

**Developing Methodology for Hydraulic Conductivity Analyses of Active Layer Soils
from Barrow, Alaska**

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1. MATERIALS & METHODS

Six individual ice cores were collected from Barrow Environmental Observatory in Barrow, Alaska, in May of 2013 as part of the Next Generation Ecosystem Experiment (NGEE). Each core was drilled from a different location at varying depths. A few days after drilling, the cores were stored in coolers packed with dry ice and flown to Lawrence Berkeley National Laboratory (LBNL) in Berkeley, CA. 3-dimensional images of the cores were constructed using a medical X-ray computed tomography (CT) scanner at 120kV. Hydraulic conductivity samples were extracted from these cores at LBNL's Richmond Field Station in Richmond, CA, in February 2014 by cutting 5 – 8 inch segments using a chop saw. Samples were packed individually and stored at freezing temperatures to minimize any changes in structure or loss of ice content prior to analysis.

Hydraulic conductivity was determined through falling head tests using a permeameter [ELE International, Model #: K-770B] (Appendix A). Samples were placed in a latex membrane via a membrane stretcher while frozen. Use of a membrane stretcher made the membranes easier to secure and minimized contact with the sample. A clear polycarbonate sleeve, fabricated with a stainless steel ring at the bottom to keep the sleeve from floating, was placed around the sample inside the permeameter to minimize deformation during analysis. The permeameter was filled with water and 1.0 PSI of air was applied for confining pressure during sample defrost. Outflow valves were left open to allow for incremental thawing and samples were left to thaw for approximately 12 hours.

After approximately 12 hours of thaw, initial falling head tests were performed. When the flow was significantly too fast or too slow, the analysis was stopped and the burette size was adjusted accordingly (i.e. a larger diameter burette was used for flows that were faster than desired or a smaller diameter burette was used for flows that were slower than desired). Two to four measurements were collected on each sample and collection stopped when the applied head load exceeded 25% change from the original load. Analyses were performed between 2 – 3 times for each sample. The final hydraulic conductivity calculations were computed using methodology of Das et al., 1985.¹

¹ Das, Braja M. *Principles of Geotechnical Engineering*. Stamford, CT: Cengage Learning, Print.

2. APPENDICES

APPENDIX A. Standard Operating Procedure of Falling Head Test

1.0 Scope and Objective

To determine the hydraulic conductivity of arctic soil samples from Barrow, Alaska, through a falling head test.

2.0 Interferences and Potential Obstacles

- Difficult to determine when the sample is fully thawed and the point at which analysis can begin
- Pulling a vacuum may compromise the integrity of the sample, thus resulting data would be an inaccurate measure of permeability
- Soil textures of samples are unknown so a large range of hydraulic conductivities are expected between samples and therefore head loads need to be adjusted accordingly
- Membranes that are too thick may crush the sample and alter the natural structure but membranes that are too thin may easily get torn under pressure

3.0 Materials

- Permeameter [*ELE International, Model #: K-770B*]
- End caps machined out of PVC with a pattern on the inside surface contacting the sample to distribute water evenly throughout the cross-sectional area of the sample (Fig. 1, 2 and 3)
 - Dimensions:
 - 1.77'' diameter x 1'' length
 - 2.87'' diameter x 1'' length
- Latex membranes to securely fit around each sample but with a wall thin enough to not crush the sample
 - Dimensions:
 - 1.5'' diameter x 8'' length x 0.012'' thickness
 - 2.8'' diameter x 10'' length x 0.012'' thickness
- Membrane stretchers to easily secure the membranes around each sample (Fig. 4 & fig. 5)
 - Dimensions:
 - 3.5'' inside diameter x 7'' length
 - 2.25'' inside diameter x 6'' length
- Clear polycarbonate sleeves to keep samples upright
- 20-gallon carboy which will gravity-feed water into the permeameter to act as the confining pressure
- 3500 mL beaker placed on a scale [*Mettler PM6000*] with a 6100g-capacity

- Pump [*Masterflex L/S, Model #: 7518-62*] to fill inflow tubing with degassed water prior to analysis and refill carboy when water level becomes low
- Confining pressure column [*Alltech, 100psi maximum*]
- Pressure regulator [*Control Air Inc., 0-15psi range and 250psi maximum*] to control and record confining pressure
- Air source to supply confining pressure
- Equipment to degas water that will flow through sample
- Burettes of varying diameters to supply adequate head to each sample

4.0 Equipment Set-up

- Adhere wear-resistant nylon mesh (198 X 198 Mesh, 0.0035" Opening) with nitro-cellulose household cement (Brand name: "Duco Cement") to the sample-side of each end cap and allow to dry overnight. The mesh will reduce the number of fine particles that flow out of the sample and reduce the chance of clogs occurring in the outflow tubes.
- Sand down the bottom of the lower end cap until completely smooth and apply vacuum grease to seal to the bottom plate of the permeameter. Secure the bottom end cap by screwing it into the bottom plate of the permeameter from underneath.
- A range of hydraulic conductivity is expected between samples; therefore, burettes of varying sizes will be used depending on the initial flow rate through the sample.

5.0 Procedure

1. Prior to running NGEE samples, the permeameter should be checked for leaks by performing the analysis on a blank, which refers to securing a latex membrane around the top and bottom end caps without any sample in between. To avoid leaks, make sure:
 - a. fittings are installed properly and tightly
 - b. the bottom end cap is smooth enough for the vacuum sealant to adhere to the bottom disk
2. Before inserting the sample, prime the inflow and outflow tubing with water to ensure no air bubbles will be introduced into the sample.
3. Line the membrane stretcher with wear-resistant nylon mesh before inserting the membrane. Vacuum the membrane to the sides of the membrane stretcher with a 140-cc syringe and place over the bottom end cap. Insert the sample into the membrane and push the top end cap inside until it is in contact with the sample. Release the vacuum and secure the membrane around both end caps with tight-fitting O-rings on the outside.
4. Attach the top end cap to the tubing that connects with the valves labeled "upper". Insert polycarbonate clear tube around sample and secure with stainless steel ring (Fig. 7).
5. Assemble and secure the walls and top plate of the permeameter.
6. Attach the top plate of the permeameter to the column connected with the air supply that will serve as the confining pressure.
7. Check that all pore pressure valves are closed. Loosen the top of the confining column. Fill the permeameter with water by opening the confining valve and keep filling until the water level in the confining column is 1-inch below the top.

8. Tighten the upper cap on the confining column and mark the water level.
9. Close the valve that connects the air supply to the psi gauge and confining column. Turn the pressure dial all the way counter-clockwise and open the bottom quick release valve. Turn on the air supply. Open the valve to allow air to flow through the gauge and out the quick release valve. Open the other release valve that allows 1psi to pass through. Close the quick-release valve and turn the pressure dial clockwise until the gauge reads 2psi. Close the 1psi release valve and adjust the pressure until the gauge reads 3psi. Mark the water level of the confining column. If the gauge reads anything above the desired pressure, open the bottom quick release valve to release the unwanted air and readjust the dial accordingly.
10. Degas the water that will be used to flow through the sample.
11. Attach outflow tubing to the “upper” valves. Run the outflow tubing up the height of the permeameter and fasten so it spills out into a large beaker that sits on top of a scale.
12. Tare the scale before starting the test so readings will accurately reflect how much water has flowed through the sample.
13. Connect the tubing attached to the burette to the pump. Insert the end of the pump into a supply of degassed water. Pump degassed water into the tubing, making sure no air bubbles settle in the tubing, until the burette is filled to the desired level. Adjust the height of the burette so that the bottom reading is in line with the outflow tubing (where flow will be equilibrated since there will be no difference in height of inflow and outflow heads). Start at the lowest height for the first test, and increase height as needed to avoid compromising the sample structure by applying too high of a head load initially.
14. Periodically check the water level of the confining column to make sure there is no loss of water.
15. Open the “upper” and “lower” valves. Check to make sure no leaks are present. Measure the height of the water level in the burette relative to the bottom of the permeameter. Also measure the height of the spill-over from the outflow tubing relative to the bottom of the permeameter.
16. Allow the sample to sit for sufficient time to thaw completely, ideally overnight. Keep U1 and U2 open during the thawing process. Water flowing out of the U1 & U2 tubing and onto the scale is a sign that the sample is thawing.
17. When the sample has finished thawing, open the valve to the burette and begin the flow through the sample as you simultaneously start the stopwatch. Record the level of the meniscus in the burette and the weight of the outflow water every 30 seconds until flow begins to slow significantly. Record a reading every time the time period doubles (i.e. 1, 2, 4, 8, 16 minutes etc.). Also record the weight of the spillover with each reading.
18. If the flow is significantly too fast or too slow, stop the analysis and switch the burette to the appropriate size (i.e. use the larger diameter burette for flows that are faster than desired or the smaller diameter burette for flows that are slower than desired). Repeat steps 13-17 until a minimum of four measurements are taken over doubling time periods at flow rates that allow for precise measurements.
19. Repeat the test three times to ensure quality results.

20. When the test has finished, close all valves. Move outflow head tubing down to the floor so pressure change does not compromise the structure of the sample.
21. Release confining pressure by turning off air source, opening V2 and turning the PR dial all the way counterclockwise. Turn V1 to the closed position.
22. Unscrew the top cap on the confining column. Disconnect C1's tubing from the carboy and place tubing into a bucket on the floor. Open C1 and let drain until all of the water is out of the permeameter. If the sample's membrane starts to increase in size, stop everything and hook a vacuum of minimal mmHg to U1 and U2 and continuing the draining process. You can also take off the top plate once the confining column has finished draining to further reduce the confining pressure on the sample.
23. Make a note of the length of the sample since it may have shrunk after thawing to use in final calculations.
24. Take apart permeameter, undo U1 and U2 tubing to the top end cap and unscrew the bottom end cap from the lower plate on the permeameter. Undo the sample from end caps over a trashcan and discard the membrane and sample.
25. Wash the end caps thoroughly with water to get rid of any fines lodged in the mesh or holes. Rinse lower plate of permeameter. Re-grease bottom end cap and screw into place on lower plate of permeameter. Attach a clean membrane and the top end cap and secure the U1 and U2 tubes. Refill the pipette and flush U1, U2, L1 & L2 tubing with water until noticeably clear and free of fines. Make sure L1 & L2 tubing is full of water and no air is trapped in tubing before turning off valves which will avoid pumping air into the sample at the beginning of the next analysis.
26. Re-grease both O-rings on permeameter plates and wipe down any leftover fines.
27. If running another sample, begin from step 3 in the procedure list.

6.0 Calculations

Refer to Appendix B.

7.0 Health and Safety

- Make sure all laboratory equipment used above the countertop is secured down and earthquake-safe.

8.0 References

- 9.0 Das, Braja M. *Principles of Geotechnical Engineering*. Stamford, CT: Cengage Learning, Print.

10.0 Photos and Diagrams



Figure 1. PVC end caps with patterns that connect onto the soil sample being analyzed.



Figure 2. Reverse sides of each end cap with holes for fittings to connect to the “upper” valves of the permeameter (left) and holes for “lower” valve flows, a center screw-hole to secure the bottom end cap to the bottom plate and a small hole for the reference pin (right).



Figure 3. End cap with nylon mesh netting glued to the top.



Figure 4. Side-view of cylindrical membrane stretchers with 3.5''-inside diameter (left) and 2.0''-inside diameter (right) attached to a 140-cc syringe



Figure 5. Top-view of cylindrical membrane stretchers with 3.5''-inside diameter (left) and 2.0''-inside diameter (right) attached to a 140-cc syringe

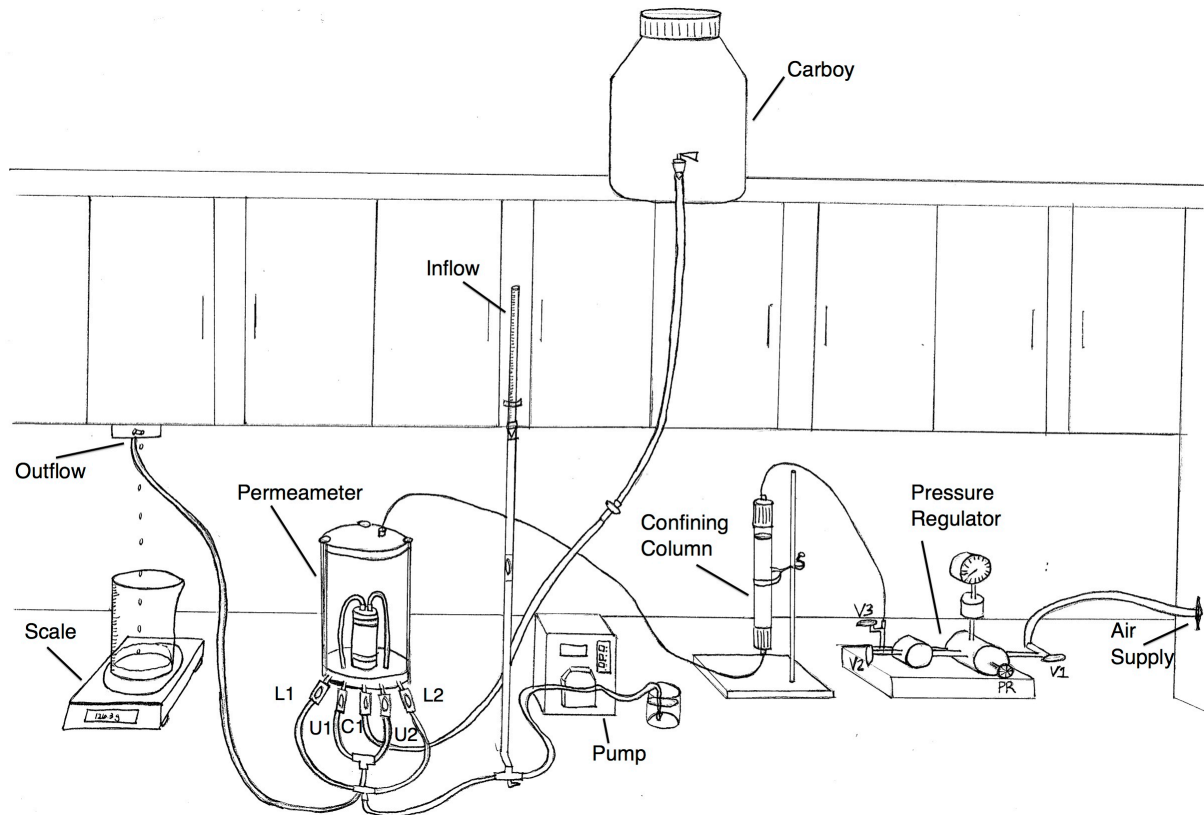


Figure 6. Schematic of falling head test where L1 & L2 = lower tubing valves; U1 & U2 = upper tubing valves; C1 = confining tubing valve; V1, V2 and V3 = valves on pressure regulator; and PR = pressure regulator nob.

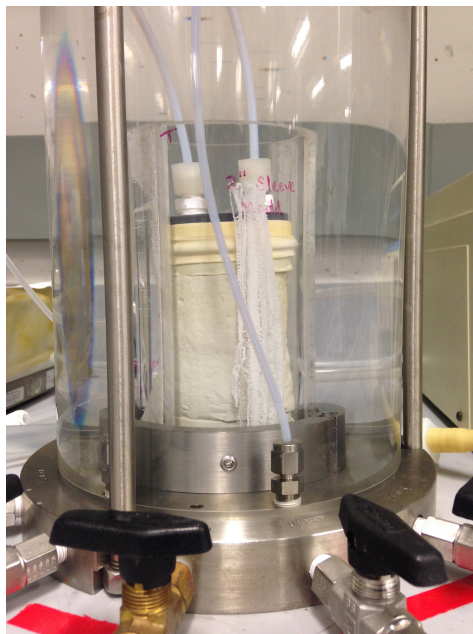


Figure 7. Permeameter with clear polycarbonate sleeve placed around the sample to keep the sample upright.

APPENDIX B. Considerations for Setting Confining Pressure in Hydraulic Conductivity Measurement

1.0 Purpose

For consistency, and to ensure that the latex membrane conforms to the sample walls, confining pressure is set to be 1 psi greater than the maximum pore pressure in the sample. Following is a discussion of the effect of confining pressure and effective stress with respect to the cores features and it's impact on measured K.

2.0 Introduction

NGEE cores vary in their texture and stiffness. All have frozen water, which may support features such as open cracks as imaged by CT scans. Confining pressure in the permeameters is set 1 psi above the maximum pore pressure in each test. The pressure regulators have a precision of about 0.3 psi.

The latex membranes conform well to the sample walls (even when large chunks of ice on the wall melt) and prevent fast-path flow along the walls. Internal sample features seen in the CT scans, like cracks held open by ice, may close once the ice melts. Decreases in K by 25-30% in sequential trials may be due to these features closing up.

We did not determine if lower effective stress would make a difference in the K measurement, however in future efforts, we should consider setting effective stress via confining pressure to approximate the sample's in-situ conditions. We should also consider using shorter samples, which would decrease the required inlet pressure. If the confining pressure is set according to the maximum inlet pressure, having a lower inlet pressure would reduce the average effective stress (i.e., the effective stress at the outlet compared to the inlet). High-precision pressure regulators would improve measurement consistency at the low confining pressures that would be used.

3.0 Effective Stress

Total vertical stress, σ_v , is

$$\sigma_v = \rho_b (1 + \Theta_m) gz \quad (1)$$

where ρ_b is bulk density of the soil (typically $1.0 \leq \rho_b \leq 1.8 \text{ g/cm}^3$), Θ_m is gravimetric water content (mass water/mass bulk soil), g acceleration of gravity, and z depth from surface to sample.

Θ_m can be calculated from the soil porosity, n , water saturation of the pore space the fraction of water in the pore-space, S_w , the density of water, ρ_w , and soil bulk density ρ_b :

$$\Theta_m = \frac{n S_w \rho_w}{(1 - n) \rho_b} \quad (2)$$

Total horizontal stress, σ_h , is

$$\sigma_h = \frac{v}{1-v} \sigma_v \quad (3)$$

where v is the soil's Poisson ratio, typically ranging from 0.25 to 0.4, which implies $0.3\sigma_v \leq \sigma_h \leq 0.7\sigma_v$

Effective stress, σ' , is the difference between total stress and pore-pressure, u hydrostatic below the water table, and equal to

$$u = \rho_w g z' \quad (4)$$

where ρ_w is the density of water, and z' is the depth of the sample below the water table.

Above the water table, pore-pressure is near atmospheric pressure, and effective stress approximately equals total stress.

4.0 K-Measurements

The permeameters apply hydrostatic confining stress to the sample. Pore pressure is determined by the elevation of the outlet during the sample-defrosting period, and by the elevation of the inlet during the falling-head K test. Confining pressure is set so that it is 1 psi greater than the pore-pressure, initially set during the defrosting period, then adjusted when flow begins according to the pore-pressure arising from the initial inlet elevation. Inlet elevation is adjusted between tests to obtain adequate flow to measure K within a period of several hours to overnight. The decrease in inlet elevation during a test is limited to 75% of the initial inlet elevation in order to minimize the change in effective stress during the test.

5.0 Estimate of in-situ Effective Stress in Samples

A range of values of effective stress is calculated from the sample depths, and assumptions of sample attributes of water content, soil bulk density, and depth to water table. These attributes may be measured and available at a later date to refine the estimates.

Summary of effective stress calculations for each sample									
Sample_ID	Depth (cm bgs)		cut sample length (cm)	Estimated Effective Stress in-Situ (psi)				effective stress in permeameter (psi)**	
	interval			max		min		sample inlet***	sample outlet
	top	bottom		(sample bottom)*	(sample top)*	(sample bottom)*	(sample top)*		
AB_117_PWR_1	5.5	13	7.80	0.47	0.19	0.13	0.05	1.00	2.85
AB_117_PWR_2	13	24	10.60	0.86	0.48	0.23	0.13	0.95	1.45
AB_117_PWR_3	46	56	10.00	2.01	1.65	0.56	0.46	0.94-0.18	2.65-2.75
BD_001_PWR_1	28	37	6.615	1.33	1.09	0.34	0.28	0.97	2.05
BD_001_PWR_2	37	42	4.40	1.51	1.35	0.41	0.37	1.08-1.00	2.05
BD_06_PWR_1	10	23	6.825	0.82	0.58	0.17	0.10	0.13-0.51	1.05-1.55
BD_06_PWR_2	23	27	4.50	0.97	0.81	0.27	0.23	1.15-0.93	1.45
DTLB_19_PWR_1	4	19	6.66	0.68	0.44	0.11	0.04	0.40	0.95
DTLB_38_PWR_1	20	37	6.51	1.33	1.09	0.26	0.20	0.99	2.25
DTLB_38_PWR_2	44	62.5	6.6	2.24	2.00	0.50	0.44	0.94-1.00	2.35-2.75
DTLB_40_PWR_1	34	46	6.57	1.65	1.41	0.40	0.34	1.02	1.85
DTLB_40_PWR_2	47	54	6.555	1.94	1.70	0.53	0.47	1.00	2.05
* assumes bottom of cut length coincides with bottom of sample interval									
** a range of numbers reflects change in pore-pressure between trials due to change in elevation of inlet or outlet burette.									
***initial pore-pressure (from initial height of burette) is used in calculation. This will give the minimum effective stress.									

5.1 Conditions for Maximum Effective Stress

Conditions that give rise to maximum effect stress from Eq. (1) are as follows:

1. depth to sample bottom
2. assume the samples are above the water table (i.e., no pore pressure)
3. bulk density of 1.8
4. gravimetric water content of 0.4 (using porosity of 0.5 and water saturation of 0.8 in Eq. (2))
5. Effective stress equals vertical stress in Eq (1)

5.2 Conditions for Minimum Effective Stress

Conditions that give rise to minimum effective stress are as follows:

1. depth to sample top
2. assume water table is at surface
3. bulk density of 1.0
4. gravimetric water content of 0.7 (using porosity of 0.4 and water saturation of 1 in Eq. (2))
5. Effective stress equals vertical stress in Eq (1), minus pore pressure in Eq (4)

Estimates of effective stress, in the table above, range from 0.05 psi for the top of the shallowest sample, to 2.24 psi at the bottom of the deepest sample.

Appendix C. Calculation of Hydraulic Conductivity from Falling Head Test

1.0 Purpose

Explain the calculation of hydraulic conductivity K with the falling head method. Three measurement trials with sample BD01_PWR_1 are used to test the calculation method. Detailed protocol (or SOP) for conducting the tests is provided in a separate document.

2.0 General Equation

$$t = \frac{aL}{AK} \ln\left(\frac{h_1}{h_2}\right) \quad (1)$$

where h_2 is water height as a function of t , h_1 is the initial water height, a is the cross-sectional area of the burette, A is the cross-sectional area of the sample, L is the sample length and K is the hydraulic conductivity.

2.1 Calculation option 1

Derive K from slope of plot of $\ln(h_2)$ vs t . Rearranging Eq (1) into the form of $y=mx+b$:

$$\ln(h_2) = -\frac{AK}{aL}t + \ln(h_1) \quad (2)$$

the slope m is:

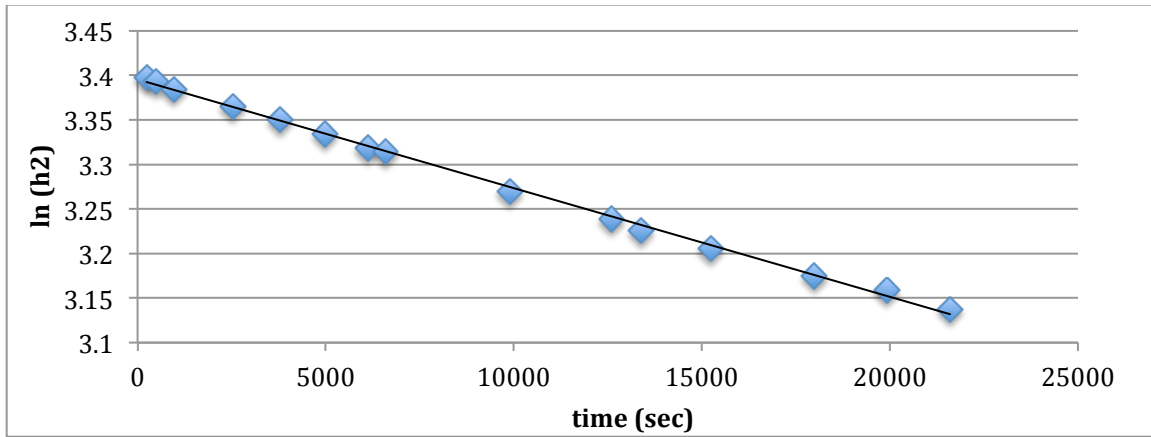
$$m = -\frac{AK}{aL} \quad (3)$$

and rearranging gives:

$$K = -\frac{aL}{A}m \quad (4)$$

Example BD01-PWR-1 Trial 3, $a = 15.97 \text{ cm}^2$, $A = 15.55 \text{ cm}^2$, $L = 6.47 \text{ cm}$
 note, no change in inflow head over first 240 seconds.

Time (sec)	Inflow Head Height (in)
0	29.875
60	29.875
120	29.875
240	29.875
480	29.74974945
960	29.49924835
2520	28.93562087
3780	28.49724394
4980	28.05886702
6120	27.62049009
6600	27.49523954
9900	26.30535931
12600	25.49123073
13380	25.17810435
15240	24.67710215
18000	23.92559885
19920	23.54984719
21600	23.04884499



Check the plot of the data to ensure a linear trend. Calculate slope of the plot (slope function in excel), and the correlation coefficient (correl function in excel). For this example, the slope, m , is equal to 1.22×10^{-5} , and the correlation coefficient is 0.999.

Inserting the values above into Eq (4), $K = 8.10 \times 10^{-5}$ cm/s. The correlation includes data from the first point where the change in flow is measured (at 240 s).

Eliminating the first few data points until the outflow equals the inflow to within 75%² (at 480 s) and using the rest of the dataset gives $K = 8.06 \times 10^{-5}$ cm/s.

The same calculation method using just the first 83 minutes of measurement (5 data points, starting at 480 s) gives $K = 8.48 \times 10^{-5}$ cm/s (~5% greater than K using all of the data). Using the last five data points gives $K = 7.03 \times 10^{-5}$ cm/s (13% less than K using all of the data points).

The reduction in K calculated from the first five compared to the last five data points is about 20%.

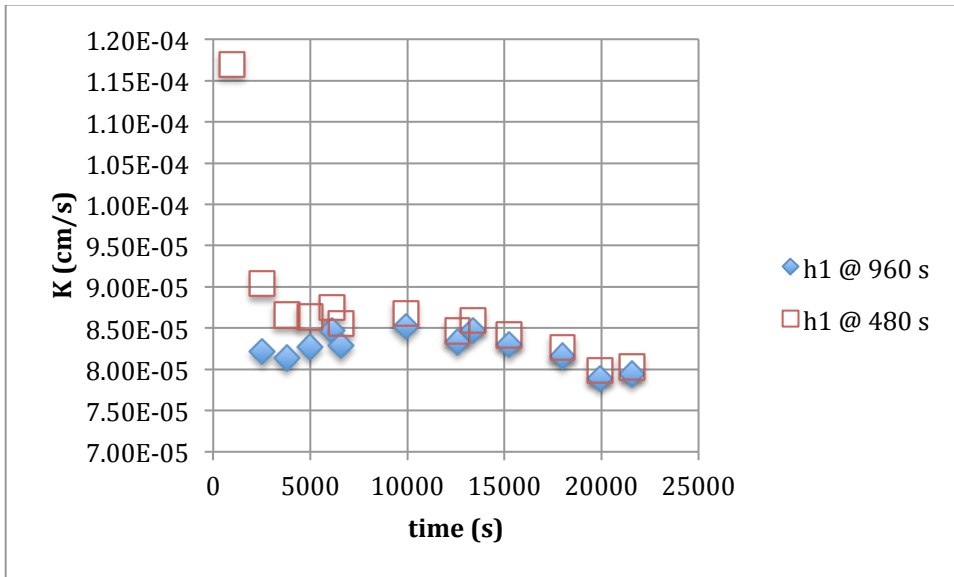
Correlation coefficients in all the above examples are 0.999.

2.2 Calculation option 2

Calculate K directly from values in table (trial 3) using Eq (1)

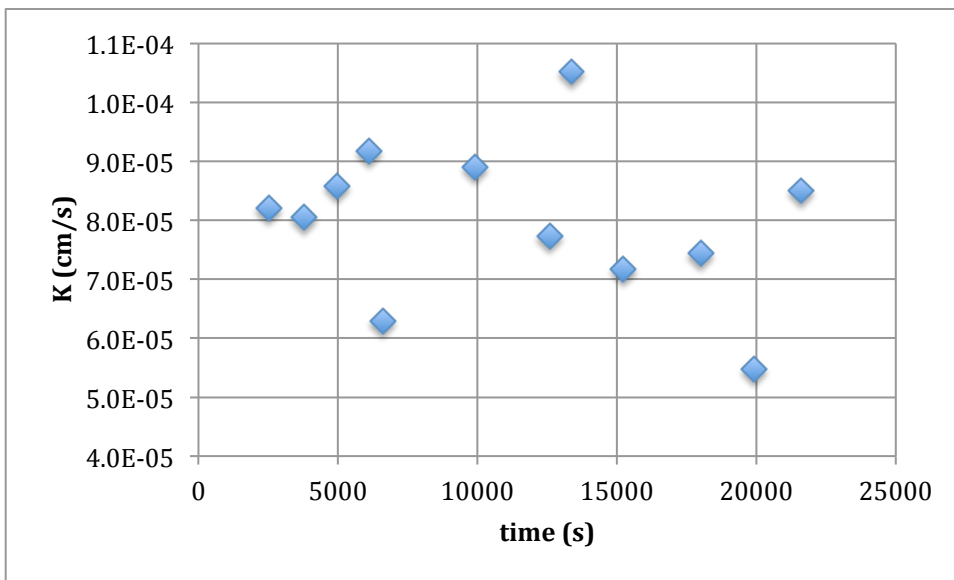
The plot below shows two calculations for K where h_1 is set at the time indicated in the legend, and K is calculated using h_2 at each subsequent time.

² ASTM D5084-03 Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter



Even though h_1 at 480 s meets the criterion for inflow to outflow, the calculated values of K decrease over time. Using the 960 s value for h_1 results in a more stable trend of K over time, with a range of 7.99×10^{-5} to 8.55×10^{-5} .

The following plot shows the results if Eq (1) is applied to each increment of measurement.



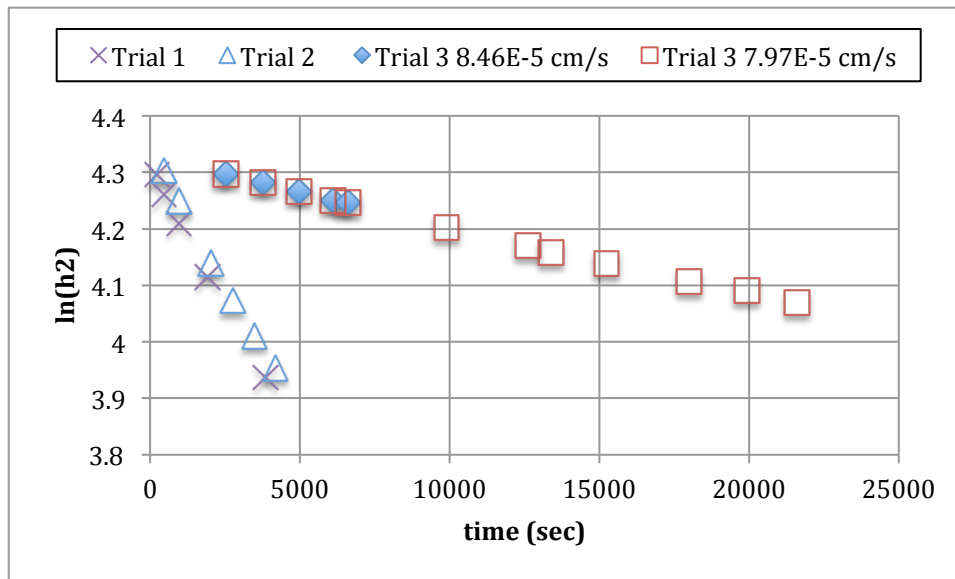
During the course of the trial, K values, calculated “differentially” from 960 s to the end of measurement, ranged from 5.45×10^{-5} to 1.05×10^{-4} , with an average of 8.01×10^{-5} and a standard deviation of 1.3×10^{-5} , or 16% of the average.

3.0 Comparison of Trials Using Slope Method (option 1)

trial	h (initial)/ used in calc (cm)	h final (cm)	Effective Stress (psi)	K (1E-5 cm/s)	data range
Trial 1	(78.42)/73.37	52.3	1.86-2.16	8.07	last five data points
Trial 2	(78.42)/73.88	52.15	1.85-2.16	7.74	last five data points
Trial 3	(75.88)/73.49	69.83	1.86-1.91	8.46	5 data points
Trial 3	(75.88)/73.49	58.55	1.86-2.07	7.97	12 data points

Confining pressure was 2.9 psi (204 cm H₂O) in all tests. “ h ” is distance measured from above the outlet water height. The outlet water height is 59.7 cm above the inlet to the permeameter. Effective stress is calculated at the bottom of (inlet to) the sample for the first and last data points used in the calculation of K . The top of the sample effective stress is constant at 2.05 psi. The hydraulic gradient is initially around 11, and finally around 9. Trial 1 and 2 used 1.6 cm dia burette, Trial 3 used 4.5 cm dia burette.

The plot below shows the data points used in each calculation. The smaller slope in Trial 3, compared to Trials 1 and 2, is due to the larger diameter burette used in Trial 3. All trials started with the same inlet pore pressure (equivalent to h from the above table), but final pore pressure in Trial 3 was higher than in Trials 1 and 2, which may explain the higher K obtained for ‘Trial 3 with five data points.’ The decrease in K measured in ‘Trial 3 with 12 data points’ may be due to the lower pore pressure at the end of the run, close to that of Trials 1 and 2. Because confining pressure was the same in all samples, higher pore-pressure decreases the effective stress on the sample, and K may increase with reduced effective stress.



The sample BD_001_PWR_1 is from the center of a high center polygon, depth 28-37 cm. The soil description is “mineral soil, gray silt, porous ice, vertical cracks with sublimated ice < 1 mm thick.” Depending on the relative strength of this sample, the effect of pore pressure on K could be greater or less in other samples.

4.0 Summary

The slope calculation (option 1) is preferred because it produces one value of K that averages measurement inconsistencies over the selected range of inlet water height. The start of the data range should be taken when the ratio of outlet water flow to inlet water flow is between 0.75 and 1.25.

To the extent possible, the starting and ending height of feed water should be consistent among samples. The burette diameter can be changed if needed to ensure precision of head measurement and similar change in height between start and end of trial.

ASTM D5084-03 recommends maximum hydraulic gradient according to hydraulic conductivity, in order to minimize risk of sample disturbance:

Hydraulic Conductivity (cm/s)	Recommended maximum hydraulic gradient
1E-3 to 1E-4	2
1E-4 to 1E-5	5
1E-5 to 1E-6	10
1E-6 to 1E-7	20
1E-7 and less	30

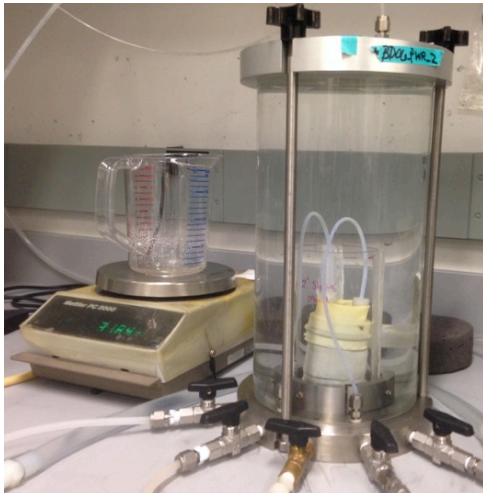
BD01-PWR-1 has a K of $\sim 1\text{E-}4$ at a hydraulic gradient of ~ 10 . Lowering the gradient would increase the measurement time. In our trials, the values of K did not vary significantly, so the gradient used appears to be OK. The recommendations may be more strictly followed for the softer samples. Sample “softness” may be evaluated based on the extent the sample shrinks from frozen to defrosted condition.

APPENDIX D. Presentation Summary of Results and Findings (selected slides that are not shown in other parts of this document)

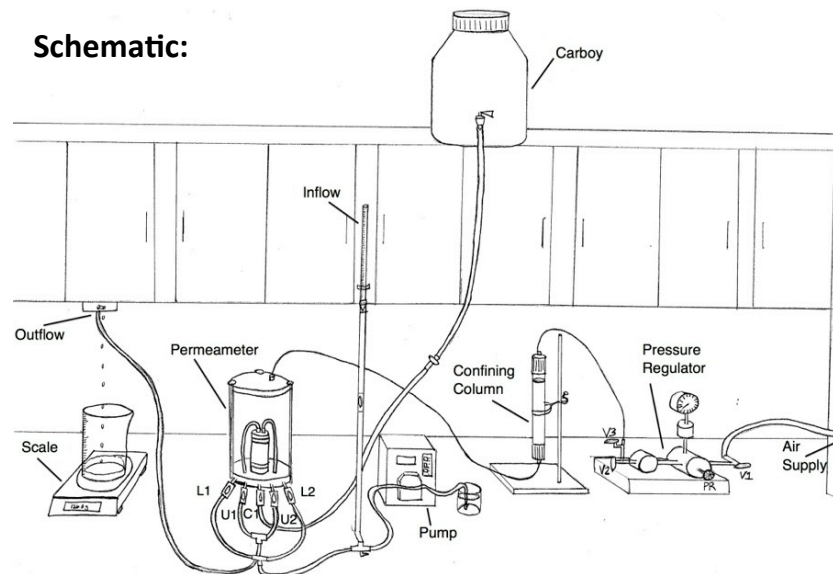
Brief Summary of Method:

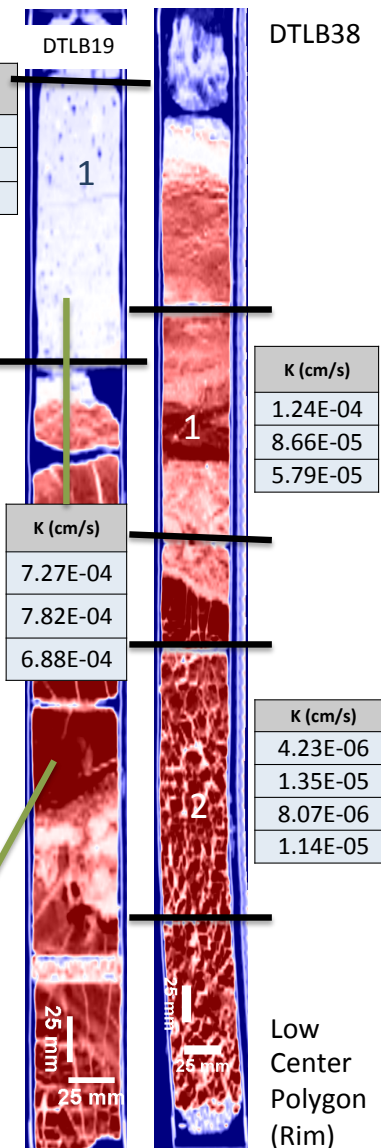
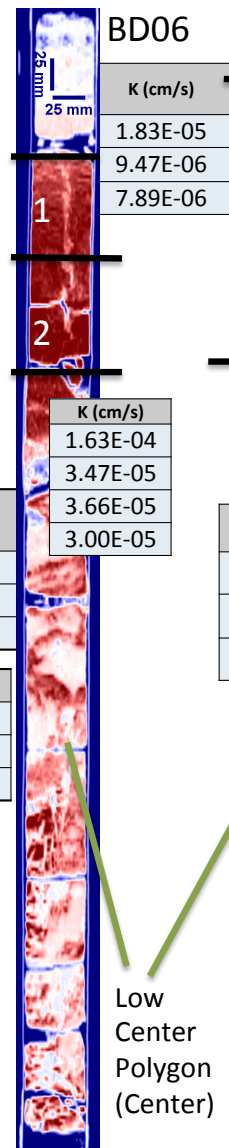
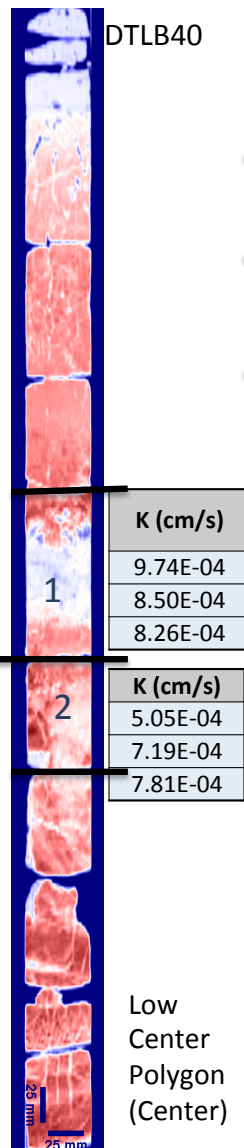
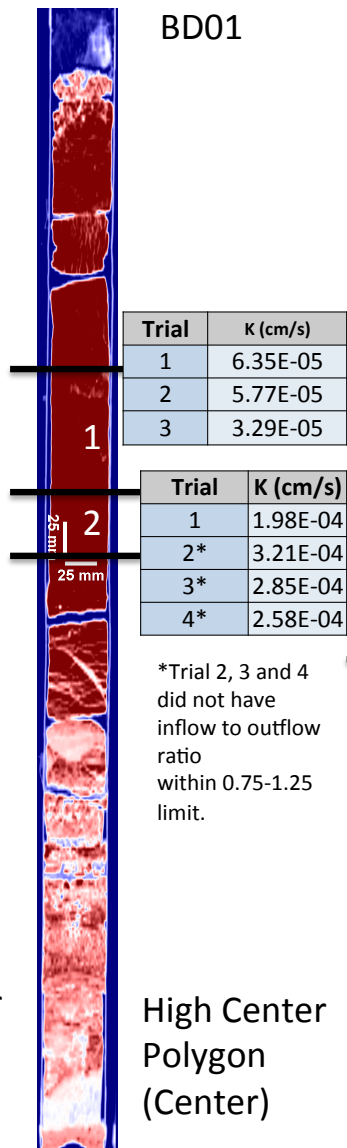
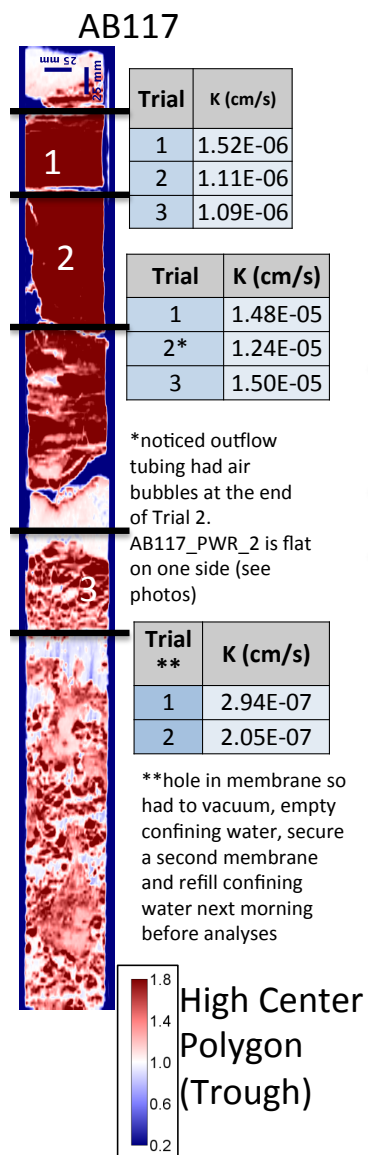
- Perform falling head test on 12 samples
- Use membrane stretcher to insert frozen sample
- Assemble permeameter, fill confining water and apply confining pressure
- Allow sample to thaw overnight (approx. 15 hours) with outflow tubing valves open
- Prime outflow tubing to eliminate air bubbles
- Position burette, filled with de-gassed water, 1ft. above outlet and monitor inflow and outflow over time
- Adjust height of burette and/or size of burette if necessary
- Perform 2 – 4 trials, check $0.75 < \text{inflow} : \text{outflow} < 1.25$, remove sample and storing for further analyses

Permeameter:

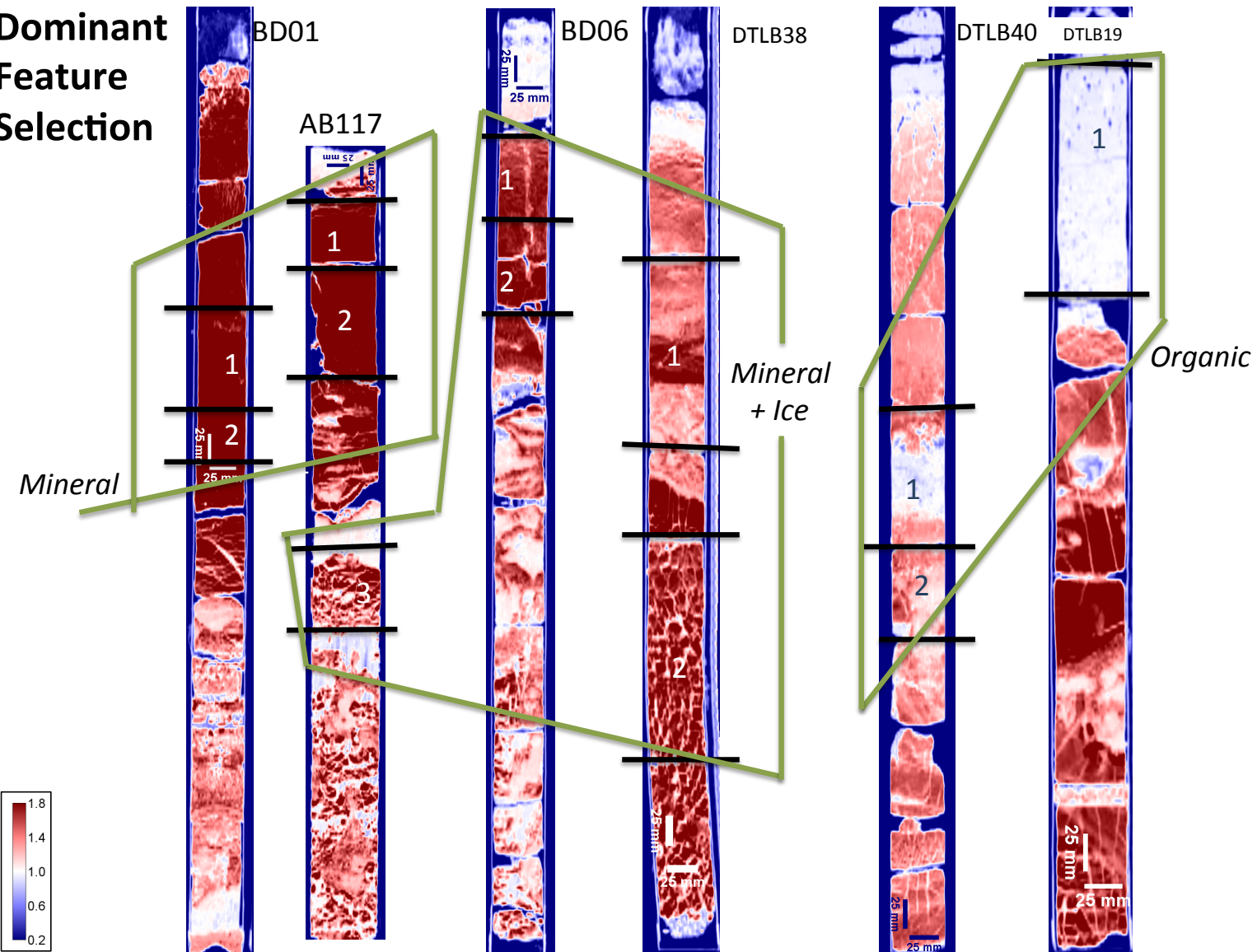


Schematic:

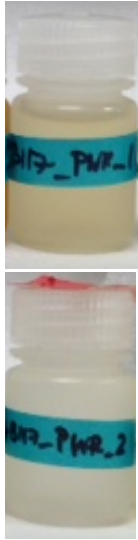




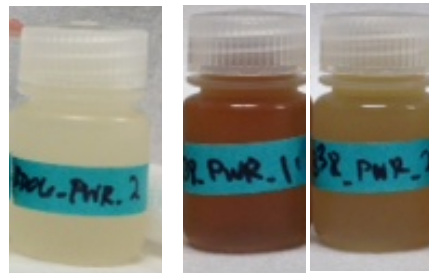
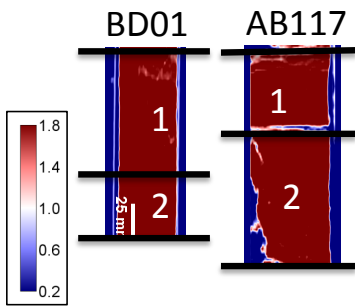
Dominant Feature Selection



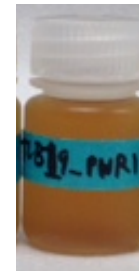
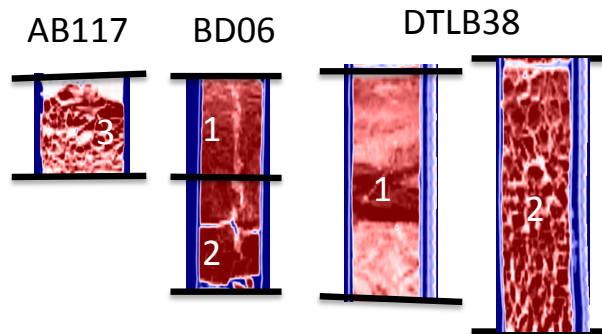
Dominant Feature + Pore Water Color



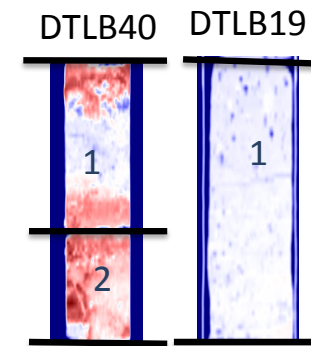
Mineral



Mineral + Ice



Organic



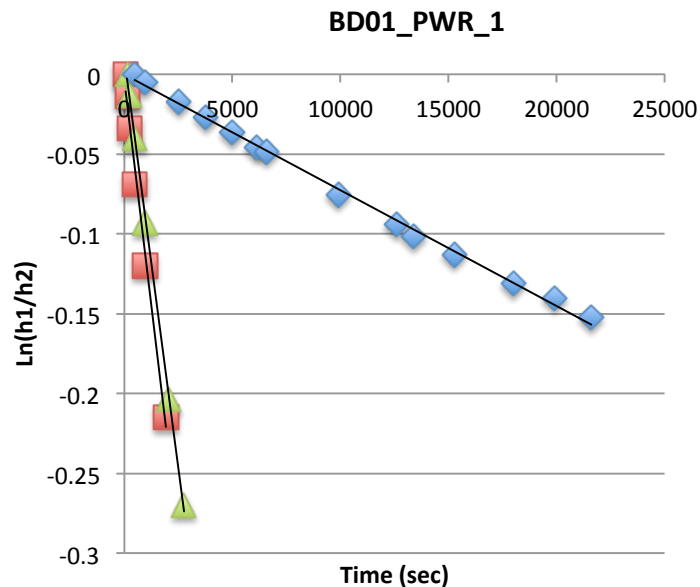
Correction for plots when inlet burette diameter is changed between trials

$$t = \frac{aL}{AK} \ln \left(\frac{h_1}{h_2} \right)$$

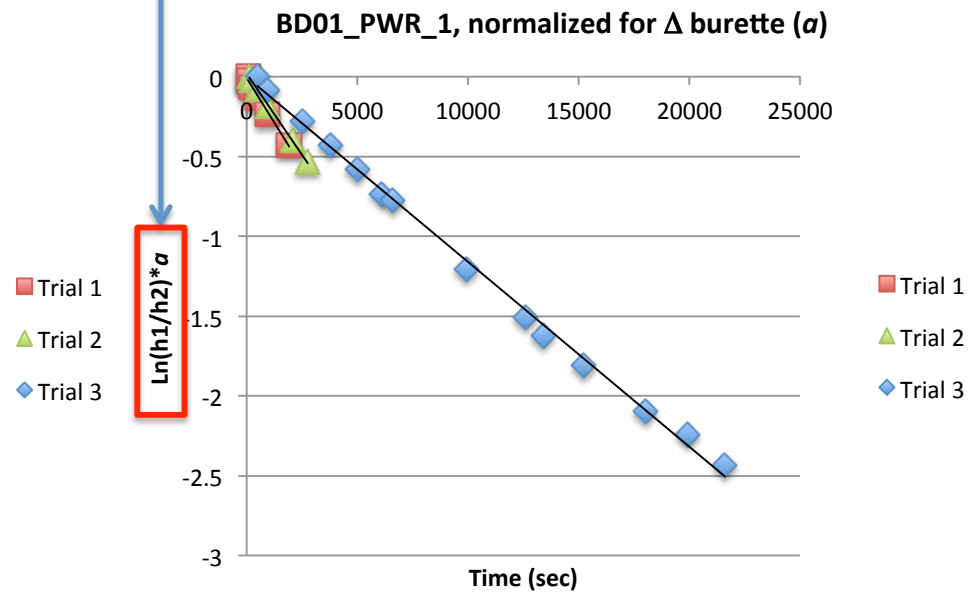
Equation for K under conditions of falling head, where a is the x-sectional area of the inlet burette, L is sample length, A is x-sectional area of sample and h_1 is the inlet height of water in the burette and h_2 the outlet.

Sample ID	Trial	K (cm/s)	a (cm ²)
BD01_PWR_1	1	6.35E-05	2.0
	2	5.77E-05	2.0
	3	3.29E-05	16.3

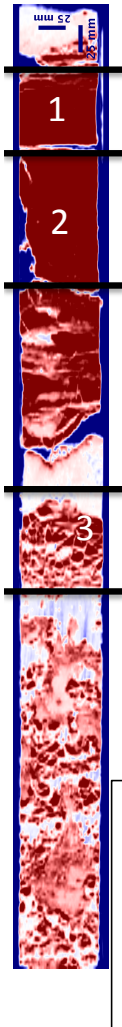
Plots of $\ln(h_1/h_2)$ vs t , have slope= AK/aL therefore change of a produces a larger change in slope than just the difference in K between trials



To normalize plots for change in a , $\ln(h_1/h_2)$ is multiplied by a , so difference in slope reflects difference in K only.



High Center Polygon (Trough)



Sample ID	Trial	K (cm/s)
AB117_PWR_1	1	1.52E-06
	2	1.11E-06
	3	1.09E-06

Where $h(t)$ = inlet head over time and $h(0)$ = inlet head at $t=0$.

Sample ID	Trial	K (cm/s)
AB117_PWR_2	1	1.48E-05
	2*	1.24E-05
	3	1.50E-05

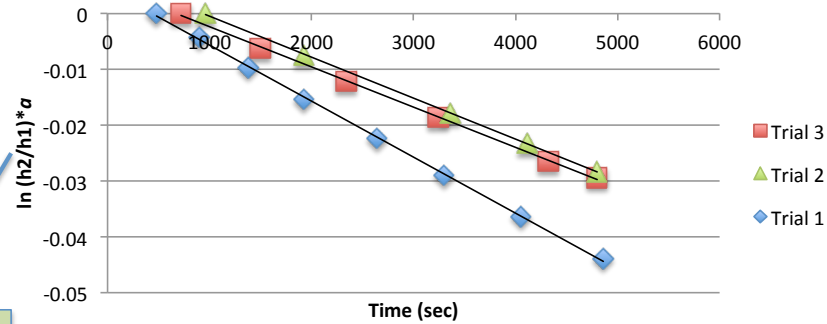
*noticed outflow tubing had air bubbles at the end of Trial 2.

AB117_PWR_2 is flat on one side (see photos)

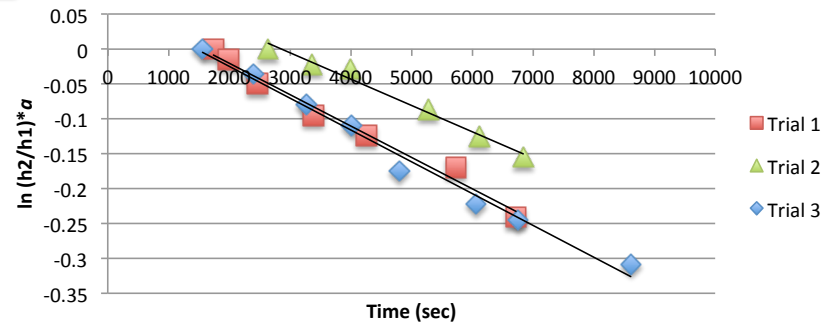
Sample ID	Trial	K (cm/s)
AB117_PWR_3**	1	2.94E-07
	2	2.05E-07

**hole in membrane so had to vacuum, empty confining water, secure a second membrane and refill confining water next morning before analyses

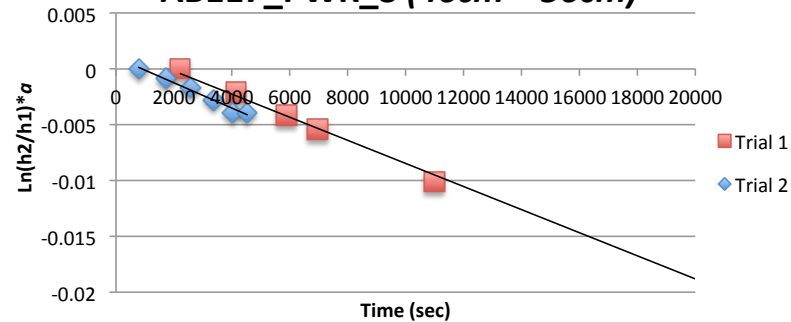
AB117_PWR_1 (5.5cm-13cm)



AB117_PWR_2 (13cm – 24 cm)



AB117_PWR_3 (46cm – 56cm)



High Center Polygon (Trough)



Sample ID	Trial	K (cm/s)
AB117_PWR_1	1	1.52E-06
	2	1.11E-06
	3	1.09E-06



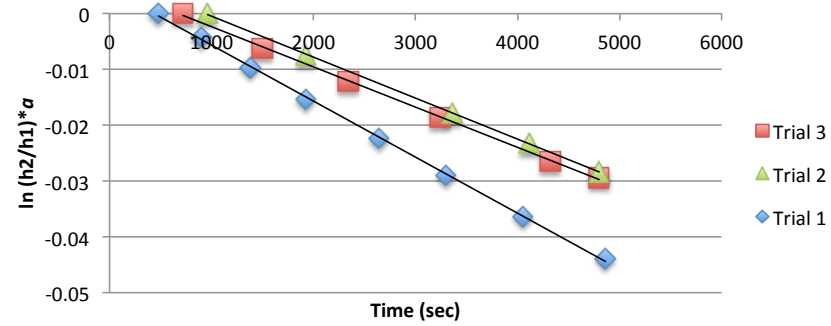
Pre-analysis
measurements taken
before placing in
permeameter

Frozen sample (Friday, July 18 @ 6pm)

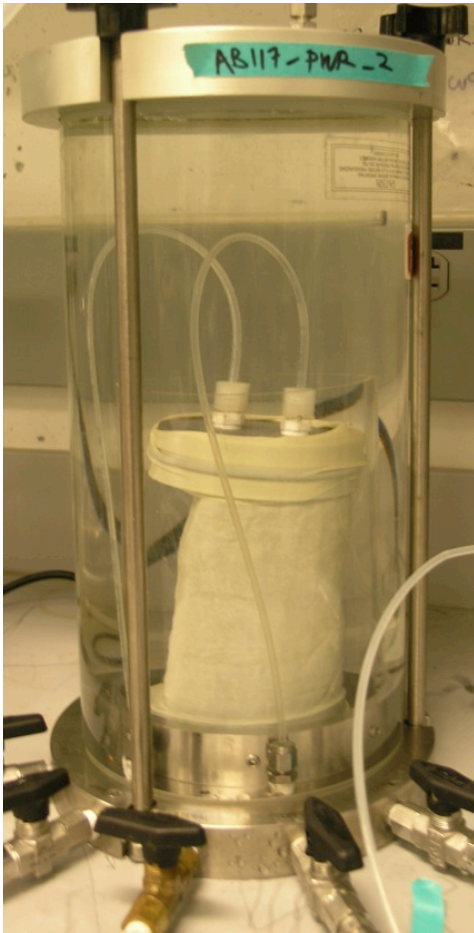
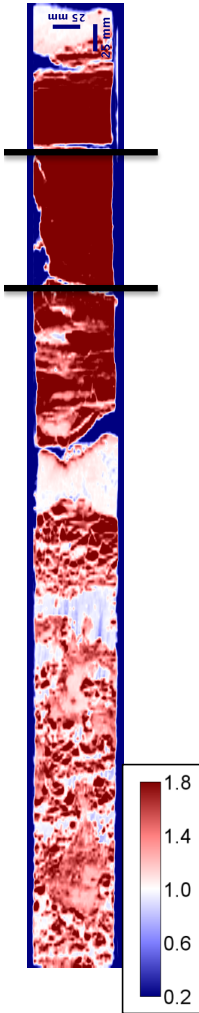


Post-thaw (Sunday, July 20 @ 2pm)

AB117_PWR_1 (5.5cm-13cm)

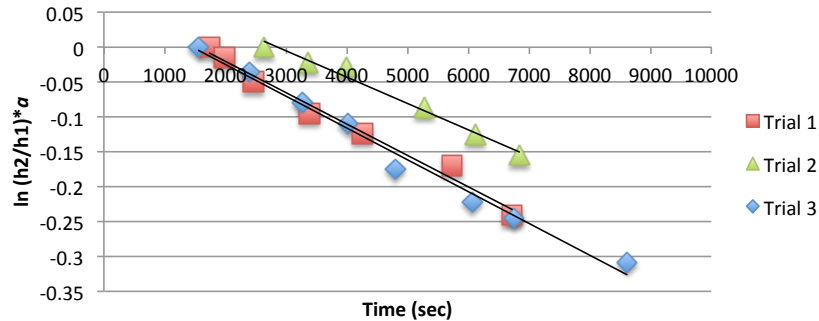


High Center Polygon (Trough)



Post-thaw

AB117_PWR_2 (13cm – 24 cm)



Sample ID	Trial	K (cm/s)
AB117_PWR_2	1	1.48E-05
	2*	1.24E-05
	3	1.50E-05

*noticed outflow tubing had air bubbles at the end of Trial 2.

AB117_PWR_2 is flat on one side (see below)

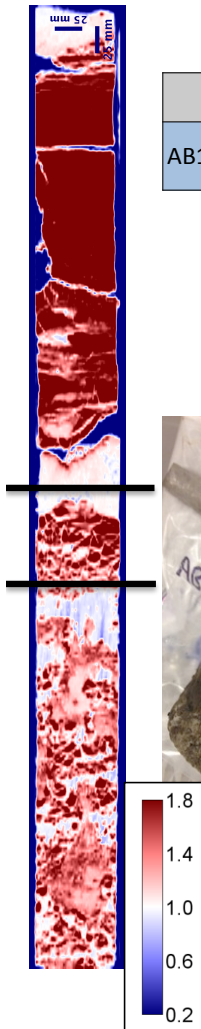


Post-vacuum; fine soil



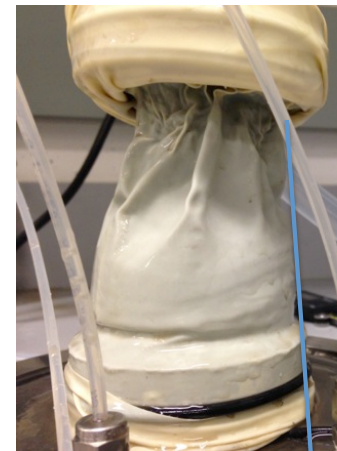
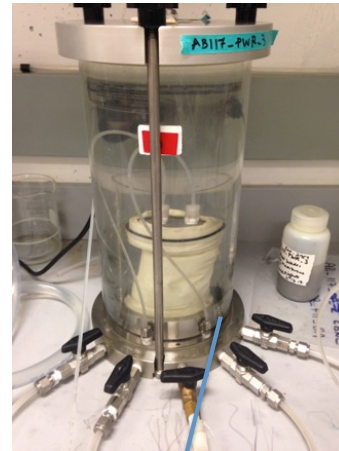
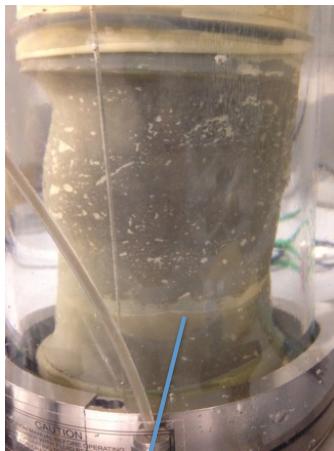
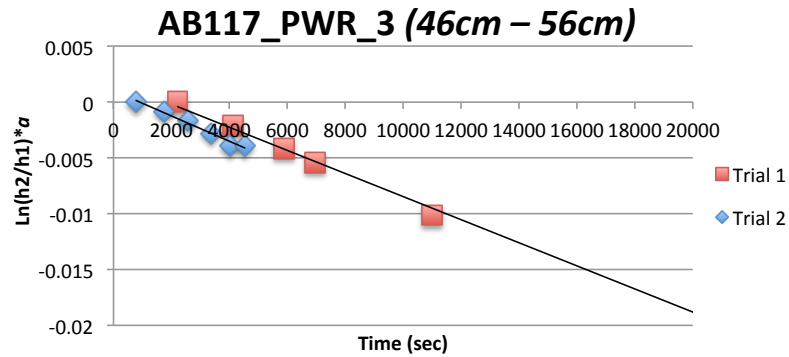
Post-vacuum

High Center Polygon (Trough)



Sample ID	Trial	K (cm/s)
AB117_PWR_3**	1	2.94E-07
	2	2.05E-07

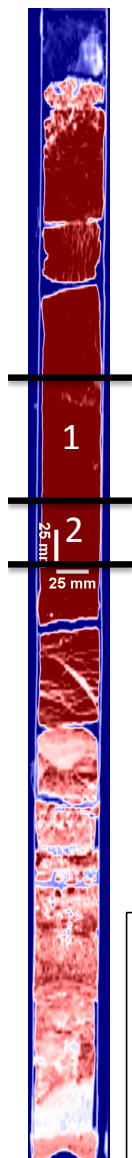
**hole in membrane so had to vacuum, empty confining water, secure a second membrane and re-fill confining water next morning before analyses



Most likely a hole in membrane

Second membrane secured over membrane with hole

Single membrane at end of analyses, before removing sample



High Center Polygon (Center)

Sample ID	Trial	K (cm/s)
BD01_PWR_1	1	6.35E-05
	2	5.77E-05
	3	3.29E-05

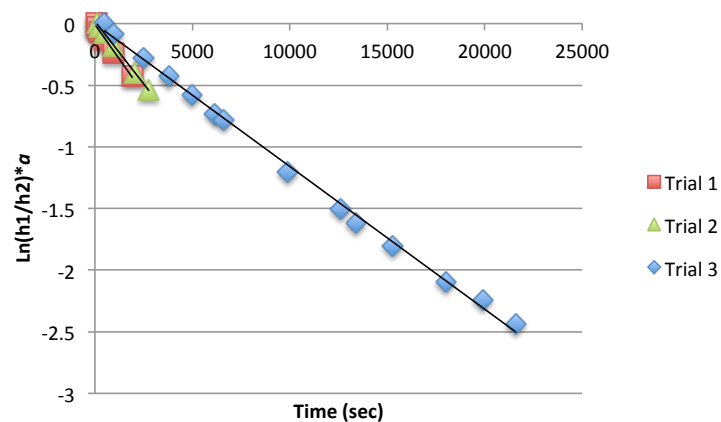


Outflow water of BD01_PWR_1 was slightly more yellow than BD01_PWR_2

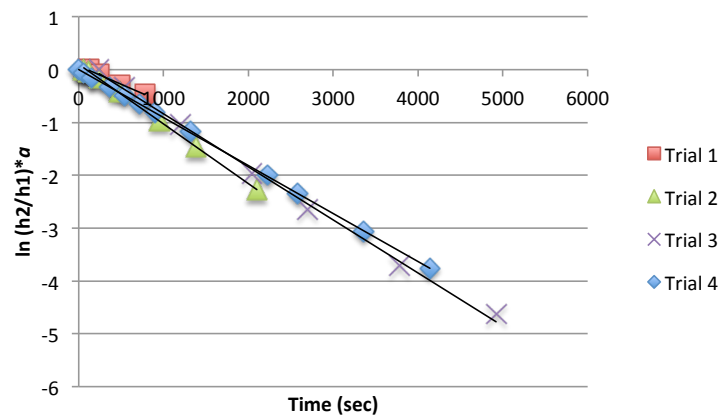
Sample ID	Trial	K (cm/s)
BD01_PWR_2	1	1.98E-04
	2*	3.21E-04
	3*	2.85E-04
	4*	2.58E-04

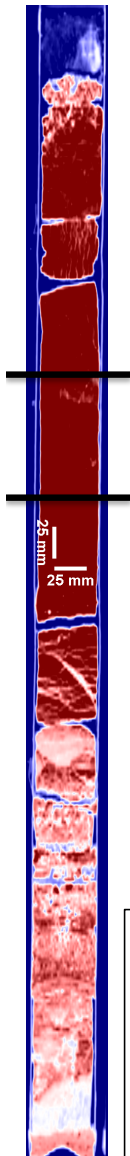
*Trial 2, 3 and 4 did not have inflow to outflow ratio within 0.75-1.25 limit.

BD01_PWR_1 (28.0cm – 37.0cm)



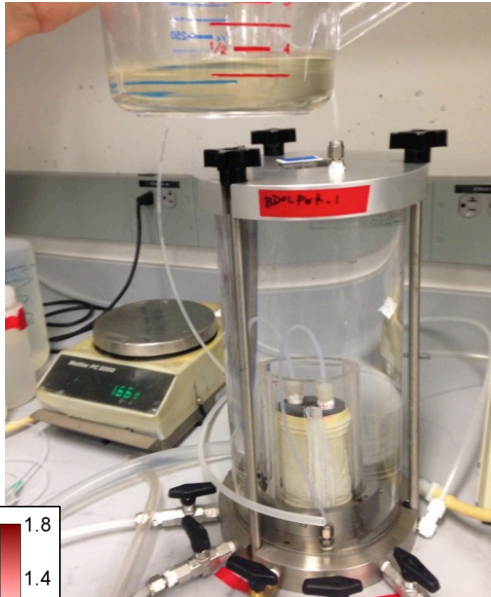
BD01_PWR_2 (37.0cm – 42.0cm)





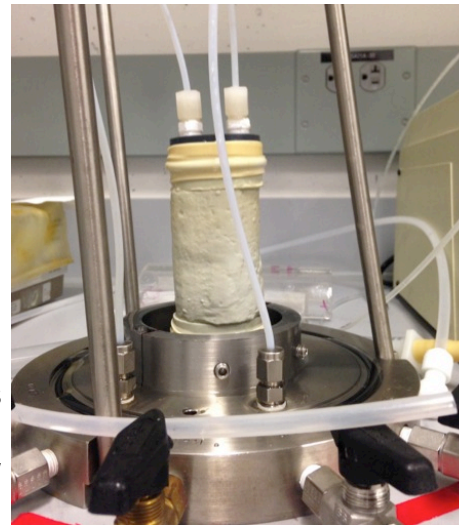
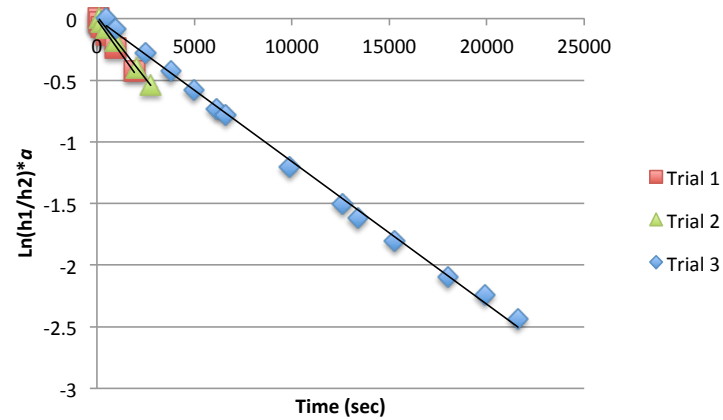
High Center Polygon (Center)

Sample ID	Trial	K (cm/s)
BD01_PWR_1	1	6.35E-05
	2	5.77E-05
	3	3.29E-05

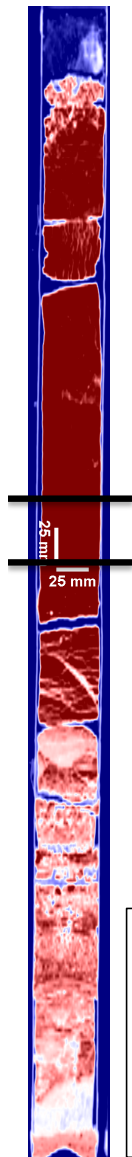


→ Sample during analysis with slightly yellow outflow water

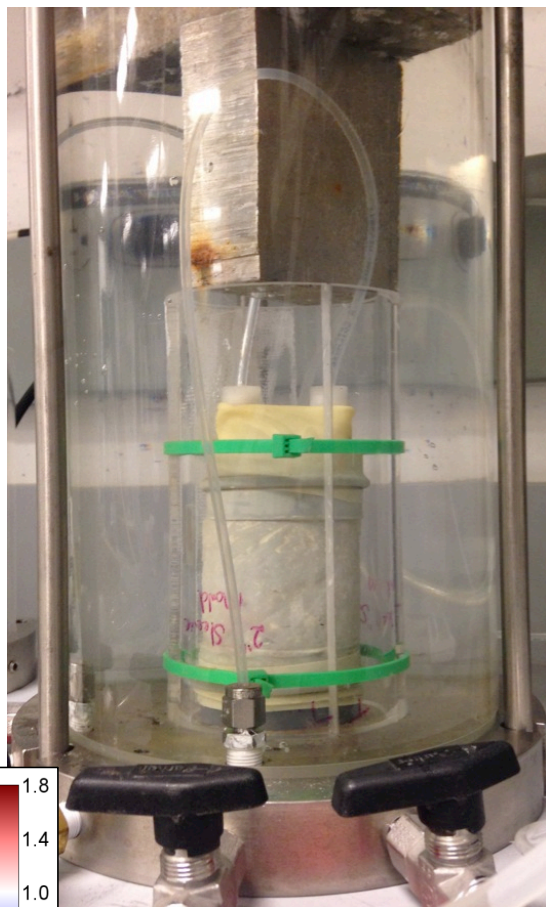
BD01_PWR_1 (28.0cm – 37.0cm)



→ Sample after final analysis. Vacuum applied (~25 in. Hg) while draining confining water to maintain structure

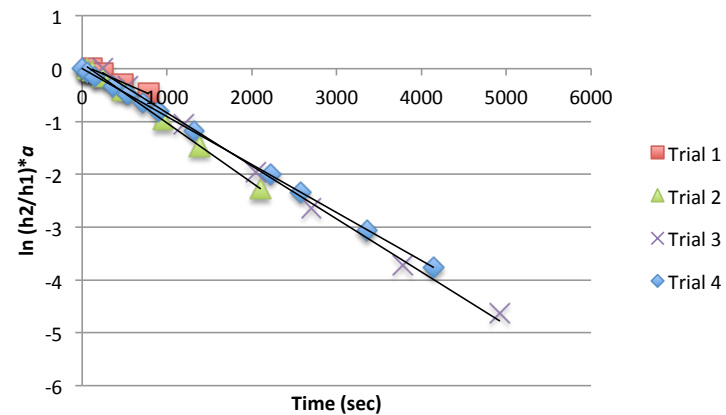


High Center Polygon (Center)



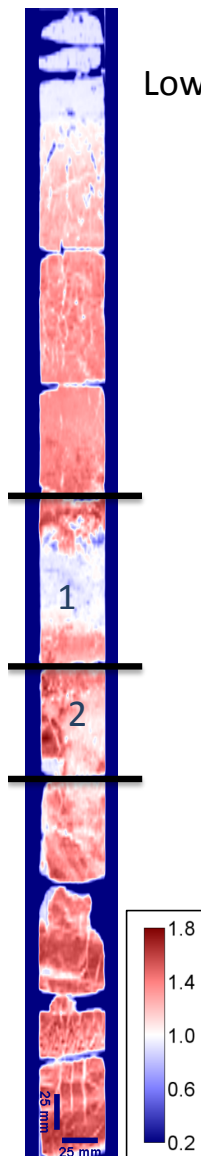
Post-thaw

BD01_PWR_2 (37.0cm – 42.0cm)



Sample ID	Trial	K (cm/s)
BD01_PWR_2	1	1.98E-04
	2*	3.21E-04
	3*	2.85E-04
	4*	2.58E-04

*Trial 2, 3 and 4 did not have inflow to outflow ratio within 0.75-1.25 limit.

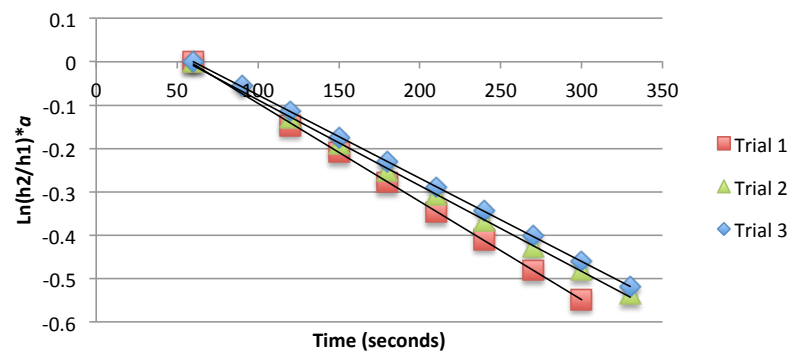


Low Center Polygon (Center)

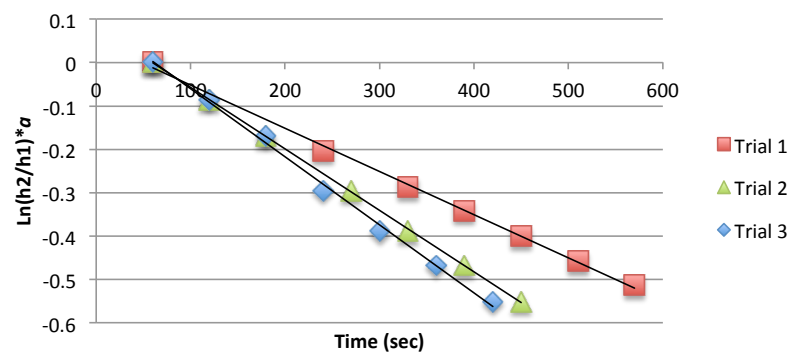
Sample ID	Trial	K (cm/s)
DTLB40_PWR_1	1	9.74E-04
	2	8.50E-04
	3	8.26E-04

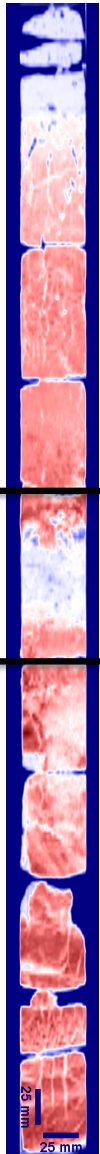
Sample ID	Trial	K (cm/s)
DTLB40_PWR_2	1	5.05E-04
	2	7.19E-04
	3	7.81E-04

DTLB40_PWR_1 (34.0cm – 46.0cm)



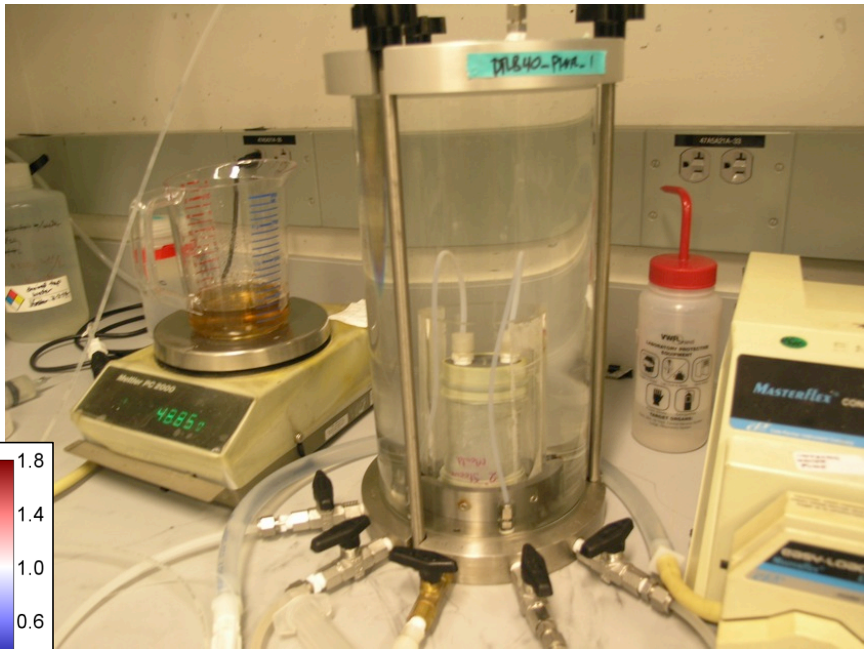
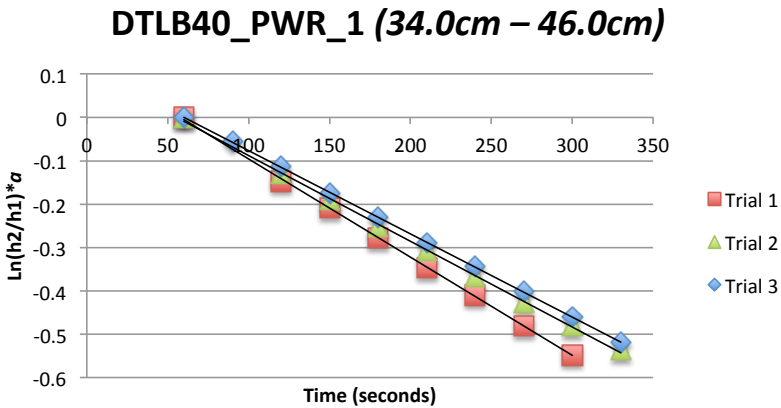
DTLB40_PWR_2 (47.0cm – 54.0cm)



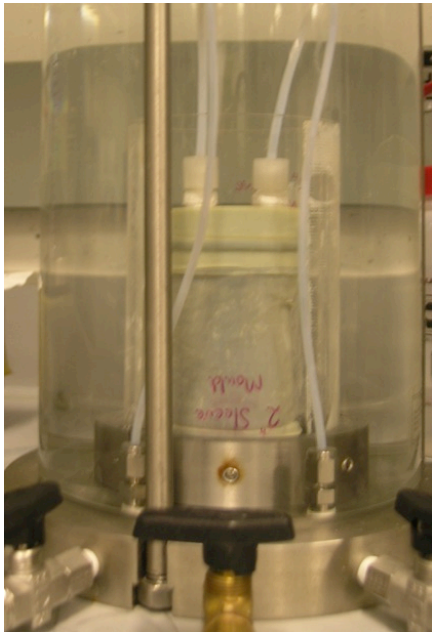


Low Center Polygon (Center)

Sample ID	Trial	K (cm/s)
DTLB40_PWR_1	1	9.74E-04
	2	8.50E-04
	3	8.26E-04



Dark brownish-orange outflow water

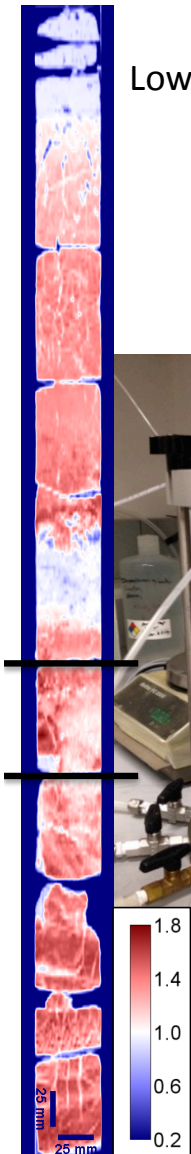
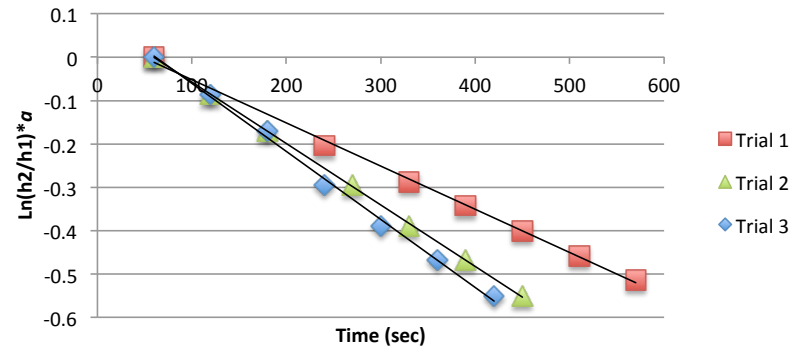


Post-thaw; maintained original shape

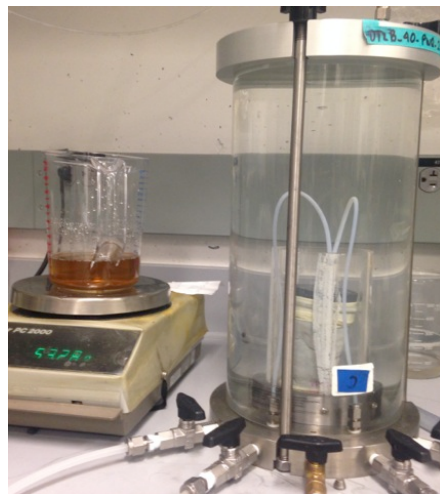
Low Center Polygon (Center)

Sample ID	Trial	K (cm/s)
DTLB40_PWR_2	1	5.05E-04
	2	7.19E-04
	3	7.81E-04

DTLB40_PWR_2 (47.0cm – 54.0cm)



Beginning of
overnight thaw

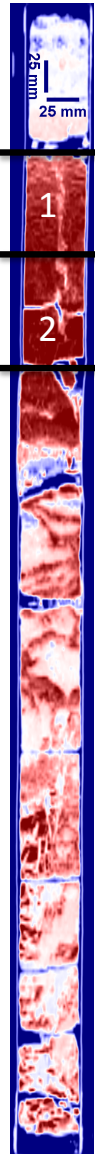


During analyses



End of analyses; noticeable shrinkage
and creases in sample





Low Center Polygon (Center)

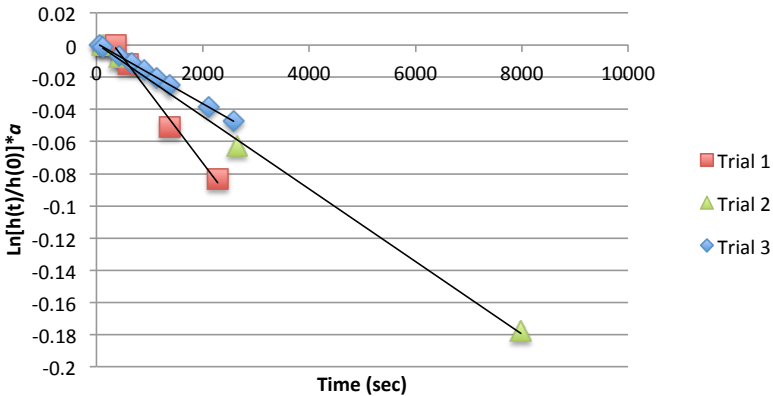
Sample ID	Trial	K (cm/s)
BD06_PWR_1	1*	1.83E-05
	2*	9.47E-06
	3	7.89E-06

*Trial 1 and 2 did not have inflow to outflow ratio within 0.75-1.25 limit.

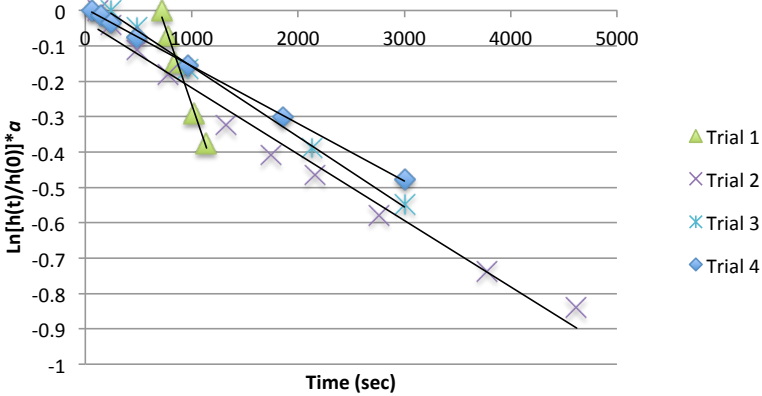
Sample lost approximately 9cm³ of volume during Trial 1.

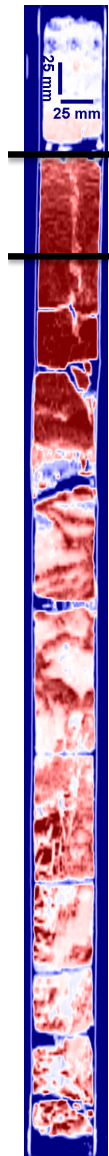
Sample ID	Trial	K (cm/s)
BD06_PWR_2	1	1.63E-04
	2	3.47E-05
	3	3.66E-05
	4	3.00E-05

BD06_PWR_1 (10cm - 23cm)



BD06_PWR_2 (23cm - 27cm)



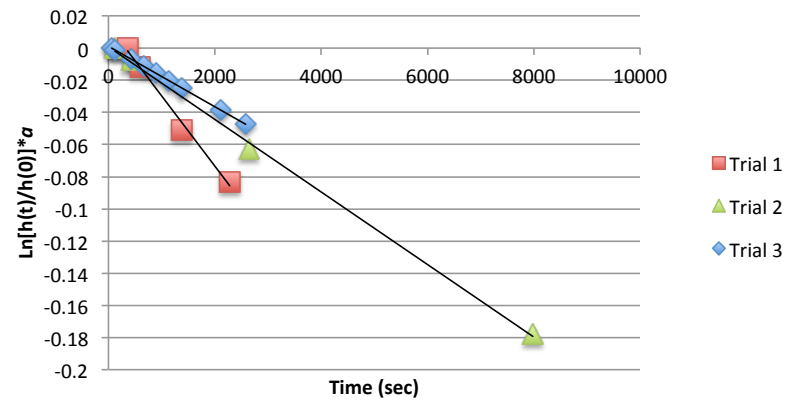


Low Center Polygon (Center)



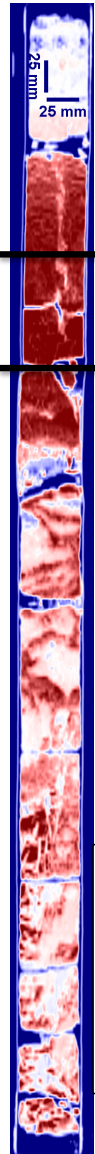
Post-thaw; maintained original shape

BD06_PWR_1 (10cm - 23cm)

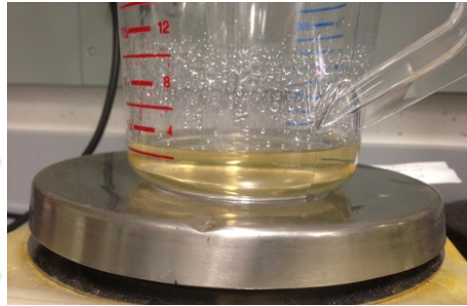


Sample ID	Trial	K (cm/s)
BD06_PWR_1	1*	1.83E-05
	2*	9.47E-06
	3	7.89E-06

*Trial 1 and 2 did not have inflow to outflow ratio within 0.75-1.25 limit. Sample lost approximately 9cm³ of volume during Trial 1.



Low Center Polygon (Center)

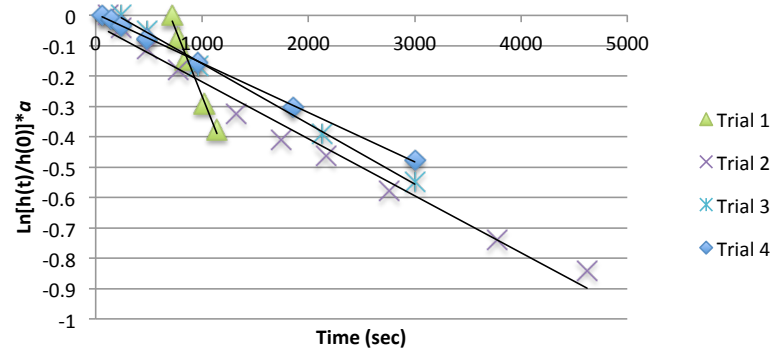


Clear yellow outflow water

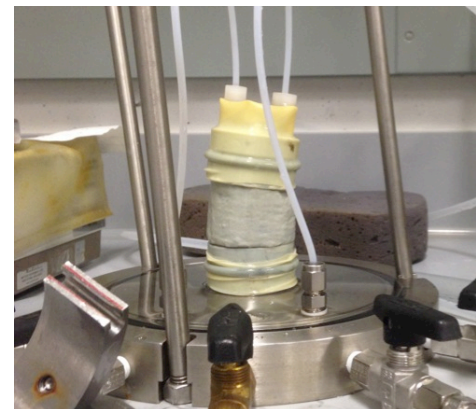


Post-thaw and after first trial; slight lean after thawed

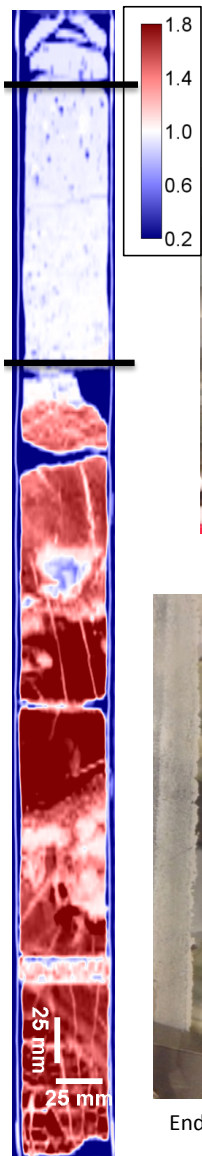
BD06_PWR_2 (23cm - 27cm)



Sample ID	Trial	K (cm/s)
BD06_PWR_2	1	1.63E-04
	2	3.47E-05
	3	3.66E-05
	4	3.00E-05



Post-vacuum



Low Center Polygon (Center)



Beginning of defrost



During defrost

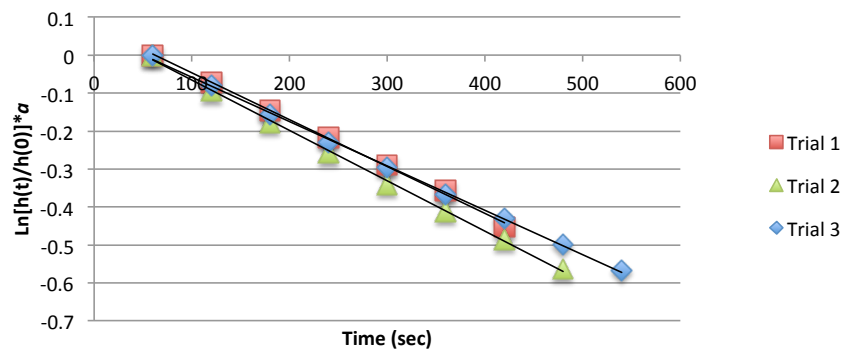


End of defrost / during trials



End of trails after vacuum applied

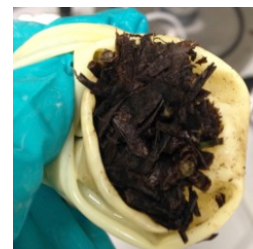
DTLB19_PWR_1 (4cm - 19cm)



Sample ID	Trial	K (cm/s)
DTLB19_PWR_1	1	7.27E-04
	2	7.82E-04
	3	6.88E-04



Bottom of sample; fine soil→



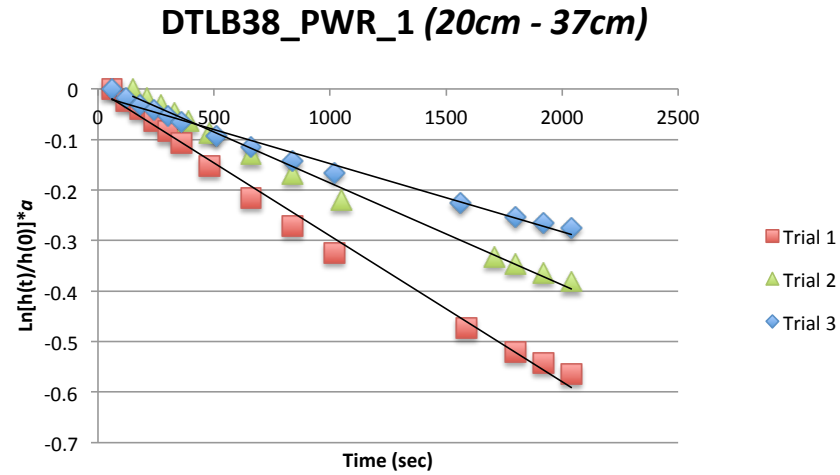
Top of sample;
grassy and woody



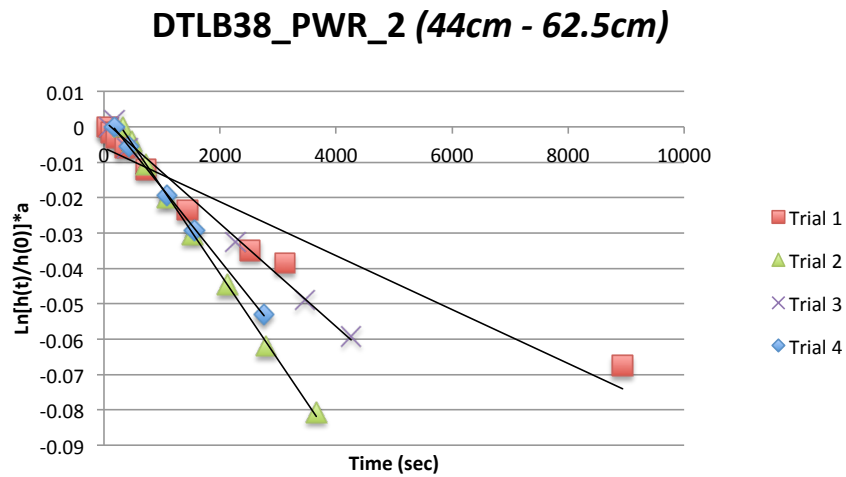
Bottom of sample; fine soil→

Low Center Polygon (Rim)

Sample ID	Trial	K (cm/s)
DTLB38_PWR_1	1	1.24E-04
	2	8.66E-05
	3	5.79E-05

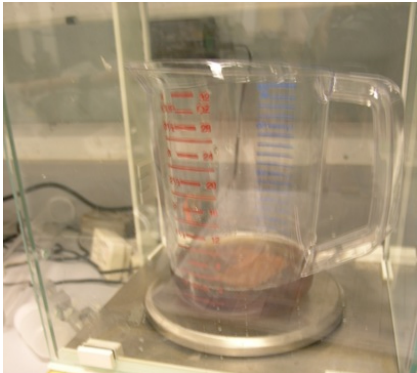


Sample ID	Trial	K (cm/s)
DTLB38_PWR_2	1*	4.23E-06
	2	1.35E-05
	3	8.07E-06
	4	1.14E-05

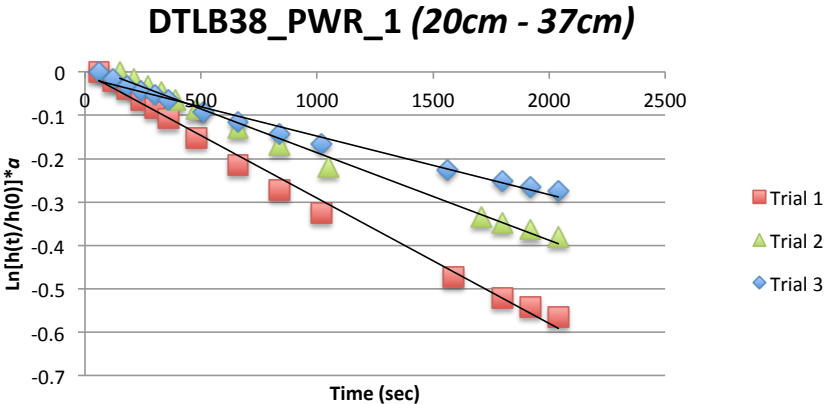


*Trial 1 K=7.18E-06 cm/s
when excluding last
datapoint

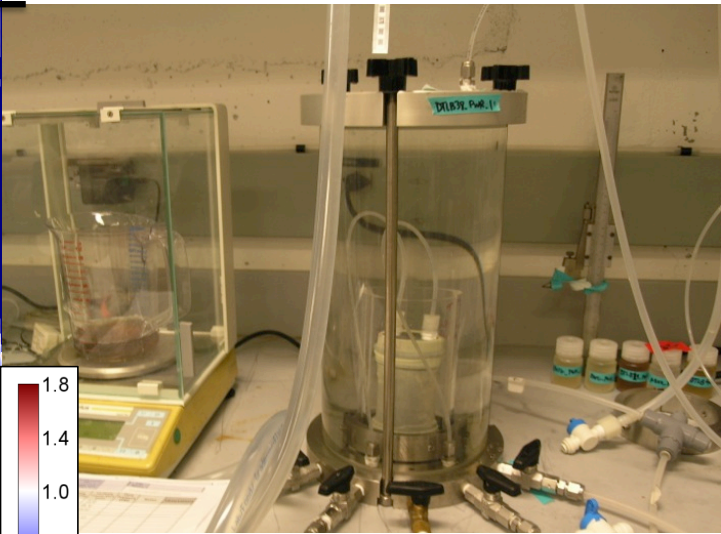
Low Center Polygon (Rim)



Clear, dark brown outflow water



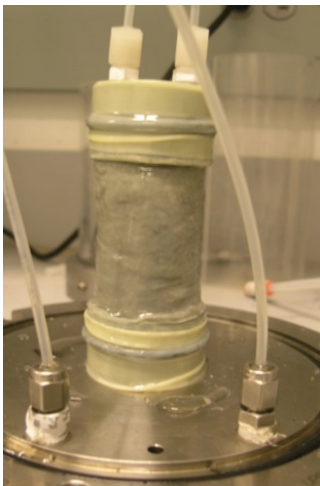
Sample ID	Trial	K (cm/s)
DTLB38_PWR_1	1	1.24E-04
	2	8.66E-05
	3	5.79E-05



Post-thaw; maintained original shape

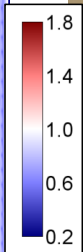
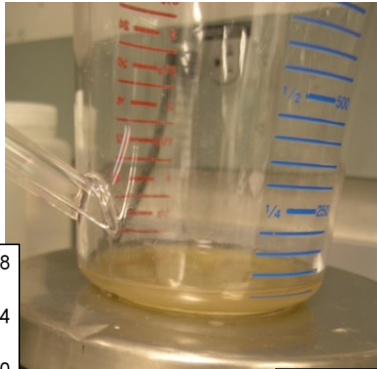


After trials completed



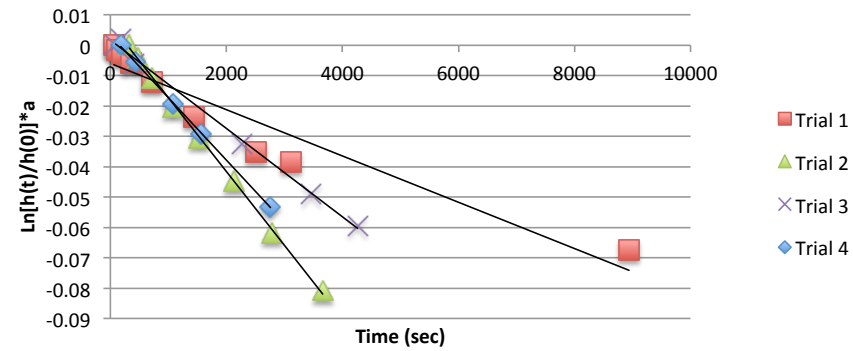
Post-vacuum

Low Center Polygon (Rim)



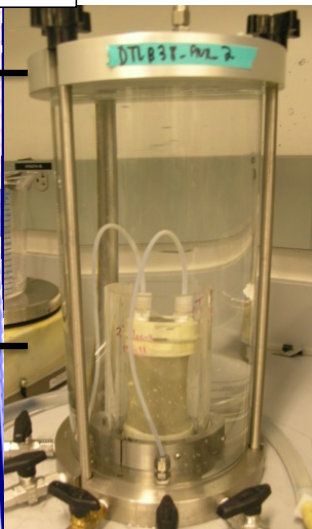
Cloudy, yellow outflow water

DTLB38_PWR_2 (44cm - 62.5cm)



Sample ID	Trial	K (cm/s)
DTLB38_PWR_2*	1	4.23E-06
	2	1.35E-05
	3	8.07E-06
	4	1.14E-05

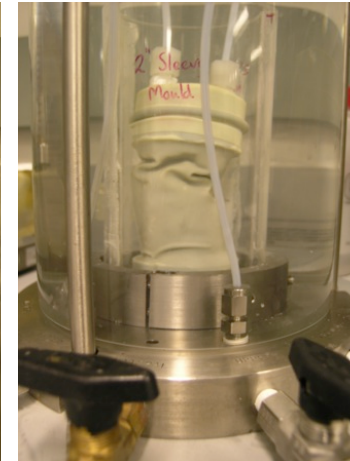
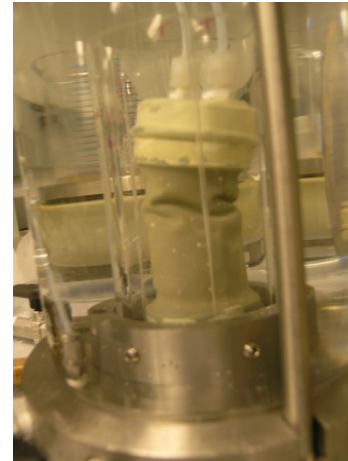
*Lost about 36g of water 1 hour after defrost began. Creases formed overnight. Confining column drained completely overnight.



Beginning of defrost

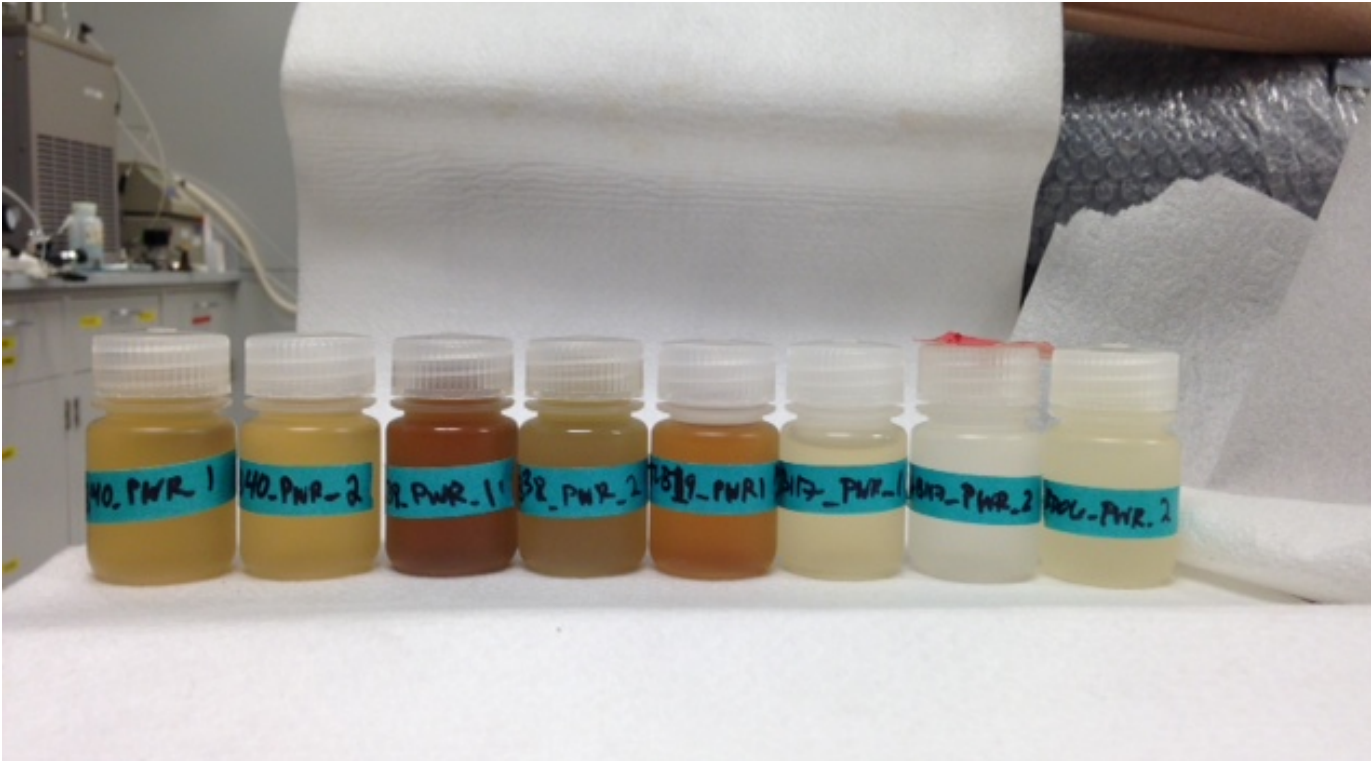


Creases formed shortly after defrost began



Morning after defrost period; beginning of trial 1

Variability in outflow water color:



From left to right: DTLB40_PWR_1, DTLB40_PWR_2, DTLB38_PWR_1, DTLB38_PWR_2, DTLB19_PWR_1, AB117_PWR_1, AB117_PWR_2*, BD06_PWR_2

*Outflow water of AB117_PWR_2 mostly tap water that primed outflow tubing since little flow occurred throughout sample during trials