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Key Points:
- Frictional healing rates of mirror-like fault surfaces (fault mirrors) are an order of magnitude lower than those of typical fault rocks.
- The low frictional healing rate of fault mirrors can be attributed to the low chemical reactivity of densely sintered gouges in fault zones.
- Fault mirrors could be a source of aseismic creep owing to their impeded frictional healing.

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

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Abstract Frictional healing of faults is a key mechanism controlling fault strength recovery, which enables the development of repeating earthquake cycles. Carbonate fault rocks are commonly characterized by shiny mirror-like surfaces, sometimes referred to as fault mirrors. Despite the prevalence of fault mirrors in both natural and experimental fault rocks, their frictional healing behavior has not yet been studied. We measured frictional healing rates of experimentally simulated carbonate fault mirrors and found them to be an order of magnitude lower than those of other carbonate fault rocks. Microstructurally, the fault zone of fault mirror specimens is characterized by densely packed sintered nanogouges. We infer that this tight nanograin structure hinders the chemical and physical processes that cause frictional healing. Fault mirrors showing extremely low frictional healing rates are likely to creep aseismically.

Plain Language Summary An increase in the static friction between two stationary bodies, called “frictional healing,” may be a prerequisite for repetitive earthquake cycles. Frictional healing allows a fault to regain energy following an earthquake, thus allowing repeating earthquakes. Natural and experimental fault rocks commonly have shiny, mirror-like fault surfaces, sometimes referred to as “fault mirrors.” In this study, we simulated carbonate fault mirrors experimentally, revealing that the frictional healing rate of the simulated fault mirrors is much lower than that of typical carbonate fault rocks. This indicates that frictional healing depends not only on the mineralogy but also on the physical structure of a fault rock. Because a low frictional healing rate hinders stress recovery, carbonate fault mirrors in an active fault zone may creep aseismically.

1. Introduction

Tectonic motions of plates build up stress in active fault zones. The release of this accumulated stress by earthquakes is accompanied by a drop in fault strength. For earthquakes to occur repeatedly in an existing fault zone, fault strength must be recovered during interseismic periods. The increase in static friction between stationary surfaces over time, known as “frictional healing,” is a key factor in the recovery of fault strength. Since an understanding of frictional healing of fault surfaces is crucial for unraveling the characteristic recurrence intervals, dynamic stress drops, and spectral properties of earthquakes (Dieterich, 1972; Marone et al., 1995; McLaskey et al., 2012), researchers have studied frictional healing in various lithologies (e.g., Carpenter et al., 2016, and references therein). However, the frictional healing behavior of light-reflective, mirror-like fault surfaces (herein, “fault mirrors”: Siman-Tov et al., 2013) remains unclear, even though fault mirrors are commonly present in both natural and experimental fault zones.

A fault mirror is an extremely smooth surface layer consisting of tightly packed nano-sized grains on fault wall rocks (Siman-Tov et al., 2013). Fault mirrors can be produced in the laboratory under various experimental conditions, including both subseismic and seismic slip rates (Aubry et al., 2020; Fondriest et al., 2013; Hirose et al., 2012; Passelègue et al., 2019; Smith et al., 2013; Verberne et al., 2014). The presence of fault mirrors in exhumed natural silicate and carbonate fault zones has also been widely reported (Demurtas et al., 2016; Siman-Tov et al., 2013; Tesei et al., 2013).

During this study, we conducted slide-hold-slide (SHS) tests at a subseismic slip rate on experimentally produced carbonate fault mirrors at seismic slip rates and studied their frictional healing. For comparison, we also measured the frictional healing rates of two other types of carbonate fault rock with different
microstructures and found that the frictional healing rates of experimentally simulated carbonate fault mirrors are an order of magnitude lower than those of other carbonate fault rocks. We examined the microstructures of the three types of fault rocks before and after the friction experiments. Here, we discuss possible reasons for the impeded frictional healing of fault mirrors relative to that of the other carbonate fault rocks.

2. Methods

2.1. Slide-Hold-Slide Friction Tests

We conducted 10 SHS friction tests on specimens of three types of simulated fault rocks using a low-to-high-velocity rotary-shear apparatus at the Kochi Institute for Core Sample Research, Japan (Figure S1a). All experiments were conducted at room temperature under a constant normal stress of 1 MPa exerted by a servo-controlled hydraulic piston. Because of the velocity gradient across the cylindrical specimens in rotary shear experiments, we used the equivalent slip rate and displacement according to the method of Shimamoto (1994; see also Supporting Information). Equivalent slip rate and displacement are referred to hereafter as “slip rate” and “displacement,” respectively. To prepare the simulated fault specimens, we first “pre-sheared” a pair of Carrara marble cylinders, each with a diameter of 25 mm, for 1 h at a slip rate of $1.7 \times 10^{-2}$ m s$^{-1}$, to ensure good contact between the two sliding surfaces of the cylindrical specimens. We then produced the following three types of fault rock specimen with different microstructures by varying the slip history on the specimens after pre-shearing:

1. Pre-sheared bare rock (BR): We refer to fault specimens immediately after the pre-shearing procedure as “pre-sheared bare rock specimens” (Figure 1a). The slip history of BR specimens before the SHS test includes pre-shearing only. The specimens thus represent an incipient fault surface that has not experienced any seismic events since its formation.

2. Fault mirror (FM): To produce fault specimens covered with a fault mirror, we sheared BR specimens at a seismic slip rate of $0.2$ m s$^{-1}$ (total displacement 21 m). We examined the fault surfaces of two representative specimens sheared under these conditions and confirmed visually that shiny fault mirrors covered most areas of the fault surfaces after this shearing (Figure 1b).

3. Crushed fault mirror (CF): To test the effects of the characteristic structure of a fault mirror on its frictional healing behavior, we prepared CF specimens by shearing FM specimens at a subseismic slip rate of $3.5 \times 10^{-3}$ m s$^{-1}$ (total displacement 1.6 m) to destroy the fault mirror structure. To determine the experimental conditions necessary to destroy the fault mirror structure, we referred to Siman-Tov et al. (2015), who reported that fault mirrors could be destroyed by slip at relatively low rates ($<0.07$ m s$^{-1}$). We also examined the fault surface of a representative CF specimen and confirmed that the shiny fault mirror had been destroyed (Figure 1c).

After producing the three types of simulated fault rocks, we conducted SHS tests at room humidity (relative humidity of 34%–37%) using hold periods of 3–6,760 s (Table S1). Before each SHS test, a run-in displacement of 0.64–2.22 mm was used to reach steady-state friction (Figure S2a). All experiments, including both the run-in displacements and the SHS tests, were conducted at a constant slip rate of 1 μm s$^{-1}$ under a normal stress of 1 MPa and at room temperature (25°C –28°C). Because some previous studies have suggested the existence of water-assisted healing mechanisms (e.g., Frye & Marone, 2002), we also conducted SHS tests in a dry N$_2$ atmosphere to investigate whether water-assisted frictional healing mechanisms affected our experimental results. For experiments under an N$_2$ atmosphere, we installed an acrylic vessel around the specimens (Figure S1b) and filled the vessel with nitrogen gas to create a relatively dry atmosphere during the SHS tests. Relative humidity under the N$_2$ atmosphere was approximately zero, as measured by a humidity sensor (Humidity Sensor TAS02, TOPLAS Engineering). All experimental procedures, including the preparation of the three types of simulated fault rock, are summarized in a schematic flow chart (Figure 1d).

2.2. Microstructural Observations

After the experiments, the fault rock specimens were impregnated with epoxy resin and cut perpendicular to the simulated fault plane to make thin sections. Microstructural observations of polished thin sections...
were conducted with a field-emission scanning electron microscope (FE-SEM, Hitachi SU-70) at the Korea Basic Science Institute (KBSI) of Seoul, South Korea. The specimens were also observed with a field-emission transmission electron microscope (FE-TEM, FEI Tecnai F20 G2) at the Korea Institute of Science and Technology (Seoul, South Korea). A focused ion beam (Quanta 3D FEG) at the KBSI was used to prepare specimens for the FE-TEM analysis.

3. Results

3.1. Slide-Hold-Slide Tests and Frictional Healing Behaviors of FM, CF, and BR Specimens

During the run-in shearing, the steady-state friction coefficient became ∼0.60–0.65, regardless of the fault rock type, except in experiments PHV 409 and 421, for which the steady-state friction coefficients were ∼0.90 and ∼0.45, respectively (Figures S2e and S3). Because our experiments were conducted under a relatively low normal stress (1 MPa), surface roughness variation can account for this variation in the friction coefficient (Byerlee, 1978). Friction coefficients of 0.6–0.65 are typical for carbonate rocks and gouges in other friction experiments (Carpenter et al., 2014; Paterson & Wong, 2005; Scuderi et al., 2013; Tesei et al., 2014). Here, frictional healing is defined as the difference in the friction coefficient (Δμ) between peak friction after a holding stage and the preceding steady-state friction (Marone, 1998) (Figure 2a inset).

For FM specimens, re-shearing after the holding stage resulted in only a slight increase in static friction that was largely independent of holding time, whereas for CF and BR specimens the sharp peaks of static friction observed after re-shearing increased as holding time increased (Figure 2a). CF and BR specimens

Figure 1. Experimental specimens and flowchart of experiments. (a) Pre-sheared bare rock surface. (b) Shiny fault mirror surface after slip at a slip rate of 0.2 m s⁻¹. (c) Crushed fault mirror with fault surface covered by gouge material following slip at a slip rate of 0.0035 m s⁻¹. (d) Flow chart summarizing specimen preparation and slide-hold-slide friction test procedure.
showed typical frictional healing behavior in which $\Delta \mu$ increases logarithmically with holding time (Figure 2b). We estimated the frictional healing rate by least-squares fitting of a logarithmic equation with frictional healing rate $\beta = \Delta \mu / \log_{10} t_h$, where $t_h (>1)$ is holding time, to the $\Delta \mu$–holding time relationship. $\beta$ is positive in both CF and BR specimens, but higher in CF ($\beta = 8.06 \times 10^{-3} \pm 9.22 \times 10^{-4}$) than in BR ($\beta = 4.55 \times 10^{-3} \pm 7.92 \times 10^{-4}$) specimens. These values are consistent with studies that reported gouge materials with frictional healing rates of the same order of magnitude (Carpenter et al., 2016; Chen et al., 2015; Paterson & Wong, 2005; Tesei et al., 2014). In contrast, the frictional healing rate of FM specimens ($\beta = 9.27 \times 10^{-4} \pm 5.16 \times 10^{-4}$) is one order of magnitude lower than those of CF and BR specimens.

We conducted one experiment under dry conditions with each of the three fault rock types and found their frictional behaviors during SHS tests to be essentially similar to their behaviors in experiments conducted at room humidity: FM showed little increase in static friction regardless of holding time (Figure S2d), whereas CF and BR showed clear sharp peaks of static friction that increased in magnitude with holding time (Figures S2e and S2f). No dramatic changes in frictional healing rate, compared with the rates observed at room humidity, were observed in any of the three specimen types. In particular, the frictional healing rate of the FM specimen is as low as that obtained from the room-humidity experiments ($\beta = 6.80 \times 10^{-4} \pm 7.08 \times 10^{-4}$) (Figure 2c).

### 3.2. Microstructures of Experimental Fault Zones

The fault zone of FM specimens before the SHS tests includes (1) gouge patches, up to $\sim 150$ $\mu$m thick, of sintered calcite nanograins smeared into the rough surface of damaged wall rocks and (2) a sintered
nanogouge layer with a thickness of up to $\sim 200 \, \mu m$ between the wall rocks (Figure 3a). A straight, discrete Y-shear surface defines the boundary between the sintered nanogouge layer and the nanograin patches. Both the patches and the sintered nanograin layer near the Y-shear consist of tightly packed calcite nanograins (50–500 nm in size) displaying a foam texture with straight grain boundaries (Figures 3b and 3c). Farther from the Y-shear plane, porosity increases in the patches (Figure S4). A ring-type selected-area electron diffraction pattern indicates that the sintered nanograins have a random distribution of lattice orientations (Figure 3c inset). Similar to previously reported carbonate fault mirror specimens that were produced under seismic slip rates (De Paola et al., 2015; Pozzi et al., 2018), the sintered nanogouge layers in FM specimens are composed of crystalline calcite and show no evidence of decarbonization microstructures (Collettini et al., 2013) or the diffraction peaks of decarbonated phases (see Figure S6).
CF specimens before the SHS test contained remnant patches of sintered nanograins on wall rocks inherited from the original FM specimen and a crushed gouge layer between the wall rocks (Figure 3d). The microstructures of the patches are identical to those of the FM specimens. However, the gouge layer of the CF specimens exhibits microstructures that differ markedly from those of the FM specimens. Riedel (R-) shear fractures are pervasively developed in the gouge layer between the wall rocks. The gouge layer itself consists of a matrix of angular nanograins with a grain size ranging from a few nanometers to 100 nm, and fragments of calcite aggregate with a foam structure floating within the matrix (Figure 3e). The angular shape of nanograins in the matrix, which lack the foam structure (Figure 3f), suggests cataclastic deformation during the destruction of the FM specimens. Calcite nanograins in the gouge layer show agglomeration by adhesion, but grain-to-grain contacts are rather porous and the grains are less tightly packed than the sintered nanograins in the FM specimen.

The fault zone of BR specimens consists of a gouge layer (∼100 μm thick) and a damaged wall rock zone up to 150 μm thick (Figure 3g). The gouge layer is composed of micrometer-sized angular fragments of wall rock (1–50 μm in size) set in a matrix of calcite nanograins (a few of which were ∼100 nm in size) (Figures 3h and 3i). As in the CF specimens, the gouge layer of BR specimens shows pervasive development of R-shear fractures, and the calcite grains in the matrix of the layer similarly show agglomeration by adhesion.

Due to the relatively small total slip distances in SHS tests compared with the specimen preparation procedures, the microstructures of the fault rocks before and after SHS test do not differ significantly. After the SHS tests, the FM and CF specimens showed evidence of cataclastic flow within the gouge layer; for example, the proportion of angular fragments of nanograin aggregates increased in the FM specimen (Figure s5a). In addition, intact aggregates of sintered nanograins at the Y-shear plane suggest that rigid-body translation occurs along the Y-shear planes. In the CF specimens, microstructures were similar to those before the SHS test except that the amount of micrometer-sized angular fragments decreased by further cataclasis (Figures S5b and S5c). The final microstructures of the BR specimens do not differ noticeably from those before the tests showing micrometer-sized angular fragments and a fine nanograin matrix in the gouge layer between the damaged wall rocks (Figures S5d and S5e).

4. Discussion and Implications

4.1. Extremely Low Friction Healing Rate of Fault Mirror Specimens

The mechanical data obtained from the SHS tests show remarkably weak frictional healing of carbonate fault mirrors. Such a low frictional healing rate has been reported previously only for phyllosilicate-rich gouges (Carpenter et al., 2011; Katayama et al., 2013; Olsen et al., 1998).

Dieterich and Kilgore (1994) attributed frictional healing behavior to the growth of asperity contact under loading, but more recent studies have suggested that the behavior results from the strengthening of inter-particle bonding (or cohesion) rather than from the growth of the contact area as a result of asperity creep (Li et al., 2011; Muhuri et al., 2003; Thom et al., 2018). Processes such as time-dependent desorption of contamination films (Hirth & Rice, 1980) or capillary bridge formation (Bocquet et al., 1998) have also been proposed as mechanisms of frictional healing. Frictional healing can also be induced by the welding of granular particles by diffusion processes (Yasuahara et al., 2005). All of these processes are closely related to the specific surface area of fault gouge materials.

The experiments that were conducted under a dry N₂ atmosphere showed no significant difference in the frictional healing rate compared with the room-humidity experiments. This result can be interpreted to indicate that water-assisted frictional healing mechanisms (Frye & Marone, 2002) are not major processes in our experiments. However, a possible role of moisture cannot be excluded because it is not certain whether moisture adsorbed onto the nanogouge surface was completely removed in our experiments under dry N₂ conditions. To prevent any disruption of the fault gouge structure, we applied the dry atmosphere without unloading the normal stress on the sample, meaning that the humidity of the samples might not have reached equilibrium with the dry atmosphere. In contrast, Frye and Marone (2002), for instance, exposed and equilibrated samples to controlled humidity conditions before normal stress loading. Nonetheless, even without considering a water-assisted healing mechanism such as capillary bridge formation, the presence...
of agglomerated nanograins in the CF and BR specimens (Figures 3e and 3i) suggests that gouge strengthening by inter-particle sintering was an active frictional healing mechanism.

Given that the sintered nanogouge layer in the FM specimens (Figure 3c) has an annealed, tightly sintered structure and larger grain size, the nanograins in this layer are inferred to have a smaller surface area overall compared with the nanograins in the gouge layers of the CF or BR specimens (also see Sawai et al., 2012; Togo & Shimamoto, 2012). The smaller surface area would lead to weak surface interactions and low chemical reactivity of the nanograins. For example, Goldberg et al. (2016) demonstrated the low chemical reactivity of carbonate fault mirrors by dissolution experiments. As the surface area becomes smaller, agglomeration by surface adhesion is inhibited. Furthermore, particles in FM are less likely to exhibit inter-particle strengthening because of the already densely sintered structure of the FM specimens; as a result, processes such as the formation of additional chemical bonds or sintering during the hold period would have been inhibited. The actual microstructures of FM after the SHS tests show an increase in fracturing in the aggregates of sintered nanograins but no obvious formation of new bonds between nanograins compared with the specimen before the SHS tests (Figure S5a). Furthermore, water adsorption or capillary bridge formation processes would have been inhibited because moisture would not be effectively adsorbed onto the nanograins of the tightly packed nanogouges in FM.

In contrast, the grains composing the crushed gouge of former FM specimens (CF) can be expected to have the highest surface area among the three types of fault rock because of the small grain size (several tens of nanometers) (Figure 3f). Furthermore, the loose nanograin layer of the CF specimens would have been more likely to undergo inter-particle strengthening during the hold time than the tightly sintered nanograins of FM specimens. Microstructural observations of CF showed agglomerates of relatively loosely packed fine nanograins (Figures 3f and S5c). The mechanism responsible for the formation of the agglomerates at the initial stage of frictional healing might be adhesion due to capillary, van der Waals, or electrostatic forces (Bowling, 1988), all of which act more effectively on relatively loosely packed finer grains having a larger overall surface area. These forces would play a substantial role in forming aggregates, leading to more effective healing by sintering and other chemical bonding processes (Chen et al., 2015).

Even though nanograins in the pre-sheared carbonate rock (BR) specimens are similar in size to those of the CF specimens, micrometer-sized angular fragments that originated from erratic failure of the wall rocks were probably being mixed into the gouge layer continuously during the SHS tests, thereby inhibiting agglomeration of the nanograins (e.g., Figure 3h). As a result, the frictional healing rate of the BR specimens, which contained large angular fragments, is intermediate between those of the FM and CF specimens.

4.2. Implications of the Fault Mirror Having Low Frictional Healing Rate in Natural Fault Zone

The mode of tectonic slip on the fault mirror would be determined by its frictional stability and the stiffness of the surrounding fault zone (e.g., Scholz, 1998). Frictional stability can be represented by the friction rate parameter $a - b$, defined as follows:

$$a - b = \frac{d\mu_s}{d(\ln V)}$$

where $\mu_s$ is the steady-state friction coefficient, $V$ is the slip velocity, and $a$ and $b$ are empirically driven frictional properties. If $a - b$ is positive, the fault rock exhibits velocity-strengthening friction and is frictionally stable. In the case of velocity-weakening friction, the fault rock would be conditionally unstable, leading to stick-slip motion depending on the stiffness of the surrounding fault zone. Considering the frictional evolution suggested by the aging law of Dieterich (1978), $b$ is identical to the frictional healing rate for long hold periods (Scholz, 2019). Since $a$ is always larger than 0, the extremely low frictional healing rates of the carbonate fault mirrors observed in this study (Figure 2b) suggest that the values of $a - b$ for the fault mirror patches are likely to be positive, hence frictionally stable. The low frictional healing rates of fault mirrors would also hinder strength recovery, thus keeping the stress around the fault mirror patches low compared with neighboring areas. This hindered strength recovery would further make the fault mirror less likely to host regular earthquakes and more prone to aseismic creep. Nonetheless, the friction-velocity dependence of a fault mirror would be dependent on various parameters such as temperature and fluid pore pressure.
For instance, Verberne et al. (2014) investigated the velocity dependence of mirror-like surfaces formed from calcite gouges, which exhibit velocity-strengthening and -weakening behavior under temperature conditions of 18°C and 140°C, respectively. Further investigations of the velocity dependence and healing rate of fault mirrors under various pressures, temperatures, and fluid conditions are needed for a better understanding of the role of fault mirrors in faulting mechanics.

Exhumed carbonate fault rock surfaces are commonly characterized by fault mirrors (Demurtas et al., 2016; Fondriest et al., 2013; Siman-Tov et al., 2013; Tesei et al., 2013), and experimental studies have shown that carbonate fault mirrors can be generated under a range of normal stresses and slip rates (Fondriest et al., 2013; Siman-Tov et al., 2015; Smith et al., 2013; Verberne et al., 2014). In view of these previous results, fault mirrors can be presumed to be prevalent on active carbonate fault surfaces. The prevalence of fault mirrors and their low frictional healing rates imply that we should take into account the frictional behavior of fault mirrors for modeling the fault zone containing fault mirror patches. Given the characteristic low frictional healing rate of the carbonate fault mirror specimens identified in this study, carbonate fault zones containing fault mirror patches would likely exhibit substantial spatial heterogeneity with respect to frictional properties, which would lead to complex earthquake nucleation and fault slip, as reported for the 2009 L'Aquila (Italy) earthquake (Carpenter et al., 2014; Di Stefano et al., 2011).

Fault mirrors consisting of sintered nanograins of non-carbonate minerals have often been reported (Kuo et al., 2016; Power & Tullis, 1989; Viti et al., 2016). Our finding that carbonate fault mirrors show extremely low frictional healing rates suggests that fault mirrors composed of other minerals might also have comparably low frictional healing rates, once they are composed of tightly packed sintered nanograins. We suggest that impeded frictional healing may be a common behavior of fault mirrors that consist of densely packed sintered minerals. Further frictional experiments with various types of fault mirrors are needed to improve our understanding of the frictional healing behavior of fault mirrors.

5. Conclusion

We performed SHS friction tests on experimentally produced carbonate fault mirrors and specimens of two other types of carbonate fault rock (pre-sheared bare rocks and crushed fault mirrors). Our experimental results showed that the carbonate fault mirrors have a frictional healing rate an order of magnitude lower than those of the other two types of carbonate fault rock. The low frictional healing rate of fault mirrors can be attributed to deterred healing processes caused by the densely sintered structure of the fault gouge. We expect impeded frictional healing to be a common behavior of fault mirrors that consist of tightly sintered nanograins. Fault mirrors may also be a source of aseismic creep owing to their impeded frictional healing, and consequently might cause the fault zone to become heterogeneous with respect to frictional properties and earthquake generation modes.

Data Availability Statement

Mechanical data used in this study are available online at https://doi.org/10.4121/14634021.v1. All experiments are summarized in Table S1.

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