Depth Relationships in Porosity and Permeability in the Mount Simon Sandstone (Basal Sand) of the Midwest Region: Applications for Carbon Sequestration

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Abstract

Porosity and permeability values collected from core analyses in the Upper Cambrian Mount Simon sandstone indicate a predictable relationship with depth owing to diagenetic changes in the pore structure. This predictive relationship is useful for evaluating the geological carbon sequestration capacity in the Midwestern region. Porosity logs from wells in the study area provide additional sources of petrophysical data. The regional trend of decreasing porosity with depth is described by the equation: $\phi_{Core}(d) = 16.36 * e^{-0.00012*d}$ (r^2=0.41), where ϕ equals porosity and d is depth in feet. The correlation between burial depth and porosity can help predict the petrophysical character of the Mount Simon sandstone in more deeply buried and largely undrilled portions of the basin. Understanding the relationship among porosity, permeability, and depth also provides information for use in numerical models that simulate supercritical carbon dioxide flow within the Mount Simon sandstone. The decrease of porosity and permeability with depth generally holds true on a basinwide scale. However, localized stratigraphic and spatial variations in sedimentary facies also affect reservoir quality. In some areas, we observed a reversal in the porosity/depth relationship. Careful documentation of the mineralogical and sedimentological characteristics of the reservoir are critical to the successful prediction of the petrophysical attributes of deep saline aquifer systems and how they perform at a given locality.

Previous Studies

Studies on the relationship of porosity and burial suggest that porosity generally decreases with depth. Most of the porosity observed in the Mount Simon sandstone in the Illinois Basin is secondary, formed by post depositional processes such as dissolution of authigenic cements, grains, and fractures (Hoholick et al., 1984). These data indicate that the decline in porosity with depth is best described by the exponential equation: $\phi(d) = 31.08 * e^{-0.00026*d}$ (figure 1a). Extrapolation of these results suggests that at depths greater than 7,000 ft, porosity decreases exponentially to values below 5%. Similarly, core analyses from 828 samples taken in the Illinois Basin (J. R. Bowersox, personal comm.) suggest that porosity decreases exponentially to values as low as 5% at approximately 6,500 ft (figure 1b).

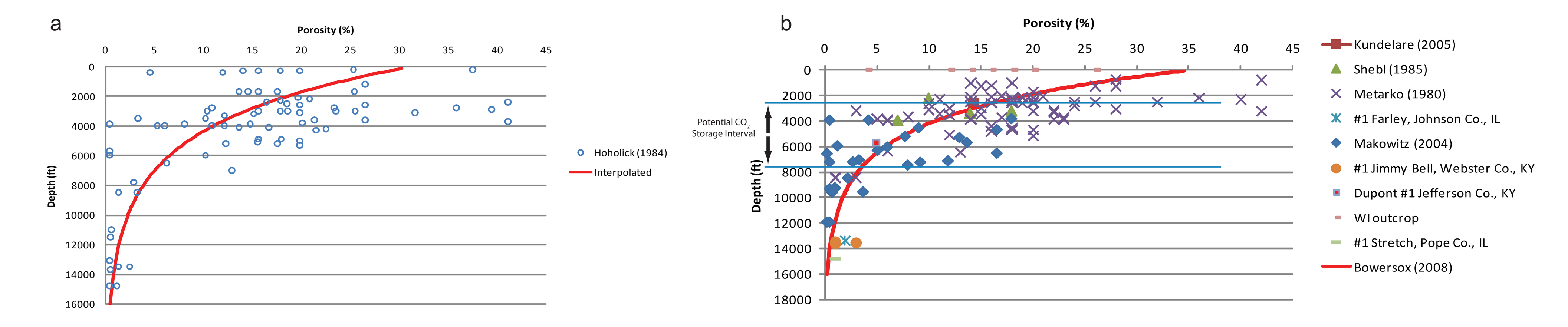


Figure 1a: Porosity-depth relationships from 89 samples of Mount Simon sandstone (Hoholick et al., 1984); and 1b: porosity-depth relationships from 828 samples of Mount Simon sandstone in the Illinois Basin (modified from Bowersox, personal comm.). Data from Kundelare (2005) were averaged due to the large number of data points (690).

The main factors that control the effective sequestration of carbon dioxide in deep saline aquifers are: depth interval, thickness of the reservoir, and effective porosity distribution. We compiled and processed regional information from the Mount Simon sandstone that included subsurface reservoir data, and digital log curves in order to quantify the effective volumetric pore space. This analysis is a critical step in determining the potential of the Mount Simon sandstone for CO_2 sequestration. The term "Mount Simon sandstone" is used in this study to denote the "basal sand" as mapped by the Midwest Regional Carbon Sequestration Partnership (MRCSP) (Wickstrom et al. 2005).

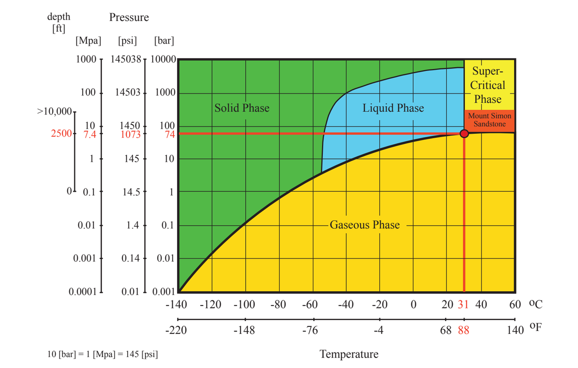


Figure 2: Phase diagram of CO_2 indicating pressure and temperature conditions at which CO_2 behaves as a supercritical fluid. The red rectangle indicates the P-T conditions of the Mount Simon reservoir throughout the study area.

Minimum Depth

In order to ensure that the CO_2 injected into deep saline aquifers is in the supercritical phase (and hence avoiding the gaseous phase), the pressure and temperature in the reservoir should be at least 7.4 MPa and 31ºC (above the critical point of CO_2). At surface conditions (25ºC and 0.1 MPa), CO_2 behaves as a gas (ρ=1.8 kg/m³). A phase diagram of CO_2 is suited to visualize the pressure and temperature conditions at which CO_2 is behaving as a supercritical phase (figure 2).If we assume a geothermal and pressure gradients of 30ºC/km and 10.5 MPa/km (0.43 psi/ft), respectively, CO_2 can be stored as a supercritical fluid at minimum depths of 800 m (~2,500 ft). This minimum threshold value corresponds to a minimum density of CO_2 of 260 kg/m³, allowing for greater quantities of CO_2 to be stored in deeper aquifers. The top of the Mount Simon sandstone occurs at depths greater than 2,500 ft throughout the region (figure 3), corresponding to supercritical P, T conditions for CO_2.

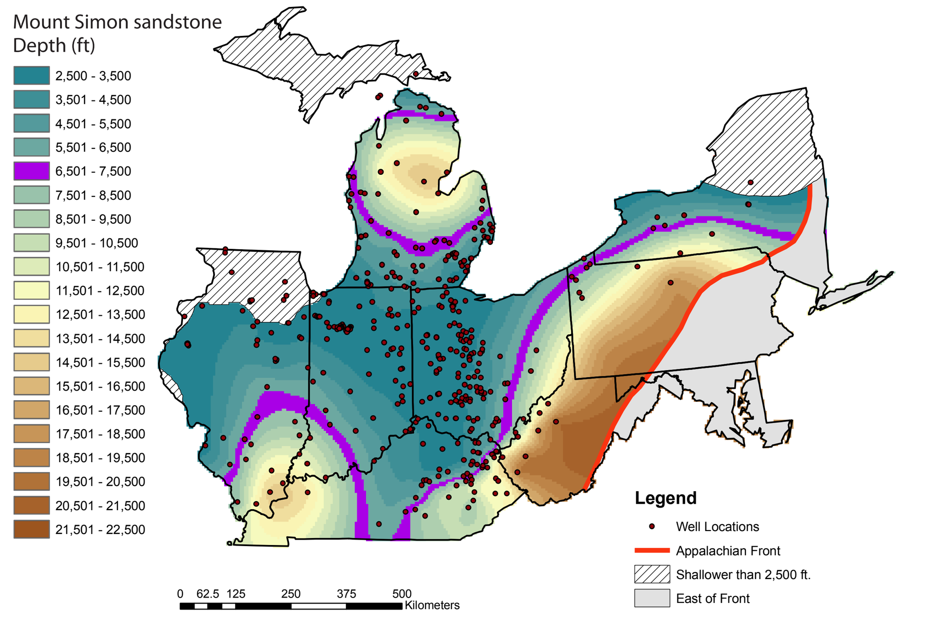


Figure 3: Raster interpolation of data from 400 wells for the top of the Mount Simon sandstone in the study area (MRCSP Region).

Thickness and Net Porosity Feet Distribution

Thickness and porosity control the total pore volume available for the disposal of CO_2 into the Mount Simon sandstone (figure 4). A suitable parameter to determine pore volume is porosity feet, which consists of the measured porosity (from calibrated geophysical logs, figure 5) multiplied by the vertical extent measured in each well (figure 7). Geophysical logs that were analyzed include gamma ray, neutron, sonic, and density logs (figure 6). We calculated net porosity feet in each well with the formula:

$$\emptyset_{feet}(net) = \begin{cases} \sum_i \emptyset_i * h_i, & GR < 75, \emptyset_i > 7\% \\ 0, & GR \geq 75\ (API\ Counts) \end{cases}$$

Where h_i is the vertical interval over which the net porosity feet is measured. In order to limit the analysis to sand, a maximum gamma ray value of 75 API units was chosen as a cutoff for estimation purposes.

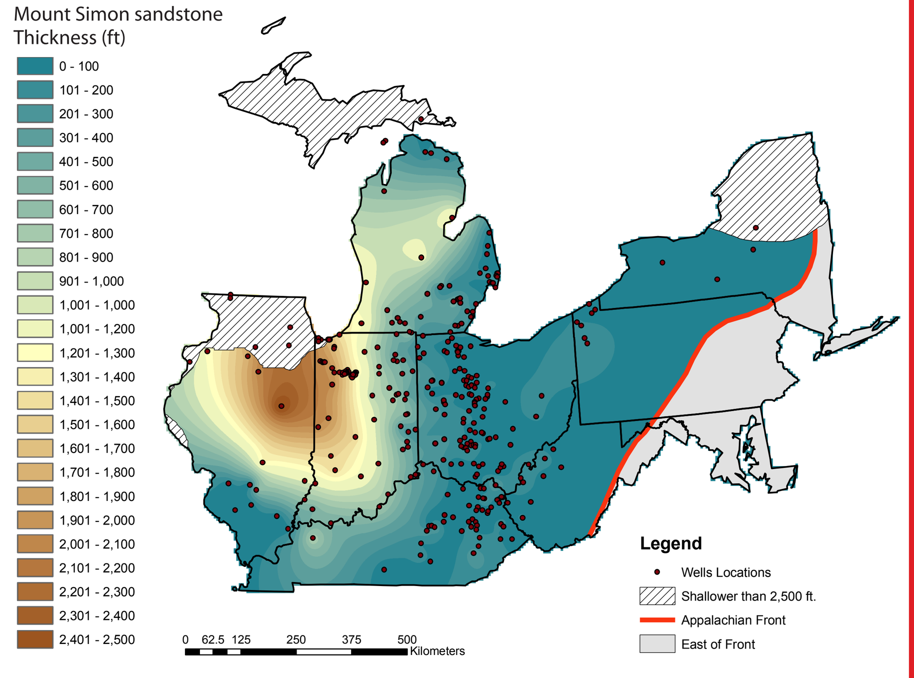


Figure 4: Thickness distribution of the Mount Simon sandstone (382 wells).

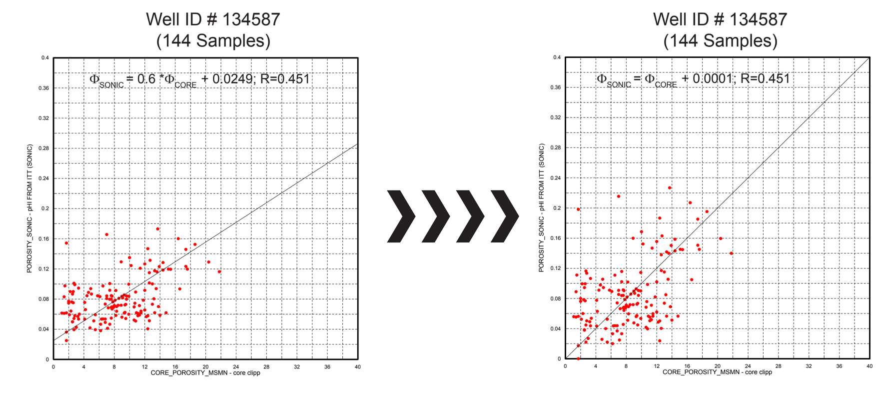


Figure 5: Geophysical Log Calibration Using Core Data: An example.

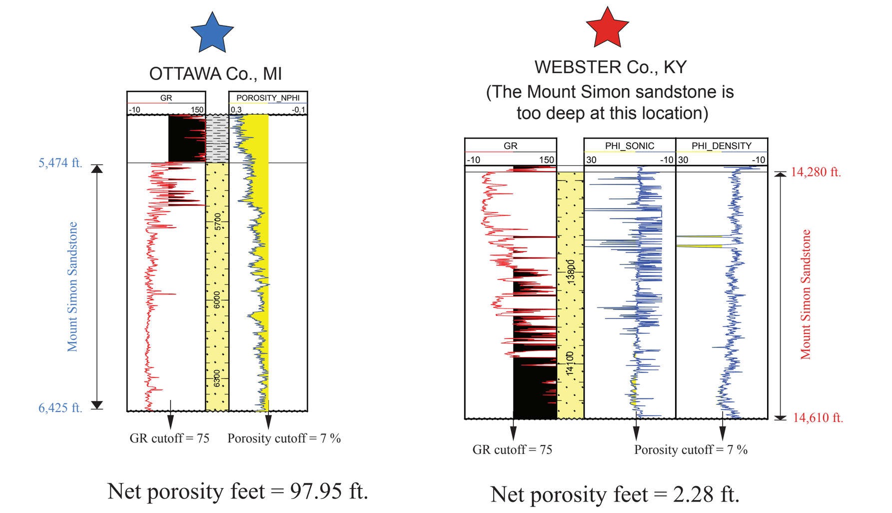


Figure 6: Porosity relationships with depth in two Mount Simon sandstone wells.

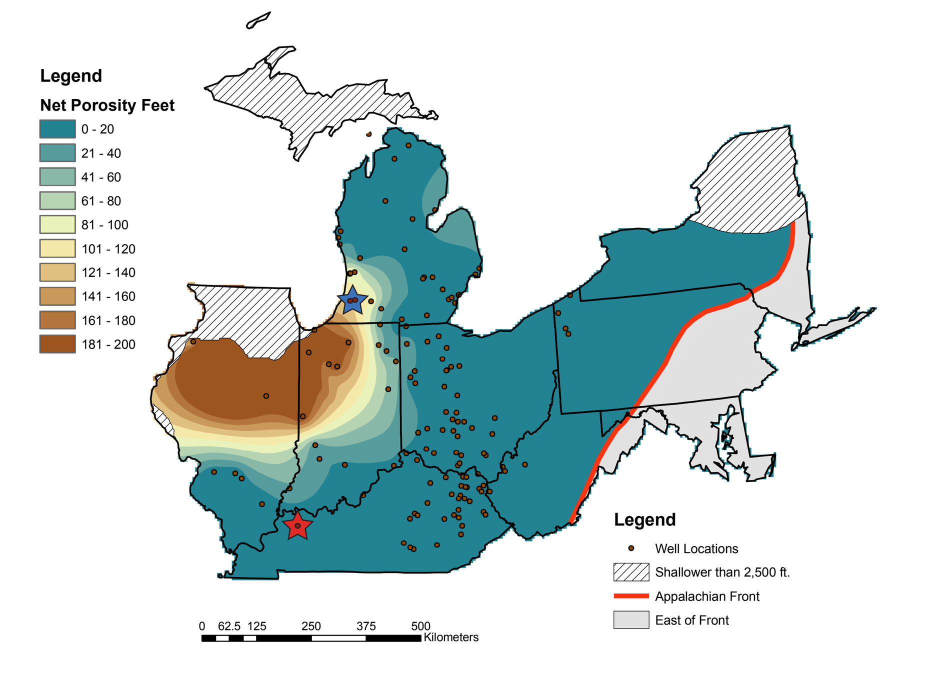
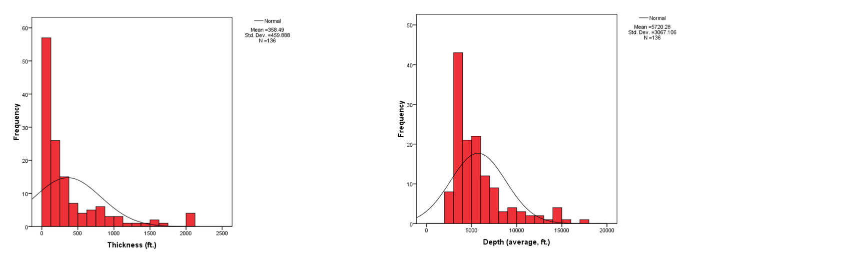
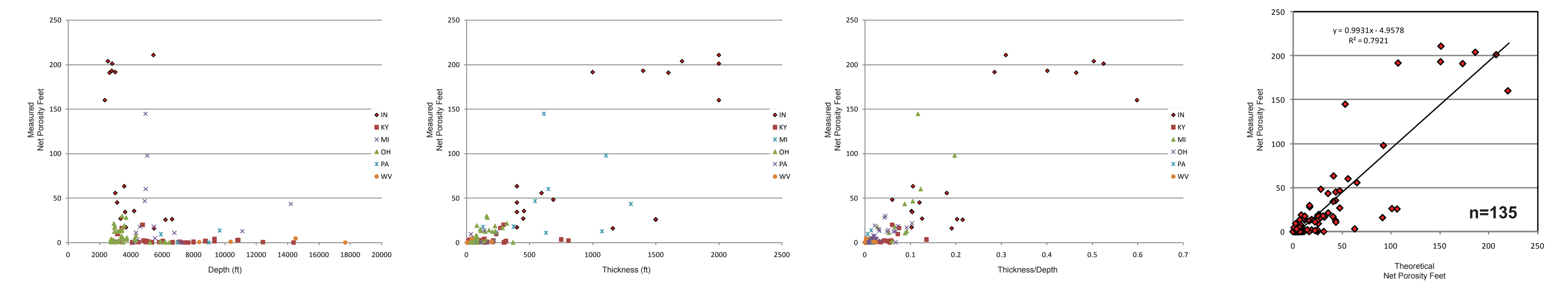


Figure 7: Distribution of porosity feet in the study area.



Theoretical vs. Calculated Net Porosity Feet

$$Net\ Porosity\ Feet = \sum_i \emptyset(z) * dz = \int_{z_{top}}^{z_{bottom}} \emptyset(z)\partial z = \int_{z_{top}}^{z_{bottom}} 0.1636 * e^{-0.00012*z}\partial z = -1363.33 * (e^{-0.00012*z_{bottom}} - e^{-0.00012*z_{top}})$$



Porosity-Depth Relationships

Available core data and geophysical logs from the MRCSP region indicate a wide range of porosity values in the depth range 2,000-16,000 ft (figure 8). This trend is consistent with those observed by Hoholick et al. (1984) and Bowersox (2008, personal comm.) (figure 9).

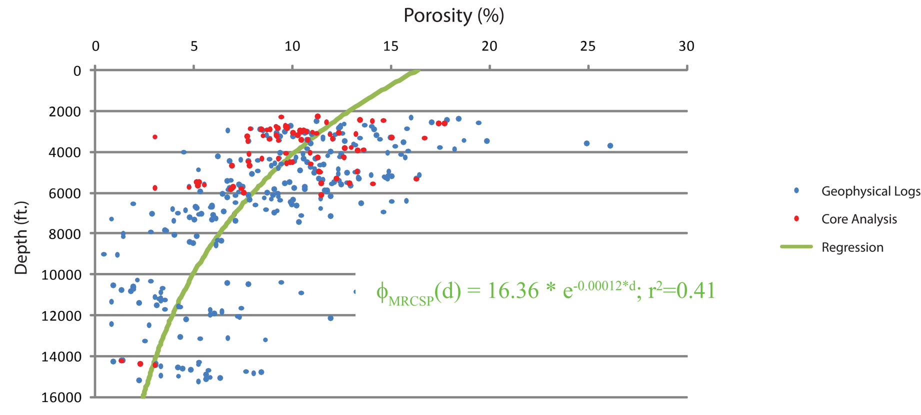
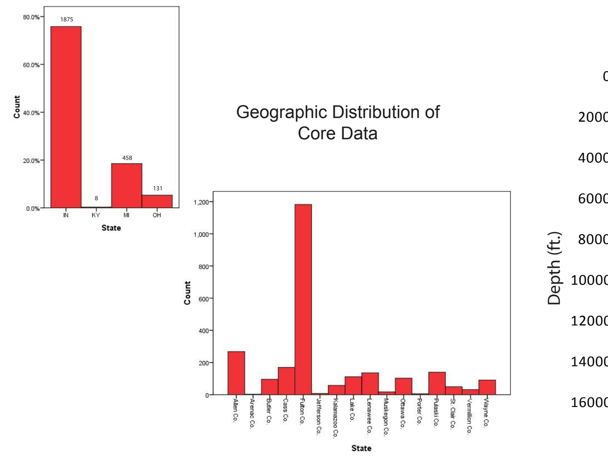


Figure 8. Core analyses from 3,714 data points in Indiana, Michigan, Ohio, and Kentucky. An exponential regression between the mean porosity and depth was conducted.



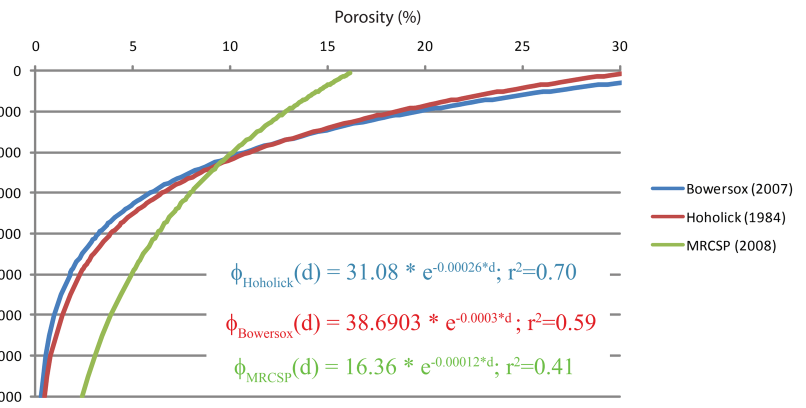


Figure 9: Our results (in green) compared to the depth/porosity trends obtained by Hoholick et al. (1984) and Bowersox (2008, personal comm.)

Permeability-Porosity-Depth Relationships

The reservoir characterization is incomplete if permeability (k) and porosity (ϕ) are analyzed independently (figures 10 and 11). Analyzing k and ϕ simultaneously is more effective and leads to a more realistic characterization of the porous media (Beaumont and Foster, 1999 eds.). The k/ϕ ratio or the r_{35} method (Pittman,1992) is applied here to determine the quality of the Mount Simon Sandstone as an effective reservoir (figure 12). Higher values of k/ϕ or r_{35} reflect the higher quality of the reservoir. The equations for the r_{35} values as a function of k and ϕ were obtained from Beaumont and Foster (1999).

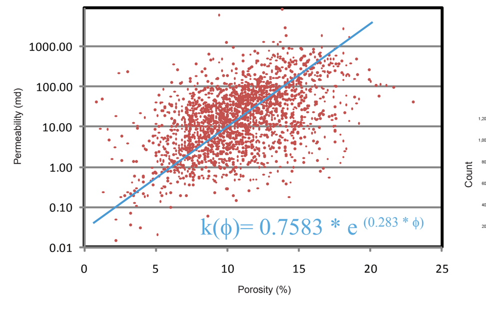


Figure 10: k vs. ϕ for the MRCSP region.

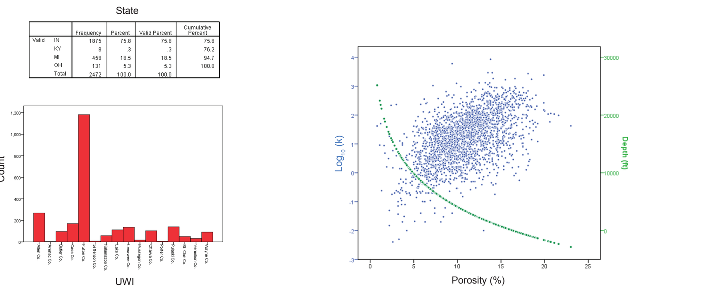


Fig 11: log(k) versus ϕ from core data (blue), and depth versus ϕ (green) obtained from regression using core data and geophysical logs.

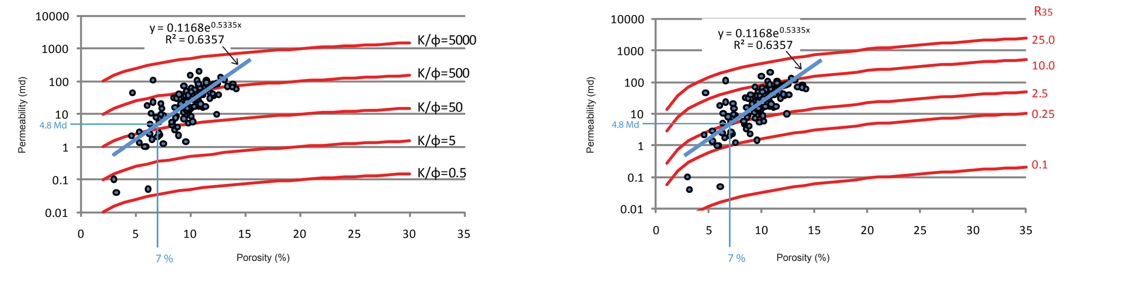
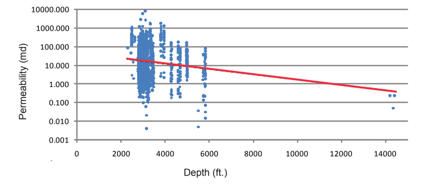


Figure 12: Average k vs. ϕ in context of k/ϕ and r_{35} values for the MRCSP region.

DIRECT METHOD

An empirical equation of k (md) as a function of depth (feet) was determined using core data:



$k = 46.243 * e^{-0.0003 * d}$

n=2164; r^2=0.0171

Figure 13: Average k versus depth for the MRCSP region.

INDIRECT METHOD

Using k(ϕ) and ϕ(d) to obtain k(d):

$k_{CORE}(\phi) = 0.7583 * e^{0.283*\phi}$ and $\phi_{MRCSP}(d) = 16.369 * e^{-0.00012*d}$

$\ln(k) = -0.276 + 4.6324 * e^{-0.00012 * d}$

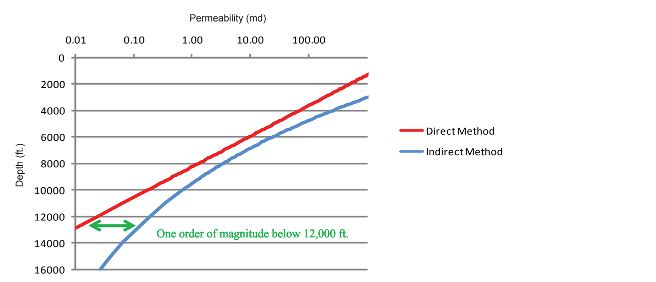


Figure 14: Comparison of k versus depth curves obtained from the direct and indirect methods.

Conclusions

1. Previous studies agree that at depths lower than 7,500 ft, porosity decreases exponentially to less than 7%. Therefore, areas below this depth may not be suitable as candidates for the effective sequestration of CO_2.
2. We have not yet established the acceptable minimum values of thickness for the secure and effective storage of CO_2. Further flow modeling is needed to understand vertical displacement of injected fluids from buoyancy forces and the horizontal displacement of CO_2 within the reservoir. Vertical continuity of high-porosity zones will also impact the efficiency of injected CO_2 displacement.
3. We agree with some authors who have identified an exponential relationship between porosity and depth of burial (Hoholick et al., 1984).
4. Regression analyses allowed us to determine relationships among permeability, porosity, and depth, but a lack of data at depths below 7,000 ft means that a high degree of uncertainty remains. Log-derived porosity will be used to estimate permeability and reduce this uncertainty at the deepest part of the basin. Future studies will incorporate facies characterization to investigate the role that lithology plays in reservoir quality.

References

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Acknowledgements

This work is funded by the DOE and is part of the regional carbon sequestration assessment being conducted by the Midwest Regional Carbon Sequestration Partnership (MRCSP).