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Slow Dynamics of Earth Materials: An Experimental Overview

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Abstract—In 1996 JOHNSON *et al.* were the first to identify peculiar rate effects in resonant bar experiments on various earth materials. The effects were evident on time scales of minutes to hours. They were also seen in both sedimentary and crystalline rocks, and have since been seen in geomaterials like concrete. Although these effects resemble some aspects of creep and creep recovery, they can be induced by a sinusoidal acoustic drive at strains three orders of magnitude below typical creep experiments. These strains are only a few tenths of a microstrain. Moreover, unlike most creep behavior, the effects have been shown to be macroscopically reversible and repeatable, over hundreds of experiments spanning nearly a year. The unique excitation and character of these rate effects cause them to be called *slow dynamics*. A review and discussion of slow dynamics is presented, pointing out similarities and differences with ordinary creep and focusing on laboratory experiments. A brief description of some possible mechanisms is included, and a new experiment on a sample of Berea sandstone in ultra high vacuum is shown to point out new research that hopes to help ascertain the role of water as a potential mechanism.

Key words: Slow dynamics, emergent creep, creep, stress relaxation, creep recovery.

1. Introduction

Since before recorded history, mankind has been carving out dwellings, hammering out monuments, and even building cities out of rocks. We extract oil and gas from rocks, and try to mimic their resilience and durability with concrete. The imperfect way in which grains end up being cemented together dictates the way fluids can move in oil or gas reservoir rocks. In addition, understanding friction and brittle fracture growth in rocks is essential for understanding faulting and earthquakes (e.g., SCHOLZ, 2002). Thus, the dynamic behavior of rocks has been a topic of great interest and continuing scientific study for well over a century.

By observing and measuring the dynamic behavior of a rock, one can hope to learn about its structure and how it may fail without having to actually destroy it in the process. *Slow dynamics* is perhaps one of the most interesting yet little known dynamic behaviors a rock can have and is the subject of the experiments discussed in this overview. Slow dynamics, by definition, is behavior reminiscent of creep, although induced by strains *three orders of magnitude* below a typical creep experiment. In addition, this creep-like behavior can be excited by a small *sinusoidal* acoustic source excitation and is remarkably reversible and repeatable. A careful study of slow dynamics may make it possible to learn about emergent behavior, e.g., subcritical crack growth, healing, contact rate growth, friction, etc., with a simple set of experiments. Slow dynamics may provide new insight into a little studied regime, one not quite brittle or ductile, perhaps a glasslike state in between.

Much of the slow dynamics behavior discussed in this paper is similar to behavior seen in the earth over a wide range of scales. For example, earth's mantle and crust are known to show elastic aftereffect and viscous creep for medium to long time stress durations (e.g., SCHEIDEGGER, 1957). On a smaller scale, seismic waveforms of repeating multiplets after the 1989 Loma Prieta earthquake have shown temporal changes over a period of 5 years very similar to what is seen in slow dynamics recovery (BAISCH and BOKELMANN, 2001). In a similar vein, RUBINSTEIN and BEROZA (2004) examined temporal changes with 55 repeating earthquake sequences after the 1989 Loma Prieta and Chittenden aftershock earthquakes. A different approach, spectral ratios, was used to examine

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temporal changes after the Izmit and Düzce earthquake; an excellent discussion of this and related work with possible links to laboratory experiments may be found in Wu *et al*. (2009).

In addition, experiments in rocks using (1) applied and released loads on various rocks carried out by Lomnitz (1957) and Pandit and Savage (1973); (2) abrupt changes of humidity (Clarke, 1980); and (3) sudden temperature changes (Darling *et al*., 2006) also result in behavior reminiscent of slow dynamics. For the interested reader, Chapter 10, *Quasistatic Measurements*, in Guyer and Johnson (2009) presents a careful overview and a context for some of these later laboratory scale experiments and other related work beyond the scope of this review.

It has been suggested (TenCate *et al*., 2000) that slow dynamics might be a new, emergent form of creep. Admittedly, however, there still is *not* general agreement on the nature of slow dynamics in spite of having first been carefully studied in the mid-1990s. Thus, this paper begins with a brief review of classic laboratory observations in rocks of reversible creep (and creep recovery) to set the context for an overview of slow dynamics experiments. The paper continues with a description of the main results of several slow dynamics experiments on various samples along with discussion of parallels and significant differences of the observed behavior when compared with creep. Finally, an introduction to just a few of the possible mechanisms that have been proposed is presented, and the paper concludes with new experiments that are starting to explore mechanisms for slow dynamics, e.g., hydrolyzed bonding.

There is no one single place to find a summary and overview of slow dynamics experiments to date; much of it is scattered in the physics, geophysics, and acoustics literature. The primary purpose of this review is to bring more attention to laboratory-scale slow dynamics by assembling an experimental overview that directs the researcher to places where more can be learned. Slow dynamics may well prove to be an indicator and precursor to brittle deformation and fracture, and may also help us learn about processes that happen well before fracture, a regime that has not yet been fully studied.

2. Historical Perspective

Rocks have been known to be nonlinear and hysteretic since the turn of the last century (e.g., Adams and Coker, 1906). Numerous cyclic quasistatic stress-strain measurements were made on a variety of rocks at that time, exploring their unique and peculiar behavior. Some of the deformation that resulted was permanent, but in almost all cases very repeatable hysteresis stress-strain "loops" were obtained after the initial permanent deformation. Rocks and other earth materials were modeled in the late 1970s using a Preisach approach because of similarities with the hysteresis seen in magnetic systems—see Bertotti (1998) for a good introduction to Preisach models. Holcomb (1978, 1981) performed initial pioneering work using a Preisach model for rocks, and Guyer and numerous colleagues then fully developed and extended the modeling to present-day state-of-the-art (e.g., Guyer, 2006). Modeling a rock and its hysteresis with a Preisach approach—a collection of discrete phenomenological hysteretic elements—is not perfect however.

It is well known that rocks are highly nonlinear (Johnson *et al*., 1996). Yet, in addition, important rate effects are also always present in their dynamic behavior, effects even apparent in Adams and Coker's experiments of 1906. Creep was observed upon application of an initial stress; removal of that applied stress resulted in creep recovery. (Note that creep recovery is sometimes called *elastic aftereffect*, *stress-relaxation* or *stress-recovery*, depending on the field or experiment.) Although creep as a result of an applied stress often results in permanent plastic deformation, much of it is often recoverable; subsequently, creep recovery or elastic aftereffect (Mack, 1946) returns the rock to its initial state in a characteristic log(*recovery time*) behavior. Notably, understanding and untangling intrinsic properties like hysteresis from rate-dependent processes like creep or elastic aftereffect can be complicated. Claytor *et al*. (2009), for example, showed that if a quasistatic stress-strain measurement for a sample of Berea sandstone is done slowly enough (e.g., over a few days), allowing the rock to fully "equilibrate" after each incremental change of stress, both hysteresis and rate effects disappear entirely and no permanent damage or other changes remain. Note that GUYER and JOHNSON (2009) point out that any of these intermediate steps is essentially a non-equilibrium steady state (NESS).

We now explore a significant departure from classic creep observations in stress-strain experiments. The measurements and observations described above are responses to a *static* change applied to a sample (which we denote 'DC', as an analog to electric current) and, in the case of most quasi-static stress-strain measurements, were done at strains of about 10^{-3}. The focus is now a different set of experiments where the rock is subjected to an applied *sinusoidal acoustic* (AC) drive that, surprisingly, results in some similar creeplike behaviors to those described above and at applied strains three orders of magnitude smaller.

3. *Slow Dynamics: a Different Kind of Experiment*

A long thin rod or core sample has a clearly defined set of resonances. Exciting a sample by sweeping through a quasi-1D Young's mode resonance is a common way to measure wave speed and attenuation of a core sample; resonance itself also makes it easy to produce a considerable amount of strain amplitude. In addition, shifts of resonance frequencies of 1 ppm are easy to detect and measure. Studying resonances of a known geometry can even occasionally yield information about the full elastic tensor of the rock. However, a sweep through a resonance frequency also coincidentally yields an applied increasing and then decreasing strain energy, much like the increasing and decreasing force protocol in a quasi-static stress-strain measurement. What is different in a resonance experiment is that the energy is applied via a sinusoidal acoustic (AC) drive and is considerably smaller than a sample would experience in a load frame. We now report on several observations where creeplike behavior was seen in resonant bar experiments, behavior coined "slow dynamics" because of how it is excited and to clearly distinguish it from ordinary creep and creep recovery.

Observations of induced slow dynamics behavior from a small—less than a microstrain—applied sinusoidal acoustic drive and subsequent relaxation effects in thin rock core sample were first noted in the early 1990s (JOHNSON *et al.*, 1996). Although the focus of the paper was nonlinearity, the authors noted that sweep rate and relaxation effects in resonant bar experiments were always present for a wide variety of samples. Moreover, they pointed out that the applied acoustic drive always softened the modulus of the rock during the resonance sweep. TENCATE and SHANKLAND (1996) explored the acoustic sweep-rate behavior in great detail and dubbed the behavior "slow dynamics" to distinguish it from standard engineering creep and creep recovery behavior. Slow dynamics, as originally defined in that paper, included *both* the induced softening-modulus behavior (called conditioning) and the relaxation back to the starting modulus (recovery). Notably, both the conditioning and recovery measurements on the same rock in a controlled environment were reversible and repeatable over many months and hundreds of experiments.

An experiment was performed showing how slow dynamics rate effects manifest themselves in resonant bar measurements, and the results are shown in Fig. 1. Full experimental details of how these experiments are performed can be found in TENCATE and SHANKLAND (1996). As an example, a series of upward (blue) and downward-going (red) frequency sweeps over a resonance was made on a ~300cm-long, 25.4-mm (1 in.) diameter sample of red Vosges sandstone at increasing drive levels. At low amplitudes, upward and downward curves completely overlap, and the shape is the expected characteristic Lorentzian function, the resonance shape of a linear forced oscillator. However, at higher drive levels—yet still at strains as small as a few tenths of a microstrain (PASQUALINI *et al.*, 2007)—the upward and downward curves trace out different upward and downward paths depending on sweep rate and direction. The red and blue curves separate at strains of around 1×10^{-6}. The increasing and decreasing strain protocol from going through resonance results in (1) the modulus softening during the increasing strain phase and (2) recovering and stiffening during the decreasing strain phase. The results are peculiar bent-over resonance curves that show both nonlinearity and slow dynamics. Such behavior is not unusual and has been observed in a wide range of

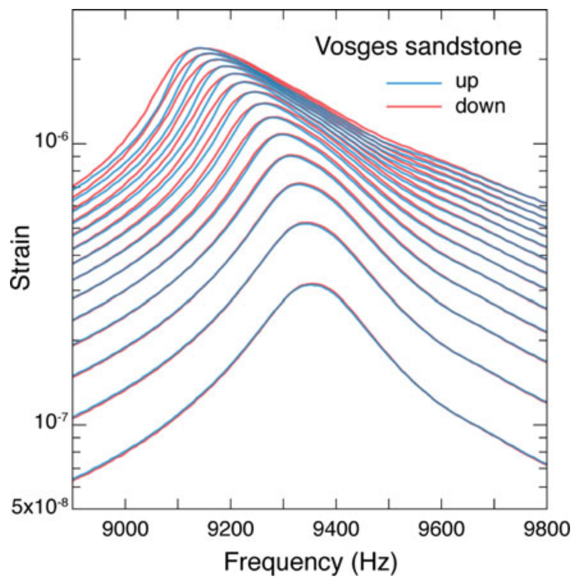

Figure 1
A family of swept resonance curves, frequency versus strain, for a 0.30-m-long, 25.4-mm-diameter (i.e., industry standard 1 in cores) bar of Vosges sandstone for 14 different drive levels. *Blue curves* are taken going up in frequency; *red curves* are taken going down in frequency. Upward and downward going curves overlap at low drive levels and begin to separate at strains of around 10^{-6}. The second lowest longitudinal mode is shown here

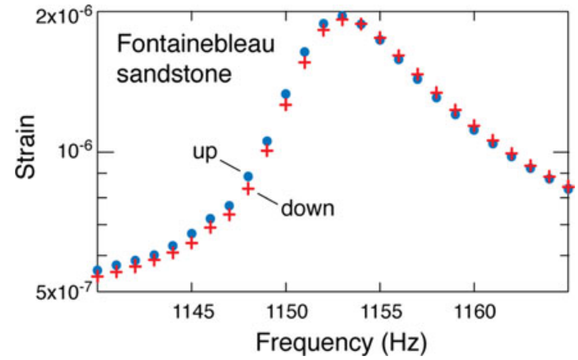

Figure 2
A single up/down resonance curve for a Fontainebleau sandstone sample, 25.4 mm diameter and 0.33 m long, mounted in an environmental chamber to minimize effects of temperature. The frequency "sweep" was performed by stepping the frequency, waiting 8 h for the rock to "equilibrate," and then taking a measurement. As in Fig. 1, *blue* data are taken going up in frequency; *red* data are taken going down. *Errors bars* have been omitted for clarity. However, within the *error bars*, the two curves are essentially identical. Rate effects have been eliminated in this measurement

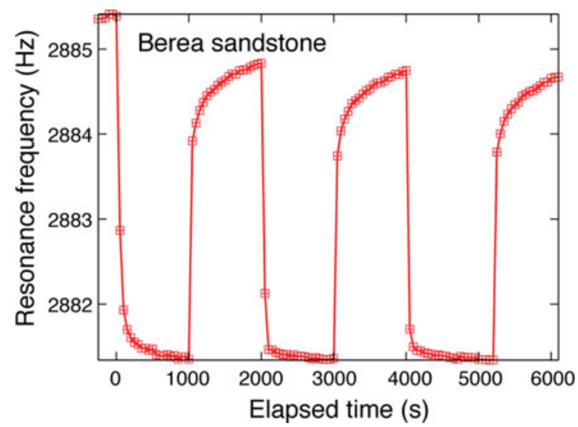

Figure 3
Resonance frequencies plotted as a function of time for a Berea sandstone bar 25.4 mm diameter and 0.35 m long. At time $t = 0$, a (conditioning) strain of 10^{-6} was applied for 1,000 s ($\sim$15 min) and then turned off for the same period of time (recovery) and repeated twice more. Resonance frequency was tracked throughout the experiment with a very small strain frequency sweep

both sedimentary and crystalline rocks (e.g., Johnson *et al*., 1996).

Other observations have been made from these resonant bar experiments. TenCate and Shankland (1996) reported that stopping and waiting at a point on the resonance curve result in the resonance curve "creeping" to some new equilibrium value between the upward and downward curves. Indeed, if the resonance sweep is done slowly enough, the upward and downward resonance curves merge. Figure 2 shows just such a slowly made resonance curve for a Fontainebleau sandstone; upward-going data points are the circles, and downward-going are the pluses. Within the error bars (omitted for clarity) the curves overlap; TenCate *et al*. (2004) show a similar plot for a Berea sandstone (in Fig. 3 of that paper). Doing a resonance sweep experiment very slowly eliminates the slow dynamics effects in resonance curves. Both these results are reminiscent of the disappearing hysteresis loop observed in slow quasi-static stress-strain experiments done at millistrain levels (Claytor *et al*., 2009) mentioned earlier.

4. Slow Dynamics: Conditioning and Recovery Experiments

Slow dynamics, as originally defined, consists of both the conditioning and recovery phases induced by a small-amplitude, sinusoidal acoustic drive. Conditioning and recovery of several different samples have been examined, and a review of some old and some new results are the topic of this section. A resonance bar experiment (ca. 1998) was designed so the sample was excited at a microstrain near its lowest (Young's mode) resonance frequency while constantly monitoring how the resonance frequency/modulus changed with time. Since the applied acoustic drive softens the rock, a feedback loop was programmed into the experiment to keep the applied strain constant during the conditioning phase. A lock-in amplifier was used to track the resonance frequency. After ~15 min of constant strain conditioning, the excitation was turned off. The whole cycle was repeated and the modulus tracked with time via repeating very-low-strain resonance curves. Behavior of the modulus was inferred from the low-strain resonance curves during both conditioning and recovery.

Figure 3 shows the resonance frequency as a function of time for a sample of Berea sandstone taken through the conditioning-recovery experiment described above. The initial at-rest state of the sample had a resonance frequency of about 2,885 Hz. At time $t = 0$ s, the conditioning drive is turned *on* and the resonance frequency drops (the modulus of the sample softens); at 1,000 s, the conditioning drive is turned *off* and the cycle is repeated. Resonance curves are taken every 50 s. (It is worth mentioning that waiting at least overnight is necessary for the sample to fully return to its at-rest initial resonance frequency.) If just the recovery parts of this sample are examined, the results are that the recovery goes as log(time). Several samples have been studied over the past 10 years, from sedimentary and crystalline rocks to cement and concrete samples (Johnson and Sutin, 2005). Figure 4 shows typical results for four samples (adapted from TenCate *et al.*, 2000). It is important to note that the log(time) recovery starts at very early times—approximately 100 ms for a sandstone sample (see Lobkis and Weaver, 2009)—and finally transitions to a non-log(time) behavior after times on order of 30 min and sometimes much longer.

Interestingly, the conditioning phase of these experiments has received less attention. If just the moduli of the conditioning parts of Fig. 3 are examined, they too appear to be log(time), although with an opposite sign as seen in Fig. 5. (The data are somewhat noisier because the presence of the conditioning drive reduces the signal-to-noise ratio and following the actual resonance frequency in time is somewhat more difficult even with a lock-in amplifier.) This conditioning result together with the recovery log(time) results is an interesting parallel to the results of Pandit and Savage (1973). For creep of a sandstone sample in flexure for strains around 10^{-5}, they show log(time) conditioning and recovery. Here we have produced similar results, this time with a sinusoidal acoustic excitation at strains of around 10^{-7}.

5. *Some Possible Mechanisms and New Experiments*

The mechanisms that result in slow dynamics in intact rocks and their possible links to fault gouge and earthquake dynamics are a topic of current discussion and continuing experiments. While a complete discussion is outside the scope of this paper, we highlight some important work to date with the hope of provoking more research. At strains of 10^{-7} in a 0.3-m-long intact sample, for example, it seems reasonable that grain-to-grain sliding is not occurring during slow dynamics experiments. It is also notable that slow dynamics appears in a wide range of rocks and geomaterials (like concrete), and there appears to be no shared geochemistry, scale, or microstructure between these materials. Perhaps the most interesting question associated with slow dynamics is how, at the microscopic level, strain energy of such low amplitudes gets stored and accumulated in the rock during conditioning. This section highlights some of the key papers and research to date.

Because slow dynamics in rocks resembles recoverable creep, perhaps it is only natural that proposals for the cause of slow dynamics in intact rocks should begin with the physics responsible for creep. Rutter (1983), for example, suggests three general possibilities: (1) diffusive flow where atoms move through grain boundaries or within the lattice, (2) grain sliding or fracturing (cataclasis), and (3) intracrystalline plasticity or movement of dislocations in the lattice of the grains. The latter is not likely at room temperature where most of the present experiments were performed and hasn't been considered to

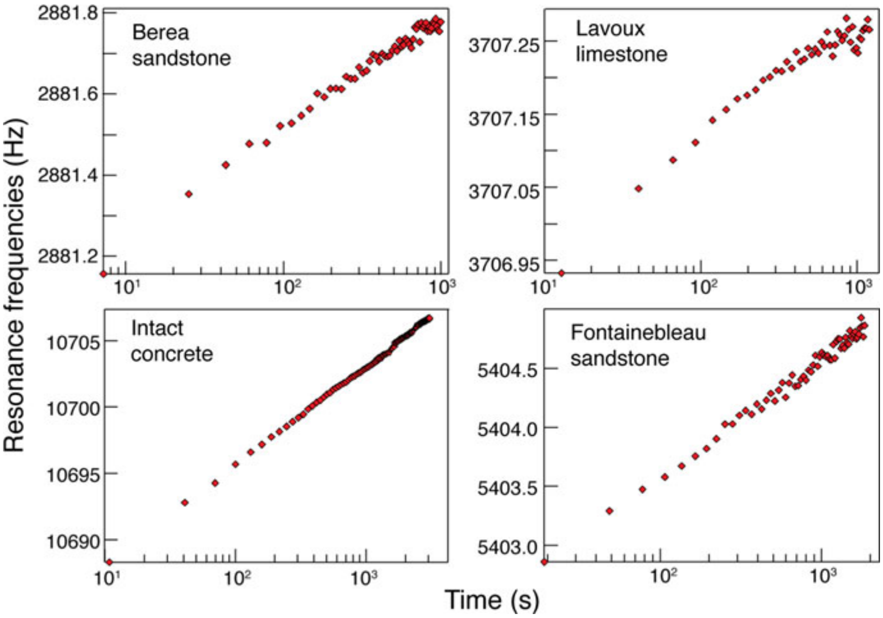

Figure 4
Resonance frequency versus log(time) recovery curves for four different geomaterials, all 25.4 mm diameter and approximately 0.3 m long. A similar length concrete sample was not available; this sample is 0.12 m long. Each sample was conditioned for 1,000 s with a strain of 10^{-6}, the conditioning drive turned off, and the resonance frequency peak tracked with time. The log(time) behavior of all these samples is remarkable and typical of many rocks. Note that the Lavoux limestone shows signs of departing from log(time) behavior at around 800 s. Errors in determining the resonance frequencies for these samples are around 0.1 Hz

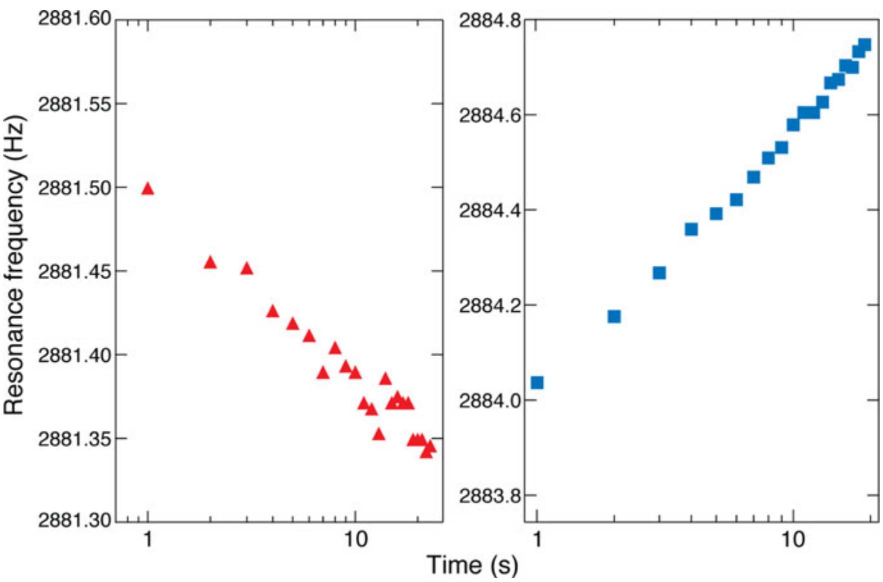

Figure 5
Comparison of resonance frequencies versus log(time) for the same Berea sandstone sample of Fig. 3. Conditioning resonance frequencies are shown on the *left* plot, recovery resonance frequencies are shown on the *right* plot (similar to those shown in Fig. 4). Both conditioning and recovery in slow dynamics appear to go as log(time). This figure should be compared with Fig. 1c of (Pandit and Savage, 1973) where those authors studied creep with time during and after excitation of a flexural mode in a sandstone sample

our knowledge. However, sticky fractures and microcracks (i.e., damage) as a source of slow dynamics in *intact* rocks have been the topic of several papers. ZAITSEV *et al*. (2003) and PECORARI (2004) began looking at microcracking as a possible mechanism; ZAITSEV looked at thermo-elastic effects at a crack tip, PECORARI at the behavior of a sticky crack. ALESHIN and VAN DEN ABEELE (2007) greatly extended the microcracking description with a very detailed analysis of how contact adhesion along the entire complex surface of the crack could be expected to play a role.

Closely related to the study of recoverable damage in intact rocks are studies of temporal changes and recovery of fault zone material after strong earthquakes.

While fault zone material is not an intact rock, many similarities are present, and linking and comparing the two seems instructive. For example, RUBINSTEIN and BEROZA (2004), PENG and BEN-ZION (2006), and WU *et al*. (2009) suggest that strong earthquakes can damage fault zone material by opening up cracks that can gradually heal over time, giving the characteristic log(time) recovery behavior seen after many strong earthquakes. LYAKHOVSKY *et al*. (1997) and HAMIEL *et al*. (2004) developed a damage rheology model that was used recently to describe and model nonlinearity and wave resonance in rocks (LYAKHOVSKY *et al*., 2009). While the authors note that resonance shifts can result from temporal changes of the damage state of a rock, they do not include the rate of damage recovery in their recent model. However, they suggest it can be incorporated easily enough. The authors also point out that to properly address the question of mechanism, rate and state friction and contact theory must be invoked and should be included. While such a discussion is also outside the scope of this paper, the reader is referred to SLEEP and HAGIN (2008) as an introduction.

Related to this discussion, it has also been pointed out that slow dynamics resembles the sudden loss of contact area seen in static friction; recovery goes as log(time) in static friction too. However, damage accumulation is *not* seen in slow

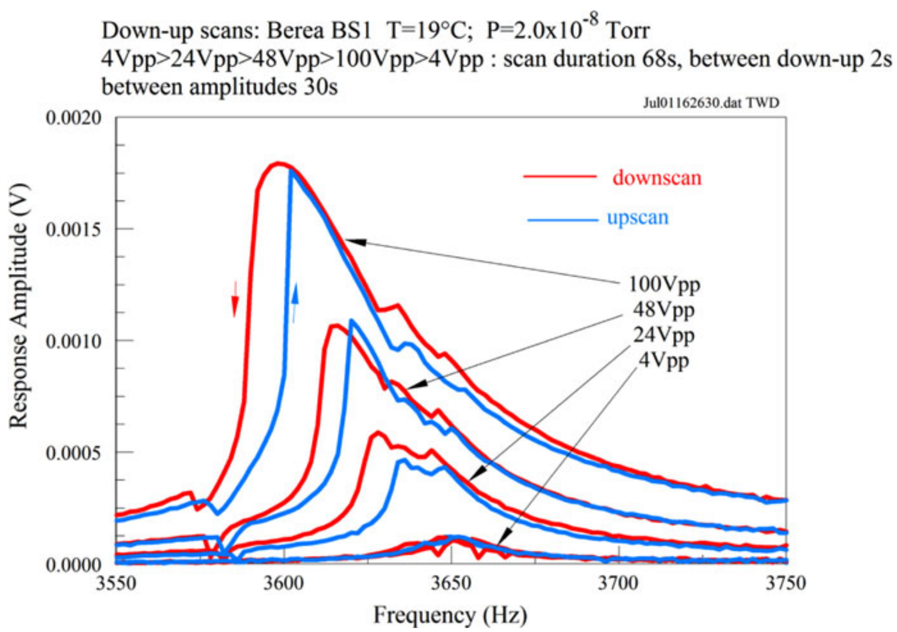

Figure 6
Preliminary ultra high vacuum measurements (DARLING, 2010). Shown here are a series of up/down resonance curves for 5 increasing drive levels of the lowest longitudinal mode. The sample is a 25.4-mm-diameter, 0.35-m-long bar of Berea sandstone and has been placed in ultra high vacuum, 2×10^{-8} Torr. Results were taken at room temperature (19°C) after a lengthy baking protocol. Slow dynamics differences between upward and downward-going curves are clearly evident even at ultra high vacuum

dynamics; it is, within experimental error, macroscopically perfect over hundreds of experiments. The combination of these last two points raises the question of whether slow dynamics may arise from a glasslike state at contact surfaces or points. Indeed, experiments and observations have shown that glass does exist in the cement between quartz grains of Fontainebleau sandstone (PAGE *et al.*, 2004, HADDAD *et al.*, 2006).

The effects of water in its various forms have been considered as well, although very few publications on the role of water on slow dynamics have appeared to date. Diffusive flow, perhaps aided by pressure solution, is affected by the presence of water in ordinary creep (MACK, 1946). Hydrolyzed bonds in the cementation between grains are weaker, and ruptured intergrain and interlamina cohesive bonds in the presence of water can enhance hysteretic phenomena (VAKHNENKO *et al.*, 2004). However, nearly all the experiments to date have been done at room dry conditions where "water" is mostly hydroxylated or bound to the surfaces within the rock in an almost icelike state (XU *et al.*, 2010).

To attempt to study what effects water have on slow dynamics, a new experiment was designed to focus on removing as much water as possible from a sample of Berea sandstone. The sample is a 25.4-mm-diameter, 0.35-m-long sample previously studied at Los Alamos. The sample was placed in an ultra high vacuum chamber with the capability to bring the temperature of the rock to whatever "bake-out" protocol is desired. Currently, the rock is in possibly the driest atmosphere a terrestrial rock of this size has ever been, 2×10^{-8} Torr at room temperature. A preliminary resonance measurement on the lowest Young's mode has been made, and the characteristic rate-effect differences between up/down curves are plainly visible (see Fig. 6). In addition, immediately after the experiment, some softening remained and slowly recovered over a day. Surprisingly, slow dynamics appears to be present even in this very "dry" sample. Conditioning and recovery experiments are now underway, and the results will be reported in a paper to appear soon (DARLING, 2010). Research continues along these lines to determine how much water remains inaccessible inside the rock, and much work remains.

6. Summary

Slow dynamics is a rate effect that has been reported in different rocks and geomaterials since the mid 1990s. Moreover, there appears to be no shared geochemistry, scale, or microstructure between these materials. Slow dynamics is different from creep in that it, by definition, arises from a sinusoidal AC driving function and at very small strains. Yet its hallmarks are similar to ordinary creep, namely, a log(time) behavior in the modulus, both while it is being excited, and in the way the rock recovers after the excitation is removed. Slow dynamics can be studied experimentally with relative ease, does not damage the sample, and may yield information about the damage state and a rock's ultimate failure modes. While some mechanisms have been examined, considerable work remains before a link between measurements and a physical property can be made. Slow dynamics is behavior in an interesting regime, not elastic or brittle.

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