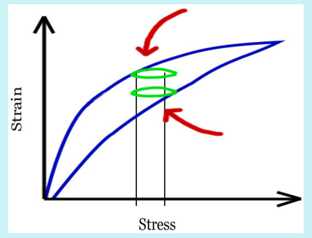
# Data

*Does it compress the same if it has been squished before?* **Can we learn any more by sending acoustic waves through a rock?**
**What can slowly squishing a rock tell us about its behavior?** Does temperature effect compressibility? *Are all sandstones alike?* **What do the insides of a rock look like?** ***See Below!***
*What if we compress it faster?*
Can we change the behavior of a rock? How much compression can a rock take? Is there any relation to slow, strong squishing? *What bonds the grains in a rock?*

# Quasi-static Stress-Strain Measurements

## Congruence




### Lining up with inner loops

What if we sweep through a small stress range on both the compression and return portions of a stress-strain curve (see left)? The history and strain of the rock is different, should the results be any different?

To test for this phenomenon, called congruence, the inner loop values for the increasing part of the curve (bottom) were subtracted from the values along the return curve (top). The difference is plotted in Figures 7 and 8. The plateaus indicate that the majority of the inner loops are congruent, or similar, while the sudden change in difference occurs when the load frame was reversing direction.

In the PM space model, the explanation is provided through the reasoning that the sweep through the small stress range closes and opens the same triangle on the return curve as on the increase curve. The translation coming from the history of the rock.

Due to history effects, the loops at lower pressure should also be more separated and have a greater difference value than at high pressures, which is seen to an extent in Figure 8.

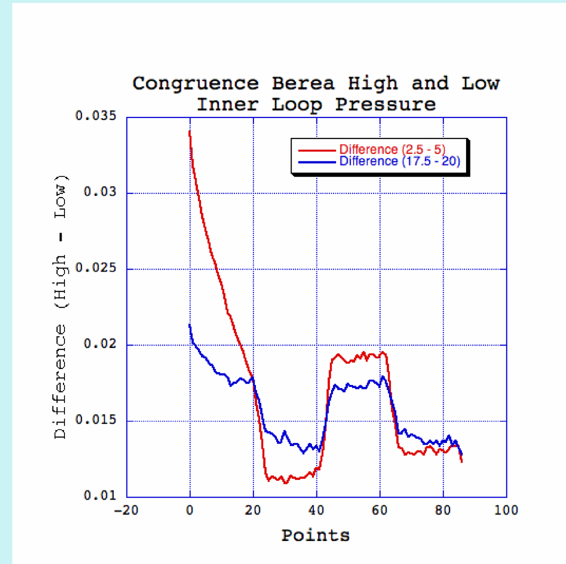



Figure 7: Berea congruence between inner loops at 2.5 - 5 Mpa and 17.5 - 20 MPa. The flat regions indicate that the inner loops are identical but transformed along the strain axis (by the y value). Although slightly noisier at the high pressure, the inner loops are still congruent.

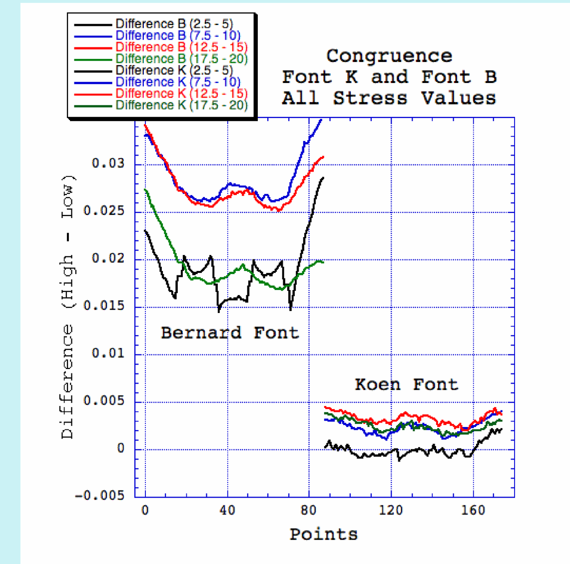



Figure 8: Congruence for the two Fontainebleau samples. The Bernard samples shows congruence much more similar to that seen in Berea, while the Koen sample shows congruence centered more on zero, as a consequence of it's almost linear behavior.

## Endpoint Behavior

### The (stress) memory of rocks

A memory dependent phenomenon, such as hysteresis, has incorporated into it a "memory" of where it was; the previous stress maximum(s) have been recorded in the structure of the rock. This is explained in terms of PM space in Holcomb (1981), Guyer (1996), and Ostrovsky (2001), but the result of this that is of interest here is that rocks exhibit a phenomenon known diversely as endpoint, return point, or discrete memory. After generating an inner loop, such as those seen in the congruence data above, the strain resumes from the point at which it diverged when the stress decreased.

A matter of debate has been how exactly the stress-strain approaches the endpoint. Holcomb's data show the strain approaching the endpoint, then curving off and gradually rejoining the larger stress-strain loop far after the endpoint. PM space, on the other hand, predicts that the stress-strain curve should return to *exactly* the point at which the initial turn was made, and join in at a distinctly different angle. The data taken here, as well as data elsewhere support the first part of the PM space hypothesis. There has not been a thorough investigation into the second part of the hypothesis, however. Figures 9 through 12 show three different ways used to examine the behavior that approaches the endpoint, as well as some of the difficulties encountered. A definitive result has not yet been observed.

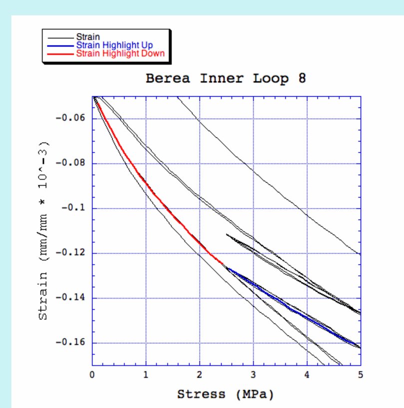



Figure 9 (left): The stress-strain loop with the segments at the end of the inner loop and the continued portion of the outer loop. The endpoint shown is well defined compared to those in Holcomb's data.

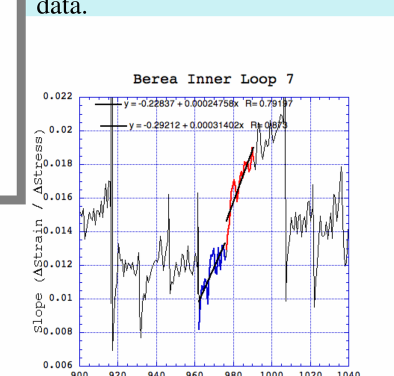



Figure 10 (right): A 2-point slope was performed on the data, and the regions highlighted. The large jump between the fits indicate a sharp discontinuity in slope.

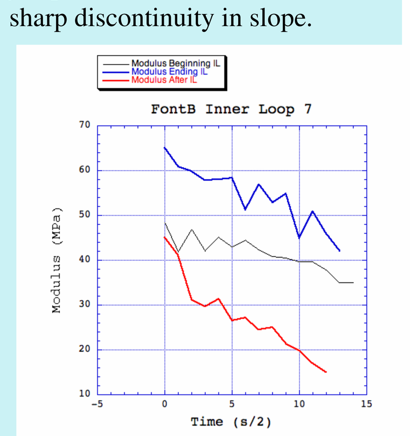



Figure 11 (left): The modulus (inverse slopes) of the inner loop should draw gradually closer to that before the inner loop if a smoother joining (eg; Holcomb) is observed.

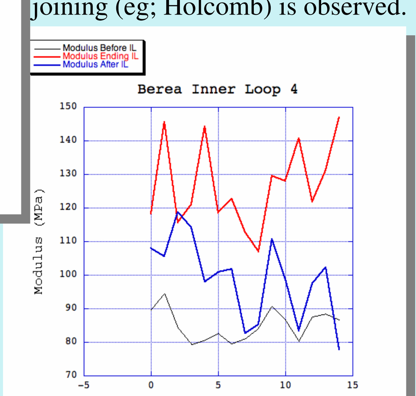



Figure 12 (right): Most of the data was not as clear cut as in Figures. 10 and 11, instead showing very close overlapping slopes, as shown here. A better analysis method is being developed.

## Rate Dependence

### Once closed, always closed?

If HEU's are time dependent and decide to return to their open state before the pressure has decreased to their opening pressure, then we would expect to see a different stress-strain curve for a slower test. As can be seen in Figure 13 for a $10^2$ change in the speed of the test, all of the loops were fairly identical within the temperature variance.

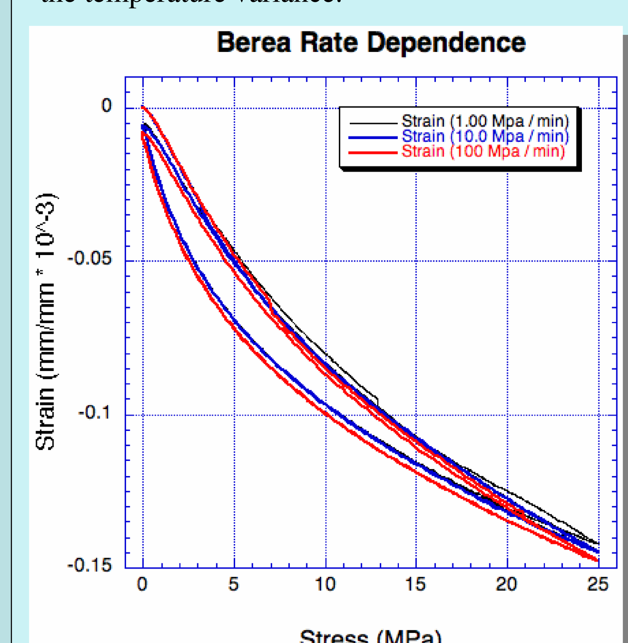



Figure 13: A test for rate dependence on the Berea sample. The results show that hysteresis is not a rate dependent effect.

## Progressive Damage

### Visualizing failure

In an attempt to generate nonlinear behavior in the fairly linearly behaving Koen Font sample, it was cycled many hundreds of times with an inner loop profile run every few hundred cycles, displayed in Figure 14 (Top). As can be seen the width of the hysteresis loop may first increase (post 100 cycles), but then subsequently decreases, with the overall strain decreasing as well, until the sample fails (the pink (post ~570 cycles) curve). This occurred in a Berea sample as well (Figure 14 (Bottom)). However, it showed increased nonlinear behavior after it had been cycled several times ($12^{th}$ curve), but still showed the interesting failure curve ($18^{th}$ curve).

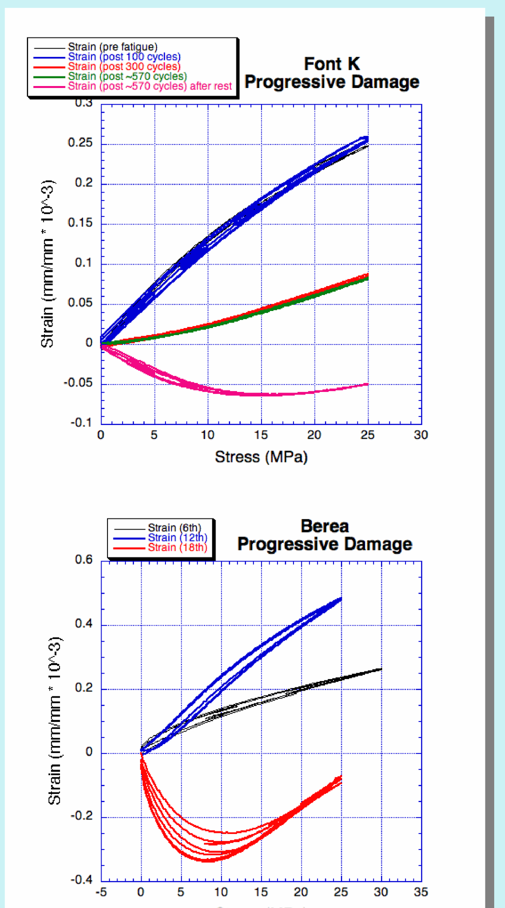



Figure 14 (Right): Top: Stress strain loops as a sample of Fontainebleau is cycled several hundred times. The final pink curve indicates that the sample has failed (it has substantial internal, also often external defects).

Bottom: Stress strain loops on a Berea sample that had been cycled for other tests. The failure stress-strain curve shows the same overall behavior as that in the Fontainebleau. Moreover this sample showed visible cracking and flaking around the top and bottom edges.

## Temperature Effects

### A hot dry rock

Temperature was begun logging simultaneously with a stress strain test, and recorded the temperature for an 18.5 hour period as the sample was compressed 17 times in that period with 1 hour rests at 0 stress in between. The peak strain (defined as the strain value at the maximum stress value) was then plotted against temperature, however, no strong correlation between the two was found (Figure 15).

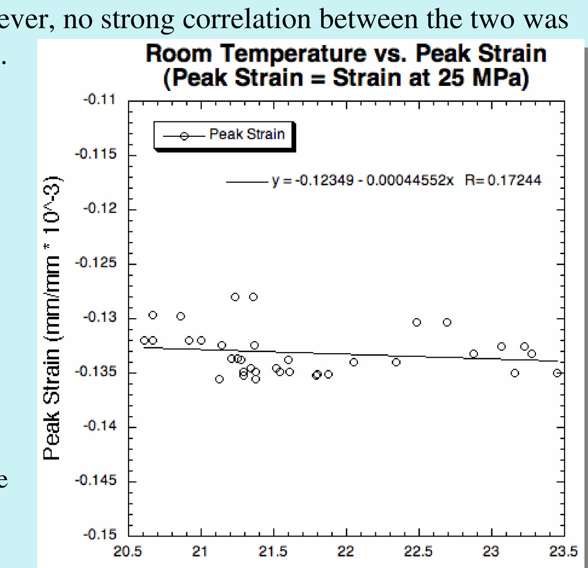



Figure 15 (Right): The peak strain plotted against the temperature at which it occurred. As can be seen, there is no strong correlation between the two for the small temperature change recorded.

# Nonlinear Resonant Ultrasound Spectroscopy

### Making a note play flat

A Nonlinear Resonant Ultrasound Spectroscopy (NRUS) experiment gives us information on how rocks behave when subjected to high frequency, but low strain. A resonance is excited at higher and higher amplitudes, causing the rock to soften and the resonance peak to shift down in frequency. Other, linear, materials, such as Lucite (Plexiglas), do not show this behavior; the peak frequency stays constant as the strain increases. Moreover, the peak shift is not constant in rocks per increased strain, but rather increases nonlinearly with strain. An interesting result is that the same curve is not obtained if one is sweeping the frequency down rather than up (as a result of the rock softening during the sweep).

This method was performed on the two different Fontainebleau samples. Bernard's Font was from a position in the quarry that has been above and below the water table, and displayed a large frequency shift. Koen's Font is from the same region, however, it was quarried from a section that has constantly been below the water table, and barely shows any nonlinearity.

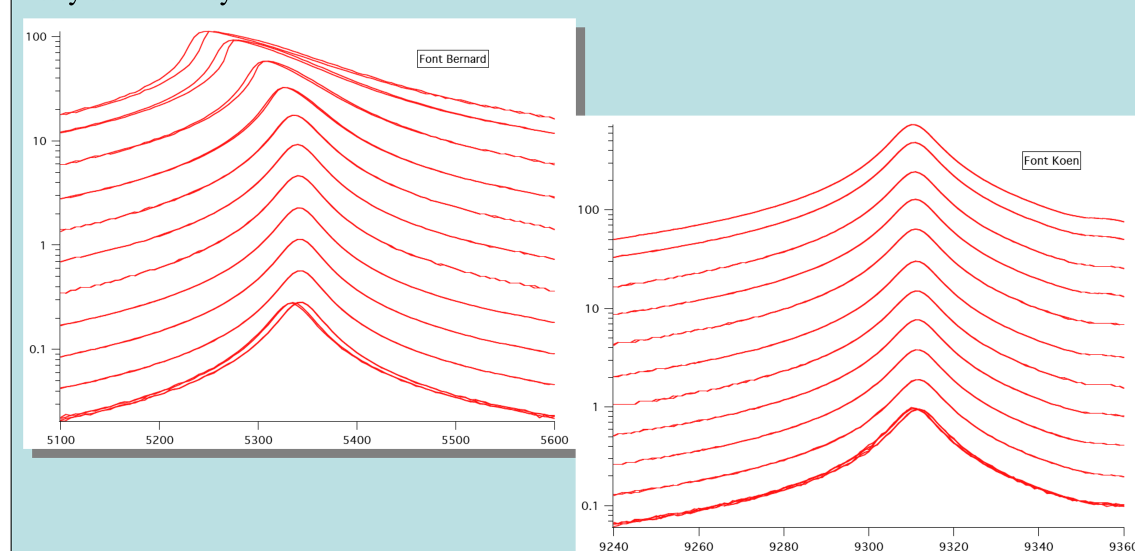



Figure 16: NRUS measurements on Font B and Font K (left and right, respectively). Given the different parameters of the samples, they were brought to roughly equal strains. The lowest amplitude sweep was repeated at the end of the experiment, showing a minor temperature / conditioning shift in the Bernard sample, and practically no shift in the Koen sample.

# Neutron Scattering - LANSCE

### Finding the underlying mechanism

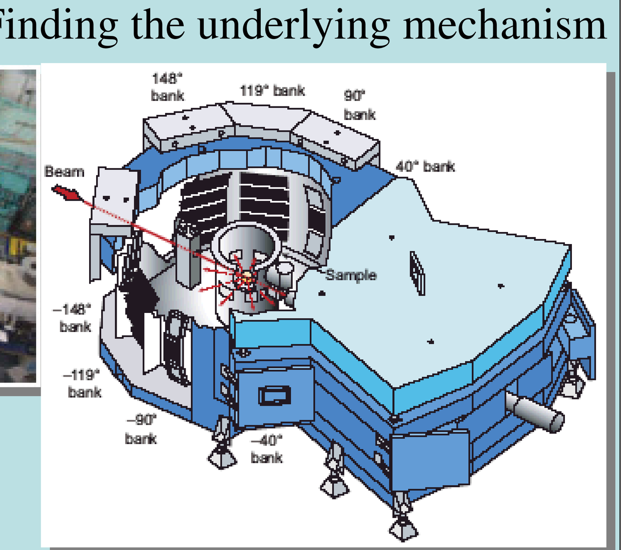



Figure 17: The NPDF experiment at LASCENCE, the scattering of neutrons yields information about the composition and structure of the sample while leaving it fully intact.

Neutron Pair Distribution Function (NPDF) is a method of nondestructively interrogating a sample to determine its composition by sending a directed neutron beam through a sample and imaging the diffraction of the neutrons. The method analyzes both elastic neutron scattering as well as Brag diffraction, yielding information on both long and short range order (crystalline and glassy structure, respectively). Here NPDF was used to examine the linear and nonlinear Fontainebleau sandstone samples, in an attempt to determine if the bond structure was the fundamental source of nonlinearity.

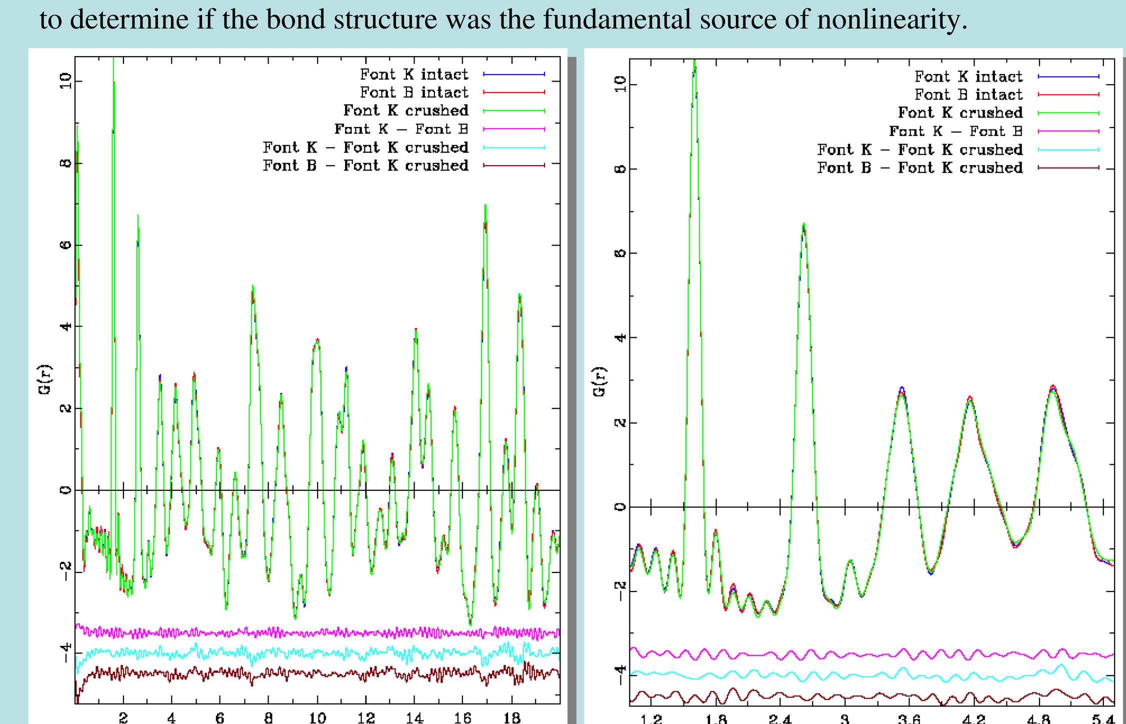



Figure 18: Neutron PDF data. The right image is a zoom of the first few peaks in the left graph. Interestingly all the samples appear to be highly similar, that is all samples share equal crystalline and glassy structure, even when crushed. This is evidence against the theory that glassy bonds alone are behind hysteresis. This is not to say that the role that glass plays in each of these samples may not be different and important to hysteresis. However, no fit was available at time of print for comparison.

# Discussion

These results obtained from the numerous measurements on several different apparatuses help to give a more complete picture of rock mechanics and behavior.

- The phenomenon of congruence was investigated on many rocks, and was observed on all, validating this property as one that a model would have to incorporate.
- The data on the endpoint memory phenomenon was less clear cut. Data supporting both methods of memory, was observed.
  - A method of quickly analyzing for both is being developed, and will be used to obtain more definitive statistics that hopefully will provide a useful answer.
  - The reality may be a mix of the two depending on which stress regime the rock is in and the stress history it has been subjected to. For example, discontinuous behavior may be more prominent at the lower stresses where it is predicted to be greater.
- The experiment preformed here does not see a dependence on a time scale that varies by a factor of 100.
  - An additional cursory investigation was done into the behavior when the sample was paused with a medium amount of stress on it. The preliminary results show what could be a time dependent recovery, however, temperature (and possibly humidity) effects soon take over, and a more controlled experiment will need to be performed.
- Both samples, and several others besides them, show very interesting strain behavior before partial or complete failure. This provides another method by which one can perform damage analysis
- The lack of humidity control and only moderate temperature variation do not show any clear trend. Hopefully, a controlled environment will be constructed around the sample, allowing for better investigation of temperature and humidity effects on stress-strain loops.
- The NRUS experiments provided a dynamic confirmation (Figure 19) of the quasistatic results between the two sandstones, the nonlinear effects of Bernard's Font accentuated to an even greater degree.
- The NPDF measurements unfortunately proved inconclusive. Although the material responsible for grain bonding (amorphous or crystalline) may still play a role in how it is arranged in the material, there are equal amounts of both in the two Fontainebleau samples.

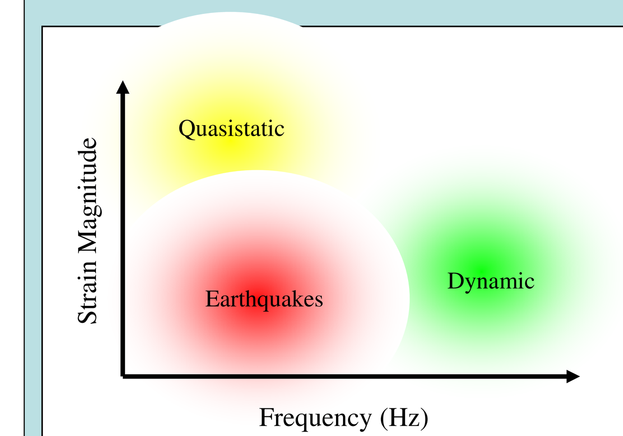



Figure 19: A cartoon showing the different frequency and strain regimes explored in this experiment. Quasistatic tests are low frequency, but high strain tests, while NRUS experiments are the inverse. Little is known about the area in between. Earthquakes fall into this area, as they are low frequency, relatively low strain events. Perhaps the data between the two regimes will be merged to give more information on these seismic events.

# Conclusions

Overall these experiments give the geophysics community considerably more to think about. They have confirmed some previously held hypotheses (such as congruence). The lack of rate dependence shown here casts a cloud of doubt over some rate dependent and healing crack models.

Many questions remain, however, such as the exact role that temperature and humidity play in stress-strain measurements. Additionally, the endpoint memory behavior requires a more rigorous analysis to determine the exact behavior.

Perhaps the most interesting (and important) question that remains is the unique behavior between the two sandstones. It hints at several possible physical mechanisms that are responsible for hysteresis, including porosity (determined to be roughly the same), amorphous or crystalline bonding material (which NPDF disproved), and pre-existing cracks, which were not generated in the Font Koen sample up to the point of failure. Once this is understood, a better grasp on geomaterials as a whole will result.

# References & Acknowledgements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