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INTRODUCTION

In 1988, an experimental research site was established in the Kansas River alluvium near Lawrence, Kansas by the Kansas Geological Survey (Figure 1). This research site, known as the Geohydrologic Experimental and Monitoring Site (GEMS), was envisioned as serving as an area for the development and testing of new technology for describing the physical properties of subsurface material in the complex geologic setting presented by unconsolidated alluvial sequences. Another focus of the research work envisioned for this site was the exploration of the dependence of hydraulic conductivity on measurement scale.

As part of recent work at this site, a sampling device for obtaining relatively undisturbed cores of saturated, unconsolidated coarse sands and gravels has been developed (McElwee et al., 1990). This device allows the variations in the physical properties of the media to be explored at the core scale in considerable detail. In the last two years, over 100 ft of core has been taken through the sand and gravel section of the alluvium. The hydraulic conductivity (K), porosity (n), and the grain-size distribution of these cores have been measured in the laboratory. This presentation describes the initial results of these laboratory analyses.

HYDRAULIC PROPERTIES

The subject of this presentation is the cores obtained from the sand and gravel section of the alluvial sequence underlying GEMS, which, as shown in the cross-section through one of the well nests at the site (Figure 2), extends from 11-21 meters below land surface. The highest percentage of core recovery was obtained from the three wells at which the latest sampler design was employed. These three wells, GEMS26, GEMS41, and GEMS51, are the major focus of this discussion. Cores were also taken from three other wells using an earlier sampler design (Butler et al., 1989). The recovery from these three wells was significantly lower.

Hydraulic conductivity along the axis of the core was measured in the laboratory using a constant-head permeameter. Prior to placement in the permeameter, the cores were carefully cut into sections approximately 15 cm in length. Figure 3 displays profiles of laboratory-measured hydraulic conductivity versus depth at GEMS26, GEMS41, and GEMS51. These profiles suggest that the sand and gravel section of the Kansas River alluvium at GEMS is quite heterogeneous at the core scale. Very distinct lenses of low K are visually apparent at several wells, although there appears to be little continuity of these lenses between wells. Note that the horizontal distance between wells GEMS26 and GEMS41, GEMS26 and GEMS51, and GEMS41 and GEMS51 is 30.79 m, 10.79 m, and 22.0 m, respectively. More closely spaced wells would be required in order to develop an understanding of the lateral continuity of the low K lenses at this site. The profiles of GEMS26 and GEMS51 indicate that hydraulic conductivity appears to have a general trend of increasing with depth. A statistical summary of measured hydraulic conductivity at each well is given in Table 1. Note that variations of over three orders of magnitude are seen in some wells. Since the current convention is to assume that hydraulic conductivity is a log-normally distributed quantity (e.g., Freeze, 1975), the statistics of the log-transformed conductivities are also presented. A comparison of the variance in ln(K) obtained from this study with other studies in material of a similar mean ln(K) (Smith, 1981; Byers and Stephens, 1983; Sudicky, 1986; and Wolf, 1988) indicates that the hydraulic conductivity at this site has considerably more variability than that reported elsewhere.

Figure 4 displays the results of an initial analysis of the correlation structure of ln(K) at the wells of Figure 3. The experimental semivariogram is modelled using a nugget and an exponential structure. The practical range of the exponential model is 1.2 meters. Note that the experimental semivariogram displays an additional increase above 3 meters. We feel that the increase above 3 meters is a product of the trend displayed at wells GEMS26 and GEMS51 on Figure 3. We are in the process of carrying out a more complete analysis of the correlation structure in which we work with data from which the trend has been removed.

Porosity was estimated in the laboratory from the average particle density of the sample (estimated using a pycnometer) and its bulk density. Figure 5 displays profiles of porosity versus depth for the same wells as in Figure 3. The porosity profiles do show some of the same trends as illustrated in the conductivity data. Note, however, that the variation in porosity is much smaller than that seen with hydraulic conductivity.

Many previous workers have observed a relationship between hydraulic conductivity and various grain-size parameters. In order to explore this relationship at GEMS, sieve analyses were performed on all of the collected cores using standard methods (Gee and Bauder, 1986). The sieve data allowed various grain-size parameters to be calculated and their variation with depth to be assessed. The geometric mean grain size was one of the parameters calculated as part of this analysis. Figure 6 displays profiles of mean grain size versus depth for the same wells as used previously. Note that the profiles of mean grain size show considerably more similarity to the conductivity profiles than do the porosity profiles. The use of grain-size parameters to estimate hydraulic conductivity is discussed in a later section. Table 2 displays statistics on both the porosity and mean grain size measurements.

COMPARISON OF CONDUCTIVITY VALUES FROM THE ORIGINAL AND REPACKED CORES

Most previous laboratory work with unconsolidated sand and gravel cores has focussed on the measurement of repacked cores (e.g., Smith, 1981; Sudicky, 1986) as a result of the difficulty in obtaining undisturbed core in the sampling procedure. White (1988) and Uma et al. (1989) discuss the possible problems that might arise when using conductivity values from repacked cores to characterize in-situ values. White (1988), based on a study of five cores, found that hydraulic conductivity estimates from repacked cores were lower and had more variability than the original measurements. Since the sampling procedure employed at GEMS enables relatively undisturbed cores to be obtained, it is a good opportunity to evaluate the difference that might exist between estimates obtained from original and repacked cores.

Permeameter tests on repacked cores were conducted for all of the 200 cores. The repacking was done so that the porosity of the original and repacked cores remained approximately equal. Table 3 presents the results of the repacking experiments. Figure 7 displays profiles of the original and repacked conductivities for the three wells used earlier. The statistics of Table 3 and the profiles of Figure 7 clearly indicate that the repacked cores, on average, had a larger conductivity than the original cores. Although the original and repacked cores had approximately the same porosity, repacking did destroy the original sedimentary structures in the cores. We hypothesize that thin horizontal layers of low conductivity material existed in the original cores and played an important role in controlling the value of K along the axis of the core. The destruction of the layering resulted in this finer material being spread throughout the repacked core, producing less of an effect on the K measurements. An examination of the variance at each well indicates that considerable additional work is required before a conclusive statement about the effect of repacking on the variance of K measurements can be made.

ESTIMATION OF HYDRAULIC CONDUCTIVITY FROM GRAIN-SIZE PARAMETERS

Traditionally, a common approach for estimating field hydraulic conductivity has been through the use of relationships between K and various grain-size parameters determined from sieve analyses (Freeze and Cherry, 1979). Predictive equations based on both theoretical and empirical studies have been proposed. Since most of these equations have been developed for ideal systems (e.g., glass beads) or well-sorted sediments, the cores from GEMS present an opportunity to examine the relationship between K and particle-size data in a natural system with considerable variability.

The initial approach was to use previously proposed equations for the prediction of K from grain-size data. Five equations of varying degree of empiricism were used here. These five equations were those proposed by Hazen (1893), Krumbein and Monk (1942), Bedinger (1961), Kozeny-Carmen (Bear, 1972), and Fair-Hatch (1933). Table 4 displays the results of the comparison of the K values predicted from these equations with the original and repack values measured in the laboratory. In all cases, the predicted K values exceeded the actual measurements by a considerable amount. We hypothesize that the over estimation is a result of these equations being developed for very well sorted materials. Note that the expression that best predicts the actual K is that proposed by Bedinger (1961) based on a study of sand samples from the Arkansas River Valley, a geological environment of considerable similarity to the Kansas River Valley.

Given the poor results obtained from the application of previously proposed approaches, we attempted to develop a new relationship through multiple regression. The K values measured in the laboratory were taken as the dependent variables and porosity and various grain-size parameters were taken as the independent variables in the regression. Initially, a large number of independent variables was employed, this included sieve-size fractions ranging from D5 through D90 raised to the first and second powers, and various functions of porosity that had been proposed by previous workers. All 200 cores were used and a separate regression was performed for the original and repacked cores. As a result of the large correlation between many of the independent variables, most of these variables were eliminated during the regression procedure. Only two (repacked cores) and three (original cores) variables remained in the final relationships determined by the multiple regression procedure performed using the SPSSX package (SPSS Inc., 1983).

Table 5 displays the results of the multiple regression analysis of the measurements from the original cores. The regression results indicate that approximately 80% of the variation in the original K measurements can be explained by variations in three variables: D5 (grain-size diameter for which 5% of the grains are finer and 95% are coarser) raised to the second power, porosity, and the mean grain diameter calculated by the method of moments (Blatt et al., 1980). The standard error of the estimated K values is .014 cm/sec. Over 76% of the values fall within one standard error of the regression line and 95% of the values fall within two standard errors of the line. The arithmetic mean and variance of the hydraulic conductivity predicted by this equation are .034 cm/sec and .0008 $(cm/sec)^2$, which are quite similar to those of the measured values (.034 and .0010, respectively). Further work is required to assess whether the correlation relationship that would be obtained using the predicted values is similar to that obtained using the original measurements.

Table 6 displays the results of the multiple regression analysis of the measurements from the repacked cores. The regression results indicate that approximately 89% of the variation in the repacked K measurements can be explained by variations in two variables: D5 raised to the second power and porosity. The standard error of the estimated K values is .0195 cm/sec. Over 80% of the values fall within one standard error of the regression line and 93% of the values fall within two standard errors of the line. The arithmetic mean and variance of the hydraulic conductivity predicted by this equation are .057 cm/sec and .0031 $(cm/sec)^2$, which are quite similar to those of the measured values (.057 and .0035, respectively).

CONCLUSIONS

The results of the initial laboratory analysis of 100 ft of core taken through the sand and gravel section of an experimental research site in the Kansas River alluvium have been described. Several interesting findings have been obtained from this analysis:

1) The variability of hydraulic conductivity on the core scale in the sand and gravel section at this site is considerably greater than that reported from other studies in sediments of a similar mean conductivity. We speculate that the larger variability is a result of the material at this site being more poorly sorted than that at previously studied sites;

2) At this site, the repacking of cores produces values of hydraulic conductivity that are considerably larger than those of the original measurements. We speculate that the destruction of original sedimentary structures in the repacking procedure is the primary factor responsible for this difference;

3) Previously reported equations for the prediction of hydraulic conductivity from grain-size parameters are of limited use at this site. We speculate that the unsatisfactory performance of these equations is a result of the relatively poor sorting of the sediments at this site. New relationships for conductivity prediction have been developed based on multiple regression analyses. These regression relationships do an excellent job in reproducing the mean and variance of the laboratory-measured values of hydraulic conductivity.

The findings presented here are of a preliminary nature, so more work is required before we can draw any significant conclusions from these data. Ongoing work at the Kansas Geological Survey should enable us to better assess the importance of these results.

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TABLE 1

STATISTICS OF ORIGINAL MEASUREMENT OF HYDRAULIC CONDUCTIVITY (K)

Well No.	No. of Cores	Variables	Mean	Variance
GEMS05	28	K(cm/s)	0.014	0.0002
		ln(K)	-4.918	1.837
GEMS07	18	K(cm/s)	0.026	0.0004
		ln(K)	-4.151	1.544
GEMS15	30	K(cm/s)	0.038	0.0008
		ln(K)	-3.505	0.493
GEMS26	40	K(cm/s)	0.038	0.0010
		ln(K)	-3.793	1.522
GEMS41	38	K(cm/s)	0.033	0.0006
		ln(K)	-3.846	1.365
GEMS51	46	K(cm/s)	0.042	0.0018
		ln(K)	-3.890	2.173
TOTAL	200	K(cm/s)	0.034	0.0010
		ln(K)	-3.972	1.669

TABLE 2

STATISTICS ON POROSITY AND MEAN (GEOMETRIC) GRAIN SIZE (GM)

Well No.	GEMS05	GEMS07	GEMS15	GEMS26	GEMS41	GEMS51	TOTAL
No. of Cores	28	18	30	40	38	46	200
POROSITY							
Mean	.300	.305	.320	.304	.304	.303	.305
Variance	.0004	.0008	.0004	.0005	.0006	.0007	.0006
GM (mm)							
Mean	.845	.882	1.091	1.297	1.173	1.290	1.139
Variance	.170	.108	0.306	0.356	0.217	0.431	0.313

TABLE 3

COMPARISON OF THE ORIGINAL AND REPACKED CORE VALUES

		Original ln(K)		Repacked ln(K)	
Well No.	No. of Cores	Mean	Variance	Mean	Variance
GEMS05	28	-4.918	1.937	-5.104	3.105
GEMS07	18	-4.151	1.544	-3.664	0.677
GEMS15	30	-3.505	0.493	-3.605	0.772
GEMS26	40	-3.793	1.522	-2.864	0.667
GEMS41	38	-3.846	1.365	-3.153	0.592
GEMS51	46	-3.890	2.173	-3.064	1.711
TOTAL	200	-3.972	1.669	-3.462	1.732

TABLE 4

COMPARISON OF LABORATORY MEASURED HYDRAULIC CONDUCTIVITIES WITH THOSE ESTIMATED USING THE FIVE EMPIRICAL EQUATIONS

	Mean of K (cm/sec)	Variance of K
Original Core	.034	.0010
Repacked Core	.057	.0035
Hazen	.168	.0330
Bedinger	.151	.0230
Fair-Hatch	.166	.0350
Kozeny-Carmen	.600	.4620
Krumbein & Monk	.225	.0630

TABLE 5

RESULTS OF MULTIPLE REGRESSION ANALYSIS ON THE ORIGINAL K

Multiple R	R Square	Adjusted R Square	Standard Error
.8936	.7988	.7956	.0140

Analysis of Variance

	Degree of Freedom	Sum of Squares	Mean Square
Regression	3	.1542	.0514
Residual	197	.0389	.0002

Regression Equation

Variables	B	95% Confidence Interval of B	
Mean	0.0087	0.0050	0.0123
Porosity	0.3364	0.2592	0.4198
D5 Square	0.2498	0.2169	0.2827
Constant	-.1017	-.1268	-.0765

TABLE 6

RESULTS OF MULTIPLE REGRESSION ANALYSIS ON THE REPACKED K

Multiple R	R Square	Adjusted R Square	Standard Error
.9445	.8921	.8911	.0195

Analysis of Variance

	Degree of Freedom	Sum of Squares	Mean Square
Regression	2	.6219	.3109
Residual	198	.6752	.0004

Regression Equation

Variables	B	95% Confidence Interval of B	
Porosity	0.2933	0.1776	0.4090
D5 Square	0.6732	0.6361	0.7103
Constant	-.0842	-.1187	-.0496

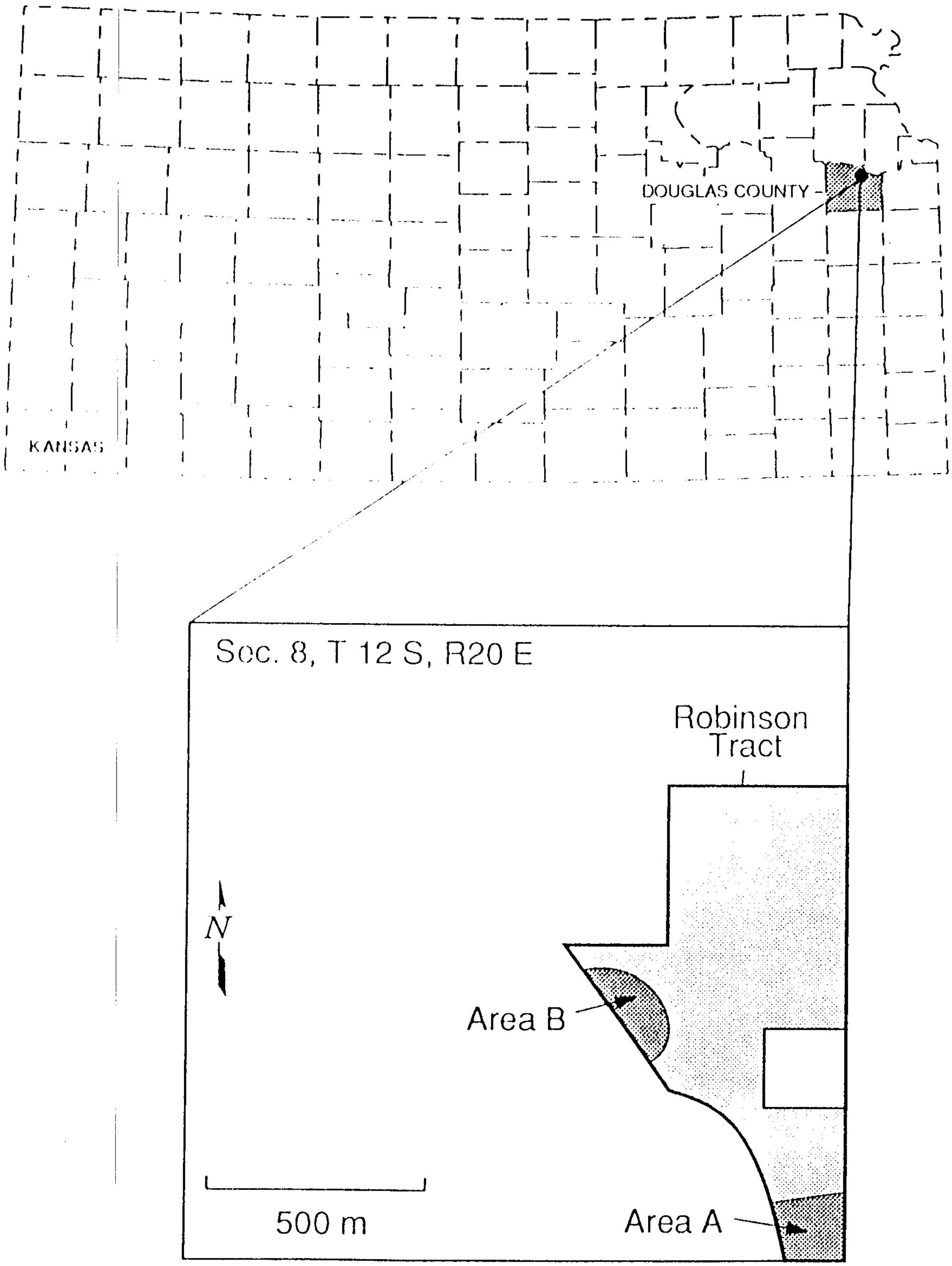


FIGURE 1. Location map of the Geohydrological Experimental and Monitoring Site (Area A and B). Research described here took place in Area A.

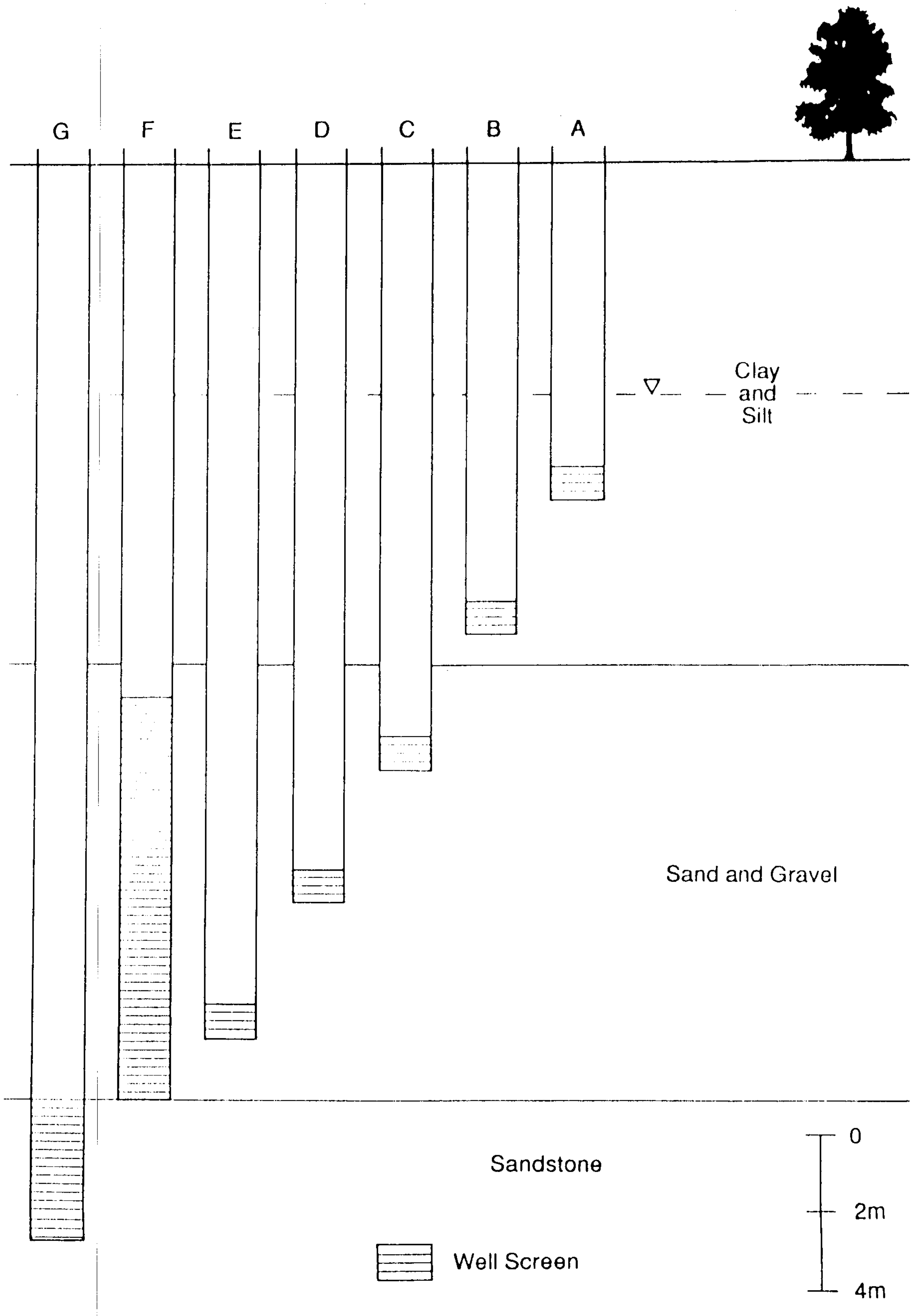


FIGURE 2. Cross-sectional view through a nest at GEMS. Screened interval is .76 m for wells A-E, 9.14 m for well F, and 3.05 m for well G.

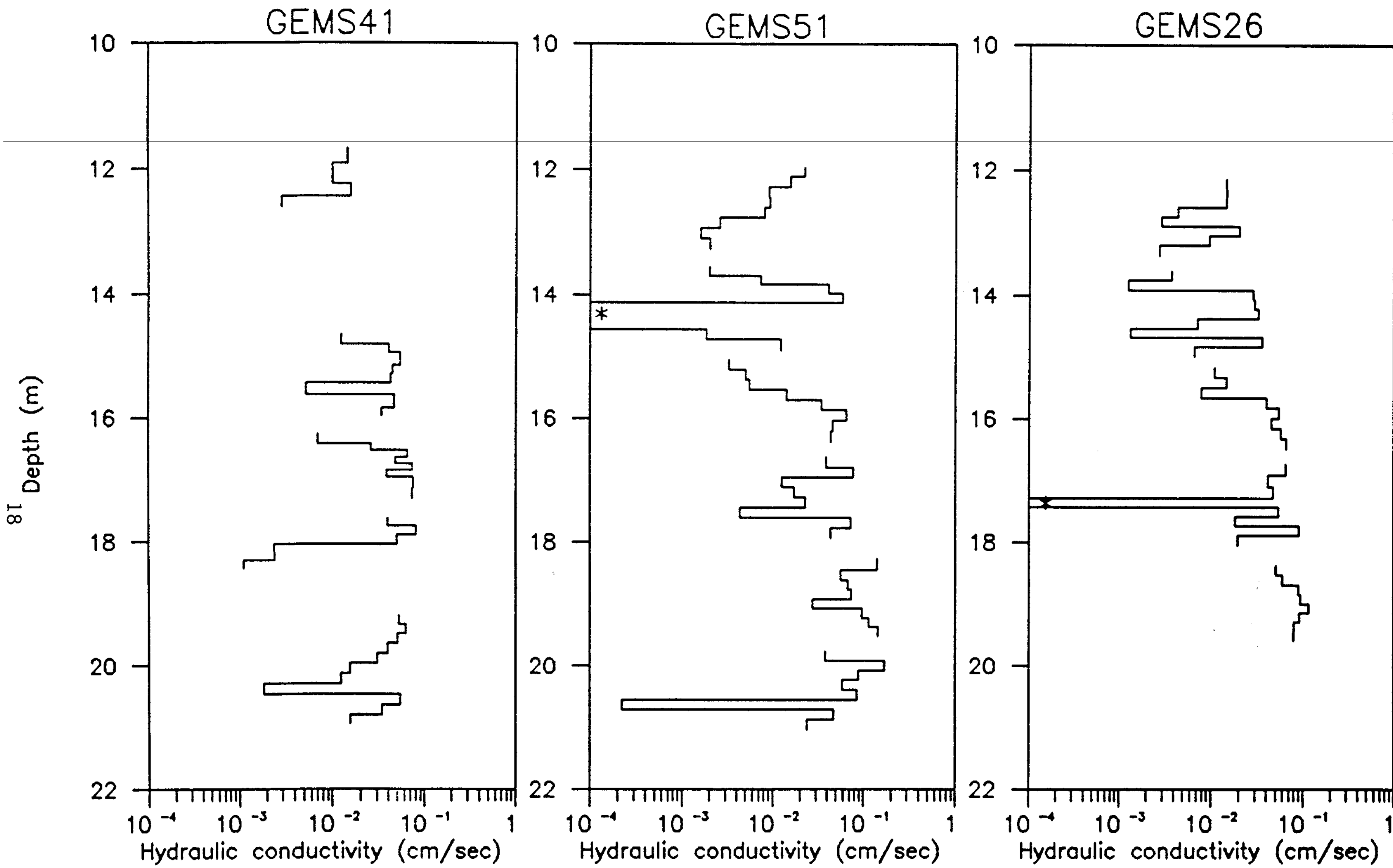
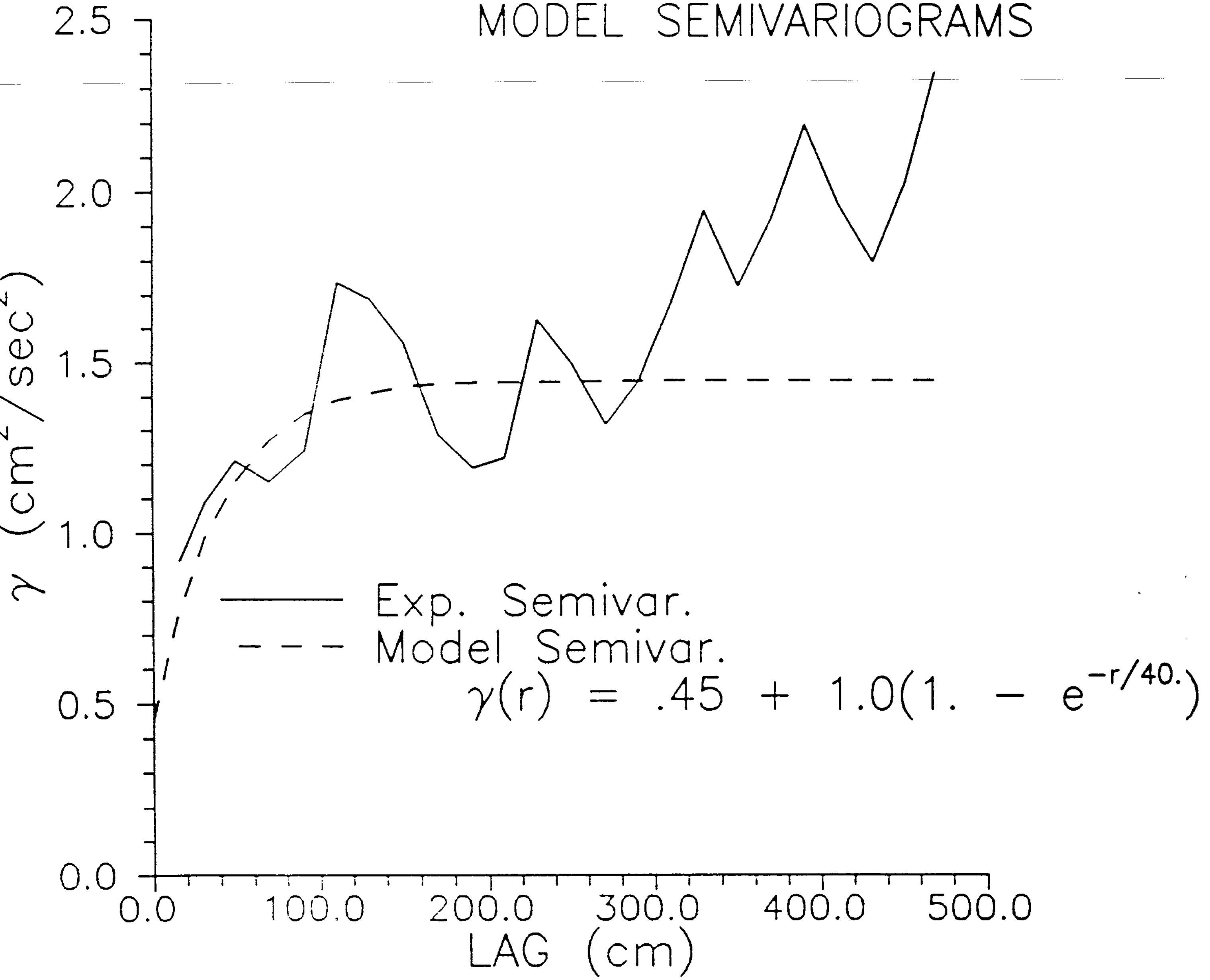


FIGURE 3. Hydraulic conductivity profiles for wells GEMS41, GEMS51, and GEMS26 (* indicates clay layer – K too low for measurement).

FIGURE 4
COMPARISON OF EXPERIMENTAL AND
MODEL SEMIVARIOGRAMS



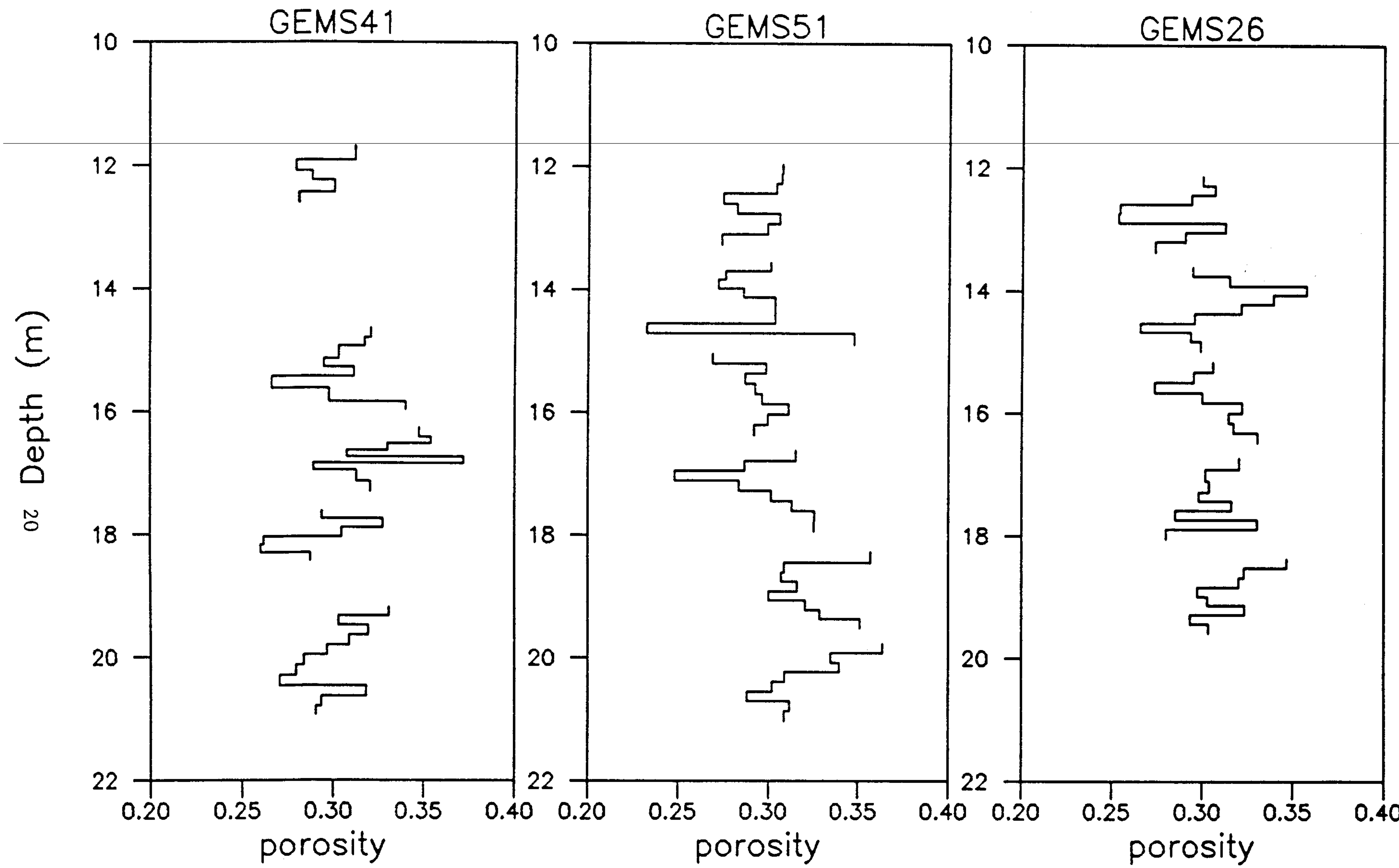


FIGURE 5. Porosity profiles for wells GEMS41, GEMS51, and GEMS26.

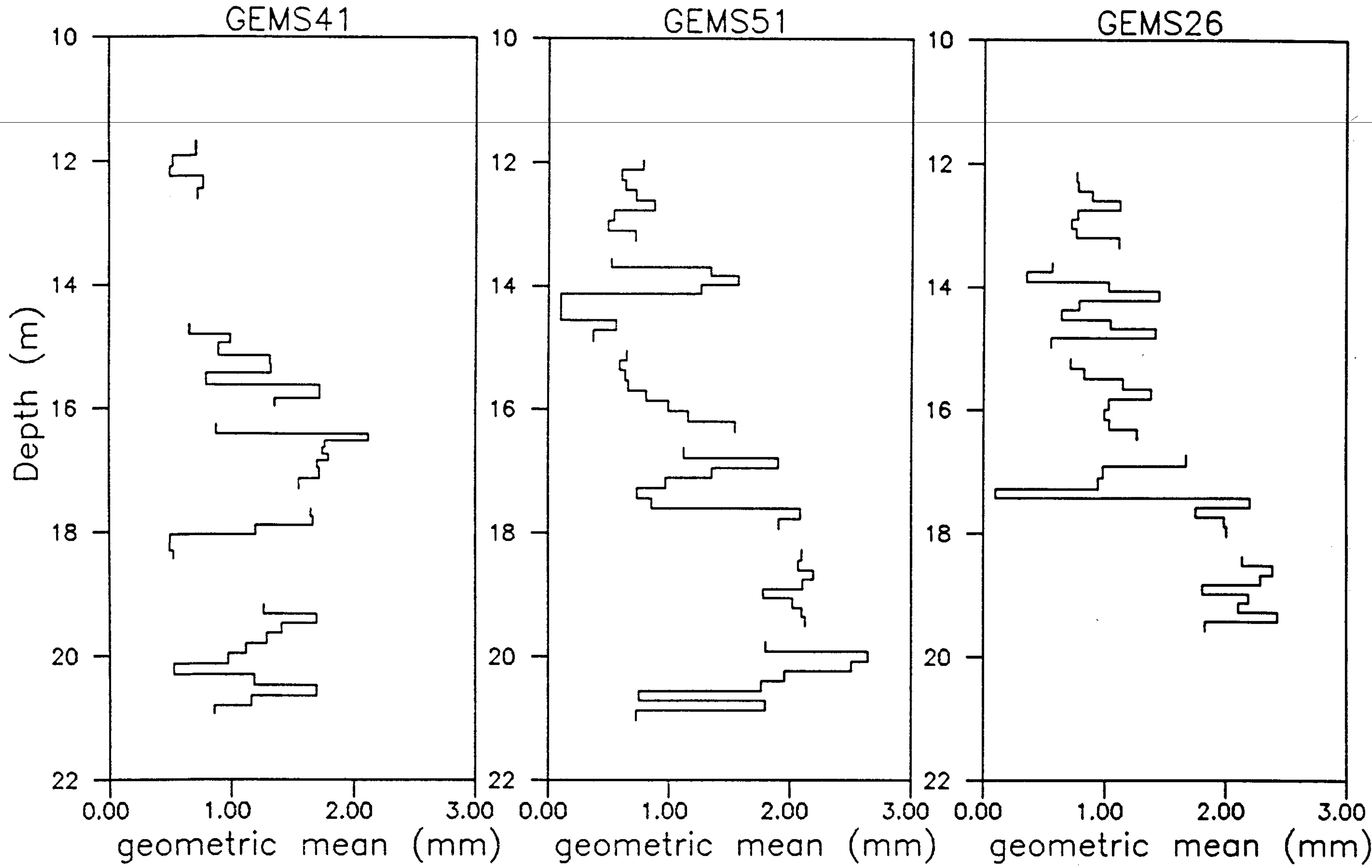


FIGURE 6. Mean (geometric) grain size profiles for wells GEMS41, GEMS51, and GEMS26.

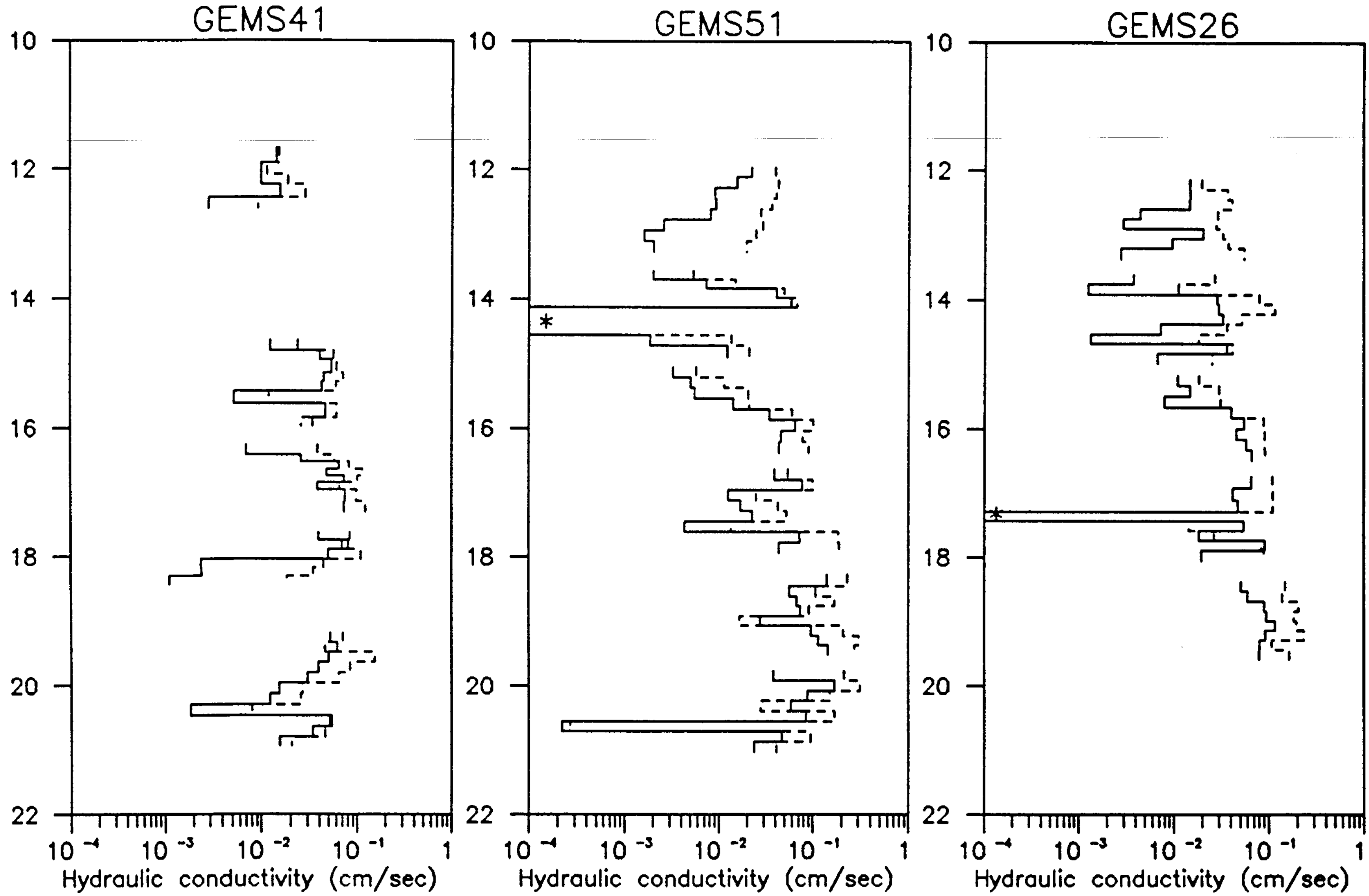


FIGURE 7. Original (solid line) and repacked (dashed line) K profiles for wells GEMS41, GEMS51, and GEMS26 (* indicates clay layer – K too low for measurement).