Effects of Water Saturation and Temperature on the Deformation and Transport Properties in Indiana Limestone

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Abstract

When subject to an applied stress or change in pore pressure, a rock will respond with either a compaction or dilation of pore space, consequently affecting fluid transport properties such as porosity and permeability. The observed deformation depends upon rock composition; silicate-based rocks such as sandstones and granites will follow a different deformation path than calcite-based rocks such as limestones. Calcite requires lower shear stresses to initiate twinning and dislocation slip relative to quartz (Vajdova et al., 2004); this difference leads to radically different types of deformation. The means to understand and predict the occurrence and degree of deformation is based on a fundamental understanding of the failure mode, inelastic behavior, and brittle-ductile transition. Indiana limestone is the focus of our experiment because its near compositional homogeneity makes it an excellent specimen in which to observe calcite deformation behavior. Transport property evolution via calcite deformation in Indiana Limestone samples are observed during hydrostatic and triaxial deformation experiments at different temperature conditions. Qualitative and quantitative microstructural observations of deformed samples detect for evidence of crystal plasticity; point counts in thin sections of deformed cores detect for twinning, a characteristic property of crystal plasticity. Additionally, some deformed cores exhibit macroscopic damage indicating the presence of plastic deformation. Previous experiments on Indiana Limestone have been conducted by Vajdova et al. Our data follows, showing weaker elastic modulii and greater reduction in permeability in high-temperature samples and, additionally, a weakening effect due to water saturation.

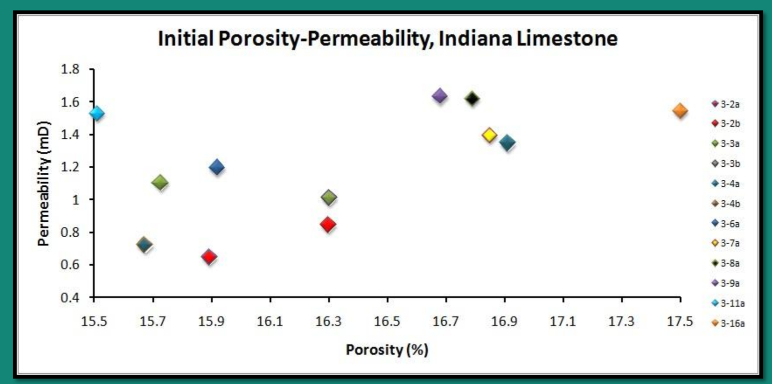
Hypotheses

The means to understand and predict the occurrence and degree of deformation is based on a fundamental understanding of the failure mode, inelastic behavior, and brittle-ductile transition. Our hypotheses are as follows:

1. Crystal plasticity plays an important role in the deformation behavior of Indiana Limestone.
2. As temperature increases, crystal plasticity will be more pronounced.

Experiment Design

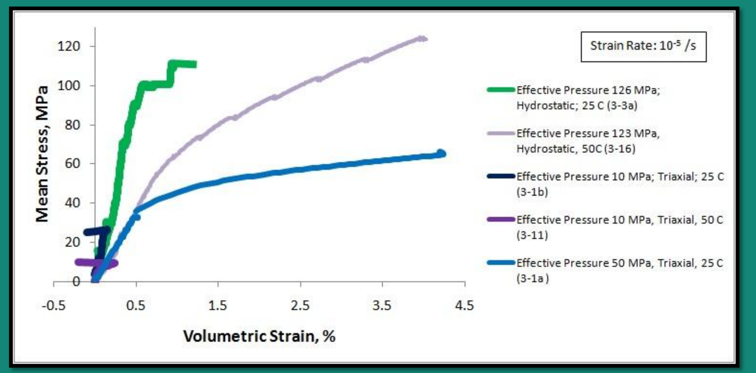
Measurements of length, diameter, and weight of each core are taken. Initial porosity and permeability values are then obtained. A 0.005" copper foil is soldered securely around the core (jacketing). The jacketed core is then loaded into the machine and exposed to a confining pressure of 10 MPa, but no pore pressure (seating). Seating will form the jacket to the outer pores, and, when done prior to attaching strain gages, minimizes damage to the strain gages. Three strain gages are attached; 2 axial and 1 radial. The core is saturated in distilled water before loading into the machine for the deformation experiment. Strain gage leads are attached; these transmit the signal into a readable measurement of deformation. The core is loaded into the machine where confining and pore pressures are set according to the experiment schedule. Permeability and velocity measurements are taken at regular intervals to monitor deformation and evolution of transport properties. The sample is then unloaded to be prepared for post-deformational analysis. Macroscopic and microscopic analysis are indicative of whether plastic deformation has occurred.



Initial porosity and permeability measurements for the cores. The average porosity and permeability is 16.3% and 1.2 mD, respectively.

Core	Effective Pressure	Pressure Conditions	Temperature
3-1a	50	Triaxial	25
3-1b	10	Triaxial	25
3-2a	70	Hydrostatic	25
3-2b	70	Hydrostatic	50
3-3a	126	Hydrostatic	25
3-3b	50	Hydrostatic	136
3-4b	126	Hydrostatic	25
3-11a	10	Triaxial	50
3-16a	123	Hydrostatic	50

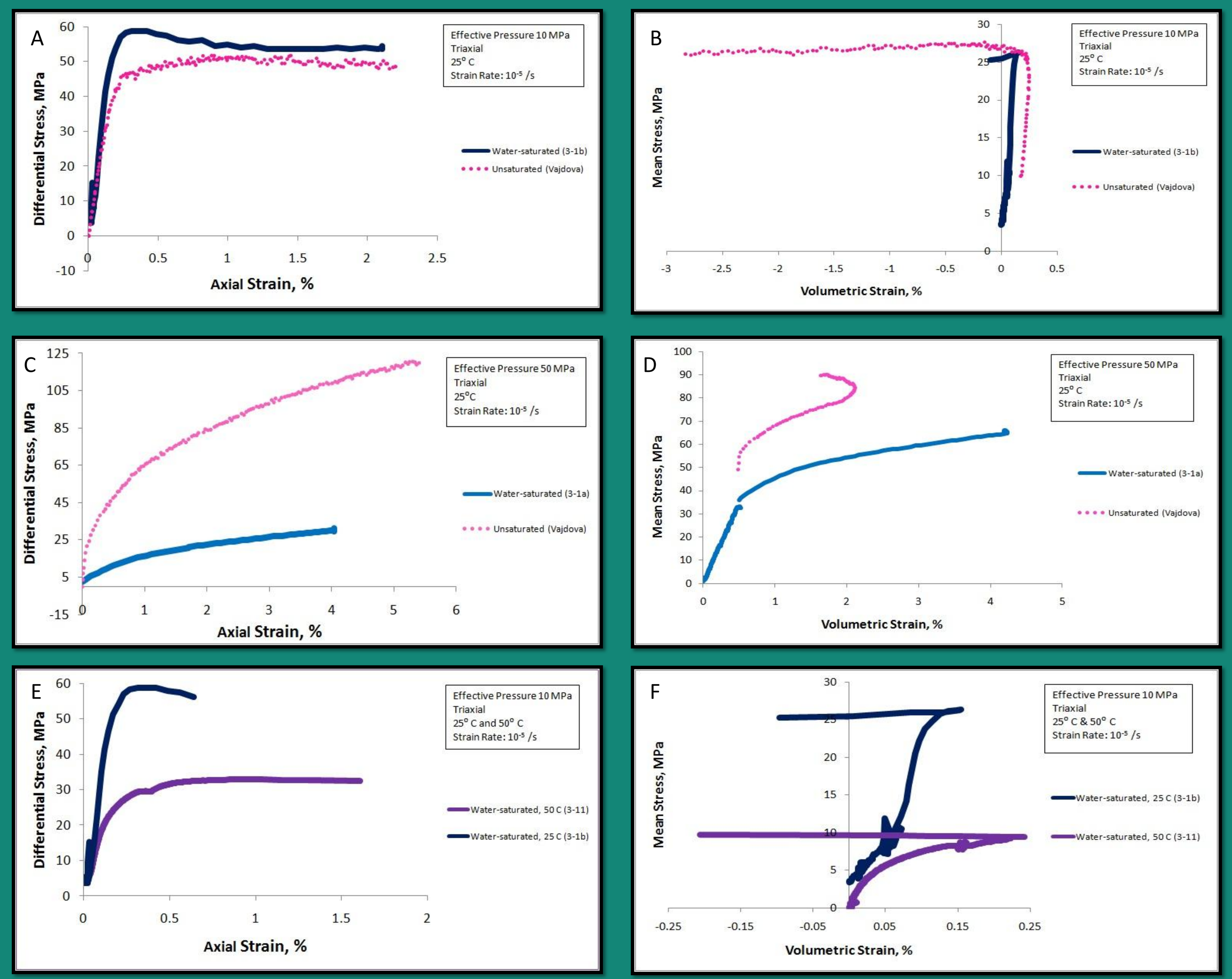
List of cores and their respective experimental conditions.



Bulk Modulus: Resistance to Compression

Effects of temperature and stress on deformation. UMD experiments held at 25⁰C/hydrostatic; elevated temperature (50⁰)/hydrostatic; 50⁰C/triaxial. Comparing the two hydrostatic and two triaxial experiments, the gentler slope of the 50⁰C experiments compared with 25⁰C shows the effect of temperature on deformation. Comparing hydrostatic to triaxial, the effect of an applied stress is seen by following change in volumetric strain.

Water Weakening and Temperature Effects



A) Effect of water saturation on deformation (10 MPa).

B) Effect of water saturation on dilatancy: the water-saturated core does not experience as much dilatancy as the dry core held at otherwise similar conditions.

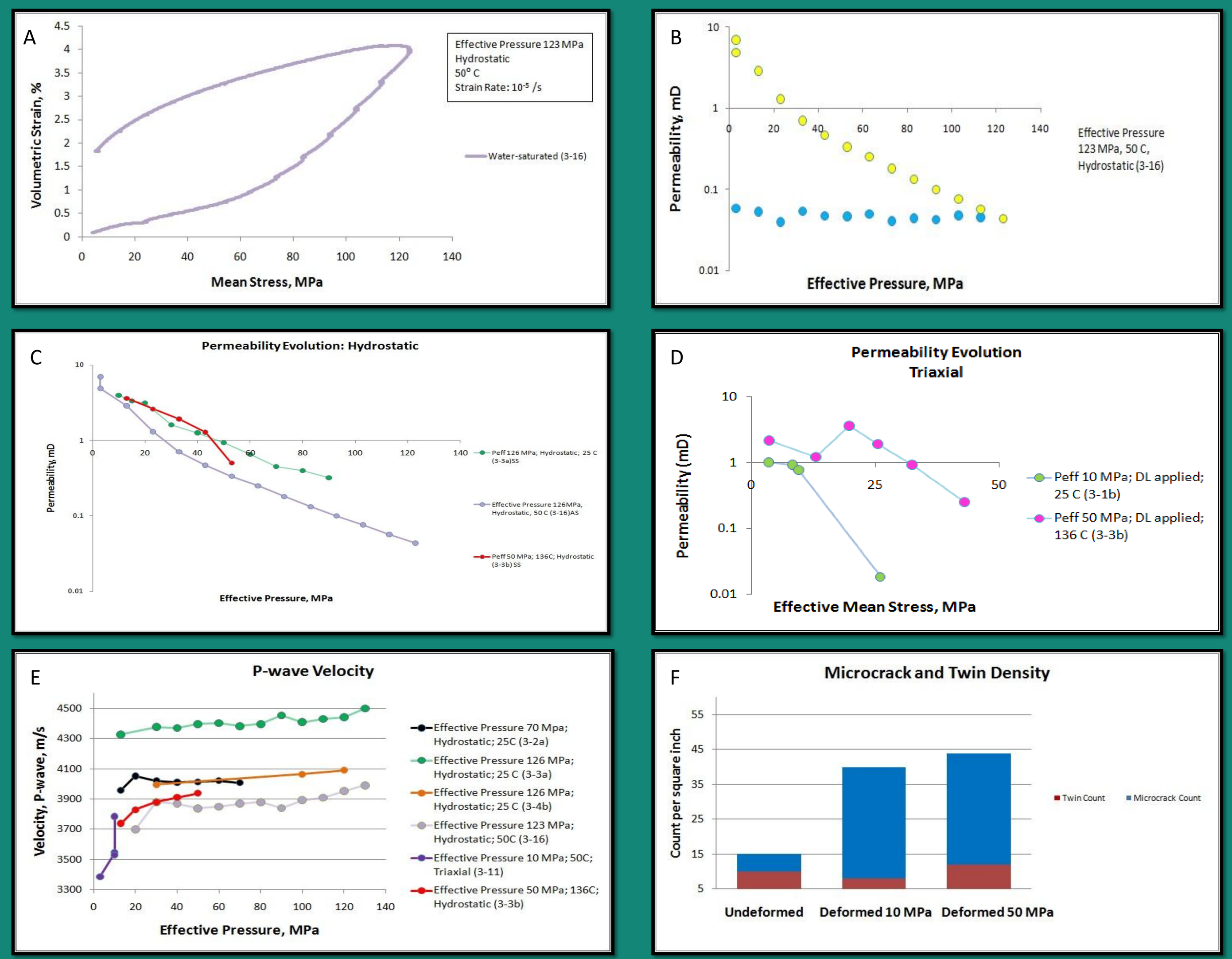
C) The onset of dilatancy at a much lower stress in the UMD core compared to Vajdova et al. shows the weakening effect due to water saturation.

D) The effect of water saturation dampening a rock's response to dilatancy is seen even more at elevated pressures; UMD core 3-1a does not appear to dilate at all, whereas the unsaturated core does.

E) Temperature effects on deformation: elevated temperatures promote weakness in sample 3-11 compared to 3-1b, which was conducted at room temperature.

F) Effect of temperature on volumetric strain: elevated temperatures promote a greater amount of dilatancy.

Mechanical Data



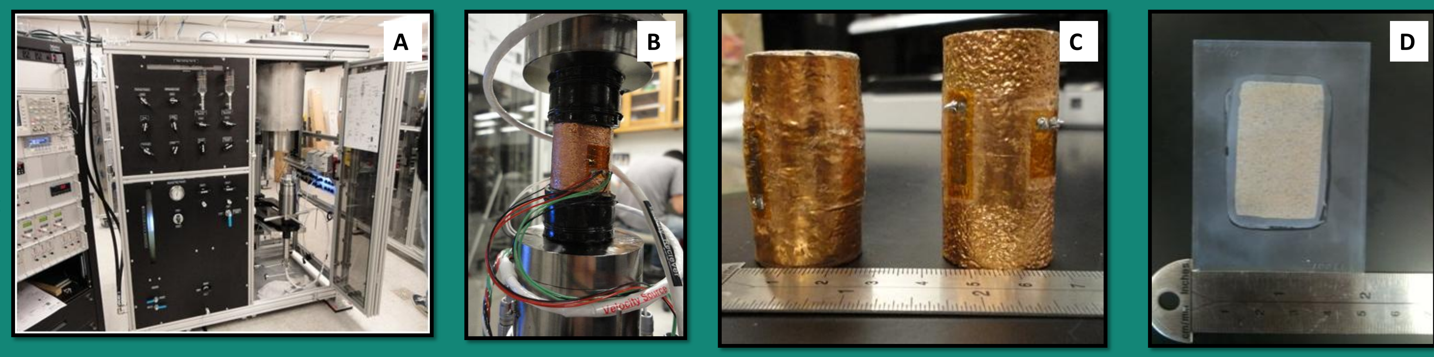
A/B) Loading and unloading paths of mean stress-volumetric strain and permeability evolution for core 3-16. The amount of volumetric strain increase is followed closely with a decrease in permeability. Partial volumetric strain recovers during unloading,; however, the reduction in permeability is permanent.

C) Permeability evolution of samples deformed in hydrostatic conditions.

D) Permeability evolution of samples deformed in triaxial conditions.

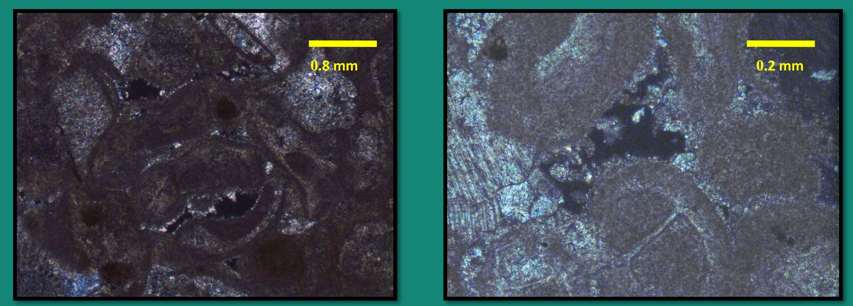
E) P-wave velocity as a function of increasing stress. An increase in velocity is indicative of compaction; as a rock compacts, it becomes denser, allowing the P-wave to travel faster.

F) Microcrack and twin point counts from deformed core thin sections. Larger amounts of microcracks were found in both deformed cores compared to the undeformed. However, a larger amount of twinning was only seen in the core deformed at effective pressure 50 MPa.



A) Autolab 1500c, the machine in which the deformation experiments are conducted.
B) Prepared sample, pre-deformation.
C) Core 3-11 (left) and 3-16 (right) post-deformation: the bulging core is indicative that plastic deformation has occurred.
D) Thin section of deformed core. Microstructural analysis is indicative of whether crystal plasticity is apparent.

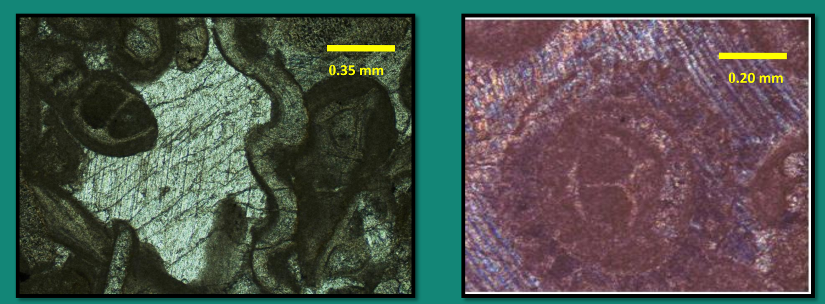
Pore Collapse



Left: Initial conditions, undeformed Indiana Limestone.

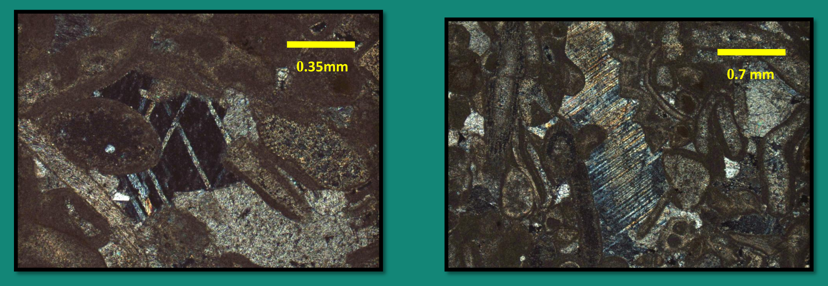
Right: Pore space collapse due to compaction and the subsequent microcracks in the grains. Microcracking breaks the grains into several smaller grains which then fill in the initial pore space (black). Both porosity and permeability are affected.

Microcracking



Microcracking induced by dilatancy. Transgranular cracks, above, are indicative of a shear-induced increase in dislocation density (Gold, 2003).

Twinning



Twinning is characteristic of crystal plasticity. Above, the effects of effective pressure and effective mean stress are apparent; a higher degree of twinning is seen in the core that has undergone a higher effective pressure and stress. Both experiments were held at room temperature (25⁰ C).

Discussion of Results

Bulk Modulus

There is a negative correlation between experiment temperature and sample resistance to compression. Additionally, the effect of water weakening on sample acts in a similar manner. The effect of water weakening is seem by comparing UMD cores to previous experiments on dry samples; our experiments involved saturated cores with pore fluid pressure maintained throughout the experiment.

Differential Stress-Axial Strain

There is a pronounced effect of temperature on onset of dilatancy. UMD core 3-11 (50⁰ C) has a drastically lower onset compared to both the UMD 25⁰C experiments and the Vajdova et al. dry cores at 25⁰C. The onset of dilatancy occurs at a differential stress of ~25 MPa compared to ~60 MPa (UMD) and ~45 MPa (Vajdova et al.). Further, the water saturation also lowers the onset of dilatancy.

Permeability Evolution

Hydrostatic: Decrease in permeability throughout all samples. With increasing temperature, decrease is slightly more rapid.

Triaxial: Two cores were plotted: room temperature (3-1b) and elevated temperature (3-11). Both experiments were conducted at an effective pressure of 10 MPa; there was about an order of magnitude greater decrease in permeability in the room temperature core. This is reasonable and consistent with our hypotheses because all other variables equal, at elevated temperatures, a rock is more prone to dilation at lower pressure/stress. Limestone has a positive porosity-permeability relationship; as dilatancy, a precursor to brittle faulting, occurs, a reduction in permeability decrease is to be expected.

Velocity Measurements

An increase in P-wave velocity corresponds to compaction of the sample. Observations indicate that an increase in pressure or stress on a sample leads to larger velocities.

Conclusions

• Deformation behavior is affected by changes in temperature, pressure, and other factors including water saturation.

1 .Water saturation induces a weakening effect on our samples. This is seen through the onset of dilatancy at lower stress levels and the reduced amount of dilatancy experienced

2. Additionally, increased temperatures cause a similar weakening effect.

•These observations support our hypotheses and open up the opportunity to expand research to include finer details.

Acknowledgements

This project would not have been possible without the support of several people. First and foremost, I would like to thank my advisor, Dr. Wen-lu Zhu for giving me the opportunity to work on this project with her and further my learning. I would also like to thank graduate students Tommy Tamarkin and Jill Gribbin as well as Harry Lisabeth for their help training me on the equipment and with sample preparation. Lastly, this project would not exist without funding from ExxonMobil.

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