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Laboratory evidence for particle mobilization as a mechanism for permeability enhancement via dynamic stressing

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ABSTRACT

It is well-established that seismic waves can increase the permeability in natural systems, yet the mechanism remains poorly understood. We investigate the underlying mechanics by generating well-controlled, repeatable permeability enhancement in laboratory experiments. Pore pressure oscillations, simulating dynamic stresses, were applied to intact and fractured Berea sandstone samples under confining stresses of tens of MPa. Dynamic stressing produces an immediate permeability enhancement ranging from 1 to 60%, which scales with the amplitude of the dynamic strain (7×10^{-7} to 7×10^{-6}) followed by a gradual permeability recovery. We investigated the mechanism by: (1) recording deformation of samples both before and after fracturing during the experiment, (2) varying the chemistry of the water and therefore particle mobility, (3) evaluating the dependence of permeability enhancement and recovery on dynamic stress amplitude, and (4) examining micro-scale pore textures of the rock samples before and after experiments. We find that dynamic stressing does not produce permanent deformation in our samples. Water chemistry has a pronounced effect on the sensitivity to dynamic stressing, with the magnitude of permeability enhancement and the rate of permeability recovery varying with ionic strength of the pore fluid. Permeability recovery rates generally correlate with the permeability enhancement sensitivity. Microstructural observations of our samples show clearing of clay particulates from fracture surfaces during the experiment. From these four lines of evidence, we conclude that a flow-dependent mechanism associated with mobilization of fines controls both the magnitude of the permeability enhancement and the recovery rate in our experiments. We also find that permeability sensitivity to dynamic stressing increases after fracturing, which is a process that generates abundant particulate matter in situ. Our results suggest that fluid permeability in many areas of the Earth's crust, particularly where pore fluids favor particle mobilization, should be sensitive to dynamic stressing.

1. Introduction

Earthquakes can cause changes in hydrologic properties of the Earth's crust up to thousands of kilometers from the mainshock. Transient changes in water well levels, anomalous tidal responses, mud volcanoes and geysers, and anomalous stream- and spring-discharge all occur surprisingly far from the causative earthquakes (Coble, 1965; Roeloffs, 1998; Brodsky et al., 2003; Elkhoury et al., 2006; Xue et al., 2013; Manga et al., 2003; Manga and Rowland, 2009; Manga, 2007; Manga and Wang, 2007). At such large distances the static stress changes caused by slip on the ruptured fault are very small, and only dynamic stresses, i.e. shaking, can be invoked to explain the observations. Dynamic shaking can also enhance oil recovery, which explains the long history of study on stimulation by low-amplitude stresses to enhance fluid flow in petroleum reservoirs (Beresnev and Johnson, 1994; Nikolaevskiy et al., 1996; Kouznetsov et al., 1998; Roberts et al., 2003).

A growing body of evidence suggests that many of these hydrological responses to seismic waves are most easily explained by increases in permeability that persist after the passage of the seismic waves (Manga et al., 2003; Manga and Brodsky, 2006; Elkhoury et al., 2006; Doan et al., 2007; Elkhoury et al., 2011; Xue et al., 2013). The dynamic strains of passing seismic waves can result in large oscillations in pore pressure which in turn drive permeability changes (Brodsky et al., 2003). More speculatively, this cascade of interactions between earthquakes and water may even remotely trigger earthquakes (Brodsky et al., 2003; van der Elst et al., 2013). In this scenario, dynamic stresses increase the aquifer permeability and accelerate diffusion of pore pressure into faults, causing destabilization.

Seismically-generated permeability changes are well-documented in direct water well measurements, but the mechanism by

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which dynamic stressing, via seismic waves or otherwise, causes persistent permeability changes is unknown. Although permeability changes due to persistent changes in effective stress have long been known (e.g., Gangi, 1978), the persistent permeability increase in response to oscillatory transient forcing requires a new explanation (Manga et al., 2012). Mobilization of particles has been a leading candidate, yet there has been no direct evidence for its efficacy (Roberts, 2005; Roberts and Abdel-Fattah, 2009; Liu and Manga, 2009; Elkhoury et al., 2011). Oscillations in pore pressure resulting from the passage of seismic waves could drive a flow that dislodges fine particles clogging pore throats, which would generate dynamic permeability enhancement (Brodsky et al., 2003; Roberts, 2005; Elkhoury et al., 2011). In this case, the gradual recovery of permeability to its initial state could be related to re-clogging of pore throats via slow migration of fine particles after the dynamic stimulation. Another possibility is that the transient stresses cause micro-fracturing damage. The pore-pressure oscillations result in effective stress oscillations that could result in crack growth. Growth of micro-cracks that heal quickly could lead to persistent, but recoverable permeability changes (Liu and Manga, 2009; Manga et al., 2012). A third possibility is that poroelastic flow out of a fracture could impose a separation between the direct increase in fracture aperture and recovery processes that results in a long-term increase in fracture permeability immediately after an oscillatory perturbation (e.g., Faoro et al., 2012).

Prior laboratory experiments show that pore pressure oscillations can produce permeability increases in lithified rock that: (1) scale with amplitude of the perturbations and (2) persist long after the oscillations cease (Elkhoury et al., 2011). Here we expand on existing works and report on a systematic set of experiments to explore the evolution of permeability for intact and fractured rock for a range of water solution chemistries and flow rates. Our experimental set-up is designed to separate the three major candidate mechanisms: (i) dislodging of fines by oscillatory flow followed by the progressive re-clogging of pore throats via slow migration of fines, (ii) damage followed by micro-fracture healing, (iii) direct increase in aperture followed by poroelastic drainage resulting in prolonged fracture opening. We impose dynamic stresses via pore fluid pressure oscillations and analyze the resulting evolution of permeability. We also studied pore structure and fracture microstructure before and after sample deformation. Our experiments are qualitatively different than other studies of permeability evolution that focused on sand or glass-bead packs (Thomas and Chrysikopoulos, 2007), step-changes in fluid pressure (Faoro et al., 2012) or solid mechanical stress (Roberts, 2005; Liu and Manga, 2009).

We begin by summarizing the laboratory configuration and experiment details and then outline our study strategy of four distinct experimental tests with their mechanistic implications. Following an overview of the results to orient the reader, we carefully articulate the test predictions and then proceed with a point-by-point comparison of the data to the predictions of each mechanism. Our results indicate that particle mobility is the most likely candidate, and thus we close with an examination of the theoretical basis for coupling particle mobilization to fluid chemistry, including the possibility that dynamic permeability enhancement is most effective in regions, or times, with unusual water chemistry.

2. Experimental apparatus and set-up

The experimental apparatus consists of a pressure vessel within a biaxial load frame (Samuelson et al., 2009; Ikari et al., 2009). Rock samples are subjected to a true triaxial stress state under controlled pore fluid pressure via two applied loads and the confining pressure (Fig. 1). Each axis of triaxial loading is servo-controlled independently and all stresses, strains, fluid pressures and fluid volumes were measured continuously during experiments. Fluid permeability was measured using upstream and downstream pore-pressure intensifiers (Fig. 1).

All stresses, displacements and strains were measured with a 24-bit analog to digital converter at 10 kHz and averaged to recording rates of 1 to 100 Hz depending on the experiment stage. Vertical and horizontal load point displacements were measured with Direct-Current Displacement Transducers (DCDT) mounted on the biaxial load frame (Fig. 1). To determine elastic strain and damage across the future fracture plane, we used a Linear Variable Differential Transformer (LVDT) mounted within the pressure vessel (Fig. 1(d)). All displacements were recorded with ± 0.1 μm precision. Applied stresses were measured with strain gauge load cells, calibrated with a proving ring traceable to the National Bureau of Standards, and recorded with force resolution of ± 10 N ($\sim$4.4 kPa on the eventual fracture plane which has nominal dimensions of 45 mm $\times$ 50 mm, Fig. 1). Fluid pressures were measured using transducers mounted at the pressure intensifiers accurate to ± 0.007 MPa.

We used samples of Berea Sandstone, which were: (1) cut into L-shaped blocks measuring 68 $\times$ 45 $\times$ 50 $\times$ 29 mm (Fig. 1(b)), (2) presaturated with the pore fluid to be used during the experiment, (3) jacketed in a latex membrane, and (4) placed in the direct shear configuration (Fig. 1).

Experiments started with application of a small stress applied in the direction normal to the major plane of the L-shaped sample (this will be the normal stress across the future fracture plane), after which confining pressure was applied. Normal stress and confining pressures were then raised to the target values of 10–40 MPa and 5–16 MPa, respectively, (Table 1). These stresses were maintained constant via fast-acting servohydraulic controllers. The vertical ram of the biaxial load frame was used to apply stress to the top of the sample, via a displacement rate boundary condition. We explored a range of effective normal stresses from 9.5–40 MPa, depending on the applied pore pressure (Table 1).

After the triaxial stress state on a sample was established, we initialized fluid flow through the samples using de-aired, distilled water or brine (Table 1). Pore pressures were servo-controlled independently and applied via a line source at an inlet and outlet, such that flow occurred along the future fracture plane (Fig. 1). The fluid inlet and outlet consist of a narrow channel (1 mm wide 45 mm long, Fig. 1) fed by five 1.6 mm dia. holes in order to homogeneously distribute the flow along the width of the sample (Fig. 1(e)). We applied first a pore pressure Pp at the outlet and flushed the system until clear fluid (without any air bubbles) flowed from the inlet, which was open to the atmosphere. Then the inlet Pp line was connected and we applied a controlled differential pore pressure ΔPp at a given mean value (Table 1). For our suite of experiments, Pp and ΔPp were 2.75–3 MPa and 0.1–0.5 MPa, respectively (see Table 1). Pore pressures were then maintained constant except for imposed pore pressure oscillations.

In order to simulate dynamic stresses, we imposed sinusoidal oscillations in the upstream pore pressure while holding the downstream pore pressure constant (Fig. 2), following the technique of Elkhoury et al. (2011). Dynamic stresses were applied at constant total normal stress via oscillating fluid pressure at the upstream end of the sample (Fig. 1). A range of dynamic stress perturbations were tested (Table 1). We then raised the shear stress until the sample fractured (Fig. 2). For each experiment, we imposed multiple sets of pore pressure oscillations of varying amplitude (0.01–0.5 MPa) on both the intact and fractured sample. We explored the affect of Pp oscillation amplitude but kept the duration (120 s) and period (20 s) constant. The waiting time between sets of dynamic stressing varied between 5 and 45 min (Fig. 2).