Analyzing the Effect of Olivine Mineralization on the Strength of the Oceanic Lithosphere

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Introduction

The strength of the lithosphere is the maximum load that it can withstand without breaking. The maximum strength of the lithosphere cannot exceed the strength of the rocks that it is made of. Currently, constraints of the strength of oceanic lithosphere come from deformation experiments on olivine. At low temperatures, olivine rocks deform in a brittle regime, in which fractures occurs once the load exceed the rock strength [3].

Olivine mineralization occurs when olivine reacts with H_2O and dissolved CO_2 to form hydrous silicates (e.g. serpentine), Fe-oxides (e.g. magnetite), and carbonates (e.g. calcite, magnesite, and dolomite). With progressed alteration, there is a transformation from olivine to serpentine with the final product being some combination of the minerals talc, magnesite, and quartz (listvenite).

It is estimated that 10-30% of basement rock found at crustal levels (depths < 7 km below seafloor) consist of serpentinized peridotite. Deformation experiments on slightly serpentinized peridotite samples demonstrate that small amounts of serpentine will significantly weaken peridotite [1]. Observations have also established that olivine carbonation has a contribution to the formation and evolution of the oceanic lithosphere. The process olivine carbonation generates a major change in rock's brittle shear strength. However to date, the change in shear strength due to olivine carbonation is unknown.

Hypotheses

- The hydration of peridotite reduces the shear strength of the rock as it is altered to serpentinite.
- The carbonation of serpentinite will further reduce the shear strength of the rock, as it becomes altered into soapstone.

I have tested my hypotheses by running deformation experiments with samples of dunite (unaltered olivine), serpentinite, and soapstone. These rocks have originated as part of the oceanic lithosphere and have been hydrated and carbonated through natural processes.

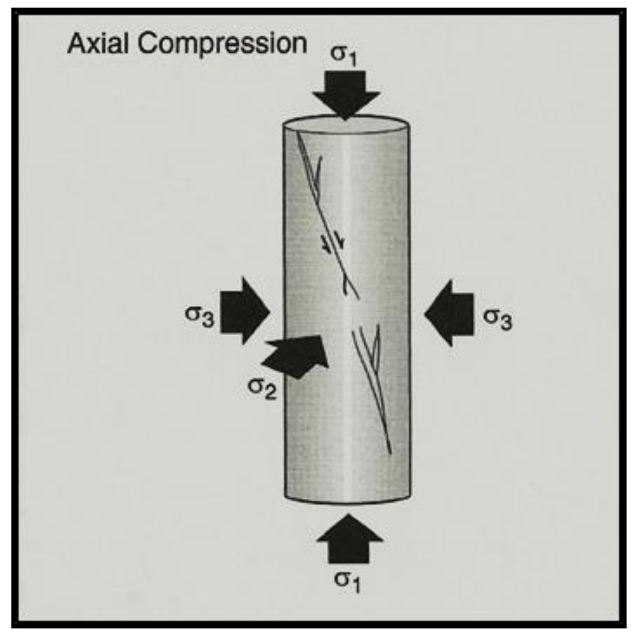
Experiment

The experiments were conducted in the servo-controlled Autolab 1500 axial deformation apparatus. I wanted to study the in situ response of the rocks present within oceanic lithosphere during loading. To produce these conditions there needs to be one primary stressor (σ_1) and two minor stressors (σ_2 & σ_3), which are equal.

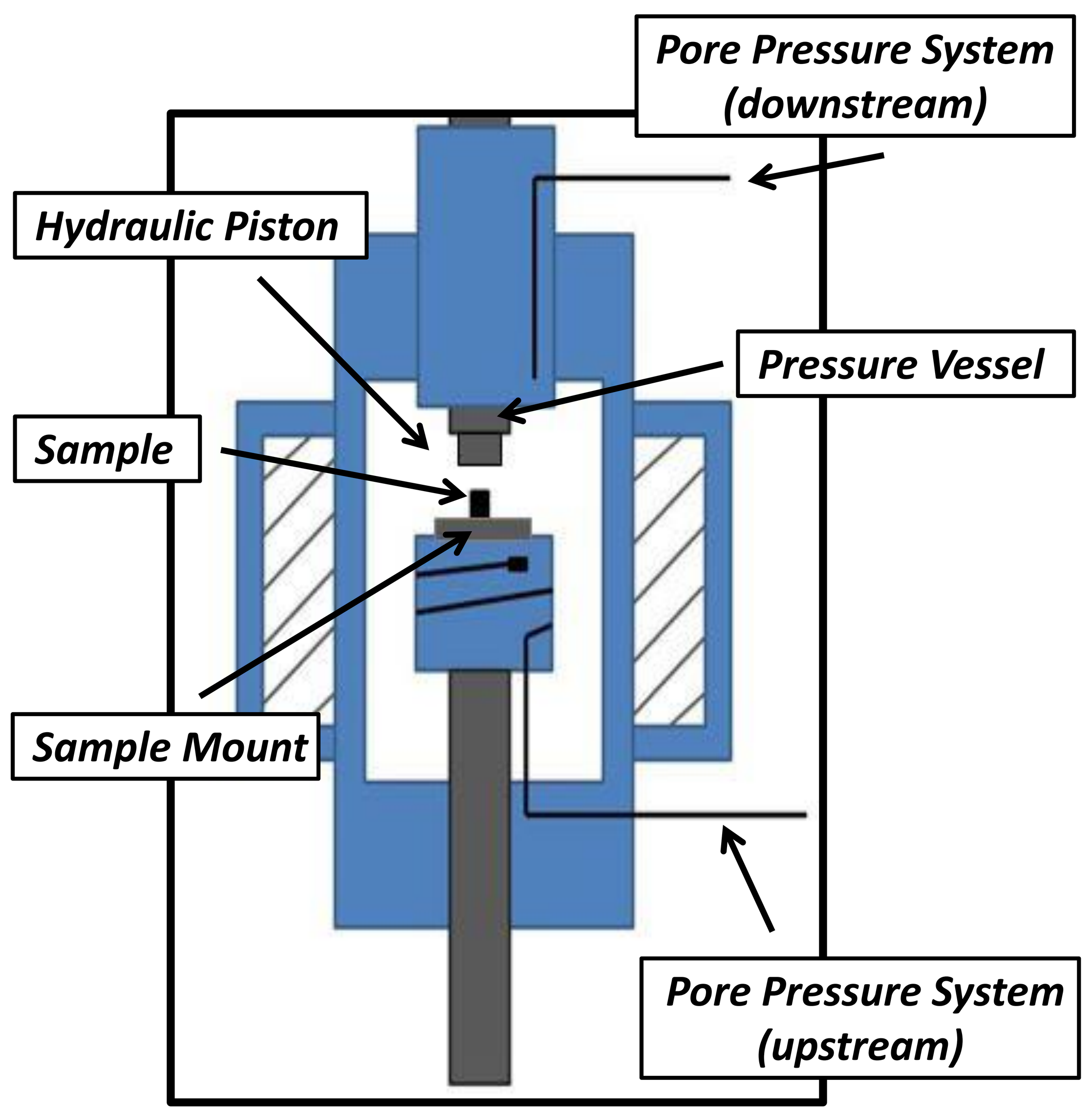
The primary stressor is raised continuously by axial displacement, this produces the condition of loading in the lithosphere. The two minor stressors simulate the confining pressure of the experiment, which is the hydrostatic component of the experiment. Axial displacement is executed until the point of failure in the rock. This peak stress is recorded as differential stress in MPa. This peak stress is the overall strength of the rocks in my experiment.

Experimental Conditions	
Temperature	~ 25˚C
Confining Pressure	50 MPa
Strain Rate	3.5×10^{-5} s^{-1}

Sample Dimensions	
Length	38.3 mm
Diameter	18.45 mm
Length	25.6 mm
Diameter	12.75 mm



Schematic for Autolab 1500 axial deformation apparatus



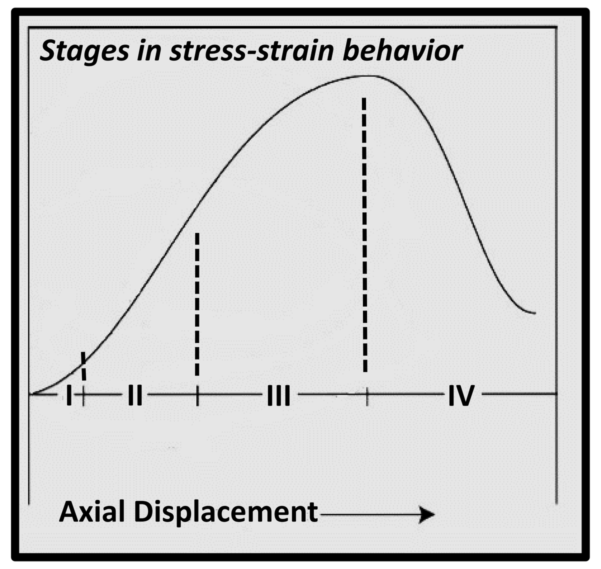
Typical, stress-strain behavior for rocks during axial compression [2]

Stage I. There is an upward concavity in the curve of a plotted graph of stress vs strain. This is attributed to the closure of pre-existing cracks.

Stage II. The plotted graph forms a straight and linear line. This stage represents elastic deformation for the rock.

Stage III. This section of the plot deviates from elastic behavior. Micro-cracks and fractures develop.

Stage IV. Stage IV represents post-failure after the peak stress has been achieved. Macroscopic cracks have formed at this point.



Mineralization Reactions in the Oceanic Lithosphere

olivine + water → serpentine + brucite

$$2Mg_2SiO_4 + 3H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$$

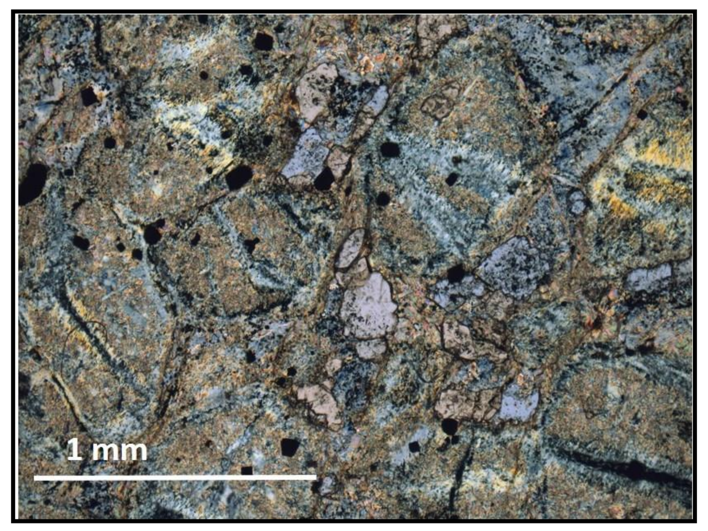
serpentine + CO_2 → talc + magnesite + water

$$2Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3MgCO_3 + 3H_2O$$

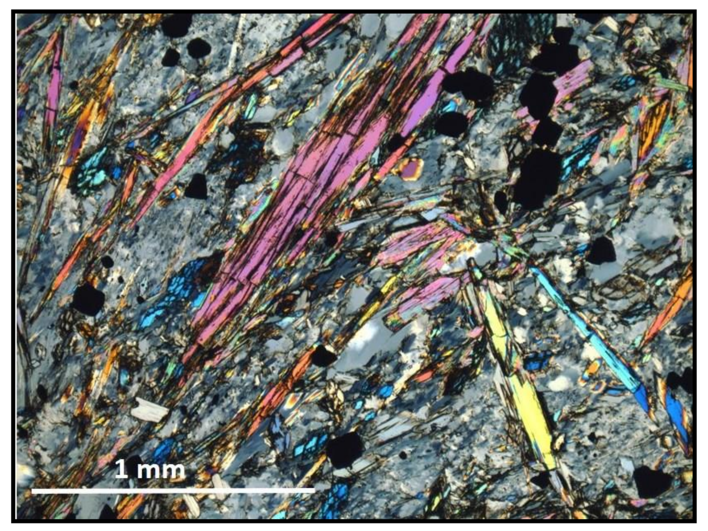
talc + CO_2 → quartz + magnesite + water

$$Mg_3Si_4O_{10}(OH)_2 + 3CO_2 \rightarrow 4SiO_2 + 3MgCO_3 + H_2O$$

Microstructural Observations



Serpentinite (XPL, 5x magnification)
Serpentine 70-90%; pseudomorph structures; infiltration of cracks and voids; 1st order grey interference colors.
Orthopyroxene ~ 15%; **Opaque minerals** ~5%



Soapstone (XPL, 5x magnification)
Talc 25-35%; random orientation; sheet like appearance; interference colors of 3rd order purple and green
Serpentine 45-60%; **Opaque minerals** 5-10%

Results

Dunite. The dunite sample behaved elastically in response to the stress in the experiment. The graph displays a linear plot of the strain, common in stage II of strain. The post-failure behavior was cataclastic with a sudden drop in stress tolerance.

Serpentinite. The responses observed in the serpentinite experiment were more subtle. The elastic response was less linear, which is why there is more variance in the calculated Young's modulus. The behavior of the sample during stage III and stage IV are the most clear; these stages are related the portion of the experiment when microfractures develop and propagate through the sample.

Soapstone. At the start of the experiment it is apparent that stage I response has occurred; the plotted strain has a concave shaped curve. The pre-existing cracks and void spaces in the sample are closed. The post-failure reaction in soapstone is similar to the serpentinite. The presence of serpentine and talc facilitate sliding on cracks; this transpired both before and after the peak stress has been reached.

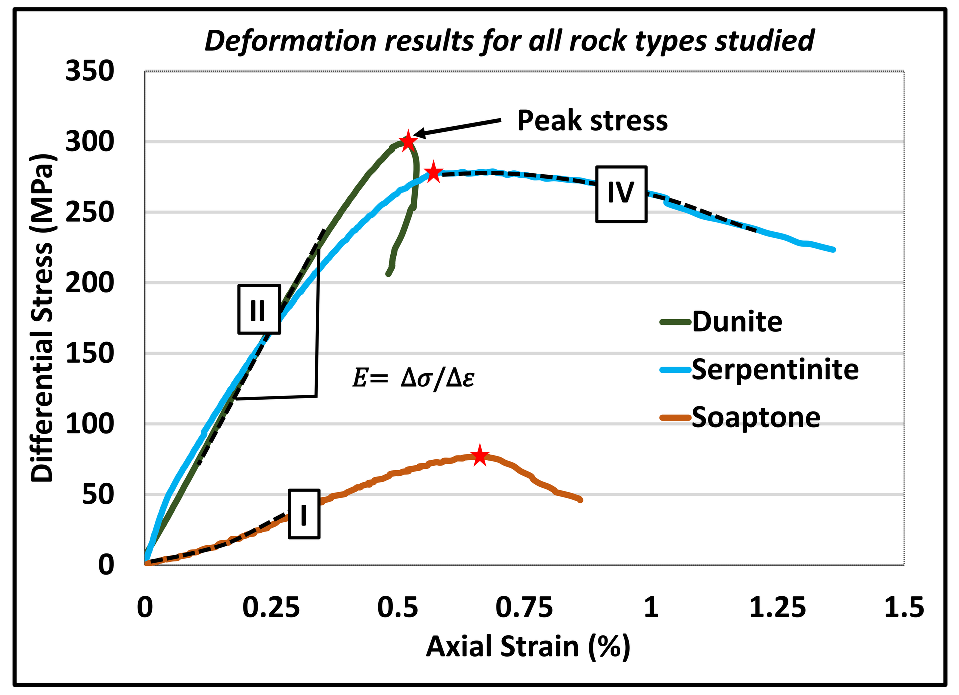
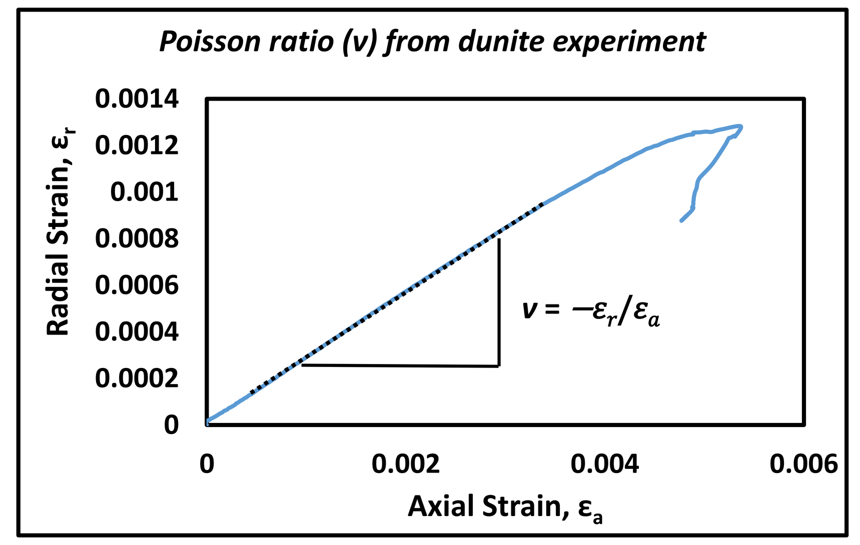


Figure above
--- Dashed lines accompanied with roman numerals, mark different stages in observed responses

★ Stars mark failure point in experiment



Rock Type	*Porosity (%)*	*Young's Modulus, E (GPa)*	*Poisson's Ratio, v*	*Shear Modulus, G (GPa)*	*Shear Strength (MPa)*
Dunite	0.63 ± 0.23	64.2 ± 3.19	0.28 ± 0.01	25.2 ± 1.6	301.4 ± 1.0
Serpentinite	0.27	50.0 ± 12.3	0.44 ± 0.03	17.4 ± 3.87	278.9 ± 1.0
Soapstone	0.28	14.4 ± 1.26	-	-	76.9 ± 1.0
Data recorded with σ_1					

Conclusion

As a result of olivine mineralization in the oceanic lithosphere, the mineral composition of the rocks within are changed. Serpentine and talc are alteration minerals that typically form as a result of this process. Observations show that these minerals have a considerable effect on the strength the oceanic lithosphere [1]. The presence of theses minerals have been linked to the localization of failure in faults [1].

Experimental rock failure is considered to be analogous to localized shear zones in the earth [3]. From my experiments, I observed that peridotite has a greater shear strength and larger elastic moduli then serpentinite; when comparing serpentinite to soapstone the same trend was noted. Therefore, my hypotheses were not rejected. I learned from these experiments that the rheology of the rocks in the oceanic lithosphere are dictated by the weakest minerals present, even in small quantities (~ 10%).

References

[1] Escartin, J. J., Hirth, G. G., & Evans, B. B. (2001). Strength of slightly serpentinized peridotites; implications for the tectonics of oceanic lithosphere. Geology [Boulder], 29(11), 1023-1026.
[2] Paterson, M.S., & Wong, T. (2005). Experimental rock deformation – The brittle field (2nd ed). The Netherlands: Springer.
[3] Kohlstedt, D. L., Evans, B., & Mackwell, S. J. (1995). Strength of the lithosphere; constraints imposed by laboratory experiments. Journal of Geophysical Research, 100(B9), 17. doi:10.1029/95JB01460