Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Geologic carbon sequestration: Assessment of mid-continent rift core porosities and permeabilities in Wisconsin

December 1, 2023

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Wisconsin Geological and Natural History Survey

Open-File Report 2023-06 | 2023

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Introduction

Levels of carbon dioxide (CO_2) in the atmosphere are now higher than any time in recorded history. These higher levels have been linked to global climate change. One way to manage our emissions of CO_2 is to capture it and then store it in geologic reservoirs. This storage is called geologic sequestration. The geologic reservoirs are expected to sequester the CO_2 from the atmosphere for the very long time needed to help stabilize the global climate.

Geologic sequestration of CO_2 requires deep porous reservoir rock that can accept and store the CO_2, a seal that prevents the CO2 from migrating upward, and non-potable or saline water so that an aquifer is not impacted. One possible, regionally extensive candidate for CO_2 sequestration in the Upper Midwest is the Keweenawan sedimentary rock in the basins flanking the mid-continent rift (fig. 1). Within the Keweenawan sediments, the Copper Harbor Formation, a conglomerate, would be the storage reservoir and the overlying Nonesuch Formation, a fine-grained sandstone, would likely form the seal.

We measured the porosities, densities, and permeabilities of core from the rift basin in Wisconsin. The porosity of the reservoir rock gives a measure of how much CO_2 can be stored in the reservoir. The permeability of the seal rock must be low enough so that the CO_2 is not able to migrate upwards out of the reservoir while the permeability of the reservoir rock must be high enough to allow the CO_2 to be injected but not so high that the CO_2 can easily migrate laterally out of the reservoir. The data are presented in table 1 and dataset 1. Additional data including a lithologic description of the individual samples is available in appendix 1.

These measurements provide basic data for an assessment of these rocks for use in sequestration of CO_2. The rocks were divided into four lithologies: Portage Lake volcanics, conglomerates from the Copper Harbor formation, sandstones from the Copper Harbor formation, and fine-grained sandstones from the Nonesuch formation. These data (table 1; dataset 1) are meant to provide a starting point for study of these sediments in Wisconsin and are not meant to be a final assessment of the rift sediments potential to sequester CO_2. A more in-depth analysis of sequestration is available from the Minnesota Geological Survey, in a report available from their website, Potential Capacity for Geologic Carbon Sequestration in the Midcontinent Rift System in Minnesota (Thorleifson, 2008).

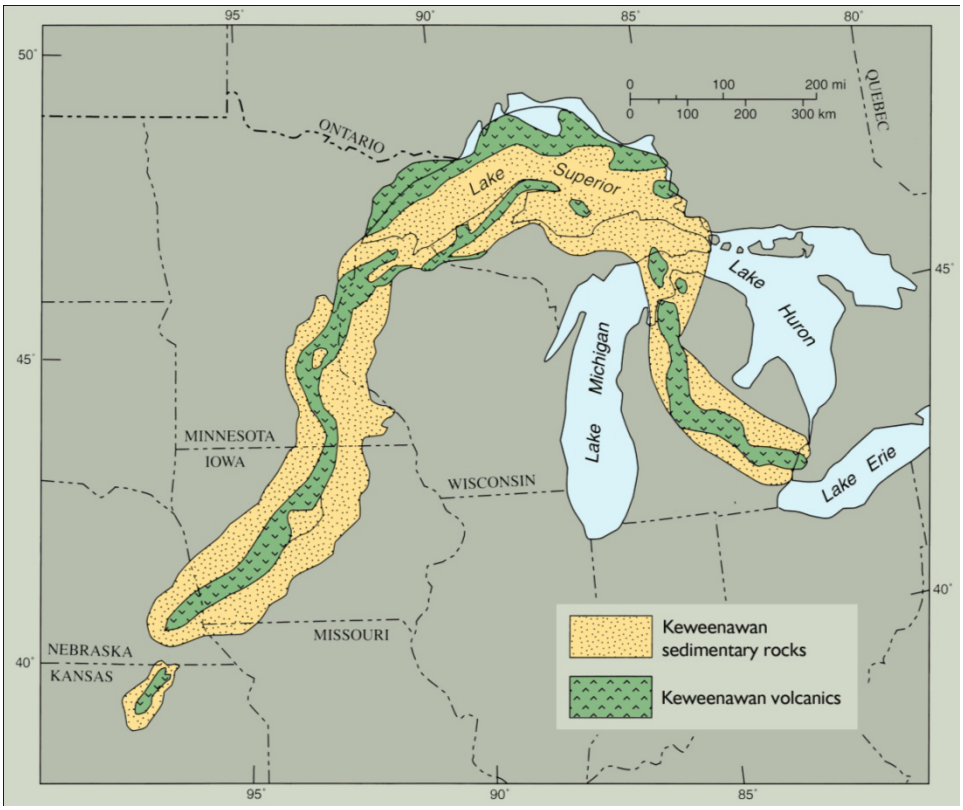


***Figure 1**. Location of the Keweenawan rift sediments (Ojakangas and others, 2001).*

Table 1. *Porosities, permeabilities, and densities of Wisconsin's mid-continent rift sediments.*

WGNHS ID	Sample ID	Latitude	Longitude	Formation	Lithology	Depth (ft bgs)	Porosity	Dry density (g/cm^3)	Wet density (g/cm^3)	Grain density (g/cm^3)	Permeability at 1 MPa (mD)	Permeability at 15 MPa (mD)
16000456	DO-10-02	46.510140	-91.731728	Portage Lake Volcanics	Basalt	986.5	12.5%	NA	NA	NA	2.4×10^{-1}	2.6×10^{-5}
16000456	DO-10-03	46.510140	-91.731728	Copper Harbor	Pebble breccia	986	19.0%	2.17	2.36	2.68	7.8×10^{-1}	7.8×10^{-5}
16000456	DO-10-04	46.510140	-91.731728	Copper Harbor	Pebble breccia	985	12.0%	2.37	2.49	2.7	NA	NA
16000456	DO-10-05	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	981.5	5.1%	2.52	2.57	2.66	1.9×10^{0} *	1.1×10^{-3}
16000456	DO-10-06	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	977	9.1%	2.36	2.45	2.61	NA	NA
16000456	DO-10-07	46.510140	-91.731728	Copper Harbor	Sandstone	965	24.5%	1.97	2.21	2.61	8.1×10^{1}	2×10^{-3} **
16000456	DO-10-08	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	958	10.5%	2.39	2.5	2.67	3.5×10^{-1}	NA
16000456	DO-10-09	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	947	11.3%	2.38	2.49	2.66	3.5×10^{0}	3.6×10^{-3}
16000456	DO-10-10	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	938	12.3%	2.28	2.49	2.61	5.3×10^{-1}	NA
16000456	DO-10-11	46.510140	-91.731728	Copper Harbor	Sandstone	935	27.3%	1.9	2.18	2.61	8.9×10^{-2}	3.8×10^{-5}
16000456	DO-10-12	46.510140	-91.731728	Copper Harbor	Sandstone	934	27.3%	1.89	2.16	2.61	4.2×10^{0}	1.9×10^{-4}

WGNHS ID	Sample ID	Latitude	Longitude	Formation	Lithology	Depth (ft bgs)	Porosity	Dry density (g/cm^3)	Wet density (g/cm^3)	Grain density (g/cm^3)	Permeability at 1 MPa (mD)	Permeability at 15 MPa (mD)
16000456	DO-10-13	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	922	17.2%	2.2	2.37	2.65	NA	NA
16000456	DO-10-14	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	907.5	18.7%	2.17	2.35	2.65	3.3×10^{0}	NA
16000456	DO-10-15	46.510140	-91.731728	Copper Harbor	Volcanic clasts	869	2.5%	2.57	2.59	2.65	1.2×10^{-1}	3.4×10^{-6}
16000456	DO-10-16	46.510140	-91.731728	Copper Harbor	Pebble conglomerate	864	7.2%	2.48	2.55	2.65	5.4×10^{-1}	3.1×10^{-2}
16000456	DO-10-17	46.510140	-91.731728	Copper Harbor	Sandstone	863.75	18.9%	2.14	2.33	2.64	2.6×10^{-1}	5.5×10^{-5}
16000456	DO-10-18	46.510140	-91.731728	Copper Harbor	Sandstone	863.5	19.7%	2.15	2.35	2.69	6.2×10^{-1}	2.8×10^{-3}
16000456	DO-10-19	46.510140	-91.731728	Copper Harbor	Sandstone	857	19.3%	2.19	2.38	2.71	4.7×10^{-2}	6×10^{-4}
16000456	DO-10-20	46.510140	-91.731728	Copper Harbor	Sandstone	856	18.8%	2.17	2.36	2.67	4.9×10^{-1}	2.2×10^{-5}
16000460	DO-14-01	46.481787	-91.583448	Copper Harbor	Sandstone	3211	16.0%	2.29	2.45	2.73	1.4×10^{2}	1.3×10^{-3}
16000460	DO-14-02	46.481787	-91.583448	Copper Harbor	Sandstone	3207	2.7%	2.64	2.66	2.71	1.1×10^{0}	3.5×10^{-3}
16000460	DO-14-04	46.481787	-91.583448	Nonesuch	Sandstone	3165	1.1%	2.68	2.69	2.71	3.2×10^{-1}	5.2×10^{-3}
16000460	DO-14-05	46.481787	-91.583448	Nonesuch	Sandstone	3068	1.4%	2.61	2.63	2.65	2.6×10^{0}	9.9×10^{-3}

WGNHS ID	Sample ID	Latitude	Longitude	Formation	Lithology	Depth (ft bgs)	Porosity	Dry density (g/cm^3)	Wet density (g/cm^3)	Grain density (g/cm^3)	Permeability at 1 MPa (mD)	Permeability at 15 MPa (mD)
16000460	DO-14-06	46.481787	-91.583448	Nonesuch	Sandstone	3070	2.7%	2.59	2.62	2.67	9.1×10^{-2}	3.6×10^{-3}
16000460	DO-14-07	46.481787	-91.583448	Nonesuch	Sandstone	2950	1.7%	2.66	2.68	2.71	4.9×10^{-2}	9.1×10^{-6} **
16000460	DO-14-08	46.481787	-91.583448	Nonesuch	Sandstone	2949	8.7%	2.51	2.6	2.72	NA	NA
4000210	WC-02-01	46.407400	-91.165600	Copper Harbor	Sandstone	926	3.6%	2.66	2.7	2.77	1.3×10^{-1}	2.9×10^{-6}
4000210	WC-02-02	46.407400	-91.165600	Copper Harbor	Sandstone	916	2.9%	2.68	2.71	2.76	1.8×10^{-1}	3.3×10^{-3}
4000210	WC-02-03	46.407400	-91.165600	Copper Harbor	Sandstone	906	1.8%	2.71	2.73	2.76	1.2×10^{-1}	1.4×10^{-3}
4000221	WC-13-01	46.423599	-91.458388	Copper Harbor	Sandstone	3297	5.1%	2.62	2.68	2.77	4.5×10^{0}	3.2×10^{-4}
4000221	WC-13-02	46.423599	-91.458388	Copper Harbor	Sandstone	3293	3.9%	2.69	2.73	2.82	2.6×10^{0}	1.1×10^{-5}
4000221	WC-13-03	46.423599	-91.458388	Copper Harbor	Sandstone	3286.7	4.9%	2.62	2.67	2.74	1.9×10^{1}	5.3×10^{-5}
4000221	WC-13-04	46.423599	-91.458388	Copper Harbor	Sandstone	3286.5	4.9%	2.72	2.77	2.86	5.2×10^{0}	4.8×10^{-5}
4000221	WC-13-05	46.423599	-91.458388	Copper Harbor	Sandstone	3285	5.1%	2.62	2.67	2.74	1.1×10^{1}	2.9×10^{-5}
4000221	WC-13-06	46.423599	-91.458388	Copper Harbor	Sandstone	3284	9.2%	2.83	2.92	3.11	5.9×10^{1}	5.2×10^{-4}

WGNHS ID	Sample ID	Latitude	Longitude	Formation	Lithology	Depth (ft bgs)	Porosity	Dry density (g/cm^3)	Wet density (g/cm^3)	Grain density (g/cm^3)	Permeability at 1 MPa (mD)	Permeability at 15 MPa (mD)
4000221	WC-13-07	46.423599	-91.458388	Copper Harbor	Sandstone	3277	8.8%	2.46	2.55	2.71	NA	NA
4000221	WC-13-09	46.423599	-91.458388	Copper Harbor	Sandstone	3271	12.0%	2.5	2.62	2.78	NA	NA
4000221	WC-13-10	46.423599	-91.458388	Nonesuch	Sandstone	3252	2.1%	2.68	2.71	2.73	9.3×10^{-3}	5.2×10^{-6}
4000224	WC-16-01	46.392722	-91.143906	Copper Harbor	Pebble breccia	1564	7.4%	2.58	2.65	2.78	5.1×10^{1}	2.6×10^{-1}

* Measurement taken at 1 Mpa

** Measurement taken at 7 Mpa

Discussion of porosity

Porosity is the percentage of void space in a rock. It is defined as the ratio of the volume of the voids or pore space divided by the total volume, as illustrated by equation 1:

$$n = \frac{V_{pore\ space}}{V_{total}}$$

The porosity of rift sediments is the most basic measurement of the storage potential for carbon sequestration. It can give the total possible volume for storage. We measured porosity on 39 samples from the four lithologies: Portage Lake volcanics, conglomerates from the Copper Harbor formation, sandstones from the Copper Harbor formation, and fine-grained sandstones from the Nonesuch formation.

The porosity of a rock depends on many factors, including the rock type and how the grains of a rock are arranged. For example, crystalline rock such as granite has a very low porosity (<1%) since the only pore spaces are the tiny, long, thin cracks between the individual mineral grains. Sandstones, typically, have much higher porosities (10–35%) because the individual sand or mineral grains do not fit together closely, allowing larger pore spaces. In general, porosity often decreases with depth, as the pore volume is lost as the rock consolidates due to the increasing stress.

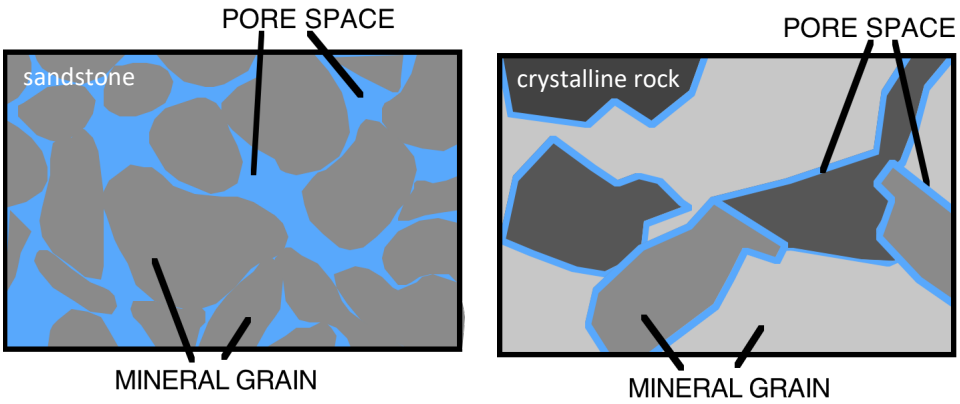


***Figure 2**. Illustrations of porosity in sandstones and crystalline rock.*

Porosity measurements of Wisconsin rift sediments

The porosities of the rocks measured vary from 1% to 27%. All of the lithologies have some samples with significant porosity greater than 5%. Table 1 lists the porosities of the tested samples and figure 3 below shows the range and distribution of porosities by lithology. Each point in the dot plot below represents a single measurement and sample. The porosity of the Portage Lake basalt sample is 12%. The Nonesuch sandstones all have lower porosities, mostly less than 3% with the largest value of 9%. The Copper Harbor conglomerates have mid-range porosities from 2 to 20% with an even distribution across that range. The Copper Harbor sandstones have the greatest range going from 2 to 27% porosity.

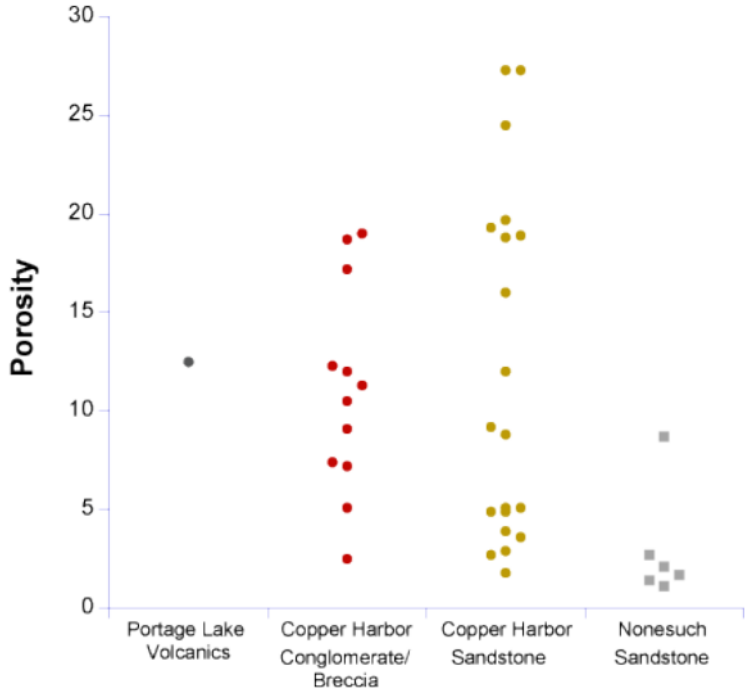


Figure 3. *Range and distribution of porosities for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

The porosity of the Copper Harbor sandstones appears to show dependence with depth. Figure 4 shows the porosity of the samples plotted with depth of the core. Each lithology is shown with different symbols. The Copper Harbor sandstone shown as the brown dots was collected from two different sets of core. One set was collected from around 1000 feet, the other set was collected from 3300 feet. The shallow core has a much higher upper range 27%. The upper range of the deeper core is only 16%. This reduction could be due to consolidation of the rock with increasing stresses at the greater depths.

In addition to the depth, there is also a relationship between lithology and the porosity. Figure 5 shows the porosity of Copper Harbor sandstones decreasing with depth from 3270 to 3298 feet from 12 to 5%. This reduction corresponds to a change in color from grey to red in the sandstone. The core below 3284 feet is reddish and all has a porosity of around 5%.

These two controls, color and depth are not always useful. A comparison of the porosity of Copper Harbor sandstone samples from boreholes WC-2 and DO-10 at the same depths gives different overall porosities. Even though both samples are reddish and from a depth of around 1000 feet with similar grain sizes, the samples from WC-2 have porosities of less than 5% while the DO-10 samples have porosities greater than 15%. Samples from these two sites are identified in figure 6.

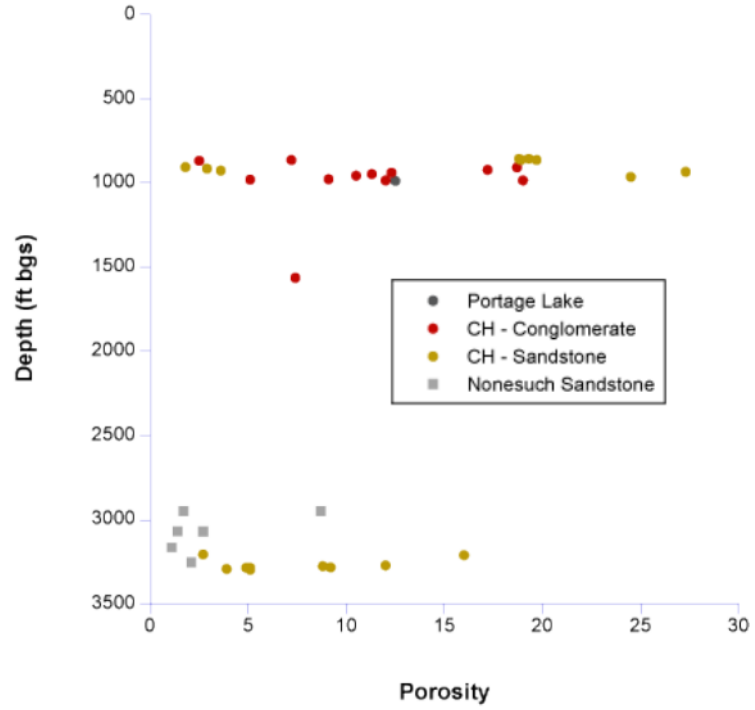


Figure 4. *Variation of porosity with depth for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

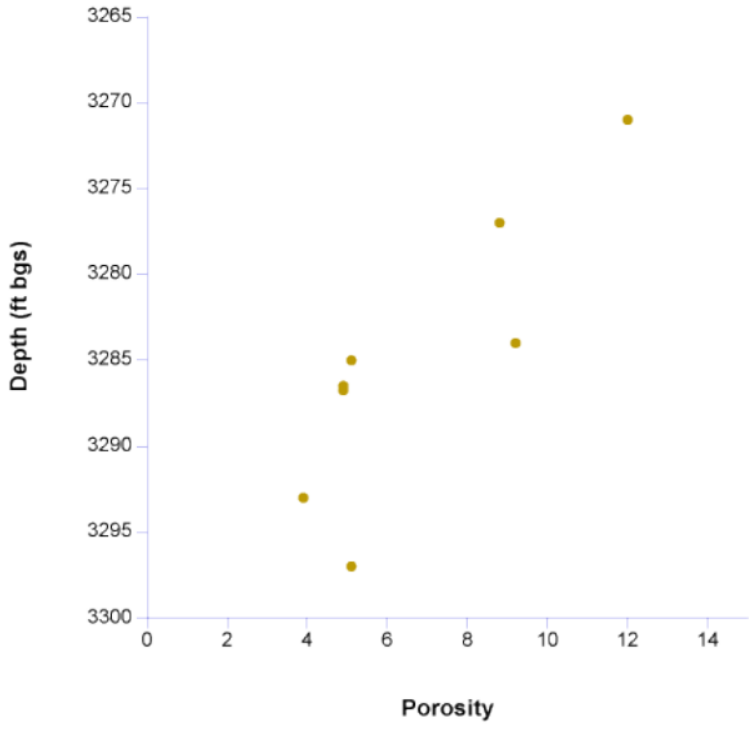


Figure 5. *Variation of porosity with depth for Copper Harbor sandstones.*

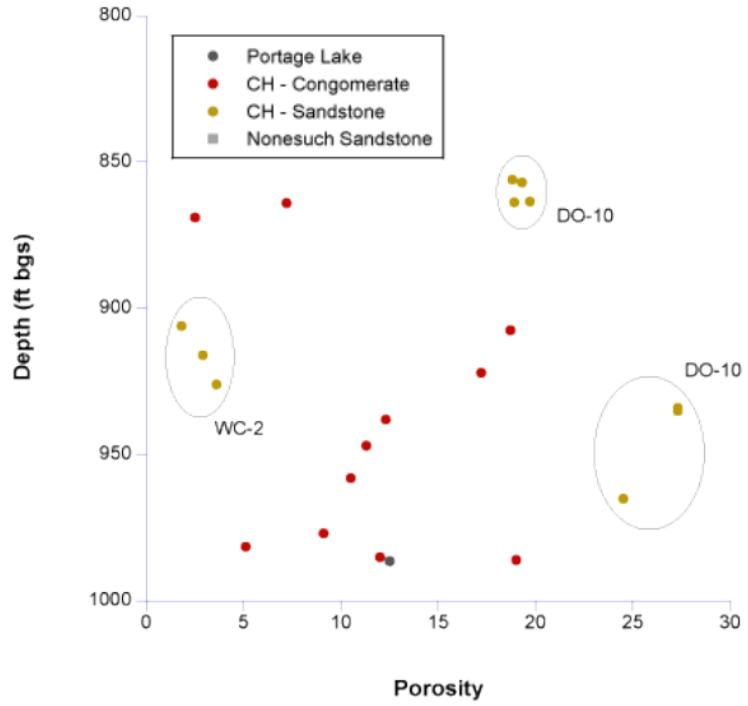


Figure 6. *Variation of porosity with depth for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

Discussion of density

Density measurements of Wisconsin rift sediments

Dry density measurements and distribution

Dry density is measured on rocks without any water or fluid in their pores, as shown in equation 2:

$$\rho_{dry} = \frac{m_{solid}}{V_{total}}$$

See figure 7 for dry density distribution for shale and sandstone. The range of densities exhibited here is due to the wide range of porosities. Each dot represents a measurement and sample.

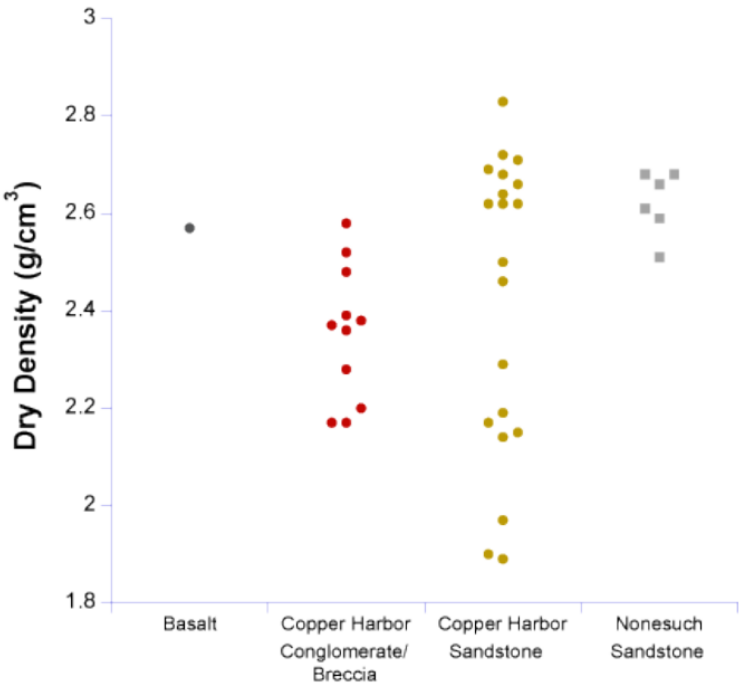


Figure 7. *Distribution of dry density for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

Wet density measurements and distribution

Wet density assumes that the rock is fully saturated, as seen in equation 3:

$$\rho_{wet} = \frac{m_{solid} + m_{pore\ fluid}}{V_{total}}$$

See figure 8 for wet density distribution for shale and sandstone.

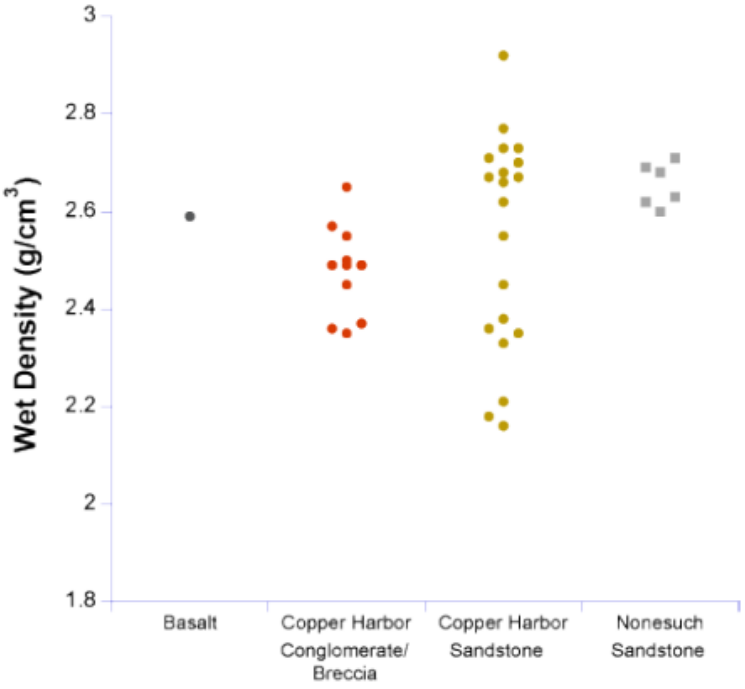


***Figure 8**. Distribution of wet density for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

Grain density measurements and distribution

Grain density describes the density of solid or mineral grains of the rock, as seen in equation 4:

$$\rho_{grain} = \frac{m_{solid}}{V_{solid}}$$

Grain density can give an indication of the mineralogy of the rock. More mafic minerals like olivine, pyroxene, and biotite have grain densities greater than 3 g/cm^3. Felsic minerals like quartz, feldspars, and muscovite have grain densities of around 2.7 g/cm^3.

Shales are composed of several minerals that have different densities in different relative amounts. The minerals may include clays such as illite (p = 2.6–2.9 g/cm^3) and kaolinite (p = 2.6 g/cm^3) mixed, for example, with dolomite (p = 2.8–3.1 g/cm^3) and calcite (p = 2.71 g/cm^3).

See figure 9 for grain density distributions of the different lithologies.

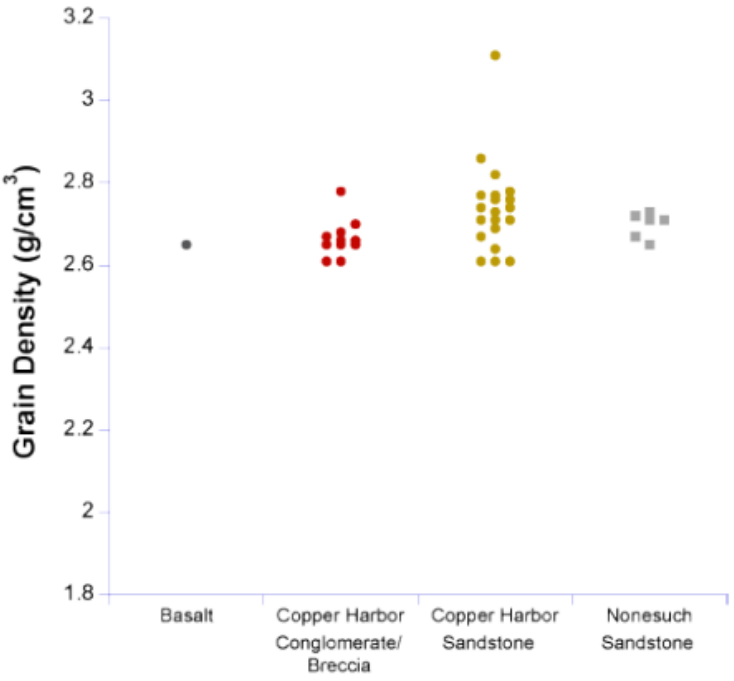


Figure 9. *Distribution of grain density for Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones.*

Results:

- Portage Lake Volcanics= 2.65 g/cm^3

This density suggests that the lava was more rhyolitic than basaltic or that the basalt has been altered to less mafic minerals. Because calcite has a density of around 2.7 g/cm3, the calcite infilling in the Portage Lake sample would reduce the grain density.

- Copper Harbor Conglomerate, = 2.65-2.8 g/cm^3

These densities correspond to mostly felsic minerals. The sample with the density approaching 2.8 might be more mafic.

- Copper Harbor Sandstones, = 2.6–3.1 g/cm3

Most of these cores seem to be predominately felsic with the exception of the one core with the density of 3.1 g/cm^3

- Nonesuch Sandstones, = 2.7 g/cm^3

Most of these core seem to be predominately felsic.

Discussion of permeability

Permeability is a measure of how well a material transmits a fluid. We measured permeabilities of the rift core at several different confining stresses to simulate different depths of burial. Table 1 shows the permeability results in milliDarcy at stresses of 1 MPa and 15 MPa. These confining stresses correspond to depths burial of approximately 200 ft and 3000 ft, respectively. We report permeability in millidarcy because units used for hydraulic conductivity, e.g. cm/s, are not appropriate for different pore fluids such as liquid CO_2.

Figure 10 shows histograms of the all the sample permeabilities at 1 MPa and 15 MPa plotted on a log scale. The distribution of permeabilities at 1 MPa for all the samples is approximately log normal with the median value around 1 mD ranging from just less than 0.01 mD to just greater than 100 mD.

These samples are very sensitive to confining stress and show a decrease of around 3 orders of magnitude for the median value of around 0.001 mD at 15 MPa. At the higher stress of 15 MPa the distribution of permeabilities also changes. The range increases from four orders of magnitude at 1 MPa to five orders of magnitude at 15 MPa, going from 10^{-6} mD to 0.1 mD. The log distribution also seems to become bimodal with peaks at 10^{-4} and 10^{-2} mD.

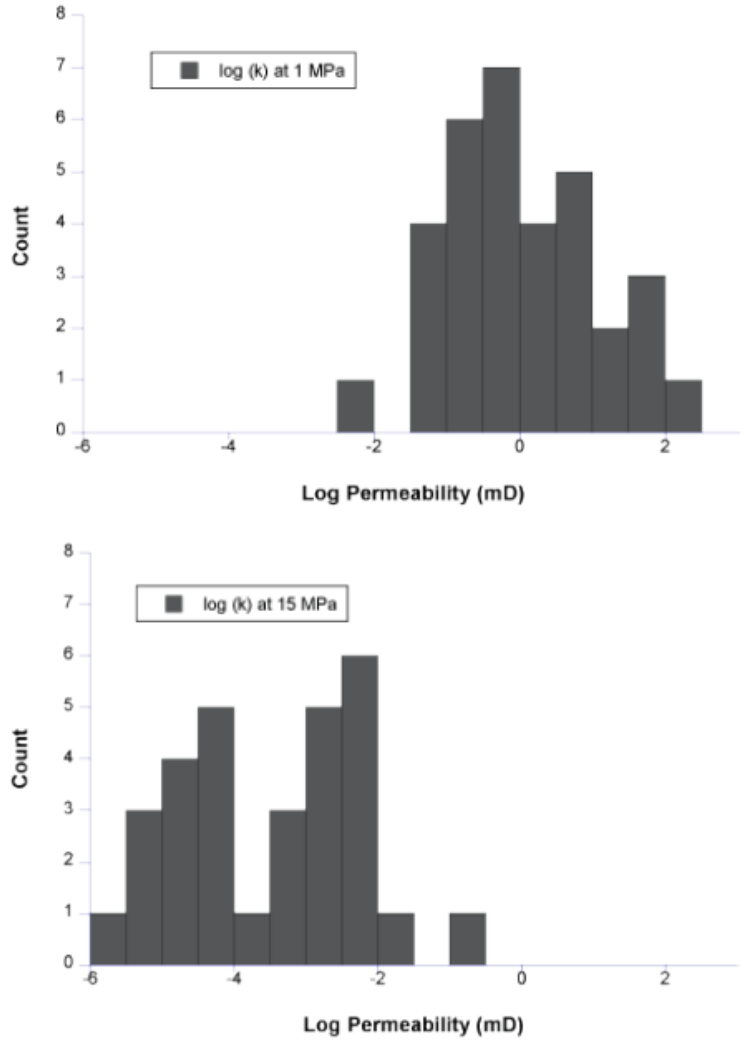


Figure 10. *Histograms showing permeability of rift sediment samples at 1 MPa (upper) and 15 MPa (lower).*

Figure 11 shows dot plots of the permeabilities of the four rift sediment lithologies: Portage Lake Volcanics, Copper Harbor conglomerate, Copper Harbor sandstone, and Nonesuch sandstone at 1 MPa (circles) and 15 MPa (diamonds) confining stresses. At 1 MPa there is overlap in permeability values among the four different lithologies. Increasing the confining stress to 15 MPa affected the lithologies differently. The Portage Lake Volcanics and the Copper Harbor sandstone reacted similarly; the individual samples decreased by about 3-4 orders of magnitude in permeability. The Copper Harbor conglomerates and the Nonesuch sandstones showed a variable decrease. For these lithologies, the more permeable samples decreased fewer orders of magnitude than the less permeable samples, increasing the range of permeability. Figure 12 shows the permeability decrease for a Copper Harbor sandstone sample, DO-14-1, as a function of stress.

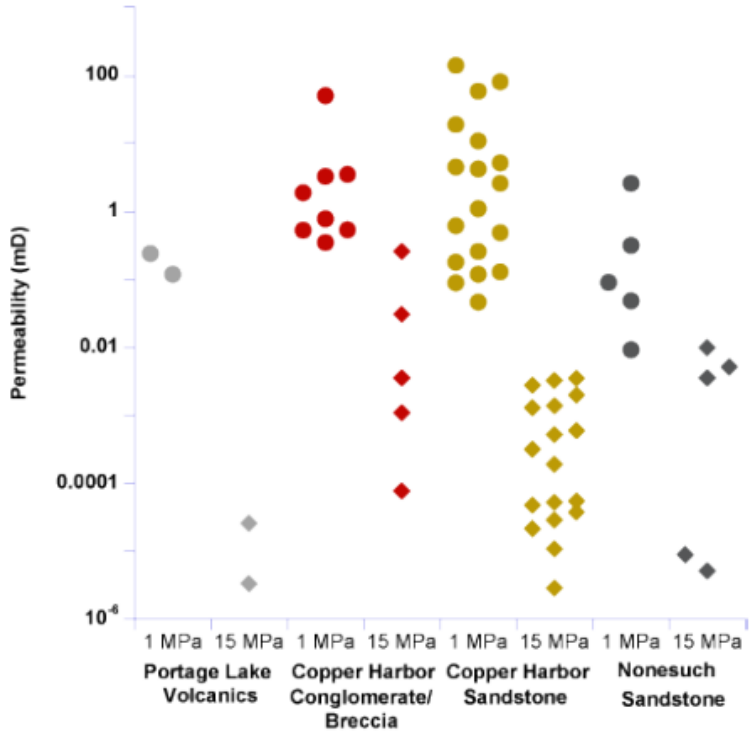


Figure 11. *Dot plots showing permeabilities of Portage Lake basalts, Copper Harbor conglomerates, Copper Harbor sandstones, and Nonesuch sandstones at 1 MPa and 15 MPa.*

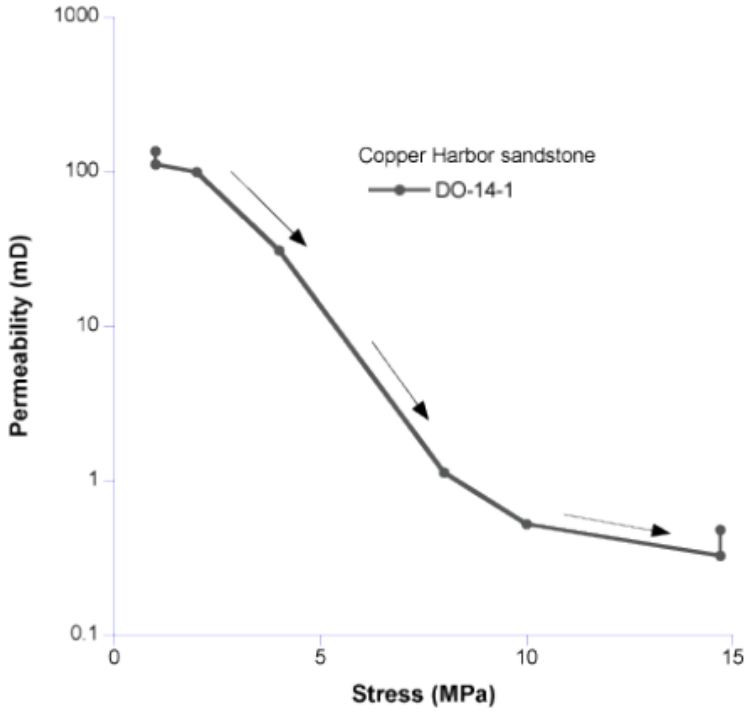


Figure 12. *Permeability decreases with stress for Copper Harbor sandstone sample DO-14-1.*

The dramatic decreases in permeability were unexpected. In contrast to the several orders of magnitude decrease seen in these rocks, we tested Mansfield sandstone, a standard rock mechanics sample, and saw a permeability decrease of less than 1/2 going from 640 mD at 1 MPa to 350 mD at 15 MPa. In contrast the rift sediment sample permeabilities decreased by around 1/1000. We cycled three of the rift sediment samples from 1 to 15 to 1 MPa to see if the permeability loss was permanent or recoverable. The permeability with stress is shown in figures 13. In all three samples, the permeability loss was between 1 and 2 orders of magnitude just from cycling the rock from 1 MPa to 15 MPa and back to 1 MPa.

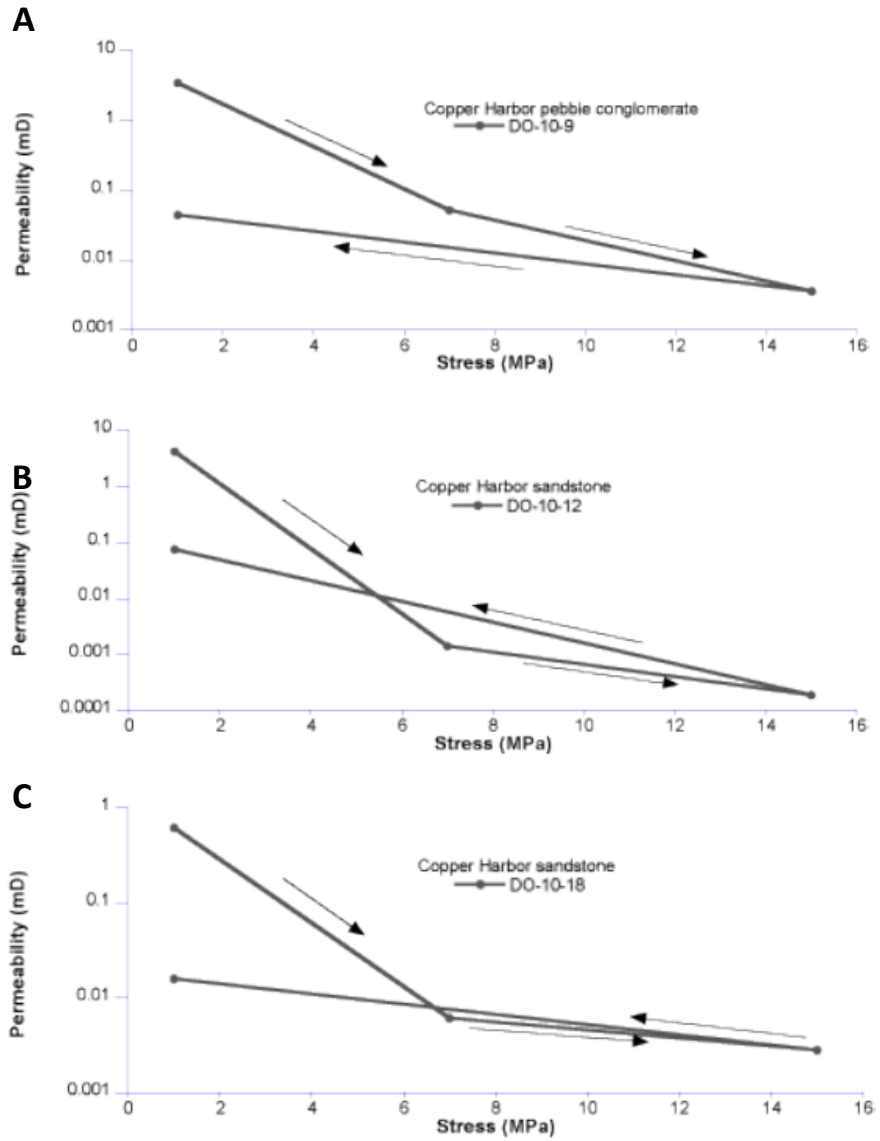


Figure 13. *Permeability cycling with stress for rock samples from Copper Harbor. Panel A, pebble conglomerate sample DO-10-9. Panel B, sandstone sample DO-10-12. Panel C, sandstone sample DO-10-18.*

This permeability loss has implications for the Copper Harbor Formation as a sequestration reservoir for carbon. If changing the stresses on the rock by injecting fluids and drilling reduces the ability of the rock to accept the CO2 then the Copper Harbor Formation is unlikely to be a good candidate for sequestration.

Sample preparation and measurement

Sample preparation

Samples were cut to the desired length (generally ~0.75-inch) using a rotating table drop saw with diamond bit and ground parallel using a semi-automatic high precision surface grinder with a tolerance of 0.001-inches (fig. 14). Due to weak cementation of some samples, samples were manually cut and hand sanded to achieve parallel core ends. Samples were then dried in a vacuum with no heat, as not to alter the sample's mineralogy.

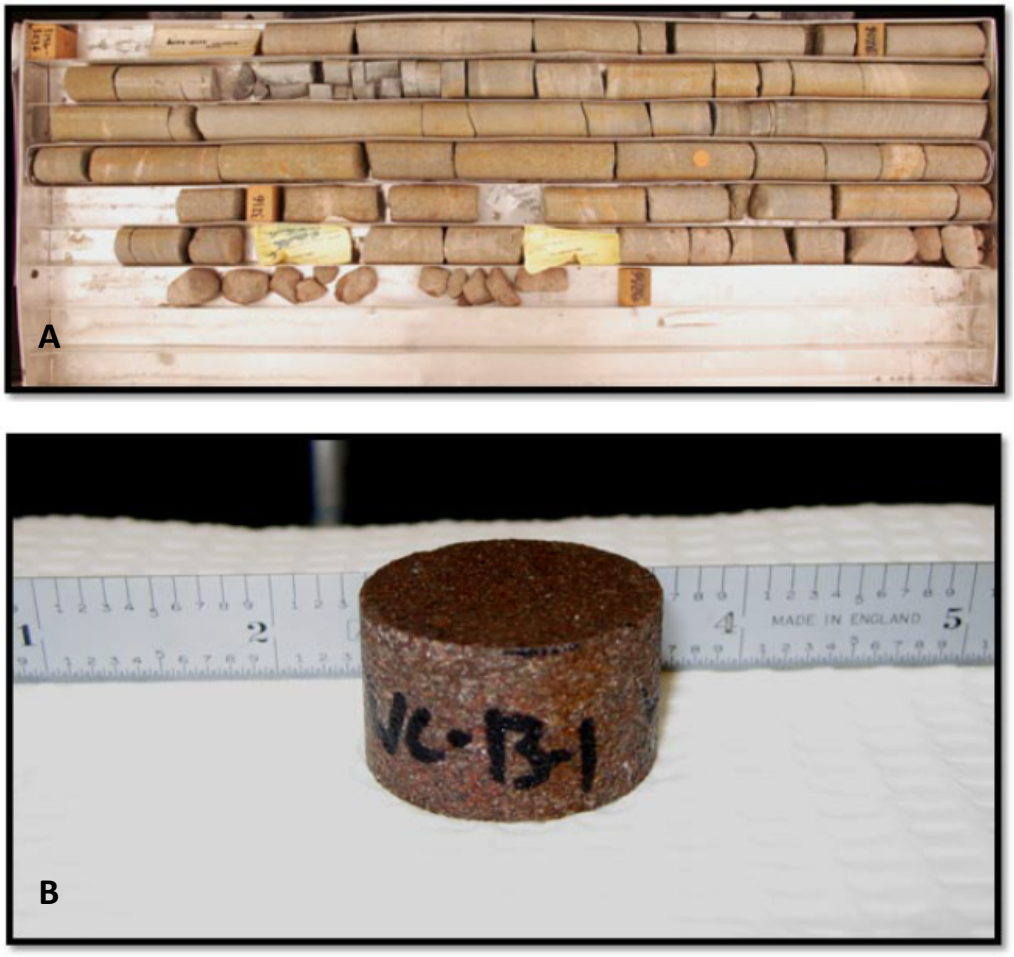


Figure 14. *Examples of sample preparation. Panel A, core box pulled from the WGNHS Core Repository in Mt. Horeb, WI. Panel B, saturated cut and ground sample from the Copper Harbor Formation. Saturation was completed while samples were under vacuum.*

Measuring pore space volume

Pore space volume was determined using a helium pycnometer. The helium pycnometer makes use of Boyle's Law (P1V1=P2V2) and helium gas, which quickly penetrates small pores and is nonreactive, to determine the solid portion of a sample. The core is placed in a sample chamber of known volume. A reference chamber, also of known volume, is pressurized. The two chambers are then connected, allowing the helium gas to flow from the reference chamber to the sample chamber. The ratio of the initial and final pressures is used to determine the volume of the sample solid. The pore volume is the difference between the total volume and the solid volume as determined by the helium pycnometer. This technique can only be used to measure pores that are interconnected. Helium and water do not penetrate into isolated pores, so these pores are not included in the porosity measurement.

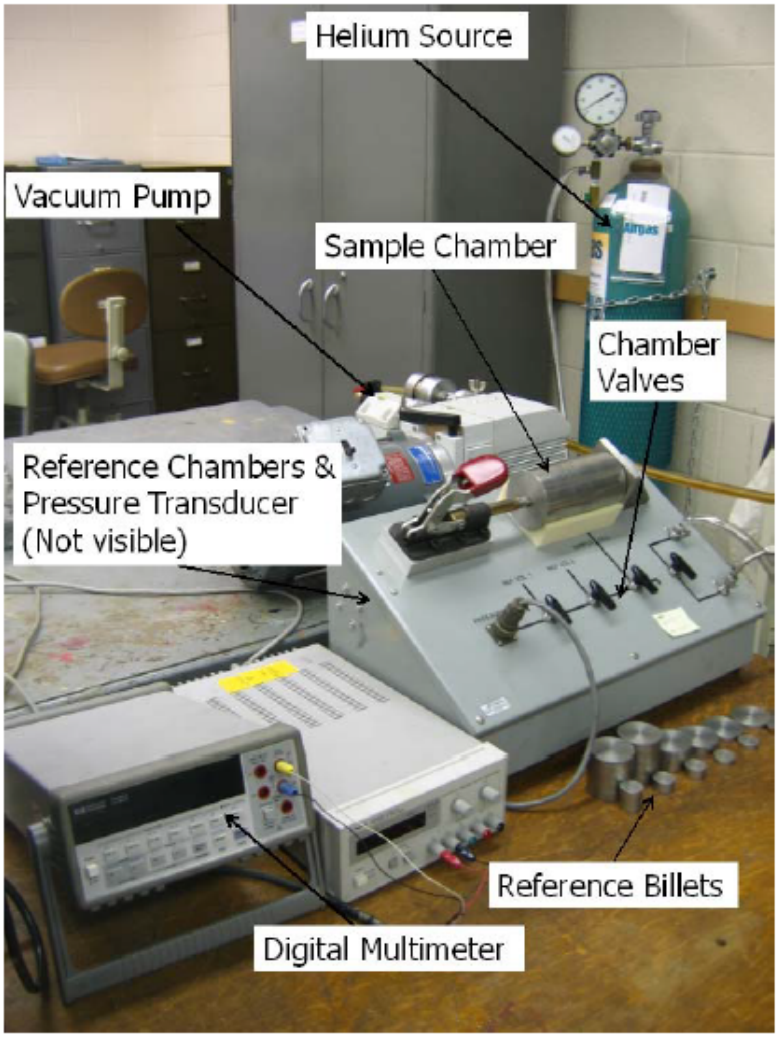


Figure 15. *Photo of Helium porosimeter and associated components. For each sample three tests were completed: sample chamber empty, sample chamber fill with reference billets, and sample chamber filled with reference billets and the sample.*

Measuring density

Dry densities were determined by weighing the samples after drying and dividing the mass by the total sample volume. Wet densities were then calculated by assuming the porosity of the sample was filled with water, adding that mass to the dry measured mass and dividing the sum by the total sample volume. Grain density was calculated by subtracting the pore space volume from the total sample volume and then dividing the difference by the dry mass.

Measuring permeability

We measured core permeability using either the constant pressure or pulse decay methods over a range of effective stresses from 1 to 15 MPa. These stresses represent the in-situ stresses at burial depths of 200 to 3000 ft. In the constant head test, a constant pressure gradient is applied across the sample and the flow rate through the rock is measured. This allows the permeability to be calculated directly from Darcy's law, see equation 5:

$$Q = -\frac{k}{\mu}\frac{\Delta P}{L}A$$

where Q is the flow rate, k is the permeability, μ is the fluid viscosity, ΔP is the pressure change across the sample, L is the sample length, and A is the cross-sectional area of the sample. All of the variables are known or measured except the permeability k, which can then be calculated.

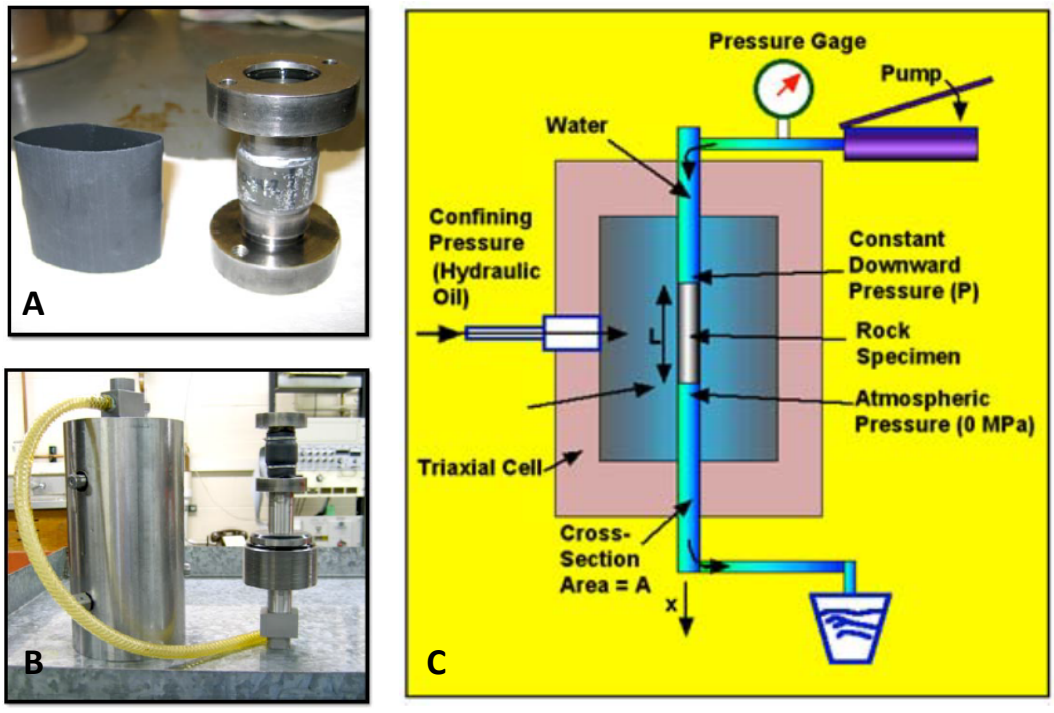


Figure 16. *Panel A, prepped sample showing 2 layer heat shrink jacket. Panel B, disassembled sample holder used for constant head and pulsed decay permeability testing. Panel C, diagram of the constant pressure permeability apparatus (Haimson, pers. commun., 2007).*

The lower permeability rock was tested using the pulse decay method (Brace and others, 1968; Hart and Wang, 1993). This test was usually conducted after a constant head test. In this test, a valve was closed between the pump and pressure gage forming a pressurized reservoir between the valve and the rock specimen. The pressure in this reservoir was observed with time as the fluid drained from the reservoir across the sample. This test is analogous to a falling head test, except the fluid volume flowing through the rock is determined from the pressure and compressibility of the reservoir and fluid rather than the head and volume of the standpipe. Since the fluid reservoir storage was larger than the rock storage we applied the analysis of Brace and others, 1968, rather than attempt to determine specific storage (Hart and Wang, 1993). Figure 17 shows plots of the data for sample WC-13-06. The constant head tests correspond to the regions of constant Ppore and are numbered 1 ch to 4 ch. The pulse decay tests correspond to the regions of exponentially declining pore and are numbered 3 pd and 4 pd. The fluid flow (LVDT) and pore pressure (Ppore) were normalized to fit on the graph by dividing by 5 and multiplying by 4 respectively. To recover the actual values, LVDT (ml) should be multiplied by 5 and Ppore (MPa) divided by 4.

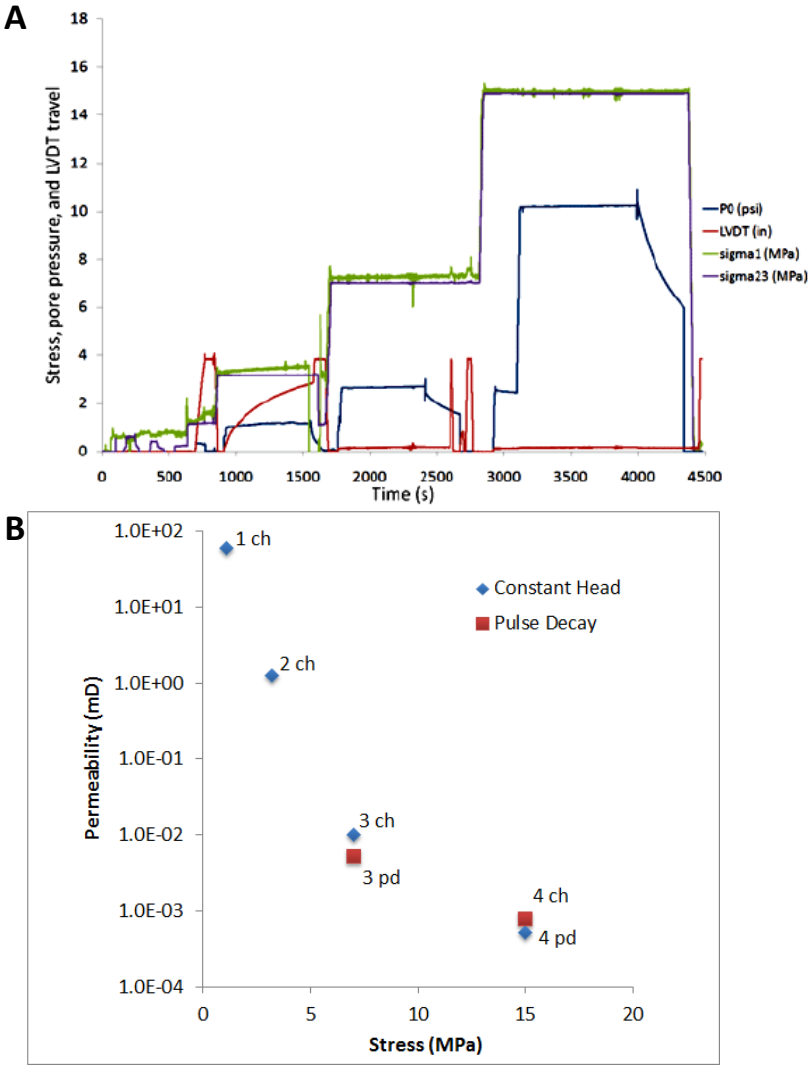


Figure 17. *Panel A, Constant Head and Pulse Decay permeability tests data. All test are being conducted at hydrostatic stresses of approximately 1, 7 and 14.8 MPa. Note that the pore pressure being applied to the samples is generally less than 0.69, 1.38 and 2.76 MPa, respectively and has been normalized on the plot. Panel B, Permeability and associated hydraulic conductivity dramatically decrease with increased hydrostatic stress conditions. The constant head and pulse decay results are similar for similar stresses.*

Supplemental material

Dataset 1: Data from Geologic carbon sequestration: Assessment of mid-continent rift core porosities and permeabilities in Wisconsin.
One spreadsheet (.csv format) showing porosities, permeabilities, and densities of Wisconsin's mid-continent rift sediments (also Table 1).

References

Brace, W.F., J.B. Walsh, and W.T. Frangos, 1968, Permeability of Granite under High Pressure: Journal of Geophysical Research, v 73, no. 6, p. 2225-2236, https://doi.org/10.1029/JB073i006p02225.

Ojakangas, R.W., G.B. Morey, and J.C. Green, 2001, The mesoproterozoic midcontinent rift system, Lake Superior Region. USA: Sedimentary Geology, v. 141-142, p. 421–442, https://doi.org/ 10.1016/S0037-0738(01)00085-9.

Thorleifson, L. H., ed., 2008, Potential capacity for geologic carbon sequestration in the Midcontinent Rift System in Minnesota: Minnesota Geological Survey Open File Report 08-01, 138 p., https://hdl.handle.net/11299/117609.

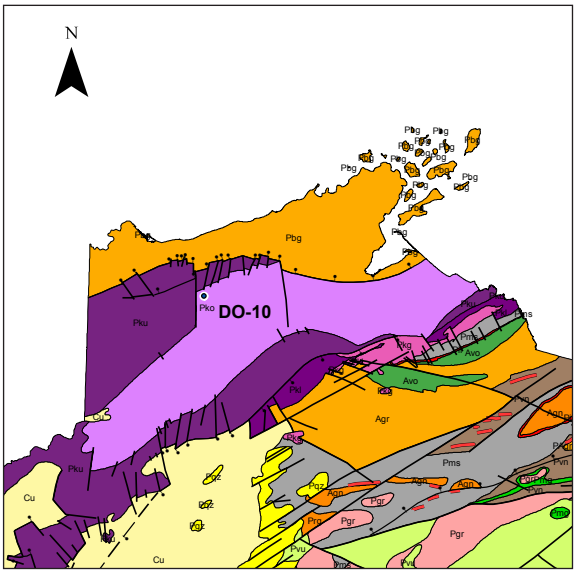
Wang, H.F. and D.J. Hart, 1993, Experimental error for permeability and specific storage from Pulse Decay Measurements: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v 30, no. 7, p. 1173-1176, https://doi.org/10.1016/0148-9062(93)90089-V.

Appendix 1

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-02
Depth: 986.5 ft bgs
Formation: Portage Lake Volcanics
Lithology: Basalt
Notes: Basalt, amygdaloidal with calcite and or zeolite infill



Measured parameters

Porosity: 12.50%
Dry density: NA g/cm^3
Wet density: NA g/cm^3
Grain density: NA g/cm^3
Permeability (1 MPa): 0.24 mD
Permeability (15 MPa): 2.60E-05 mD

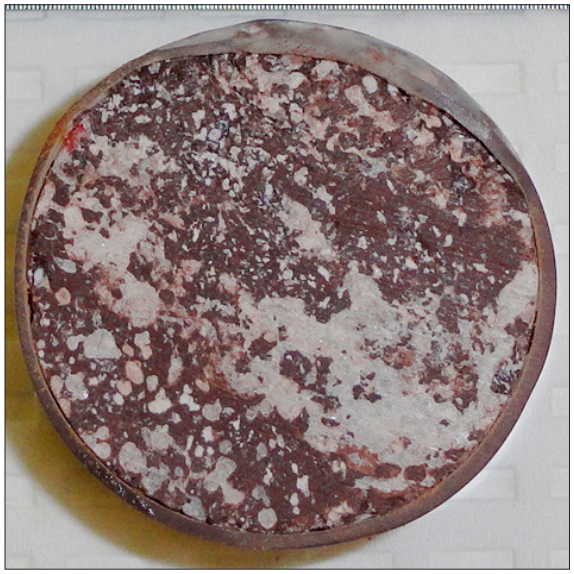


Figure A1.1. Geologic map of northern Wisconsin showing the location of sample DO-10-02 and photograph of core section used in analysis. Cores are 1 inch in diameter.

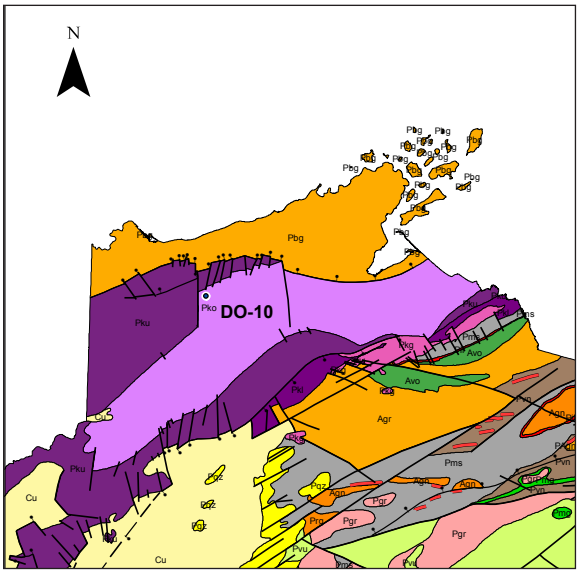
Porosity/Permeability Sample Details

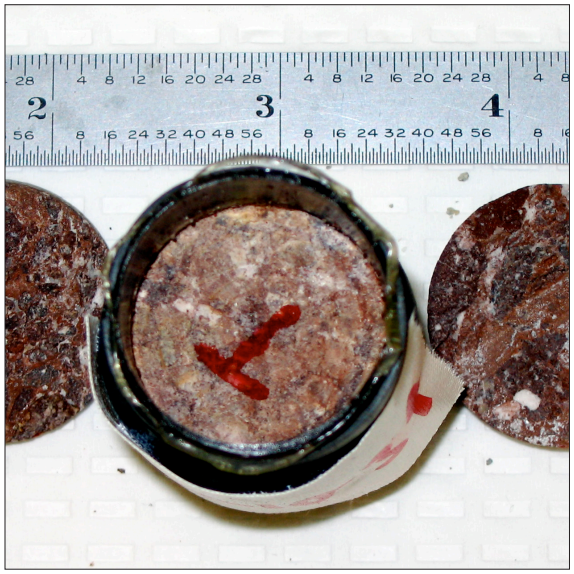
General core data

WGNHS ID: 16000456
Sample ID: DO-10-03
Depth: 986 ft bgs
Formation: Copper Harbor
Lithology: Pebble breccia
Notes: Pebble breccia with very coarse cement - Tested sample has horizontal fracture

Measured parameters

Porosity: 19.00%
Dry density: 2.17 g/cm^3
Wet density: 2.36 g/cm^3
Grain density: 2.68 g/cm^3
Permeability (1 MPa): 0.78 mD
Permeability (15 MPa): 7.80E-05 mD





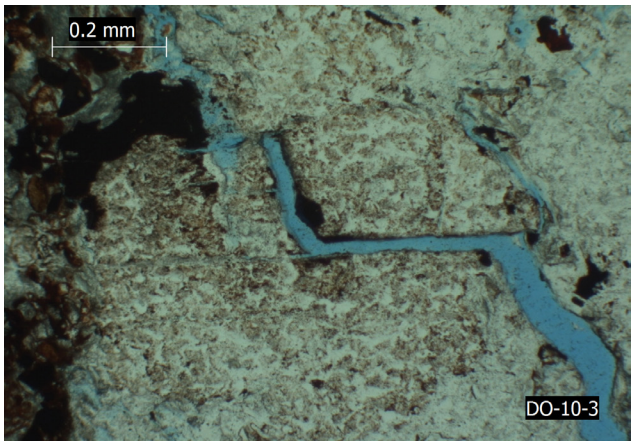


Figure A1.2 Geologic map of northern Wisconsin showing the location of sample DO-10-03 and photograph of core section (and thin section, if applicable), used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-04
Depth: 985 ft bgs
Formation: Copper Harbor
Lithology: Pebble breccia
Notes: Pebble breccia with very coarse cement

Measured parameters

Porosity: 12.00%
Dry density: 2.37 g/cm^3
Wet density: 2.49 g/cm^3
Grain density: 2.7 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

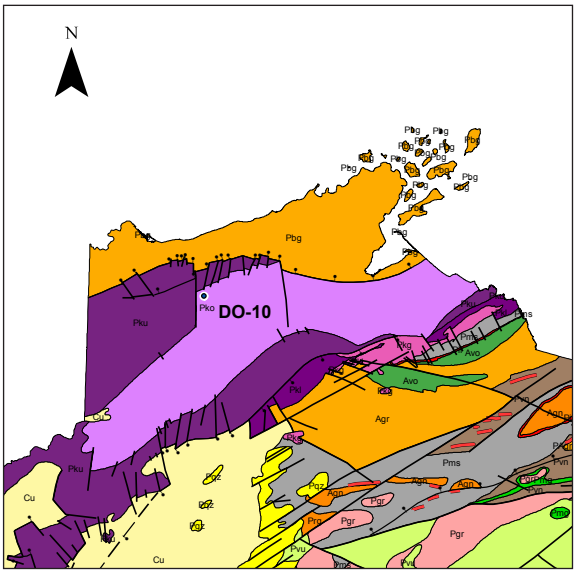
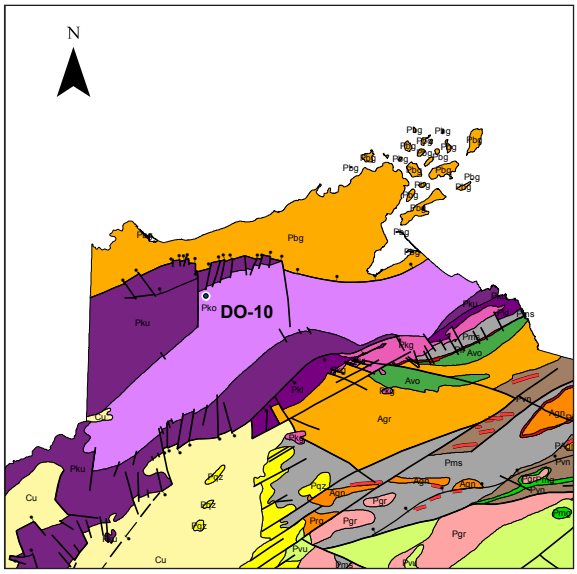


Figure A1.3 Geologic map of northern Wisconsin showing the location of sample DO-10-04.

Porosity/Permeability Sample Details

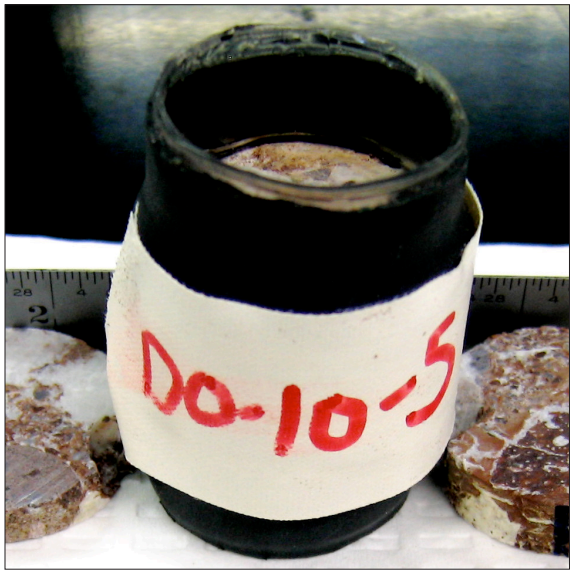
General core data

WGNHS ID: 16000456
Sample ID: DO-10-05
Depth: 981.5 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate
Notes: Pebble conglomerate with very coarse cement



Measured parameters

Porosity: 5.10%
Dry density: 2.52 g/cm^3
Wet density: 2.57 g/cm^3
Grain density: 2.66 g/cm^3
Permeability (2 MPa): 1.9 mD
Permeability (15 MPa): 1.10E-03 mD



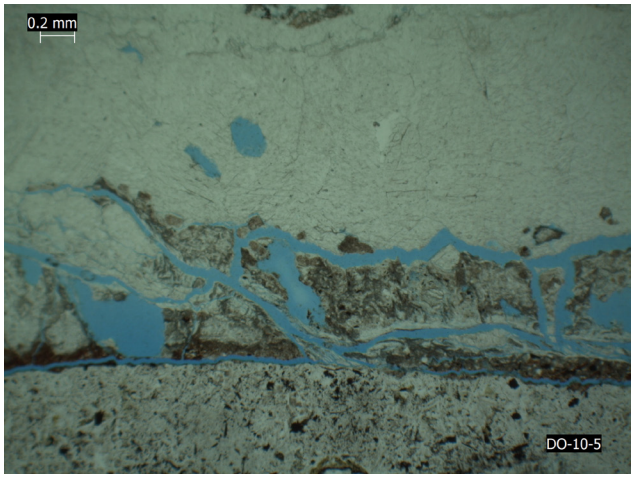


Figure A1.4 Geologic map of northern Wisconsin showing the location of sample DO-10-05 and photograph of core section (and thin section, if applicable), used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-06
Depth: 977 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate
Notes: Pebble conglomerate with very coarse cement

Measured parameters

Porosity: 9.10%
Dry density: 2.36 g/cm^3
Wet density: 2.45 g/cm^3
Grain density: 2.61 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

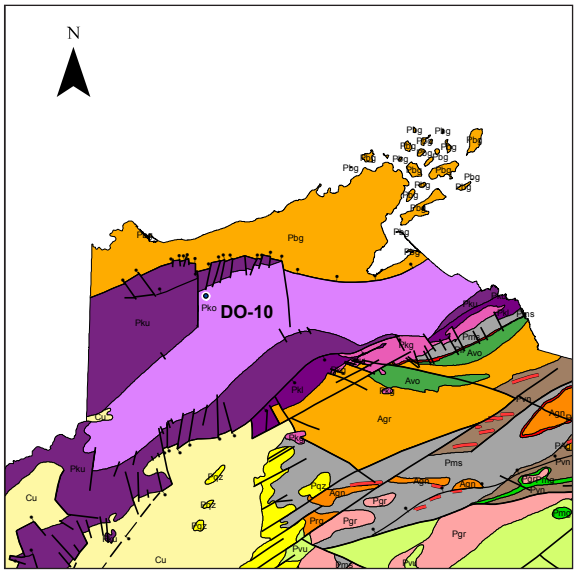


Figure A1.5 Geologic map of northern Wisconsin showing the location of sample DO-10-06.

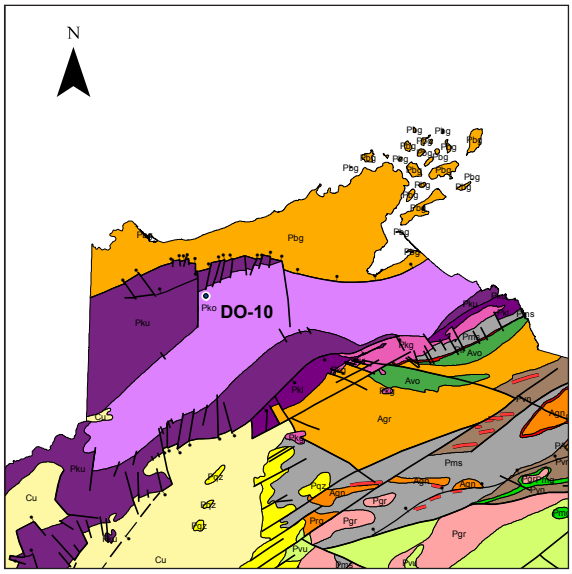
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-07
Depth: 965 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone

Measured parameters

Porosity: 24.50%
Dry density: 1.97 g/cm^3
Wet density: 2.21 g/cm^3
Grain density: 2.61 g/cm^3
Permeability (1 MPa): 81 mD
Permeability (7 MPa): 2.00E-03 mD



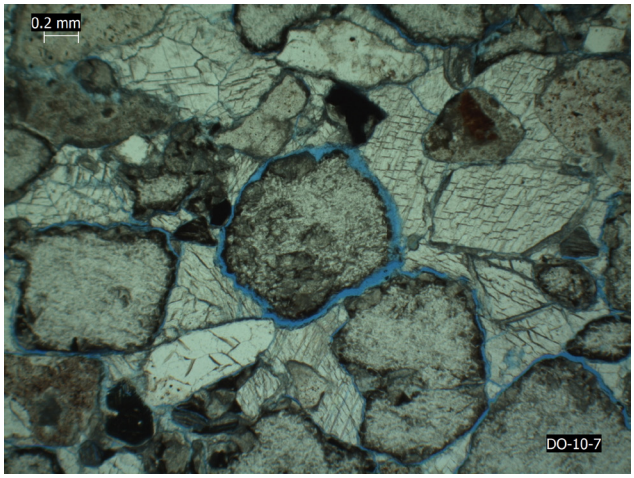


Figure A1.6 Geologic map of northern Wisconsin showing the location of sample DO-10-07 and photograph of core section (and thin section, if applicable), used in analysis. Cores are 1 inch in diameter.

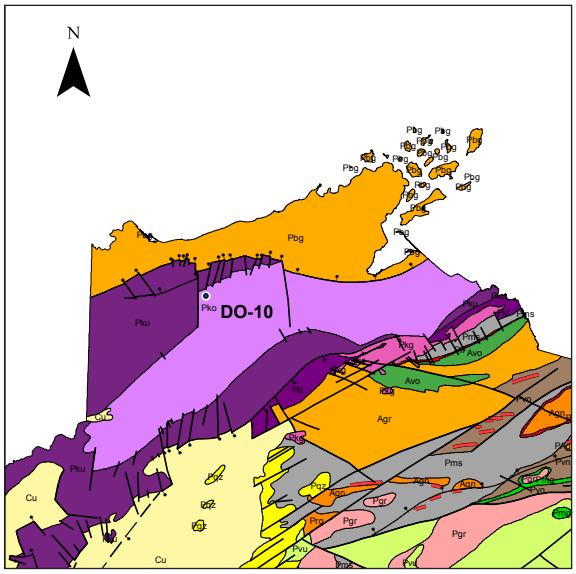
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-08
Depth: 958 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate

Measured parameters

Porosity: 10.50%
Dry density: 2.39 g/cm^3
Wet density: 2.5 g/cm^3
Grain density: 2.67 g/cm^3
Permeability (1 MPa): 0.35 mD
Permeability (15 MPa): NA mD



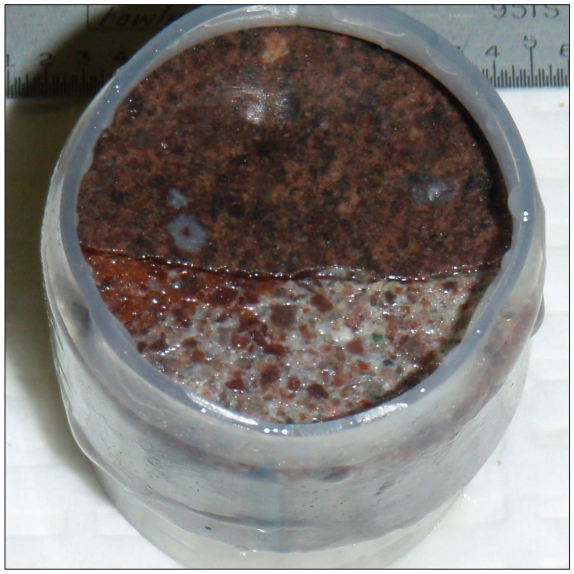


Figure A1.7 Geologic map of northern Wisconsin showing the location of sample DO-10-08 and photograph of core section used in analysis. Cores are 1 inch in diameter.

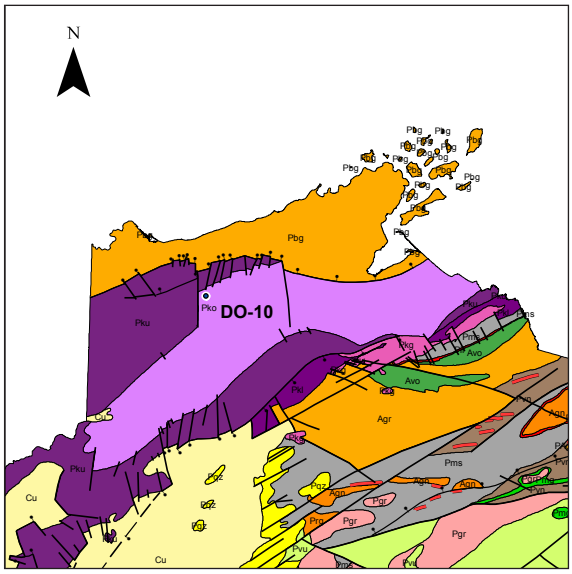
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-09
Depth: 947 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate

Measured parameters

Porosity: 11.30%
Dry density: 2.38 g/cm^3
Wet density: 2.49 g/cm^3
Grain density: 2.66 g/cm^3
Permeability (1 MPa): 3.5 mD
Permeability (15 MPa): 3.60E-03 mD



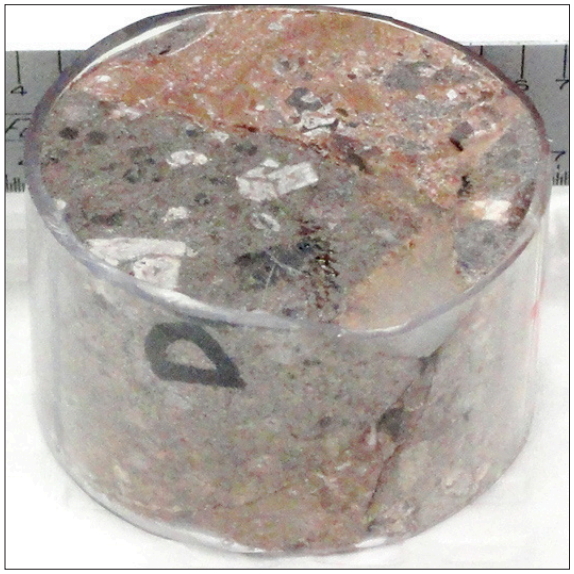


Figure A1.8 Geologic map of northern Wisconsin showing the location of sample DO-10-09 and photograph of core section used in analysis. Cores are 1 inch in diameter.

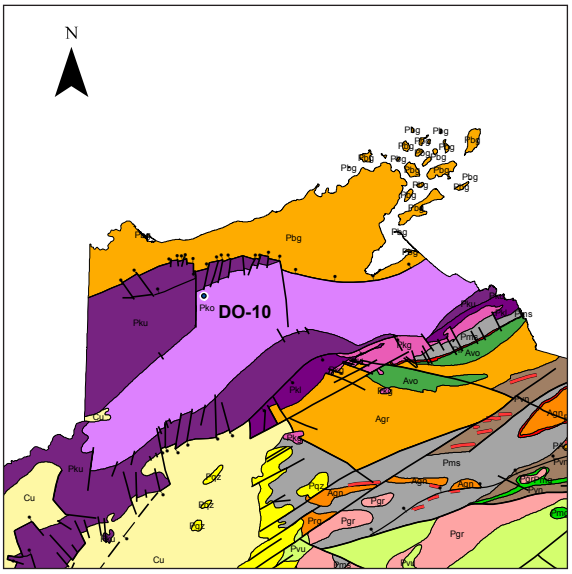
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-10
Depth: 938 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate

Measured parameters

Porosity: 12.30%
Dry density: 2.28 g/cm^3
Wet density: 2.49 g/cm^3
Grain density: 2.61 g/cm^3
Permeability (1 MPa): 0.53 mD
Permeability (15 MPa): NA mD



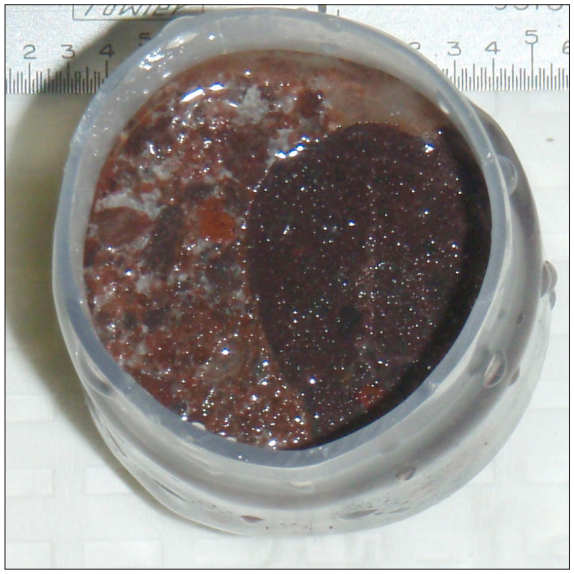


Figure A1.9 Geologic map of northern Wisconsin showing the location of sample DO-10-10 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-11
Depth: 935 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone with pebbles

Measured parameters

Porosity: 27.30%
Dry density: 1.9 g/cm^3
Wet density: 2.18 g/cm^3
Grain density: 2.61 g/cm^3
Permeability (1 MPa): 0.089 mD
Permeability (15 MPa): 3.80E-05 mD

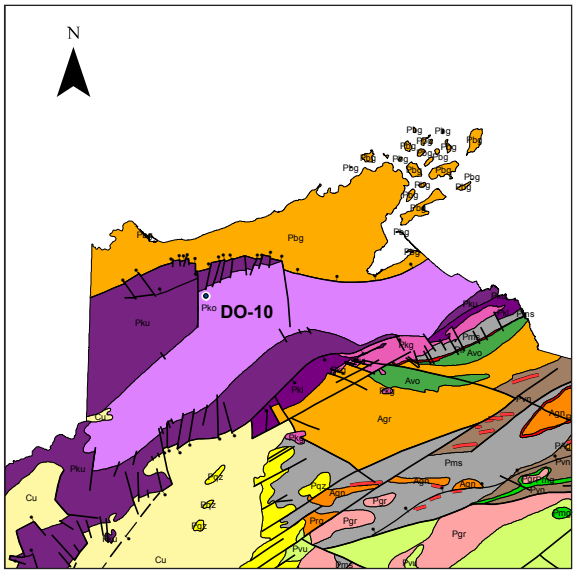


Figure A1.10 Geologic map of northern Wisconsin showing the location of sample DO-10-11 and photograph of core section used in analysis. Cores are 1 inch in diameter.

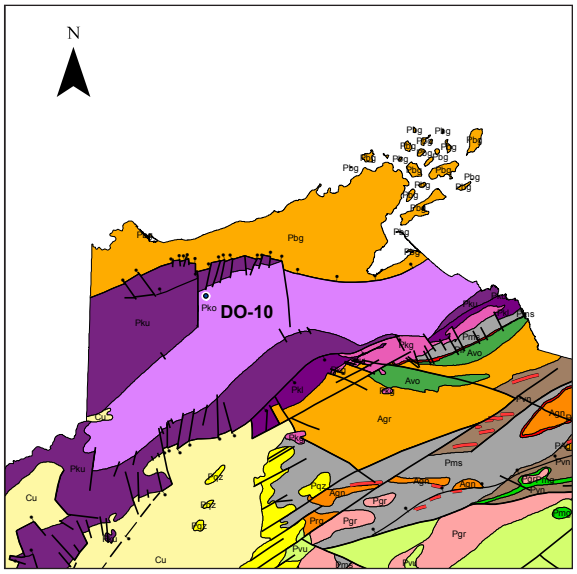
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-12
Depth: 934 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone with pebbles

Measured parameters

Porosity: 27.30%
Dry density: 1.89 g/cm^3
Wet density: 2.16 g/cm^3
Grain density: 2.61 g/cm^3
Permeability (1 MPa): 4.2 mD
Permeability (15 MPa): 1.90E-04 mD



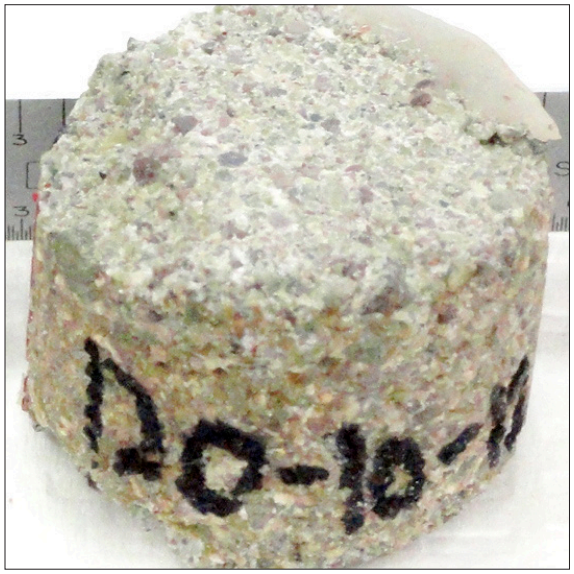


Figure A1.11 Geologic map of northern Wisconsin showing the location of sample DO-10-12 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-13
Depth: 922 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate
Notes: Pebble conglomerate with very coarse cement

Measured parameters

Porosity: 17.20%
Dry density: 2.2 g/cm^3
Wet density: 2.37 g/cm^3
Grain density: 2.65 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

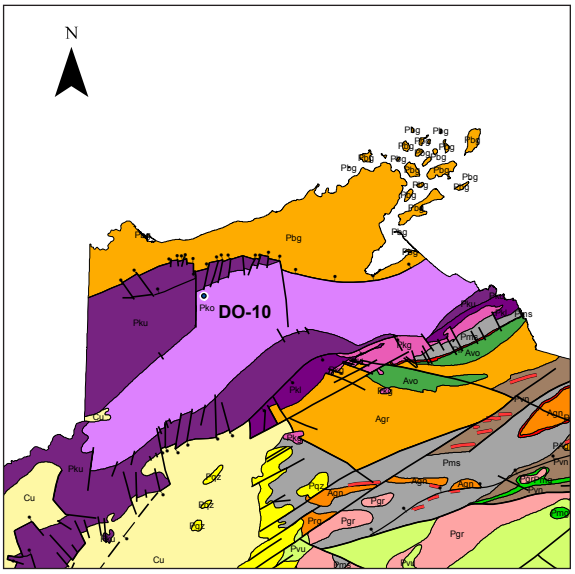


Figure A1.12 Geologic map of northern Wisconsin showing the location of sample DO-10-13.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-14
Depth: 907.5 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate

Measured parameters

Porosity: 18.70%
Dry density: 2.17 g/cm^3
Wet density: 2.35 g/cm^3
Grain density: 2.65 g/cm^3
Permeability (1 MPa): 3.3 mD
Permeability (15 MPa): NA mD

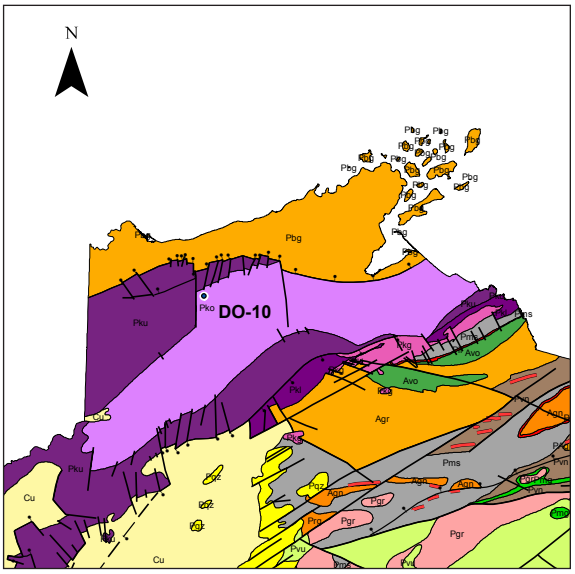
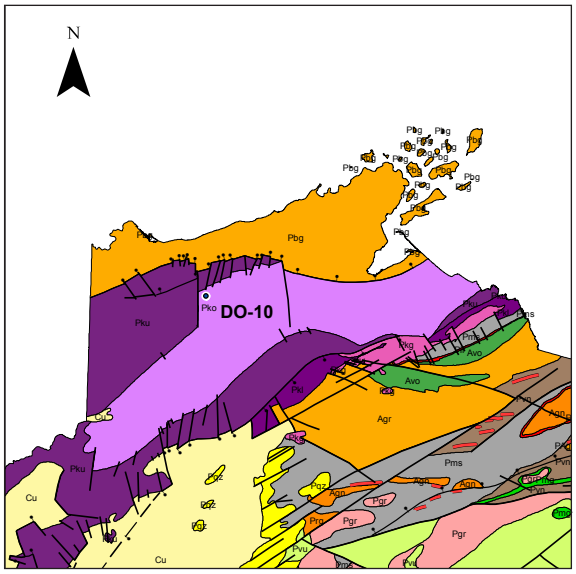


Figure A1.13 Geologic map of northern Wisconsin showing the location of sample DO-10-14 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-15
Depth: 869 ft bgs
Formation: Copper Harbor
Lithology: Volcanic clasts
Notes: Volcanic clasts, basalt or andesite



Measured parameters

Porosity: 2.50%
Dry density: 2.57 g/cm^3
Wet density: 2.59 g/cm^3
Grain density: 2.65 g/cm^3
Permeability (1 MPa): 0.12 mD
Permeability (15 MPa): 3.40E-06 mD

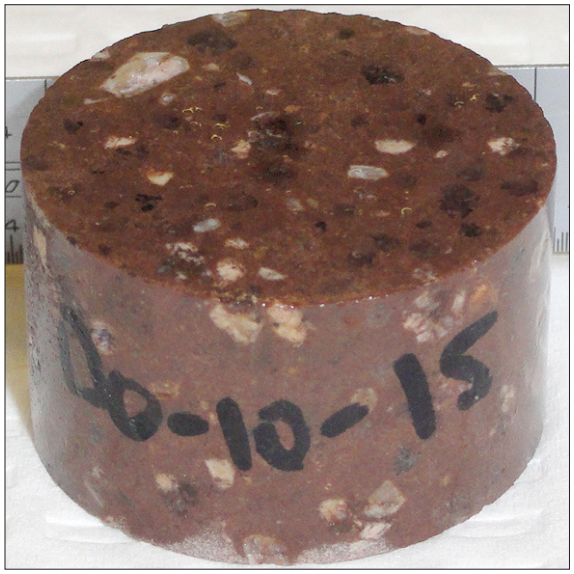
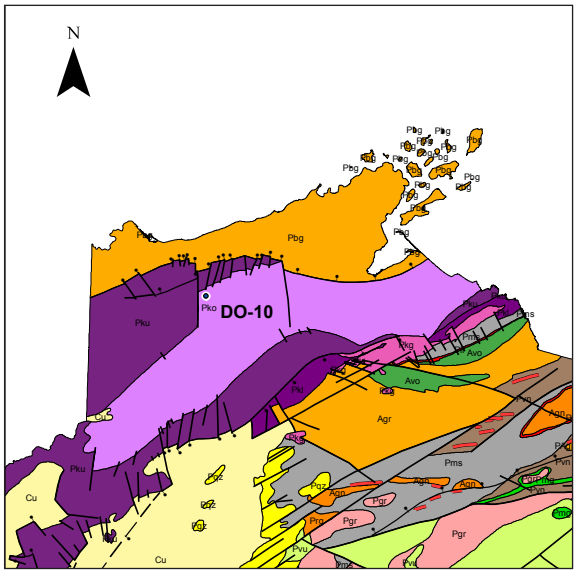


Figure A1.14 Geologic map of northern Wisconsin showing the location of sample DO-10-15 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-16
Depth: 864 ft bgs
Formation: Copper Harbor
Lithology: Pebble conglomerate
Notes: Pebble conglomerate with very coarse cement



Measured parameters

Porosity: 7.20%
Dry density: 2.48 g/cm^3
Wet density: 2.55 g/cm^3
Grain density: 2.65 g/cm^3
Permeability (1 MPa): 0.54 mD
Permeability (15 MPa): 3.10E-02 mD

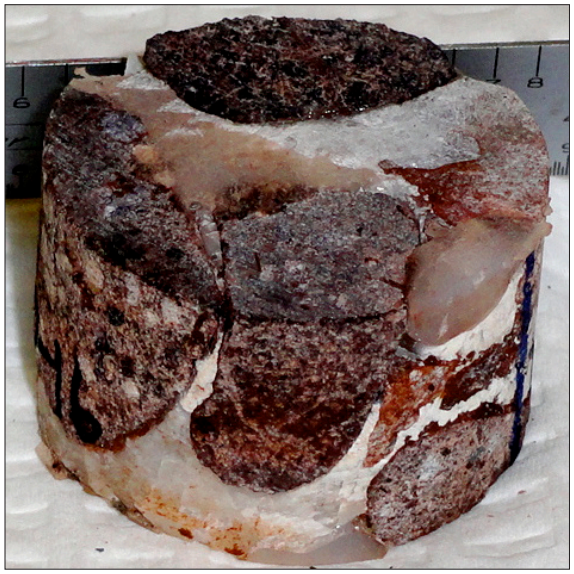
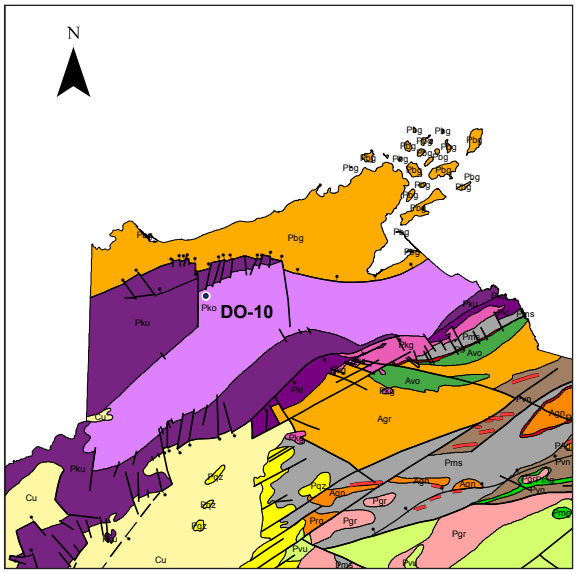


Figure A1.15 Geologic map of northern Wisconsin showing the location of sample DO-10-16 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-17
Depth: 863.75 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone



Measured parameters

Porosity: 18.90%
Dry density: 2.14 g/cm^3
Wet density: 2.33 g/cm^3
Grain density: 2.64 g/cm^3
Permeability (1 MPa): 0.26 mD
Permeability (15 MPa): 5.50E-05 mD

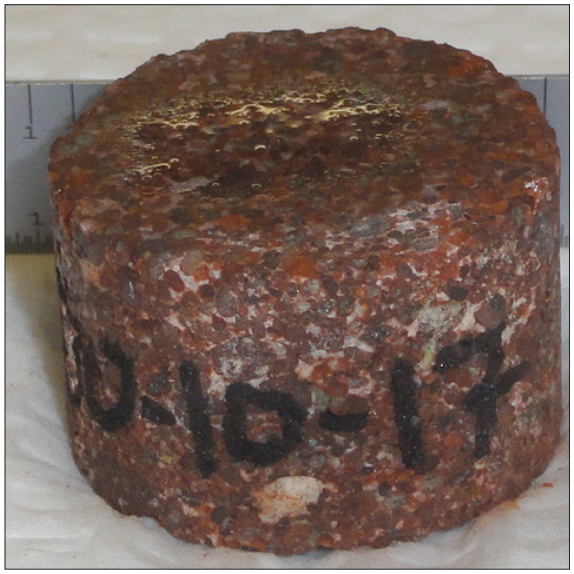
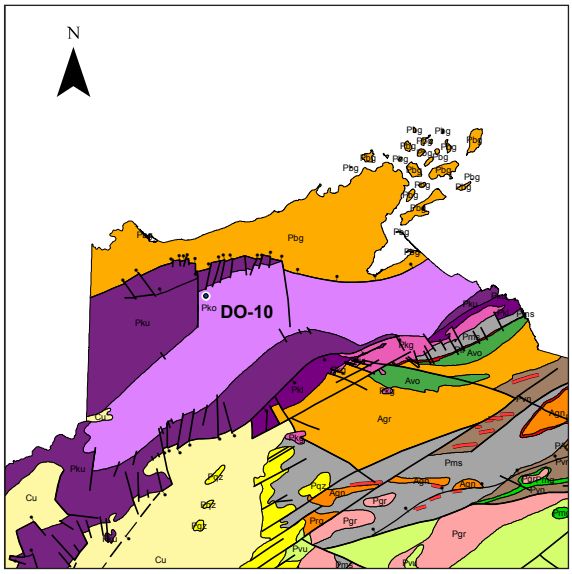


Figure A1.16 Geologic map of northern Wisconsin showing the location of sample DO-10-17 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-18
Depth: 863.5 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone



Measured parameters

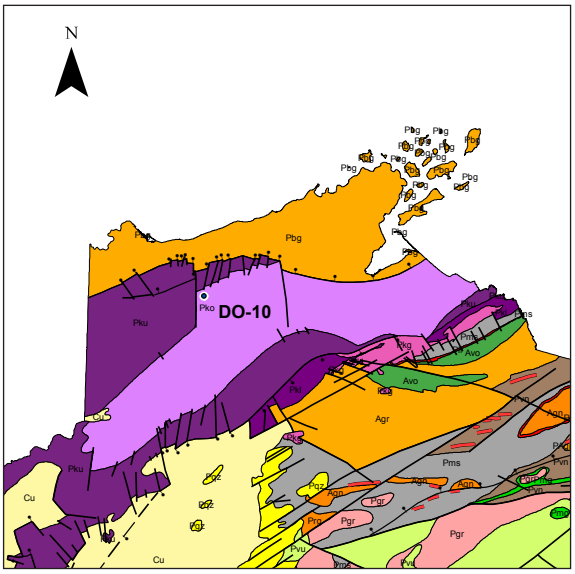
Porosity: 19.70%
Dry density: 2.15 g/cm^3
Wet density: 2.35 g/cm^3
Grain density: 2.69 g/cm^3
Permeability (1 MPa): 0.62 mD
Permeability (15 MPa): 2.80E-03 mD

Figure A1.17 Geologic map of northern Wisconsin showing the location of sample DO-10-18 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-19
Depth: 857 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone



Measured parameters

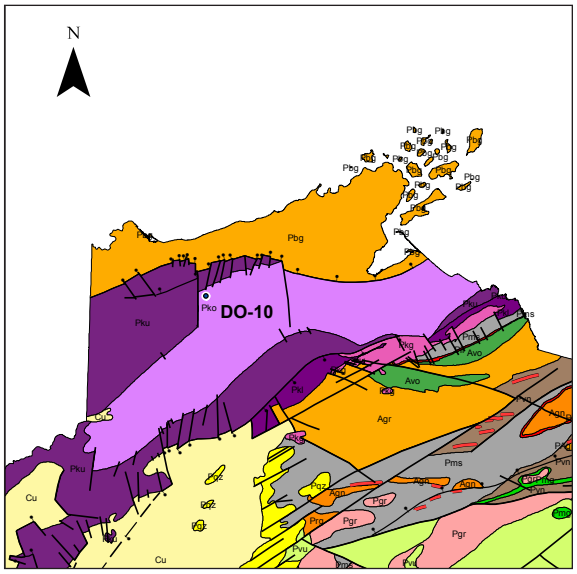
Porosity: 19.30%
Dry density: 2.19 g/cm^3
Wet density: 2.38 g/cm^3
Grain density: 2.71 g/cm^3
Permeability (1 MPa): 0.047 mD
Permeability (15 MPa): 6.00E-04 mD

Figure A1.18 Geologic map of northern Wisconsin showing the location of sample DO-10-19 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000456
Sample ID: DO-10-20
Depth: 856 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone



Measured parameters

Porosity: 18.80%
Dry density: 2.17 g/cm^3
Wet density: 2.36 g/cm^3
Grain density: 2.67 g/cm^3
Permeability (1 MPa): 0.49 mD
Permeability (15 MPa): 2.20E-05 mD

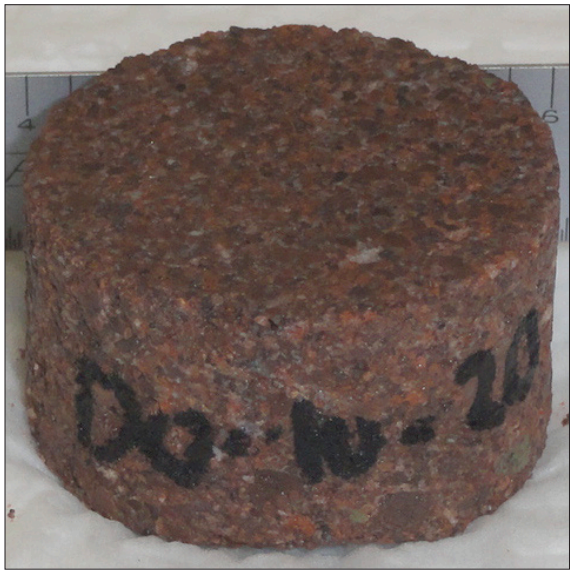


Figure A1.19 Geologic map of northern Wisconsin showing the location of sample DO-10-20 and photograph of core section used in analysis. Cores are 1 inch in diameter.

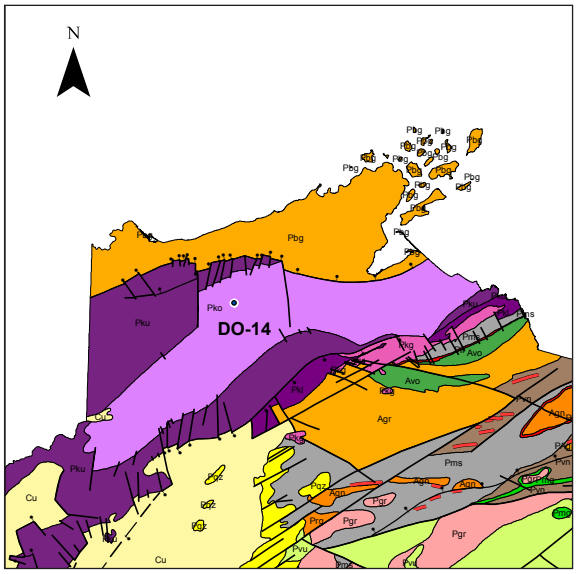
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-01
Depth: 3211 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Medium-grained sandstone

Measured parameters

Porosity: 16.00%
Dry density: 2.29 g/cm^3
Wet density: 2.45 g/cm^3
Grain density: 2.73 g/cm^3
Permeability (1 MPa): 140 mD
Permeability (15 MPa): 1.30E-03 mD



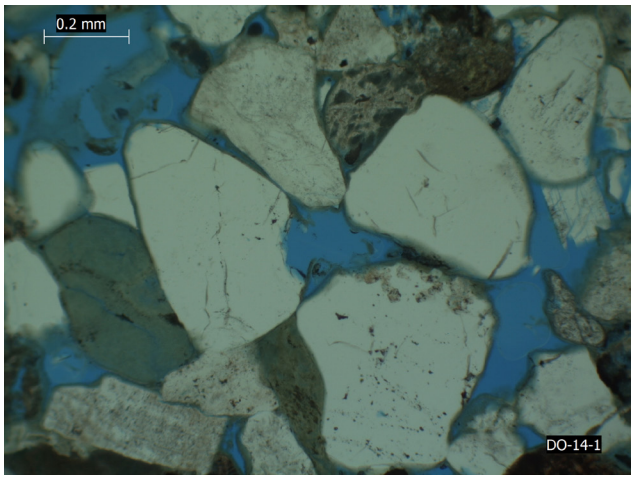


Figure A1.20 Geologic map of northern Wisconsin showing the location of sample DO-14-01 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

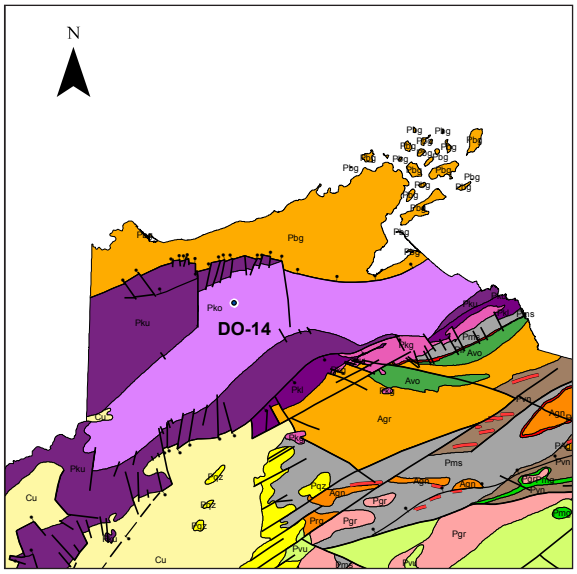
Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-02
Depth: 3207 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Fine-grained sandstone

Measured parameters

Porosity: 2.70%
Dry density: 2.64 g/cm^3
Wet density: 2.66 g/cm^3
Grain density: 2.71 g/cm^3
Permeability (1 MPa): 1.1 mD
Permeability (15 MPa): 3.50E-03 mD



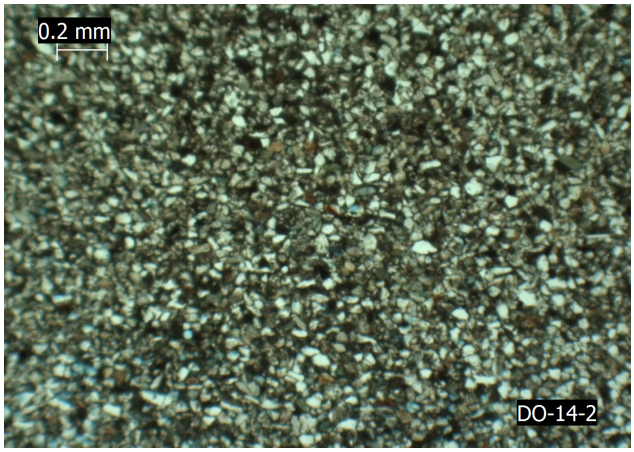
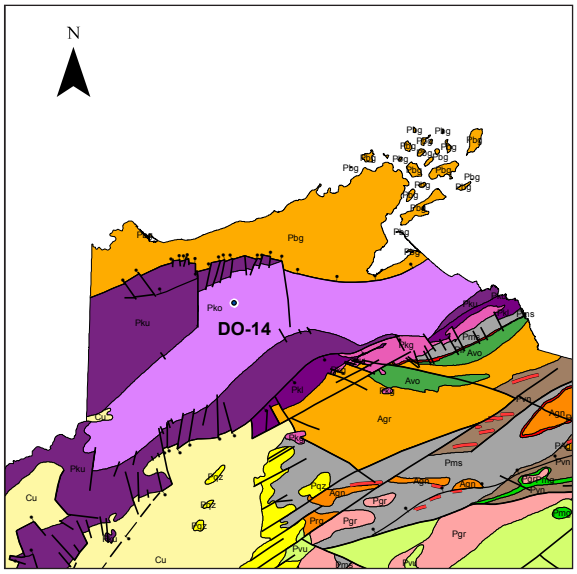


Figure A1.21 Geologic map of northern Wisconsin showing the location of sample DO-14-02 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-04
Depth: 3165 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Fine-grained sandstone



Measured parameters

Porosity: 1.10%
Dry density: 2.68 g/cm^3
Wet density: 2.69 g/cm^3
Grain density: 2.71 g/cm^3
Permeability (1 MPa): 0.32 mD
Permeability (15 MPa): 5.20E-03 mD

Figure A1.22 Geologic map of northern Wisconsin showing the location of sample DO-14-04 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-05
Depth: 3068 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Fine-grained sandstone with fracture

Measured parameters

Porosity: 1.40%
Dry density: 2.61 g/cm^3
Wet density: 2.63 g/cm^3
Grain density: 2.65 g/cm^3
Permeability (1 MPa): 2.6 mD
Permeability (15 MPa): 9.90E-03 mD

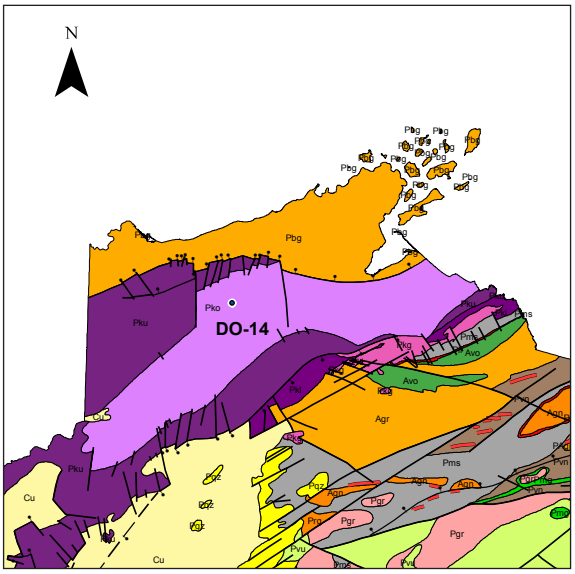


Figure A1.23 Geologic map of northern Wisconsin showing the location of sample DO-14-05 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-06
Depth: 3070 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Very fine laminated sandstone

Measured parameters

Porosity: 2.70%
Dry density: 2.59 g/cm^3
Wet density: 2.62 g/cm^3
Grain density: 2.67 g/cm^3
Permeability (1 MPa): 0.091 mD
Permeability (15 MPa): 3.60E-03 mD

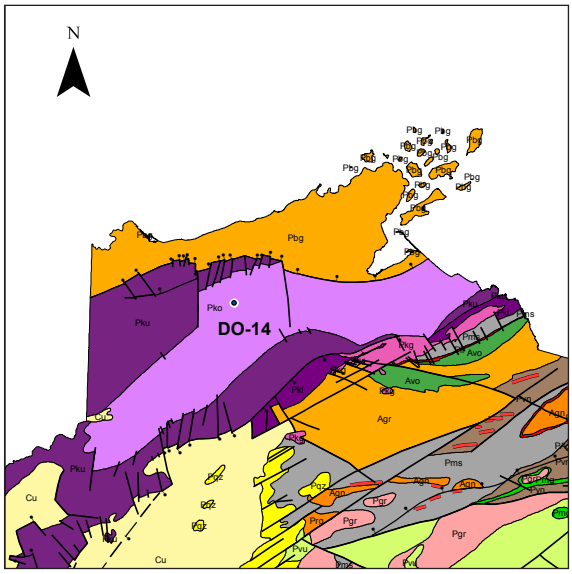
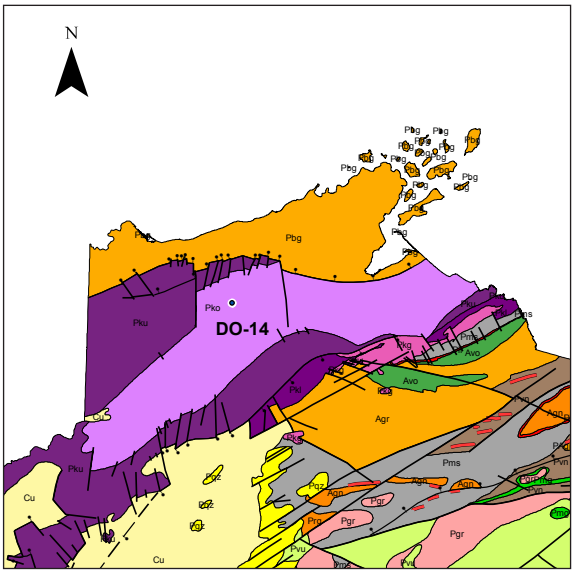


Figure A1.24 Geologic map of northern Wisconsin showing the location of sample DO-14-06 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-07
Depth: 2950 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Fine-grained sandstone



Measured parameters

Porosity: 1.70%
Dry density: 2.66 g/cm^3
Wet density: 2.68 g/cm^3
Grain density: 2.71 g/cm^3
Permeability (1 MPa): 0.049 mD
Permeability (7 MPa): 9.10E-06 mD

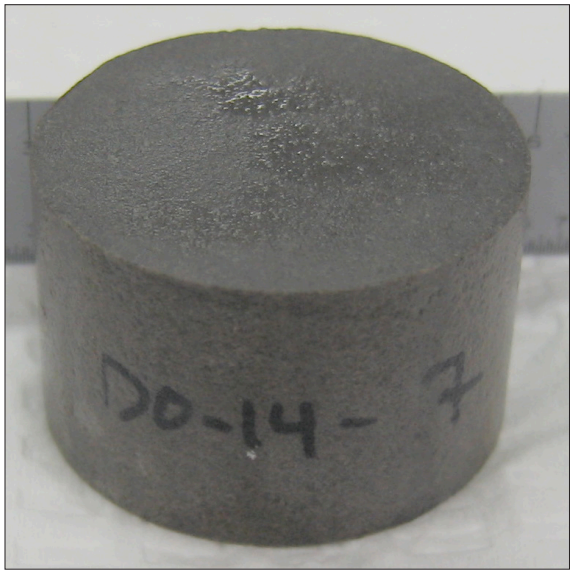


Figure A1.25 Geologic map of northern Wisconsin showing the location of sample DO-14-07 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 16000460
Sample ID: DO-14-08
Depth: 2949 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Very fine laminated sandstone to siltstone

Measured parameters

Porosity: 8.70%
Dry density: 2.51 g/cm^3
Wet density: 2.6 g/cm^3
Grain density: 2.72 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

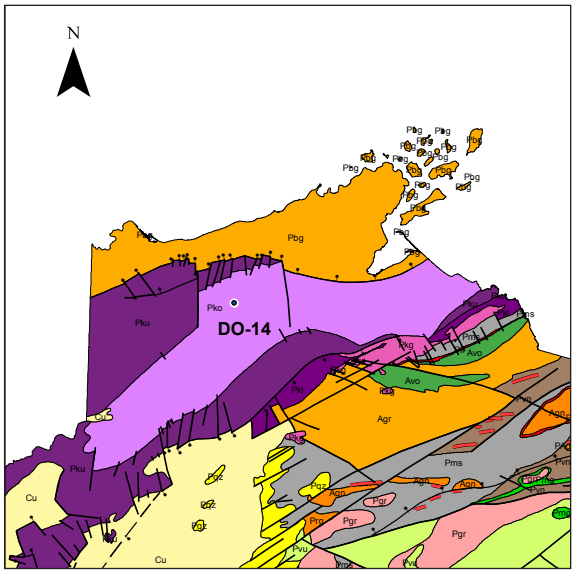
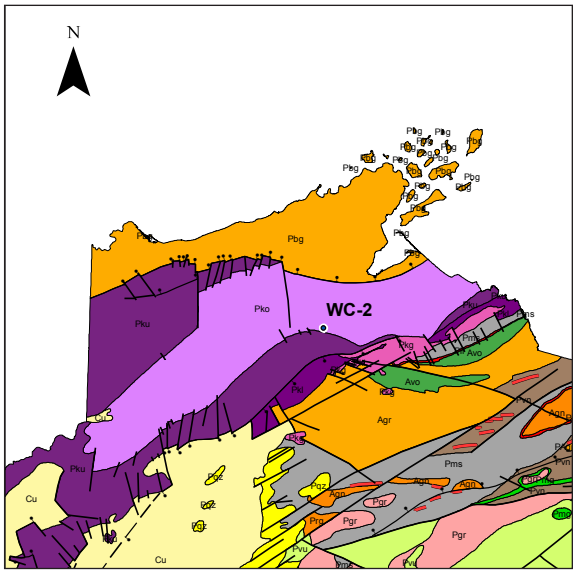


Figure A1.26 Geologic map of northern Wisconsin showing the location of sample DO-14-08.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000210
Sample ID: WC-02-01
Depth: 926 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Very fine laminated sandstone



Measured parameters

Porosity: 3.60%
Dry density: 2.66 g/cm^3
Wet density: 2.7 g/cm^3
Grain density: 2.77 g/cm^3
Permeability (1 MPa): 0.13 mD
Permeability (15 MPa): 2.90E-06 mD

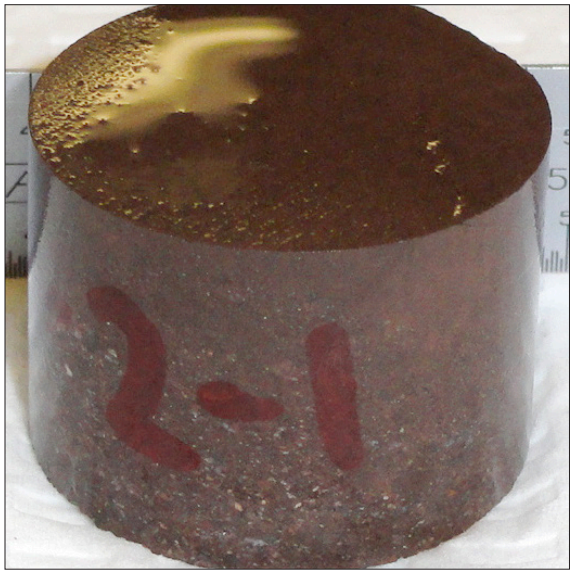


Figure A1.27 Geologic map of northern Wisconsin showing the location of sample WC-02-01 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000210
Sample ID: WC-02-02
Depth: 916 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone

Measured parameters

Porosity: 2.90%
Dry density: 2.68 g/cm^3
Wet density: 2.71 g/cm^3
Grain density: 2.76 g/cm^3
Permeability (1 MPa): 0.18 mD
Permeability (15 MPa): 3.30E-03 mD

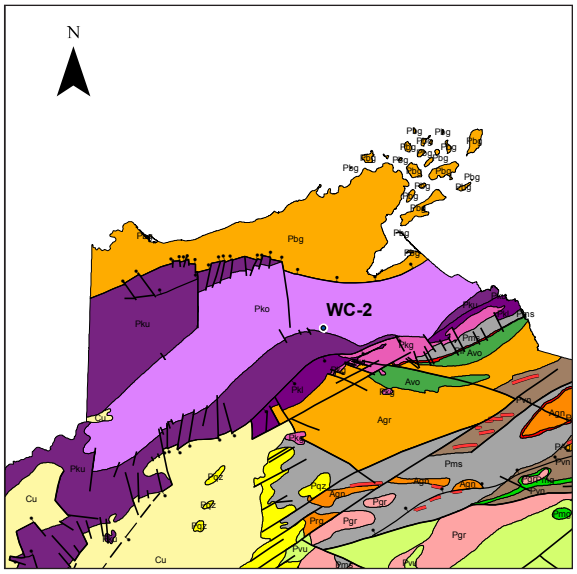
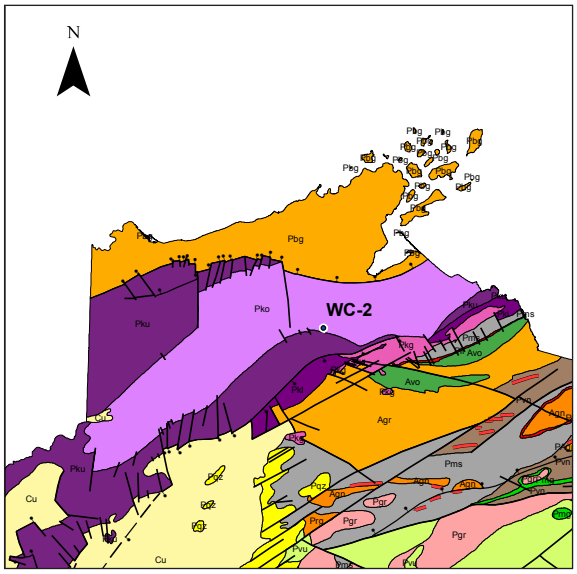


Figure A1.28 Geologic map of northern Wisconsin showing the location of sample WC-02-02 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000210
Sample ID: WC-02-03
Depth: 906 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone with pebbles



Measured parameters

Porosity: 1.80%
Dry density: 2.71 g/cm^3
Wet density: 2.73 g/cm^3
Grain density: 2.76 g/cm^3
Permeability (1 MPa): 0.12 mD
Permeability (15 MPa): 1.40E-03 mD

Figure A1.29 Geologic map of northern Wisconsin showing the location of sample WC-02-03 and photograph of core section used in analysis. Cores are 1 inch in diameter.

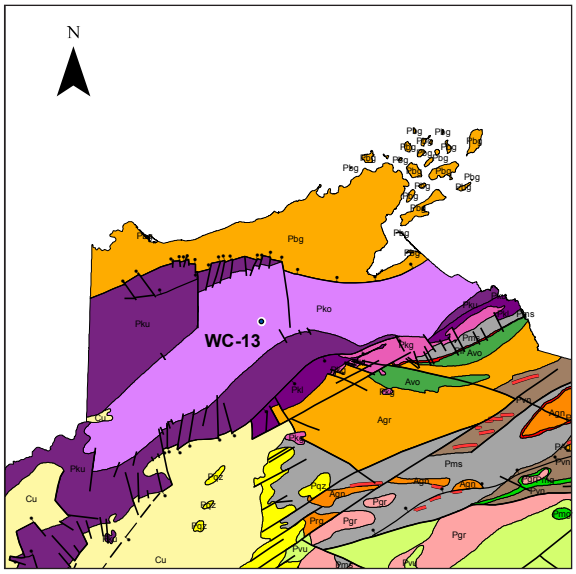
Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-01
Depth: 3297 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone

Measured parameters

Porosity: 5.10%
Dry density: 2.62 g/cm^3
Wet density: 2.68 g/cm^3
Grain density: 2.77 g/cm^3
Permeability (1 MPa): 4.5 mD
Permeability (15 MPa): 3.20E-04 mD



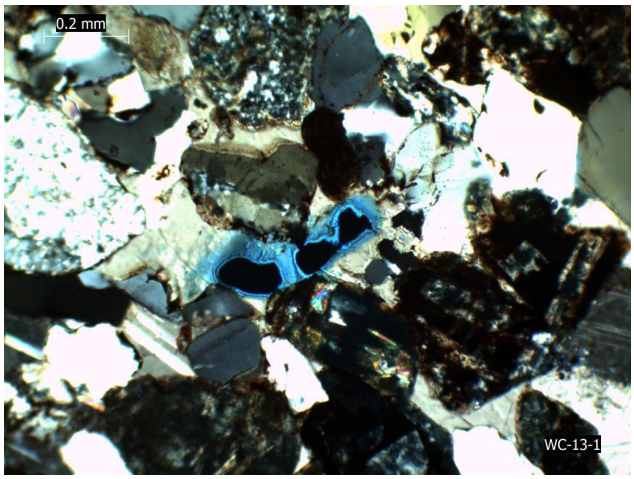
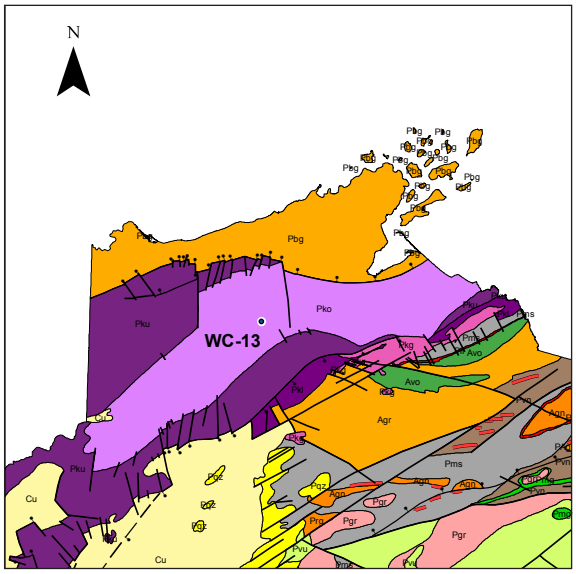


Figure A1.30 Geologic map of northern Wisconsin showing the location of sample WC-13-01 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-02
Depth: 3293 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone



Measured parameters

Porosity: 3.90%
Dry density: 2.69 g/cm^3
Wet density: 2.73 g/cm^3
Grain density: 2.82 g/cm^3
Permeability (1 MPa): 2.6 mD
Permeability (15 MPa): 1.10E-05 mD

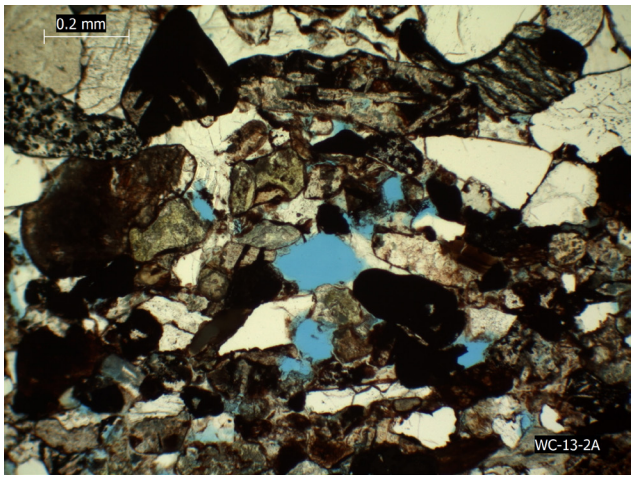


Figure A1.31 Geologic map of northern Wisconsin showing the location of sample WC-13-02 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-03
Depth: 3286.75 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone with pebbles

Measured parameters

Porosity: 4.90%
Dry density: 2.62 g/cm^3
Wet density: 2.67 g/cm^3
Grain density: 2.74 g/cm^3
Permeability (1 MPa): 19 mD
Permeability (15 MPa): 5.30E-05 mD

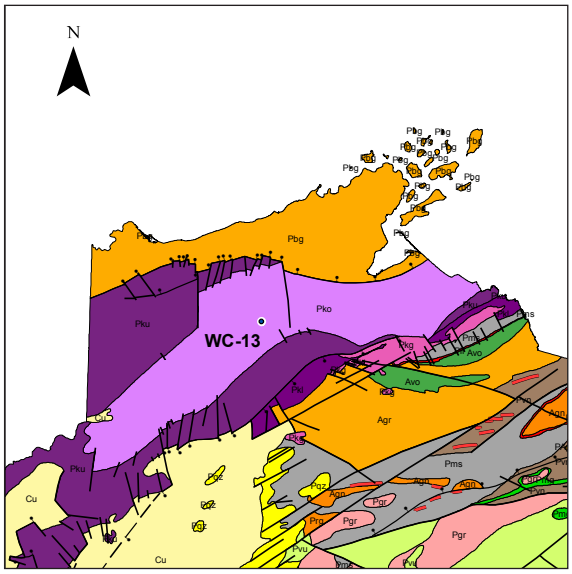


Figure A1.32 Geologic map of northern Wisconsin showing the location of sample WC-13-03 and photograph of core section used in analysis. Cores are 1 inch in diameter.

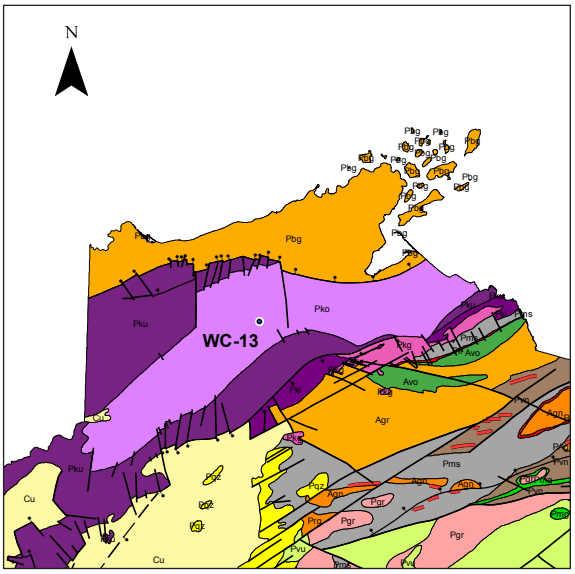
Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-04
Depth: 3286.5 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Fine-grained sandstone

Measured parameters

Porosity: 4.90%
Dry density: 2.72 g/cm^3
Wet density: 2.77 g/cm^3
Grain density: 2.86 g/cm^3
Permeability (1 MPa): 5.2 mD
Permeability (15 MPa): 4.80E-05 mD



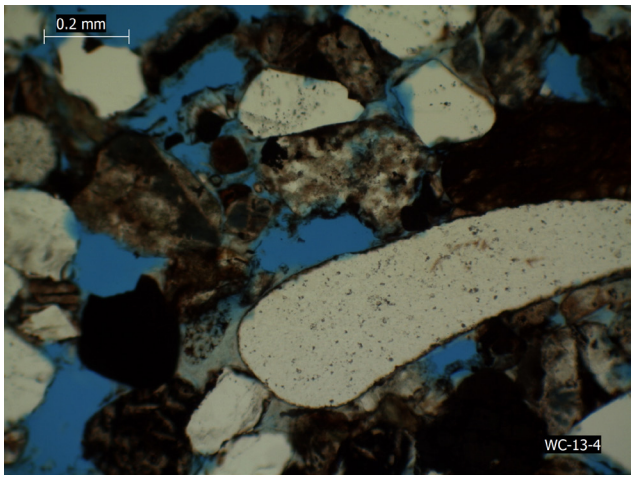
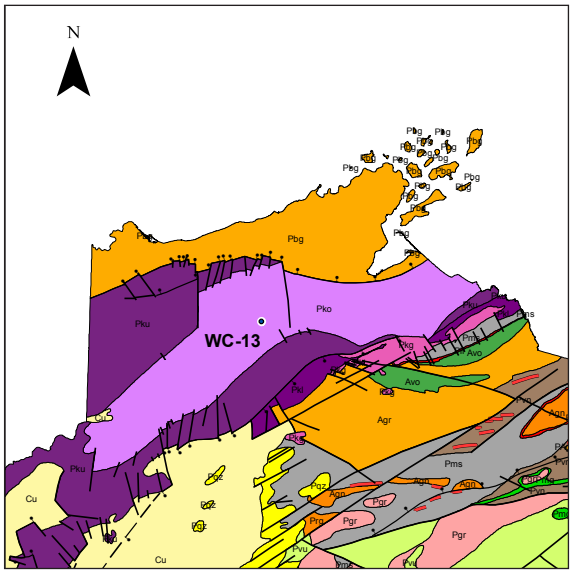


Figure A1.33 Geologic map of northern Wisconsin showing the location of sample WC-13-04 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-05
Depth: 3285 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Medium-grained sandstone



Measured parameters

Porosity: 5.10%
Dry density: 2.62 g/cm^3
Wet density: 2.67 g/cm^3
Grain density: 2.74 g/cm^3
Permeability (1 MPa): 11 mD
Permeability (15 MPa): 2.90E-05 mD

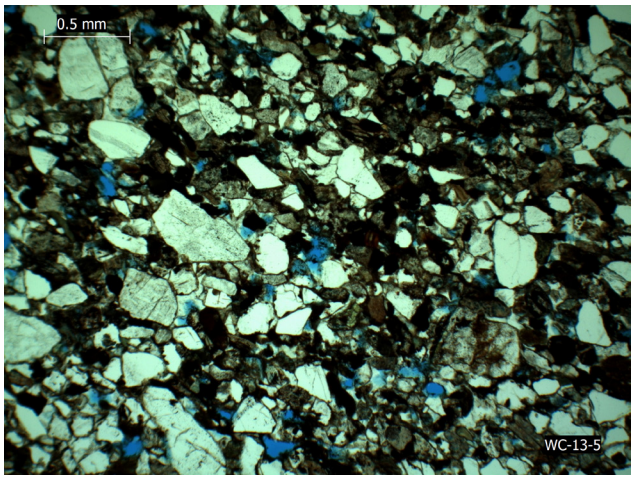
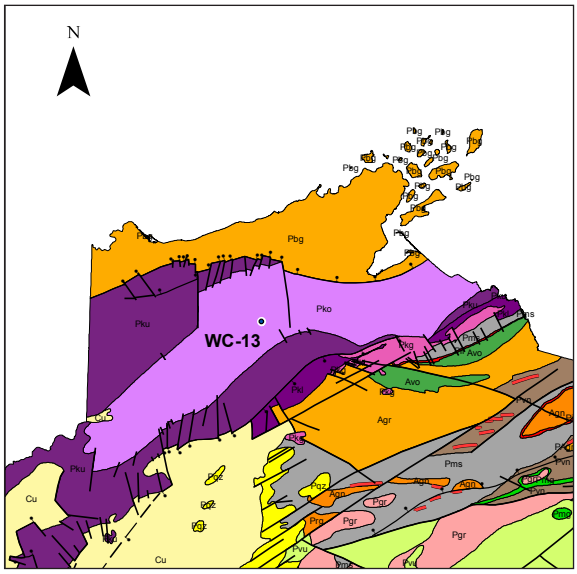


Figure A1.34 Geologic map of northern Wisconsin showing the location of sample WC-13-05 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-06
Depth: 3284 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Medium-grained sandstone



Measured parameters

Porosity: 9.20%
Dry density: 2.83 g/cm^3
Wet density: 2.92 g/cm^3
Grain density: 3.11 g/cm^3
Permeability (1 MPa): 59 mD
Permeability (15 MPa): 5.20E-04 mD

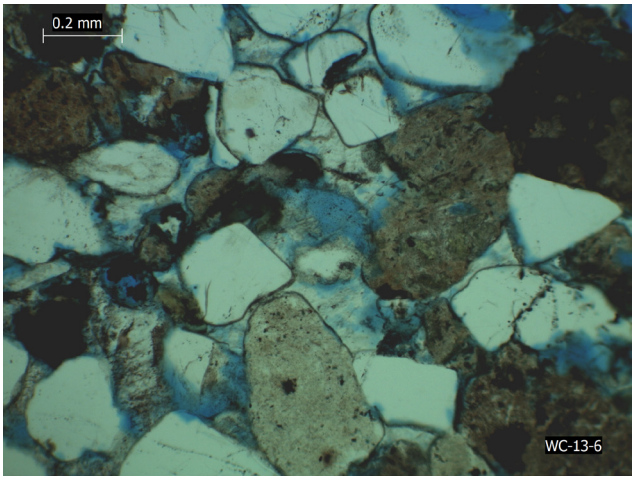


Figure A1.35 Geologic map of northern Wisconsin showing the location of sample WC-13-06 and photograph of core section and thin section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-07
Depth: 3277 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Medium-grained sandstone

Measured parameters

Porosity: 8.80%
Dry density: 2.46 g/cm^3
Wet density: 2.55 g/cm^3
Grain density: 2.71 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

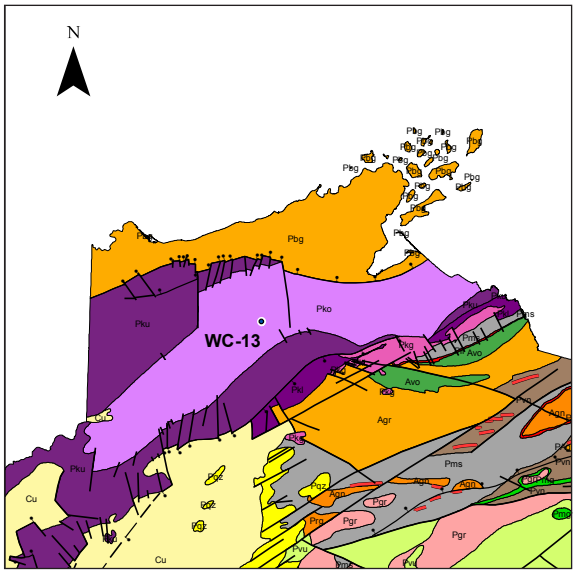


Figure A1.36 Geologic map of northern Wisconsin showing the location of sample WC-13-07.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-09
Depth: 3271 ft bgs
Formation: Copper Harbor
Lithology: Sandstone
Notes: Coarse sandstone

Measured parameters

Porosity: 12.00%
Dry density: 2.5 g/cm^3
Wet density: 2.62 g/cm^3
Grain density: 2.78 g/cm^3
Permeability (1 MPa): NA
Permeability (15 MPa): NA

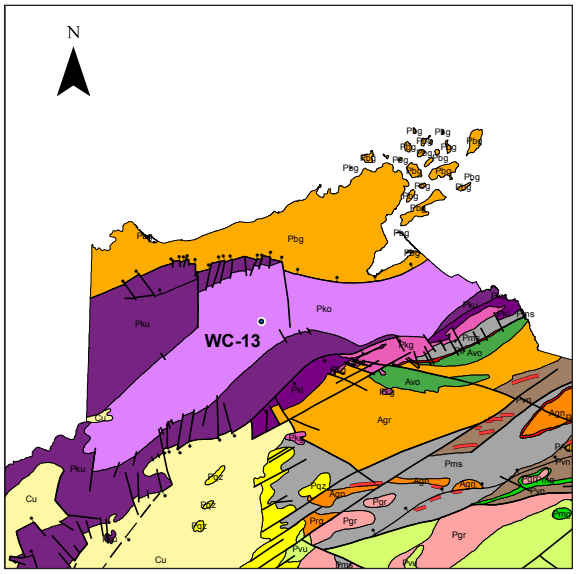
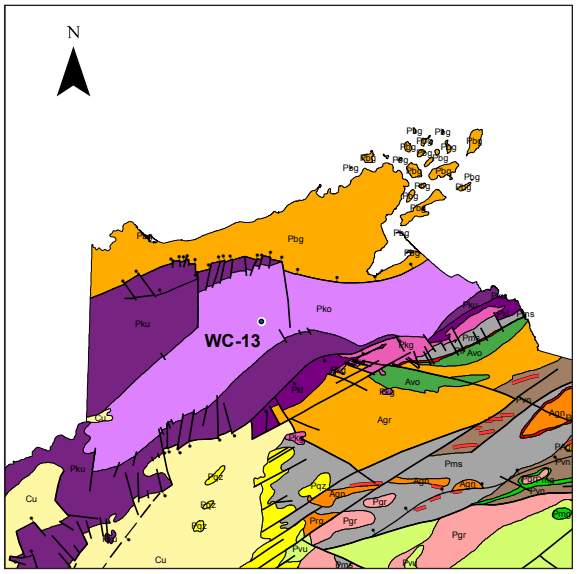


Figure A1.37 Geologic map of northern Wisconsin showing the location of sample WC-13-09.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000221
Sample ID: WC-13-10
Depth: 3252 ft bgs
Formation: Nonesuch
Lithology: Sandstone
Notes: Fine-grained sandstone



Measured parameters

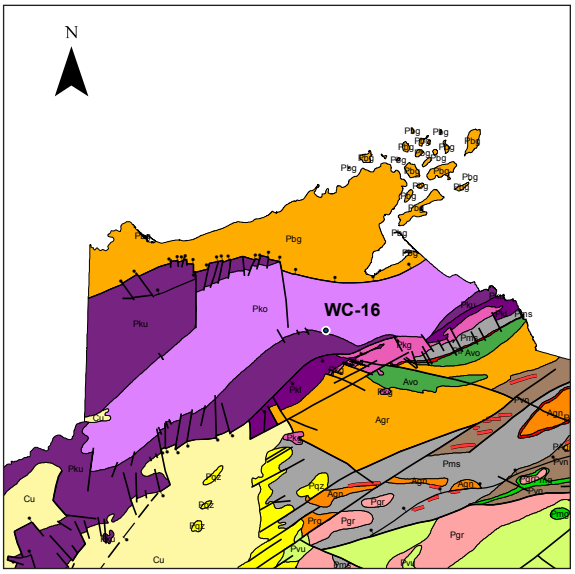
Porosity: 2.10%
Dry density: 2.68 g/cm^3
Wet density: 2.71 g/cm^3
Grain density: 2.73 g/cm^3
Permeability (1 MPa): 0.009 mD
Permeability (15 MPa): 5.20E-06 mD

Figure A1.38 Geologic map of northern Wisconsin showing the location of sample WC-13-10 and photograph of core section used in analysis. Cores are 1 inch in diameter.

Porosity/Permeability Sample Details

General core data

WGNHS ID: 4000224
Sample ID: WC-16-01
Depth: 1564 ft bgs
Formation: Copper Harbor
Lithology: Pebble breccia
Notes: Pebble breccia with very coarse cement



Measured parameters

Porosity: 7.40%
Dry density: 2.58 g/cm^3
Wet density: 2.65 g/cm^3
Grain density: 2.78 g/cm^3
Permeability (1 MPa): 51 mD
Permeability (15 MPa): 2.60E-01 mD

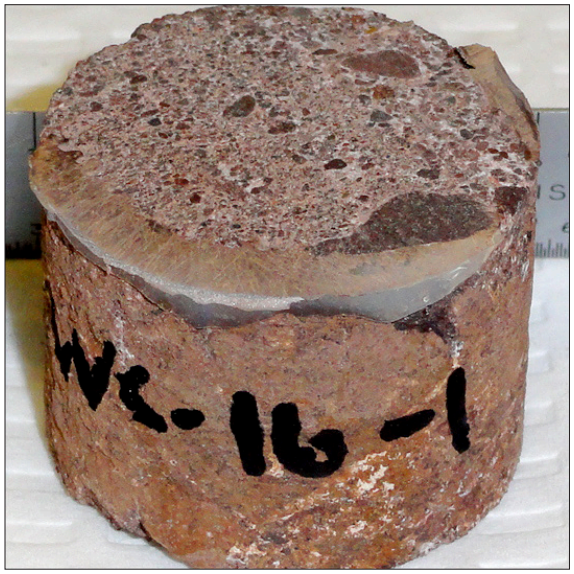


Figure A1.39 Geologic map of northern Wisconsin showing the location of sample WC-16-01 and photograph of core section used in analysis. Cores are 1 inch in diameter.