EXPERIMENTAL LOAD CYCLING IN THE BRITTLE FIELD PRODUCES A MORE DISTRIBUTED FRACTURE NETWORK

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Keywords: rock mechanics, permeability enhancement, micro-tomography

ABSTRACT

A crucial parameter in the efficiency of a geothermal system is the ease with which fluids can be extracted, where the permeability is a critical rock mechanical reservoir parameter. For low permeability reservoirs, creating fractures via hydrofracture is one of the geoengineering options available to increase reservoir permeability. It is known from literature that cyclic loading can result in a gradual weakening of rock materials. To determine if it also changes the characteristics of the fracture network, we performed conventional uniaxial failure experiments as well as cyclic loading experiments on Bentheim sandstone, Indiana limestone and Benin granite. The sandstone and limestone are assumed to be representative for conventional reservoirs, which represents the wide variability in geothermal reservoirs. We perform post-experimental micro-tomography scans to determine the difference in fracture density between the conventional uniaxial failure experiments and the cyclic loading experiments.

The results show that cyclic loading causes all rocks (except the limestone) to weaken progressively, up to ~20%, compared to material that has been loaded to failure in one single cycle. The tomography indicates that the fractures that form during cyclic loading are more distributed throughout the sample. Single loading experiments leads to more localized fractures. These results thus imply that to increase the connectivity and distribution of fractures, cyclic loading with fluid pressure pulses can be attempted. It is expected that in these cases a better distributed network of fractures is formed, which should increase the permeability and thereby improve the recovery of heat. However, the progressive weakening of the material due to cyclic loading may cause an earlier loss of integrity of seals, which also needs to be taken into account in seasonal storage of fluids in subsurface reservoirs. Moreover, these results are of importance in any setting in which material is subjected to cycling stress levels, such as seasonal storage of hydrocarbons or CO_2 in depleted reservoirs, thermal stress cycling due to injection of cold water or load imposed by magma movement in active volcanoes.

1. INTRODUCTION

Geological geothermal reservoirs are found in different lithologies and at different depths. Conventional subsurface reservoir rocks are sandstone and limestone, where the reservoir is usually topped by an impermeable salt or shale caprock. A special case for geothermal reservoirs can be found in magmatic rocks. This type of reservoir has very low permeability but high heat flow. A crucial parameter in the efficiency of any geothermal system is the ease with which fluids can be extracted, with permeability as the critical parameter. With increasing depth permeability decreases and temperature increases. This means that with depth there is a trade-off between how much fluid can be extracted versus how much heat can be obtained. For deeper reservoirs permeability can be increased through a number of measures, such as hydrofracturing (often combined with proppant injection) or chemical stimulation. Hydrofracturing uses relatively a lot of water, and isn't always effective.

Changes in fluid injection and production rates lead to stress cycles in the reservoir. In rock mechanics, this is simulated by load-cycling experiments. These have shown decades ago that material strength is decreased due to material fatigue (for example, Burdine, 1963, Haimson and Kim, 1972, Attewell and Farmer, 1973, Singh, 1989, Zhenyu and Haihong, 1990, Ishizuka et al., 1990), and elastic parameters are affected. Changes in Young's modulus are also dependent on the initial fracture stress condition of the rock material and the region in which load-cycling is applied (elastic/non-elastic). The Poisson's ratio increases with increasing numbers of load-cycles (Niandou et al., 1997, Heap and Faulkner, 2008, Heap et al., 2009, Xiao et al., 2010). In all of these studies the initial fracture condition and the region in which load-cycling was applied were different. Niandou et al. (1997) started load-cycling of intact rocks in the linear elastic regime and found an increase of the Young's modulus with increasing numbers of load cycles. Xiao et al. (2010) started load-cycling of intact rocks in the fracturing regime and observed a decrease of the Young's modulus with increasing numbers of load cycles. Heap and Faulkner (2008) and Heap et al. (2009) started load-cycling of rock materials with pre-existing fractures in the linear elastic regime and observed a decrease of the Young's modulus with increasing numbers of load cycles.

The clearly documented change in material strength and elastic parameters imply that a change in crack damage is plausible. An improvement of the fracture network would be beneficial to the recovery of geothermal energy. Hence, this study aims to determine the difference in fracture networks of a single loading experiment versus load cycling experiments. We performed uniaxial loading experiments and load cycling experiments with post-experimental microtomography to determine the fracture network. The elastic parameters (Youngs modulus and Poisson's ratio) and the failure point for both types of experiments is compared to determine the effect of load-cycling on the material strength. Results of this research has also implications for our understanding of cyclical storage of fluids in subsurface reservoirs, such as seasonal storage of hydrocarbons (Teatini et al., 2011), CO_2 storage in depleted hydrocarbon reservoirs (Rohmer et al., 2016) or load imposed by magma movement in active volcanoes (Heap et al., 2009).

Figure 1: Sample inside the 500 kN loading frame with dummy sample ('steel help + rock material').

2. METHODS

We used Bentheim sandstone (ϕ = 24.95 ± 0.58 %), Indiana limestone (ϕ = 13.98 ± 2.18 %), and Benin granite (ϕ = 0.79 ± 0.20 %). Samples had a diameter of 30 mm, and a length of approximately 60 mm, i.e., length/diameter ratio ~ 2.

Experiments were performed with a 500 kN Loading Frame (see Figure 1), either as standard uniaxial loading (UCS) or load-cycling (Cyclic) experiments. All experiments were unconfined and at room temperature. They were performed at a constant displacement rate, such that the axial strain rate was 10^{-5} s^{-1}. Vertical sample strain is measured with two Linear Variable Differential Transformers (LVDT), and horizontal strain was measured by a chain gap type LVDT extensometer (see Figure 1). Compressive strains are positive. Note that since all measurements were performed directly on the rock sample, no elasticity correction for assembly and/or apparatus compliance is required.

In the UCS experiments, the sample is loaded until failure. In the cyclic experiments, the stress is increased in each cycle with 2 MPa compared to the preceding cycle, after which samples are unloaded to ~0.10 MPa. After failure cycling is continued for as long the samples had a load carrying capacity, evaluated by visual inspection (usually another 3-5 cycles). The stress level at failure is considered as a measure of the material strength, also for the load cycling experiments. Young's modulus and Poisson's ratio are determined for each cycle. They were automatically determined between by a linear regression on the stress-strain data between 30 and 70% of the maximum load within each cycle. These limits are imposed to avoid non-linear behaviour due to crack closure / assembly settling at low stresses and crack initiation / propagation at high stresses (e.g., Bakker et al, 2016; Heap et al., 2009). Only the loading part of the cycle is used. Note that the 'elastic parameters' calculated after failure are not really elastic, but measures of Δstress/Δstrain. They do not represent elastic behaviour, but are still considered a useful tool to track the sample response to loading.

Post-experimental microtomograpy was performed using a Phoenix NanoTom (180kV, 0.5mA), with a voxel resolution of approximately 50 μm/voxel. Fracture apertures can thus be resolved for 50 μm or larger.

3. RESULTS

Figure 2 shows the stress-strain curves of both UCS and cyclic experiments. Bentheim sandstone and Benin granite are weaker in the cyclic test than in the UCS test (10 and 25 MPa respectively). The limestone is 7 MPa weaker in the UCS test than in the cyclic test (UCS-1 red curve panel B), However, a sister-plug (test UCS-2, blue curve in Figure 2B) revealed a failure stress about 4 MPa higher. Elastic properties derived for these experiments are shown in table 1.

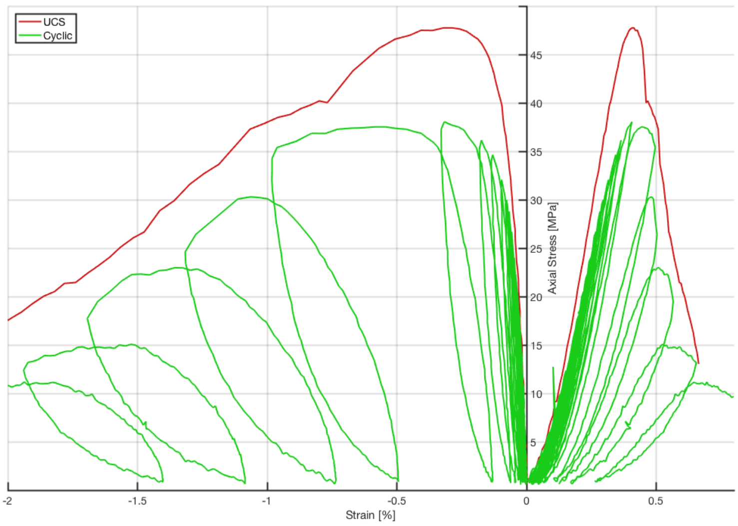
Table 1: Elastic properties as derived from individual UCS experiments

Rock Type / experiment	Young's Modulus	Poisson's Ratio
Bentheim Sandstone	15.00	0.42
Indiana Limestone 1	13.38	0.13
Indiana Limestone 2	21.83	0.24
Benin Granite	48.53	0.22

For cyclic loading experiments, all samples exhibit hysteresis loops (i.e., cycle n+1 starts at a slightly higher strain than cycle n), which are especially pronounced after failure. Remarkably, these hysteresis loops are also present in the linear regime of the envelope of the load-cycling curves. Due to the different failure stresses for the different samples the three rock types exhibited a different number of load cycles before failure.

The evolution of the dynamic elastic parameters with load-cycling is shown in Figure 5, 6 and 7. For all three rock types the Young's modulus increased in each load cycle before failure. The maximum Young's modulus is reached just before or at failure (Figure 5A; 6A; 7A), where the increase in each cycle slows down after the sample yields. These maximum values compare well with UCS derived values. The Young's modulus in Bentheim sandstone increased from 8 to 14 MPa, in Indiana limestone from 6 to 16 MPa and for Benin granite from 15 to 45 MPa. Only in the Benin granite the Young's modulus increased non-linearly with increasing cycle number, with a break in slope at 10-15 cycles, and a stabilization between 60 and 74 cycles. The Poisson's ratio shows a more complicated pattern (Figure 5B; 6B; 7B), where until just before the yield point the Poisson's ratio increases approximately linearly with increasing numbers of load cycles. After yield the Poisson's ratio increased rapidly until failure in all samples. In the Benin granite especially, yield leads to a jump in Poisson's ratio of 0.2 to 0.3, after which it rapidly increases linearly to 0.45 at failure. In Figure 5C; 6C and 7C the maximum obtained axial stresses are noted for each cycle.

A



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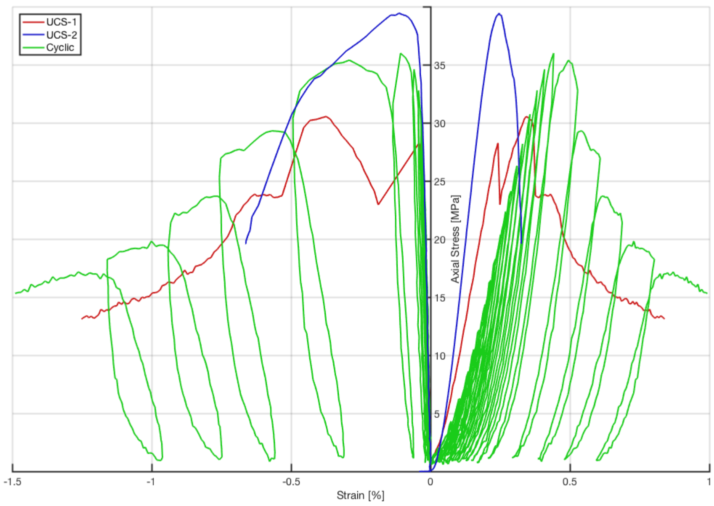

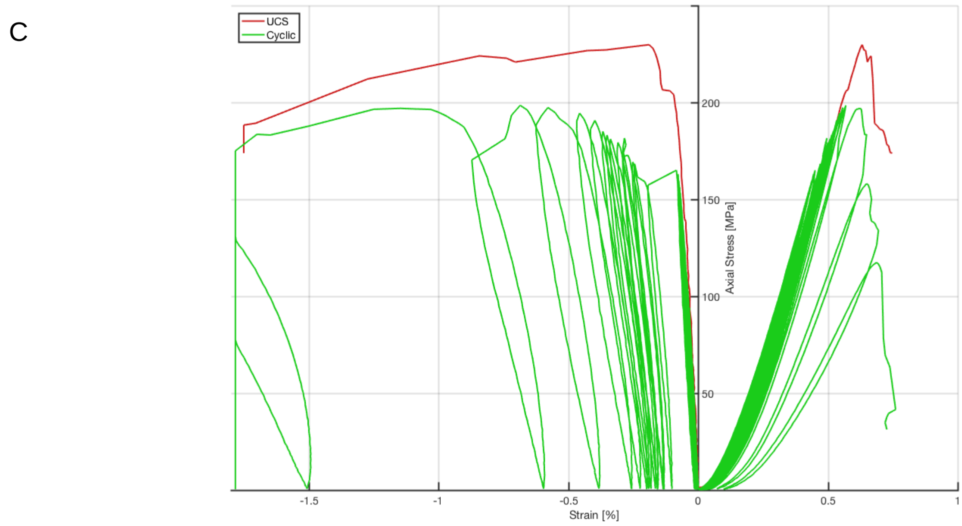

Figure 2. Stress-strain curves of UCS (red (+ blue for panel B)) and load cycling experiments (green) on A) Bentheim sandstone; B) Indiana limestone and C) Benin granite. Axial strain is positive (compression) and radial strain is negative (extension).

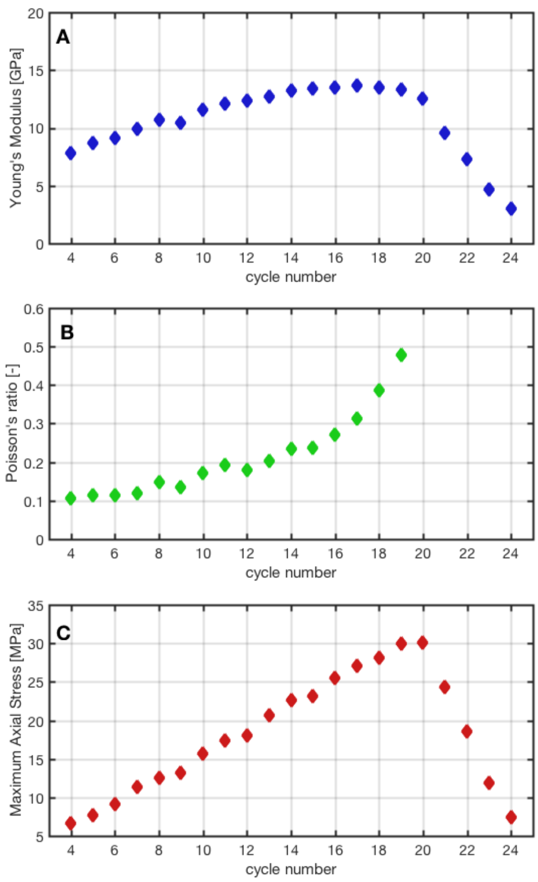

Figure 5. Mechanical parameters of load cycling experiments of Bentheim sandstone. The sample yields at cycle 16, and fails in cycle 20 (peak stress). A) Young's modulus vs. cycle number; B) Poisson's ratio vs. cycle number; C) maximum stress vs. cycle number

A qualitative analysis was performed on the fracture network generated by the load-cycling experiments and compared with fractures generated by the UCS experiments (Figure 8), looking at characteristics and density of fractures, including the micro-fractures. Note that comparing fracture aperture between different samples with post-experimental microtomography is difficult, since differences can also be caused by sample handling. Connectivity within a sample due to overall higher aperture is deemed a reliable facture though. Fracture density is defined as the number of fractures per bulk volume.

In Figure 8A (UCS) versus 8B (Cyclic) there is no clear improvement in fracture density for Bentheim Sandstone at this scale. Both samples exhibit a conjugate fracture set, with one main fracture. The load cycling experiment does show better connectivity due to an on average higher aperture throughout the sample. Comparing Figure 8C (UCS) versus 8D (Cycle) for Indiana Limestone indicates an increase in fracture density for the load cycling experiment, with many smaller fractures. Due to the high density of small fractures, especially in the centre of the sample, the connectivity of the network is also improved. In Figure 8E (UCS) versus 8F (Cycle) there is also a significant increase in fracture density and connectivity for Benin granite. Interestingly, the UCS experiment led to sample splitting along the edges of the sample, i.e. 2 concentrated failure zones, whereas in the load cycling experiment there is a network across the entire sample. In summary, all samples exhibit an improved fracture network due to load cycling.

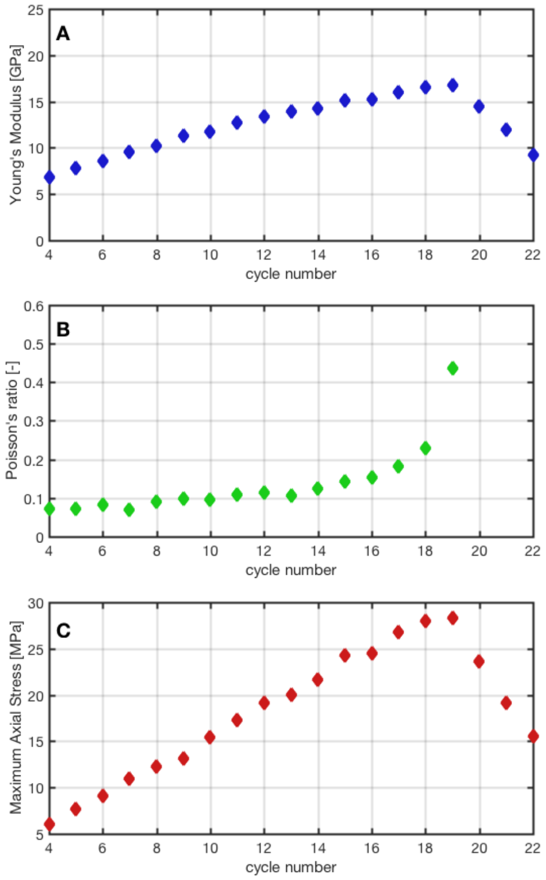

Figure 6. Mechanical parameters of load cycling experiments of Indiana limestone. Sample yields in cycle 13, and fails in cycle 19 (peak stress). A) Young's modulus vs. cycle number; B) Poisson's ratio vs. cycle number; C) maximum stress vs. cycle number

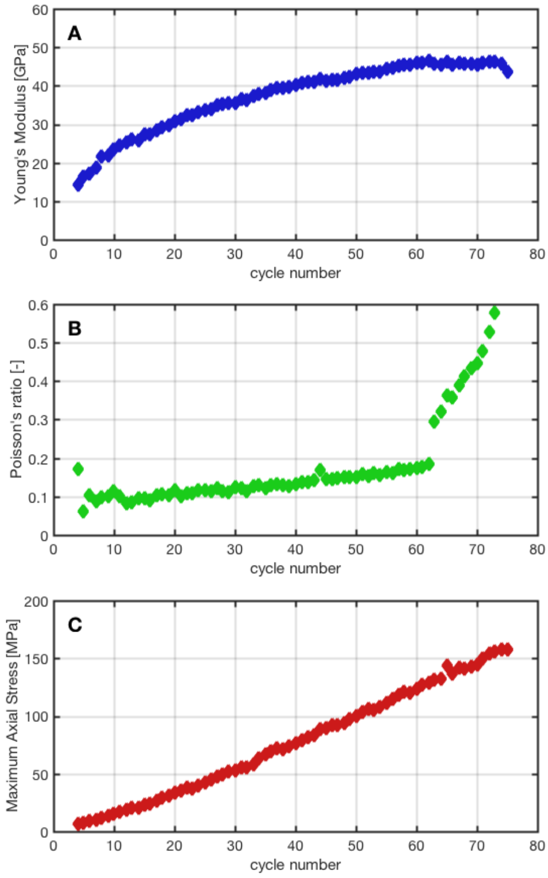

Figure 7. Mechanical parameters of load cycling experiments of Benin granite. Sample yields in cycle 62, and fails in cycle 75 (peak stress). A) Young's modulus vs. cycle number; B) Poisson's ratio vs. cycle number; C) maximum stress vs. cycle number.

4. DISCUSSION AND CONCLUSIONS

According to Ishizuka et al. (1990), load-cycling leads to fatigue damage which is a natural phenomenon for many materials, including rocks. Due to the fatigue damage the rock materials fail at a much lower stress level when compared to UCS experiments (Xiao et al., 2010). Bagde and Petros (2005) did a literature review on the effect of load-cycling on rock and concrete strength, indicating a reduction of maximum supported stress between 13 and 85 MPa. Initially stronger rocks also exhibit a larger stress reduction. However, the conditions of these collected experiments differ, such as the cyclic frequency (number of cycles per second) and the loading wave form (sine or triangle wave form). The strength reduction observed for our sandstone and granite samples fall within the expected range. One of the Indiana limestone experiments exhibited a strength increase from UCS to cyclic loading. However, due to its high fossil content, it is also the most heterogeneous of the three rocks. Barnhoorn et al. (2018) show three UCS experiments on Indiana limestone samples, w. The high sample variability of Indiana limestone is thus a likely cause for the difference in peak stress.

Even though most of our cycles occurred during what is typically interpreted to be the fully elastic regime, we still observed changes in (apparent) Young's Modulus and Poisson's Ratio. Our study isn't the only study observing changes in the elastic parameters during load cycling (Niandou et al., 1997, Heap and Faulkner, 2008, Heap et al., 2009, Xiao et al., 2010). The evolution of elastic parameters with load-cycling under uniaxial conditions may differ from confined conditions (Christensen and Wang, 1985). However, the evolution in this study shows comparable results with that of Niandou et al. (1997), where samples were confined. The change in elastic parameters is thus considered realistic for a subsurface reservoir where rocks were intact before stress cycling. This change, together with the hysteresis observed in the stress-strain curves, imply that the rock behaviour during our experiments isn't fully elastic during the imposed stress cycle. During the unloading to a negligible load the sample almost fully relaxes, even though cracks and flaws have been created during the loading phase. Upon reloading this new population of cracks and flaws is activated, leading to different elastic parameters and eventually to a more diverse final fracture pattern. In other words, even though we use the same sample, the observed change in parameters indicate that the sample is actually marginally but critically different during each loading phase.

Geothermal reservoirs are typically exploited using different pore fluid extraction and injection rates, and hence the subsurface reservoirs are experiencing stress cycles. Our experiments show that even when cycles take place in the elastic regime there can be consequences for the fracture patterns and final stress supported. This strength reduction observed in the laboratory can thereby potentially cause an earlier failure of reservoir and/or caprocks. Temperature fluctuations during production and injection may result in thermal stress-cycles (e.g. Xia et al., 2015), which supposedly may lead to similar reductions in rock strength.

Load-cycling experiments returned an improved fracture network when compared with UCS experiments, indicated by higher connectivity and/or a higher fracture density with microfractures. Qualitatively speaking, improvement was best for the granite, then for the limestone, then for the sandstone. Potential causes for this differences are the initial porosity, the initial flaw content and/or sample heterogeneity. This is the first study that studies the microstructure for different experimental procedures. The observed fracture network improvement due to load-cycling may have consequences for hydraulic fracturing. Hydraulic fracturing is commonly applied to enhance the production of oil and gas from underground reservoirs (Yew and Weng, 2015). The design of hydraulic fracturing involves the optimization of operational parameters in order to increase the sweep efficiency in low-permeability reservoirs (Speight, 2016), also known as integral fracturing (Renpu, 2011). The study in this report showed that load-cycling results can result in an improved fracture network, at least when fully unloaded in between stress cycles. We postulate that load-cycling by varying the fluid pressure may be applied to increase the sweep efficiency in low-permeable reservoirs. This would be beneficial to the recovery of geothermal energy.

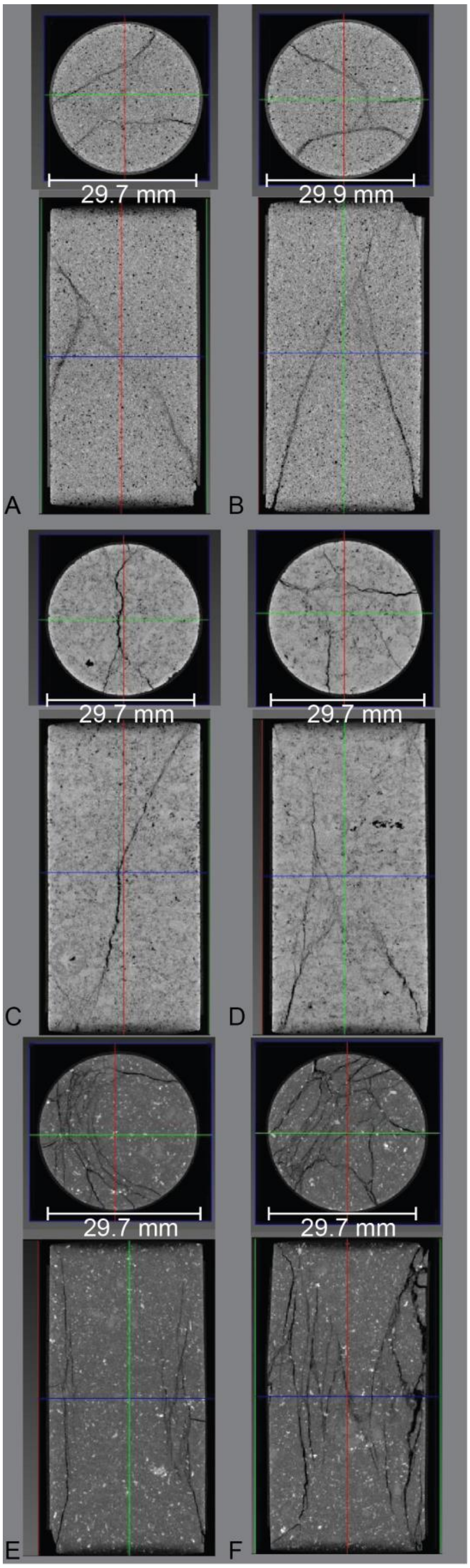

Figure 8 (right). Post-experimental micro-tomography images of A) UCS and B) Load cycling of Bentheim sandstone; C) UCS and D) Load cycling of Indiana limestone; E) UCS and F) Load cycling of Benin granite. All samples exhibit a more diverse fracture pattern after load cycling than after a UCS experiment.

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ACKNOWLEDGEMENTS

The authors would like to thank the technical staff of the GSE laboratory, particularly Wim Verwaal & Arno Mulder for their help with deformation experiments, and Ellen Meijvogel - de Koning for 3D imaging.