Permeability, porosity, and grain-size distribution of selected Pliocene and Quaternary sediments in the Albuquerque Basin

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Permeability, porosity, and grain-size distribution of selected Pliocene and Quaternary sediments in the Albuquerque Basin

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Abstract

As part of an investigation of natural and artificial recharge in the northern Albuquerque Basin, ten outcrops of aquifer-related Pliocene and Quaternary sediments were studied in the Albuquerque municipal area. Permeability of surface exposures were measured with a lightweight syringe-based air-minipermeameter. Permeability was measured in situ, porosity of the deposit was determined, and a sediment sample was taken from the point of measurement. Grain-size distributions of sediment samples were determined by mechanical sieving. Permeability was correlated with porosity, degree of cementation, and a number of grain-size-distribution parameters of the outcrop samples. Porosity is not a good estimator of permeability, as a weak correlation between porosity and permeability was observed. Sandy sediments with relatively minor amounts of cementation were found to have reduced permeability. A strong correlation was observed between measured permeability and mean grain size, and measured permeability and the Kruger effective diameter. Correlation of permeability with the 10 and 20% passing sieve diameters is also high. Grain-size-distribution parameters generally correlate better with measured permeability if grains larger than 2 mm in diameter are excluded from the samples before calculating distribution parameters. Multiple regression analysis was used to formulate predictive permeability equations based on grain-size-distribution parameters. A regression based on d_{10} and mean grain size explains 78% of the variability in permeability values of the outcrop samples. Several commonly used empirical permeability equations based on porosity and grain-size distribution correlate poorly with measured permeability.

Introduction

Published permeability equations based on the porosity and grain-size distribution of sandy sediments are used by researchers to estimate the permeability of well core. These equations, however, are based on empirical studies, and the results are not necessarily transferable from one location to another. It is therefore important to determine which permeability equations are appropriate for use in the northern Albuquerque Basin. In this study, measured permeability was compared to permeability values derived from a number of commonly used permeability equations, and multiple regression analysis was applied to sample grain-size-distribution parameters to generate predictive permeability equations for use on sediments common to the shallow subsurface of the Albuquerque Basin.

Estimation of permeability from grain-size distributions can be used to check permeability values obtained by other methods. Slug test and pump test permeability data are influenced by well construction and rely on a number of assumptions, and geophysical well-log analysis provides only relative permeability values. If quality core samples are obtained from wells, the resolution of permeability estimations based on sedimentary texture is better than those obtained from slug tests or pump tests, and may be used to calibrate permeability estimates from geophysical well-log analysis.

Methods

Outcrops of river alluvium, valley-border alluvium, piedmont-slope alluvium, and upper Santa Fe Group hydrostratigraphic units were sampled in the Albuquerque municipal area (Hawley and Haase, 1992). The outcrops selected are typical deposits of the respective hydrostratigraphic units and have a large exposed area. Samples were collected from every major sedimentary structure or bed in each outcrop. Outcrop sampling included an in situ measurement of permeability and the collection of sediment samples for grain-size analysis and calculation of porosity. The degree of cementation of the samples was also recorded. Sampling was limited to deposits with permeabilities in the range measurable by the air-minipermeameter, which is approximately 0.8 to 270 darcys (approximately 0.5 to 165 m/day, for water at 10°C). This range corresponds with permeabilities common to poorly to moderately lithified sand and silty sand deposits in the Albuquerque Basin.

The air-minipermeameter used in this study is a lightweight device that is considerably more portable than compressed-gas-type permeameters. It weighs approximately 2 kg, measures 13×15×23 cm, and is supported by a neck strap when in use. Its primary components are a 100-cm^3 ground-glass syringe, timing circuit, and tip seal to direct air flow through the soil matrix. The syringe piston falls at a steady rate under its own gravitational force, applying a small constant pressure through the tip seal. A digital stopwatch wired to optical switches measures the time required for a known volume of air to diffuse through the outcrop material. This design allows rapid, nondestructive in situ measurement of outcrop permeability. Davis et al. (1994) discuss the design, operating principles, and calibration of the air-minipermeameter.

Permeability was measured parallel to bedding and perpendicular to the outcrop surface because many outcrop surfaces are vertical or nearly vertical. A plug of sediment was cored from the outcrop at the point where permeability was measured, allowing comparison of permeability and grain-size-distribution parameters. A second sediment sample was collected adjacent to the point where permeability was measured to determine sample porosity. Porosity was calculated from the bulk mass density and the particle mass density where

$$n = 1 - \frac{\rho_{bulk}}{\rho_{grain}} \quad (1)$$

(Lambe, 1951).

Qualitative estimates of cementation were recorded in the field. The outcrop samples ranged from uncemented to moderately cemented. Samples labeled moderately cemented were still somewhat friable and were easily disaggregated with a mortar and pestle. Dissolution of cements was not required, and many samples required no disaggregation beyond what occurred in sampling and handling. Phreatic and pedogenic cementation was not differentiated. A set of 21 sieves were used for grain-size analysis using standard sieving procedures. Sieve diameters ranged from 2.00 mm to 0.045 mm. Most of the outcrop samples had only small percentages of silt and clay, and no wet-sieving was necessary.

Particle-size-distribution statistics and representative diameters were calculated for two sets of data. The first group includes the entire particle-size distribution of the samples, whereas the second excludes all grains retained on the 2-mm sieve. Moment calculations, as opposed to graphical methods, were used to calculate the mean, standard deviation, and skewness of each outcrop sample. Effective diameters were determined from common cumulative percent graphs. The effective diameter d_{10} is simply the sieve diameter through which only the smallest 10% of the sample by weight will pass. An effective diameter based on the entire grain-size distribution was also computed for each sample. This effective diameter d_e was proposed by Kruger (Vukovic and Soro, 1992), and is calculated as

$$\frac{1}{d_e} = \sum_{i=1}^{N} \frac{\Delta g_i}{d_i} \qquad (2)$$

where g_i is the fractional percent weight retained on individual sieves, and d_i is the mean grain diameter in millimeters of the corresponding fraction. Effective diameters were determined in millimeters, then converted to phi units for subsequent correlations with permeability. Phi units are calculated as $\phi = -\log_2 d$, where d is grain diameter in millimeters.

The SYSTAT statistical software package, Version 5.2, was used to determine Pearson correlation coefficients for measured permeability and a number of grain-size-distribution and outcrop parameters. The same software was used to formulate predictive permeability equations. Stepwise multiple regression analysis was applied to various parameters found to have high correlation with the measured permeability of the outcrop samples.

Results

Permeability, porosity, and cementation

There is a poor correlation between porosity and permeability among the samples analyzed in this study. Inspection of sample data indicates that the degree of cementation, sorting, and packing influences the relationship between porosity and permeability. Fig. 1 is a scatter plot showing the association between porosity and permeability. Most outcrop samples with high porosity values and low measured permeability are moderately cemented, and samples with high permeability and low porosity values tend to be coarse and poorly sorted. Fig. 2 displays the observed relationship between cementation and permeability of the outcrop samples in which permeability decreases with higher degrees of cementation.

Permeability and grain-size-distribution parameters

Measured permeability was correlated with a number of particle-size parameters. Scatter plots were generated to compare measured permeability with a number of effective diameters and particle-size-distribution parameters. There is a strong correlation between permeability and effective diameters representing the size and abundance of fine grains in the sediment samples. Pearson correlation coefficients for permeability correlated with sample parameters are in Table 1. Complete sample values were derived from the entire sediment sample, and cut sample values were calculated with clasts larger than 2 mm in diameter excluded. Data points are clustered more densely for the cut samples than for the complete distributions. However, correlation of measured permeability with d_{10}, d_{15}, and d_{17} in phi units is better for the complete samples than the cut samples.

Figs. 3 and 4 are scatter plots of d_{10} and d_{20} of the complete samples plotted with measured permeability. The d_{10} diameter in millimeters has a correlation of $r = 0.803$ with measured permeability. The effective diameter d_{10} in phi units has a correlation coefficient of $r = 0.836$, whereas d_{20} has a correlation coefficient of $r = 0.818$. Squaring the correlation coefficients reveals how much of the variance in the permeability values is explained by each parameter. The effective diameter d_{10} in millimeters explains 64.5% of the variability in permeability, and d_{10} in phi units explains 69.9% of the variability in the permeability measurements. The Kruger effective diameter, determined from the entire grain-size distribution of each sample, has a correlation of $r = 0.821$ with measured permeability (Fig. 5).

The correlation of $(d_{10})^2$, $(d_{17})^2$, and $(d_{20})^2$ with permeability for the complete samples is considerably worse than correlation with unsquared effective diameters. The effective diameter term $(d_{10})^2$ is used in several published permeability equations, including the Beyer and Hazen equations (Vukovic and Soro, 1992), and is

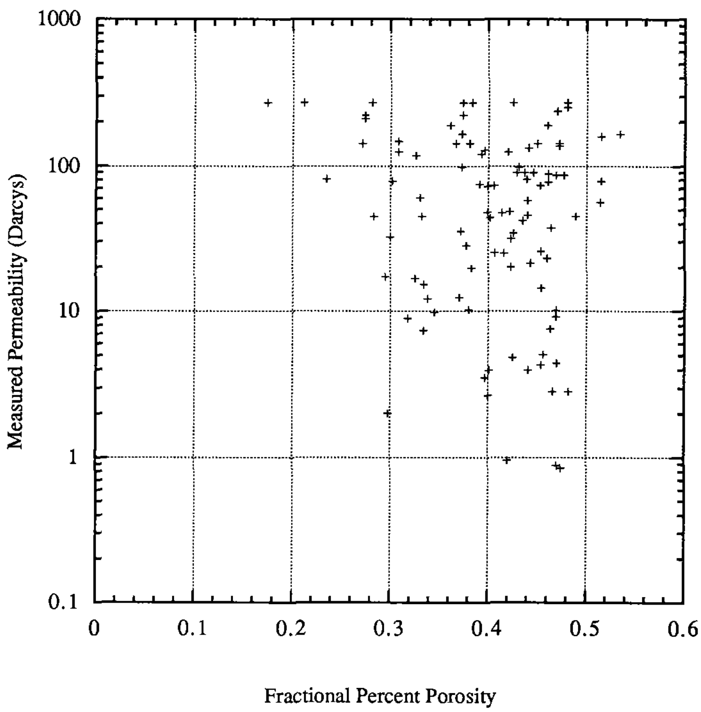

FIGURE 1—Influence of porosity on permeability.

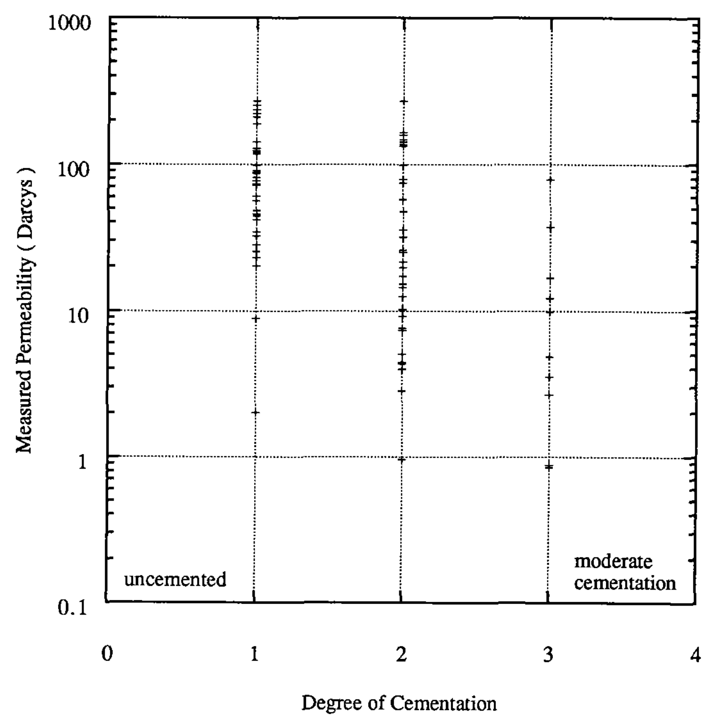

FIGURE 2—Influence of cementation on permeability.

found in this study to have a correlation coefficient of only $r = 0.654$ with measured permeability. Correlation is slightly better with squared diameters taken from the cut samples.

Grain-size-distribution parameters, determined by moment measurements, are compared with permeability. Mean grain size is the only traditional statistical distribution parameter with meaningful correlation with permeability. Skewness, percent

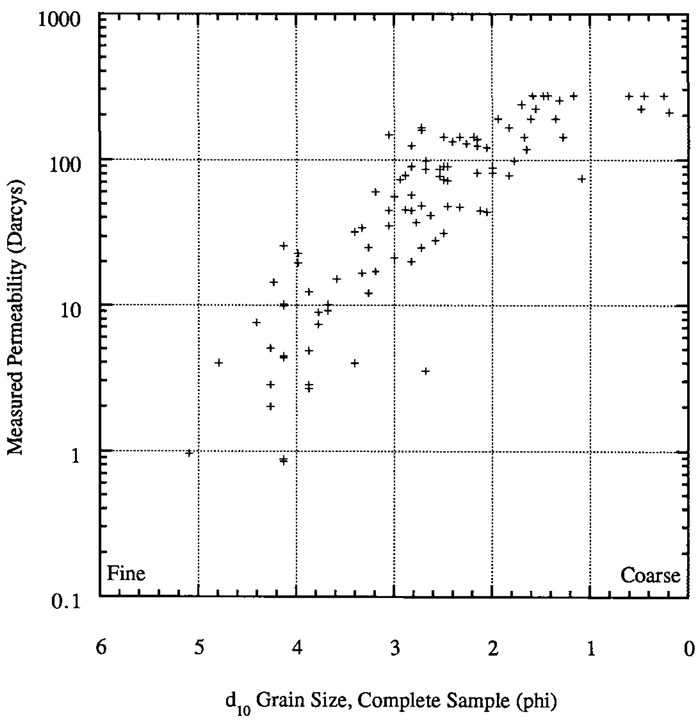

FIGURE 3—Influence of d_{10} phi on permeability, complete distribution.

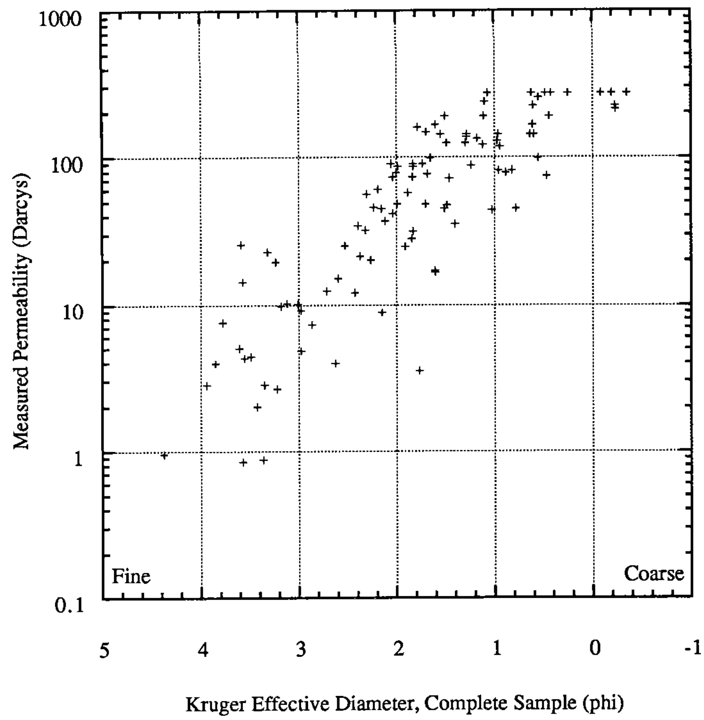

FIGURE 5—Influence of Kruger effective diameter on permeability.

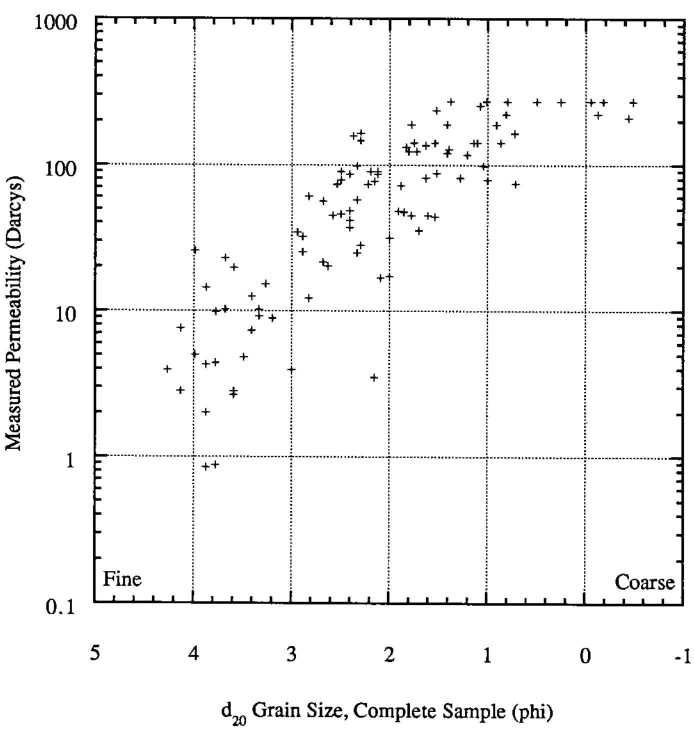

FIGURE 4—Influence of d_{20} phi on permeability, complete distribution.

fines, and degree of cementation have correlation coefficients near $r = 0.5$. The standard deviation of the samples evaluated in this study has essentially no correlation with measured permeability.

Effective diameters and grain-size-distribution parameters were correlated with the $\log_{10}$ of measured permeability in darcys. As shown in Table 2, correlation is slightly better with the

TABLE 1—Pearson correlation coefficients for measured permeability and grain-size-distribution parameters. Cut samples exclude grains larger than 2 mm in diameter.

Variable	Complete samples	Cut samples
d_{10}, mm	0.803	0.819
d_{15}, mm	0.794	0.837
d_{17}, mm	0.789	0.839
d_{20}, mm	0.782	0.842
d_{50}, mm	0.571	0.812
Kruger, mm	0.821	0.844
d_{60}/d_{10}, mm	−0.049	0.154
d_{10}^2, mm	0.654	0.754
d_{17}^2, mm	0.636	0.765
d_{20}^2, mm	0.633	0.762
d_{10}, phi	−0.836	−0.796
d_{15}, phi	−0.833	−0.815
d_{17}, phi	−0.827	−0.818
d_{20}, phi	−0.818	−0.823
d_{50}, phi	−0.680	−0.782
Kruger, phi–0.801	−0.791	
d_{60}/d_{10}, phi–0.509	−0.714	
Mean	−0.718	−0.785
Standard deviation	−0.034	−0.102
Skewness	0.321	0.505
Percent fines	−0.407	−0.405
Percent pebbles	0.478	—
Max. clast diameter, phi	−0.402	—
Porosity	−0.198	−0.198
Cementation	−0.444	−0.444

TABLE 2—Pearson correlation coefficients for $\log_{10}$ of measured permeability and grain-size-distribution parameters. Cut samples exclude grains larger than 2 mm in diameter.

Variable	Complete samples	Cut samples
d_{10}, mm	0.669	0.749
d_{15}, mm	0.659	0.747
d_{17}, mm	0.655	0.746
d_{20}, mm	0.649	0.746
d_{50}, mm	0.524	0.734
Kruger, mm	0.723	0.813
d_{60}/d_{10}, mm	0.000	0.218
d_{10}, phi	−0.851	−0.846
d_{15}, phi	−0.842	−0.856
d_{17}, phi	−0.848	−0.861
d_{20}, phi	−0.834	−0.863
d_{50}, phi	−0.741	−0.852
Kruger, phi	−0.858	−0.885
d_{60}/d_{10}, phi	−0.396	−0.668
Mean	−0.776	−0.872
Standard deviation	−0.018	−0.117
Skewness	0.261	0.439
Percent fines	−0.634	−0.634
Percent pebbles	0.397	—
Max. clast diameter, phi	−0.430	—
Porosity	−0.161	−0.161
Cementation	−0.611	−0.611

TABLE 3—Pearson correlation coefficients for measured permeability and published permeability equation values. Cut samples exclude grains larger than 2 mm in diameter.

Equation	Complete samples	Cut samples
Beyer	0.629	0.713
Hazen	0.697	0.653
Kruger	0.783	0.723
USBR	0.584	0.712
Zamarin	0.753	0.690

effective diameters in phi units than in millimeters. The correlation coefficient between d_{10} and permeability is $r = 0.851$ for the complete samples, and $r = 0.846$ for the cut samples. Correlation between d_{20} and permeability for the complete samples is $r = 0.834$, and $r = 0.863$ for the cut samples. The mean grain diameter of the cut samples correlate well with the $\log_{10}$ of measured permeability, with a coefficient of $r = 0.872$. Squaring this term shows that 76% of the variability in the measured permeability values can be explained by the mean grain size of the samples. Correlation of the $\log_{10}$ of permeability with the standard deviation, skewness, percent pebbles, and maximum intermediate diameter of the largest clast of the samples is poor.

Comparison of measured permeability with published permeability equations

Table 3 presents Pearson correlation coefficients for measured permeability values compared to values predicted by a number of published empirical permeability equations. Comparisons are based on 100 outcrop samples, representing the most common beds in the deposits studied in this report, having permeabilities in the measurement range of the air-minipermeameter. The Beyer, Hazen, Kruger, USBR, and Zamarin equations were applied to the outcrop samples. All equations are taken from Vukovic and Soro (1992). The original equations predict hydraulic conductivity,

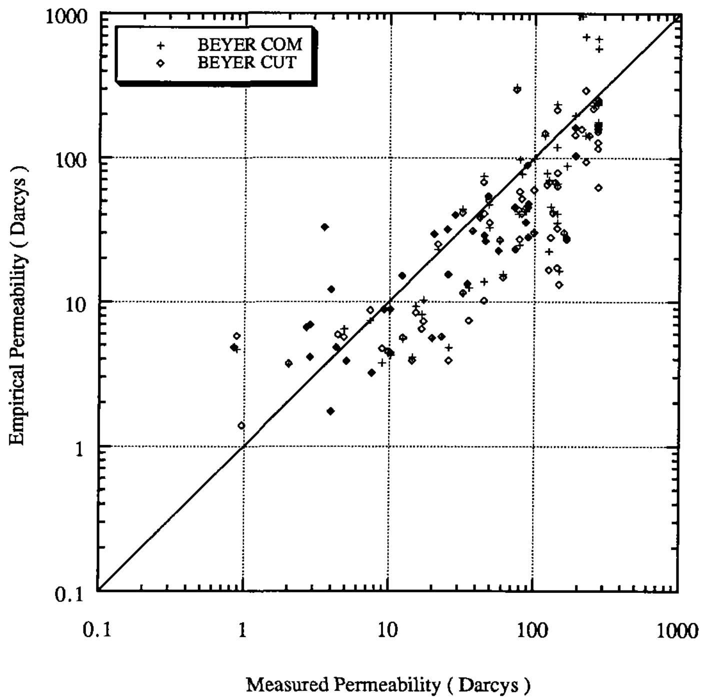

FIGURE 6—Permeability predicted by Beyer equation, compared to measured values.

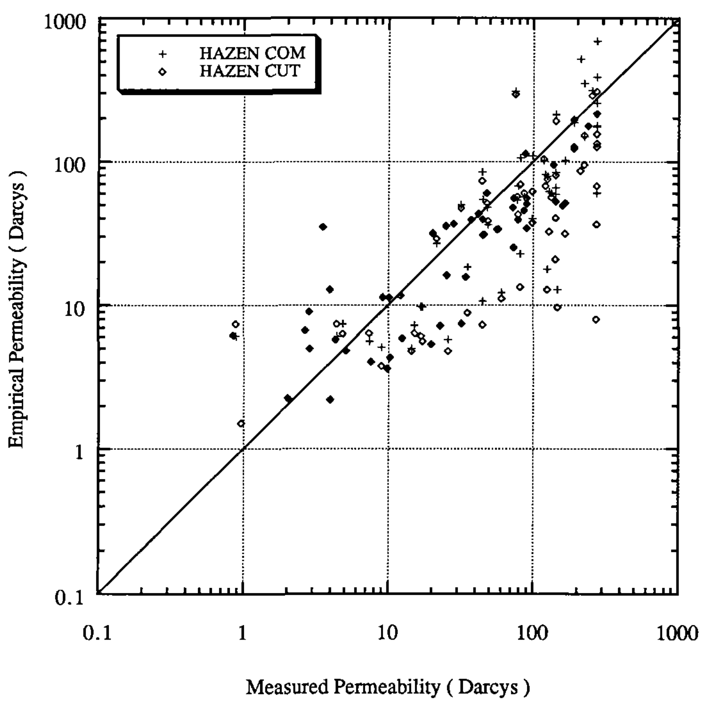

FIGURE 7—Permeability predicted by Hazen equation, compared to measured values.

which is converted to darcys for comparison with measured permeability values. A water temperature of 10°C was used for all conversions. Figs. 6 through 10 compare measured permeability values to those predicted by the equations listed below.

The Beyer equation has the form

$$K = C \cdot (d_{10})^2 \qquad (3)$$

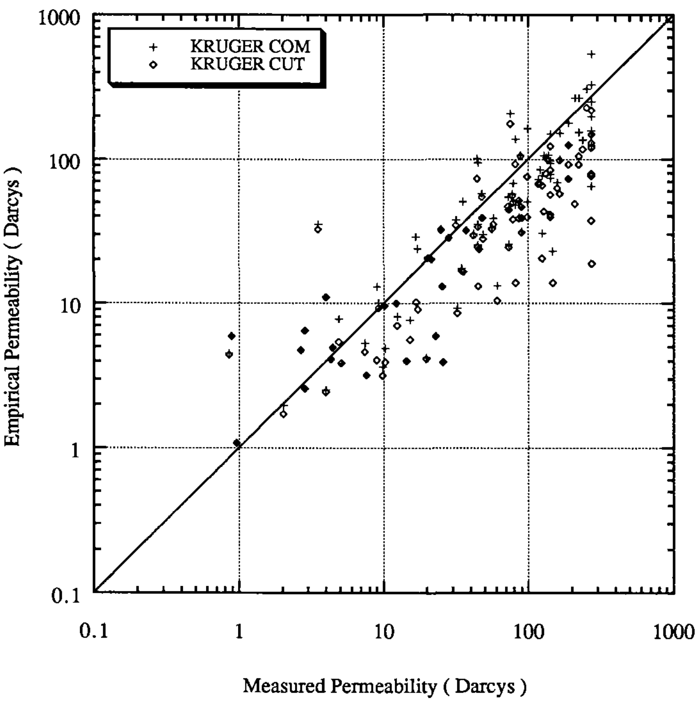

FIGURE 8—Permeability predicted by Kruger equation, compared to measured values.

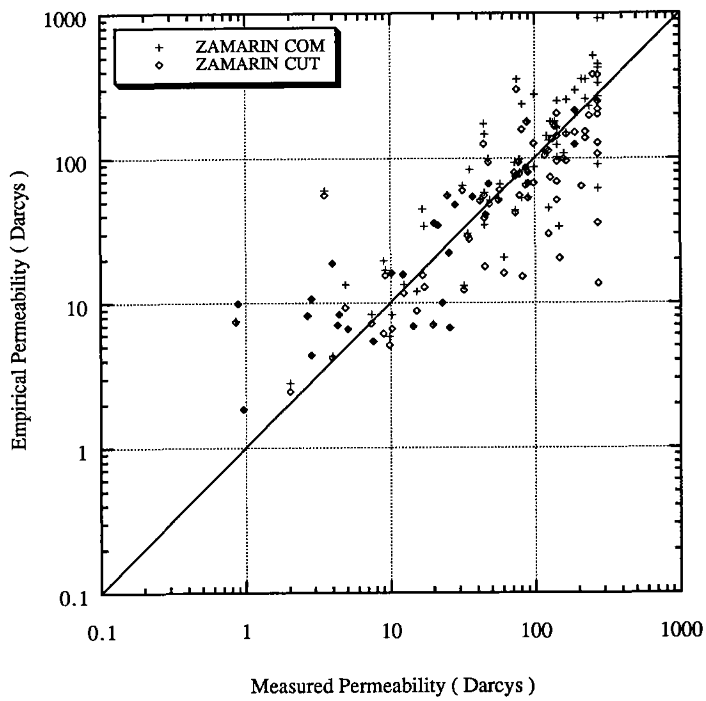

FIGURE 10—Permeability predicted by Zamarin equation, compared to measured values.

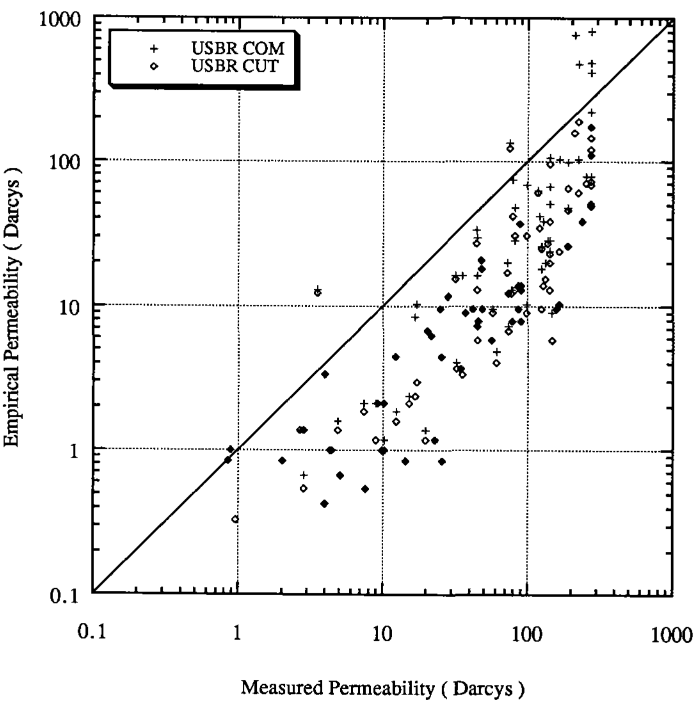

FIGURE 9—Permeability predicted by USBR equation, compared to measured values.

where the empirical C term is $4.5\times10^{-3}\log(500/U)$. The effective diameter d_{10} is in mm, U is the uniformity coefficient d_{60}/d_{10}, and K is hydraulic conductivity in meters per second. The Beyer equation is the only equation using the coefficient of uniformity instead of a porosity term common to several of the other equations applied here. The Beyer equation has a correlation of $r = 0.713$ with the measured permeability of the cut samples, providing one of the best fits of the models applied here.

The Hazen equation is

$$K = A \cdot C \cdot t\,(d_{20})^2 \qquad (4)$$

The term A determines the dimensions of hydraulic conductivity, being 1 for K in meters per day, and 0.00116 for K in centimeters per second. C is a function of porosity, approximated by $C = 400+40(n-26)$, where n is percent porosity. The t term is a correction for water viscosity, $0.70+0.03(^{\circ}C)$, and d_{10} is in millimeters. Measured permeability values correlate well with Hazen values for the complete samples, with a correlation coefficient of $r = 0.697$. Hazen values for the cut samples tend to underestimate permeability.

The Kruger equation is

$$K = 240\,\frac{n}{(1-n)^2}\,d_e^2 \qquad (5)$$

The effective diameter d_e is in millimeters, calculated as described above. Fractional percent porosity is n, and K is reported in meters per day. This equation provides the best correlation with permeability for both the complete and cut samples, with correlation coefficients of $r = 0.783$ and $r = 0.723$ respectively.

The USBR equation is

$$K = 0.36 \cdot (d_{20})^{2.3} \qquad (6)$$

The effective diameter d_{20} is reported in millimeters and hydraulic conductivity is in centimeters per second. Permeability values calculated by this equation underestimate permeability fairly significantly. Correlation of the cut-sample values with measured permeability is $r = 0.712$, and correlation with complete samples is $r = 0.584$.

The Zamarin equation has the form

$$K = 8.07\,\frac{n^3}{(1-n)^2}\,C \cdot t \cdot d_e^2 \qquad (7)$$

The C term is a function of porosity, equaling $(1.275-1.5n)^2$, with

n as a fractional percent. The value for t is 0.807 for a water temperature of 10°C. The variable d_e is similar to the Kruger effective diameter term, which is substituted here. Hydraulic conductivity is reported in meters per day. Correlation with measured permeability for the complete samples is $r = 0.753$. Correlation with the cut samples is $r = 0.690$, and permeability values are fairly accurate in general.

Multiple regression analysis

Multiple regression analysis was applied to sample parameters to generate predictive permeability equations. Correlation of these simple regressions compare favorably to several more complex published permeability equations that require an estimation of porosity. Grain-size-distribution parameters were correlated to measured permeability in darcys and to the $\log_{10}$ of measured permeability in darcys. Table 4 details the regression equations, listing the parameters used in the regressions, Pearson correlation coefficients, and squared correlation coefficients, which reveal the percentage of the variability of the permeability explained by the regressions.

Two regressions with measured permeability and grain-size-distribution parameters are presented. The first uses d_{20} in millimeters as the sole input parameter. The d_{20} diameter regression has a correlation of $r = 0.842$ with the measured permeability (Fig. 11). The second regression with measured permeability includes parameters from the entire grain-size distribution. Parameters include the Kruger effective diameter in millimeters, mean grain size in phi units, and the weight percentage of silt and clay in the sample. This model is referred to as MSP1 (Fig. 12), and has a correlation of $r = 0.849$ with measured permeability. Both models use parameters from the cut-sample distributions. The models slightly overestimate permeability in the lower ranges, but the fit over the entire range of permeabilities is good.

Regression analysis was repeated with the $\log_{10}$ of measured permeability. For each sample parameter, correlation with the log of permeability is better than correlation with permeability in darcys. This indicates that permeability tends to be log-normally distributed, as suggested by a number of researchers (Nelson, 1994). As listed in Table 2, effective diameters in millimeters do not correlate well with the log of permeability, so diameters in phi units are used in the following regressions. Regressions using d_{10} and d_{20} for the complete and cut distributions all yield similar results, and a correlation coefficient of $r = 0.854$ is observed with d_{10} of the cut distribution (Fig. 13). Overestimation of the lower permeability values is still present but to a lesser degree than with the correlations to permeability. Regressions LMSP1 and LMSP4 show good correlation with the log of measured permeability for both the complete and cut distributions. The models for the cut samples are slightly better than for the complete samples. Model LMSP1 uses the Kruger diameter in phi units, mean grain size, and weight percent fines as input parameters, and has a correlation coefficient of $r = 0.887$ with the log of measured permeability. Model LMSP4 relies on d_{10} diameters in phi units and mean grain size to achieve a correlation of $r = 0.882$ with the log of measured permeability. Figs. 14 and 15 show the results from models LMSP1 and LMSP4.

Discussion

One of the interesting findings of this study is a slight negative correlation between porosity and permeability. If cementation and sorting of the samples are considered, the negative correlation is partially explained. Samples with relatively high porosity values and low measured permeability are moderately cemented. This suggests that the permeability of sandy sediments is reduced by relatively minor amounts of cementation. Cemented samples were not examined in detail, but it is possible that cementation is sufficiently developed to close pore throats (meniscus cements) but not so prevalent as to cause a large reduction in porosity. The samples with low porosity and high permeability values can also be characterized. Samples in this region of the plot are primarily scour and fill structures, being poorly sorted with an abundance of coarse grains. A high percentage of large grains (with zero porosity) surrounded by fine matrix material increases the bulk density of the sample, resulting in a lowered porosity value (Pryor, 1973). If moderately

TABLE 4—Permeability regression analysis.

	Pearson correlation r	r^2
Regressions with measured permeability:		
d_{20} mm cut		
425.80 (d_{20} mm cut) – 15.88	0.842	0.709
MSP1 cut		
372.36 (Kruger mm cut)		
– 16.57 (mean cut)		
+ 3.32 (% fines cut) + 0.58	0.849	0.721
Regressions with $\log_{10}$ of measured permeability:		
d_{10} phi cut		
– 0.590 (d_{10} phi cut) + 3.298	0.844	0.712
LMSP1 cut		
– 0.456 (Kruger phi cut)		
– 0.145 (mean cut)		
– 0.003 (% fines cut)		
+ 2.802	0.887	0.787
LMSP4 cut		
– 0.221 (d_{10} phi cut)		
– 0.374 (mean cut) + 2.865	0.882	0.778

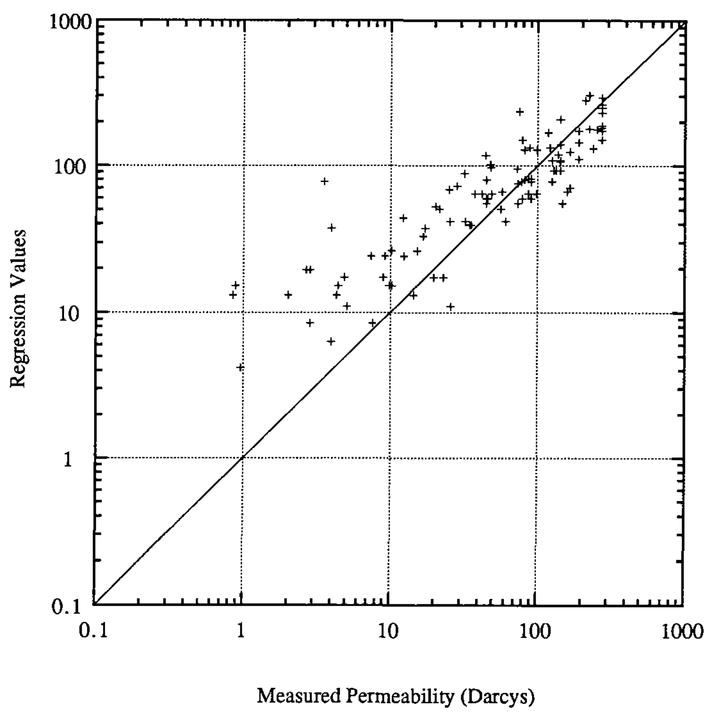

FIGURE 11—Permeability predicted by d_{20} regression, compared to measured values.

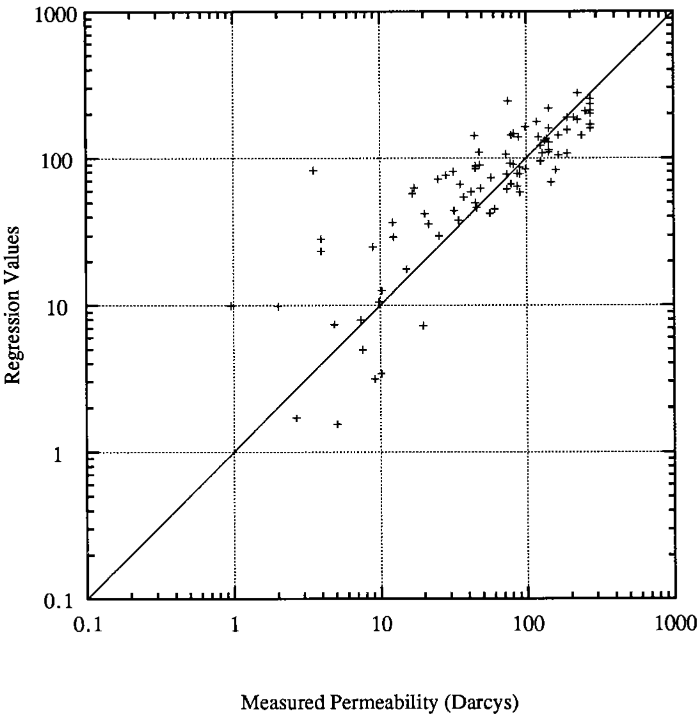

FIGURE 12—Permeability predicted by regression MSP1, compared to measured values.

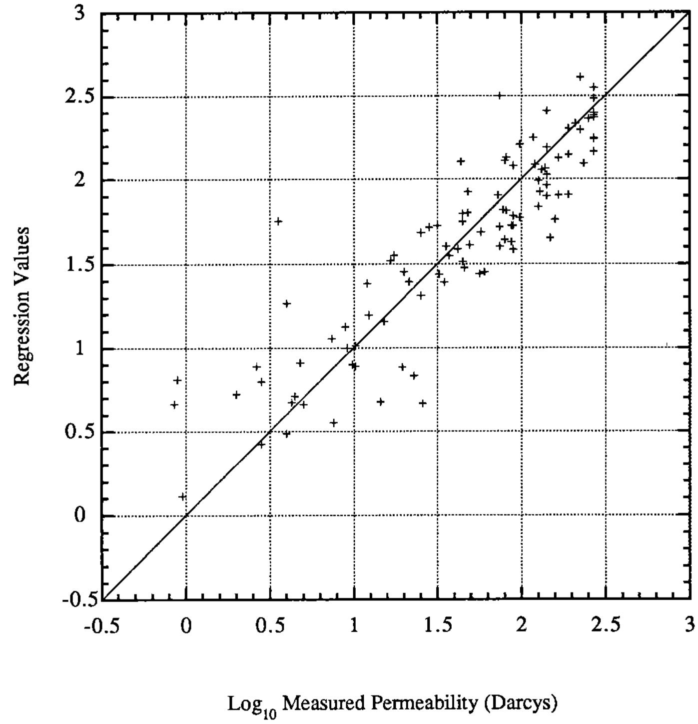

FIGURE 14—Permeability predicted by regression LMSP1, compared to measured values.

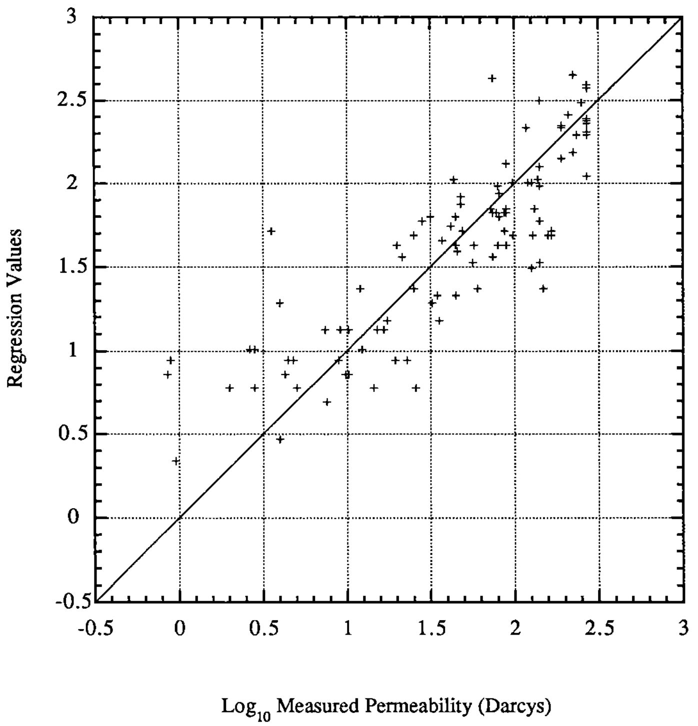

FIGURE 13—Permeability predicted by d_{10} regression, compared to measured values.

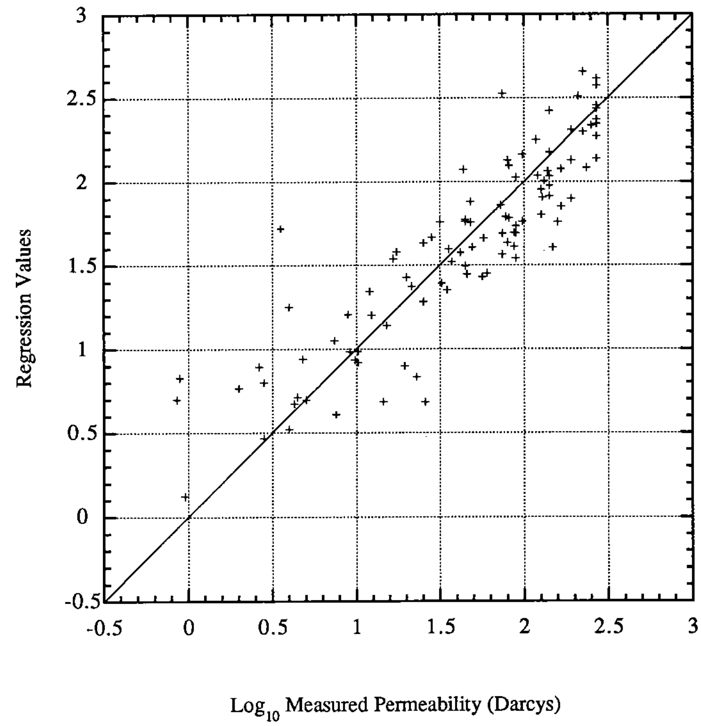

FIGURE 15—Permeability predicted by regression LMSP4, compared to measured values.

cemented samples and coarse, poorly sorted samples are removed from the plot, correlation between porosity and permeability remains poor.

Some researchers have documented a strong positive relationship between porosity and permeability, as summarized by Nelson (1994). The motivation for most of these studies was evaluation of the quality of reservoir rocks for oil and gas recovery. Consequently, studies have dealt primarily with sandstone that has been buried to significant depths and compacted by the weight of overlying sediments. Diagenesis is common at depth, with pore-filling cements and compaction causing reductions in porosity and permeability, resulting in a positive correlation between porosity and permeability. Inspection of plots relating permeability to porosity in many of these reservoir studies reveals that permeability exceeds 1 darcy in only a few cases, and porosity values range from 2 to 30%. Considering that sediments in the study area were never buried to significant depths, it is not surprising that porosity-permeability trends are poorly defined in the deposits examined in this study.

It is recognized that cementation has a significant influence on permeability, but cementation is difficult to quantify in outcrop, much less in the subsurface. The inclusion of a term for sample cementation did not significantly improve any of the regression models. Given the difficulty of assigning cementation values in a consistent manner and the small improvements they made in the multiple regressions, they were not included in any of the regression equations. However, it is noted that if sediments are more than moderately cemented, the influence on permeability is significant, and relationships between grain-size distributions and permeability are obscured.

For nearly every effective diameter and grain-size-distribution parameter, correlation with permeability is better with the cut samples than with the complete samples (Tables 1 and 2). An abundance of large grains in a sample of average sorting will increase the mean grain size, but if smaller grains fill the spaces between the larger grains, the permeability of the sample will not be highly dependent on mean grain size. Excluding grains larger than 2 mm in diameter from the samples results in a better correlation of mean grain size and permeability. Higher correlation coefficients generally exist if effective diameters from the cut distribution are converted to phi units and correlations are made with the $\log_{10}$ of measured permeability. Correlations of permeability with some effective diameters are as good as correlations with the Kruger diameter and mean grain size. This is a significant finding because much less sieving is required to determine effective diameters of d_{20} and smaller, compared to mean grain size and the Kruger diameter. Sieves covering the entire range of grain diameters are required to determine mean grain size, whereas d_{10} and d_{20} can be accurately determined with half as many sieves.

A number of rational and empirical equations relating permeability to porosity and grain-size parameters exist. Many of these models are based on an empirical relationship developed by Kozeny, and later modified by Carmen, known as the Kozeny–Carmen equation (Bear, 1972). The two basic components of the equation are a particle-size (diameter) term and a porosity term. The diameter term is squared, derived as an expression of specific surface area with respect to a unit volume of porous medium. The porosity term is $n^3/(1-n)^2$, where n is fractional percent porosity (Bear, 1972). Although the squared diameter term has a proven theoretical and empirical basis, it was not found to be appropriate in this study because the results presented here suggest that unsquared diameter terms correlate better with measured permeability. With the exception of the Beyer and USBR equations, the permeability equations applied in this study include a porosity term. The poor correlation of porosity and permeability observed in the outcrop samples appears to contribute to the inaccuracy of the empirical equations. The difficulty of obtaining porosity values, coupled with the poor correlation of porosity and permeability observed in the study area, suggest that it may not be worthwhile to collect porosity values when evaluating the permeability of sandy sediments in shallow aquifer units in the Albuquerque Basin. A major advantage of the regression equations formulated in this study is the exclusion of a porosity term.

Empirical permeability equations were applied to the outcrop samples, allowing comparison of measured and predicted permeability values. The Pearson correlation coefficients for predicted and measured permeability values are listed in Table 3. The Kruger and Zamarin equations yield the highest correlations with measured permeability, with the complete samples yielding better results than the cut samples. The Beyer and USBR equations correlate equally well with measured permeability when applied to the cut samples, but the Beyer equation slightly underestimates permeability, and the USBR equation significantly underestimates permeability.

Multiple regression analysis was applied to grain-size-distribution parameters to formulate predictive permeability equations for use on sediments common to the northern Albuquerque Basin. Correlation with measured permeability yields coefficients ranging from $r = 0.785$ to $r = 0.854$ for regressions based on a single effective diameter, and coefficients as high as $r = 0.887$ are attained with regressions including mean grain size, Kruger effective diameter, and percent fines. Inspection of scatter plots of the regressions reveals that values are centered around the 1:1 line of measured to predicted permeability. This is significant because it shows that there is no systematic overestimation or underestimation of permeability by these equations.

The regression equations developed here are based on a relatively small data set. Sampling was limited to sediments with permeability between approximately 0.8 and 270 darcys. It is uncertain whether the truncated distribution of permeability measurements influences the regression equations. The accuracy of predicted permeability values beyond the measurement range of the air-minipermeameter is unknown. The regression equations were not applied to an independent data set, and further validation and refinement of these regressions may be necessary before they are widely applied to sediments of the northern Albuquerque Basin.

The prediction of permeability based on the grain-size distribution of uncemented sandy sediments is appropriate for use only in the shallow subsurface. Compaction curve studies show that porosity decreases exponentially with depth (Baldwin and Butler, 1985). Sediments in the Albuquerque Basin are subject to compaction with increased depth of burial, altering the original packing of the sediments. With progressive compaction there is a reduction in pore volume, and estimation of permeability based on grain-size distribution (and the inferred depositional packing) becomes problematic.

Conclusions

There is no clear relationship between porosity and measured permeability in outcrop samples from shallow aquifer units in the northern Albuquerque Basin. However, a number of grain-size-distribution parameters correlate well with measured permeability. Mean grain size, the Kruger effective diameter, and effective diameters ranging from d_{10} to d_{20} have high correlation coefficients with measured permeability. Correlations are generally better if grains larger than 2 mm in diameter are excluded from the sample before calculating grain-size-distribution parameters. Cementation in relatively minor amounts has an appreciable influence on the permeability of sandy sediments.

The use of a portable air-minipermeameter allows evaluation of the accuracy of a number of published permeability equations based on porosity and grain-size distribution of sandy sediments. The Kruger and Zamarin equations were found to correlate well with measured permeability, but both equations use porosity values, which are difficult to obtain. Of the equations based on texture alone, the Beyer equation provides the best results. Several of the regression equations generated in this study provide superior correlations with measured permeability. The regressions were developed for use in the study area and have the advantage of not using a porosity term.

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