Pore Fluid Reactivation of Normal and Reverse Faults

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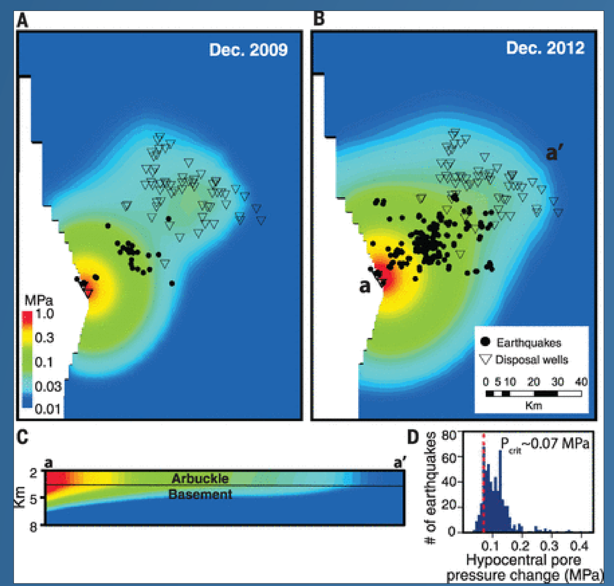
Introduction

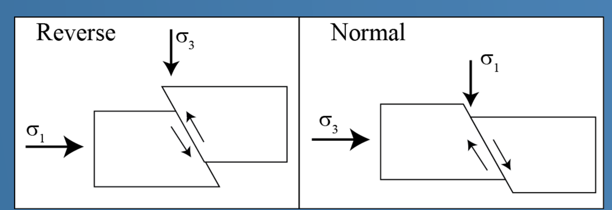


Locations of earthquakes and disposal wells are shown in relation to the amount of pore pressure change over the area. It was found that and average increase of 0.07 MPa triggered earthquakes (Keranen 2014).

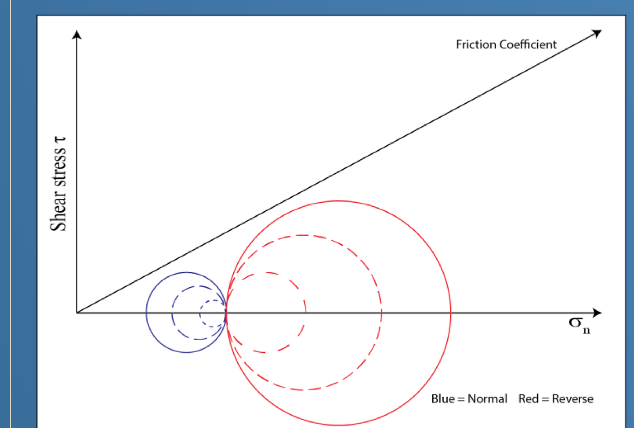
The rise of hydraulic fracturing and need for waste water disposal combined with record numbers of earthquakes in Oklahoma (Keranen 2014) due to waste water injection has made it clear that the hazards of waste water injection are not fully understood. A step to understanding what is happening in Oklahoma is to investigate the effects of pore fluid pressure on normal and reverse faults.

Background

Mohr's stress diagram represent the stress state of a material. The center of the circle represents the average stress of the sample. The radius of the circle represents the differential stress on the material. The edge of the circle shows the stress state for any given angle through the rock. The slope of the failure criteria line referred to as the coefficient of friction and is a material property that changes with every material



Main principal stresses for normal and reverse faults. For normal faults the maximum principal stress is in the vertical direction while it is in the horizontal direction for reverse faults.



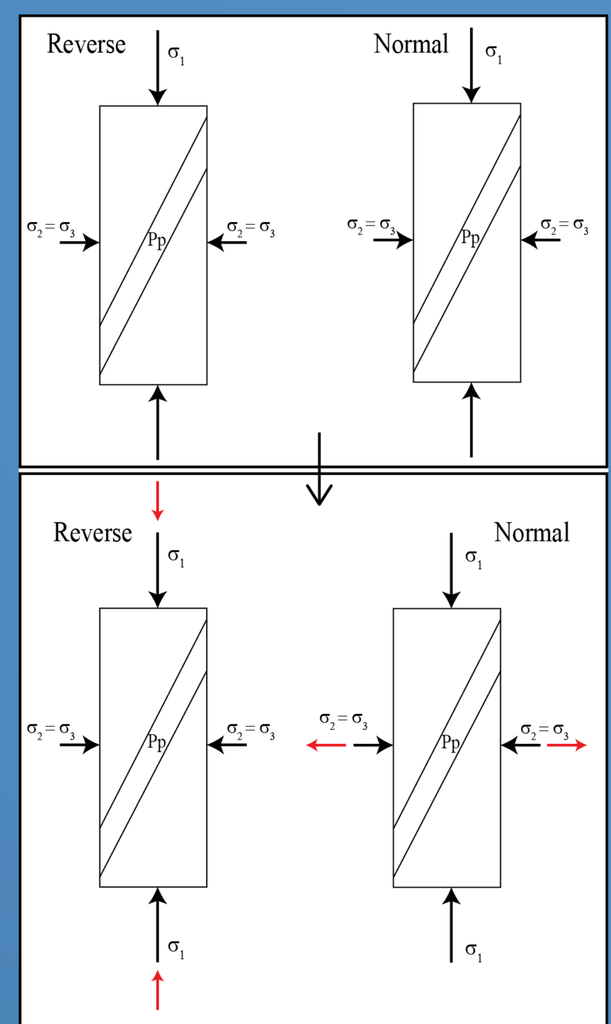
Two series of Mohr's stress diagrams. The red series shows tectonic forces increasing, while the series of blue circles shows tectonic forces decreasing.

Hypothesis

My hypothesis is that pore fluid pressure will behave differently for normal and reverse faults causing different types of movement along the faults. The reasoning behind this hypothesis is as follows. Rocks will start to behave plastically when the differential stress that they are under is a certain proportion of the differential stress required to completely fracture the rock. In a pre-cut sample like the ones used in these experiments the samples creep along the fault. Changes in pore fluid pressure are felt more readily during normal faulting because it takes a smaller increase in pore fluid pressure to reactivate the fault compared to reverse faulting.

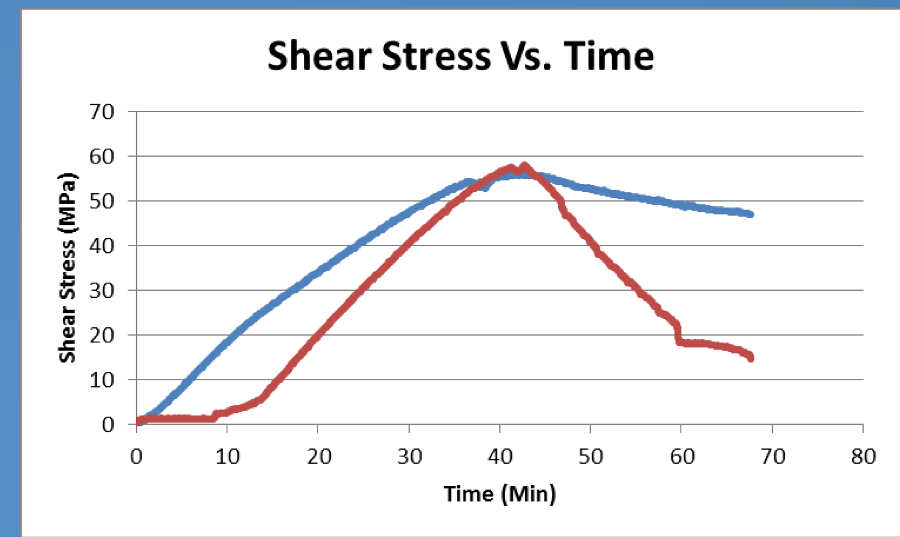
Experimental Design

For the reverse faulting experiments the first step is to bring the confining pressure $Pc = \frac{\sigma 1+\sigma 2+\sigma 3}{3}$ up to 65 MPa. Once this pressure is reached the confining pressure is held constant. The sample is then stressed axially by a hydraulic piston which provides differential stress. The differential stress is increased until the sample begins to behave plastically and creep begins along the fault. The pore pressure is then raised steadily until the end of the experiment. Experiments with no increase in pore fluid pressure are only stressed axially.



Top: Initial stress state for normal and reverse experiments. **Bottom**: Red arrows show axial stress increasing for reverse faults and confining pressure decreasing for the normal faults.

The normal faulting experiments start by increasing the confining pressure to 65 MPa. Once the confining pressure is reached the samples are again stressed axially until the samples behave plastically and there is creep along the fault. The axial stress is then stopped and the confining pressure is lowered. While the confining pressure is being lowered the pore fluid pressure is raised, in the experiments that require it.



Shear stress vs. time with blue showing the path of a reverse faulting experiment and red following the path of a normal faulting experiment

Materials/Equipment

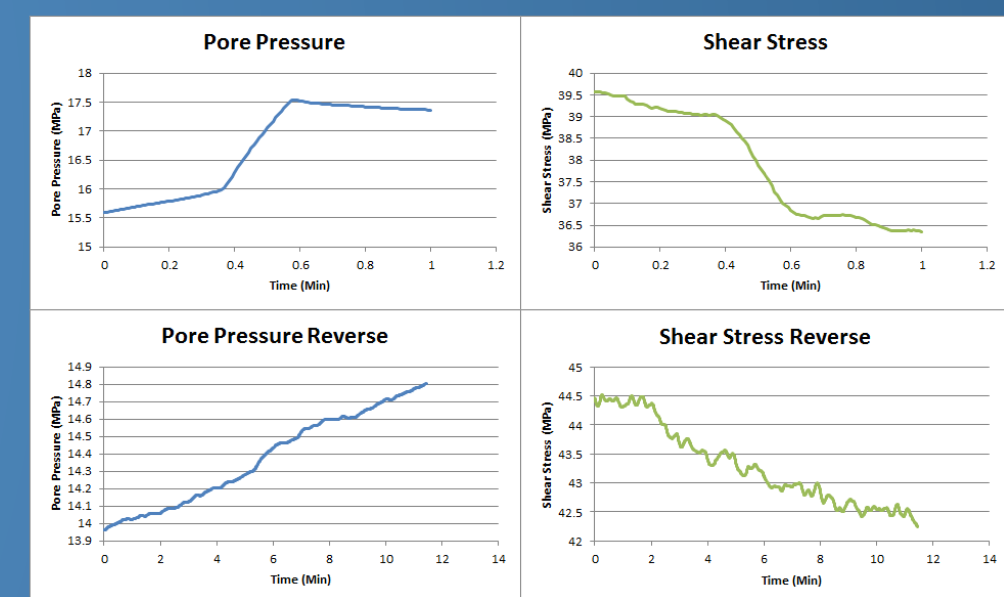
The experiments will use two types of saw-cut, porous sandstone samples. The use of a porous rock allows the samples to be easily saturated. Samples must be fully saturated so that the effects of pore fluid pressure can be transmitted throughout the entire sample. A saw cut runs through the samples at a 30 degree angle. This saw acts as a preexisting fault that will be reactivated during the experiment. The saw cut allows for better reproducibility between multiple experiments. The 30 degree angle of the saw-cut is the ideal fault orientation.

Upper Left: Sample that is almost finished preparation. **Upper Right**: Tri-axial Deformation machine. **Lower Left**: Sample after deformation. **Lower Right**: Face of a sample after deformation.

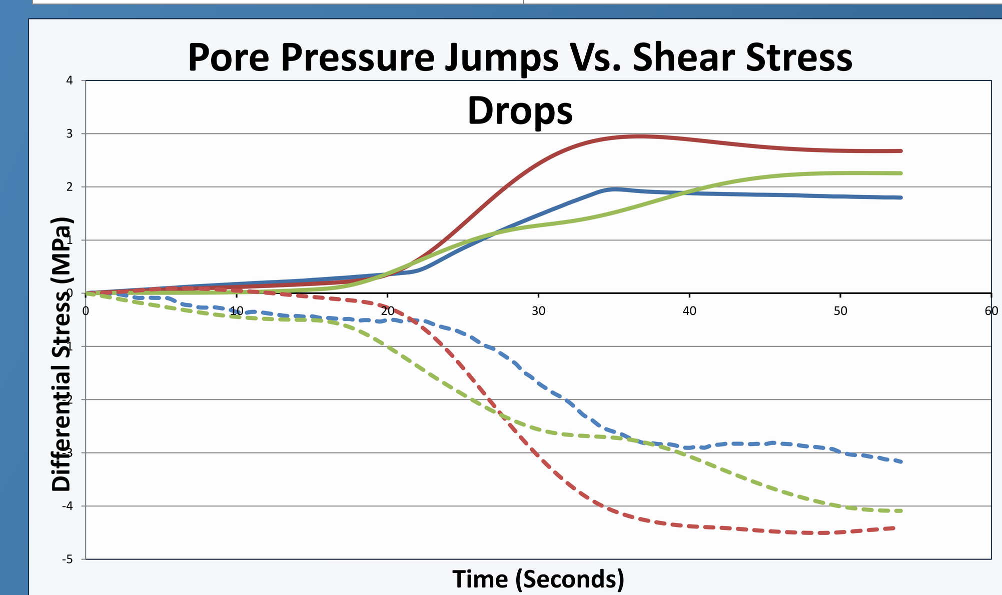
Results

The pore pressure increases only occurred in normal faulting experiments with pore fluid injection. Normal faulting experiments without injection showed no pore pressure increases. The rate of pore fluid injection also plays an important part in the characteristic of shear stress drops. Slower injection rates showed less pronounced shear stress drops compared to faster injection rates and though there were still noticeable pore pressure increases.

Experiment	Stone Type	Fault Type	Confining Pressure	Pore Pressure Rate	Number of events	AVE PPJ	AVE SSD
B4_F	Berea	Normal	62	0	0	N/A	N/A
Bcut30	Berea	Normal	61	1.1	2	2.5	3.75
DD4_F	Darley Dale	Normal	62	0	0	N/A	N/A
DD1_F	Darley Dale	Normal	62	0.9	1	1.5	2.25
Bcut21	Berea	Reverse	51	0	0	N/A	N/A
Bcut22	Berea	Reverse	52	0.08	0	N/A	N/A
DD7_F	Darley Dale	Reverse	64	0	0	N/A	N/A
DD6_F	Darley Dale	Reverse	62	0.32	0	N/A	N/A



Top: Compilation of experiment variables for all experiments used. **Side**: pore pressure jumps and corresponding shear stress drops



Left: pore pressure increases and corresponding shear stress drops with the solid lines showing the increases and the dashed lines showing the shear stress drops

Conclusion

Understanding how all types of faults react to increasing pore fluid pressure will help in the planning of where waste water wells can be placed and how fast water can be injected. The knowledge that injection along normal faults causes an increase in seismicity can be used in the future in waste water management and hazard mitigation. However, these processes are not fully understood so more research must be completed.

Acknowledgments

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Works Cited

Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection K. M. Keranen, M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge *Science 25 July 2014: 345 (6195), 448-451.Published online 3 July 2014 [DOI:10.1126/science.1255802]*