with a median value of 0.00021. Generally, wet samples show no clear trend in healing rate with stress, but a decrease in healing rate with increasing normal stress is observed in R2806 and R4654. No clear trends in dilation rates are seen in these samples with changing stress. These data can be found in Figures 6c, 6d, 7c, and 7d as well as in Table B2 and Figures S6–S8 in Supporting Information S1.

Finally, at 30 and 50 MPa normal stress under dry conditions R4641 and R4648 exhibit negative healing rates for hold times larger than approximately 100 s, Figure 9. These negative healing rates (i.e., the change in healing for a further increase in hold time) translate to actual negative healing (i.e., the total amount of healing compared to the pre-hold apparent friction) for hold times of approximately 1,000 s or larger. In dry conditions, R4641 exhibits negative healing rates, β^{neg} , of −0.0094 and −0.0224 at 30 and 50 MPa, respectively. R4648 exhibits β^{neg} values of −0.146 and −0.254 at 30 and 50 MPa, respectively. While samples R2806 and R4654 do not exhibit negative

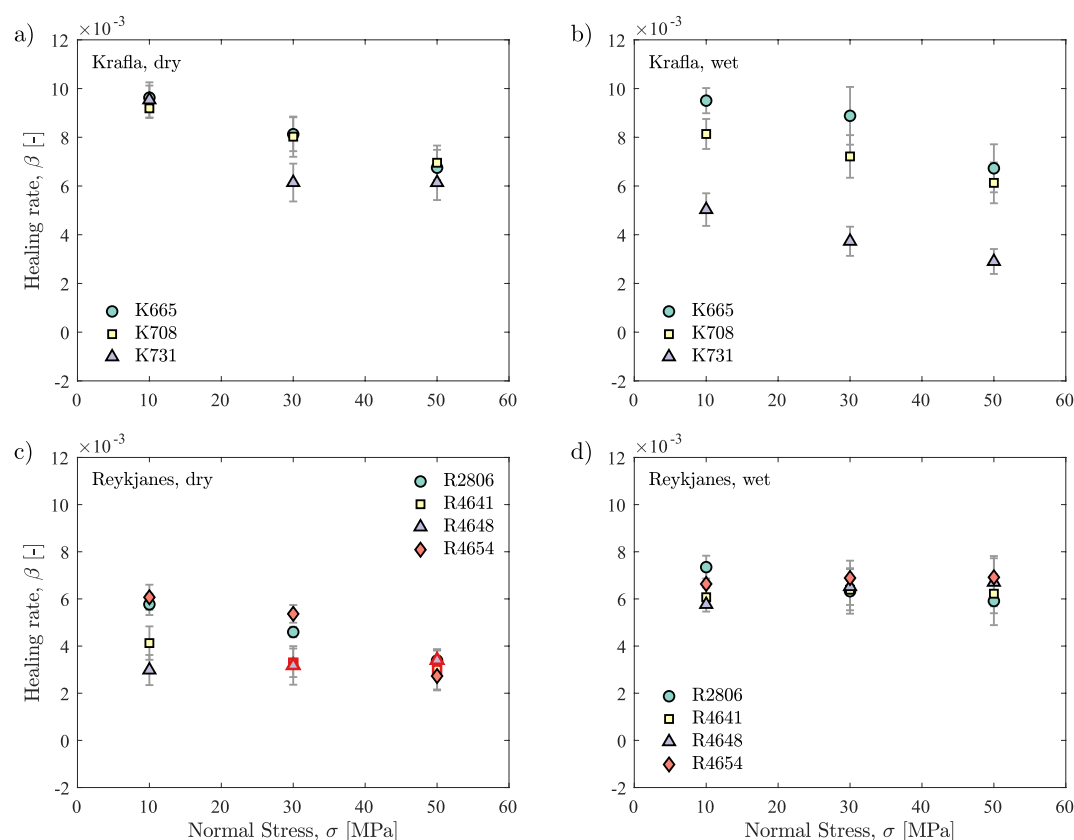


Figure 6. The healing rate, β , recorded for each experiment in dry (a, c) and wet (b, d) conditions. Each region is shown individually, with Krafla (a, b) and Reykjanes (c, d). In the case that the healing becomes negative for large hold times, the data point is outlined in red.

healing, the healing rate for large hold times appears to be becoming negative, suggesting that negative healing rates may become present for hold times larger than 3,000 s. No negative healing rates were observed for any Reykjanes samples under wet conditions. Negative healing will be further discussed in Section 5.1.

4.4. Overall Summary of Friction Coefficients

While measured friction coefficients represent a system response (i.e., there is dependence on the experimental setup), they are informative with regard to the relative strengths of different materials. Here, coefficients of frictional yield have a mean value of approximately 0.279 in dry conditions and 0.251 in wet conditions, with any water weakening that is present generally within the errors of the calculations. The only exception seems to be K731, which has significant and clearly reproducible water weakening for the coefficient of frictional yield. Dry dynamic friction coefficients have values which are typically between 0.60 and 0.61, with the lowest value being 0.56 and the highest 0.63. Dynamic friction coefficients have clear water weakening in the Krafla samples, albeit with water weakening also occurring in the phyllosilicate-containing Reykjanes sample R2806, Figure 10a. All Krafla samples exhibit water weakening of at least 0.07, with the most extreme water weakening seen in K731, a difference of 0.21 or 38%.

4.5. Overall Summary of Velocity Steps

Of the seven samples tested, in four cases a is larger in wet conditions than in dry conditions. In five instances b is larger in wet conditions than in dry conditions. Ultimately, however, $a - b$ is generally larger in wet conditions than in dry conditions for all of the samples, Figure 10b. Regarding the critical slip distance, D_c is often larger (for six out of seven samples) in wet conditions than in dry conditions. Finally, α is larger in wet conditions than in dry conditions for six of the samples.

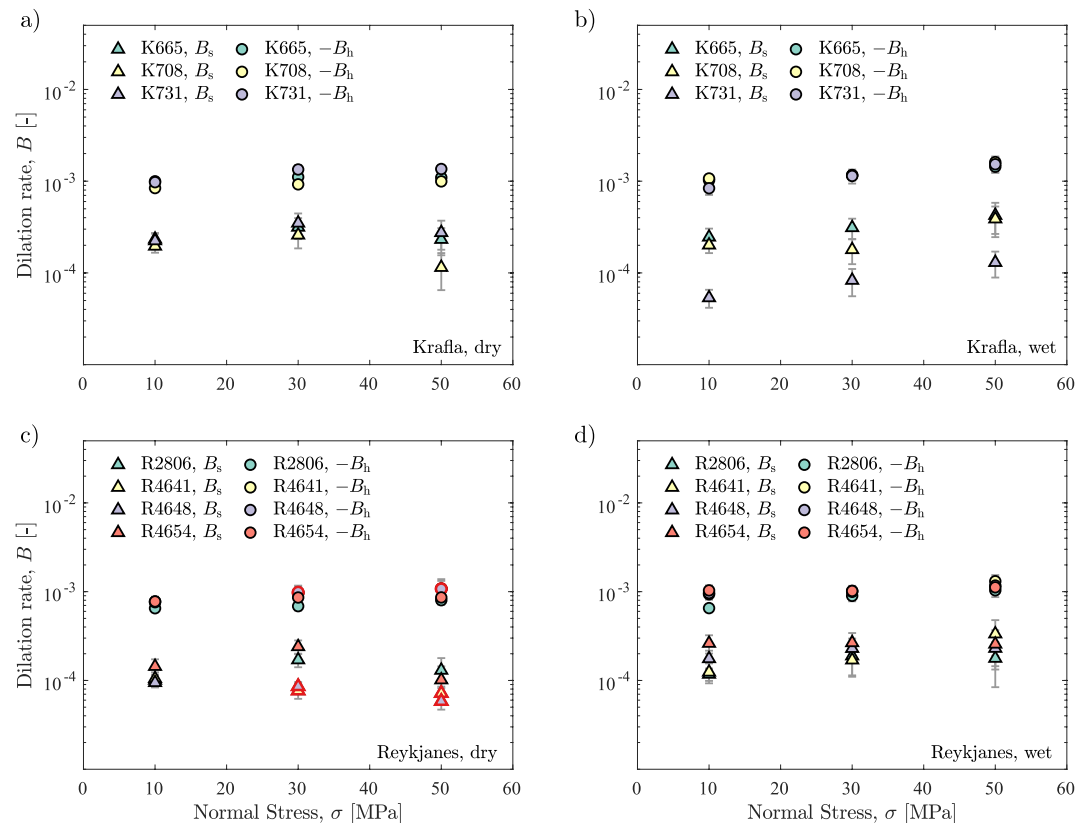


Figure 7. The dilation rates during the holds, B_h , and re-shear, B_s , of a series of slide-hold-slides. Data are shown for experiments performed under dry (a, c) and wet (b, d) conditions. Each region is shown individually, with Krafla (a, b) and Reykjanes (c, d). In the case that the healing becomes negative for large hold times, the data point is outlined in red.

As normal stress increases, a decreases for all but one of the samples. Similarly, b decreases with increasing normal stress for six of the samples. Finally, however, $a - b$ increases with increasing normal stress for three of the samples, decreases for one sample, and displays no clear trend with normal stress for three samples. The critical slip distance decreases with increasing normal stress for two samples, decreases with increasing normal stress for two samples, and displays no clear trend with normal stress for three samples. α increases with increasing normal stress for two samples, decreases for one sample, but displays no clear trend for the other four samples.

4.6. Overall Summary of Frictional Healing

The healing rate does not consistently vary with water presence when all of the samples are taken together; however, increasing phyllosilicate content does result in lower healing rates in wet conditions when compared to dry conditions, Figure 10c. When the healing rate varies with normal stress, most often it decreases as normal stress increases, otherwise it remains approximately constant.

Values for B_h are greater in wet conditions than in dry conditions for almost all of the experiments performed. The values for B_s are also greater in wet conditions compared to wet conditions for Reykjanes samples, but this trend is not clearly present for Krafla samples. For higher normal stresses, B_h is often greater, but this trend is not clearly present for samples from Reykjanes. A similar, but less consistent, trend persists for B_s , particularly in wet conditions.

Finally, negative healing rates were consistently observed in samples R4641 and R4648 in dry conditions for large hold times. These negative healing rates led to negative healing for large hold times, generally at either 1,000 or 3,000 s. An indication that negative healing may begin for larger hold times still was present in R2806 and R4654 in dry conditions.

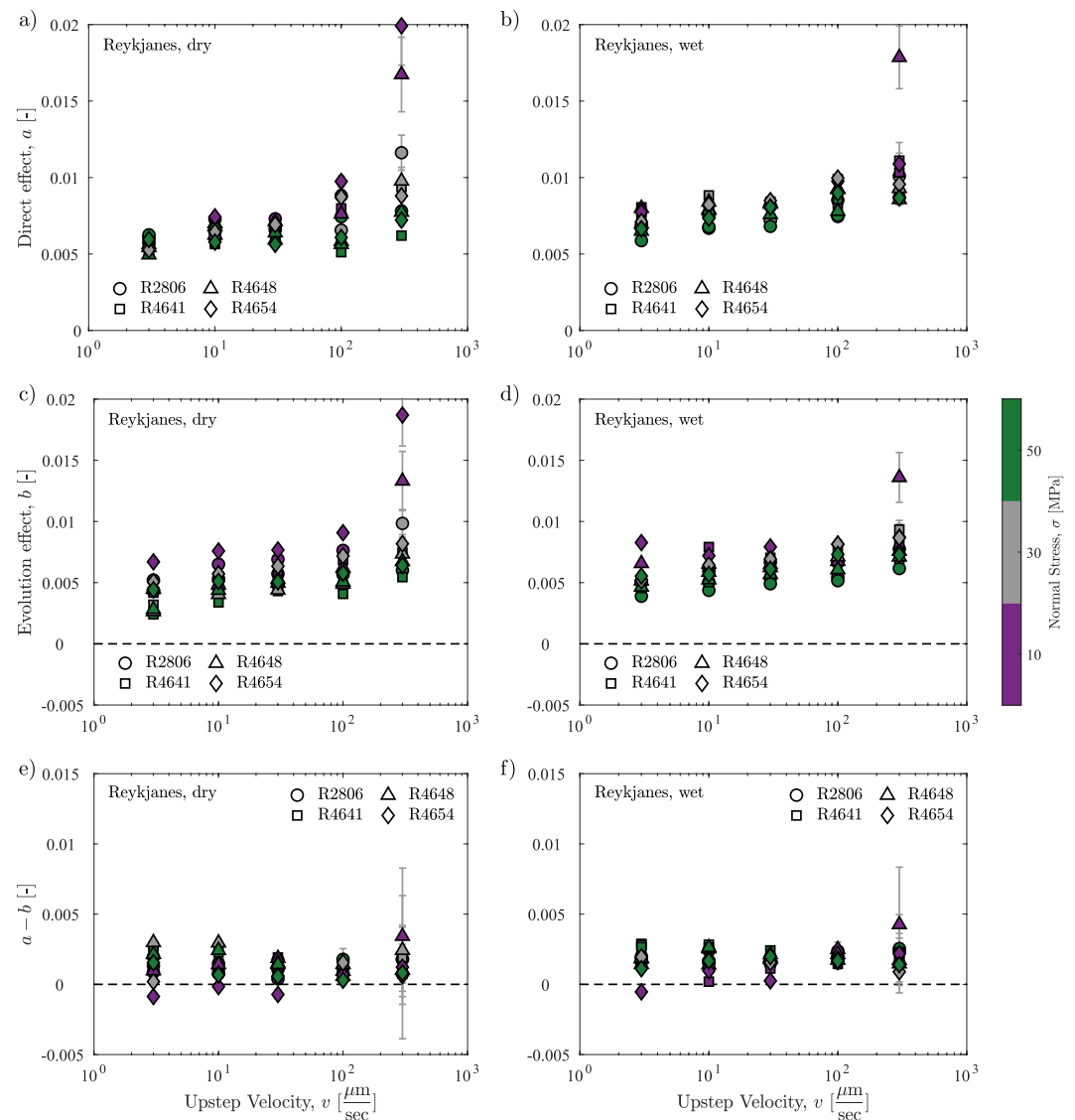


Figure 8. A summary of the velocity steps recorded for samples from Reykjanes. (a, b) The direct effect, a , (c, d) evolution effect, b , and (e, f) $a - b$ recorded for each experiment for dry (a, c, e) and wet (b, d, f) conditions. Velocity steps where either a or b was found to be above 0.02 were excluded because they were considered to be anomalous values related to difficulties in keeping a constant normal stress at high velocities.

4.7. Post-Mortem Microstructure

The post-mortem microstructures of the samples in Figure 11 show fabrics typical of brittle deformation. Significant cataclasis and grain cracking are observed, in particular for samples low in phyllosilicate content. Samples poor in phyllosilicates generally deform in a brittle manner, exhibiting principal shear zones and low-strain domains typical of this deformation (Logan et al., 1992; Volpe et al., 2022), Figures 11c, and 11d. Samples with higher (>20%) phyllosilicate contents exhibit less obvious localization, Figures 11a, and 11b. Further, cataclasis (as well as layer thickness reduction) generally increases in wet conditions. For example, shear in sample R4648 is localized along zones of increased cataclasis measuring less than 100 μm in width in dry conditions, Figure 11c, while the same sample in wet conditions has zones of increased cataclasis measuring over 500 μm in width. In this sense, wet conditions also lead to more distributed, less localized deformation, indicating a shift in the mode of deformation. However, strain localization occurs in all samples.

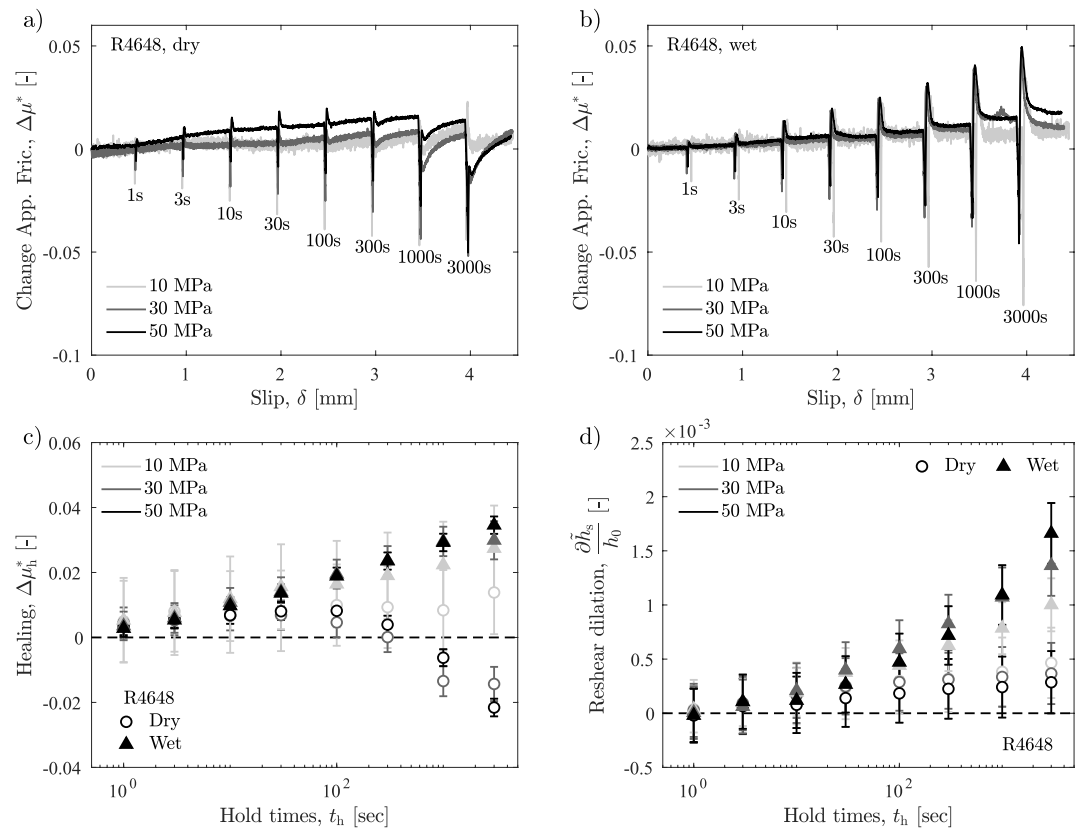


Figure 9. Slide-hold-slides for R4648 in both (a) dry and (b) wet conditions. The length of the hold is written under the minimum value of apparent friction reached during each hold. The (c) healing, $\Delta\mu_h^*$, and (d) dilation upon reshear, $\frac{\partial h_s}{\partial h_0}$, as a function of hold time, t_h , for these cases. R4648 is an amphibole-altered dolerite from IDDP-2. Similar negative healing can be seen in R4641, Figure S7 in Supporting Information S1. R2806 and R4654 begin to potentially exhibit a negative healing rate for holds of 3,000 s; however, longer holds would be required to confirm this trend, Figures S6 and S8 in Supporting Information S1.

5. Discussion

Samples with phyllosilicates all exhibit water weakening, Figure 10, with this water weakening increasing with increasing phyllosilicate content, see Figure S9 in Supporting Information S1. Indeed, the samples with the largest amounts of phyllosilicates have the lowest friction coefficients. These samples also show increased velocity strengthening behavior with increased values of $a - b$, in particular due to a reduction in b , decreased levels of frictional healing (β), and reduced dilation during a velocity step or re-shearing phase of a slide-hold-slide. These trends are in good agreement with those seen in previous work on phyllosilicate-rich gouge regarding frictional strength, velocity dependence, and frictional healing (e.g., Giorgetti et al., 2015; Logan & Rauenzahn, 1987; Summers & Byerlee, 1977; Tesei et al., 2012). The globally velocity strengthening behavior of all the samples is in agreement with the general nature of mid-ocean ridges, which are characterized by aseismic slip and occasional large seismic events (Parnell-Turner et al., 2021). While velocity-strengthening behavior indicates an inability to nucleate a seismic event, unstable slip may occur when perturbations are large (Rice & Ruina, 1983). Further experiments would be required to extrapolate these results to crustal temperatures.

Additionally, increased velocity strengthening behavior and the value of $a - b$ are associated with increased dilation upon a velocity step. The healing occurring during a slide-hold-slide also increases linearly with dilation, with more compaction during a hold and more dilation upon reshear for larger amounts of healing, Figure 12. This trend also holds in terms of rates, such that larger dilation-upon-reshear rates (B_s) correspond to larger healing rates (β), in particular for dry experiments. However, the trend between dilation-upon-hold (B_h) and β is poor to

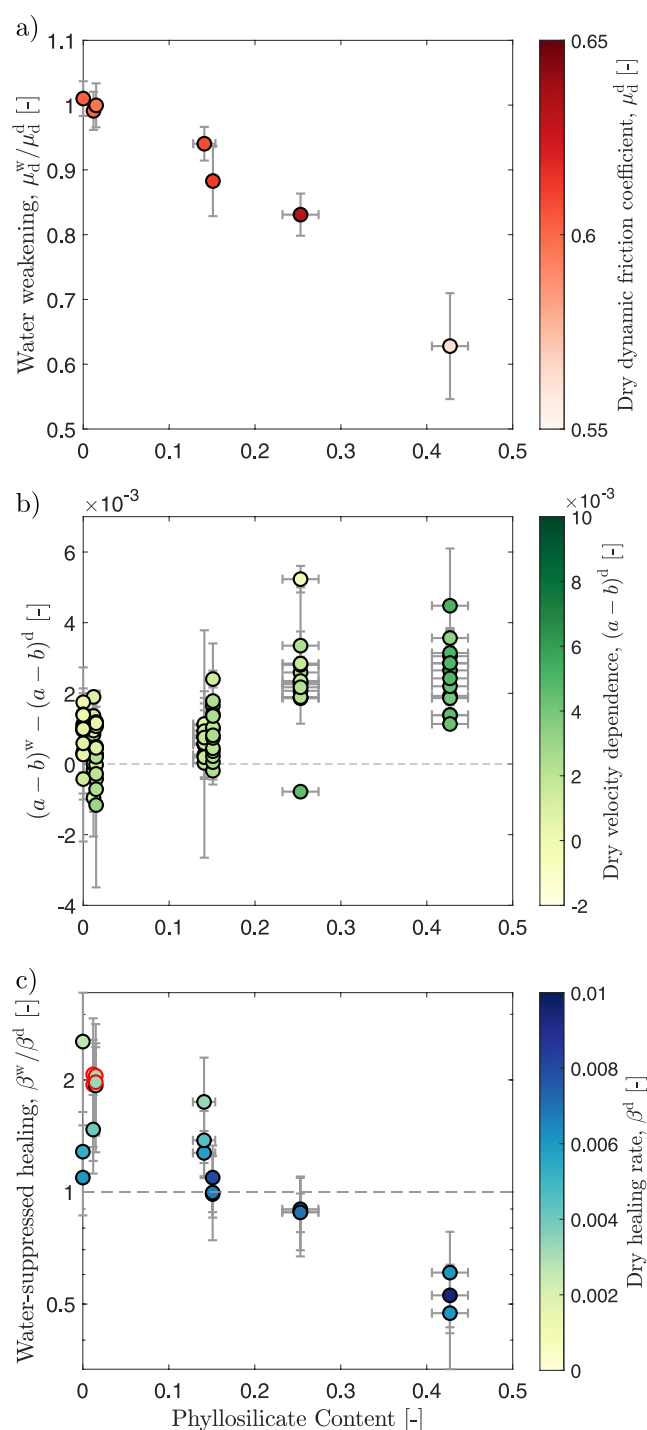


Figure 10. Water's effect on the frictional behavior varies with phyllosilicate content. (a) The water weakening of the dynamic friction coefficient as a function of increasing phyllosilicate content. (b) The tendency for more velocity strengthening behavior in wet samples vs. dry samples increases with increasing phyllosilicate content. (c) The tendency for lower healing rates in wet samples versus dry samples increases with increasing phyllosilicate content. Note that samples with very low phyllosilicate contents (Reykjanes samples) have significant amounts of amphibole minerals (>20%), and are linked to negative healing in dry conditions. Experiments which had clear negative healing rates are outlined in red; in these cases the healing rate is taken for small hold times.

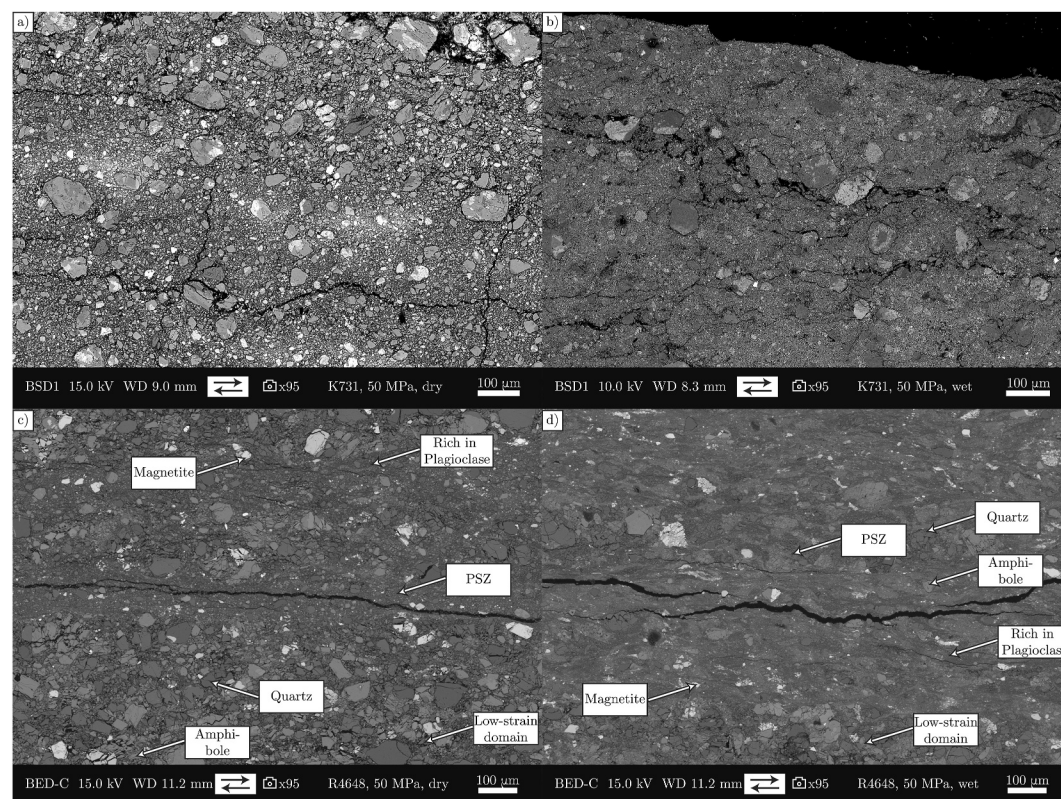


Figure 11. Images of post-mortem samples taken during scanning electron microscope analysis with backscattered electrons, illustrating electron density contrast. All images are deformed at 50 MPa under (a, c) dry conditions and (b, d) wet conditions. Images (a, b) are of K731 and images (c, d) are of R4648. K731 is a hyaloclastite sample which is 42.7% phyllosilicate, 23.9% plagioclase, and 1.4% amphibole by weight. R4648 is a dolerite dike sample which is 1.5% phyllosilicate, 40.1% plagioclase, and 32.8% amphibole by weight. Identification of minerals was made using Energy-Dispersive X-ray spectroscopy analysis. Note that R4648 showed negative healing in dry conditions (c). It should be noted that the part of the thin section near the teeth was often not recovered. Localization often occurs in this part of the gouge, so lack of clear localization in the image does not mean localization did not occur. Arrows represent the direction of shear. PSZ refers to principal shear zone.

non-existent, Figure S10 in Supporting Information S1. This implies that the dilation required to reshear the sample is a stronger control on its strength than its propensity to compact during a hold.

5.1. Negative Frictional Healing

An example of negative healing is shown in Figure 9 for sample R4648. Similar results were found for R4641, Figure S7 in Supporting Information S1. Previously, Tesei et al. (2017) observed negative healing on carbonate bare surfaces, relating it to the formation of new fractures. Yet, negative healing was observed here in gouge material. Orellana et al. (2018) proposed that temporary undrained conditions may be the cause of the negative healing observed in their samples of Opalinus clay fault gouge. Fryer et al. (2025) also observed negative healing in wet conditions, possibly related to the presence of expandable clays. Jeppson et al. (2023) observed negative healing rates only in wet conditions on bare-surface granite samples, and suggested that dissolution and leaching associated with pore fluids may lead to the negative healing observed in their samples, also suggesting that the development of alteration products such as phyllosilicates may lead to the weakening of the fault. Feng et al. (2025) found similar negative healing in feldspar, which was possibly thermally activated, water-assisted and chemical in origin. Contrary to those examples, however, negative healing was observed here only in the dry specimens; the wet samples showed positive healing rates. Pozzi et al. (2023) observed negative healing in magnetite-rich serpentinite gouge in nominally dry conditions. In the current suite of experiments, however, negative healing was observed only in amphibole-rich (>20%) samples with near-zero (<2%) phyllosilicate contents (R4641 and R4648). R4654, which has no measured phyllosilicate content, and R2806, which despite being amphibole and plagioclase rich (42.1% and 31.2% by weight, respectively) also contains approximately

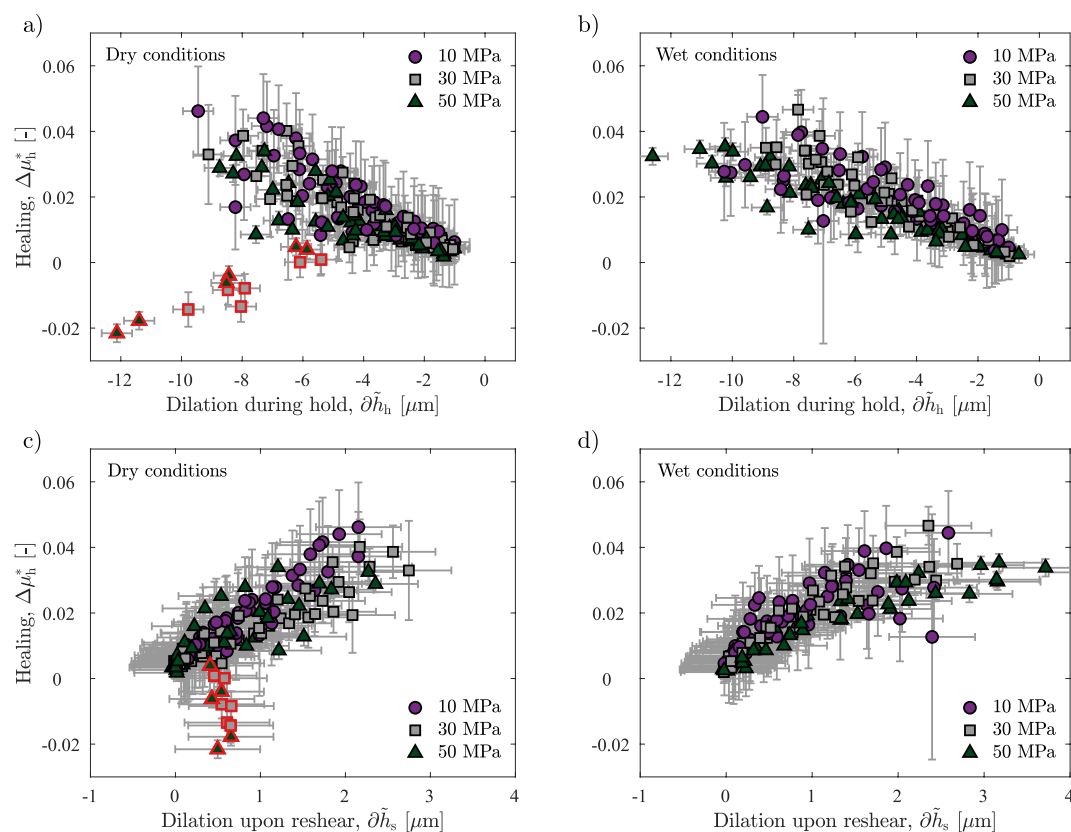


Figure 12. The healing of a given slide-hold-slide as a function of the dilation during the hold (a, b) and the dilation upon reshear (c, d). Results from both dry (a, c) and wet (b, d) conditions are shown. Data points outlined in red exhibited either a negative healing rate or negative healing. In the case of negative healing, the gouge still compacts during the hold, (a) and Figure S11a and S11b in Supporting Information S1, but dilation required during reshear is an approximately constant low value around 0.5 μm , (c), Figure 9d, and Figure S11c in Supporting Information S1. Negative healing occurs only in dry conditions here. When negative healing does not occur, the healing generally scales with the dilation during the hold and the dilation during reshear, with both wet and dry conditions showing similar results.

14% chlorite, both also presented a concave down frictional healing versus logarithm of time trend in dry conditions, but at the hold times tested no negative healing was observed. Note that R4654 has less amphibole than R4641 and R4648 (20.8% vs. 22.9% and 32.8% by weight, respectively). Sample R4648 was also retested, inverting the order of the holds to test for strain dependence (e.g., Noël et al., 2024), Figure S12 in Supporting Information S1. However, negative healing was still observed and still only for large hold times. Further tests include changing the sample thickness and initial grain size, Figures S13 and S14 in Supporting Information S1. Additionally, the possibility of mineral alteration during the experiment was also evaluated with post-mortem XRD analyses, but no mineral alteration was observed, Figure S15 and Table S6 in Supporting Information S1.

The four Reykjanes samples are rich in amphibole. Amphibole is comprised of crystals with anisotropic dimensions which contain cleavage planes (e.g., Fagereng & Ikari, 2020; Hacker & Christie, 1990). The frictional healing of gouge and wafer samples composed of pure amphibole has been tested (Tesei et al., 2012). These authors noted the generally high frictional strength of these samples compared to phyllosilicate-rich rock and concluded that the preferred orientation of the amphibole's foliations could not induce frictional weakening without the presence of phyllosilicate. However, they also interpreted that the preferred orientations of amphibole fibers in solid-rock samples results in initially larger contact area and therefore reduced ability for asperity expansion during slide-hold-slide holds, which in turn results in reduced healing rates. Marked weakening has been observed in amphibole due to dislocation creep (Wang et al., 2023) and unknown mechanisms (Hacker & Christie, 1990).

Single amphibole crystals have shown considerable strength anisotropy in the laboratory. For example, Hacker and Christie (1990) demonstrated strength anisotropy related to slip-system activity under crystal-plastic conditions. The lineation of larger amphibolite samples has also been invoked to explain strength anisotropy (Hacker & Christie, 1990). Indeed, amphibole-rich rocks deformed both in the laboratory (Getsinger & Hirth, 2014; Kim & Jung, 2019; Ko & Jung, 2015; Tokle et al., 2023; Wang et al., 2023) and in nature (Allison & La Tour, 1977; Babaie & La Tour, 1994; Berger & Stünitz, 1996; Díaz Aspiroz et al., 2007; Elyaszadeh et al., 2018; Giuntoli et al., 2018; Imon et al., 2004; Nyman et al., 1992; Tatham et al., 2008) have been shown to exhibit crystallographic- (or equivalently lattice-) or shape-preferred orientation (CPO, LPO, and SPO, respectively). For example, type-I CPO, a CPO whereby the [001] axis aligns sub-parallel to the shear direction (e.g., Ko & Jung, 2015, p. 4), is commonly observed in naturally deformed amphibolites (e.g., Berger & Stünitz, 1996; Díaz Aspiroz et al., 2007; Tatham et al., 2008), with further references in Ko and Jung (2015), Kim and Jung (2019). However, these observations relate to plastic deformation occurring in very different pressure and temperature conditions than those reproduced here where cataclastic deformation dominates.

It is possible that SPO and/or CPO of amphibole grains is able to develop during extended hold periods during dry experiments due to rigid body rotation, leading to progressive weakening in amphibole-rich rocks, potentially through slip on now well-oriented cleavage planes (e.g., Tewksbury-Christie, C., 2021). To investigate this possibility two new deformation experiments were performed following the same procedure as that which led to negative frictional healing in dry conditions (R4648, 50 MPa, dry and wet conditions), but the samples were unloaded prior to the final reshearing phase. The deformed samples were recovered and a thin section prepared. Electron Backscatter Diffraction (EBSD) was performed on multiple low-strain domains and principal shear zones, Figures 13a and 13b, Figures S16–S19 in Supporting Information S1.

The analyses reveal SPO development in amphibole grains in the principal shear zones of both of the post-mortem samples in the macroscopic direction of shear to a similar degree, Figures 13e and 13f. Consistent with this measurement, amphibole crystal orientations for the [001] hornblende axis (its long axis) of both samples in the principal shear zone display a preferred orientation, tilted approximately 45° from the macroscopic direction of shear, Figures 13c and 13d. The cleavage planes of amphibole (110) also display a preferred orientation for both dry and wet post-mortem samples in the principal shear zones. However, this preferred orientation differs between dry and wet experiments. The dry experiment resulted in the poles to the (110) planes being oriented at approximately 45° from the macroscopic normal load, tilted toward the applied shear load, Figure 13c. The wet experiments, on the other hand, resulted in the poles to the (110) planes being oriented approximately perpendicular to both the applied macroscopic normal and shear loads, Figure 13d. The low strain domains show a reduced SPO and CPO, Figure S18 in Supporting Information S1. The pole figures are one-point-per-grain, with 3,932 and 3,235 grains in the low strain domain and boundary shear band, respectively, for the dry sample and 3,278 and 1,785 grains for the wet sample. Values of multiples of the uniform distribution (MUD) of approximately 2.5 are present in the low-strain domain and principal shear zones for amphibole. Additionally, the M-index (Skemer et al., 2005) was also calculated, showing values of 6e–5 and 0.006 in the principal shear zones of the dry and wet samples, respectively, Figure S20 in Supporting Information S1. Note that this must be classified as a weak CPO, in particular for the dry sample where the CPO is very weak, despite the large number of grains used in the analyses (between 1,785 and 3,932). Importantly, although weak in absolute terms, the dry sample's amphibole crystals are mechanically more favorable for shear along cleavage planes than the wet sample's (even if only considering the wet sample's CPO as significant). Further while the CPO observed in these short-duration, room-temperature experiments is weak, it may represent a lower-bound analog of the stronger CPO documented in naturally deformed hornblende-rich rocks (e.g., Tatham et al., 2008), such that the mechanisms observed in the lab could be amplified under natural conditions. Further research is required to explore the potential development of CPO during seismic stasis and its possible connection to negative frictional healing.

While it is not conclusive that the weak CPO which developed during the dry experiments is responsible for the negative healing, the difference in CPO resulting from wet experiments is intriguing. This is particularly true considering the similar SPO present in both cases, such that it is unlikely that SPO alone explains the weakening. Note, however, that it is not likely that crystal plasticity is active at these conditions considering the low (50 MPa) normal stress, lack of confining stress, and ambient temperature conditions. Additionally, while plagioclase is also present in large quantities in these samples, it does not develop CPO during these experiments, Figure S19 in Supporting Information S1. Further, while SPO does develop in plagioclase in the dry experiments, it also does so in the wet experiments, Figure S19 in Supporting Information S1, meaning plagioclase is unlikely to be

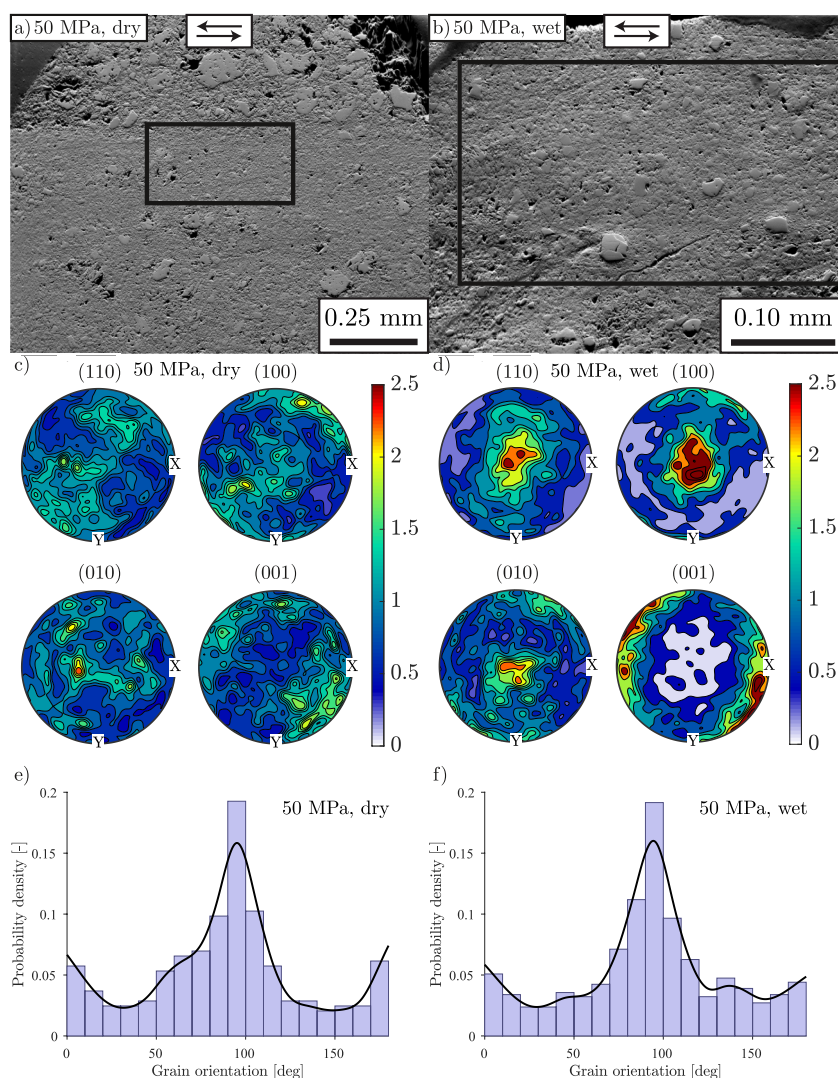


Figure 13. CPO in amphibole grains and its connection to negative healing. Electron Backscatter Diffraction (EBSD) analyses for sample R4648 at 50 MPa under (a, c, e) dry and (b, d, f) wet conditions. This sample exhibits negative healing in dry conditions, Figure 9. For these analyses, the samples were unloaded prior to the final reshear (but after the final 3,000 s hold). (a, b) Forward scatter detector images of indicating the zones of interest, both principal shear zones. (c, d) The pole figures resulting from EBSD analyses on amphibole (hornblende). One point per grain is used, and the values are displayed in multiples of the uniform distribution (MUD). Note that in (c, d) the cleavage planes of amphibole are represented by the (110) pole figures. The long axis of amphibole is represented by the (001) plane, such that large values of MUD on this pole figure indicate that the long [001] axis of amphibole is oriented in this direction. (e, f) The SPO of amphibole minerals in these samples. The macroscopic shear direction is represented by 90°. (c–f) These results represent a stack from the zones shown in the forward scatter detector images (a, b) as well as additional comparable zones, for example, Figure S17 in Supporting Information S1. 3,235 and 1,785 grains were used in (c, e) and (d, f), respectively. The EBSD maps, which provide information on indexing rates, are given in Figure S16 in Supporting Information S1.

responsible for the observed negative healing. Note, however, that feldspar has recently been linked to negative healing in hydrothermal conditions (Feng et al., 2025).

As far as why the CPO differs between the dry and wet experiments, it is interesting to note the differences in the post-mortem microstructures, Figures 11c and 11d. In dry conditions, an increased level of cataclasis has occurred along relatively narrow (100 μm) zones, centered around principal shear zones. In wet conditions this zone is much wider (500 μm or more) and covers nearly the entire sample fabric. These differences in cataclasis are related to the increased tendency for localization in dry experiments. More cataclasis is commonly observed in wet as opposed to dry experiments, even for samples which do not exhibit negative healing; for example,

Figures 11a and 11b. This may occur due to water weakening on the grain scale (here water weakening is taken to mean a reduction in both mode-I fracture toughness and frictional strength; see Noël et al. (2021) for water weakening in both parameters for sandstones). One possible explanation for the lack of negative healing in wet experiments is therefore that the compaction occurring during a given hold is distributed more broadly throughout these larger zones of increased cataclasis. This would mean that in dry samples this zone of increased cataclasis experiences a much higher compactant strain than the same zone in a wet sample. If crystals require a certain amount of compactant strain in order to properly rotate, as previously indicated (e.g., Tatham et al., 2008, p. 124), and weaken the fault fabric, it may be that this negative healing will also be present in wet samples, but for much larger macroscopic strains or hold times. If this is the case, it is possible that this mechanism could also operate in wet fault gouge on geologic time scales. In order to test this hypothesis, further experiments could be carried out at higher normal stresses for longer hold times. Additionally, a lower shear stress could be manually applied to the gouge during holds using stress- as opposed to position-control. Note, however, that hold times up to 10^5 seconds did not show evidence of negative healing in wet conditions for this laboratory setting, Figure S21 in Supporting Information S1.

Many layered minerals (such as chlorite, talc, and lizardite among other phyllosilicates) have been shown to be frictionally weak (e.g., Summers & Byerlee, 1977), with this weakness attributed to the reorientation of platy minerals in the direction of shear (Moore & Lockner, 2004). Shear in these cases then occurs through the breaking of inter-layer bonds, forming new cleavage surfaces, with a correlation between frictional strength and the electrostatic separation energy (Moore & Lockner, 2004). While amphiboles are not layered minerals, they possess cleavage planes. As discussed above, preferential shearing along these easy-slip planes following their reorientation sub-parallel to the direction of shear is a possible explanation for the progressive frictional weakening observed here. This is only evident when the inter-layer bond strength is weak (and when the mineral fabric is able to optimally orient itself with respect to the local stress field), otherwise more energy is required to slip along these well-oriented boundaries than to initiate other frictional processes which then dominate shear. This explains why R2806 showed less negative healing—it contains a significant amount of chlorite, which is frictionally weak and thus monopolizes slip. It is potentially for this reason that other workers have observed amphibole to be frictionally strong (Fagereng & Ikari, 2020; Tesei et al., 2012), as CPO was not able to sufficiently or appropriately develop in their testing conditions.

In summary, it seems that the negative healing may be attributable to a developing CPO, which may result from grain rotation. This CPO is very weak, but develops with the (110) planes oriented at approximately 45° to the applied normal and shear loads making them more optimally oriented for shear. In the wet samples, which do not develop weakness for long holds, while the CPO is stronger, the (110) planes are parallel to both of the applied loads and therefore not optimally oriented for shear. These observations indicate that CPO development may play a contributory role in the observed behavior, but they may not uniquely explain the occurrence of negative healing. Additional processes, including grain-scale damage, cataclasis, and fluid-assisted effects, are likely also important. Further experimental constraints are therefore required to isolate the mechanisms responsible for the observed weakening.

5.2. Implications

5.2.1. Weakening Along Slow-Spreading Mid-Ocean Ridges

At slow- and ultra-slow-spreading ridges, large-offset normal faults, also known as detachment faults, are responsible for the exhumation of mantle-derived ultra-mafic rocks and act as an explanation of the presence of mantle material on the ocean floor in these regions where a limited magma supply is not sufficient to do so (Cannat, 1993). These faults are typically, but not always (Escartín et al., 2003), thought to root in or around the brittle-ductile transition (e.g., Bickert et al., 2021; Cannat et al., 1991; Picazo et al., 2012; Tucholke et al., 1998). The precise origin of detachment faulting is not completely clear; however, it is generally believed that their development begins with the plastic to semi-brittle deformation of peridotite, likely through dynamic recrystallization and grain size reduction, prior to the onset of mineral alteration (Bickert et al., 2020, 2021; Cannat et al., 1992; Karson et al., 2006; Schroeder & John, 2004; Vieira Duarte et al., 2020). This deformation is likely anhydrous, occurring at temperatures above 800°C (Karson et al., 2006; Picazo et al., 2012). However, it facilitates gabbroic intrusions, in particular at locations where peridotite is entering the brittle lithosphere (Picazo

et al., 2012). The ongoing deformation allows for fluid penetration, which, enabled by the presence of the gabbroic intrusions, then results in the formation of amphibole minerals as alteration products (Albers et al., 2019; Bickert et al., 2021; Boschi et al., 2006; Karson et al., 2006; Picazo et al., 2012; Vieira Duarte et al., 2020). These amphibole minerals may form and deform under conditions which present temperatures too elevated for the initiation of serpentinization ($>400^{\circ}\text{C}$) (Albers et al., 2019; Bickert et al., 2023; Evans, 2004; Picazo et al., 2012; Vieira Duarte et al., 2020) and which are not suitable for the formation of talc (low water-to-rock ratio) (Albers et al., 2019). Chlorite may be present and is frictionally weak (e.g., K708, K731) but is not always present (e.g., R4641, R4648, R4654). These amphibole- and, often, talc- and/or chlorite-containing regions then act to localize deformation in discrete shear zones (Boschi et al., 2006; Cannat et al., 1991, 1992; Picazo et al., 2012). These shear zones have been thought to deform in a plastic to semi-brittle manner, and allow for large strains and an increased supply of seawater to the shear zone (Cannat et al., 1991; Picazo et al., 2012). This ultimately leads to the serpentinization of (partially) exhumed mantle material at lower temperatures, which acts to further weaken the fault and results in large along-fault displacement and an increased supply of seawater (Escartín et al., 1997a, 1997b; Karson et al., 2006; Picazo et al., 2012).

Generally, modeling investigations which attempt to understand and recreate the characteristics of detachment faults, such as their shallowing dip angle with decreasing depth, consider, initially, the plastic deformation occurring at the root of the fault and, later, the brittle deformation occurring at shallower depths where the serpentinization of mantle material has resulted in the formation of weak phyllosilicate minerals such as lizardite (Bickert et al., 2020). It has been pointed out, however, that there is likely at least one additional intermediate weakening mechanism responsible for the structure of detachment faults (Bickert et al., 2020, 2021; Cannat et al., 1992). It has additionally been suggested that the formation of amphibole shear zones may provide this mechanism (Bickert et al., 2020; Boschi et al., 2006; Cannat et al., 1992), and indeed amphiboles have been observed in numerous shear zones along detachment faults (Albers et al., 2019; Boschi et al., 2006; Escartín et al., 2003; Picazo et al., 2012; Schroeder & John, 2004). However, at least from a frictional standpoint, amphiboles are generally considered to be strong (Fagereng & Ikari, 2020; Tesei et al., 2012), agreeing with Byerlee's law for rocks composed of limited amounts of clay material (Byerlee, 1978).

Evidence has been provided here that the reorientation of amphibole crystals during periods when shear deformation is not occurring (or occurring at a very low rate) may result in a transient weakening of the rock mass. This phenomenon may act as a mechanism which weakens and localizes deformation along the base of detachment faults in mid-ocean ridge settings, Figure 14. Further, as this mechanism weakens the fault in the direction perpendicular to the maximum principal stress, it would encourage the development of a lower angle in detachment faults, since the maximum principal stress is vertical in these settings. While the total amount of accumulated weakening is relatively small (e.g., after a 3,000 s hold, R4648 at 50 MPa in dry conditions had a healing of $\Delta\mu_h^* = -0.02$), the negative healing rates are significant (for this experiment $\beta^{\text{neg}} \approx -0.025$) and the experiments performed here are limited to a human time scale. If this healing rate were to hold for 1 year, it would yield $\Delta\mu_h^* \approx -0.12$; over 1,000 years it would yield $\Delta\mu_h^* \approx -0.20$. It is likely that negative healing does not continue without bounds; however, the CPO present after the dry experiments is still weak and may be able to develop further, potentially resulting in the strong CPO seen in some natural samples (e.g., Tatham et al., 2008); meaning it might be possible that negative healing is capable of producing strength reductions on the order of those associated with, for example, the presence of phyllosilicates (Escartín et al., 1997a, 1997b). Further investigation is required to assess the potential magnitude of weakening on geologic time scales.

The addition of a weakening mechanism, in between the zones of ductile deformation where grain size reduction plays a large role and brittle deformation where the formation of phyllosilicate minerals can significantly weaken a fault, may have a significant influence on either the stabilization of an existing and/or the initiation of a new detachment fault (Bickert et al., 2020). However, it should be emphasized that, while it is very possible that this negative healing mechanism would be present in wet conditions for the reasons outlined in Section 5.1, here negative healing was only observed in dry conditions. It remains to be tested whether similar processes could become active in water-saturated conditions over longer timescales such as relevant for this setting.

Finally, amphibole shear zones have been reported to deform plastically (Albers et al., 2019; Boschi et al., 2006; Picazo et al., 2012), and the high temperatures relevant for the detachment fault setting may call into question the relevance of friction experiments performed at room temperature. However, amphiboles are considered,

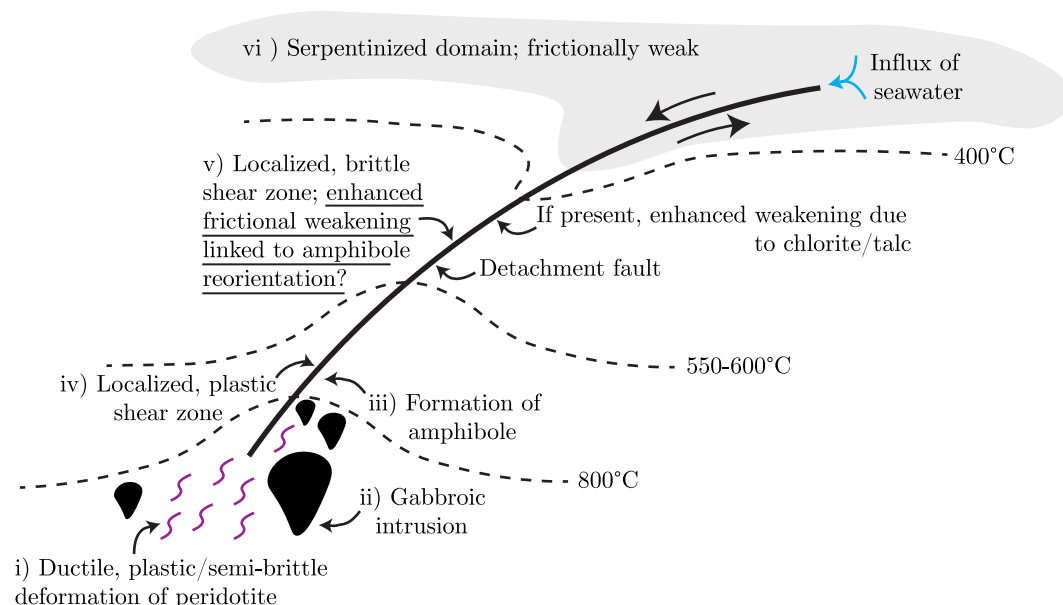


Figure 14. An example schematic of a detachment fault along a slow-spreading mid-ocean ridge. (i) Initial ductile, plastic or semi-brittle deformation in peridotite at the base of the future detachment fault results in grain-size reduction and weakening. (ii) The weakening allows for the intrusion of gabbroic bodies. (iii) The ongoing semi-brittle deformation allows for some water influx. The combination of water, peridotite, and gabbro allows for the formation of amphiboles through mineral alteration. (iv) The localized deformation of amphibole at high temperatures results in the formation of plastic or semi-brittle shear zones, with grain cracking in olivine and pyroxene grains and plastic deformation in amphibole. (v) At moderate to high temperatures, amphibole deformation is localized and brittle. As shown in this work, amphibole crystal reorientation may result in time-dependent frictional weakening which may help to explain the morphology of detachment faults. Talc and chlorite may provide additional weakening in this zone. (vi) Below approximately 400°C, serpentinization of partially exhumed mantle material can occur, resulting in further weakening of the detachment fault through the formation of lizardite. Antigorite forms at higher temperatures but is frictionally strong. Serpentinization results in increased brittle deformation and an enhanced influx of seawater. Note that temperatures are approximate and the illustration is not to scale. See text for details and references.

depending on strain rate, to undergo brittle deformation in amphibolite facies conditions up to temperatures of 600–750°C (Berger & Stünitz, 1996; Brodie & Rutter, 1985; Hacker & Christie, 1990; Imon et al., 2004; Kim & Jung, 2019; Ko & Jung, 2015; Lafrance & Vernon, 1993), leaving at least a 200°C window between the onset of plastic deformation in amphiboles and the onset of the phyllosilicate-forming serpentinization at 350–400°C (Evans, 2004). Indeed, strain along amphibole shear zones related to detachment faulting has also been reported as highly localized (Boschi et al., 2006), semi-brittle (Picazo et al., 2012; Schroeder & John, 2004), or even brittle (Albers et al., 2019). Cataclasis, an inherently brittle process, has also been observed in detachment-fault amphiboles on numerous occasions (Albers et al., 2019; Escartín et al., 2003) and is expected even in high-grade metamorphic conditions for amphibole-rich rocks (Brodie & Rutter, 1985). Amphibole-rich rocks at temperatures of approximately 500°C are generally considered to initially deform by cataclasis and fracturing before then deforming by dissolution-precipitation creep (Berger & Stünitz, 1996; Brodie & Rutter, 1985; Giuntoli et al., 2018; Imon et al., 2004; Lafrance & Vernon, 1993; Nyman et al., 1992), where dissolution-precipitation can be considered a “plastic” process (Rutter, 1986). Indeed, amphiboles have been shown to be capable of developing type-I CPO in conjunction with brittle deformation at temperatures up to 600°C (Ko & Jung, 2015). Further, rocks deformed under these conditions may appear macroscopically ductile while the dominant deformation mechanism is actually microscopic brittle deformation (e.g., Kim & Jung, 2019, p. 13,001). Crystal plasticity is not considered to be relevant for amphiboles deformed in amphibolite facies conditions (at least to 600°C) (Berger & Stünitz, 1996; Brodie & Rutter, 1985), in particular when contained within a matrix comprised of weaker minerals (e.g., Ildefonse et al., 1990). Yet, even in situations where deformation is principally plastic, the frictional strength of a rock likely places bounds on its strength (Meyer et al., 2019; Meyer & Violay, 2023). While the experiments performed here demonstrate one mechanism by which amphibole-rich rock may be

mechanically weak, further studies on these minerals under high-temperature, high-pressure conditions should be performed to further constrain their rheologies in conditions relevant for detachment faulting, expanding on previous investigations (e.g., Baïssat et al., 2024; Brodie & Rutter, 1985; Getsinger & Hirth, 2014; Hacker & Christie, 1990; Kim & Jung, 2019; Ko & Jung, 2015; Park et al., 2020; Tullis & Yund, 1980, 1987; Wang et al., 2023).

5.2.2. Alteration Zones and Geothermal Energy

The alteration of mafic rock in settings such as Reykjanes and Krafla may result in a number of alteration products depending upon, in particular, the temperature at which the alteration occurred. For example, at low temperatures (100°C–200°C) zeolites and smectites are the dominant alteration minerals which form (Kristmannsdóttir, 1975, 1979). At approximately 200°C smectite-chlorite interstratification forms, with discrete chlorite becoming dominant above 230°C (Kristmannsdóttir, 1975, 1979). At slightly higher temperatures, and often associated with chlorite, epidote and prehnite form (Kristmannsdóttir, 1979). Various forms of amphibole may result from alteration at still higher temperatures (Zierenberg et al., 2021). Here, it has been demonstrated that the phyllosilicate-rich zones containing smectite and chlorite will be frictionally weaker than the amphibole-rich zones, Figure 10a. In wet conditions, they will further be more velocity-strengthening and have reduced frictional healing compared to dry conditions. However, the amphibole-rich zones are liable to exhibit negative frictional healing during large periods of seismic stasis, resulting in transient weakness.

Considering its location on an active spreading axis and consistent seismic activity (e.g., Mortensen et al., 2015), it is not unreasonable to assume that the Krafla geothermal system, for example, will contain faults which are critically stressed. The results here imply that the higher the level of alteration and the higher the percentage of phyllosilicate content along the fault, the weaker the fault will be. In a normal faulting stress regime where the vertical stress is given by the lithostatic gradient, this implies that the minimum horizontal stress (the minimum principal stress in this case) will be *larger* in zones which are heavily altered than in zones where alteration is not as severe. In Krafla, these heavily altered zones are thought to act as clay caps, with the productive reservoir zones being found in faults and fractures in between these zones (e.g., Ármannsson et al., 1987, 2014; Mortensen et al., 2015). This implies that there may exist a stress jump between the clay caps and the productive reservoir zones, similar to those seen in sedimentary basins (e.g., Lucier et al., 2006; Teufel, 1989; Wileveau et al., 2007) and suggested for mid-ocean ridges due to serpentinization (Escartín et al., 1997a, 1997b). Stress jumps such as these have implications (e.g., Adachi et al., 2010; Gao & Rice, 1989) for the propagation and potential containment of any thermally induced fractures which may propagate due to cooling of the reservoir. A similar, but larger-scale reduction in the minimum principal stress can be expected with increasing temperature as the dominant alteration product changes from chlorite to epidote and amphibole. Amphibole has been shown here and elsewhere (Fagereng & Ikari, 2020) to be frictionally strong, albeit presenting negative frictional healing for faults which are stuck for large periods of time. Epidote has also been shown by Fagereng and Ikari (2020) to be frictionally strong. Based on the above, a generic profile of a geothermal system along a mid-ocean ridge is given in Figure 15.

6. Conclusion

Core samples have been collected from the Krafla and Reykjanes geothermal systems, allowing for the study of the effect of alteration on the frictional properties of basic rocks. It has been shown that the presence of phyllosilicate minerals enables water to reduce frictional strength, promote velocity-strengthening behavior, and reduce frictional healing, allowing for an improved understanding of the frictional behavior of geothermal reservoir horizons in these contexts. Further, the samples from Reykjanes offered a unique opportunity to study the effect of amphibole alteration on samples with limited low-temperature overprinting. It was shown that the presence of amphibole results in frictionally strong gouge which is less velocity strengthening than phyllosilicate-rich gouge. However, amphibole grains assume a crystallographic-preferred orientation when compacted, potentially resulting in negative frictional healing. This negative healing may result in progressive weakening in detachment faults along mid-ocean ridges at temperatures too elevated for serpentinization. This may provide a third weakening mechanism for detachment faults in these contexts, with dynamic recrystallization and grain size reduction operating at high ($\approx 800^\circ\text{C}$) temperatures, serpentinization at low ($< 400^\circ\text{C}$) temperatures, and brittle

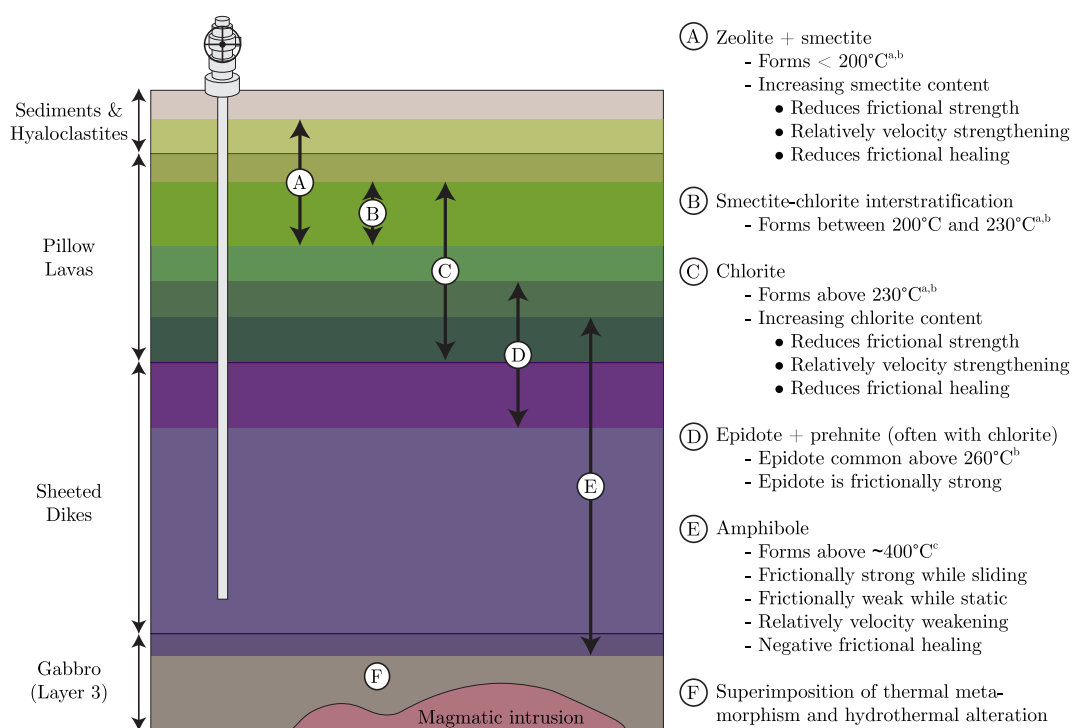


Figure 15. A generic profile for a geothermal system along a mid-ocean ridge. The frictional properties of faults and fractures will be dependent on the type and degree of alteration present. (A) Low-temperature alteration (<200°C) results in zeolite and smectite alteration (Kristmannsdóttir, 1975, 1979). Increasing smectite content results in a reduction in frictional strength, increased velocity-strengthening behavior, and reduced frictional healing. (B) At higher temperatures (between 200°C and 230°C), smectite-chlorite interstratification forms. The frictional properties will depend to a first order on the total phyllosilicate content. (C) Above 230°C significant discrete chlorite may form (Kristmannsdóttir, 1975, 1979). Increasing chlorite content results in a reduction in frictional strength, increased velocity-strengthening behavior, and reduced frictional healing. (D) Epidote is common above 260°C (Kristmannsdóttir, 1979) and is frictionally strong (Fagereng & Ikari, 2020). Epidote and prehnite are often found with chlorite. (E) Amphibole alteration occurs at still higher temperatures (although the specific temperature will depend on the type of amphibole). Amphibole is frictionally strong while sliding and more velocity weakening than phyllosilicate-rich zones. However, amphibole exhibits negative frictional healing and may be weak while static. The alteration zones shown are general and any given zone may be more or less extensive depending on the in situ conditions. Alteration zones may overlap and are not restricted to the zones of the oceanic crust in which they are depicted here. The shapes of alteration zones are arbitrary. The depth of the alteration zones may vary spatially. The schematic is not to scale. The temperature ranges are general, and variation may exist. For example, in Krafla chlorite, corrensite, and smectite crystallized in the temperature domain up to 200°C but for different fluid-protolith mass ratios and alteration processes (Escobedo et al., 2021). Temperature ranges are taken from (a) Kristmannsdóttir (1975), (b) Kristmannsdóttir (1979), and (c) for example, Zierenberg et al. (2021).

crystallographic-preferred-orientation induced weakening in amphibole-rich material, potentially in combination with talc and chlorite, at intermediate temperatures, allowing for the improved numerical modeling of detachment faults. More precisely, the alignment of the crystalline structures of amphibole with the stress field along detachment faults coupled with these minerals' excellent cleavages, may mean that inter-granular fracture during seismic stasis weakens the fault through a reduction in contact area and/or quality, ultimately resulting in a loss of strength with time. It should be noted that, for the moment, evidence of this mechanism has only been tentatively found in dry conditions at room temperature and laboratory time scales; further experiments have been proposed to demonstrate it wet conditions, which are more pertinent for these settings.

Appendix A: Velocity-Step Data

A1. Krafla

The velocity-step data are summarized here for Krafla and Reykjanes samples. The rate-and-state parameters provided correspond to the slip law.

Table A1
A Summary of the Velocity-Step Parameters for K665

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0102 ± 0.0001	0.0077 ± 0.0000	24.0 ± 0.2	0.00041 ± 0.00008
10	Dry	10	0.0120 ± 0.0001	0.0095 ± 0.0001	18.1 ± 0.2	0.00030 ± 0.00008
10	Dry	30	0.0130 ± 0.0002	0.0106 ± 0.0002	17.2 ± 0.4	0.00036 ± 0.00009
10	Dry	100	0.0139 ± 0.0003	0.0114 ± 0.0003	18.8 ± 0.6	0.00035 ± 0.00009
10	Dry	300	0.0239 ± 0.0025	0.0199 ± 0.0024	5.9 ± 1.1	0.00032 ± 0.00010
10	Wet	3	0.0086 ± 0.0000	0.0063 ± 0.0000	28.9 ± 0.2	0.00049 ± 0.00009
10	Wet	10	0.0110 ± 0.0001	0.0085 ± 0.0001	18.5 ± 0.3	0.00034 ± 0.00009
10	Wet	30	0.0118 ± 0.0002	0.0092 ± 0.0002	17.1 ± 0.5	0.00036 ± 0.00010
10	Wet	100	0.0138 ± 0.0002	0.0110 ± 0.0002	15.3 ± 0.2	0.00035 ± 0.00009
10	Wet	300	0.0222 ± 0.0029	0.0167 ± 0.0029	6.0 ± 1.5	0.00028 ± 0.00011
30	Dry	3	0.0098 ± 0.0000	0.0078 ± 0.0000	22.0 ± 0.1	0.00041 ± 0.00010
30	Dry	10	0.0104 ± 0.0000	0.0086 ± 0.0000	21.5 ± 0.1	0.00038 ± 0.00011
30	Dry	30	0.0109 ± 0.0000	0.0089 ± 0.0000	21.8 ± 0.2	0.00032 ± 0.00012
30	Dry	100	0.0127 ± 0.0001	0.0101 ± 0.0001	16.1 ± 0.2	0.00035 ± 0.00011
30	Dry	300	0.0138 ± 0.0005	0.0115 ± 0.0005	14.5 ± 0.9	0.00032 ± 0.00012
30	Wet	3	0.0087 ± 0.0000	0.0062 ± 0.0000	23.7 ± 0.1	0.00049 ± 0.00011
30	Wet	10	0.0102 ± 0.0000	0.0074 ± 0.0000	18.8 ± 0.1	0.00036 ± 0.00012
30	Wet	30	0.0108 ± 0.0001	0.0078 ± 0.0001	19.8 ± 0.2	0.00038 ± 0.00013
30	Wet	100	0.0121 ± 0.0001	0.0088 ± 0.0001	18.4 ± 0.3	0.00038 ± 0.00012
30	Wet	300	0.0140 ± 0.0004	0.0099 ± 0.0004	16.7 ± 1.0	0.00041 ± 0.00014
50	Dry	3	0.0084 ± 0.0000	0.0064 ± 0.0000	28.0 ± 0.1	0.00041 ± 0.00010
50	Dry	10	0.0095 ± 0.0000	0.0070 ± 0.0000	17.2 ± 0.1	0.00030 ± 0.00010
50	Dry	30	0.0096 ± 0.0000	0.0071 ± 0.0000	20.8 ± 0.1	0.00034 ± 0.00012
50	Dry	100	0.0096 ± 0.0001	0.0081 ± 0.0001	23.5 ± 0.3	0.00035 ± 0.00011
50	Dry	300	0.0113 ± 0.0003	0.0087 ± 0.0003	15.7 ± 0.9	0.00033 ± 0.00012
50	Wet	3	0.0088 ± 0.0000	0.0054 ± 0.0000	28.1 ± 0.1	0.00051 ± 0.00011
50	Wet	10	0.0092 ± 0.0000	0.0059 ± 0.0000	27.1 ± 0.1	0.00040 ± 0.00012
50	Wet	30	0.0111 ± 0.0000	0.0068 ± 0.0000	16.9 ± 0.1	0.00044 ± 0.00013
50	Wet	100	0.0118 ± 0.0001	0.0079 ± 0.0001	20.7 ± 0.2	0.00048 ± 0.00012
50	Wet	300	0.0127 ± 0.0002	0.0087 ± 0.0002	22.8 ± 0.8	0.00045 ± 0.00013

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Table A2
A Summary of the Velocity-Step Parameters for K708

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0102 ± 0.0000	0.0071 ± 0.0000	28.7 ± 0.2	0.00047 ± 0.00009
10	Dry	10	0.0111 ± 0.0001	0.0086 ± 0.0001	19.9 ± 0.3	0.00029 ± 0.00009
10	Dry	30	0.0115 ± 0.0001	0.0088 ± 0.0001	23.0 ± 0.4	0.00033 ± 0.00010
10	Dry	100	0.0134 ± 0.0003	0.0101 ± 0.0003	18.2 ± 0.8	0.00039 ± 0.00009
10	Dry	300	0.0204 ± 0.0020	0.0157 ± 0.0020	7.5 ± 1.5	0.00031 ± 0.00010
10	Wet	3	0.0105 ± 0.0000	0.0056 ± 0.0000	27.0 ± 0.1	0.00056 ± 0.00010
10	Wet	10	0.0120 ± 0.0001	0.0072 ± 0.0001	18.4 ± 0.3	0.00040 ± 0.00010

Table A2
Continued

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Wet	30	0.0130 ± 0.0002	0.0077 ± 0.0002	18.2 ± 0.6	0.00044 ± 0.00011
10	Wet	100	0.0137 ± 0.0003	0.0081 ± 0.0003	23.8 ± 1.2	0.00045 ± 0.00011
10	Wet	300	0.0224 ± 0.0035	0.0135 ± 0.0035	6.7 ± 2.3	0.00039 ± 0.00012
30	Dry	3	0.0092 ± 0.0000	0.0069 ± 0.0000	19.6 ± 0.1	0.00033 ± 0.00011
30	Dry	10	0.0095 ± 0.0000	0.0074 ± 0.0000	19.8 ± 0.1	0.00023 ± 0.00011
30	Dry	30	0.0099 ± 0.0001	0.0079 ± 0.0001	22.4 ± 0.2	0.00030 ± 0.00012
30	Dry	100	0.0107 ± 0.0001	0.0107 ± 0.0001	28.8 ± 0.3	0.00039 ± 0.00011
30	Dry	300	0.0124 ± 0.0004	0.0100 ± 0.0004	15.9 ± 1.0	0.00026 ± 0.00012
30	Wet	3	0.0094 ± 0.0000	0.0052 ± 0.0000	25.4 ± 0.1	0.00049 ± 0.00011
30	Wet	10	0.0104 ± 0.0000	0.0062 ± 0.0000	21.3 ± 0.1	0.00035 ± 0.00012
30	Wet	30	0.0114 ± 0.0001	0.0067 ± 0.0001	20.0 ± 0.2	0.00039 ± 0.00013
30	Wet	100	0.0129 ± 0.0001	0.0076 ± 0.0001	19.0 ± 0.4	0.00038 ± 0.00012
30	Wet	300	0.0141 ± 0.0004	0.0083 ± 0.0004	19.8 ± 1.4	0.00040 ± 0.00013
50	Dry	3	0.0108 ± 0.0001	0.0062 ± 0.0001	14.1 ± 0.2	-0.00001 ± 0.00011
50	Dry	10	0.0093 ± 0.0001	0.0069 ± 0.0001	11.8 ± 0.1	0.00023 ± 0.00011
50	Dry	30	0.0085 ± 0.0000	0.0068 ± 0.0000	19.7 ± 0.2	0.00029 ± 0.00013
50	Dry	100	0.0108 ± 0.0001	0.0085 ± 0.0001	11.8 ± 0.2	0.00028 ± 0.00012
50	Dry	300	0.0107 ± 0.0002	0.0088 ± 0.0002	14.4 ± 0.5	0.00027 ± 0.00013
50	Wet	3	0.0087 ± 0.0000	0.0049 ± 0.0000	32.6 ± 0.1	0.00058 ± 0.00012
50	Wet	10	0.0099 ± 0.0000	0.0057 ± 0.0000	22.6 ± 0.1	0.00046 ± 0.00013
50	Wet	30	0.0100 ± 0.0000	0.0059 ± 0.0000	27.9 ± 0.2	0.00051 ± 0.00014
50	Wet	100	0.0111 ± 0.0001	0.0066 ± 0.0001	26.3 ± 0.3	0.00054 ± 0.00013
50	Wet	300	0.0122 ± 0.0003	0.0075 ± 0.0002	25.9 ± 1.3	0.00056 ± 0.00015

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Table A3
A Summary of the Velocity-Step Parameters for K731

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0107 ± 0.0000	0.0072 ± 0.0000	23.9 ± 0.2	0.00047 ± 0.00010
10	Dry	10	0.0122 ± 0.0001	0.0084 ± 0.0001	19.8 ± 0.3	0.00036 ± 0.00010
10	Dry	30	0.0132 ± 0.0001	0.0088 ± 0.0001	20.4 ± 0.5	0.00041 ± 0.00011
10	Dry	100	0.0162 ± 0.0003	0.0104 ± 0.0003	15.8 ± 0.7	0.00045 ± 0.00010
10	Dry	300	0.0190 ± 0.0009	0.0124 ± 0.0009	15.7 ± 1.6	0.00055 ± 0.00011
10	Wet	3	0.0099 ± 0.0001	0.0029 ± 0.0001	6.8 ± 0.1	0.00033 ± 0.00012
10	Wet	10	0.0088 ± 0.0001	0.0022 ± 0.0001	14.5 ± 0.8	0.00018 ± 0.00012
10	Wet	30	0.0104 ± 0.0002	0.0029 ± 0.0002	11.8 ± 1.0	0.00019 ± 0.00013
10	Wet	100	0.0124 ± 0.0003	0.0040 ± 0.0003	14.4 ± 1.4	0.00019 ± 0.00012
10	Wet	300	0.0195 ± 0.0041	0.0095 ± 0.0040	6.5 ± 3.4	0.00019 ± 0.00014
30	Dry	3	0.0109 ± 0.0000	0.0061 ± 0.0000	18.2 ± 0.1	0.00050 ± 0.00012
30	Dry	10	0.0111 ± 0.0000	0.0065 ± 0.0000	19.0 ± 0.2	0.00041 ± 0.00012
30	Dry	30	0.0118 ± 0.0001	0.0069 ± 0.0001	21.4 ± 0.2	0.00048 ± 0.00014

Table A3
Continued

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
30	Dry	100	0.0130 ± 0.0001	0.0079 ± 0.0001	22.1 ± 0.4	0.00047 ± 0.00013
30	Dry	300	0.0141 ± 0.0004	0.0089 ± 0.0003	26.3 ± 1.6	0.00052 ± 0.00014
30	Wet	3	0.0119 ± 0.0001	0.0057 ± 0.0001	3.8 ± 0.0	0.00033 ± 0.00012
30	Wet	10	0.0093 ± 0.0001	0.0033 ± 0.0001	10.2 ± 0.2	0.00022 ± 0.00013
30	Wet	30	0.0101 ± 0.0001	0.0033 ± 0.0001	15.1 ± 0.5	0.00028 ± 0.00014
30	Wet	100	0.0127 ± 0.0002	0.0044 ± 0.0002	10.2 ± 0.6	0.00032 ± 0.00013
30	Wet	300	0.0130 ± 0.0005	0.0034 ± 0.0005	16.7 ± 2.8	0.00037 ± 0.00015
50	Dry	3	0.0100 ± 0.0000	0.0059 ± 0.0000	26.9 ± 0.1	0.00052 ± 0.00012
50	Dry	10	0.0103 ± 0.0000	0.0060 ± 0.0000	24.5 ± 0.1	0.00041 ± 0.00012
50	Dry	30	0.0111 ± 0.0000	0.0066 ± 0.0000	25.9 ± 0.2	0.00048 ± 0.00013
50	Dry	100	0.0127 ± 0.0001	0.0078 ± 0.0001	22.7 ± 0.3	0.00048 ± 0.00012
50	Dry	300	0.0137 ± 0.0002	0.0088 ± 0.0002	25.1 ± 0.7	0.00052 ± 0.00014
50	Wet	3	0.0111 ± 0.0001	0.0052 ± 0.0001	10.2 ± 0.3	0.00048 ± 0.00014
50	Wet	10	0.0089 ± 0.0001	0.0033 ± 0.0001	28.4 ± 0.7	0.00043 ± 0.00015
50	Wet	30	0.0110 ± 0.0002	0.0042 ± 0.0002	18.3 ± 0.9	0.00029 ± 0.00017
50	Wet	100	0.0119 ± 0.0003	0.0045 ± 0.0003	19.0 ± 1.4	0.00043 ± 0.00015
50	Wet	300	0.0125 ± 0.0003	0.0047 ± 0.0003	32.4 ± 3.0	0.00055 ± 0.00017

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

A2. Reykjanes

Table A4
A Summary of the Velocity-Step Parameters for R2806

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0061 ± 0.0001	0.0052 ± 0.0000	20.3 ± 0.3	0.00026 ± 0.00008
10	Dry	10	0.0073 ± 0.0001	0.0065 ± 0.0001	12.6 ± 0.3	0.00015 ± 0.00009
10	Dry	30	0.0073 ± 0.0001	0.0069 ± 0.0001	15.0 ± 0.3	0.00019 ± 0.00010
10	Dry	100	0.0088 ± 0.0003	0.0076 ± 0.0003	11.9 ± 0.7	0.00021 ± 0.00009
10	Dry	300	0.0206 ± 0.0053	0.0183 ± 0.0053	2.7 ± 1.1	0.00019 ± 0.00010
10	Wet	3	0.0069 ± 0.0001	0.0051 ± 0.0000	21.9 ± 0.3	0.00030 ± 0.00009
10	Wet	10	0.0075 ± 0.0001	0.0060 ± 0.0001	18.5 ± 0.4	0.00021 ± 0.00009
10	Wet	30	0.0082 ± 0.0002	0.0067 ± 0.0002	16.5 ± 0.6	0.00022 ± 0.00010
10	Wet	100	0.0075 ± 0.0003	0.0055 ± 0.0003	29.6 ± 2.5	0.00019 ± 0.00009
10	Wet	300	0.0279 ± 0.0115	0.0245 ± 0.0115	2.2 ± 1.4	0.00022 ± 0.00010
30	Dry	3	0.0057 ± 0.0000	0.0044 ± 0.0000	16.1 ± 0.1	0.00024 ± 0.00009
30	Dry	10	0.0064 ± 0.0000	0.0053 ± 0.0000	11.5 ± 0.1	0.00007 ± 0.00009
30	Dry	30	0.0068 ± 0.0001	0.0057 ± 0.0001	12.6 ± 0.2	0.00015 ± 0.00011
30	Dry	100	0.0066 ± 0.0001	0.0058 ± 0.0001	18.0 ± 0.5	0.00022 ± 0.00010
30	Dry	300	0.0116 ± 0.0011	0.0098 ± 0.0011	5.9 ± 1.1	0.00017 ± 0.00011
30	Wet	3	0.0067 ± 0.0000	0.0051 ± 0.0000	22.5 ± 0.1	0.00034 ± 0.00009
30	Wet	10	0.0067 ± 0.0000	0.0050 ± 0.0000	19.3 ± 0.2	0.00021 ± 0.00010
30	Wet	30	0.0072 ± 0.0001	0.0054 ± 0.0001	18.1 ± 0.3	0.00023 ± 0.00011

Table A4
Continued

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
30	Wet	100	0.0085 ± 0.0001	0.0066 ± 0.0001	14.6 ± 0.3	0.00023 ± 0.00010
30	Wet	300	0.0101 ± 0.0005	0.0077 ± 0.0005	11.5 ± 1.1	0.00023 ± 0.00011
50	Dry	3	0.0063 ± 0.0000	0.0043 ± 0.0000	10.2 ± 0.1	0.00024 ± 0.00010
50	Dry	10	0.0060 ± 0.0000	0.0045 ± 0.0000	13.9 ± 0.1	0.00016 ± 0.00010
50	Dry	30	0.0066 ± 0.0000	0.0049 ± 0.0000	12.3 ± 0.1	0.00019 ± 0.00011
50	Dry	100	0.0074 ± 0.0001	0.0057 ± 0.0001	11.5 ± 0.2	0.00018 ± 0.00010
50	Dry	300	0.0078 ± 0.0004	0.0060 ± 0.0004	15.0 ± 1.4	0.00020 ± 0.00012
50	Wet	3	0.0059 ± 0.0000	0.0039 ± 0.0000	27.4 ± 0.1	0.00036 ± 0.00010
50	Wet	10	0.0068 ± 0.0000	0.0044 ± 0.0000	18.6 ± 0.1	0.00024 ± 0.00010
50	Wet	30	0.0068 ± 0.0000	0.0049 ± 0.0000	22.6 ± 0.2	0.00027 ± 0.00012
50	Wet	100	0.0075 ± 0.0001	0.0052 ± 0.0001	21.1 ± 0.4	0.00025 ± 0.00011
50	Wet	300	0.0087 ± 0.0002	0.0062 ± 0.0002	18.2 ± 0.9	0.00026 ± 0.00012

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Table A5
A Summary of the Velocity-Step Parameters for R4641

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0052 ± 0.0000	0.0042 ± 0.0000	31.7 ± 0.4	0.00026 ± 0.00008
10	Dry	10	0.0067 ± 0.0001	0.0055 ± 0.0001	13.6 ± 0.3	0.00021 ± 0.00008
10	Dry	30	0.0064 ± 0.0001	0.0056 ± 0.0001	25.0 ± 0.3	0.00021 ± 0.00009
10	Dry	100	0.0080 ± 0.0002	0.0068 ± 0.0002	17.7 ± 0.9	0.00025 ± 0.00008
10	Dry	300	0.0243 ± 0.0061	0.0208 ± 0.0061	2.8 ± 1.2	0.00028 ± 0.00009
10	Wet	3	0.0081 ± 0.0000	0.0052 ± 0.0000	26.9 ± 0.3	0.00033 ± 0.00008
10	Wet	10	0.0081 ± 0.0001	0.0079 ± 0.0001	43.7 ± 0.9	0.00036 ± 0.00008
10	Wet	30	0.0082 ± 0.0001	0.0070 ± 0.0001	33.9 ± 0.8	0.00029 ± 0.00009
10	Wet	100	0.0082 ± 0.0002	0.0067 ± 0.0002	35.5 ± 1.5	0.00032 ± 0.00008
10	Wet	300	0.0103 ± 0.0007	0.0080 ± 0.0007	21.0 ± 2.6	0.00031 ± 0.00009
30	Dry	3	0.0055 ± 0.0000	0.0032 ± 0.0000	17.3 ± 0.1	0.00034 ± 0.00010
30	Dry	10	0.0058 ± 0.0000	0.0043 ± 0.0000	17.3 ± 0.2	0.00019 ± 0.00010
30	Dry	30	0.0061 ± 0.0000	0.0047 ± 0.0000	21.9 ± 0.3	0.00026 ± 0.00011
30	Dry	100	0.0059 ± 0.0001	0.0048 ± 0.0001	31.4 ± 0.8	0.00027 ± 0.00010
30	Dry	300	0.0094 ± 0.0005	0.0075 ± 0.0005	10.9 ± 1.0	0.00029 ± 0.00011
30	Wet	3	0.0078 ± 0.0000	0.0050 ± 0.0000	21.6 ± 0.1	0.00040 ± 0.00010
30	Wet	10	0.0088 ± 0.0000	0.0060 ± 0.0000	14.1 ± 0.1	0.00027 ± 0.00010
30	Wet	30	0.0083 ± 0.0001	0.0065 ± 0.0001	19.6 ± 0.3	0.00029 ± 0.00011
30	Wet	100	0.0099 ± 0.0001	0.0077 ± 0.0001	12.8 ± 0.4	0.00025 ± 0.00010
30	Wet	300	0.0111 ± 0.0005	0.0093 ± 0.0005	11.8 ± 0.9	0.00024 ± 0.00011
50	Dry	3	0.0051 ± 0.0000	0.0024 ± 0.0000	19.1 ± 0.1	0.00032 ± 0.00009
50	Dry	10	0.0056 ± 0.0000	0.0034 ± 0.0000	13.2 ± 0.1	0.00024 ± 0.00009

Table A5
Continued

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
50	Dry	30	0.0062 ± 0.0000	0.0043 ± 0.0000	11.5 ± 0.2	0.00034 ± 0.00010
50	Dry	100	0.0051 ± 0.0001	0.0041 ± 0.0001	25.3 ± 0.5	0.00023 ± 0.00010
50	Dry	300	0.0062 ± 0.0002	0.0054 ± 0.0002	14.4 ± 0.9	0.00022 ± 0.00011
50	Wet	3	0.0072 ± 0.0000	0.0046 ± 0.0000	20.9 ± 0.1	0.00043 ± 0.00009
50	Wet	10	0.0077 ± 0.0000	0.0050 ± 0.0000	21.4 ± 0.1	0.00028 ± 0.00009
50	Wet	30	0.0084 ± 0.0000	0.0060 ± 0.0000	14.8 ± 0.1	0.00031 ± 0.00010
50	Wet	100	0.0086 ± 0.0001	0.0067 ± 0.0001	15.6 ± 0.3	0.00026 ± 0.00010
50	Wet	300	0.0086 ± 0.0002	0.0069 ± 0.0002	17.0 ± 0.8	0.00029 ± 0.00011

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Table A6
A Summary of the Velocity-Step Parameters for R4648

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0054 ± 0.0000	0.0045 ± 0.0000	34.7 ± 0.4	0.00031 ± 0.00010
10	Dry	10	0.0062 ± 0.0001	0.0048 ± 0.0001	18.7 ± 0.4	0.00022 ± 0.00010
10	Dry	30	0.0071 ± 0.0002	0.0053 ± 0.0002	14.4 ± 0.6	0.00025 ± 0.00011
10	Dry	100	0.0076 ± 0.0002	0.0062 ± 0.0002	20.1 ± 1.1	0.00028 ± 0.00010
10	Dry	300	0.0167 ± 0.0024	0.0133 ± 0.0024	4.6 ± 1.3	0.00033 ± 0.00012
10	Wet	3	0.0080 ± 0.0000	0.0066 ± 0.0000	48.3 ± 0.4	0.00044 ± 0.00008
10	Wet	10	0.0079 ± 0.0001	0.0065 ± 0.0001	35.4 ± 0.6	0.00036 ± 0.00008
10	Wet	30	0.0084 ± 0.0001	0.0062 ± 0.0001	24.2 ± 0.8	0.00035 ± 0.00009
10	Wet	100	0.0092 ± 0.0003	0.0067 ± 0.0003	24.8 ± 1.4	0.00034 ± 0.00008
10	Wet	300	0.0179 ± 0.0020	0.0136 ± 0.0020	6.1 ± 1.4	0.00033 ± 0.00009
30	Dry	3	0.0056 ± 0.0000	0.0026 ± 0.0000	18.3 ± 0.2	0.00031 ± 0.00009
30	Dry	10	0.0070 ± 0.0001	0.0040 ± 0.0001	7.7 ± 0.2	0.00021 ± 0.00009
30	Dry	30	0.0059 ± 0.0001	0.0044 ± 0.0001	20.6 ± 0.4	0.00022 ± 0.00010
30	Dry	100	0.0058 ± 0.0001	0.0049 ± 0.0001	27.9 ± 0.8	0.00024 ± 0.00009
30	Dry	300	0.0098 ± 0.0009	0.0074 ± 0.0009	8.0 ± 1.4	0.00020 ± 0.00011
30	Wet	3	0.0070 ± 0.0000	0.0052 ± 0.0000	36.1 ± 0.2	0.00042 ± 0.00009
30	Wet	10	0.0084 ± 0.0000	0.0059 ± 0.0000	16.2 ± 0.1	0.00027 ± 0.00009
30	Wet	30	0.0083 ± 0.0001	0.0065 ± 0.0001	18.3 ± 0.3	0.00027 ± 0.00010
30	Wet	100	0.0093 ± 0.0001	0.0071 ± 0.0001	14.4 ± 0.4	0.00028 ± 0.00009
30	Wet	300	0.0093 ± 0.0005	0.0076 ± 0.0005	16.4 ± 1.6	0.00024 ± 0.00010
50	Dry	3	0.0049 ± 0.0000	0.0028 ± 0.0000	15.7 ± 0.1	0.00029 ± 0.00009
50	Dry	10	0.0068 ± 0.0000	0.0044 ± 0.0000	5.8 ± 0.1	0.00018 ± 0.00009
50	Dry	30	0.0064 ± 0.0001	0.0050 ± 0.0001	8.5 ± 0.1	0.00018 ± 0.00010
50	Dry	100	0.0056 ± 0.0001	0.0051 ± 0.0001	16.6 ± 0.3	0.00017 ± 0.00010
50	Dry	300	0.0077 ± 0.0005	0.0067 ± 0.0005	8.5 ± 0.9	0.00016 ± 0.00011
50	Wet	3	0.0065 ± 0.0000	0.0046 ± 0.0000	30.1 ± 0.1	0.00039 ± 0.00009
50	Wet	10	0.0079 ± 0.0000	0.0052 ± 0.0000	15.8 ± 0.1	0.00025 ± 0.00009

Table A6
Continued

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
50	Wet	30	0.0076 ± 0.0000	0.0057 ± 0.0000	19.1 ± 0.2	0.00028 ± 0.00010
50	Wet	100	0.0078 ± 0.0001	0.0061 ± 0.0001	19.7 ± 0.3	0.00027 ± 0.00009
50	Wet	300	0.0086 ± 0.0004	0.0071 ± 0.0004	16.0 ± 1.2	0.00022 ± 0.00011

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Table A7
A Summary of the Velocity-Step Parameters for R4654

σ (MPa)	Sat.	v ($\frac{\mu\text{m}}{\text{sec}}$)	a (–)	b (–)	D_c (μm)	α (–)
10	Dry	3	0.0058 ± 0.0000	0.0067 ± 0.0000	36.9 ± 0.4	0.00038 ± 0.00008
10	Dry	10	0.0074 ± 0.0001	0.0076 ± 0.0001	15.5 ± 0.3	0.00019 ± 0.00008
10	Dry	30	0.0070 ± 0.0001	0.0077 ± 0.0001	22.9 ± 0.5	0.00021 ± 0.00009
10	Dry	100	0.0097 ± 0.0003	0.0091 ± 0.0003	11.1 ± 0.6	0.00026 ± 0.00008
10	Dry	300	0.0199 ± 0.0026	0.0187 ± 0.0025	3.8 ± 0.8	0.00014 ± 0.00009
10	Wet	3	0.0077 ± 0.0000	0.0083 ± 0.0000	38.8 ± 0.3	0.00047 ± 0.00008
10	Wet	10	0.0082 ± 0.0001	0.0072 ± 0.0001	25.4 ± 0.4	0.00025 ± 0.00008
10	Wet	30	0.0082 ± 0.0001	0.0079 ± 0.0001	27.0 ± 0.7	0.00025 ± 0.00009
10	Wet	100	0.0098 ± 0.0002	0.0081 ± 0.0002	19.8 ± 0.9	0.00029 ± 0.00008
10	Wet	300	0.0109 ± 0.0014	0.0087 ± 0.0014	15.0 ± 3.5	0.00017 ± 0.00009
30	Dry	3	0.0053 ± 0.0000	0.0051 ± 0.0000	28.3 ± 0.1	0.00025 ± 0.00009
30	Dry	10	0.0064 ± 0.0000	0.0057 ± 0.0000	17.7 ± 0.1	0.00016 ± 0.00009
30	Dry	30	0.0069 ± 0.0001	0.0063 ± 0.0001	14.6 ± 0.2	0.00015 ± 0.00010
30	Dry	100	0.0087 ± 0.0005	0.0072 ± 0.0005	7.6 ± 0.8	0.00013 ± 0.00010
30	Dry	300	0.0088 ± 0.0008	0.0082 ± 0.0007	12.9 ± 1.6	0.00016 ± 0.00011
30	Wet	3	0.0071 ± 0.0000	0.0052 ± 0.0000	22.6 ± 0.1	0.00042 ± 0.00009
30	Wet	10	0.0082 ± 0.0000	0.0064 ± 0.0000	14.8 ± 0.1	0.00025 ± 0.00009
30	Wet	30	0.0085 ± 0.0001	0.0069 ± 0.0001	13.8 ± 0.2	0.00024 ± 0.00011
30	Wet	100	0.0100 ± 0.0001	0.0081 ± 0.0001	10.6 ± 0.3	0.00025 ± 0.00010
30	Wet	300	0.0096 ± 0.0005	0.0087 ± 0.0005	10.8 ± 0.9	0.00018 ± 0.00011
50	Dry	3	0.0060 ± 0.0000	0.0044 ± 0.0000	11.8 ± 0.1	0.00028 ± 0.00010
50	Dry	10	0.0058 ± 0.0000	0.0051 ± 0.0000	13.2 ± 0.1	0.00015 ± 0.00010
50	Dry	30	0.0056 ± 0.0000	0.0051 ± 0.0000	18.5 ± 0.2	0.00018 ± 0.00011
50	Dry	100	0.0061 ± 0.0001	0.0058 ± 0.0001	18.3 ± 0.3	0.00018 ± 0.00010
50	Dry	300	0.0072 ± 0.0004	0.0064 ± 0.0004	15.9 ± 1.4	0.00017 ± 0.00011
50	Wet	3	0.0066 ± 0.0000	0.0055 ± 0.0000	26.0 ± 0.1	0.00047 ± 0.00009
50	Wet	10	0.0073 ± 0.0000	0.0057 ± 0.0000	20.6 ± 0.1	0.00027 ± 0.00010
50	Wet	30	0.0081 ± 0.0000	0.0061 ± 0.0000	16.1 ± 0.1	0.00024 ± 0.00011
50	Wet	100	0.0090 ± 0.0001	0.0073 ± 0.0001	13.1 ± 0.2	0.00026 ± 0.00010
50	Wet	300	0.0087 ± 0.0003	0.0073 ± 0.0003	15.4 ± 1.1	0.00023 ± 0.00011

Note. The normal stress is given by σ , the upstep velocity by v , the direct effect by a , the evolution effect by b , the critical slip distance by D_c , and the normalized dilation by α . The rate-and-state parameters listed were found using the slip law.

Appendix B: Slide-Hold-Slide Data

The slide-hold-slide data are summarized here for Krafla and Reykjanes samples.

Table B1

A Summary of the Healing Parameters for Krafla

Rock	σ (MPa)	Sat.	β (–)	B_h (–)	B_s (–)
K665	10	Dry	0.0096 ± 0.0005	-0.00100 ± 0.00007	0.00023 ± 0.00004
K665	10	Wet	0.0095 ± 0.0005	-0.00102 ± 0.00009	0.00025 ± 0.00006
K665	30	Dry	0.0081 ± 0.0007	-0.00111 ± 0.00008	0.00031 ± 0.00008
K665	30	Wet	0.0089 ± 0.0012	-0.00117 ± 0.00012	0.00031 ± 0.00008
K665	50	Dry	0.0068 ± 0.0007	-0.00110 ± 0.00010	0.00023 ± 0.00008
K665	50	Wet	0.0067 ± 0.0010	-0.00144 ± 0.00019	0.00042 ± 0.00016
K708	10	Dry	0.0092 ± 0.0004	-0.00084 ± 0.00004	0.00020 ± 0.00003
K708	10	Wet	0.0081 ± 0.0006	-0.00107 ± 0.00010	0.00020 ± 0.00004
K708	30	Dry	0.0080 ± 0.0008	-0.00092 ± 0.00007	0.00026 ± 0.00007
K708	30	Wet	0.0072 ± 0.0009	-0.00116 ± 0.00015	0.00018 ± 0.00005
K708	50	Dry	0.0070 ± 0.0007	-0.00099 ± 0.00009	0.00011 ± 0.00005
K708	50	Wet	0.0061 ± 0.0008	-0.00161 ± 0.00025	0.00039 ± 0.00014
K731	10	Dry	0.0095 ± 0.0007	-0.00097 ± 0.00004	0.00022 ± 0.00004
K731	10	Wet	0.0050 ± 0.0007	-0.00084 ± 0.00013	0.00005 ± 0.00001
K731	30	Dry	0.0061 ± 0.0008	-0.00134 ± 0.00015	0.00035 ± 0.00010
K731	30	Wet	0.0037 ± 0.0006	-0.00114 ± 0.00020	0.00008 ± 0.00003
K731	50	Dry	0.0061 ± 0.0007	-0.00136 ± 0.00014	0.00027 ± 0.00010
K731	50	Wet	0.0029 ± 0.0005	-0.00153 ± 0.00030	0.00013 ± 0.00004

Note. The normal stress is given by σ , the healing rate by β , the dilation-during-hold rate by B_h , and the dilation-upon-reshear rate by B_s . Negative healing was not observed in any of the tests.

Table B2

A Summary of the Healing Parameters for Reykjanes

Rock	σ (MPa)	Sat.	β (–)	B_h (–)	B_s (–)
R2806	10	Dry	0.0058 ± 0.0005	-0.00065 ± 0.00004	0.00010 ± 0.00002
R2806	10	Wet	0.0073 ± 0.0005	-0.00065 ± 0.00004	0.00012 ± 0.00002
R2806	30	Dry	0.0046 ± 0.0002	-0.00069 ± 0.00007	0.00017 ± 0.00003
R2806	30	Wet	0.0063 ± 0.0010	-0.00090 ± 0.00012	0.00019 ± 0.00008
R2806	50	Dry	0.0034 ± 0.0005	-0.00080 ± 0.00009	0.00013 ± 0.00005
R2806	50	Wet	0.0059 ± 0.0010	-0.00104 ± 0.00017	0.00018 ± 0.00009
R4641	10	Dry	0.0041 ± 0.0007	-0.00077 ± 0.00011	0.00010 ± 0.00002
R4641	10	Wet	0.0061 ± 0.0004	-0.00094 ± 0.00012	0.00012 ± 0.00003
R4641*	30	Dry	0.0033 ± 0.0006	-0.00097 ± 0.00018	0.00008 ± 0.00001
R4641	30	Wet	0.0064 ± 0.0009	-0.00100 ± 0.00011	0.00017 ± 0.00006
R4641*	50	Dry	0.0030 ± 0.0008	-0.00108 ± 0.00024	0.00007 ± 0.00001
R4641	50	Wet	0.0062 ± 0.0008	-0.00131 ± 0.00023	0.00033 ± 0.00014
R4648	10	Dry	0.0030 ± 0.0006	-0.00076 ± 0.00005	0.00009 ± 0.00001
R4648	10	Wet	0.0058 ± 0.0003	-0.00096 ± 0.00011	0.00018 ± 0.00004
R4648*	30	Dry	0.0032 ± 0.0008	-0.00099 ± 0.00018	0.00009 ± 0.00001

Table B2
Continued

Rock	σ (MPa)	Sat.	β (–)	B_h (–)	B_s (–)
R4648	30	Wet	0.0065 ± 0.0008	-0.00102 ± 0.00015	0.00023 ± 0.00007
R4648*	50	Dry	0.0034 ± 0.0004	-0.00107 ± 0.00031	0.00006 ± 0.00001
R4648	50	Wet	0.0067 ± 0.0010	-0.00117 ± 0.00017	0.00023 ± 0.00010
R4654	10	Dry	0.0061 ± 0.0005	-0.00078 ± 0.00008	0.00014 ± 0.00003
R4654	10	Wet	0.0066 ± 0.0008	-0.00103 ± 0.00014	0.00026 ± 0.00006
R4654	30	Dry	0.0054 ± 0.0004	-0.00086 ± 0.00006	0.00024 ± 0.00004
R4654	30	Wet	0.0069 ± 0.0007	-0.00102 ± 0.00012	0.00027 ± 0.00008
R4654	50	Dry	0.0027 ± 0.0006	-0.00086 ± 0.00011	0.00010 ± 0.00004
R4654	50	Wet	0.0069 ± 0.0009	-0.00112 ± 0.00016	0.00026 ± 0.00011

Note. The normal stress is given by σ , the healing rate by β , the dilation-during-hold rate by B_h , and the dilation-upon-reshear rate by B_s . Instances of negative healing rate are marked with a *; in these cases the healing and dilation rates are calculated using holds up to the onset of negative healing.

Conflict of Interest

The sample cores were provided by Landsvirkjun and HS Orka to the Laboratory of Experimental Rock Mechanics at no cost. Landsvirkjun and HS Orka have a vested financial interest in the success of the related geothermal fields in the context of geothermal energy production. This study has relevance for induced seismicity hazard assessment, and may therefore have, for example, implications for permitting. No direct financial support was provided by Landsvirkjun or HS Orka to the Laboratory of Experimental Rock Mechanics.

Availability Statement

The raw data files, the MATLAB scripts used to treat them, and the resulting data summaries has been made available online (Fryer et al., 2024).

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