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Changes in permeability caused by dynamic stresses in fractured sandstone

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[1] Shaking-induced changes in permeability have been invoked to explain a wide range of hydrologic responses to earthquakes. We measure the evolution of permeability in fractured sandstone in response to repeated shaking under undrained conditions. The frequency and amplitude of the imposed shaking are similar to those from earthquakes at distances of $\sim$ a fault length from the ruptured fault. To assess the role of mobile particles, we also add silt-sized particles to the fractures. We find that, in general, permeability decreases after shaking. The samples with added particles show larger changes in permeability. Shaking-induced transport of particles to block narrow fracture apertures can explain some of the observations. We also find that decreases in permeability are often accompanied by a contraction of sample indicating that fracture apertures sometimes decrease, presumably by mobilizing particles and removing asperities that hold fractures open. **Citation:** Liu, W., and M. Manga (2009), Changes in permeability caused by dynamic stresses in fractured sandstone, *Geophys. Res. Lett.*, *36*, L20307, doi:10.1029/2009GL039852.

1. Introduction

[2] A great variety of hydrologic phenomena have been documented in response to earthquakes, including changes in streamflow and spring discharge, changes in the water level in wells, the eruption of mud volcanoes, and liquefaction of unconsolidated sediment (see *Manga and Wang* [2007] for a recent review). Interestingly, many of these phenomena have been documented at great distances from the ruptured fault where static stress changes are very small. Consequently, dynamic (time-varying) stresses associated with the passage of seismic waves have been proposed as the ultimate origin of the changes. In particular, many of the responses have been attributed to changes in permeability induced by the dynamic stresses generated by the earthquake [*Roeloffs*, 1998; *Brodsky et al.*, 2003]. The shaking caused by earthquakes induces time-varying flow of fluids in pore spaces and fractures. Changes in flow can remobilize particles deposited in porous materials [e.g., *Cleasby et al.*, 1963; *Bai and Tien*, 1997; *Bergendahl and Grasso*, 2000; *Gao et al.*, 2004], which in turn can change permeability. Fracture clearing and increased permeability were invoked to explain a number of hydrologic responses to distant earthquakes: water level changes in wells [*Roeloffs*, 1998; *Brodsky et al.*, 2003; *Wang and Chia*, 2008]; permeability changes [*Elkhoury et al.*, 2006]; changes in spring temperature [*Mogi et al.*, 1989]; liquefaction in the far-field [*Wang*, 2007].

[3] In the present study we apply time varying stresses under undrained conditions to a fractured sandstone, with permeabilities similar to that of the shallow crust [e.g., *Manning and Ingebritsen*, 1999], and measure the resulting permeability changes. The magnitude and frequency of the stress changes we apply are intended to be representative of those that cause distant hydrological responses – comparable to the stresses $\sim$ a fault length away from the ruptured fault. The applied stresses, 10s of kPa, are thus far smaller than failure stresses, 10s of MPa, that enhance permeability by creating microcracks and damage zones around faults [e.g., *Mitchell and Faulkner*, 2008]. We show that shaking typically reduces permeability and that repeated shaking can continue to reduce permeability.

2. Experimental Procedure

[4] We used the Mechanical Testing and Simulation 815.02 system (hereafter MTS) as a platform for generating shaking and measuring seepage. A schematic illustration of the experimental setup is provided in the auxiliary material.[3] The MTS has a strain measurement precision meeting or exceeding requirements for calibration according to ISO 9513 class 0.5 and ASTM E83 class B-1 (http://www.mts.com). We used sandstone samples from the Huainan-Guqiao mine, China, that were excavated from a depth of 300 m. The sandstone was machined into cylinders 50 mm in diameter and 100 mm long. Uniaxial compression was applied to (dry) samples until failure, about 30 MPa. Figure 1 shows the samples after failure; note that the samples did not fall apart after failure so little mass was lost from the samples. We then chose three samples that had through-going fractures, but no widespread damage, and used these to study the effects of shaking on seepage. Permeability of intact samples of this sandstone is typically of order 10^{-14} m^2. Permeability typically increased about an order of magnitude after failure.

[5] Prior to shaking the samples were saturated by soaking in water for more than 12 hours and by injection of low-pore pressure water. The saturated samples were sealed with PVC bands and thermo-shrinking plastic sleeves. We then applied an axial load of 500 N (axial stress of 255 KPa) with the MTS, and permeability was measured with a steady-flow testing method.

[6] Shaking was realized by moving a plate affixed to the bottom end of the cylinder up and down while holding

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[3]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039852.

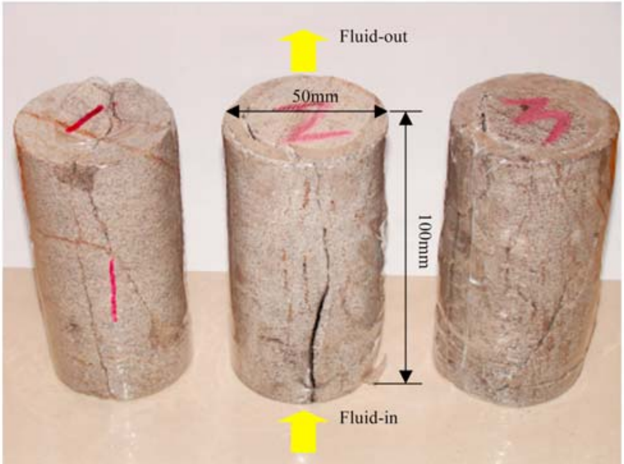

Figure 1. Fractured sandstone samples used to test the effect of shaking on permeability. Numbers indicate sample numbers.

the other end fixed. In this set of experiments we did not apply shear stresses, even though it has been proposed recently that shear waves can also change permeability [*Wang et al.*, 2009]. The displacement has the form of triangle waves (Figure 2) with an amplitude of 0.01 mm. The implied strain amplitude, 10^{-4}, is comparable to those at distances roughly a fault length away from earthquake epicenters. The frequency ranged from 0.3 Hz to 2.5 Hz. Shaking was applied in five continuous cycles. After each round of shaking, shaking ceased for at least 80 seconds in order to reach a steady seepage flow and permeability was measured using Darcy's equation (see auxiliary material for equation). Steady flow was not reached until at least 10 seconds. Permeability was not observed to change over the 30–150 seconds of steady seepage between episodes of shaking. Since the period over which pore pressure equilibrates (>10 s) is longer than the longest period of the imposed dynamic stresses, shaking occurs under close to undrained conditions. This is the relevant limit for seismic waves.

[7] Because particles and their mobility have been proposed to explain some of the shaking-induced changes in permeability [e.g., *Brodsky et al.*, 2003; *Elkhoury et al.*, 2006, also Dynamic stress stimulates flow in fractures, submitted to *Journal of Geophysical Research*, 2009], we also performed a series of measurements after adding particles to the fractures. The particles were natural silt particles, filtered to a mean diameter of 50 microns, collected from the riverbed of the Grand Canal of China around Xuzhou. The silt was injected with a syringe in order to minimize the changes in fracture geometry and to avoid damaging the seals surrounding the sample. Owing to differences in fracture width between samples, the quantity of silt injected into fractures are respectively 0.3 and 0.6 g for samples 2 and 3. Shaking was applied as before: 5 cycles of a triangular wave with strain amplitude 10^{-4} and frequency from 0.3 to 2.5 Hz.

3. Results

[8] Sample 1 was used to measure the effect of silt injection on permeability (see auxiliary material) and results are not directly relevant for the present study. The effects of shaking were characterized for samples 2 and 3. Sample 2 had a diameter of 52.09 mm after being fractured, while the diameter of sample 3 was 52.56 mm. We infer from this diameter change that the width of fractures in sample 3 were greater. Indeed, the permeability of sample 3 is slightly higher than that of sample 2. Measurements are summarized in Table S1 presented in the auxiliary material.

[9] Figure 3a shows the evolution of permeability and axial strain with each cycle of shaking. As permeability is dominated by the fractures, we use changes in the bulk measured permeability as a proxy for the evolution of fracture permeability. Each point in Figure 3a shows the measured quantity after shaking at the indicated frequency. Shaking proceeded from the lowest to highest frequencies, so the data points shown at a frequency of 2.5 Hz correspond to samples that experienced 7 sets of shaking.

[10] There are 4 features of these data that stand out. First, as expected, adding silt to the fractures decreases the permeability. Second, following the first round of shaking, the permeability decreases. With further shaking, permeability continues to decrease in the sample without silt in the fractures until it reaches a new, steady value. In general, corresponding to the decrease in permeability is an increase in axial strain (contraction), as shown in Figure 3b. Third, in the samples with added silt, permeability also typically, but not always, decreases after shaking. As shown in Figure 4, decreases in permeability, Δk, between each episode of shaking are usually, but not always, accompanied by a contraction of the sample. Fourth, the amount of permeability decrease with each new round of shaking becomes progressively smaller.

4. Discussion

[11] Dynamic strains cause time varying fluid flow that can redistribute particles within fractures and other pore spaces. In our experiments this includes both naturally formed particles on the fracture surfaces, and the silt-sized particles injected into the fractures. The redistribution of particles, as illustrated in Figure 5, can explain all the phenomena we document in these experiments.

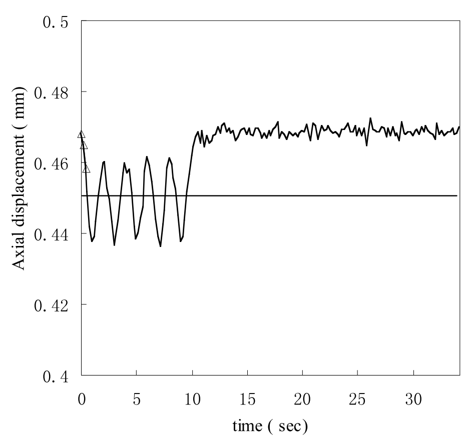

Figure 2. Example displacement applied to the sample, here for sample 3 at 0.5 Hz. 5 cycles of deformation are applied and then seepage is measured.

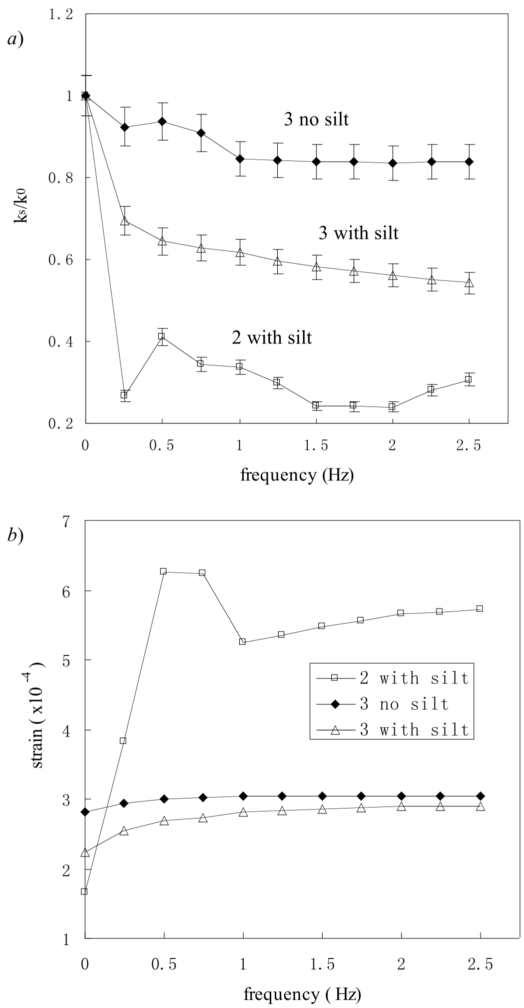

Figure 3. (a) Permeability after shaking (k_s) normalized by the permeability prior to any shaking (k_o). (b) Axial strain. In both Figures 3a and 3b, measurements are made at progressively increasing frequency of shaking, plotted on the horizontal axis.

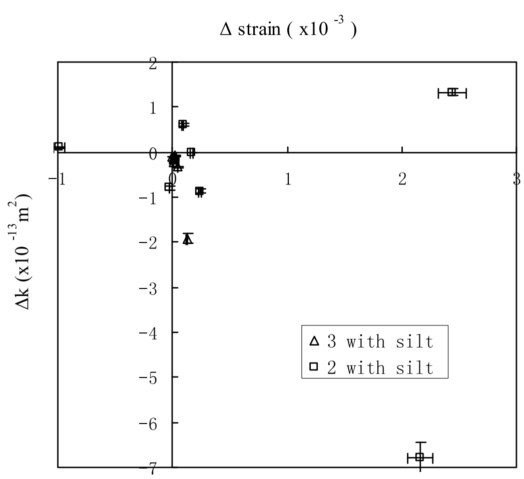

Figure 4. Relationship between the change in permeability between two successive shaking events and the axial strain between those events.

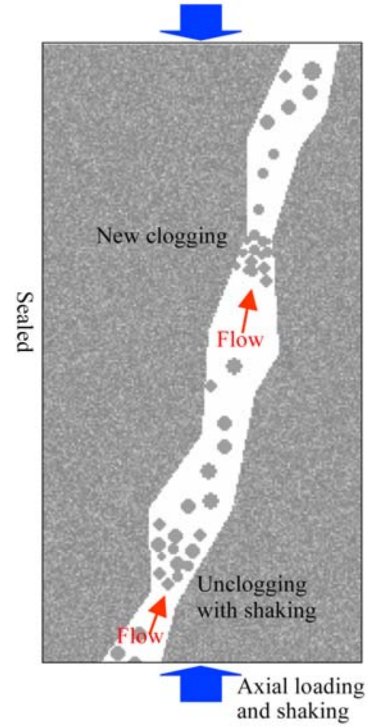

Figure 5. Clogging and unclogging of a fracture by particles.

[12] The addition of particles to the samples lowers the permeability, as expected. Measurements on sample 1 confirm that permeability decreases as the volume of particles added increases (see auxiliary material). Particles are expected to accumulate and get trapped at the narrowest constrictions along flow paths, effectively clogging the sample. Remobilization of these particles can have two competing effects. First, if clogs are removed, permeability can increase. Second, the time-varying changes in pore and fracture geometry during shaking can allow particles to move away from regions where they hold open pore spaces, and hence allow a consolidation (contraction) of the sample. The resulting decrease in mean fracture width will decrease permeability. This reduction in permeability does not continue indefinitely. For the no-silt experiment in Figure 3, permeability reaches a steady value 18% lower than the pre-shaking value. The incremental decrease in permeability for the same sample with silt is larger, but induced changes decrease with each episode of shaking.

[13] Our experiments show evidence of both effects of shaking. The increases in permeability after some episodes of shaking are most easily explained by removing particles that block flow paths. This is the most common observation resulting from time-varying flows mobilizing colloidal particles [e.g., *Cleasby et al.*, 1963; *Bai and Tien*, 1997; *Bergendahl and Grasso*, 2000; *Gao et al.*, 2004], Field observations also imply increases in permeability by distant earthquake [e.g., *Elkhoury et al.*, 2006]. The increase in permeability is uncommon, however, in our experiments. After most episodes of shaking, permeability decreases, even for the sample with added particles. Figure 3b also shows that there is usually axial contraction associated with the decrease in permeability even though the applied force

remains constant (500 N). The axial strain implies a decrease in the mean width of fracture apertures, consistent with the decrease in permeability.

[14] The importance of particles within the fracture is highlighted by the comparison of the no-silt and added-silt experiments in Figure 3a. Each episode of shaking produced a greater change in permeability for the samples with added silt.

[15] Our experiments complement the experiments of Elkhoury et al. (submitted manuscript, 2009) but differ in two ways. First, we apply time varying axial stresses whereas Elkhoury et al. (submitted manuscript, 2009) applied time varying fluid pressure differences across their samples. Second, shaking occurs under undrained conditions in our experiments, but drained by Elkhoury et al. (submitted manuscript, 2009). Owing to the long-wavelength of seismic waves, natural geological materials experience time varying stresses under undrained conditions. Interestingly, the sign of the permeability changes are the opposite in the two experiments – Elkhoury et al. (submitted manuscript, 2009) documented a permeability increase that scaled with the magnitude of the oscillations in pore pressure. Here, we found that in most cases permeability decreased. We propose two possible explanations for this difference. First, because our conditions are undrained, our (larger) particles have a more limited amount of time to be remobilized and are transported small distances. Second, because we apply an (small) axial load, the fracture aperture can change as particles are displaced. Figure 4 shows that the sample usually does contract when the permeability decreases, and for sample 3 the permeability decrease was always accompanied by contraction. We do note, however, that Elkhoury et al. (submitted manuscript, 2009) also had large residual shear stresses applied to their samples.

[16] There is an unfortunate limitation in our experimental measurements that hinders our ability to decipher the controls on permeability changes: we cannot repeat each experiment with the same initial conditions to isolate and asses the role of frequency, amplitude and amount of silt, because the geometry of the sample is different after each episode of shaking. That is, upon shaking and measurement, we cannot recover the same initial conditions.

[17] In summary, we measured the response of permeability to time varying stresses under conditions similar to those produced by earthquakes at $\sim$1 fault length from the fault. Applied dynamics stresses are well below the failure limit for which microcracks and damage will occur. Changes in permeability are instead generated by mobilization of particles and local changes in the aperture of the fractures. On the basis of our measurements, we conclude that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation for earthquake-induced hydrologic responses to earthquakes.

[18] **Acknowledgments.** We thank two reviewers and C.-Y. Wang for comments; we particularly thank Y. Li, G. Wang and Y. Tao for running the experiments. Supported by NSFC 50774083 and 40811120546, NSF EAR 0909701, "973 Program" of China 2005CB221502, and NCET of China 07-0803.

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