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Title:

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Low temperature elastic constants and nonlinear acoustic response in rocks and complex materials.

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The "P-M Space" model[1] of Guyer and McCall has some success in describing the large nonlinear effects ("slow dynamics") observed by Johnson et al[2]. in rocks. The model uses elements which couple classical nonlinear elasticity with hysteretic components. The actual processes and scales corresponding to the model elements are not yet defined, however it is reasonable to seek energy scales by studying the low-temperature dependence of the elastic constants. We have measured qualitative elastic properties of basalt and Berea sandstone from room temperature down to 4 K using Resonant Ultrasound Spectroscopy (RUS). A simple elastic solid should show a monotonic increase in the elastic constants as temperature decreases. The basalt samples show this gross behavior but the sandstone shows a very unexpected anomalous regime between 40 K and 200 K where the elastic constants decrease with decreasing temperature. Both rocks show temperature-dependent structure in both the modulus and internal friction, and also significant hysteresis, indicating history and rate-dependent properties. This data provides insight into the time and energy scales of dynamical effects observed in sandstones.

Introduction

Recent articles[1,2] on the acoustically measured mechanical response of rocks to transient strains, demonstrate that sandstones particularly, return to the initial state with a slow, logarithmic time dependence. Models which combine generic nonlinear elastic and hysteretic components are able to qualitatively describe many of the observations, but to understand these systems at the atomic and microstructural scales, we must find the physical processes which correspond to the generic elements. These processes may involve mobile defects or boundaries, mechanical ratchets, microscopic friction or strain-induced phase transitions. It is reasonable to assume there is a temperature dependence associated with these processes, - in the form of an activation or barrier energy or a phase transition temperature. Many of the characteristic temperatures of phase transitions and mobility freezing for minerals are well below room temperature, a region not often explored for geological samples. Thermal contraction produces apparent strains which correspond to high pressures, although clearly other thermodynamic quantities are changed. We have made low temperature resonance measurements on two rock samples, a sandstone that displays strong hysteretic properties, and a basalt which does not, to determine if the temperature dependence of the elastic constants can provide information on the source of the recovery behaviour.

Measurements

RUS[3] data allows us to determine the qualitative, and in some cases, the quantitative, behavior of the elastic constants and the internal friction of a sample. Our samples were cut to approximate rectangular prisms with side dimensions of 3-4 mm and masses near 0.2g The samples are held vertically between diagonal corners by piezoelectric transducers in a RUS cell made for use in liquid helium. The sample space was evacuated for several hours at room temperature. The samples were cooled to 4 K over 13 hours. A spectrum of the resonances in the frequency range 80 - 400 kHz was recorded every 2.5 K. Similar rates were used during warming to display any hysteresis. We plot peak center frequencies and widths for a number of low-lying resonances as a function of temperature.

Results

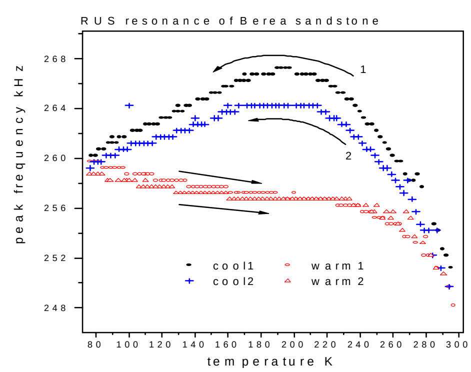

FIGURE 1. The centre frequency dependence of one sandstone resonance over two temperature cycles to 77K

Figure 1shows the effect of temperature cycling on the sandstone sample. There is a large hysteresis loop opened and an obvious temperature coefficient change on cooling near 200 K. This is apparently a bistable elastic material, since the elastic constant depends on whether the immediate previous state was above or below 200K. The frequency data also show notable differences between the two rock samples: we observe evidence of characteristic temperatures in both rocks, and a region of anomalous temperature coefficient of the elastic constants in the sandstone. The cooling and warming data show hysteresis in both samples, with a significant and repeatable loop apparent in the sandstone. Figure 2 shows that the actual low temperature close of the sandstone loop is about 35K.

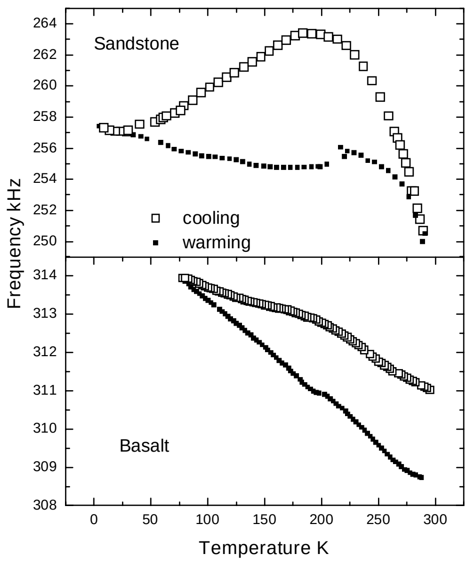

FIGURE 2. Comparison of the resonance frequency dependence (elastic constant) for sandstone and basalt

The RUS data also contains width or internal friction information. The peak width was determined at each temperature by fitting a lorentzian lineshape. Figure 3 shows the data obtained for the widths (essentially $\propto Q^{-1}$) of the lines plotted in figure 2.
Remarkably, the sandstone data does not follow the changes in the frequency, and does not show any hysteresis. The basalt result shows some hysteresis above the break in slope in the basalt frequency data.
In general, the expected elastic behaviour of a cooled solid would cause an increase in resonance frequency with lower temperatures: the basalt generally conforms to this, but below 200K the sandstone shows behaviour characteristic of an elastic instability leading to a phase transition.

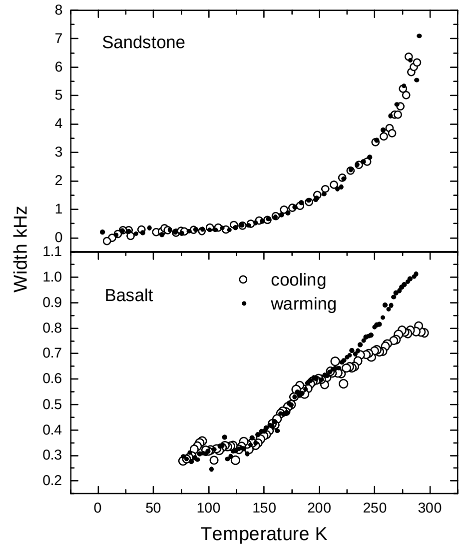

FIGURE 3 Comparison of the measured widths of the resonance peaks ($\propto Q^{-1}$)) for sandstone and basalt

DISCUSSION

We believe that the bistable nature of the sandstone seen in the temperature dependence of the elastic constants may be the temperature equivalent of the slow dynamics seen in strain driven experiments. We propose that above 200K the cooling curve represents the stable elastic state, and below 200K the warming curve is stable. At these temperatures, however, there may be insufficient thermal energy to produce a transition – further experiments are under way to test this. If a strain at room temperature produces a volume which is in the second elastic state, it may be able to relax to the original elastic state. The strain produced on cooling to 200K and the energy kT are characteristic of a process which leads to highly nonlinear, hysteretic behaviour in this sandstone.

ACKNOWLEDGEMENTS

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