NUCLEAR WASTE CONSULTANTS INC.

U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

Technical Report #11

CONFIDENCE INTERVAL ESTIMATION OF CHARACTERISTIC PERMEABILITY

Salt Repository Project
Subtask 3.5

Prepared by

Daniel B. Stephens & Associates, Inc.

for

Nuclear Waste Consultants

TECHNICAL ASSISTANCE IN HYDROGEOLOGY
PROJECT B - ANALYSIS
RS-NMS-85-009

JULY, 1987

TECHNICAL REPORT SUMMARY

Technical Report Number: 11

Title: Confidence Interval Estimation of Characteristic Permeability

Objective: The objective of this report is to examine variability and uncertainty in permeability data for HSU B and HSU C and obtain estimates of the characteristic permeability of each HSU.

Analysis: Statistical parameters describing the observed permeability data are used to calculate confidence intervals which are likely to include the average permeability of the hydrostratigraphic unit.

Conclusions: The average permeability for the Lower San Andres, Wolfcamp and Pennsylvanian units are likely to be within the following ranges:

Lower San Andres: 0.049 to 0.925 md
Wolfcamp: 0.319 to 1.112 md
Pennsylvanian: 0.352 to 1.429 md

Discussion: The calculations are based on drill stem test data which are likely to be biased toward higher permeability zones. Therefore, the average permeability calculated from DST data is likely to be somewhat greater than the actual regional average. Results of example calculations indicate that ground-water travel time from the repository to the accessible environment is not likely to be less than 1,000 years. The results are based on assumptions of no spatial correlation, fixed hydraulic head gradient and uniform porosity.

CONFIDENCE INTERVAL ESTIMATION
OF CHARACTERISTIC PERMEABILITY

Numerical Evaluation of Conceptual Models
Subtask 3.5
Technical Report #11

July 1987

DRAFT

DANIEL B. STEPHENS & ASSOCIATES, INC.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 General Statement of the Problem

Values of hydraulic conductivity for a geological material may range over more than a million-fold (for example see Freeze and Cherry, 1979). Within many geological formations hydraulic conductivity exhibits a log-normal distribution. Within a geological formation, the standard deviations of log-normal conductivity distributions typically indicate conductivity variations of about 2 orders of magnitude (Freeze and Cherry, 1979).

In the present study, the statistical distribution of permeability data for hydrostratigraphic unit B (HSU B), the Permian evaporite aquitard, and HSU C, the deep-basin brine aquifer, will be examined (see Figure 1). For both cases (HSU B and HSU C), the sample mean and sample variance of permeability will be used to estimate confidence intervals. Confidence intervals should indicate a range of permeability, at a given probability level, which will be likely to include the true mean permeability of the hydrostratigraphic unit. Example calculations are also presented in order to illustrate how the statistical data may be applied to regulatory criteria.

1.2 Statement of Relevance to NRC

EPA containment requirements (40CFR191.13) present limits for the cumulative release of radionuclide to the accessible

ERA	SYSTEM	SERIES	GROUP	FORMATION	HYDROSTRATIGRAPHIC UNIT (HSU)
CENOZOIC	QUATERNARY			RECENT FLUVIAL AEOLIAN AND LACUSTRINE DEPOSITS	FRESHWATER FLOW SYSTEM HSU A
	TERTIARY			OGALLALA AND LACUSTRINE DEPOSITS	
MESOZOIC	CRETACEOUS	COMANCHE	WASHITA FREDRICKSBURG		
			TRINITY		
	TRIASSIC		DOCKUM	TRUJILLO (Santa Rosa)	
				TECOVAS	
PALEOZOIC	PERMIAN	OCHOA		DEWEY LAKE (Quartermaster)	SHALE AND EVAPORITE AQUITARD HSU B
				ALIBATES	
		GUADALUPE	ARTESIA (WHITEHORSE)	SALADO-TANSILL	
				YATES	
				SEVEN RIVERS	
				QUEEN-GRAYBURG	
			PEASE RIVER	SAN ANDRES (BLAINE)	
		LEONARD		GLORIETA	
			CLEAR FORK	UPPER CLEAR FORK	
				TUBB	
				LOWER CLEAR FORK	
				RED CAVE	
			WICHITA		
		WOLFCAMP			DEEP-BASIN FLOW SYSTEM HSU C
	PENNSYLVANIAN	VIRGIL	CISCO		
		MISSOURI	CANYON		
		DES MOINES	STRAWN		
		ATOKA	BEND		
		MORROW			
	MISSISSIPPIAN	CHESTER			
		MERAMEC			
		OSAGE			
	ORDOVICIAN	CANADIAN	ELLENBURGER		
	CAMBRIAN		UNNAMED SANDSTONE		
	PRECAMBRIAN				

Explanation

——— Unconformity

– – – – – Boundary In Dispute

Figure 1. Generalized Hydrostratigraphic Column of the Palo Duro Basin (DOE, 1986).

environment for 10,000 years after disposal. The waste repository should be designed to provide a reasonable expectation that the likelihood of cumulative releases exceeding the EPA limits is less than one chance in 10 (40CFR191.13). NRC siting criteria (10CFR60.122) require the appropriate combination of favorable conditions sufficient to provide reasonable assurance that waste isolation performance objectives will be met. One of the favorable conditions listed is that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment substantially exceeds 1,000 years (10CFR60.122). Because ground-water travel time and the cumulative release of radionuclides to the accessible environment are inversely proportional to permeability (for a given fluid), it will be important to obtain a reliable estimate of permeability for performance assessments. Confidence intervals should provide an objective and probabilistic means for estimating the characteristic permeability of a given hydrostratigraphic unit.

1.3 Relationship to Other Analyses, etc.

Previous studies performed by Stephens & Assoc. (1986a) calculate maximum permeabilities which will allow EPA cumulative release limits (40CFR191) to be met for HSU B and HSU C. The calculated values fall within the range of permeability determined from limited testing that has been done in HSU B and HSU C. Therefore, it could not be demonstrated that the EPA cumulative release limits would be met. A statistical analysis of the permeability data may identify unrepresentative values and thus may decrease the range of likely permeability for a given hydrostratigraphic unit. Re-interpretation of previous analyses using the narrower, and perhaps more likely, range of permeability may result in less ambiguous conclusions.

2.0 FORMAL STATEMENT OF OBJECTIVE

The objective of this report is to examine variability and uncertainty in permeability data for HSU B and HSU C and to obtain estimates of the characteristic permeability of each HSU.

3.0 OPERATIONAL APPROACH-CONCEPTS & GENERAL ASSUMPTIONS

3.1 Ground-Water Flow System

The ground-water flow system of the Palo Duro Basin has been conceptualized by several investigators (Bassett and others, 1981; DOE, 1986; INTERA, 1984a, 1984b; Senger and Fogg, 1984; Wirojanagud and others, 1984; Senger and others, 1985a, 1985b). The most basic framework of the conceptual models of the Palo Duro Basin consists of three hydrostratigraphic units (HSU; Figure 1): 1) The shallow fresh-water aquifer (HSU A), 2) the evaporite aquitard (HSU B), and 3) the deep-basin brine aquifer (HSU C). Stephens & Assoc. (1986b) present a comparison of the various conceptual models for the Palo Duro Basin flow system. The DOE (1986, Table 3-3) presents a generalized stratigraphic column for the Deaf Smith County site based on data from nearby wells and regional trends. However, it should be kept in mind that the actual site stratigraphy is not known because no exploratory wells have been drilled within the Deaf Smith County site (DOE, 1986).

The shallow fresh-water aquifer (HSU A) consists primarily of relatively permeable Triassic and younger fluvial and lacustrine sediments (Figures 1, 2). While the most significant discharge from HSU A occurs by pumping, there may be some downward flow into HSU B.

The Permian evaporite aquitard (HSU B) consists of a sequence of shales, halites, anhydrites, dolomite and red beds (Figure 2). HSU B extends from the base of HSU A (Triassic-Permian boundary) to the base of the lower Permian Leonardian series (Figure 1). Flow in HSU B is generally considered to be vertically downward under saturated conditions.

Extending from the top of the lower Permian Wolfcamp series to the Precambrian crystalline basement is the deep-basin brine aquifer comprised of carbonates, shales and sandstones (HSU C, Figures 1, 2). Flow within HSU C is generally northeast toward the Amarillo-Wichita uplift where discharge is believed to occur in the subsurface. Recharge to the deep-basin brine aquifer occurs in the outcrop area west of the Pecos River and may also occur by leakage across HSU B.

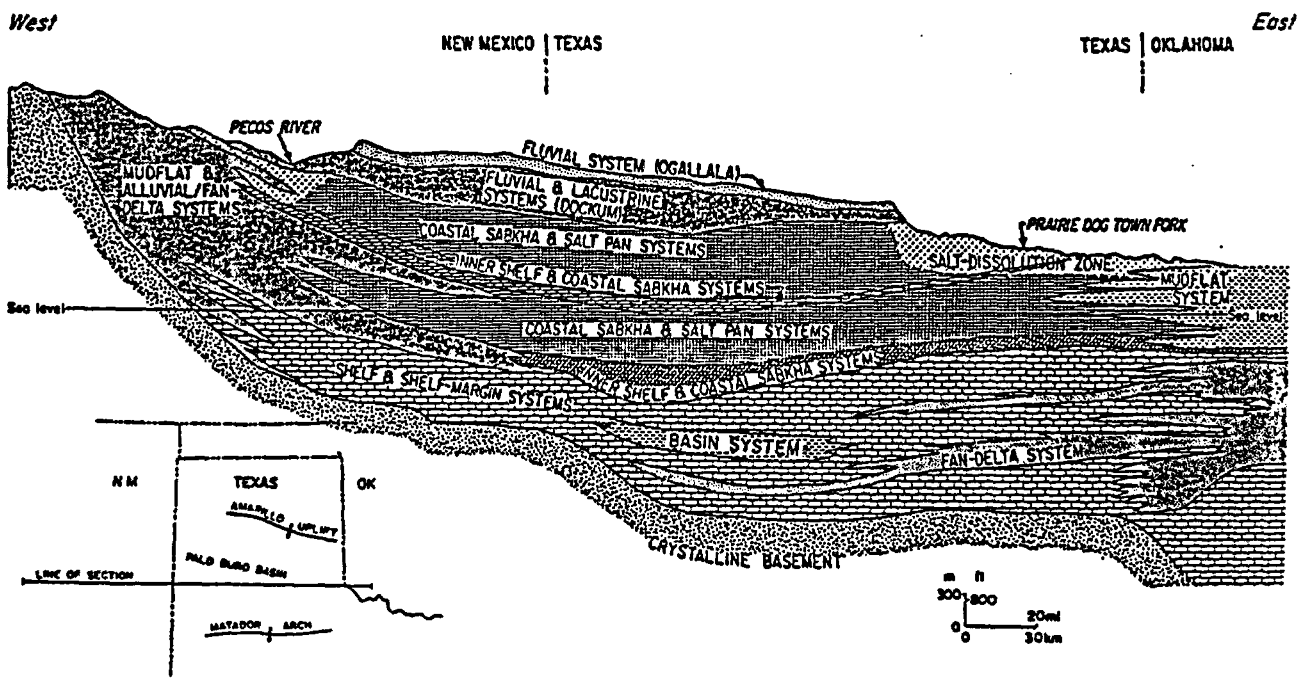


Figure 2. Regional east-west cross section through eastern New Mexico and the Texas Panhandle illustrating stratigraphic relations of the major depositional systems in the Palo Duro Basin (Senger and Fogg, 1983)

4.0 TECHNICAL APPROACH

4.1 Formal Statement of the Problem

The characteristic permeabilities of HSU B and HSU C will be estimated from statistical parameters describing the observed data. The maximum or critical permeability which will allow certain siting criteria and environmental standards to be met will be estimated. The estimated values will be compared with observed permeability data. Standard statistics will be used to estimate the likelihood that the criteria and standards will be met.

4.2 Identification of Solution Techniques

Various calculations are made in this analysis: 1) calculation of confidence intervals on observed permeability data, and 2) calculations associated with the examples (critical permeabilities and values of the t statistic). These calculations are discussed below.

4.2.1 Confidence Intervals

In this report it is assumed that permeability within a hydrostratigraphic unit is log-normally distributed (Freeze and Cherry, 1979). The analyses (which generally require a normal distribution) are therefore performed on the logarithms of the observed permeability data. Thus the logarithm of permeability within the hydrostratigraphic unit is assumed to be normally distributed. A random sample of size N from a normal population with mean μ may be used to calculate confidence intervals about the population mean. The 100(1 - α) percent confidence interval for μ is given by

$$\bar{x} + t_{\frac{1}{2}\alpha}\,(df)\frac{s}{\sqrt{N}} < \mu < \bar{x} + t_{1-\frac{1}{2}\alpha}\,(df)\frac{s}{\sqrt{N}} \qquad (1)$$

where

μ = population mean

$\bar{x}$ = sample mean

s = sample standard deviation

N = sample size

t = sampling distribution

100(1 - α) = percent confidence level

df = degrees of freedom = N - 1

(see Dixon and Massey, 1983). On the average, 100(1 - α) percent of the intervals (given by equation 1) determined from different log-permeability samples will include the actual average permeability of the hydrostratigraphic unit (the population mean μ). The confidence interval, therefore, has approximately a 100(1 - α) percent chance of including the true permeability of the hydrostratigraphic unit (based upon the observed data).

4.2.2 Critical Permeability

In order to estimate the likelihood that regulatory criteria will be met, the hypothesis that the permeability of the hydrostratigraphic unit is less than the critical permeability will be tested. The critical permeability is defined as the maximum permeability which will allow regulatory criteria to be met. The method used to test whether the permeability is likely to be less than the specified critical permeability is similar to estimating confidence intervals. A critical region is defined as values of the sample mean permeability which are sufficiently greater than the critical permeability that such values would be unlikely to occur by chance if the critical value is actually correct (Dixon and Massey, 1983). The probability that the sample mean permeability will be in the critical region when the hypothesis is true is called the level of significance α (Dixon and Massey, 1983). The critical region is estimated from

$$t > t_{1-\alpha}\,(df) \tag{2}$$

where

$$t = \frac{\bar{x} - \mu_o}{s/\sqrt{N}} \tag{3}$$

and μ_0 is the specified critical value (Dixon and Massey, 1983). $t_{1-\alpha}$ (N-1) is a value predicted from the t distribution with N-1 degrees of freedom for a level of significance of 100α percent. The remaining symbols are defined with equation 1. If the value of t calculated from the sample (equation 3) is in the critical region (equation 2), then the hypothesis that the permeability of the hydrostratigraphic unit is less than or equal to the critical value is rejected (see Dixon and Massey, 1983). In other words, if the value of t calculated from the sample (equation 3) is in the critical region (equation 2), then the mean permeability of the hydrostratigraphic unit may be greater than the maximum permeability which will allow regulatory criteria to be met.

The critical permeability for a hydrostratigraphic unit is estimated from Darcy's Law expressed in terms of groundwater travel time to the accessible environment. The average linear velocity of ground water V is defined by

$$V = q/n = Ki/n = L/T \qquad (4)$$

where

q = specific discharge $[Lt^{-1}]$

n = porosity

K = hydraulic conductivity $[Lt^{-1}]$

i = hydraulic gradient

L = length of travel path $[L]$

T = travel time $[t]$

(see Freeze and Cherry, 1979). Rearranging equation (4) to obtain hydraulic conductivity and incorporating fluid density (ρ), viscosity (μ), and gravitational acceleration (g) yields the critical permeability

$$k = (\mu nL)/(\rho giT) \qquad (5)$$

The critical permeability (in terms of regulatory criteria) is obtained from equation (5) by substituting the following:

L = distance to accessible environment

T = 1,000 years NRC criteria: 10CFR60

or

T = 10,000 years EPA criteria: 40CFR191.

Porosity n and hydraulic gradient i are estimated for the flow path from observational data. Thus the critical permeability is the maximum permeability which will allow regulatory criteria to be met.

As an example, consider the NRC siting criteria (10CFR60) which states that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment that substantially exceeds 1,000 years is a favorable condition. Substitution of T = 1,000 years into equation (5) along with appropriate values from n, L, and i will yield an estimate of the maximum hydraulic conductivity which will allow the NRC criteria to be met. Similarly for EPA criteria (40CFR191), substitution of T = 10,000 years into equation (2) will yield an estimate of the maximum hydraulic conductivity which will ensure that containment requirements will be met. The EPA containment requirements present limits for the cumulative release of radionuclides to the accessible environment for 10,000 years after disposal. These requirements will be met if the hydraulic conductivity is of such magnitude that ground-water leaving the repository does not reach the accessible environment for 10,000 years.

The critical permeability values calculated in these analyses may then be compared with observed values. The observed data should exhibit a range of values and may contain unrepresentative or erroneous values. Therefore a mean value of permeability characteristic of the flow path is compared with the calculated critical permeability. A statistical test (equations 2 and 3) is applied to the observed data in order to indicate the likelihood that the critical permeability is greater than the actual mean permeability of the flow path. In other words, the probability that the criteria will be met, based upon observed permeability data, is estimated.

4.3 Definitions and Assumptions

For the purpose of making the statistical calculations it is assumed that the permeability within a hydrostratigraphic unit is log-normally distributed.

Three simple ground-water flow models are considered in this report:

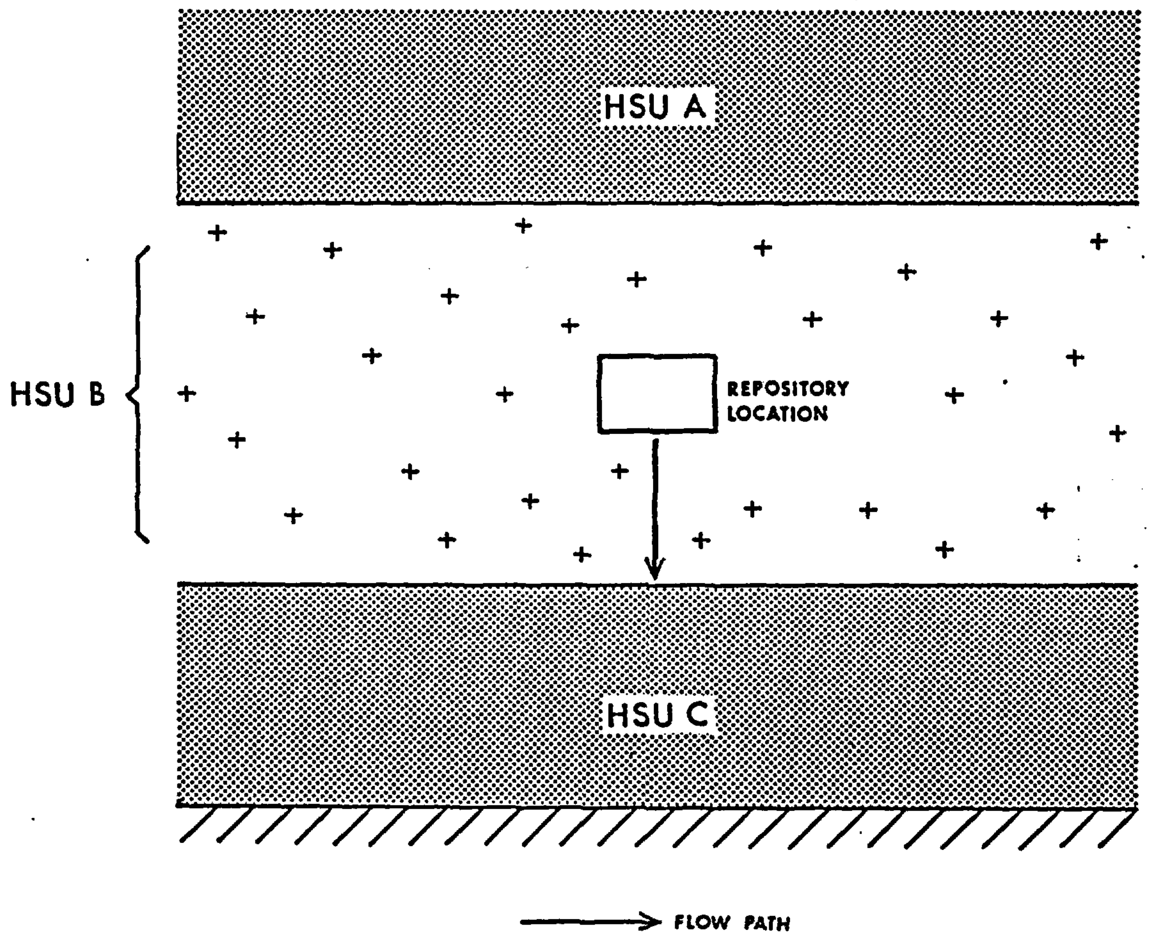
i) vertical flow through HSU B (Figure 3)

ii) horizontal flow through HSU B (Figure 4)

iii) horizontal flow through HSU C (Figure 5)

The maximum permeability which will allow certain regulatory criteria to be met will be calculated for each model using estimates of porosity, hydraulic gradient, path length and travel time (see Stephens & Assoc., 1986a). The maximum permeability is determined by assuming that the ground-water leaving the repository does not reach the accessible environment before 1,000 or 10,000 years.

For the calculation of critical permeability, it is assumed that one-dimensional, steady-state ground-water flow occurs in a homogeneous, unfractured porous media. Furthermore, temperature, density and hydrochemical processes and their effects are ignored. The distance along vertical flow paths through HSU B to the accessible environment is assumed to be 816 m (see Figure 3; base of Lower San Andres Unit 4 to top of Wolfcamp, p. 3-35, 36 in DOE, 1986). The distance along horizontal flow paths to the accessible environment is assumed to be 5 km (Figures 4 and 5; 10CFR60; 40CFR191); vertical transport from the repository to the horizontal flow path is assumed to occur instantaneously. Hydraulic gradients have been estimated from potentiometric surface maps. The following values of hydraulic gradient near the Deaf Smith County site are assumed to be reasonable:



Project Number: 85-130
Date: 3-26-87

Figure 3. Idealized flow path for vertical ground-water flow through HSU B.

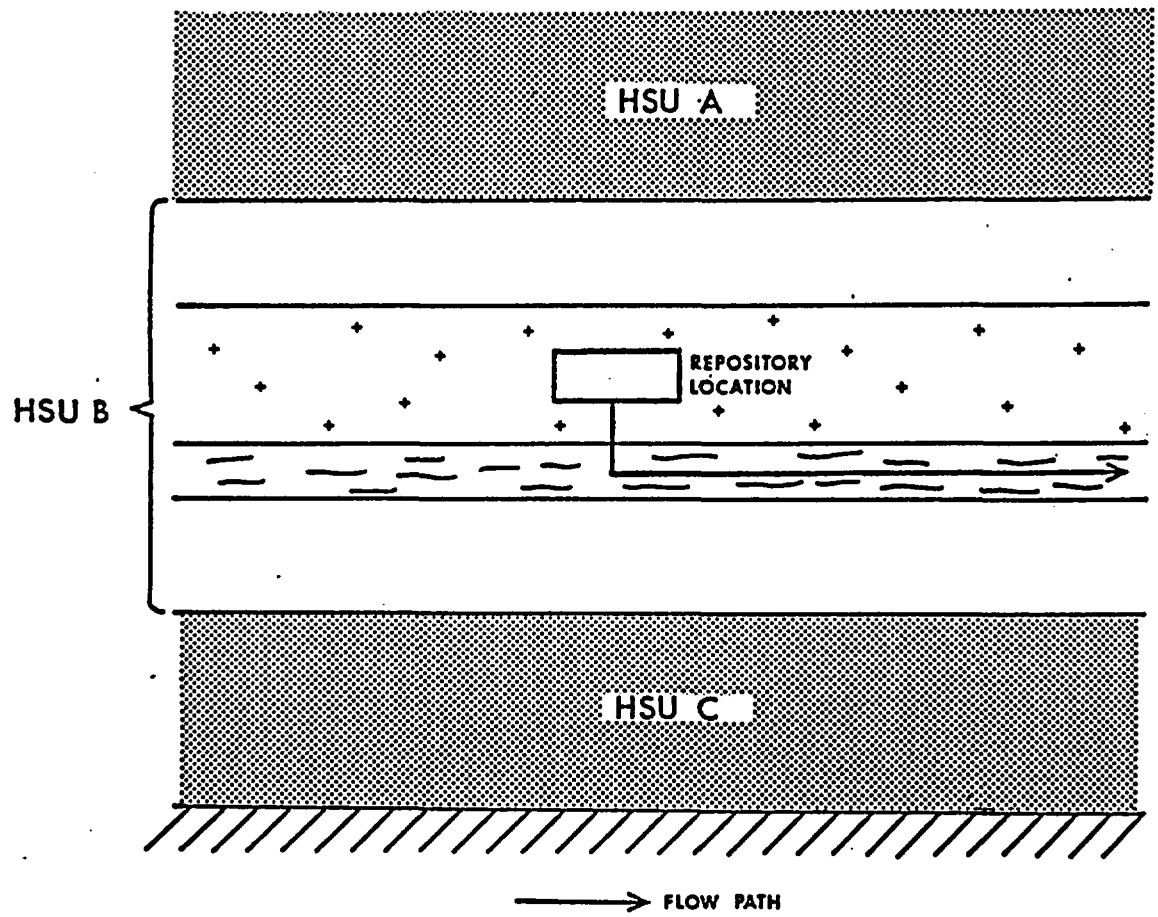


Figure 4. Idealized flow path for horizontal ground-water flow through HSU B.

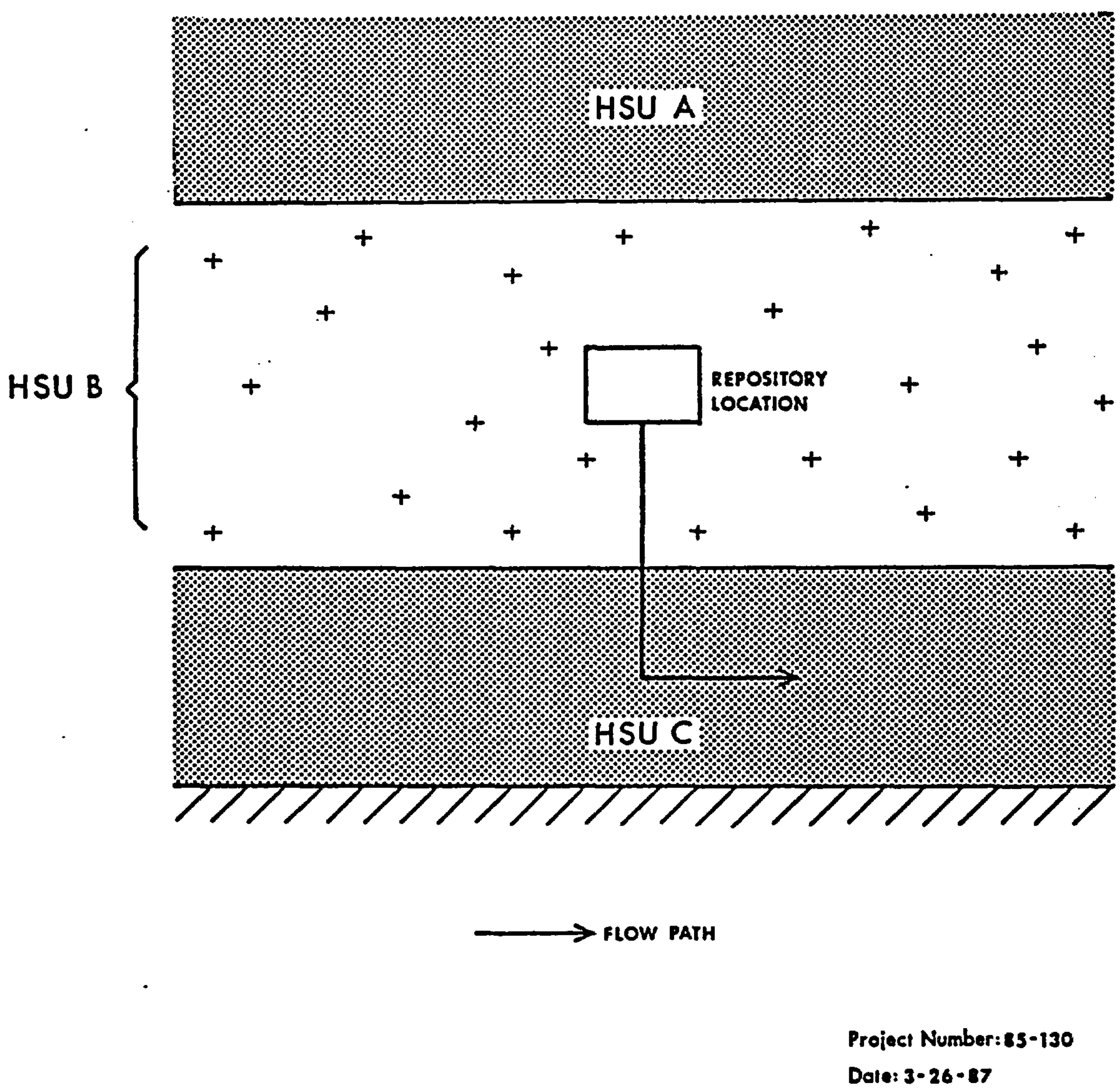


Figure 5. Idealized flow path for horizontal ground-water flow through HSU C

horizontal gradient for Lower San Andres = 0.0049; vertical gradient in Lower San Andres = 0.65; horizontal gradient in Wolfcamp = 0.0055; horizontal gradient in Pennsylvanian = 0.0025 (Figure 66 in Dutton, 1983; Figures 3-60, 3-61 and 3-62 in DOE, 1986; Table 6). Porosity values of 0.05, 0.08 and 0.10 are considered representative of the Lower San Andres, Wolfcamp and Pennsylvanian units, respectively (DOE, 1986).

5.0 ANALYSIS

The statistical analyses are performed on the logarithms of permeability data obtained from drill stem and pump tests of the lower San Andres, Wolfcamp and Pennsylvanian Formations (Tables 1, 2 and 3, Figures 6, 7 and 8 respectively). A summary of the log permeability data for the three formations is given in Table 4.

TABLE 1
LOWER SAN ANDRES PERMEABILITY DATA

Lithology: LS = limestone, CARB = carbonate, DOLO = dolomite

Well Number/Name	Test Type	Lithology	k (md)	log(k)
362	DST	DOLO	0.56115	-0.251
577	DST	DOLO	18.4318	1.266
852	DST	DOLO	0.0043	-2.364
859	DST	DOLO	0.3298	-0.482
860	DST	DOLO	1.2140	0.084
ZEECK	DST	CARB	0.3	-0.523
ZEECK	PUMP	CARB	0.18	-0.745
DETTEN	DST	CARB	0.2	-0.699
G.FRIEMEL	DST	CARB	0.1	-1.000
HARMON	DST	LS	0.01	-2.000
HARMON	DST	CARB	0.2	-0.699

Note: Permeability data identified with a well number are from Smith and others (1984). Only data located between 34° to 36° N latitude and 101° to 103° W longitude have been taken from this source (see Figure 6). The remaining data identified with a well name are from OCWRM program wells as reported by DOE (1986; Table 3-26).

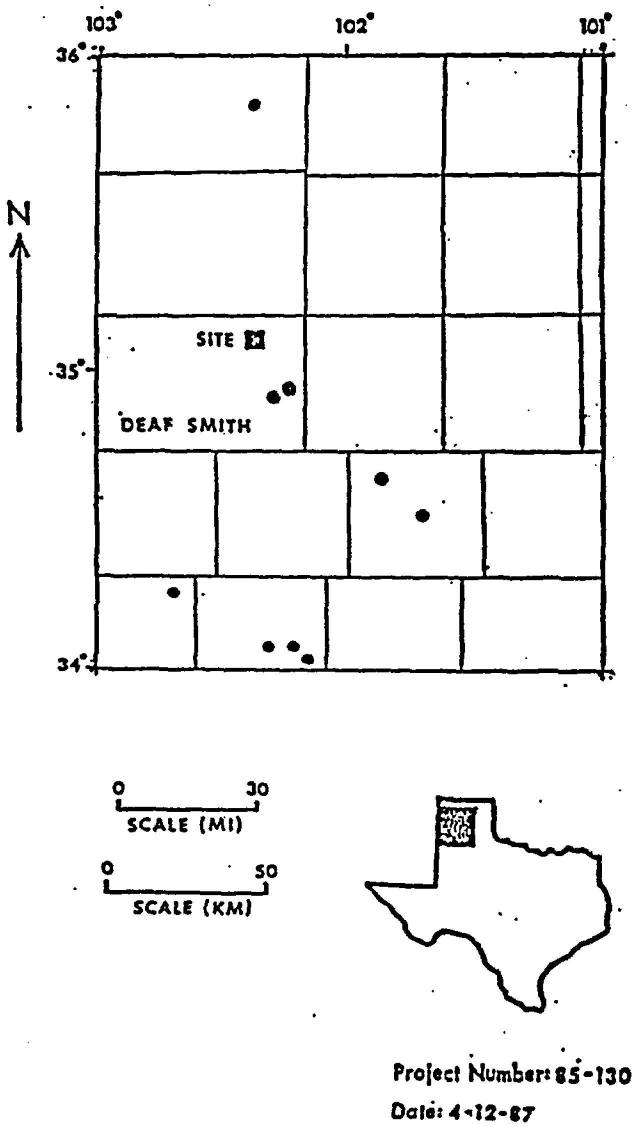


Figure 6. Location of Lower San Andres Permeability Data (after Smith and others, 1984)

TABLE 2
WOLFCAMP PERMEABILITY DATA

Lithology: DOLO = dolomite; GW = granite wash; LS = limestone; SS = sandstone; CARB = carbonate

Well Number/Name	Test Type	Lithology	k (md)	log(k)
361	DST	DOLO	0.16804	-0.775
364	DST	SS	18.9326	1.277
368	DST	DOLO	0.0665	-1.172
369	DST	DOLO	0.21641	-0.665
370	DST	DOLO	0.27059	-0.568
371	DST	DOLO	0.05094	-1.293
372	DST	DOLO	0.94590	-0.024
373	DST	LS	1.58215	0.199
374	DST	DOLO	0.03231	-1.491
375	DST	DOLO	1.23813	0.093
558	DST	GW	2.2071	0.344
559	DST	GW	8.5504	0.932
561	DST	LS	0.1082	-0.966
568	DST	DOLO	3.8809	0.589
576	DST	SS	1.5103	0.179
578	DST	LS	0.6259	-0.203
830	DST	DOLO	0.279	-0.555
831	DST	DOLO	0.220	-0.658
833	DST	GW	4.498	0.653
834	DST	GW	2.391	0.379
835	DST	DOLO	17.927	1.254
838	DST	DOLO	0.102	-0.991
839	DST	LS	0.315	-0.502
964	DST	GW	0.4845	-0.315
968	DST	DOLO	0.1476	-0.831
969	DST	LS	0.1407	-0.852
974	DST	LS	15.1726	1.181
975	DST	DOLO	0.0966	-1.015
983	DST	DOLO	0.0361	-1.443
985	DST	DOLO	0.3851	-0.414
986	DST	DOLO	0.1544	-0.811
988	DST	DOLO	0.0378	-1.422
990	DST	DOLO	0.0113	-1.947
1074	DST	DOLO	0.01518	-1.819
MANSFIELD	DST	LS	26.6	1.415
MANSFIELD	DST	LS	11.6	1.064
MANSFIELD	PUMP	LS	0.5	-0.301
MANSFIELD	PUMP	LS	4.3	0.633

TABLE 2 (Continued)
WOLFCAMP PERMEABILITY DATA

Lithology: DOLO = dolomite; GW = granite wash; LS = limestone; SS = sandstone; CARB = carbonate

Well Number/Name	Test Type	Lithology	k (md)	log(k)
SAWYER	DST	DOLO	0.2	-0.699
SAWYER	PUMP	-	6.1	0.785
J.FRIEMEL	DST	DOLO	1.0	0
J.FRIEMEL	PUMP	CARB	1.0	0
ZEECK	DST	CARB	6.8	0.833
ZEECK	PUMP	LS	6.0	0.778
ZEECK	PUMP	LS	0.1	-1.000

Note: Permeability data identified with a well number are from Smith and others (1984). Only data located between 34° to 36° N latitude and 101° to 103° W longitude have been taken from this source (see Figure 7). The remaining data identified with a well name are from OCWRM program wells as reported by DOE (1986; Table 3-26).

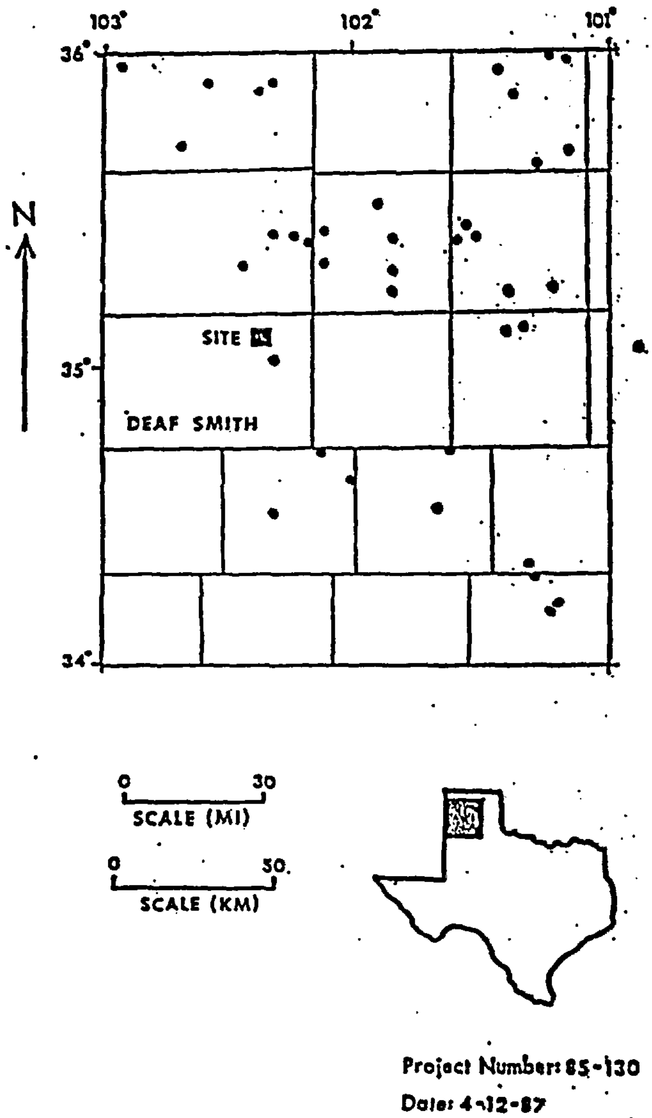


Figure 7. Location of Wolfcamp Permeability Data (after Smith and others, 1984)

TABLE 3
PENNSYLVANIAN PERMEABILITY DATA

Lithology: DOLO = dolomite; GW = Granite wash; LS = limestone
SS = sandstone; CARB = carbonate

Well Number/Name	Test Type	Lithology	k (md)	log(k)
365	DST	LS	0.1513	-0.820
366	DST	LS	7.5646	0.879
367	DST	LS	0.2877	-0.541
553	DST	LS	0.73149	-0.136
560	DST	LS	0.0043	-2.365
562	DST	GW	0.8714	-0.060
563	DST	GW	1.1328	0.054
564	DST	LS	0.4286	-0.368
566	DST	GW	0.1304	-0.885
567	DST	GW	0.5582	-0.253
569	DST	GW	4.4047	0.644
572	DST	GW	0.3675	-0.435
573	DST	GW	0.0289	-1.539
574	DST	LS	1.3822	0.141
575	DST	GW	2.9044	0.463
579	DST	GW	0.1782	-0.749
580	DST	GW	0.0223	-1.651
581	DST	GW	0.0696	-1.157
582	DST	GW	0.2546	-0.594
832	DST	SS	10.269	1.012
836	DST	SS	2.098	0.322
837	DST	SS	9.198	0.964
840	DST	LS	0.079	-1.103
841	DST	LS	0.004	-2.357
842	DST	SS	3.716	0.570
843	DST	LS	0.563	-0.250
844	DST	DOLO	0.025	-1.597
845	DST	GW	0.809	-0.092
948	DST	GW	0.3854	-0.414
962	DST	GW	0.0897	-1.047
963	DST	GW	1.5982	0.204
965	DST	DOLO	0.0107	-1.969
966	DST	GW	23.5315	1.372
967	DST	SS	0.8744	-0.058
970	DST	GW	0.0241	-1.618
971	DST	GW	0.5174	-0.286
972	DST	GW	4.6349	0.666
973	DST	LS	0.0477	-1.322

TABLE 3 (Continued)
PENNSYLVANIAN PERMEABILITY DATA

Lithology: DOLO = dolomite; GW = Granite wash; LS = limestone
SS = sandstone; CARB = carbonate

Well Number/Name	Test Type	Lithology	k (md)	log(k)
976	DST	GW	0.7927	-0.101
977	DST	LS	0.0068	-2.169
978	DST	GW	3.0265	0.481
979	DST	GW	1.6913	0.228
980	DST	GW	0.0371	-1.431
981	DST	GW	0.4674	-0.330
982	DST	GW	0.0948	-1.023
987	DST	LS	30.5303	1.485
989	DST	GW	0.0158	-1.802
994	DST	SS	0.0862	-1.064
1001	DST	GW	0.0090	-2.047
1049	DST	GW	1.9481	0.290
1073	DST	GW	2.62494	0.419
MANSFIELD	DST	-	8.8	0.944
SAWYER	PUMP	GW	2.7	0.431
J. FRIEMEL	PUMP	CARB	100.0	2.000
J. FRIEMEL	PUMP	GW	500.0	2.699
J. FRIEMEL	PUMP	GW	10.0	1.000
J. FRIEMEL	PUMP	GW	150.0	2.176
J. FRIEMEL	PUMP	GW	150.0	2.176
J. FRIEMEL	PUMP	GW	50.0	1.699
ZEECK	DST	LS	2.8	0.447
ZEECK	PUMP	CARB	6.4	0.806

Note: Permeability data identified with a well number are from Smith and others (1984). Only data located between 34° to 36° N latitude and 101° to 103° W longitude have been taken from this source (see Figure 8). The remaining data identified with a well name are from OCWRM program wells as reported by DOE (1986; Table 3-26).

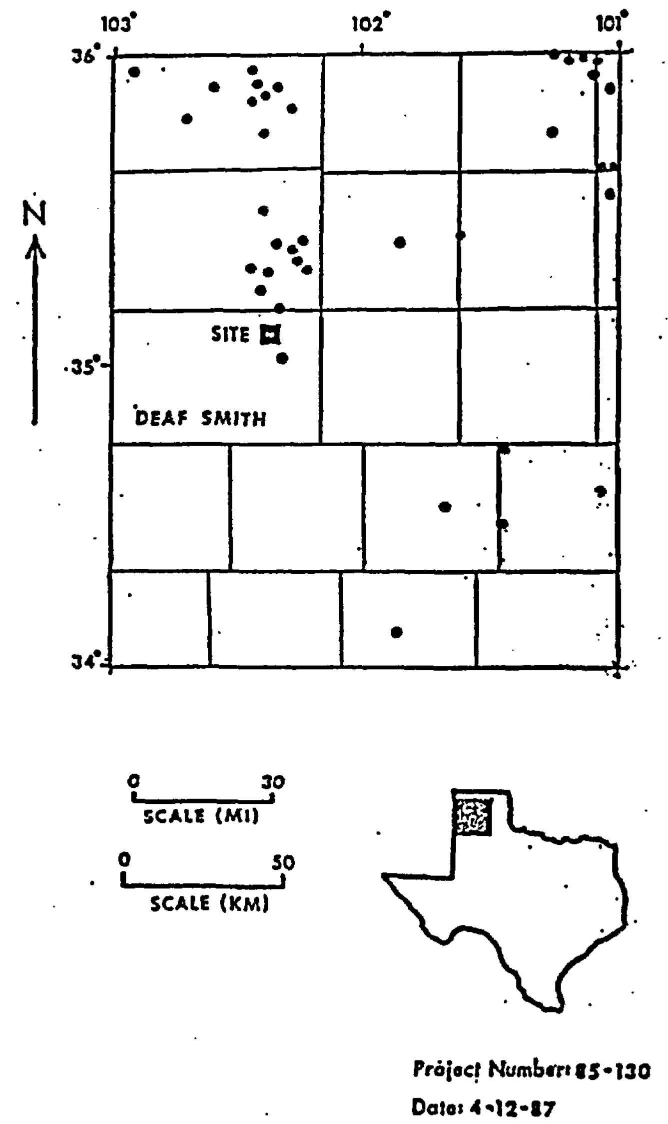


Figure 8. Location of Pennsylvanian Permeability Data (after Smith and others, 1984).

Table 4. Summary of Log Permeability Data

Unit	Number of Samples N	Sample Mean ± Standard Deviation $\bar{x} \pm s$ (log k)
Lower San Andres	11	-0.674 ± 0.965
Wolfcamp	45	-0.225 ± 0.898
Pennsylvanian	61	-0.149 ± 1.188

6.0 RESULTS

The 95% confidence intervals for the lower San Andres, Wolfcamp and Pennsylvanian Formations have been calculated from the log-permeability data in Table 4 using equation 1 (Table 5). These results may be interpreted as follows. Suppose that log-permeability is normally distributed within a hydrostratigraphic unit and that the true mean of log-permeability within the hydrostratigraphic unit is μ. Furthermore, suppose that a large number of random samples are obtained and that each sample consists of N determinations of log-permeability (each sample having its individual mean $\bar{x}$ and standard deviation s). Then many different confidence intervals can be calculated (i.e., one confidence interval per sample) using equation 1 and the t distribution at the ($1-\alpha$) percent confidence level with N-1 degrees of freedom. Because the confidence level ($1-\alpha$) has been specified, 95% of these different confidence levels will include the true mean log-permeability μ of the hydrostratigraphic unit. In this report there is only one sample of log-permeability data for each hydrostratigraphic unit rather than many different samples and that is usually the case in such computations. Therefore, a single confidence interval is reported for each hydrostratigraphic unit (Table 5). These confidence intervals have approximately a 95% chance of including the "true" mean log-permeability of the hydrostratigraphic unit as described above.

DRAFT

Table 5. 95% Confidence Intervals determined from log k values in Table 4. Interval values in millidarcies are given in parentheses for comparison. μ_k is the mean of k in millidarcies.

Unit	95% Confidence Interval Log k (md)
Lower San Andres	$-1.314 < \mu < -0.034$
	$(0.049 < \mu_k < 0.925)$
Wolfcamp	$-0.496 < \mu < 0.046$
	$(0.319 < \mu_k < 1.112)$
Pennsylvanian	$-0.453 < \mu < 0.155$
	$(0.352 < \mu_k < 1.429)$

Critical values of log-permeability, which correspond to the maximum permeability which ensures regulatory criteria will be met, have been calculated using equation 5 (Table 6). A calculated t statistic (equation 3), which compares observed log-permeability data to the critical value of log-permeability (equation 5, Table 4), is presented in Table 6. The calculated t statistic is compared to the t statistic which defines the critical region (equation 2). If the calculated t statistic falls in the critical region (equation 2) then the hypothesis that the true mean permeability of the hydrostratigraphic unit is less than the critical value is rejected. In turn, this would imply that regulatory criteria may not be met.

The results presented in Table 6 include critical values of log k, a t statistic calculated from the sample mean and sample variance, and the t statistic which defines the critical region for the 5% level of significance. (The level of significance is the probability of rejecting the hypothesis when the hypothesis being tested is true). Critical values of log k and t statistics have been calculated for NRC and EPA criteria. Calculations for NRC criteria assume ground-water travel time to the accessible environment (5 km) is 1,000 years (10CFR60.113). Ground-water travel time equal to 10,000 years ensures that EPA Containment Requirements (40CFR191.13) are met.

DRAFT

Table 6. Critical value of log k, calculated t statistic and the t statistic which defines the critical region for the 5% level of significance.

Unit	Criteria	Critical log k	t (calculated)	t (critical region)
Lower San Andres				
	NRC (horizontal)	2.22	-9.95	1.81
	EPA (horizontal)	1.22	-6.51	1.81
	NRC (vertical)	-0.69	0.055	1.81
	EPA (vertical)	-1.69	3.49	1.81
Wolfcamp				
	NRC (horizontal)	2.38	-19.46	1.68
	EPA (horizontal)	1.38	-11.99	1.68
Pennsylvanian				
	NRC (horizontal)	2.82	-19.52	1.67
	EPA (horizontal)	1.82	-12.94	1.67

7.0 CONCLUSIONS

Based upon observed permeability values and given the assumptions made in this report, the permeability range of 0.049 to 0.93 md is likely to include the average permeability of the lower San Andres Formation (Table 5). This range of permeability is characteristic of low permeable sandstones and shales (Freeze and Cherry, 1979). Similarly, the permeability ranges of 0.32 to 1.11 md and 0.35 to 1.43 md are likely to include the average permeability of the Wolfcamp and Pennsylvanian Formations, respectively (Table 5). Permeabilities in the range 0.3 to 1.4 md are characteristic of sandstones (Freeze and Cherry, 1979).

Example calculations have been performed to determine the maximum (critical) value of log permeability which will ensure that NRC and EPA criteria are met (Table 6). The examples for horizontal flow through the Lower San Andres, Wolfcamp and Pennsylvanian Formations yield values of critical permeability which are one or two orders of magnitude (EPA or NRC criteria, respectively) greater than the upper limit of the 95% confidence interval for the corresponding formation (compare log k values in Tables 5 and 6). Because these critical permeability values are outside the 95% confidence intervals, ground-water travel time to the accessible environment along horizontal flow paths in each formation most likely will exceed 10,000 (and 1,000) years. These conclusions are supported by results of t tests presented in Table 6.

Similar calculations have been performed for vertical flow paths, i.e., from the Lower San Andres to the Wolfcamp Formation. However, for this case the vertical path length is 0.82 km (base of Lower San Andres to top of Wolfcamp) rather than 5 km as in the horizontal flow models. Therefore, due to this shorter path length, the maximum permeability which is calculated for travel times of 1,000 or 10,000 years is significantly less than those values calculated for the horizontal flow models. In fact, the calculated critical permeabilities for the NRC and EPA criteria (1,000 and 10,000 years) fall within the 95% confidence interval estimated from the Lower San Andres permeability data (see Tables 5 and 6). Furthermore, based on the results of the t test, the hypothesis that the permeability of HSU B is less than the critical value for the EPA criterion is rejected. This, in turn, implies that ground-water travel time vertically downward from the Lower San Andres to the Wolfcamp Formation is likely to be less than 10,000 years. However, it should be kept in mind that once the ground water arrives at the Wolfcamp Formation (after traveling vertically downward from the repository host horizon), the ground water must travel about 5 km horizontally before arriving at the accessible environment.

8.0 DISCUSSION

Confidence intervals have been calculated for the Lower San Andres, Wolfcamp and Pennsylvanian formations. The intervals provide a range of permeability which is likely to include the actual mean permeability of the formation. The confidence interval calculation is, however, based on the observed data and some assumptions which may affect the results and the conclusions.

It has been assumed that the data used in this study have been randomly sampled from a hydrostratigraphic unit which contains a normal distribution of log-permeability. However, the permeability data have been obtained from drill stem tests and thus are not likely to be random samples. Drill stem tests are often performed in zones where permeability is suspected of being high (Smith and others, 1984). Therefore, average permeabilities estimated from drill stem test data may be somewhat higher than the actual regional average permeability.

Sample calculations that relate the observed permeability data to NRC and EPA regulations have been presented. For both cases (i.e., NRC and EPA) a critical permeability was computed using Darcy's Law, representative values of porosity and hydraulic gradient, the distance to the accessible environment and a time criteria obtained from NRC and EPA regulations. The results are based on hydraulic head data and a fixed hydraulic gradient. The results do not test sensitivity to hydraulic gradient or porosity. The computed critical permeability is essentially the maximum permeability which will ensure that certain siting criteria and environmental standards will be met (10CFR60.122; 40CRF191.13). The example calculations compare the observed permeability data to the critical permeability in order to determine whether the average permeability of the hydrostratigraphic unit is likely to be greater than the maximum allowed permeability. In other words, the observed permeability data is used to indicate if the NRC and EPA regulations are likely to be met.

Transport of radionuclides to the accessible environment is likely to involve horizontal flow paths (see Figures 4 and 5). Example calculations comparing observed permeability data to critical permeabilities for horizontal flow paths have been performed. The results suggest that the average permeability along the horizontal flow paths is likely to be low enough that ground-water travel time over 5 km distance will be greater than 10,000 years and thus also greater than 1,000 years. Therefore, it seems likely that certain siting criteria and environmental standards will be met.

It should be noted that the confidence interval calculations are based on assumptions of independence of samples. More specifically, the confidence interval calculations do not incorporate spatial correlation. The calculations therefore essentially would apply in the homogeneous porous media case where permeability variations are (1) purely random and/or (2) due to measurement error.

9.0 REFERENCES

Bassett, R.L., M.E. Bentley, and W.W. Simpkins, 1981, Regional Groundwater Flow in the Panhandle of Texas: A Conceptual Model: Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle: A Report on the Progress of Nuclear Waste Isolation Feasibility Studies, Gustavson, T.C. et al., Editors, Texas Bur. Econ. Geol., Circular 81-3, Austin, Texas, pp. 102-107

Dixon, W.J. and F.J. Massey, 1983, Introduction to Statistical Analysis, McGraw-Hill, New York

DOE, 1986, Final Environmental Assessment, Deaf Smith County Site, Texas, 3 vol.

Dutton, A.R., 1983, Regional ground-water flow system of the San Andres Formation, West Texas and eastern New Mexico, Texas Bur. Econ. Geol. Circ., 83-4, 97-101.

Freeze, R.A. and J.A. Cherry, 1979, Groundwater, Prentice-Hall, Englewood Cliffs, New Jersey

INTERA Environmental Consultants, (1984a) First Status Report on Regional Ground Water Flow Modeling for the Palo Duro Basin, Texas, ONWI-504

INTERA Environmental Consultants (1984b) Second Status Report on Regional Ground Water Flow Modeling for the Palo Duro Basin, Texas ONWI-E512-02900/TR-31, 410A-ooG-17A

Senger, R.K. and G.E. Fogg (1984) Modeling the Effects of Regional Hydrostratigraphy and Topography on Ground Water Flow, Palo Duro Basin, Texas, Texas Bur. Econ. Geol., Report OF-WTWI-1984-32

Senger, R.K.; R.D. Conti; and D.A. Smith (1985a) A Three-Dimensional Ground Water Flow Model for the Palo Duro Basin Texas: Texas Bur. Econ. Geol., Report OF-WTWI-1985-39

Senger, R.K., G.E. Fogg, and C.W. Kreitler (1985b) Effects of Hydrostratigraphy and Basin Development on Hydrodynamics of the Palo Duro Basin, Texas: Texas Bur. Econ. Geol., Report of OF-WTWI-1985-37

Senger, R.K. and G.E. Fogg, 1983, Regional Modeling of Ground-Water Flow in the Palo Duro Basin, Texas Panhandle, Texas Bur. Econ. Geol. Circ. 83-4, p.109-115

Smith, P.G., Page G.W. and J.K. Downing, 1984, Regional permeability determinations from limited drill-stem test data, Stone & Webster Engineering Corp Topical Rep., ONWI/SUB/84/E512-05000-T32.

Stephens & Assoc., 1986a, Numerical Evaluation of Conceptual Models, Subtask 3.5 Report

Stephens & Assoc., 1986b, Conceptual Model Evaluation, Subtask 3.4 Report

Wirojanagud, P., C.W. Kreitler; and D.A. Smith (1984) Numerical Modeling of Regional Ground Water Flow in the Deep-Brine Aquifers of the Palo Duro Basin, Texas Panhandle: Texas Bur. Econ. Geol., Report OF-WTWI-1984-8