Systematic diagenetic changes in the grain-scale morphology and permeability of a quartz-cemented quartz arenite

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Abstract

The material properties of sedimentary rocks are controlled by a range of parameters, including grain size, sorting, and modification of the original sediment through the diagenetic processes of compaction and cementation. To isolate the effects of diagenesis, and explore how they modify permeability, we quantified changes in grain and pore morphology accompanying progressive diagenesis of a simple system: a well-sorted, variably quartz-cemented quartz arenite of relatively uniform grain size. The most common type of authigenic cement in sandstones, quartz overgrowths are responsible for significant porosity and permeability reduction. The distribution of overgrowths is controlled by available pore space and the crystallographic orientations of individual quartz grains.

We show that progressive quartz cementation modifies the grain framework in consistent, predictable ways. Detailed microstructural characterization and multiple regression analyses demonstrate that both the number and length of grain contacts increase as the number of pores increases and the number of large, well-connected pores decreases with progressive diagenesis. The aforementioned changes progressively alter pore shape and reduce pore size variability and bulk permeability.
These systematic variations in the pore network correlate with changes in permeability, such that we can use our data to calibrate the Kozeny-Carmen relation, demonstrating that it is possible to refine predictions of permeability based on knowledge of the sedimentary system.

1. Introduction

Diagenesis results in systematic, grain-scale changes in sandstone, as both compaction and chemical processes such as cementation fundamentally alter rock structure. These changes are known to affect both the mechanical properties and permeability of the resulting lithified material (Beard & Weyl, 1973; Houseknecht, 1987; Dvorkin & Yin, 1995; Ehrenberg et al., 2008). However, quantitative correlation of diagenetic processes with resulting physical properties remains elusive, in part because of the wide variation in mineralogical and textural characteristics exhibited by sandstones. To address this gap in understanding, we investigated samples of a supermature quartz arenite collected from a portion of the Tonti Member of the St. Peter Sandstone that experienced shallow burial and a simple diagenetic history. Although the samples come from a single lithostratigraphic unit and display little variation in mineralogy, grain size and sorting, they experienced variable amounts of compaction and quartz cementation. Thus, changes in the physical characteristics of the sandstone can be directly related to variations in the degree of compaction and cementation, allowing us to quantitatively explore the effects of each of these diagenetic processes on physical properties. We focus on the grain-scale effects of these diagenetic processes on hydrologic properties here and address their impact on mechanical properties in a separate paper.
Using detailed sample characterization, image analysis, and multiple regression analysis, we quantified the effects of compaction and cementation on the grain framework and pore network of each sample, and subsequently explored the relationship between measured characteristics and permeability. The results of this study show that physical compaction and quartz cementation result in predictable changes in the physical characteristics of the grain framework and pore network (which we refer to as micromorphology) of the St. Peter sandstone. These systematic changes correlate with changes in permeability, such that we can invert our data to calibrate an empirical constant in the Kozeny-Carmen equation, a mathematical model commonly used to estimate permeability based on characteristics of the pore network. By calibrating the Kozeny constant, we demonstrate that it is possible to refine predictions of permeability based on knowledge of the sedimentary system.

2. Sandstone diagenesis

Numerous studies have identified porosity as a primary control on the hydrologic characteristics of sandstone (e.g., Nelson, 2004). Final intragranular porosity is the result of multiple diagenetic processes that can influence the grain-pore framework in different ways. In clean quartzose sandstones, porosity reduction occurs through both physical and chemical compaction and precipitation of cements, thus final porosity is a function of the relative contributions of these two processes. Compaction results in a more efficient packing with an increased number of grain – grain contacts and smaller pores. Precipitation of cement in quartz-cemented sandstones alters the grain-pore system by the addition of material at grain contacts and grain boundaries. Both processes are expected to alter grain and pore contact properties and grain and pore shapes, but in
different ways and with different efficiency.

Natural sandstones have grain-cement-pore geometries that are largely dictated by grain and cement mineralogy. For example, calcite cement in quartz arenites is commonly poikilotopic, with large calcite crystals engulfing detrital quartz grains and filling porosity (Scholle, 1979). Quartz cement, in contrast, is typically precipitated as overgrowths on quartz grains where space is available, with a geometry that is crystallographically controlled. The geometry of these quartz overgrowths is distinct from that of calcite or other cement types, and this distinction should have hydrologic effects. In other words, progressive cementation should result in systematic and predictable changes in micromorphology. These changes are controlled by cement and sandstone mineralogy and result in systematic and predictable changes in hydrologic properties.

Syntaxial quartz overgrowths are the most common form of authigenic cement in quartz sandstones (McBride, 1989; Worden & Morad, 2000). They may form at several stages in sandstone diagenesis (Vagle et al., 1994), and are thought to develop in a continuous three-stage process: (1) formation of small, rhombohedral and prismatic projections that (2) coalesce into large crystal faces and (3) ultimately form polyhedral quartz crystals (Ersnt and Blatt, 1963; Waugh, 1970; Pittman, 1972). At early stages of quartz cementation, the cement is likely to precipitate at narrow constrictions, particularly at grain contacts, but at later stages cement growth is crystallographically and space controlled (McBride, 1989; Lander et al., 2008). Examples of variable amounts of cementation of quartz arenite samples are shown in Figure 1. Grains in low-cement (< 5%) samples exhibit thin, encrusting layers of quartz with isolated crystal facets and interconnected pore spaces. In contrast, high-cement (> 10%) samples have an interconnected network of cement with well-defined facets and diminished pore
connectivity (Fig. 1).

Sedimentologists, hydrologists, and petroleum geologists are often interested in predicting type, occurrence, and distribution of cements and the associated porosity and permeability loss; rock mechanicians are interested in predicting mechanical behavior, such as strength, cohesion, sanding potential, etc.; and structural geologists are often interested in predicting style, distribution, and abundance of deformation-related features. For example, Dunn et al. (1973) documented an important mechanical transition in sandstones that corresponded to ~12% porosity. Sandstones with porosity below this threshold failed through the formation of fractures, whereas sandstones with higher porosities failed through the formation of deformation bands. Thus, understanding how the micromorphology of a sandstone changes with progressive diagenesis is of interest to a wide range of earth scientists. In particular, it will allow better predictive capabilities through better parameterization of hydrologic, mechanical, and poroelastic models. Grain contact parameters determined from real rocks can, for example, be used as model inputs to explore how microscale changes produced by diagenesis impact the macroscale response of a sandstone to pumping stresses (Plourde, 2009).

In previous work, cementation has been incorporated into models only in idealized form. For example, cements have been modeled as bridges between grains (Wong & Wu, 1995), concentric rings around circular grains (Dvorkin & Yin, 1995; Dillon et al., 2004), or as pore fill (Panda & Lake, 1995). The grain-bridging geometry is a simple, easy-to-model approximation, but we know of no significant cements in quartz arenites that have such morphologies. The concentric cement model is a better approximation of quartz overgrowths; however, it neglects important aspects of quartz cementation such as preferential early cementation of grain contacts and asymmetric
precipitation and distribution of cements (McBride, 1989). Weak, pore-filling cement, such as clays, would likely have minimal mechanical impact, but can greatly impact permeability. In addition, many conceptual models neglect the effect of compaction, often the greatest cause of porosity reduction (Lundergard, 1991). Importantly, the evolution of pore shape during diagenesis also likely impacts both permeability and mechanical behavior, as it influences both compressibility and the response of the system to changing pore pressure (Storvoll & Bjorlykke, 2004). Pores may be modeled as cracks, circles, cylinders, etc., all of which have distinct mechanical and hydrologic properties. All of these cementation and pore models can be useful; none provide a complete description of mechanical and hydrologic behavior. This paper reports a distinctly different approach to addressing this problem. We begin with a thorough, quantitative description of the micromorphologic characteristics of a sandstone, explore relationships between measured parameters, then address the impact of these characteristics on permeability.

3. St. Peter Sandstone

3.1. Geologic Setting

The middle Ordovician St. Peter Sandstone is a cratonic, super-mature quartz arenite (Odom et al., 1979; Mai & Dott, 1985). The unit is laterally extensive, blanketing a region from Michigan, Wisconsin, and Minnesota to Illinois, Missouri, and Arkansas. We collected samples from outcrops of the St. Peter Sandstone exposed along the flanks of the Wisconsin Arch in southern and central Wisconsin (Fig. 2). Although the sandstone was buried to significant depths in the Michigan and Illinois basins, burial in Wisconsin was shallow, likely less than 1000m. Kelly et al. (2007) provided two
arguments supporting this burial estimate: (1) Preserved overlying Silurian through Mississippian units have a thickness of only ~ 500 m, and Wisconsin has been above sea level, thus not receiving sediment, since Mississippian time; and (2) Paleozoic stratigraphy thins onto the Wisconsin arch, indication it has been a structural high since deposition of the St. Peter Sandstone.

The St. Peter overlies a basal unconformity, thus its thickness is variable, but is generally between 25 and 75 m thick. The St. Peter Sandstone consists of three members: Readstown, Tonti, and Glenwood. Samples collected for this study come from the Tonti Member. The environment of deposition of the St. Peter Sandstone remains controversial, but the Tonti Member is generally considered to have both fluvial and eolian components that have experienced marine reworking (Mai & Dott, 1985). The St. Peter Sandstone typically consists of greater than 97% quartz grains (Mai & Dott, 1985). In samples selected for this study, quartz is the only primary grain type present. Grains consist of fine to medium size, very well sorted and rounded sand.

Kelly et al. (2007) suggested the homogeneity of $\delta^{18}O$ values of quartz overgrowths in the St. Peter sandstone precluded a systematic regional temperature variation and concluded that quartz cements in the St. Peter Sandstone are silcretes, with $\delta^{18}O$ values consistent with precipitation at shallow depths and low temperatures. In contrast to most quartz cements, which occur between 80 and 120 °C where more sources of silica are present, silcretes typically develop in the near surface at weathering profiles or stable water tables (McBride, 1989). Silcretes can have the same textures as sandstones cemented at much greater depths under different diagenetic conditions.
3.2. Summary of diagenesis reactions/events in St. Peter

Five stages of diagenesis were previously identified within the St. Peter Sandstone: (1) local precipitation of potassium feldspar and encrusting quartz cements; (2) precipitation of local illite, smectite, kaolinite, calcite and dolomite; (3) the development of euhedral quartz overgrowths; (4) precipitation of pyrite; and (5) precipitation of kaolinite (Odom et al., 1979). Samples investigated for this study record some of these diagenetic events; however, none of the samples studied have evidence of carbonate cements and there is very little evidence of authigenic clay precipitation. In addition, the timing of diagenetic events within the St. Peter samples we have studied differs from that reported by Odom et al. (1979).

In the following paragraphs, we discuss evidence of diagenetic events in our samples in order from earliest to latest. In the samples we studied, pyrite and iron oxide abundance is typically less than 0.5% of the rock volume, but these phases appear to have precipitated early in the diagenetic history. Small pyrite crystals precipitated on grain surfaces are typically surrounded by quartz overgrowths, and pores occluded by iron oxides typically lack quartz overgrowths, whereas quartz overgrowths may be common in adjacent pores (Fig. 3a, b). In zones with significant potassium feldspar, grain contacts show no evidence of dissolution, indicating precipitation of diagenetic potassium feldspar predates significant pressure solution (Fig. 3c).

The relationship between quartz cement and pressure solution is unclear. However, quartz precipitation appears to have post-dated potassium feldspar precipitation, based on the following observations: (1) potassium feldspar precipitated directly on grain surfaces; (2) there is no evidence of feldspar precipitated on existing quartz overgrowths, and pores with significant potassium feldspar precipitation generally
lack quartz cement; and (3) where quartz and feldspar overgrowths are both present, quartz appears to have grown around feldspar overgrowths (Fig. 3d).

Just one sample contains local evidence for precipitation of clay coatings with meniscus geometries following major phases of quartz cementation (Fig. 3e), suggesting formation in the vadose zone. Additionally, some feldspar overgrowths have evidence of local dissolution, but no relative timing could be determined. The nature and relative timing of diagenetic events determined from the samples studied are summarized in Figure 4.

4. Sample Characterization

4.1. Methods

To evaluate the effects of progressive compaction and quartz cementation on sandstone grain and pore morphology, a suite of samples was chosen to encompass a range of initial porosity and cement abundance. For this exercise, a TinyPerm air minipermeameter was used as an outcrop-screening tool, under the assumption that samples with a range of permeabilities would exhibit a range of porosities.

Nine samples were selected for detailed study (Fig. 2). Although the total sample number is small, the samples were chosen to encompass a wide range in porosity and percent cement. All came from exposed surface outcrops. Six samples consisted of uniform sandstone with no evidence of bedding at the sample scale, and three samples contained cm-scale bedding heterogeneity.

Using a Hitachi S-3400 variable pressure, scanning electron microscope with Gatan PanaCL/F cathodoluminescence detector operated at 15 kV at the University of Wisconsin – Madison, a series of backscattered electron (BSE), cathodoluminescence
(CL), and secondary electron (SE) images were taken of each sample. Mosaics of images collected at 150X magnification were constructed to evaluate porosity, percent cement, grain size, and grain contact properties. Mosaics represent areas of the samples that range in size from approximately 4.4 mm by 3.3 mm to 3.7 mm by 2.7 mm, consisting of 36 or 25 images, respectively.

To evaluate sample porosity using image analysis, BSE image mosaics were used. In BSE images, epoxy in open pore spaces appears black, thus the area fraction occupied by black pixels can be used to approximate the two-dimensional porosity of the images. In addition to image analysis, bulk porosity of most samples was also evaluated at the core scale using a helium pycnometer on 1” diameter cores. Comparison of 2D calculated and 3D measured porosities allows us to assess whether images accurately represent rock characteristics. For consistency with other 2D analyses, we use the porosity results obtained through image analysis in our statistical analysis.

Cathodoluminescence images were used to evaluate percent cement and grain-grain relationships. Because quartz cements grow in optical continuity with primary grains, such features are difficult to distinguish in either standard BSE or plane-light images. However, because cements typically differ in luminescent properties from original grains, they can typically be distinguished in CL images (Sprunt and Nur, 1979; Blenkinsop & Rutter, 1986; Onasch, 1990; Laubach, 2003). In the CL mosaics of the St. Peter Sandstone samples, later-stage quartz cements commonly appear darker than primary grains. Because of color variability from grain to grain, detrital grains cannot be reliably distinguished from quartz cements using image analysis alone. Thus, two estimates of cement percentage were made for each sample: the first through image analysis of cement tracings, and the second by point-counting (300 points) of image
mosaics. The average cement value of these two measurements was used in subsequent statistical analyses.

4.2. Sample Characteristics

Sample characteristics are summarized in Table 1. Sample porosity varies from 8% to ~25%. There is remarkably good agreement between porosities estimated from 2D images and those measured using a pycnometer. We therefore assume that the 2D images provide an adequate representation of the core-scale properties. Quartz cement abundance is generally inversely proportional to porosity, with percent quartz cement varying from 0.1% to 14%. Diagenetic potassium feldspar cements are present in 8 of 9 samples at abundances of 1% or less of the entire rock volume. Unlike quartz cements, which precipitated throughout the sample volume, potassium feldspar cements were only precipitated locally, in isolated pores or groups of pores (Fig. 3d). As mentioned earlier, iron oxide cements, and rare pyrite and clay grain coatings are present in localized pore spaces of several samples. Because they represent such a small volume of the solid framework, these cements are not included in our analyses. Original porosity or intergranular volume (IGV) of all samples, calculated by adding percent porosity and percent cement, varies from 21% to 31%. Sample 14_1 had the lowest IGV of 20.9% and contained extensive sutured and interpenetrating contacts, indicating chemical compaction was active. Other samples contained no evidence of chemical compaction.

Average grain size was calculated through image analysis from the average diameter of particles, where diameter was chosen as the maximum width of a grain (including cement), a reasonable estimate of well-rounded, relatively equant grains. Because a two-dimensional slice through a three-dimensional packing of spherical
grains does not represent the actual particle size distribution, and because no corrections were applied to the resulting data, the grain size values reported are smaller than the actual three-dimensional grain sizes. The focus of this study, however, is a comparison of samples within the dataset and these values are internally consistent. Samples consisted dominantly of fine sand, with an average grain size between 0.15 mm and 0.20 mm.

5. Effects of diagenesis on micromorphology and permeability

In each of the following sections, we first address the method of measurement of a given micromorphologic parameter of interest. Each brief methods section is followed by details of the results.

5.1. Grain-grain relationships

To investigate changes in grain contact parameters associated with progressive diagenesis, a combination of BSE and CL images was used. Two primary parameters, grain contact length and bond-to-grain ratio (BGR), were measured from photomosaics. For each sample, the grain contact length was measured as the shortest width of a given contact between adjacent grains (Fig. 5a). The bond-to-grain ratio, or BGR, was approximated as the total number of grain-to-grain or grain-cement-grain contacts divided by the number of grains completely contained within each mosaic and associated with each contact (Fig. 5b).

The results of these analyses are presented in Table 2. BGR generally increases with decreasing porosity and increasing cement percentage (cf. Table 1; Fig. 6). Sample 14_1, however, with evidence of significant pressure solution, has a lower BGR than
would be expected for samples with similar porosity, and a higher BGR than samples with similar percentage cement. Average contact length generally decreases with grain size, and increases with percentage cement. Again, sample 14_1 is anomalous, with longer average and normalized contact lengths compared to samples with similar cement percentages.

5.2. Pore Shape

Images of pores, like images of grains, are 2D slices through a 3D geometric network. Because pores vary in both size and shape, 2D images are limited approximations of 3D geometry (Ehrlich et al, 1991). Nevertheless, progressive changes in 2D pore geometries will result from the changes in pore architecture that accompany diagenesis. These variations in 2D pore geometry can be characterized and compared within the dataset. Because the tools needed for thin section analysis are more broadly available than those required for 3D analysis of equivalent resolution, this approach is also more generally useful.

For pore analysis, images of pore spaces were extracted from BSE images using NIH ImageJ (Rasband, 2009). These raw images were then processed using a combination of median filters to minimize noise and emphasize the basic pore geometries. Only pores that were fully contained within the entire mosaic were analyzed. Because higher porosity samples generally contain larger pores that are more likely to be truncated by the image edge, the percentage of total pore space analyzed decreased with increasing porosity. For low porosity samples, 85% - 90% of the total porosity imaged was sampled, whereas only 45% of the imaged porosity was sampled from the highest porosity sample. In general, the smaller size fraction of pores had a higher
probability of being sampled in all cases, but this effect is most significant at higher porosities.

Several pore space descriptors were characterized for each sample: (1) total number of pores; (2) total and average pore area; (3) variation in average pore area, reported as standard deviation; (4) total and average pore perimeter; (5) a geometric pore shape factor (SF),

$$SF = \frac{p_c}{p_p},$$

where \(p_c\) is the perimeter of a circle of the same area as the pore, and \(p_p\) is the perimeter of the pore; and (6) specific surface area, SSA:

$$SSA = \frac{4 \times P_p}{\pi \times P_A},$$

where \(P_p\) is the summed perimeter of all pores within a mosaic, and \(P_A\) is the summed area of all pores. SSA is a parameter used in the Kozeny-Carman relationship to predict permeability from rock micromorphology.

Results of pore analyses are given in Table 3. The number of pores generally decreases with increasing porosity, decreasing cement, and increasing IGV. Both mean pore size and variation in mean pore size decrease with decreasing porosity, increasing cement, and decreasing IGV. More circular pores have shape factor (SF) values approaching 1, whereas more complexly shaped pores have lower values. Pores generally become more circular with increasing cementation and decreasing IGV. Sample 14_1 is again an exception, with more circular pores than samples with similar cement percentages or porosities.
5.3 Effects of diagenesis on measured and predicted permeability

Permeability measurements were conducted at New England Research, at a confining pressure of 14.5 MPa (2103 psi). The confining pressure was chosen based on estimated maximum burial conditions assuming 1 km (3281 ft) of burial and hydrostatic fluid pressure. For samples with anticipated permeabilities greater than 500 mD, a gravity flow technique was used. For low-porosity samples, a transient pressure technique was used (cf. Fetter, 2001). Both methods were utilized to measure the permeability of an intermediate porosity sample to facilitate comparison. Sample permeabilities are presented in Table 4. As expected, permeability generally decreases with decreasing porosity and increasing cement percentage; sample 14_1 is, once more, a prominent exception to these general trends.

6. Influence of diagenetic path

For quartz-cemented quartz arenites, primary sedimentary characteristics such as grain size, sorting, shape, and composition are independent of diagenesis. Secondary characteristics, such as the nature and types of grain contacts, percent cement, and cement distribution, are controlled by post-depositional diagenetic processes. Other characteristics such as IGV, pore shape, and pore size variability are a function of both primary and secondary processes. The limited variability in sorting, grain size, and grain composition and shape in the St. Peter Sandstone (Table 1; Mai & Dott, 1983) means that variations in IGV, pore size, and pore shape are primarily a function of diagenetic modifications.

Final porosity is a function of the relative contributions of compaction and cement precipitation. For this reason, micromorphologic parameters (i.e., BGR, contact length,
mean pore size, etc.) are evaluated based on the relative contributions of these two primary processes. We assume all samples had an initial porosity of approximately 40% - a typical initial porosity for quartz arenites (Beard & Weyl, 1973; Houseknecht, 1987). Lower IGV values indicate a greater departure from this original porosity and thus a greater magnitude of compaction. Given this assumption, IGV can be used as a direct proxy for compaction (Lander & Walderhaug, 1999).

To evaluate how well micromorphologic parameters such as BGR or contact length are predicted by variables such as porosity, or percent cement and IGV, data were analyzed using multiple regression. We considered the dependent variables BGR, average grain contact length, average pore size, pore size variability, specific surface area, pore shape, number of pores, and permeability in our analysis. For each dependent parameter, two primary linear regressions were computed: (1) the dependent parameter with respect to porosity; and (2) the dependent parameter with respect to IGV and percent quartz cement. We also considered whether the addition of mean grain size as an independent parameter improved the model fit. Sorting was not considered in multiple regression analyses because it varies little in this select sample set. Other measures of the grain-size distribution may be important for more heterogeneous suites of samples.

To evaluate the quality of fit of each linear regression to the data, both the $R^2$ value and an adjusted $R^2$ (a modified $R^2$, described below) were used. The addition of independent parameters (e.g., IGV plus cement compared with porosity, or porosity plus average grain size compared with porosity alone) generally increased both the $R^2$ value and the adjusted $R^2$. Because the $R^2$ will generally increase with the inclusion of additional predictors in the regression, the adjusted $R^2$ is a regression statistic that
accounts for additional predictors, and increases only when the $R^2$ increases more than would be expected by chance. Thus the adjusted $R^2$ will be less than or equal to $R^2$.

To select which linear regression model best fit the data, e.g., (1) porosity ± grain size or (2) IGV and percent cement ± grain size, an F-test was used. The F-test determines the significance of the increased $R^2$ value for each regression with an added predictor variable. An F-statistic was calculated for each pair of regressions and if the value of that statistic was less than the critical F-value for the 90% confidence level, then the more complex regression model was rejected in favor of the simpler regression model with fewer predictors.

Using the above procedure, if a regression of a particular characteristic with respect to porosity alone was selected as the best model, then we concluded that diagenetic path could be neglected, and porosity loss through diagenesis was the most important predictor of that characteristic regardless of whether it was achieved through compaction or cementation. If regression with respect to IGV and percent cement was selected as the best model, then we concluded that diagenetic path should be considered. Regardless of which primary model was chosen, grain size was a significant additional parameter in several analyses. However, it should be noted that the variation in grain size within the St. Peter Sandstone is small; larger grain size variations in otherwise similar systems might have a more significant effect on resulting parameters.

As mentioned previously, sample 14_1 has significant evidence of pressure solution, and data presented in Tables 1 – 4 indicated that pressure solution alters the grain framework differently than physical compaction and cementation. Therefore each regression was performed both with and without sample 14_1. For every model, adjusted $R^2$ improved with the exclusion of Sample 14_1 from the regression. We also
conducted a sensitivity analysis, where each regression was computed iteratively, leaving out one sample for each iteration for each dependent parameter. Sample 14_1 was the only sample whose exclusion resulted in an increase in $R^2$ for every dependent parameter. Thus, the final regression analyses for all parameters exclude sample 14_1.

Results of multiple regression analyses for micromorphologic parameters and permeability are included in Table 5. Additional information for all regressions considered is included in the Appendix. For each analysis, partial regression coefficients are reported, including statistical estimates of model fit. Regression results suggest that BGR, specific surface area, and pore size variability can be approximated as a function of porosity alone and thus the method of pore occlusion is unimportant (Fig. 6a,b,c). For a 5% decrease in porosity, BGR increases by approximately 0.26. Specific surface area has the most unexplained variability in the data. Average pore size and number of pores are best approximated as a function of porosity and grain size (Fig. 6d,e). Thus, the method of porosity reduction is unimportant for these parameters as well, but grain size should be considered.

Two parameters were found to be sensitive to diagenetic path: grain contact length and pore shape (Fig. 6f). Pore shape is a function of IGV and percent cement, whereas average grain contact length is a function of IGV, percent cement, and grain size. Cementation results in more circular pores than physical compaction alone. The magnitude of regression coefficients suggests that cementation is at least twice as important as changes in IGV to resulting contact length.

The correlation between porosity and permeability is a property of granular porous media that reflects the change from interconnected macroporosity at high porosity to more isolated, smaller pores at lower porosities (Ehrenberg et al., 2008). It is
therefore not surprising that regression analyses show that permeability is primarily a function of porosity. However the specific relationship between porosity and permeability can vary markedly between different depositional and diagenetic systems (Nelson, 2004). Thus it is also unsurprising that sample 14_1, excluded from regression analyses as indicated earlier, exhibits permeability that is distinctly different from (approximately double that of) samples of similar porosity.

Although porosity was often selected as the better fit for the data based on statistical tests, in many cases, the data were modeled with a higher $R^2$ and adjusted $R^2$ when IGV and cement were used as predictors rather than porosity. However because of the small sample size, these improvements were typically not significant. Further investigation with a larger, more varied dataset may indicate that more parameters are sensitive to diagenetic path than those identified in this study.

7. Discussion

A shortcoming of statistical approaches like the one outlined in this study is that the predictions are only useful for sandstone compositions, textures, and geologic settings similar to the initial, calibration datasets (Bloch, 1991; Gal et al., 1998; Lander and Walderhaug, 1999). We therefore do not suggest the reported regression coefficients are directly applicable to other sandstones; rather, these results indicate that there are predictable variations in micromorphology of the grain-pore system that are directly related to diagenetic processes. Understanding these relationships for a given sandstone type and diagenetic history can provide insight into the mechanical and hydrologic effects of sandstone diagenesis, with the ultimate hope of better predictive capabilities.
The evolution of grain and pore morphology reported here is therefore specific to quartz-cemented quartz arenite. Precipitation of other types of cement will result in different morphologies, distinct from quartz cements, which are expected to result in a different set of predictable variations in the grain-pore system.

7.1. Diagenetic changes in grain-pore frameworks of the St. Peter Sandstone

During diagenesis of quartz arenites, both the number and length of grain contacts increase. The number of pores increases, whereas the total porosity decreases, resulting in decreased connectivity of pores and increasing homogeneity in pore size. Table 6 demonstrates how these data can be used to anticipate variations in dependent parameters with degree of diagenesis by illustrating how micromorphological parameters would vary with a 5% increase in the independent parameters porosity, IGV, and cement percent or a 0.01 mm increase in grain size.

Statistical analyses demonstrate that porosity reduction, rather than physical compaction or cementation alone is the best predictor of BGR, a point illustrated by the strong correlation shown in Figure 6a. Thus, either compaction or cementation can effectively increase the number of grain contacts in a quartz-cemented quartz arenite. We infer that physical compaction increases the number of grain contacts because pore spaces collapse and are reorganized, whereas cementation increases the number of bridges between grains. If grains were perfectly spherical, physical compaction alone would not increase grain contact length. However, because grains are irregularly shaped, physical compaction should result in more efficient grain packing, thereby increasing contact length along with BGR. The addition of cement lengthens grain contacts, and the preferential precipitation of cements at narrow grain contacts amplifies
this effect.

Average pore size decreases as expected with porosity; however, this reduction is achieved primarily through destruction of the largest pores, producing multiple smaller pores. These largest, well-connected pores primarily control permeability. As they are preferentially destroyed, permeability and pore size variation decrease exponentially (Fig. 7). Specific surface area also decreases with decreasing porosity and destruction of the largest pores.

The number of pores does not stay the same with continued diagenesis (Gal et al., 1998). Our data show that the number of pores increases, regardless of whether porosity reduction is dominated by compaction or cementation (Fig. 6E), and pores become progressively more spherical with increasing diagenesis (Fig. 6F).

7.2. Timing of Diagenetic Events

Physical compaction and cementation were probably not coeval in the St. Peter Sandstone, since physical compaction appears to shut down after precipitation of relatively small amounts of grain contact cement (Hiatt et al., 2007; Melzer & Budd, 2008). Precipitation of even small amounts of cements at grain contacts can significantly stiffen the grain framework, increasing strength and preventing grain sliding and rotation (Spinelli et al., 2007). Thus, diagenesis in mature quartz arenites in the absence of chemical compaction may be imagined as the result of two distinct phases, an early phase dominated by physical compaction followed by a second phase dominated by quartz cementation (Fig. 8). The length of time within each “window” and the relative magnitude of each process determine the final micromorphology of the sandstone.

Figure 9a and b illustrate the potential effects of diagenesis involving physical
compaction and precipitation of cements on grain and pore properties. These diagrams are contour plots showing changes in predicted BGR and contact length (Fig. 9a), and log permeability and pore shape (Fig. 9b) with changes in IGV and percent cement. Only the diagenetic processes of compaction and cementation are considered. After deposition, initial compaction increases the number of grain contacts, with only small increases in contact length. Permeability decreases as pore throats are closed by pore collapse and cement precipitation. Once significant quartz cementation initiates, the number of contacts continues to increase, contact length and pore circularity increase rapidly, and permeability reduction slows as diagenesis progresses. Permeability decreases equally with porosity loss through cementation and physical compaction within the St. Peter Sandstone. However, without grain breakage, the final porosity achieved through physical compaction in clean quartz arenites is limited to approximately 26% (Beard & Weyl, 1973; Paxton et al., 2002). Because permeability changes vary with porosity changes in these rocks, permeability reduction through physical compaction alone is therefore also limited.

7.3. Predicting permeability in quartz-cemented quartz arenites

When permeability measurements are not available, the permeability of a granular porous medium is often estimated based on empirical or theoretical models. A commonly used model is the Kozeny-Carman relationship. The Kozeny-Carman relationship relates two easily acquired parameters from an image of a grain-pore network - specific surface area and porosity (Panda & Lake, 1994; Mowers and Budd, 1996) - to permeability as follows:


\[ k = \frac{\phi^3}{K_0 \left( \frac{L_0}{L_E} \right)^2 (1 - \phi)^2 SSA^2}, \]

where \( k \) is permeability, \( \phi \) is porosity, \( K_0 \) is an empirical Kozeny constant related to the cross-sectional area of the pore, \( \frac{L_0}{L_E} \) is the tortuosity, and SSA is the specific surface area. A proportionality constant, \( c \), is typically substituted for the \( K_0 \left( \frac{L_0}{L_E} \right) \) parameter (Mowers & Budd, 1996). For many calculations, a constant value of 5 is used for parameter \( c \), but this constant of proportionality should vary with the pore system (Carman, 1956; Mowers & Budd, 1996).

Diagenesis alters the amount and distribution of pore space, creating smaller, more disconnected pores, therefore a uniform constant of proportionality should not be sufficient to encompass differences in permeability related to physical compaction and cementation. Therefore, we use permeabilities determined from the regression equation in Table 5 to calculate variations in the proportionality constant using the equation given above. We use values of permeability from the regression analyses rather than the individual measured values in order to minimize the effect of natural sample variability. Table 7 lists the measured permeability, predicted permeability based on regression analysis (cf. Table 5), and an estimate of a calibrated constant of proportionality for each sample. The calculations indicate that for accurate predictions of permeability within this dataset, the constant of proportionality for the pore systems decreases exponentially with increasing porosity (i.e. decreasing diagenetic alteration) (Fig. 10). Since the constant of proportionality is dependent on both \( K_0 \) and \( \left( \frac{L_0}{L_E} \right) \) it is difficult to estimate either parameter without more data. Nevertheless, our analysis suggests that diagenetic alteration has a strong effect on the cross-sectional area of the pores (expressed through \( K_0 \) and/or the tortuosity, which is represented by \( \left( \frac{L_0}{L_E} \right) \)). Further, the trend
shown in Figure 10 suggests that consideration of samples with a wider range of porosities would result in a variation of approximately an order of magnitude in the constant of proportionality, resulting in a significantly greater variation in calculated permeability than is evident with the constant fixed at 5.

7.4. Effect of pressure solution on the grain-pore framework

Sample 14_1 had an anomalously low IGV (Table 1) and contained significant evidence of sutured and interpenetrating grain contacts - an indication of pressure solution despite its shallow burial. Other samples had higher IGV and contained little evidence of grain suturing. Thus, we conclude that modification of the grain framework from chemical compaction was minor in samples other than 14_1. Compared with samples that contained little or no evidence of pressure solution, sample 14_1 was an outlier in evaluation of diagenetic trends in micromorphologic parameters and was not included in any regressions. For example, sample 14_1 had a relatively low average pore perimeter, more circular pores, and lower specific surface area than would be anticipated based on trends defined by other samples.

Although only one sample exhibited these anomalous features, these observations suggest that pressure solution may affect the evolution of sandstone micromorphology differently than physical compaction and cementation alone. In this sample that has undergone moderate pressure solution, grain contacts are significantly lengthened, mimicking the effect of cement on contact length. In this way pressure solution can effectively decrease the pore perimeter by destroying elongate spaces between touching grains, thus increasing pore circularity and decreasing specific surface area. For a given porosity, a lower specific surface area results in a higher permeability.
calculated from the Kozeny-Carmen relationship. Interestingly, the permeability measured from sample 14_1 is approximately 1000 mD higher than that predicted from the characteristics of samples with no evidence of pressure solution (Table 7). Thus, although pressure solution is an important mechanism of porosity and permeability reduction, our very limited data suggest that for a given porosity, a sample with significant cementation would likely have lower permeability than a sample whose final porosity was achieved dominantly through pressure solution.

8. Conclusions

Grain-scale properties of rocks control macroscopic behavior. Therefore, understanding how rock characteristics and material properties evolve at the grain-pore scale provides insight into hydrologic and mechanical behavior at the core scale and above. In this study, we considered the effect of diagenetic processes on changes in the grain frameworks and pore network of quartz-cemented sandstones and found that these processes result in predictable changes: the number and length of grain-grain contacts increase, the number of pores increases while average pore size decreases, pore size variability decreases and pore spaces become progressively more circular with progressive diagenesis.

Diagenesis in the clean, quartz-cemented sandstones we studied likely occurred in two separate phases, the first dominated by physical compaction and the second by quartz cementation. Changes in morphology reflect this history with significant changes in grain contact length and pore shape initiating only after the onset of significant quartz cementation. Cementation increases contact length and pore circularity approximately twice as much as an equivalent reduction in IGV.
In samples that have undergone physical compaction and precipitation of quartz cements, reduction in permeability correlates well with reduction in porosity. The largest, well-connected pores control permeability. As these pores are preferentially modified through compaction and cement precipitation, pore size variability and permeability decrease. This reduction in permeability is expressed as a dramatic increase in constant of proportionality in the Kozeny-Carman relation (Fig. 10). Different sandstones should show similar trends of increasing constant of proportionality with decreasing permeability; however, the specific relationships between diagenesis and permeability, and therefore between porosity and the constant of proportionality, are expected to vary with the sandstone system. For example, the patchy development that is typical of carbonate cements in quartz arenites might result in the local preservation of large, connected pores that could serve as high permeability pathways at lower bulk porosity than would be seen in a quartz-cemented quartz arenite. Depending on the spatial distribution of carbonate patches, the calibrated constant of proportionality could be lower (i.e., the permeability would be higher) for a given porosity than the constant for the quartz-cemented quartz arenite we describe here.

Acknowledgements
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Figure 1
Figure 2
Figure 4
Figure 5
Figure 6 (continued on next page).
Figure 6
Figure 7
Figure 8

Initial Porosity ≈ 40%

Minimum IGV ≈ 26%

Physical Compaction

Cementation

Cementation

Cementation

A

B

C
Figure 10
Figure 1 - Comparison of cement micromorphology and distribution of areas of low (3.5%) and relatively high (15.6%) cement abundance. Both samples are from the Ordovician St. Peter Sandstone in Wisconsin. (a) CL images in which grains (g) are distinguished from cement (c) by differences in luminescence. (b) False-color images of the same areas. Cement is light gray, grains are dark gray, and pores are white. The intergranular area of the two images is roughly the same, but porosity in the high cement example is less than half that of the low cement location. (c) Images showing only areas of cement within each sample.

Figure 2 - Map of sample locations in central and southern Wisconsin.

Figure 3 – Back-scattered electron (BSE) images of diagenetic phases within the St. Peter Sandstone. In these images, black is open pore space, dark gray grains are quartz, light gray cements are potassium feldspar and white cements are pyrite or iron oxide. (A) Small pyrite crystals precipitated on detrital grain surfaces (arrows); later enveloped by quartz overgrowths; (B) Pore occluded by iron oxide (arrow) with no evidence of quartz overgrowths; (C) Localized area of feldspar cement (f) with no evidence of pressure solution, adjacent to areas without feldspar cements with abundant sutured contacts (sc); (D) Feldspar cements precipitating directly on grain surfaces and abutting quartz overgrowths; (E) Rare clay grain coatings and cements with meniscus geometries.

Figure 4 – Inferred sequence of diagenetic events in samples of the St. Peter Sandstone investigated for this study. Not all events are recorded in all samples; only physical compaction and quartz cementation are documented in all samples.

Figure 5 – Procedure for measuring contact length (A) and bond-to-grain ratio (BGR) (B). For cases where the contact was discontinuous, the total contact length (L_T) was calculated as the combined length of the separate segments (L_a, L_b), so that L_T = L_a + L_b.

Figure 6 – Results of multiple regression analyses. Bond-to-grain ratio (BGR) (A), specific surface area (B), and pore size variability (C) are plotted with respect to porosity. Average pore size (D) and normalized number of pores (E) are plotted with respect to both porosity and grain size. (F) Pore shape is plotted as a function of both IGV and % cement. Please note that the plots shown in (D), (E), and (F) have been rotated so that the planes illustrating relationships between the three variables shown are viewed on edge. The rotations are evidenced by the orientations of the X and Y axes.

Figure 7 – Plot of permeability versus pore size variation. Destruction of the largest pores results in an exponential decrease in both permeability and pore size variation.

Figure 8 – Schematic illustration of three possible diagenetic pathways, showing how compaction can be shut down by cementation at different stages in a quartz arenite’s burial history. The initial porosity of a quartz arenite is typically ~40%. Early cementation, represented by path A, preserves a relatively high IGV because cementation shuts down compaction before it accomplishes significant porosity loss. The cement strengthens the grain framework, so most porosity loss occurs subsequently through cementation. The sandstone in path B experiences cementation only after significant compaction, recording an IGV of ca 32%. Path C illustrates the maximum possible porosity reduction
through compaction, resulting in an IGV of 26%, with subsequent porosity loss occurring entirely through cementation.

**Figure 9** – Schematic diagrams for prediction of grain contact and pore properties of variably quartz-cemented quartz arenites based on regressions in Table 5. The red line in both figures illustrates a possible grain-pore evolution with diagenesis for sample 3_1. Solid and dashed lines are contours of predicted grain-pore parameters of interest. Regression analyses (Table 5) are used to show predicted changes in dependent parameters with variations in intergranular volume (IGV) and percent cement. For all predictions, the only porosity-reducing processes are assumed to be compaction and precipitation of cement. For cases where the dependent parameter is a function of porosity, the dependent parameter changes equally for a reduction in IGV or an equal increase in percent cement. The corresponding IGV and percent cement for a given porosity can be calculated through the relationship: Porosity = IGV - %Cement. (A) Bond-to-grain ratio (BGR) (solid lines) and contact length (mm) (dashed lines) are predicted for sandstones with a mean grain size of 0.15 mm. This can be adapted for other grain sizes by adding 0.023 mm to the contour values for contact length for every 0.05 mm increase in grain size (cf. Table 6). (B) Log permeability (mD) (solid lines) and pore shape (dashed lines) are predicted for a variety of IGV and cement percentages. Area shown in gray is outside of the calibration dataset for permeability, thus no predictions are made.

**Figure 10** – Plot of calibrated constants of proportionality versus porosity.
Table 1 - Sample characteristics, listed from highest to lowest porosity. CC - clay coatings; P - pyrite; IC - iron oxide cement.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean Porosity (%) (Image Analysis)</th>
<th>Porosity (%) (Pycnometer)</th>
<th>Mean Quartz Cement (%)</th>
<th>Potassium Feldspar Cement (%)</th>
<th>Mean IGV (%)</th>
<th>Avg. Grain Size (mm)</th>
<th>Other Phases</th>
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</thead>
<tbody>
<tr>
<td>1_2</td>
<td>24.6</td>
<td>9.25</td>
<td>1.40</td>
<td>0.72</td>
<td>5.55E-02</td>
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<td></td>
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<tr>
<td>5_2</td>
<td>24.4</td>
<td>14.52</td>
<td>1.29</td>
<td>0.74</td>
<td>3.67E-02</td>
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<td></td>
</tr>
<tr>
<td>13_1</td>
<td>20.7</td>
<td>10.16</td>
<td>1.57</td>
<td>1.04</td>
<td>6.51E-02</td>
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<td></td>
</tr>
<tr>
<td>14_1</td>
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<td>1.52</td>
<td>1.23</td>
<td>6.80E-02</td>
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<tr>
<td>3_2</td>
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<td>1.72</td>
<td>1.27</td>
<td>7.30E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3_1</td>
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<td>18.88</td>
<td>1.92</td>
<td>2.25</td>
<td>6.18E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11_2</td>
<td>35.44</td>
<td>18.16</td>
<td>1.95</td>
<td>2.19</td>
<td>6.20E-02</td>
<td></td>
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<tr>
<td>12_1</td>
<td>31.92</td>
<td>14.28</td>
<td>2.24</td>
<td>2.69</td>
<td>8.42E-02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Summary of grain contact parameters, presented from highest to lowest porosity samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of bonds per image</th>
<th>Number of grains per image</th>
<th>Bond-to-grain ratio (BGR)</th>
<th>Total Contact Length (mm) per image</th>
<th>Avg. Contact Length (mm)</th>
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</thead>
<tbody>
<tr>
<td>1_2</td>
<td>12.97</td>
<td>9.25</td>
<td>1.40</td>
<td>0.72</td>
<td>5.55E-02</td>
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<tr>
<td>5_2</td>
<td>20.16</td>
<td>14.52</td>
<td>1.29</td>
<td>0.74</td>
<td>3.67E-02</td>
</tr>
<tr>
<td>13_1</td>
<td>15.92</td>
<td>10.16</td>
<td>1.57</td>
<td>1.04</td>
<td>6.51E-02</td>
</tr>
<tr>
<td>14_1</td>
<td>18.22</td>
<td>11.97</td>
<td>1.52</td>
<td>1.23</td>
<td>6.80E-02</td>
</tr>
<tr>
<td>3_2</td>
<td>17.36</td>
<td>10.08</td>
<td>1.72</td>
<td>1.27</td>
<td>7.30E-02</td>
</tr>
<tr>
<td>3_1</td>
<td>25.97</td>
<td>18.88</td>
<td>1.92</td>
<td>2.25</td>
<td>6.18E-02</td>
</tr>
<tr>
<td>11_2</td>
<td>35.44</td>
<td>18.16</td>
<td>1.95</td>
<td>2.19</td>
<td>6.20E-02</td>
</tr>
<tr>
<td>12_1</td>
<td>31.92</td>
<td>14.28</td>
<td>2.24</td>
<td>2.69</td>
<td>8.42E-02</td>
</tr>
</tbody>
</table>

Table 3 - Summary of pore parameters, with samples listed in order of decreasing porosity

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of pores per image</th>
<th>% of Total Porosity Sampled</th>
<th>Average Pore Size (mm2)</th>
<th>Average Pore Perimeter (mm)</th>
<th>Pore Shape</th>
<th>Pore Size Standard Deviation (mm2)</th>
<th>Specific Surface Area (mm2)</th>
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<tbody>
<tr>
<td>1_2</td>
<td>6.94</td>
<td>45.22</td>
<td>8.16E-03</td>
<td>0.45</td>
<td>0.71</td>
<td>3.50E-02</td>
<td>70.01</td>
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<tr>
<td>5_2</td>
<td>10.04</td>
<td>71.84</td>
<td>8.24E-03</td>
<td>0.51</td>
<td>0.63</td>
<td>2.03E-02</td>
<td>78.31</td>
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<tr>
<td>13_1</td>
<td>8.96</td>
<td>64.54</td>
<td>7.50E-03</td>
<td>0.42</td>
<td>0.73</td>
<td>1.90E-02</td>
<td>71.38</td>
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<tr>
<td>14_1</td>
<td>9.31</td>
<td>73.78</td>
<td>7.42E-03</td>
<td>0.40</td>
<td>0.77</td>
<td>2.05E-02</td>
<td>67.98</td>
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<tr>
<td>4_1</td>
<td>9.42</td>
<td>73.08</td>
<td>6.62E-03</td>
<td>0.40</td>
<td>0.72</td>
<td>1.36E-02</td>
<td>76.81</td>
</tr>
<tr>
<td>3_2</td>
<td>14.42</td>
<td>87.03</td>
<td>4.32E-03</td>
<td>0.28</td>
<td>0.82</td>
<td>1.08E-02</td>
<td>83.70</td>
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<tr>
<td>3_1</td>
<td>19.48</td>
<td>83.55</td>
<td>2.96E-03</td>
<td>0.23</td>
<td>0.83</td>
<td>6.46E-03</td>
<td>100.53</td>
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<tr>
<td>11_2</td>
<td>20.20</td>
<td>90.93</td>
<td>2.48E-03</td>
<td>0.21</td>
<td>0.83</td>
<td>5.17E-03</td>
<td>109.21</td>
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<tr>
<td>12_1</td>
<td>19.80</td>
<td>84.04</td>
<td>1.47E-03</td>
<td>0.14</td>
<td>0.97</td>
<td>3.18E-03</td>
<td>121.24</td>
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</tbody>
</table>
Table 4 - Measured permeability. S = steady state flux technique; T = transient pressure technique.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Permeability (mD)</th>
<th>Log Permeability (mD)</th>
<th>Analytical Method</th>
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<tr>
<td>1_2</td>
<td>2860</td>
<td>3.46</td>
<td>S</td>
</tr>
<tr>
<td>5_2</td>
<td>3370</td>
<td>3.53</td>
<td>S</td>
</tr>
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<td>13_1</td>
<td>1294</td>
<td>3.11</td>
<td>S</td>
</tr>
<tr>
<td>14_1</td>
<td>2633</td>
<td>3.42</td>
<td>S</td>
</tr>
<tr>
<td>4_1</td>
<td>1240</td>
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<td>S</td>
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<td>S</td>
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<td>11_2</td>
<td>58</td>
<td>1.76</td>
<td>S</td>
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<tr>
<td>11_2</td>
<td>11.2</td>
<td>1.05</td>
<td>T</td>
</tr>
<tr>
<td>12_1</td>
<td>5.9</td>
<td>0.77</td>
<td>T</td>
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</table>
Table: Results of multiple regression analysis

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>R</th>
<th>R^2</th>
<th>n</th>
<th>Std. Error</th>
<th>Interc</th>
<th>Partial Regression Coeff</th>
<th>Regression Equation</th>
</tr>
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<tbody>
<tr>
<td>BGR</td>
<td>0.98</td>
<td>0.96</td>
<td>65</td>
<td>5.12E-02</td>
<td>-5.12E-2</td>
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<tr>
<td>Contact Length</td>
<td>0.89</td>
<td>0.80</td>
<td>63</td>
<td>1.44E-03</td>
<td>-1.44E-03</td>
<td>GVR + (2.95E-03)</td>
<td></td>
</tr>
<tr>
<td>Avg. Pore Area</td>
<td>0.89</td>
<td>0.80</td>
<td>63</td>
<td>3.28E-03</td>
<td>-3.28E-03</td>
<td>GVR + (3.26E-02)</td>
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<tr>
<td>Pore Size Vari (LogSTD)</td>
<td>0.69</td>
<td>0.65</td>
<td>63</td>
<td>8.26E-02</td>
<td>8.26E-02</td>
<td>LogSTD = -3.03 + (6.03E-02)</td>
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<td>Specific Surface</td>
<td>0.69</td>
<td>0.65</td>
<td>63</td>
<td>7.86</td>
<td>7.86</td>
<td>SSA = 144.47 + (-3.14)</td>
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<tr>
<td>Pore Shape Factor (SSA)</td>
<td>0.69</td>
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<td>63</td>
<td>2.91E-02</td>
<td>2.91E-02</td>
<td>SF = 8.52E-01 + (-9.22E-03)</td>
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<tr>
<td>Number of Pores</td>
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<td>0.81</td>
<td>63</td>
<td>48.32</td>
<td>48.32</td>
<td>P = 133.98 + (-5.28E-01)</td>
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</table>

<table>
<thead>
<tr>
<th>Dependent Variable</th>
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<th>n</th>
<th>Std. Error</th>
<th>Interc</th>
<th>Partial Regression Coeff</th>
<th>Regression Equation</th>
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<td>Log Permeability</td>
<td>0.99</td>
<td>7</td>
<td>1.45E-01</td>
<td>2.61</td>
<td>-4.77</td>
<td>IPERM = 2.61 + (1.45E-01)</td>
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</table>

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>R</th>
<th>n</th>
<th>Std. Error</th>
<th>Interc</th>
<th>Ln(Porosity)</th>
<th>Partial Regression Coeff</th>
<th>Regression Equation</th>
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</tr>
</tbody>
</table>
### Table 7 - Permeability prediction parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Log Meas. Permeability (mD)</th>
<th>Log Raw Kozeny-Carman (mD)</th>
<th>Log Predicted Permeability (mD)</th>
<th>Calibrated Constant of Proportionality</th>
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<tr>
<td>1_2</td>
<td>3.46</td>
<td>3.54</td>
<td>3.59</td>
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