Nonlinearity and Slow Dynamics in Rocks: Response to Changes of Temperature and Humidity

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Abstract. As revealed by longitudinal bar resonance experiments, materials such as rocks and concretes show a wide range of nonlinear elastic behavior. We have qualitatively examined the time-dependent changes of linear and nonlinear elastic properties of rocks in response to changes in relative humidity (RH) and temperature. A change of RH from 40% to 85% at room temperature causes velocities to drop about a percent in a limestone; in both Berea and Fountainebleau sandstones the decrease is of order 10%, even though their clay contents differ strongly. After humidity is changed, Young's modulus "creeps" toward a new equilibrium value. Like the slow dynamical response to dynamic strains of order 10^6, the effect is reversible. In contrast, when rocks are subjected to a temperature change of a few degrees, velocity drops by a percent, and Q decreases by 10%. Moreover, the sign of the change is negative *regardless of the sign of the temperature change*.

INTRODUCTION

Rocks display peculiar nonlinear behavior[1]. When excited acoustically (using a time harmonic source), their modulus decreases and attenuation increases. If we use the analog of a rock as a spring, after excitation, the rock-spring appears to be less stiff and more lossy. After the acoustic excitation is removed, the modulus and attenuation gradually recover to their original state; the recovery goes as $\log(t)$. Remarkably, this process is repeatable; no apparent damage is done to the rock during these experiments—at least none is indicated in macroscopic experiments. This behavior is called slow dynamics[2]. Moreover, since the excitation is "AC", the slow dynamics seen in rocks is fundamentally different from creep behavior seen in building materials or most metals[3].

Many of our experiments are performed in environmentally isolated chambers. During several of these measurements, we noticed effects qualitatively similar to slow dynamics. Both temperature and humidity changes caused drops in modulus and increases in attenuation (and subsequent recovery of those quantities). Curiously, the time

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scales were similar—as was the nearly $\log(t)$ recovery—to the original slow dynamics observations[2]. This paper describes some of these qualitative results and briefly discusses our future work to learn how temperature and humidity effects may play roles in the peculiar nonlinear behavior of rocks.

EXPERIMENTS

The samples used for these experiments were quite different chemically and physically. We experimented with several sandstones (with compositions ranging from pure quartz to quartz with various amounts of clays and feldspars), to an Oolitic limestone (pure calcite). Although not shown here, some measurements were also done on samples of concrete.

Several carefully controlled temperature changes were performed on a Berea sandstone sample (quartz with clays). The sample was placed in a vacuum chamber ($\approx$10 mTorr) to remove most of its water and to generally isolate it from the environment. A programmable temperature controller was used to control the temperature of the rock in the vacuum. A heating pulse to raise the sample's temperature 5°C or temporarily turning the heater off to cool the sample 5°C usually occurred within a few minutes.

More qualitative temperature experiments were performed in room-dry conditions with sealed bladders of hot or cold water carefully placed and then removed from the sample. Results using these bladders were similar enough to the carefully controlled experiments to allow us to rapidly examine several samples and watch the recovery from temperature changes.

Humidity changes were accomplished by placing the samples in a sealed box (at room temperature) and changing a salt/water solution in a removable tray at the bottom of the box. Results were similar to extremely careful experiments described in a PhD thesis done by Clark in the late 1970's (during the extensive studies done on moon rocks)[4]. It is important to note that relative humidity changes occur at rather low saturations. A general discussion of he effects of higher saturations on nonlinearity can be found in Van Den Abeele et al [5].

RESULTS: Temperature Changes

A sample of Berea sandstone (85% quartz and the rest clays) was suspended and held at 60°C—measured at the sample's surface—in a vacuum chamber (approximately 10 mTorr) for approximately a day. We monitored the sample's modulus by measuring its resonance frequency as a function of time. The temperature controller was then programmed to drop the temperature of the sample by 5°C. A cooler sample is (usually) stiffer so we expected to see the resonance frequency increase. Indeed, after several hours, the sample's resonance frequency had increased. However, it was the first 30 min or so after the temperature change that proved to be most interesting. The sandstone's modulus initially *dropped,* recovered initially as $\log(t)$, and then continued to the new

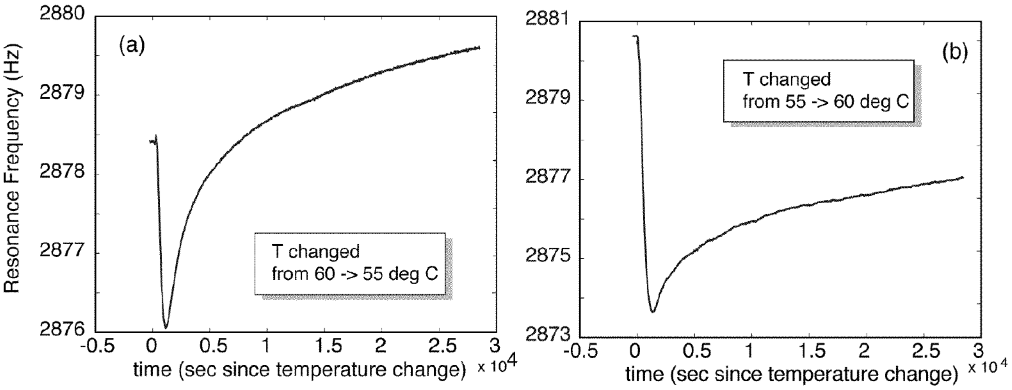

FIGURE 1. Recoveries of modulus (resonance frequency) after changes of temperature for a 2 cm diam, 33 cm long sample of Berea sandstone.

equilibrium value. The time period for this recovery was similar to the recovery observed in earlier slow dynamics measurements made on another sample of this same sandstone. See Fig. 1(a).

Similarly, after waiting for the sample to stabilize at that new temperature (55°C, about a day), we then *raised* the sample's temperature by 5°C. See Fig. 1(b). We expected a softer rock and expected the resonance frequency to decrease. Indeed, that is what happened. However, as before, the initial drop(!) in modulus was *much* more interesting. Measurements of Q (1/attenuation) although somewhat messy, show similar behavior[3]. It is very important to note that this behavior does *not* happen when we substituted a geometrically similar sample of stainless steel in place of the sandstone.

To learn if other rocks behaved in a similar fashion we tried an efficient but less controlled experiment. With the samples resting on foam, we placed several long bladders filled with varying water temperatures on the samples and monitored the resonance frequency immediately after the bladder was removed. We were pleasantly surprised to find the behavior of the Berea sandstone to be quite similar to the results obtained in the vacuum chamber. Several other rocks were examined. A Meule sandstone (mostly quartz and feldspar), a Fontainebleau sandstone (pure quartz), and a Lavoux limestone (pure calcite). [Movies of the recoveries will be shown during the oral presentation.] The sandstones share similar behavior. However, the Lavoux limestone behaves quite the opposite; during cooling the resonance frequency shifts upward, during heating downwards. Reconaissance efforts are currently underway to see how other earthlike materials (e.g., ceramics) behave.

RESULTS: Humidity Changes

Some simple, qualitative measurements were made by changing the amount of water available for a sample to adsorb. A simple sealed chamber was built with a trap door at the bottom for exchanging trays of saturated salt/water solutions (which yields

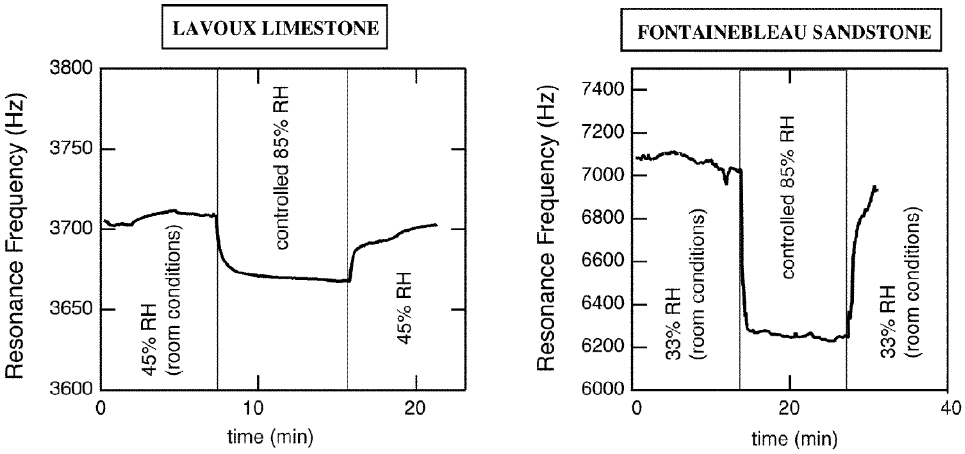

FIGURE 2. Recoveries of modulus (resonance frequency) after changes of humidity for a 2 cm diameter, 30 cm long sample of Lavoux limestone.

different humidities). Again, we had a benchmark set of careful measurements done in the late 1970's[4] for comparison. Two samples were examined. Lavoux limestone and Fontainebleau sandstone. Our initial results are shown in Fig. 2 for an increase in RH from 45% to 85% and back again. The sandstone results appear to agree with previous results. However, unlike the temperature measurements, *both* rocks show an initial drop in modulus, followed by a recovery which appears to be close to $\log(t)$. Further experiments are underway.

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