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ENVIRONMENTAL RESTORATION PROGRAM

THE MCNAIRY FORMATION IN THE AREA OF THE PADUCAH GASEOUS DIFFUSION PLANT

K. R. Davis

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THE MCNAIRY FORMATION IN THE AREA OF THE PADUCAH GASEOUS DIFFUSION PLANT

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ACRONYMS

α	aquifer compressibility
AMSL	above mean sea level
β	compressibility of water
cm/sec	centimeters/second
DNAPL	dense nonaqueous phase liquid
g	acceleration constant due to gravity
i	hydraulic gradient
i_h	hydraulic gradient in a horizontal direction
i_v	hydraulic gradient in a vertical direction
k	bulk modulus
K	hydraulic conductivity
K_h	hydraulic conductivity in a horizontal direction
K_i	hydraulic conductivity in a vertical direction
KOW	Kentucky Ordnance Works
m	natural moisture content
MEQ/L	milliequivalents/liter
MG/L	milligrams/liter
PGDP	Paducah Gaseous Diffusion Plant
PPM	parts per million
RGA	regional gravel aquifer
ρ_s	specific gravity of solids fraction
ρ_w	density of water
S_s	specific storage
SU	standard units
TCE	trichloroethene
θ	porosity
TVA	Tennessee Valley Authority
V_p	P-wave velocity
V_s	S-wave velocity

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1. CONCLUSION

The objective of this research is to determine the potential for contamination of the McNairy Formation at the Paducah Gaseous Diffusion Plant (PGDP). Previous sampling and this study indicate very little contamination exists in the McNairy Formation, other than shallow depths of the McNairy underlying heavily contaminated zones of the regional gravel aquifer (RGA). Although groundwater flows from the RGA into the McNairy flow system, advective groundwater flow in the upper McNairy is approximately only 0.2 inches per year. At this scale of flow, diffusion may be the dominant control to contaminant migration in the McNairy.

This review of existing reports and analysis of available data has defined the primary hydrogeologic attributes of the McNairy Formation that control migration of PGDP contaminants off-site. Remedial investigation sampling and analysis of sites contaminated by trichloroethene (TCE) in the form of dense nonaqueous phase liquid (DNAPL) should be adequate to confirm the conclusions in this report. The only additional drilling investigation that may be warranted would be the installation of piezometers near the Ohio River to document upward groundwater flow in the McNairy Formation to discharge to the river.

2. SUMMARY

A primary concern for PGDP has been the migration of contaminants under the Ohio River to municipal well systems in Illinois. The basal sand member of the McNairy Formation is the uppermost unit that could transport contaminants under the Ohio River. Groundwater flow rates and contaminant migration rates are insufficient for contamination to have reached the basal sand member of the McNairy Formation. Sediments of the middle McNairy Formation member, in particular, contain abundant carbon and pyrite which chemically bind and degrade contaminants. It is unlikely that contaminants will be able to migrate through the middle member. In the event that contaminants did migrate to the basal McNairy sand, hydraulic potential in the McNairy Formation would likely drive groundwater flow to discharge into the Ohio River.

Where permeable units of the McNairy Formation are contiguous with the RGA, increased flow rates are expected. However, the upper 125 feet of the McNairy underlying PGDP is characteristically a silt interlayered with clay containing small lenses of sand and gravel. The vertical extent of sand and gravel lenses is limited. Faulting is reported in outcrops of the McNairy Formation in Illinois but does not appear to increase permeability of the McNairy underlying PGDP. Analysis of water level records for McNairy Formation wells at PGDP demonstrates that the upper McNairy section behaves as a single hydrologic unit of low hydraulic conductivity.

TCE concentration and distribution in the RGA at a few areas of PGDP are evidence of the presence of DNAPL which likely penetrated to the base of the RGA. DNAPL flow is retarded by low permeability materials when the DNAPL is not the wetting fluid. In the case of a TCE leak into

an aquifer, water is the wetting fluid. Thus, the potential exists for development of a pool of TCE at the base of the RGA. It is likely that the fine textured, interlensing nature of the McNairy sediments, creating abundant permeability contrasts, has prevented any appreciable vertical flow of DNAPL beyond the base of the RGA.

On-site sampling for the recent Northeast Plume Characterization Investigation in areas where the RGA was heavily contaminated revealed contaminants at shallow depths in the McNairy Formation. Contaminant levels abruptly declined with increasing depth. Based on investigation results, the maximum depth of contamination in the McNairy at the sampled locations was approximately 50 feet. This depth should be a good estimate of the extent of contamination in the McNairy Formation.

3. INTRODUCTION

PGDP, McCracken County, Kentucky, lies near the northern limit of the Mississippi Embayment. In the area, the ancestral Tennessee River eroded through the Paleocene Porters Creek Clay and deposited Quaternary sands and gravels on the Cretaceous McNairy Formation. The Quaternary sand and gravel deposits constitute the uppermost aquifer in the area of buried valley fill.

The McNairy Formation consists of approximately 270 feet of fine-grained, clastic sediments overlying Mississippian bedrock in the PGDP area. A marked permeability contrast exists between the Quaternary sands and gravels and the Cretaceous fine-clastic sediments. The McNairy functions as the lower confining unit to the shallow aquifer system. However, the hydraulic properties of the McNairy sediments and the degree and nature of hydraulic interaction with the Quaternary sands and gravels has not been quantified.

This paper presents an analysis of the hydrogeologic data available in the area of PGDP. Regional studies by researchers of the Kentucky, Illinois, and federal geologic surveys provide valuable context for comparison and extrapolation of area data. The characteristics of the McNairy Formation in the area of PGDP are generally consistent with previously recognized trends and define local controls to groundwater flow.

4. STRATIGRAPHY

4.1 REVIEW OF SELECTED LITERATURE

Moneymaker and Grant (1954) describe the McNairy section (referred to as the Ripley formation) at the Tennessee Valley Authority's (TVA) Shawnee Steam Plant, located 2.7 miles northeast of PGDP. The paper defines lithology and thickness of three informal members constituting the McNairy Formation: an upper member of interlensing sand, clay, clayey sand, and sandy clay; a middle member of clayey sand and sandy clay; and a lower member of sand. This report adopts the three-member system proposed by Moneymaker and Grant (1954) as a basis for describing the area stratigraphy.

Pree, Walker, and MacCary (1957) characterize the McNairy Formation (Ripley formation) in the Paducah area. The authors recognize two facies: an upper interval of interbedded micaceous clays and fine-to-very-fine silty sands and a lower interval of fine-to-medium micaceous sand.

Pryor (1960) reports on studies of the depositional setting of Cretaceous sediments in the northern margins of the Mississippi Embayment. In his paper, he presents research on stratigraphy, paleontology, textural analyses, petrography, and sedimentary structures. Pryor concludes the Cretaceous sequence originated as a deltaic deposit with a McNairy delta system centered in the northeastern margin of the embayment. His analysis indicates that the McNairy sediments were predominately of fluviatile origin grading to marine sands and clays to the southwest.

Pryor and Ross (1962) describe the geologic setting of southwestern Illinois. The authors map outcrop geology across the region and define subsurface structure with maps and cross-sections. This report describes the McNairy Formation in southwestern Illinois as "fine, cross-stratified, micaceous sands with numerous thin beds of lignitic silt and clay" (p. 19). A depositional environment of sedimentary textures is presented. McNairy sand units originate from fluvial deposits. Lignitic clays and silts represent floodplain and interdistributary deposits. A well-defined, lignitic silt and clay unit termed the Levings Member is recognized in the upper McNairy of Illinois.

Davis, Lambert, and Hansen, Jr. (1973) summarize regional hydrogeologic trends of the Jackson Purchase Region, Kentucky. They note the McNairy Formation is primarily sand in the southeastern Jackson Purchase, but the lithology grades to clay with a small percentage of thin sand bodies near Paducah. The report includes regional maps of geologic structure, water quality and yield, and hydraulic potential.

4.2 STRATIGRAPHIC SETTING

The stratigraphic sequence of Mississippi Embayment sediments near PGDP consists of the Cretaceous McNairy Formation overlain by the Paleocene Porters Creek Clay and, in turn, overlain by undifferentiated Eocene sands and Miocene(?)-to-Pleistocene Continental Deposits (Figure 1).

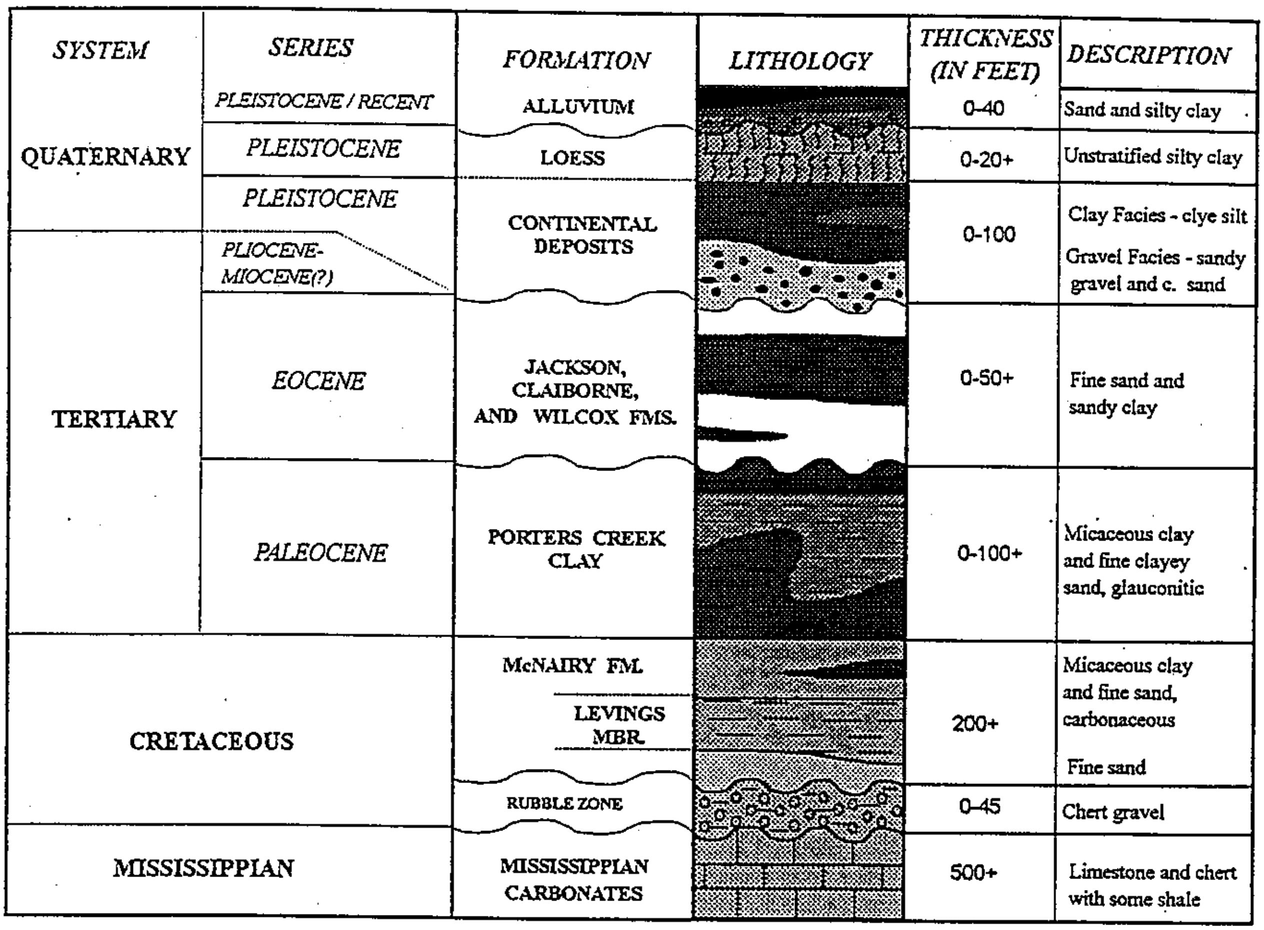


Figure 1. Columnar section of the Jackson Purchase Region.

The terrace slope marking the southern limits of the ancestral Tennessee River valley is located beneath PGDP. A subcrop of the Porters Creek Clay forms the grade. North of the terrace slope, Quaternary sands and gravel directly overlie the McNairy Formation. Porters Creek Clay overlies the McNairy Formation immediately south of PGDP (Figure 2).

McNairy sediments are found in direct contact with Mississippian limestone in many borehole locations. However, older gravel units are commonly encountered immediately below the McNairy Formation. Area researchers have attributed these gravels to outliers of the Cretaceous Tuscaloosa Formation or residual material from weathering of the Mississippian carbonate associated with the Little Bear Soil horizon. Evidence in the PGDP area suggests these gravel units, where present locally, are in situ weathered zones similar to the Little Bear Soil horizon.

Within the McNairy, three members are defined over most of the PGDP area. At PGDP, the McNairy includes an upper silt and sand member, a middle silt and clay Levings Member, and a lower sand member. The depositional environment was not conducive to the formation of laterally extensive, smaller scale, depositional units. None have been identified.

4.3 SOURCES OF DATA

Soil and groundwater investigations at PGDP have resulted in 120 borings completed in the McNairy Formation. In general, these borings terminate in the upper 10 to 50 feet of the McNairy. Cross-sections of the boring logs, such as those of the PGDP Groundwater Investigation Phase II (ERC, 1989), demonstrate the absence of laterally extensive beds in the McNairy.

Figure 3 presents the locations of borings with lithologic and/or geophysical logs used in review of the McNairy Formation in the PGDP area. Appendix A compiles logs of area McNairy boreholes available to the author for this paper. This study uses foundation and groundwater investigations at PGDP and the Shawnee Steam Plant, records of water wells maintained by the state geologic surveys of Illinois and Kentucky and U.S. Geological Survey, and logs of oil prospect boreholes for the primary sources of data.

Two borings, P4-F8 and Z16, provide sample and gamma ray logs of the entire McNairy section directly underlying PGDP. Boring P4-F8 is a result of the PGDP Groundwater Investigation Phase IV (Garner, Morti, and Smuin; 1995). Borings Z16 and Z12 (boring Z12 is located 2.1 miles northeast of PGDP) are products of the PGDP Facility Safety Analysis Program (ERCE, 1990). The log of PGDP well MW121 (CH2M Hill, 1991) provides lithologic control of the upper and middle McNairy members north of PGDP.

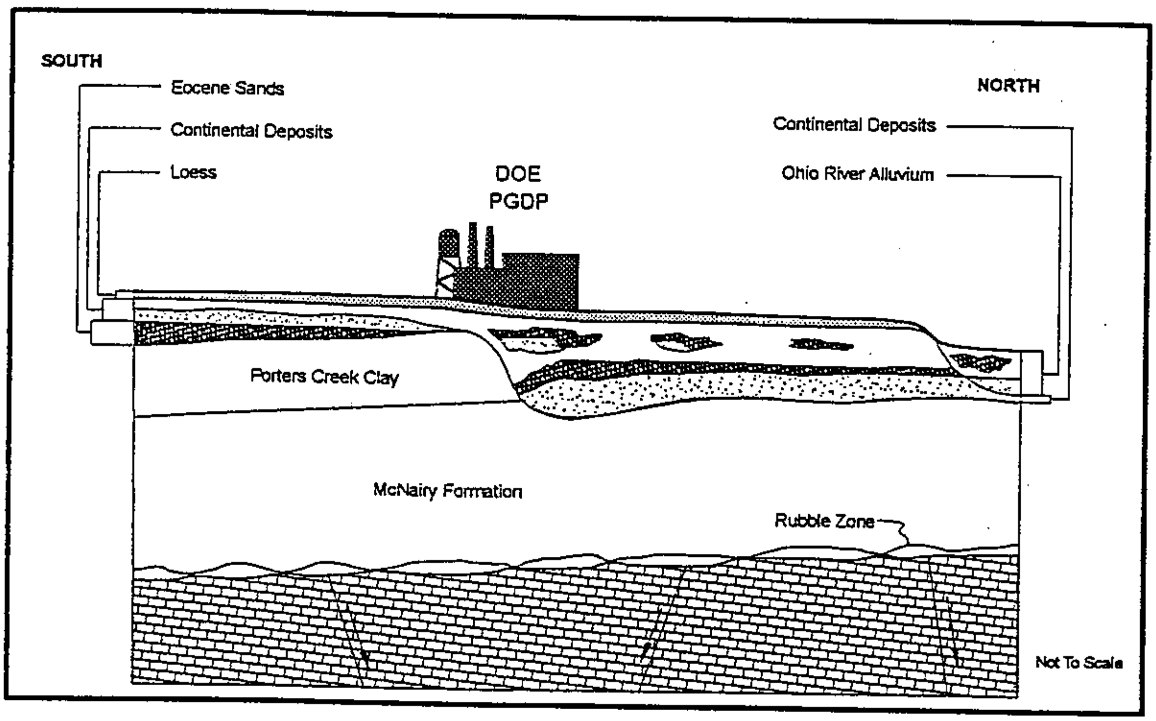


Figure 2. Schematic north-south section showing regional stratigraphic relationships (not to scale).

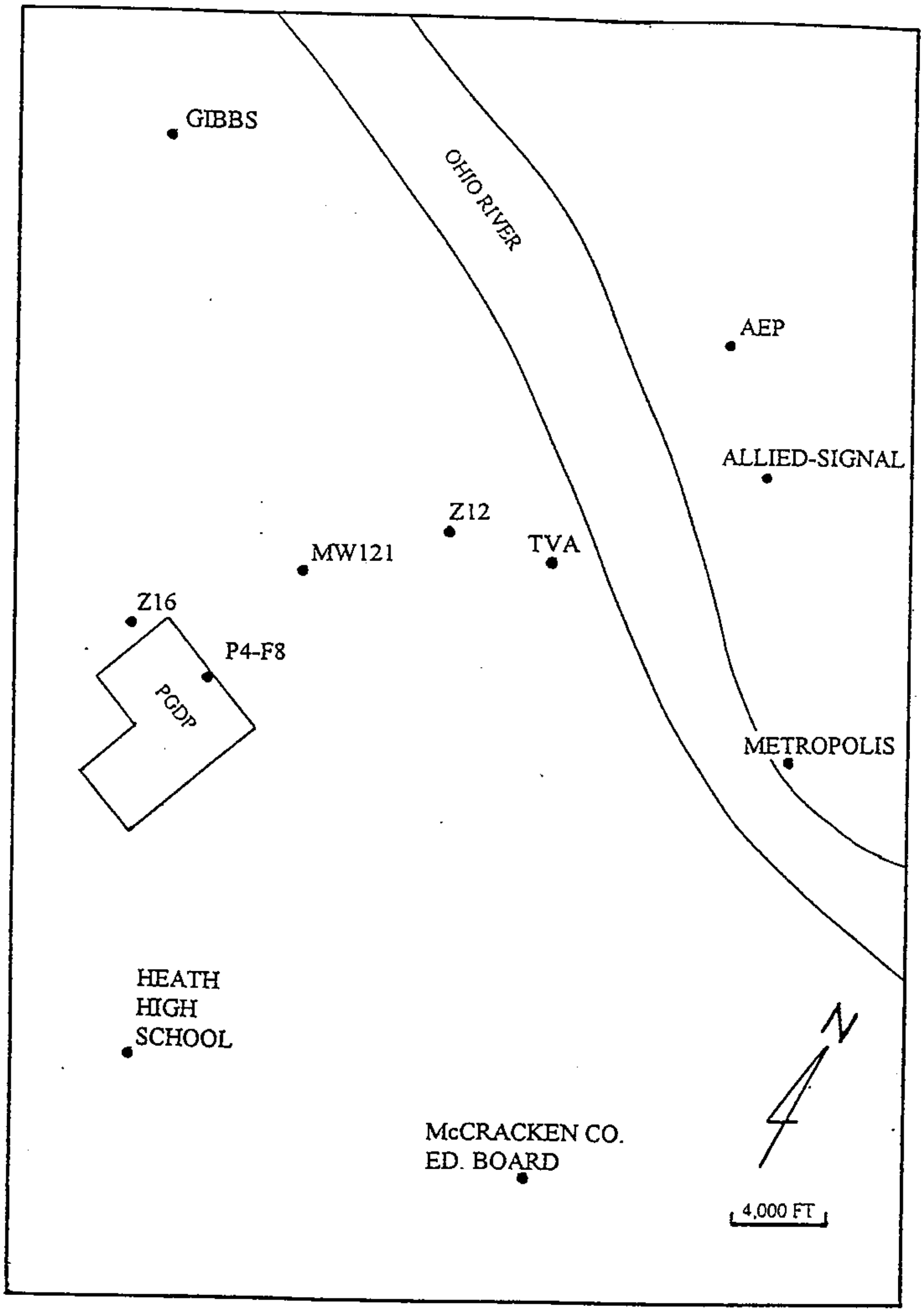


Figure 3. McNairy Formation boring and well location map.

Foundation investigations for the Shawnee Steam Plant yield lithologic logs of usable quality from 13 closely-spaced borings extending through the upper McNairy member (Kellberg, 1951). One of the borings (No. 55) fully penetrates the McNairy Formation. Two publications, Moneymaker and Grant (1954) and Finch (1967), review the lithologic records from the borings. As at PGDP, the researchers did not identify laterally extensive beds. The analysis of stratigraphy over the study area uses a composite log representing the characteristic sediments of the upper and middle McNairy members and the sample descriptions of the lower McNairy member from the deepest boring.

Gamma ray logs of the oil prospect borehole David Gibbs No. 1 and a water well located at Heath High School afford the only control of stratigraphic trends immediately east and west (respectively) of PGDP. A lithologic log of a well drilled for the McCracken County Board of Education illustrates trends further to the east.

Well logs from three Illinois locations document stratigraphic trends to the north. Lithologic description of each of the three locations is a composite of characteristic lithologies derived from several borehole logs. The AEP Service Corporation composite log summarizes sample descriptions by J. M. Masters for groundwater prospect boreholes Nos. 1, 1A, and 2. At the Allied-Signal Plant, drillers logs of plant supply wells Nos. 1, 2, 3, a sanitary water well, and a fifth well (Gwin Drilling Company, 1971) provide the basis for lithologic control. The Metropolis composite log is derived from driller's logs by Fred M. Luth (1924), W. A. Fuller (1925), and W. L. Thorne (1928).

4.4 McNAIRY UPPER MEMBER

The upper member of the McNairy Formation primarily consists of interlensing, fine-grained, sand and silt. Sand predominates in the area of the Metropolis municipal wells, the Allied-Signal Plant, and the Shawnee Steam Plant. Silt content increases to the south. Sand units comprise less than one-half of the thickness of the McNairy upper member at PGDP.

The upper member and Levings Member contact is highest in the Illinois locations and at the Shawnee Steam Plant (Figure 4). Cross-sections of the boring logs from the foundation investigation at the Shawnee Steam Plant (Figure 5) document erosion of the Levings Member. The Shawnee Steam Plant overlies the axis of a high in the top of the Levings Member where erosion would be more prone to occur. Three lines of evidence suggest the transition from the Levings Member to the upper member was not a unique cut-and-fill event across most of the study area: 1) near-consistent elevation of the top of the Levings Member in the PGDP vicinity, 2) subtle textural transition across the boundary near PGDP, and 3) lack of a basal lag deposit in the upper member.

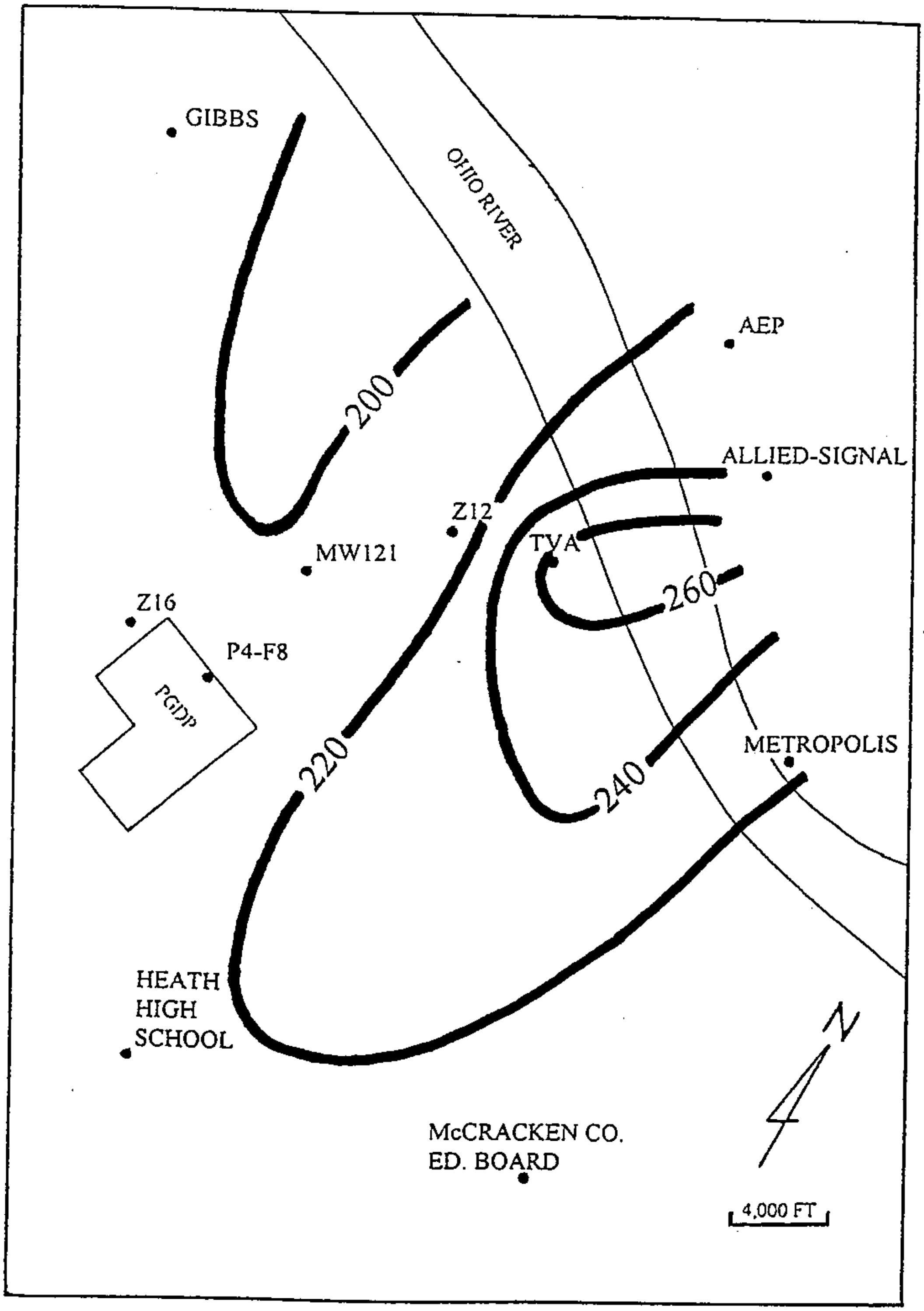
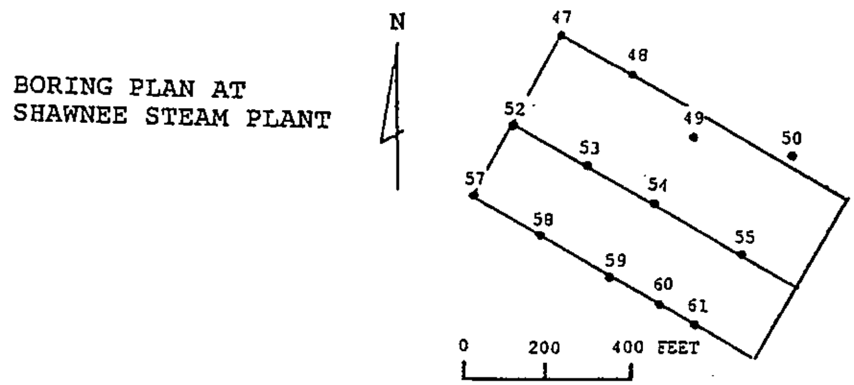


Figure 4. Top of the Levings Member (feet AMSL).



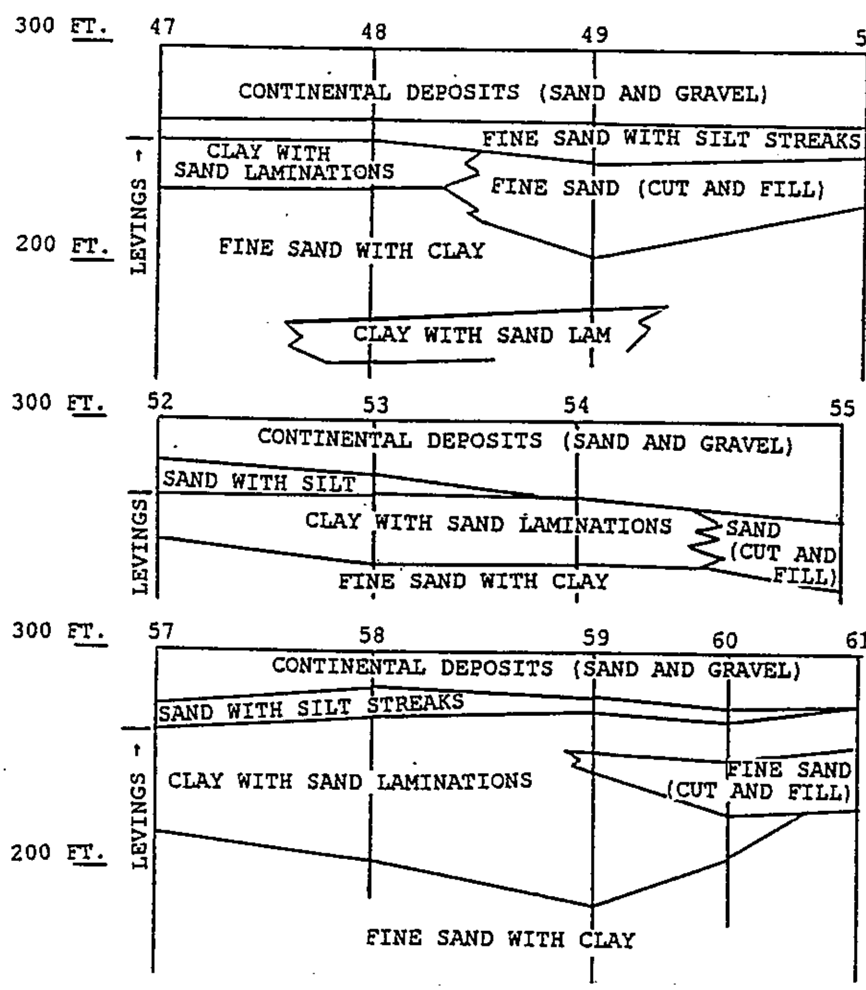


Figure 5. Geologic cross-sections of the Shawnee Steam Plant.

4.5 MCNAIRY LEVINGS MEMBER

A common interval of generally finer-grained clastic sediments exists in borings of the study area (Figures 6, 7, and 8). The lithologic character and stratigraphic position is consistent with description of the Levings Member by Pryor and Ross (1962).

The texture of the Levings Member sediments in the area of the Shawnee Steam Plant, Allied-Signal plant, and AEP Corporation borings is predominately clay. In the area of PGDP, the Levings interval has a higher percentage of silt and sand. Sample description and gamma-ray response identify a distinct finer-clastics interval in PGDP borings P4-F8 and Z12 and in the Heath High School water well and David Gibbs No. 1 boreholes. Only subtle textural change places the upper member and Levings Member contact at consistent elevation in PGDP boring Z16 and at well MW121 (208.9 and 202.9 feet above mean sea level [AMSL], respectively).

Structure of the Levings Member and lower member contact (Figure 9) marks the location of local controls to McNairy deposition. A lobate high between the Metropolis municipal wells and the Allied-Signal Plant places the location of the local distributary channel source of the lower member sediments. The site of the distributary channel persisted through the Levings interval. At the Metropolis municipal wells, the Levings interval is primarily sand, indicative of continuing channel deposition. To the northwest at the AEP Corporation boreholes, sands of the lower McNairy member are not present. The thick lower silt and clay unit suggests continuous deposition of inter-distributary sediments throughout the lower and Levings Member periods.

In the PGDP area, the upper member and Levings Member contact appears relatively planar, at an approximate elevation of 210 feet AMSL. The characteristic silt texture of the Levings Member in the PGDP area is consistent with deposition in a more distal location to the sediment source.

4.6 MCNAIRY LOWER MEMBER

The lower member of the McNairy Formation consists predominately of a well-sorted, fine sand with lesser silt and clay interbeds. Figure 10 defines the local structure at the base of the McNairy Formation. The distributary channel source to the local sands would have spilled into the basin from the north. The lower member thickens to the south and east, being absent in the vicinity of the AEP Corporation boreholes. Thickness trends suggest the local source of sediments was located in the vicinity of the Metropolis municipal wells or further to the east.

At Illinois locations, a thin bed of fine-clastic sediments commonly occurs at the base of the McNairy. Drillers describe the sediments as blue-to-black gumbo. This interval is not apparent in the two borings at PGDP. To the east of PGDP, well logs for the Heath High School well and McCracken County Board of Education bound an abrupt facies transition in the lower member. The lower sand member at PGDP largely grades to a thick clay interval to the east.

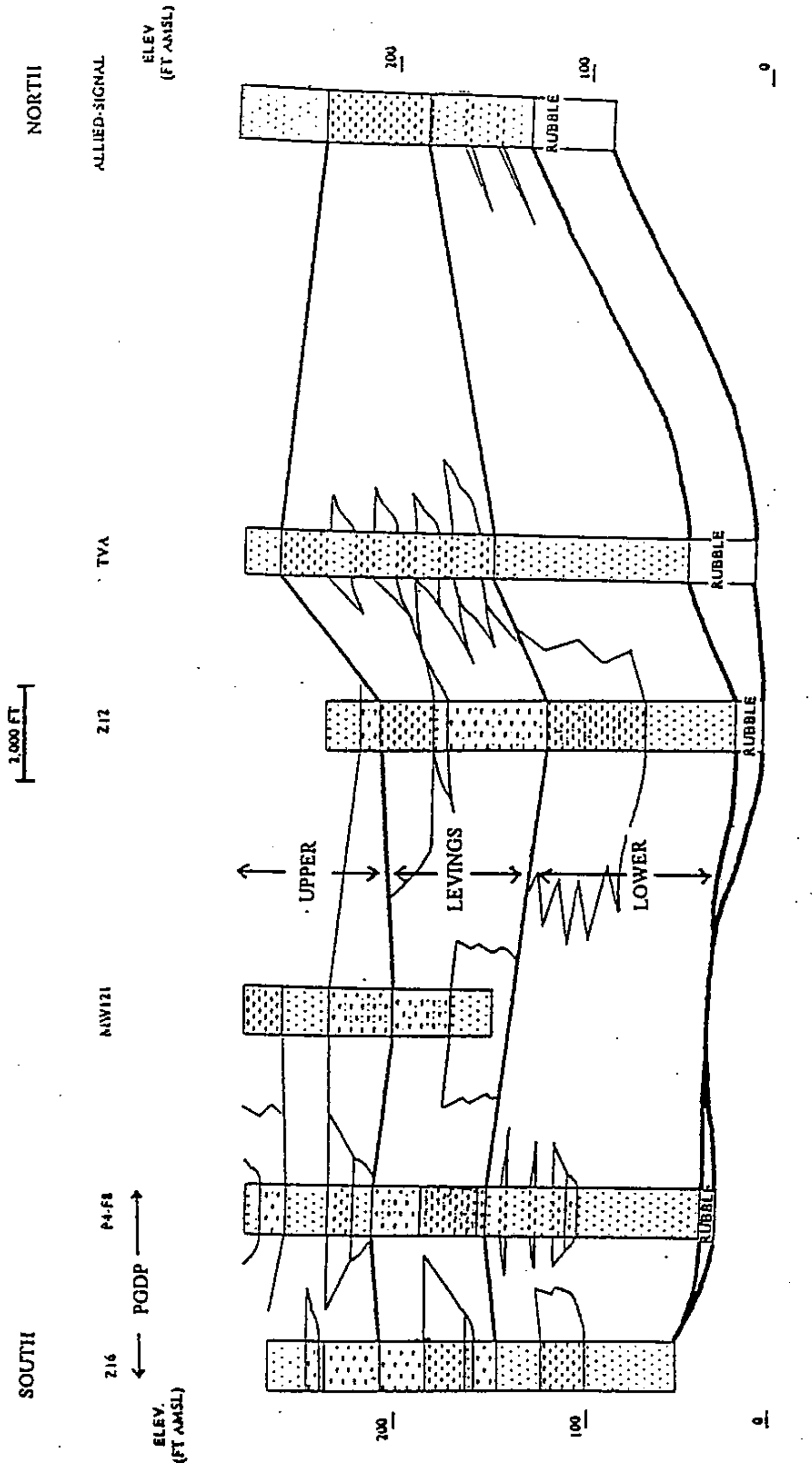


Figure 6. North-south cross-section through PGDP.

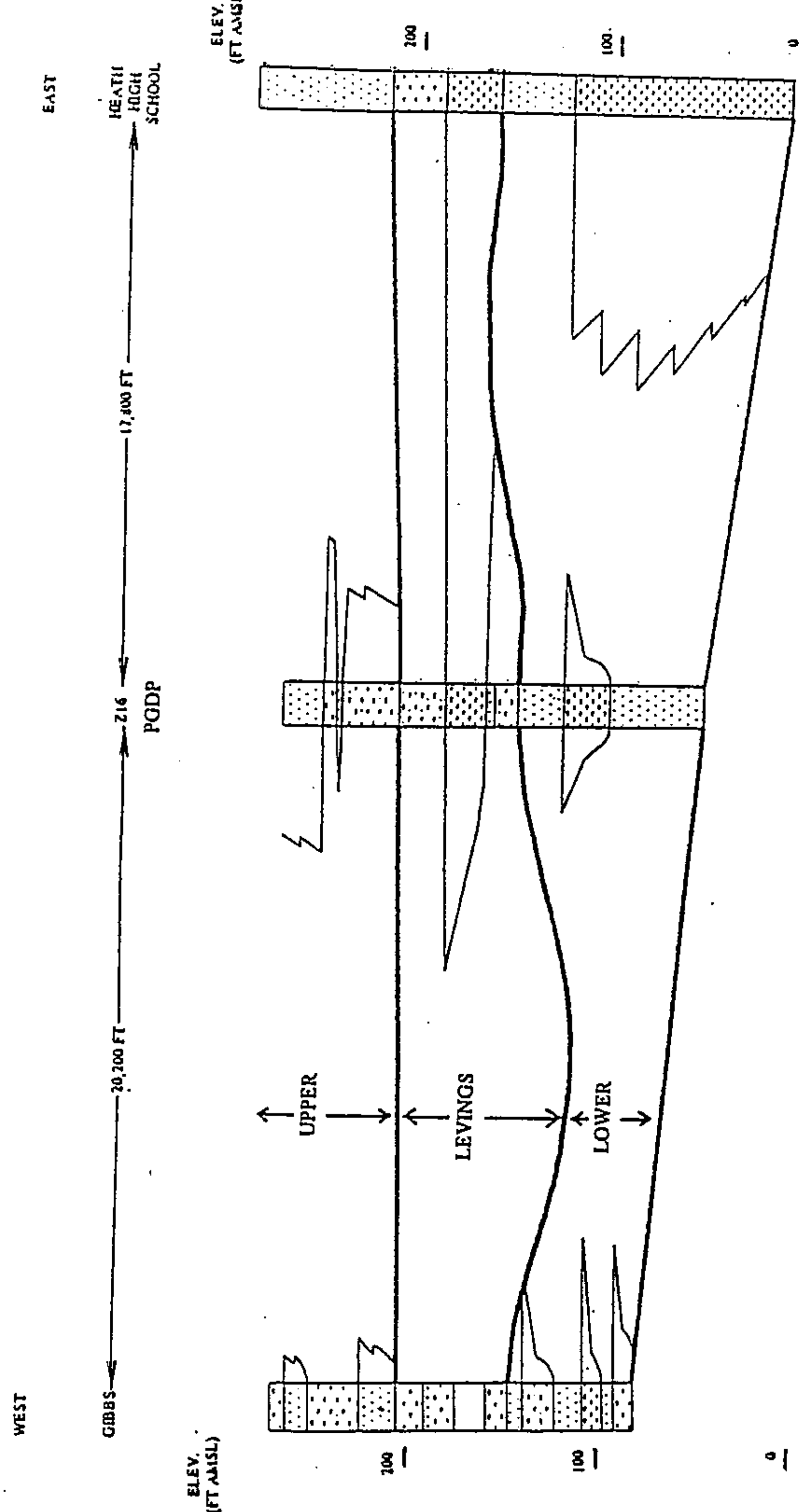


Figure 7. East-west cross-section through PGDP.

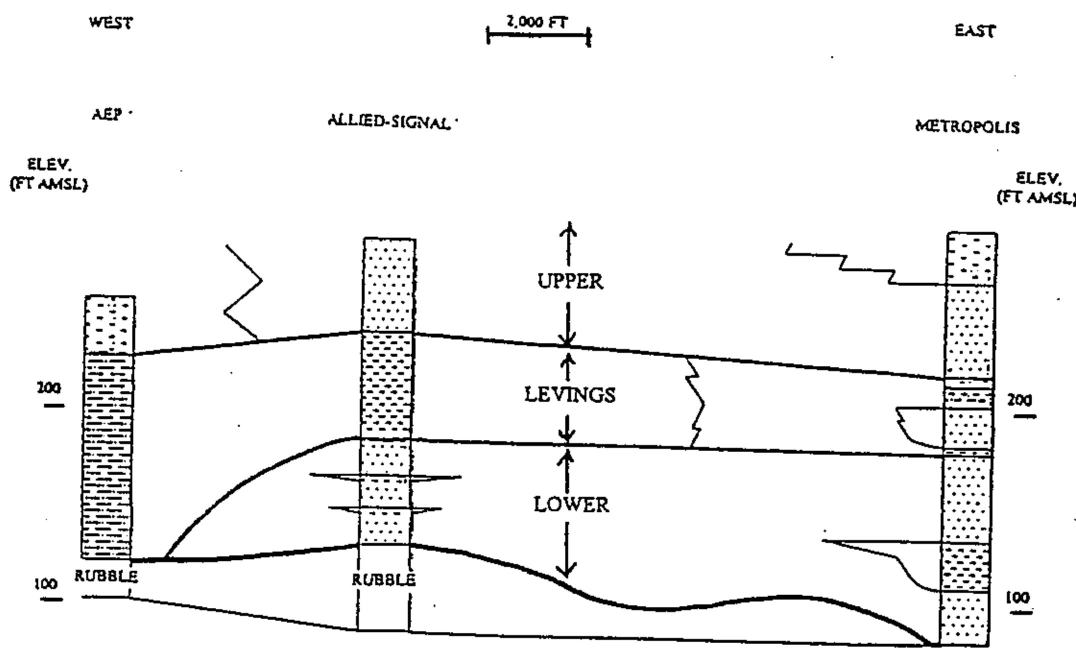


Figure 8. East-west cross-section in Illinois.

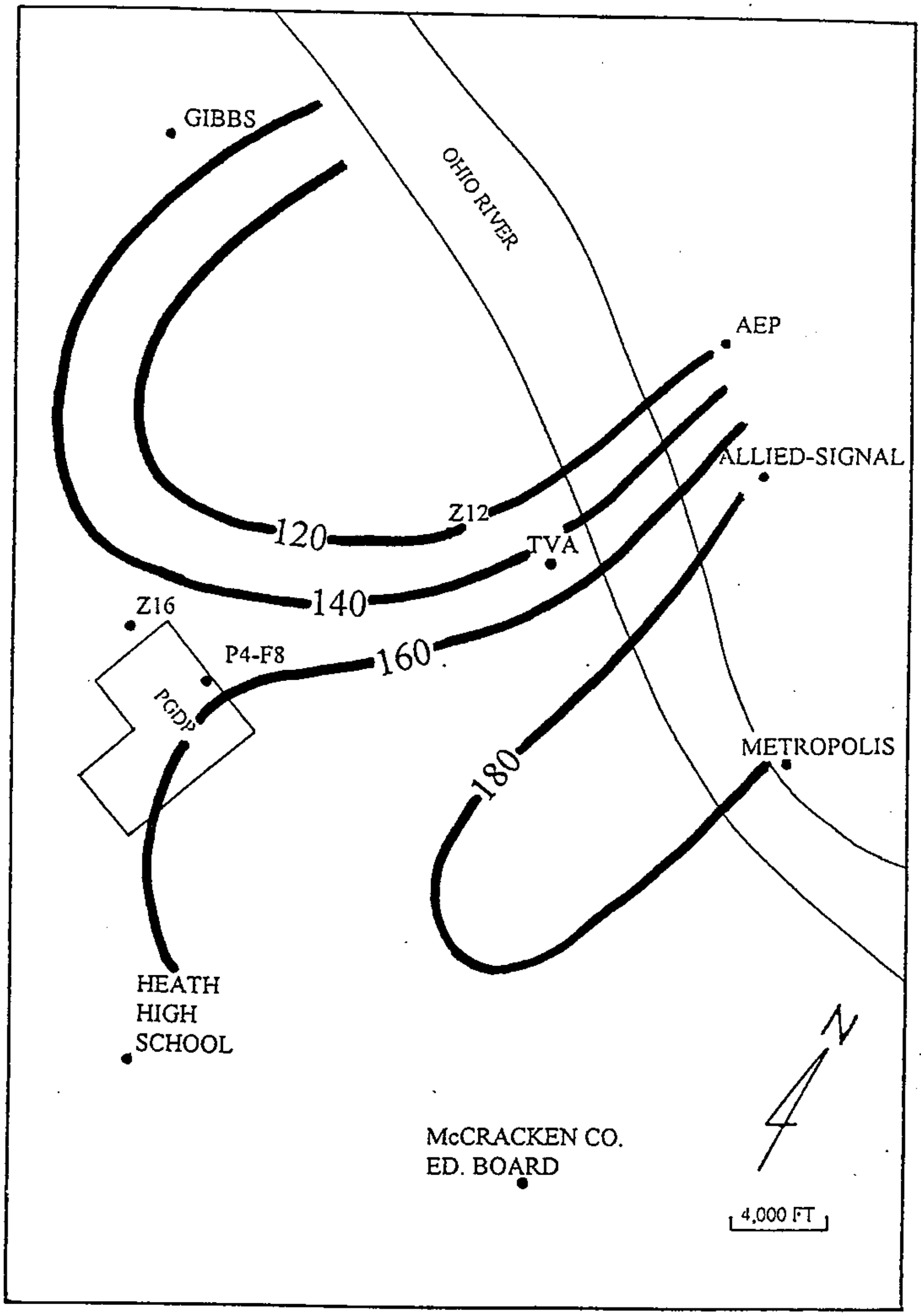


Figure 9. Base of the Levings Member (feet AMSL).

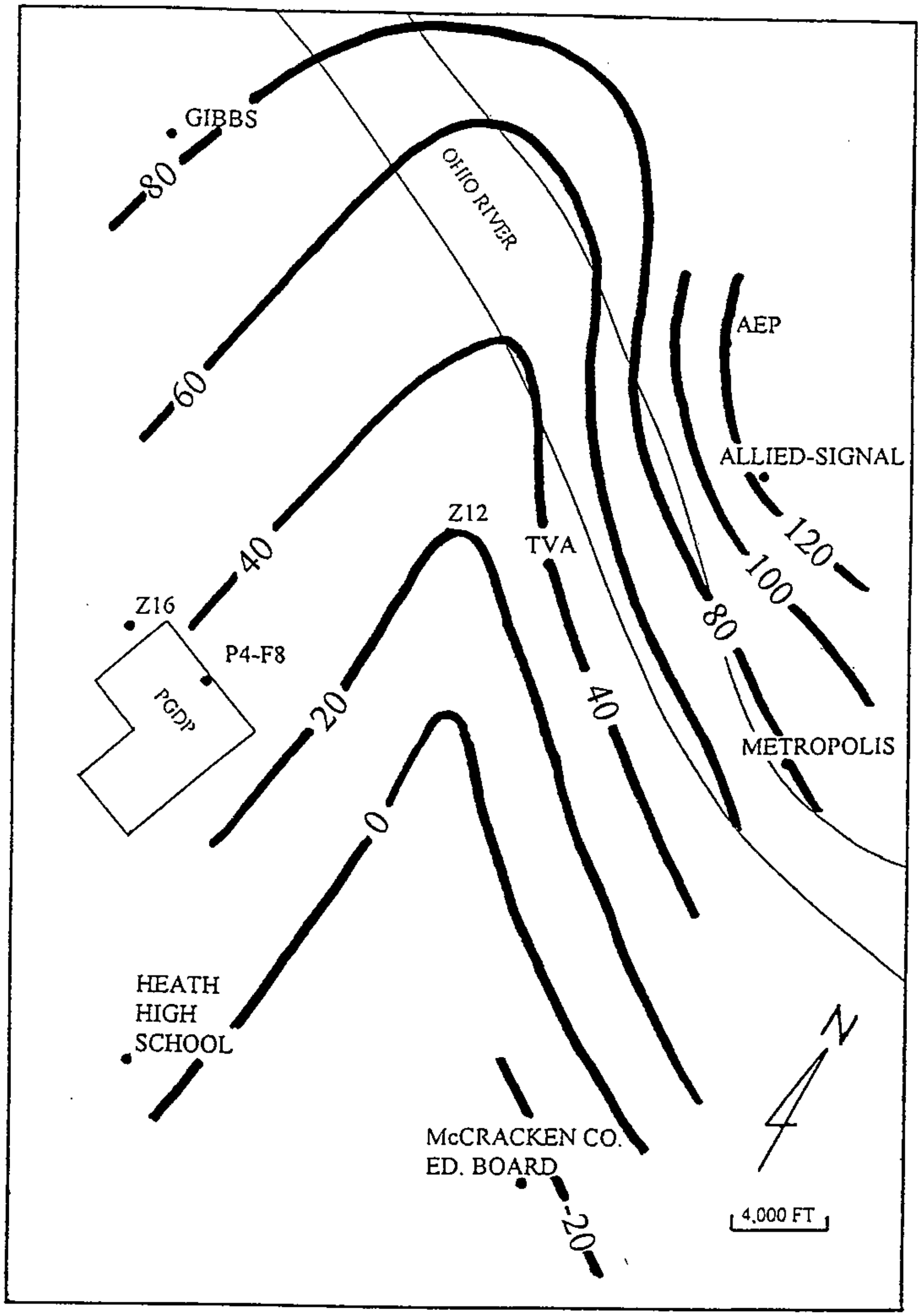


Figure 10. Base of the McNairy Formation (feet AMSL).

Appendix B presents all grain size analyses of McNairy Formation samples collected at PGDP. As noted by previous researchers (Moneymaker and Grant, 1954; Pryor, 1960; and Davis, Lambert, and Hansen, Jr., 1973), the McNairy sands are characteristically fine-grained. The sands of the lower member are uniquely well-sorted. Grain size analysis of a sand from boring Z16 at an elevation of 143 feet AMSL shows that the lower member sands retain the characteristic sorting in intervals where silt interbeds are common.

4.7 RUBBLE ZONE

Many borings in the PGDP area encounter an interval of older gravel immediately overlying the Mississippian limestone bedrock. Where identified, the gravels range from 10-feet thick (PGDP boring P4-F8) to 45-feet thick (Allied-Signal Plant borings). These gravels are commonly termed the Tuscaloosa Formation by area researchers but have also been attributed to the Little Bear Soil horizon (ERCE, 1990). Drillers logs for the Metropolis municipal wells report the interval (elevation 51 to 85 feet AMSL at Metropolis) as both the Tuscaloosa Formation (drilled by F. M. Luth in 1924) and a zone of weathered limestone (drilled by W. A. Fuller in 1925).

Comparison of thickness of the rubble zone and elevation of the zone's upper and lower contacts in the Allied-Signal Plant boreholes suggests the gravel interval is derived by in situ weathering of limestone bedrock similar to the origin of the Little Bear Soil horizon. The rubble zone is thickest where its upper contact is highest and its basal contact is lowest (Figure 11). These relationships evolve in karst settings of moderate relief and shallow water table. Well-developed cave systems under the valleys locally depress the water table and minimize weathering of overlying bedrock. Any residuum that develops in the valleys is rapidly eroded and transported away through the cave drainages. Present day analogues include the broad outcrop valleys of the Cambro-Ordovician Knox Group in the southeast United States.

5. HYDRAULIC PROPERTIES

5.1 REVIEW OF SELECTED LITERATURE

Davis, Lambert, and Hansen, Jr. (1973) report on the regional hydrogeology of the Jackson Purchase Region, Kentucky. The summary includes regional maps of geologic structure, water quality and yield, and potentiometric surfaces. Water level data suggests "the Paleozoic rocks and the McNairy Formation act as a single, interconnected hydraulic unit" (p. 34). The McNairy potentiometric surface indicates the Ohio River Valley in the area of PGDP is a discharge zone to the regional McNairy flow system.

Brahana and Mesko (1988) modeled groundwater flow in the upper Cretaceous formations of the northern Mississippi Embayment as part of the U.S. Geological Survey Regional Aquifer-System Analysis Program. In the model, McNairy groundwater flows to the Ohio River Valley and either

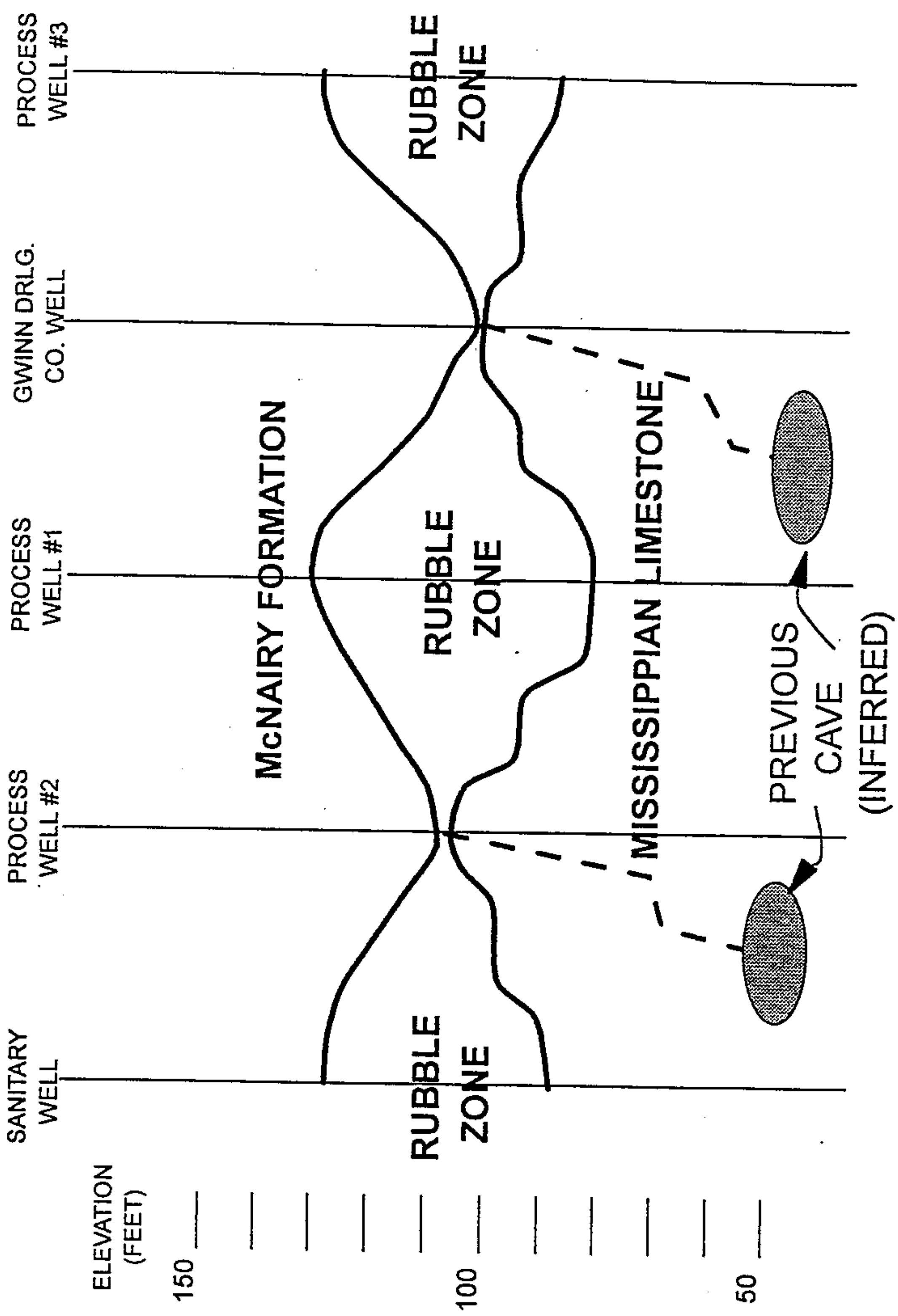


Figure 11. Rubble zone trends at the Allied-Signal Plant.

discharges directly to the Ohio River or flows parallel with the river to discharge further downstream. Tests in areas of the Mississippi Embayment where the McNairy Formation is used as an aquifer (southwestern Kentucky, western Tennessee, and southeastern Missouri) define the range of hydraulic conductivity of the McNairy to be 10^{-3} to 10^{-2} centimeters/second (cm/sec). Model calibration yielded a hydraulic conductivity value of 10^{-2} cm/sec.

The Corps of Engineers documentation for the Olmsted Lock and Dam Project (1991 and 1992), *Foundation Design Memorandum, Supplement to Design Memorandum No. 5*, includes a report of a pumping test in the upper member of the McNairy Formation at the Olmsted site (12 miles northwest of PGDP). At Olmsted, the McNairy consists of an upper member of interlensing sands, silts, and clays and a lower member (Levings equivalent) of indurated clayey silt. A straight line distance versus drawdown analysis of the test data derived a hydraulic conductivity value of 10^{-3} cm/sec for the upper McNairy member.

5.2 HYDROGEOLOGIC SETTING

The uppermost aquifer underlying PGDP and areas to the north is the RGA, primarily developed in the Quaternary sand and gravel fill of the ancestral Tennessee River valley. Groundwater flows northward in the RGA to discharge into the Ohio River. The regional potentiometric surface of the McNairy groundwater flow system dips from an outcrop recharge area at Kentucky Lake westward and northward to the Ohio River (Davis, Lambert, and Hansen, Jr., 1973). Local groundwater flow in the McNairy Formation discharges to the Ohio River.

There is only limited data to assess the hydraulic interconnection of the McNairy Formation and Mississippian bedrock in the PGDP area. Three of the four municipal wells in Metropolis produce from cavernous zones in the underlying Mississippian limestones. Domestic wells completed in Mississippian bedrock are not uncommon in McCracken County. Therefore, the Mississippian bedrock potentially has significant permeability across the area. Water levels measured during drilling of the Allied-Signal Plant supply wells suggest that both the McNairy lower member and underlying Mississippian limestone are confined aquifers (AWD Technologies, 1992). A dense cherty zone at the top of the limestone serves as the upper confining unit. This confining zone is probably limited to areas of cherty limestone subcrop and is frequently breached by fracturing.

5.3 SOURCES OF DATA

Hydrologic properties of the McNairy Formation at PGDP can be derived from several data sets. An investigation of seismic stability of the sediments underlying PGDP (ERCE, 1990) measured geotechnical parameters of McNairy core samples that allow derivation of porosity. In addition, researchers profiled seismic velocities of the McNairy sediments (Selfridge et al., 1991). Reduction of the data defines specific storage over the entire McNairy interval.

CH2M Hill (1991) reports on slug tests of PGDP monitoring wells completed in the McNairy. Two other PGDP groundwater investigations, installation of monitoring wells at the C-746-U Landfill and characterization of groundwater containment sites in the PGDP Northwest Plume, have collected McNairy core samples for permeameter testing.

The PGDP Site Investigation (CH2M Hill, 1991) and continuing Groundwater Program have developed a water level record extending over several years for McNairy and RGA monitoring wells. Cyclic water level fluctuations in the RGA and underlying McNairy flow system provide data for analysis of vertical hydraulic conductivity. The annual rise and fall of water level in McNairy wells is a response to changes in water level in the RGA. Comparison of the response of McNairy water levels with distance from the Porters Creek Clay terrace (for wells south of the terrace) versus response of McNairy water levels with depth (for wells completed below the RGA) is a direct measure of the horizontal-to-vertical ratio of hydraulic conductivity of the McNairy.

5.4 MEASUREMENTS OF POROSITY AND SPECIFIC STORAGE

The PGDP Facility Safety Analysis Program made laboratory measurements of specific gravity and moisture content for 16 McNairy core samples taken from all three members of the McNairy Formation (ERCE, 1990). Assuming the samples are completely saturated, these measurements allow calculation of sample porosity by the method:

$$\theta = [m(\rho_s)] / [\rho_w - m(\rho_w) + m(\rho_w)(\rho_s)]$$

where:

- θ = porosity, as a fraction,
- m = natural moisture content, as a fraction (measured),
- ρ_s = specific gravity of the solids, in grams/cubic centimeter (measured), and
- ρ_w = density of water (1 gram/cubic centimeter).

Appendix C derives the equation used to solve for porosity. Table 1 presents data used in the calculation and the derived porosities. The calculated porosities range from 0.22 to 0.65 with an average value of 0.48. Silts and well-sorted sands are reported to have porosity ranging up to 0.5 and clays are attributed porosity as great as 0.6 (Fetter, 1980). Assuming the average texture of the McNairy in the PGDP area is silt, the calculated porosity occurs near the upper limit of porosity range. A characteristic high porosity is consistent with drilling experience in the PGDP area. Zones of flowing sands and silts in the McNairy Formation (suggestive of higher porosity) are a common phenomenon.

Table 1. Calculation of porosity of McNairy Formation samples.

HOLE ID	SAMPLE NUMBER	DEPTH	GRAIN SIZE DESCRIPTION	NATURAL MOISTURE CONTENT	SPECIFIC GRAVITY	CALCULATED POROSITY
S-7	27	135.0-137.5	SILT, sandy	0.42	2.65	0.65
Z-1	30	124.0-125.5	SAND, silty	0.23	2.56	0.43
Z-5	33	133.5-135.0	SAND, silty	0.30	2.56	0.52
Z-12	1	137.8-139.2	CLAY, silty	0.30	2.59	0.53
	4	197.8-199.2	CLAY, sandy	0.10	2.60	0.23
	7	257.8-258.9	SILT, sandy	0.19	2.62	0.38
	10	317.8-318.2	SAND, clayey	0.27	2.75	0.51
Z-14	31	123.5-125.0	CLAY, silty	0.27	2.70	0.49
Z-16	2	137.0-139.0	SAND, clayey	0.33	2.62	0.56
	5	167.7-169.2	CLAY, sandy	0.26	2.66	0.48
	6	177.7-179.2	SAND, silty	0.25	2.65	0.47
	8	197.7-199.2	CLAY, silty	0.24	2.63	0.46
	11	227.7-228.1	SAND, silty	0.27	2.67	0.50
	14	257.7-258.8	CLAY, silty	0.25	2.65	0.46
	17	287.7-288.2	SAND, silty	0.31	2.65	0.55
	19	307.7-308.2	SAND	0.28	2.66	0.51
				AVERAGE POROSITY		**0.48**

The Facility Safety Analysis Program (Selfridge et al., 1991) tested seismic characteristics of sediments underlying PGDP. Researchers completed downhole seismic surveys of PGDP borings Z12 and Z16. However, a recorder failure on the Z12 survey prevented collection of digital data. The Z16 survey profiled the entire McNairy interval except for the basal two feet, where a lack of grout in the annular space of the borehole occurs.

The survey measures P- and S-wave travel times between the seismic source, on the surface, and two receivers located in the borehole. The two downhole geophones were spaced 10 feet apart to define characteristics of each 10-foot interval. Impact of a 12-pound sledgehammer upon a railroad tie positioned approximately 10 feet from the borehole generated the seismic source for the survey.

Reduction of P-wave (V_p) and S-wave (V_s) velocities to derive the bulk modulus (k) of the sediments is relatively direct:

$$k = (\rho_w)(V_p)^2 - (4/3)(\rho_w)(V_s)^2$$

The bulk modulus is the inverse of aquifer compressibility (α). Specific storage (S_s) is then defined as:

$$S_s = (\rho_w)(g)(\theta)(\beta) + (\rho_w)(g)(\alpha)$$

where:

g = the acceleration constant due to gravity; 980 centimeters/second^2 and
β = compressibility of water, 4.4 x 10^{-11} centimeter x second^2/gram.

Figure 12 plots the derived specific storage values versus depth for borehole Z16. Derivation of the values are presented in Appendix D. A value of 8 x 10^{-8}/centimeter appears to be characteristic of the specific storage of the McNairy Formation in the PGDP area.

5.5 FIELD AND LABORATORY CONDUCTIVITY TESTS

The PGDP Site Investigation (CH2M Hill, 1991) performed slug test analysis of two McNairy monitoring wells completed in the upper member and one McNairy monitoring well completed in the Levings Member. The two upper member McNairy wells are MW120, with a screen interval depth of 155 to 170 feet, and MW122, with a screen interval depth of 144 to 158 feet. MW121, with a screen interval over the depth range 198 to 210 feet, is the Levings Member well. Hydraulic conductivity values derived from the slug tests are 1.8 x 10^{-4} cm/sec (MW120), 2.9 x 10^{-5} cm/sec (MW121), and 9.7 x 10^{-5} cm/sec. The field procedures and data reduction are standard methods and the data produce a good fit to the modeled solution.

Permeameter tests were performed on 15 McNairy core samples collected from the PGDP Northwest Plume area and 10 McNairy core samples collected from the PGDP C-746-U Landfill. The Northwest Plume area samples represent the entire thickness of the McNairy upper member. Samples from the C-746-U area were collected at a depth of 10 feet below the top of the McNairy. Test values range from 1.8 x 10^{-8} to 5 x 10^{-4} cm/sec. Table 2 and Figure 13 present the hydraulic conductivity values derived from slug tests and measured by permeameter. In general, permeameter-derived values are one to three orders of magnitude less than those measured by slug tests. The majority of the permeameter-measured conductivities (14 of 25) are less than 5 x 10^{-7} cm/sec.

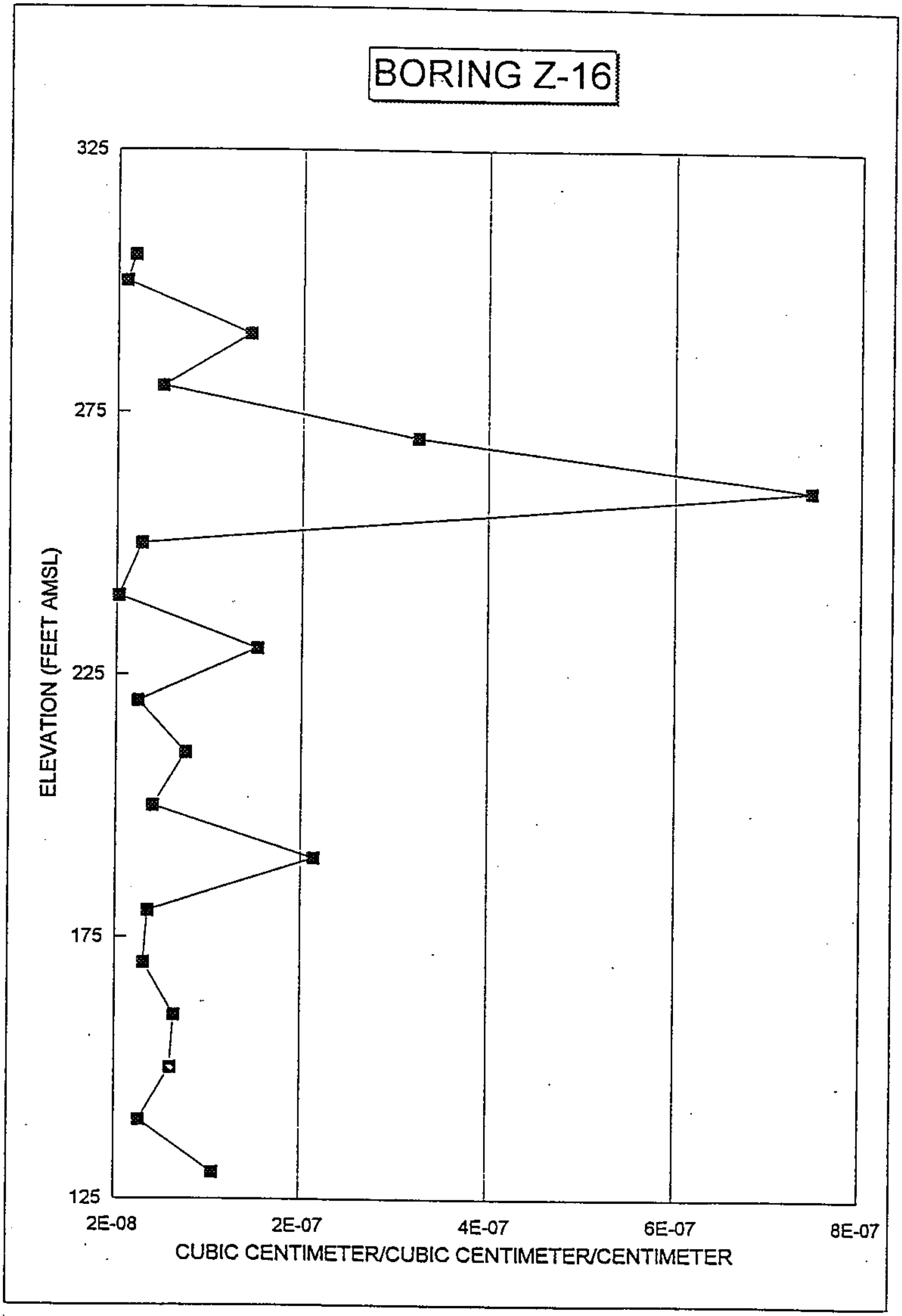


Figure 12. McNairy Formation specific storage.

Hydraulic conductivity measurements by permeameter and slug test are not directly comparable. Permeameters measure vertical hydraulic conductivity of a discrete sample. Slug tests results are predominately determined by the horizontal hydraulic conductivity. Although the slug test samples a larger interval, the effects of poor well development often compromise analysis of the data. Results of these tests describe aquifer conductivity but do not bound it.

Table 2. Laboratory (permeameter) and field (slug test) analyses of hydraulic conductivity.

WELL/ BORING ID	DEPTH (feet)	HYDRAULIC CONDUCTIVITY (cm/sec)	WELL/ BORING ID	DEPTH (feet)	HYDRAULIC CONDUCTIVITY (cm/sec)
NORTHWEST PLUME PUMP AND TREAT WELLS/BOREHOLES (PERMEAMETER)			**C-746-U LANDFILL BOREHOLES (PERMEAMETER)**		
MW-239	124-126	2.10×10^{-7}	GB-01D	86-88 #2	2.75×10^{-7}
MW-245	95-97	5.00×10^{-4}		86-88 #3	3.67×10^{-7}
MW-247	118-120	5.90×10^{-6}	GB-02D	88-90#2	4.09×10^{-8}
MW-248	98-100	9.80×10^{-5}		88-90 #3	7.25×10^{-8}
MW-250	95-97	1.20×10^{-7}	GB-03D	88-90 #2	4.66×10^{-6}
SB-28	114-116	4.10×10^{-6}		88-90 #3	2.67×10^{-6}
SB-29	114-116	3.90×10^{-8}	GB-04D	83-85 #2	4.71×10^{-5}
SB-30	114-116	2.50×10^{-7}		83-85 #3	4.12×10^{-6}
SB-31	114-116	1.60×10^{-7}	GB-05D	83-85 #2	1.25×10^{-6}
SB-33	98-100	1.80×10^{-8}		83-85 #3	2.05×10^{-6}
SB-33	174-176	1.30×10^{-7}	**CERCLA SITE INVESTIGATION - PHASE I (SLUG TEST)**		
SB-36	118-120	1.50×10^{-4}			
SB-37	88-90	4.80×10^{-7}	MW120	155-170	1.84×10^{-4}
SB-37	114-116	3.30×10^{-7}	MW121	198-210	2.88×10^{-5}
SB-38	118-120	5.40×10^{-8}	MW122	144-158	9.69×10^{-5}

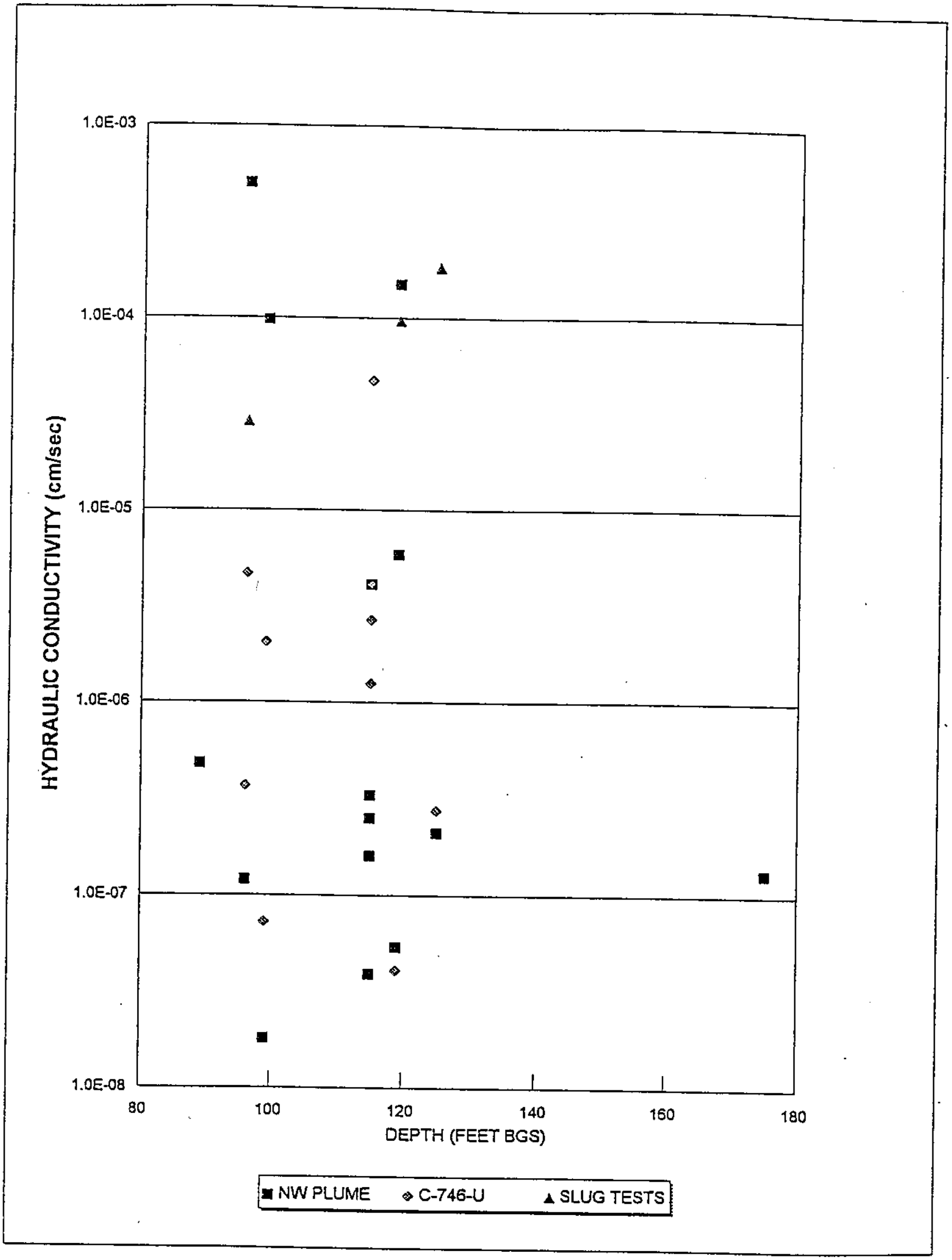


Figure 13. Laboratory and field analyses of hydraulic conductivity.

5.6 ANALYSIS OF CYCLIC WATER LEVEL TRENDS TO DETERMINE CONDUCTIVITY

The McNairy water level record at PGDP, beginning in October 1990, exhibits annual cyclic variations that are consistent with trends in the overlying RGA (Figure 14). U.S. Geological Survey Water-Supply Paper 1536-E (Ferris et al., 1962) reviews methods to assess hydraulic conductivity based on similar wave functions. The primary variable used in the analysis is decrease of range of the cyclic water level wave with distance from the source. Ocean tides and river stage events are common sources used in the analysis. In this context, the source is assumed to fully penetrate the aquifer and wells are used at increasing distance from the source to measure the decrease of the wave with distance. The analysis yields a value of horizontal hydraulic conductivity for the aquifer.

At PGDP, the source of the McNairy wave is the annual water level rise and fall in the RGA, which overlies the McNairy Formation. The wells are located at increasing depth in the aquifer. In this orientation, the hydraulic conductivity measured is in the vertical direction.

The Ohio River exhibits a similar annual high- and low-stage cycle that is a potential source of the rise and fall of water levels in the McNairy Formation. However, two lines of evidence document that the Ohio River is not the primary control on the McNairy wave function: 1) the Ohio River stage cycle is out of phase with the McNairy wave and 2) the RGA and McNairy water level cycles exhibit similar responses (one annual rise and fall) while the Ohio River cycle is a more complex function made up of distinct stage events.

McNairy wells available for analysis of vertical hydraulic conductivity are MW102, MW121, MW122, MW133, and MW140 (Figure 15). The record of RGA well MW71, located central to PGDP, provides the source term. Base of the RGA is approximated as elevation 280 feet AMSL. Table 3 summarizes depth of screen interval for the McNairy wells.

Table 3. Well screen interval of McNairy wells used in analysis of vertical hydraulic conductivity.

WELL ID	ELEVATION OF TOP OF SCREEN INTERVAL (FEET AMSL)	ELEVATION OF BASE OF SCREEN INTERVAL (FEET AMSL)	ELEVATION OF MIDPOINT OF SCREEN INTERVAL (FEET AMSL)
MW102	244	234	239
MW121	169	159	164
MW122	213	203	208
MW133	252	242	247
MW140	203	193	198

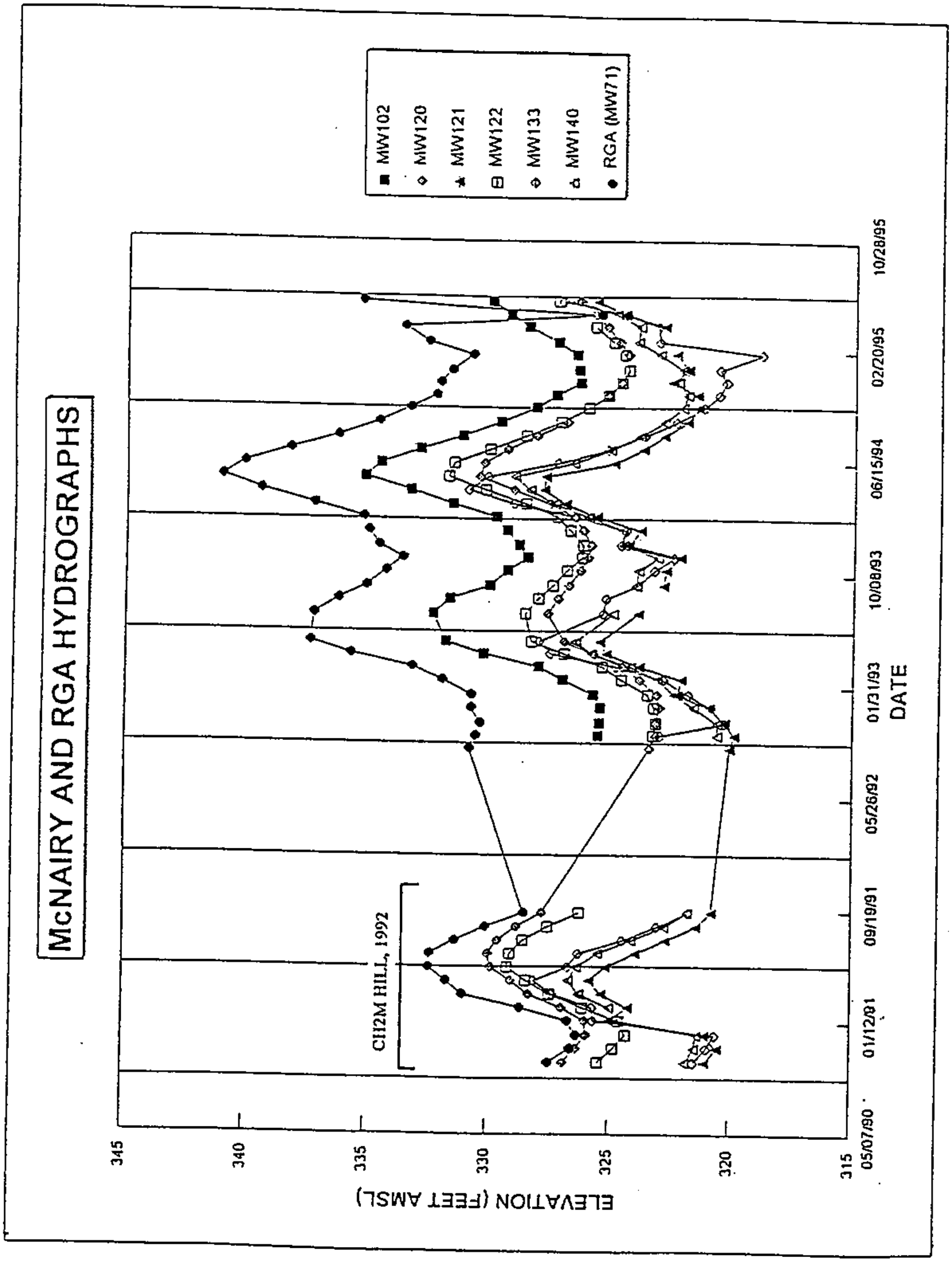


Figure 14. Hydrograph of MW71 (RGA well) and McNairy wells.

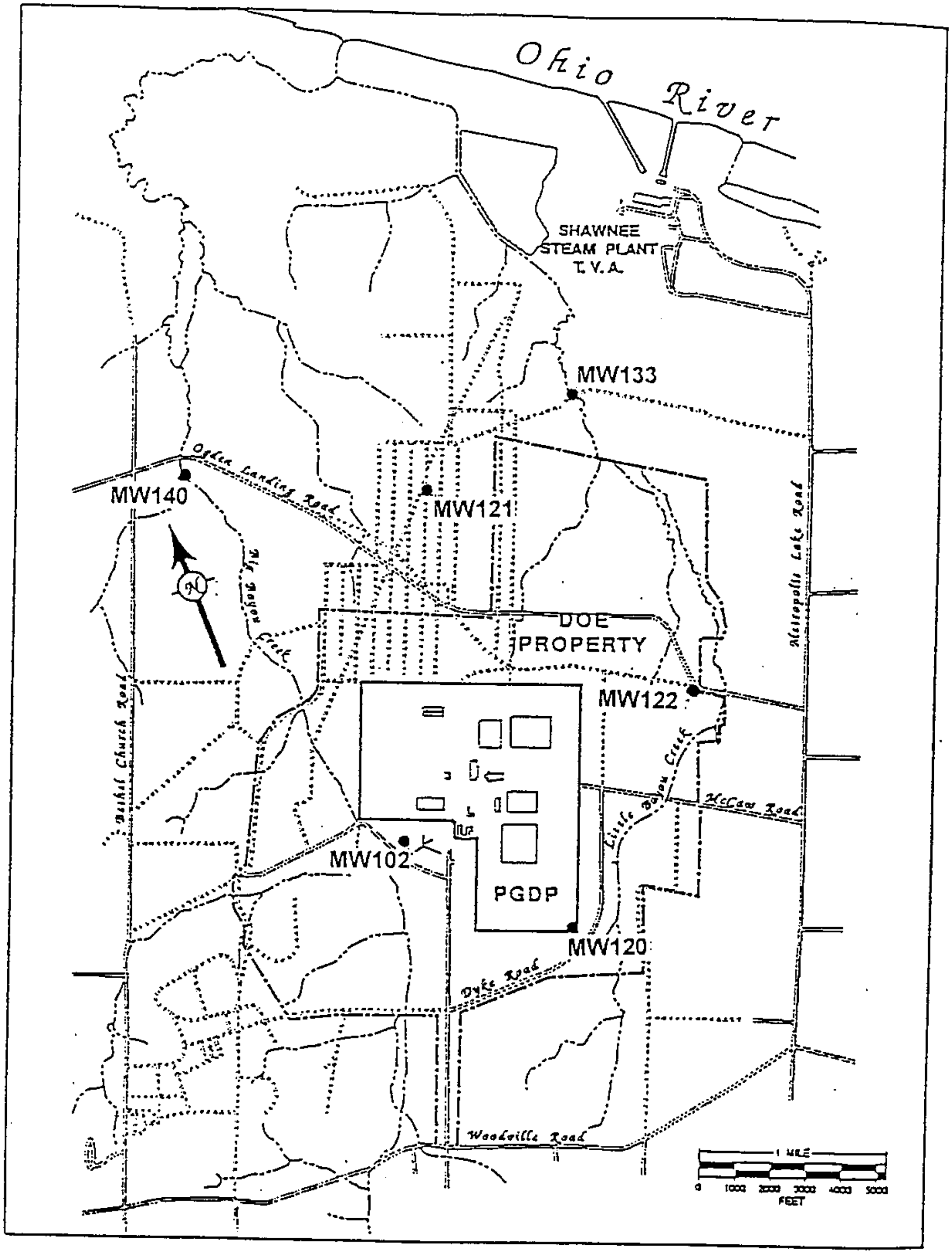


Figure 15. McNairy wells of PGDP.

The analysis compares the height of wave versus distance from source to generate the gradient variable typically employed in aquifer analysis. Period of the wave provides the time variable. The form of the analytical solution is:

$$s_r = 2s_0e^{-x[\text{square root of } (\pi S/tT)]}$$

where:

s_r = range of groundwater stage,
s_0 = amplitude or half range of the surface water stage,
x = distance from the monitoring well to the wave source,
S = coefficient of storage,
t = period of the wave fluctuation, and
T = coefficient of transmissibility.

Water-Supply Paper 1536-I (Brown et al., 1963) presents the derivation of the method to solve for transmissibility. The derivation used for this analysis is developed in Appendix E and takes the form:

$$K = 0.59(\Delta x)^2S_s/t$$

where:

K = hydraulic conductivity, in centimeters/second,
Δx = distance, in centimeters, over which hydraulic potential range decreases by one log cycle, and
S_s = specific storage in centimeters^{-1}, previously determined to be 8×10^{-8}/centimeter.

Appendix F lists the water level data for MW71 and the McNairy wells. For this analysis, the range of the wave to be used in comparison of decrease in hydraulic potential with depth is taken as the water level measured in May 1994 (highest values) less the water level measured in November 1992 (lowest values). Although the time between measurements spans 1.5 wave periods, the relative decrease in wave height remains constant. The greater difference in water levels allows a more precise evaluation of the relative decrease in hydraulic potential. The period used in the calculation of hydraulic conductivity is 365.25 days, the average length of a wave cycle.

Figure 16 plots the hydraulic potential range versus elevation. Total range in the source, the RGA, measured in MW71 is 10.71 feet. Extrapolation shows that a decrease in range of hydraulic potential to 0.1 of the range in the RGA (one log cycle reduction) occurs at a depth of 341 feet (10,394 centimeters) below the base of the RGA. These values inserted into the equation for hydraulic conductivity define a hydraulic conductivity for the McNairy Formation of 1.62×10^{-7} cm/sec.

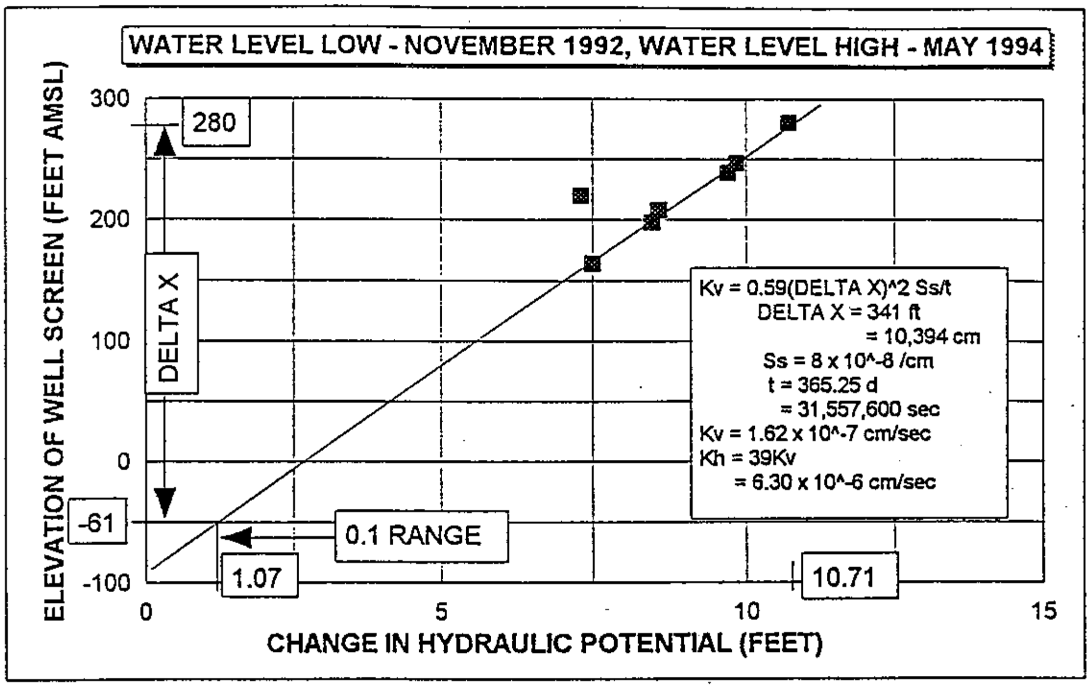


Figure 16. Hydraulic potential range in the McNairy Formation.

The linear relationship of hydraulic potential range versus elevation extends through the upper McNairy member (wells MW102 and MW133) and Levings Member (wells MW121, MW122, and MW140). This linear relationship determines a singular average hydraulic conductivity applies over the upper and Levings Members. Inclusion of the upper and Levings Members in a single hydrologic unit at PGDP is consistent with lithologic logs of area boreholes that define little textural difference between the two members.

McNairy monitoring well MW120, located 4785 feet south of the Porters Creek Clay terrace affords opportunity to compare decrease in hydraulic potential in a lateral direction to decrease in hydraulic potential in a vertical direction. This is an inverse measure of the horizontal-to-vertical contrast in hydraulic conductivity of the McNairy over sufficient distance to average the effect over characteristic lithologies.

Over the period of water level record used for this analysis, hydraulic potential in MW71 (RGA well) varies 10.71 feet. Hydraulic potential in MW120 varies 7.3 feet. Thus, the gradient of hydraulic potential decrease in a lateral direction is 7.1×10^{-4} ([10.71-7.3]/4785). Gradient of hydraulic potential decrease in a vertical direction is 2.8×10^{-2}. The gradients measure a horizontal-to-vertical contrast of hydraulic conductivity of 39 to 1.

5.7 HYDRAULIC GRADIENT

Davis, Lambert, and Hansen, Jr. (1973) map McNairy Formation water levels across the Jackson Purchase. Their map shows that the hydraulic gradient at PGDP is northeast toward the Ohio River with a hydraulic potential of 320 feet AMSL.

Wells in the McNairy Formation at PGDP generally exhibit water levels five to ten feet higher than mapped by Davis, Lambert, and Hansen, Jr. (1973). This discrepancy arises because the earlier data set represents wells only from areas where the Porters Creek Clay confines the McNairy flow system. Recharge from the RGA is not accounted for.

Comparison of water level measurements in well clusters of RGA and McNairy wells measures vertical gradients in the McNairy flow system. Water level data (Appendix G) indicate a downward vertical gradient of 0.02 at McNairy wells MW121 and MW122 and 0.04 at McNairy well MW140. An average upward vertical gradient of 0.01 occurs at the McNairy well closest to the Ohio River, MW133.

The PGDP McNairy water level measurements are not directly comparable because the wells are completed at different elevations and vertical hydraulic potential gradients exist. However, by assuming hydraulic gradients are constant with depth, water level measurements can be corrected to a reference measurement elevation. Figure 17 illustrates hydraulic potential in the McNairy Formation at the elevation of the midpoint of the MW120 well screen, 219 feet AMSL. The average lateral McNairy hydraulic gradient is approximately 4.4×10^{-4}.

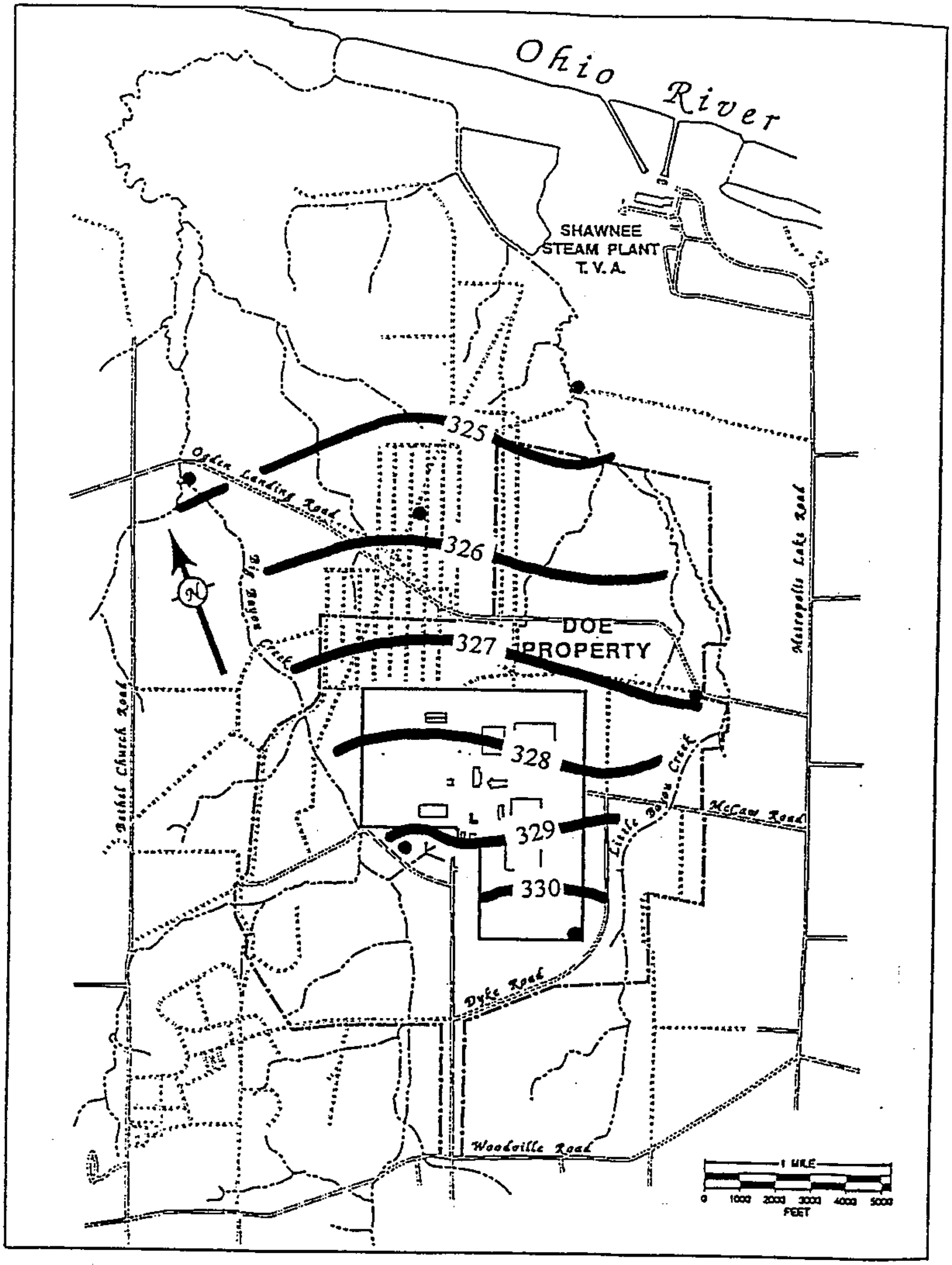


Figure 17. Hydraulic potential (feet AMSL) in the McNairy Formation at elevation 219 feet AMSL.

McNairy hydraulic potential is less than that of the RGA at PGDP and greater than that of the RGA near the Ohio River. McNairy and RGA hydraulic potential are equal near well MW133. Therefore, the RGA recharges the McNairy at the PGDP site but the McNairy discharges to the RGA north of MW133 and to the Ohio River.

Water levels measured in a well completed in the top of the McNairy Formation at the abandoned Kentucky Ordnance Works (KOW) average 331 feet AMSL (Figure 18). The KOW well is located approximately 1.2 miles south of the Porters Creek Clay terrace. This relationship suggests regional hydraulic potential is elevated because of high hydraulic potential at the Porters Creek Clay terrace but the gradient remains directed towards the Ohio River.

The U.S. Geological Survey reports depth-to-water measurement for a well cased in Mississippian bedrock at Heath High School, located approximately 2.5 miles south of the Porters Creek Clay terrace. For the five-year period of record (Figure 19), the average water level elevation is approximately 322 feet AMSL, assuming the datum elevation (not reported) is 385 feet AMSL.

Therefore, an approximate downward vertical gradient of 0.03 (331-322 feet hydraulic potential/284 feet thickness of McNairy) exists across the entire McNairy Formation. This gradient is consistent with well measurements at PGDP. A uniform gradient across the thickness of the McNairy could only exist for the case of permeable bedrock underlying the McNairy Formation.

Regionally, flow in the McNairy-Paleozoic bedrock flow system is laterally towards the Ohio River. A downward vertical gradient develops in the McNairy near the Porters Creek Clay terrace. However, the steeper lateral gradient of the RGA potentiometric surface results in a higher McNairy hydraulic potential near the Ohio River and discharge into the Ohio River.

6. GROUNDWATER GEOCHEMISTRY

6.1 MCNAIRY GEOCHEMISTRY

Quality of recharging waters and mineralogy of aquifer matrix are primary controls on the geochemistry of groundwater. U.S. Geological Survey reports by Pree, Walker, and MacCary (1957); Faust, Banfield, and Willinger (1980); and Davis, Lambert, and Hansen, Jr. (1973) provide analyses of McNairy groundwater in the region. These analyses establish a background for comparison of the PGDP area geochemistry. PGDP has analyses from eight monitoring wells completed in the McNairy Formation.

McNairy groundwater at PGDP is a strongly bicarbonate-type water with no dominant cation (Figure 20). The bicarbonate ion makes up 70 percent or more of the anion balance. Analyses of McNairy groundwater samples collected in a recent investigation of the PGDP Northeast Plume (Garner, Morti, and Smuin; 1995) show the water is slightly acidic (average pH of 6.14) with typically low-dissolved oxygen content (Figure 21).

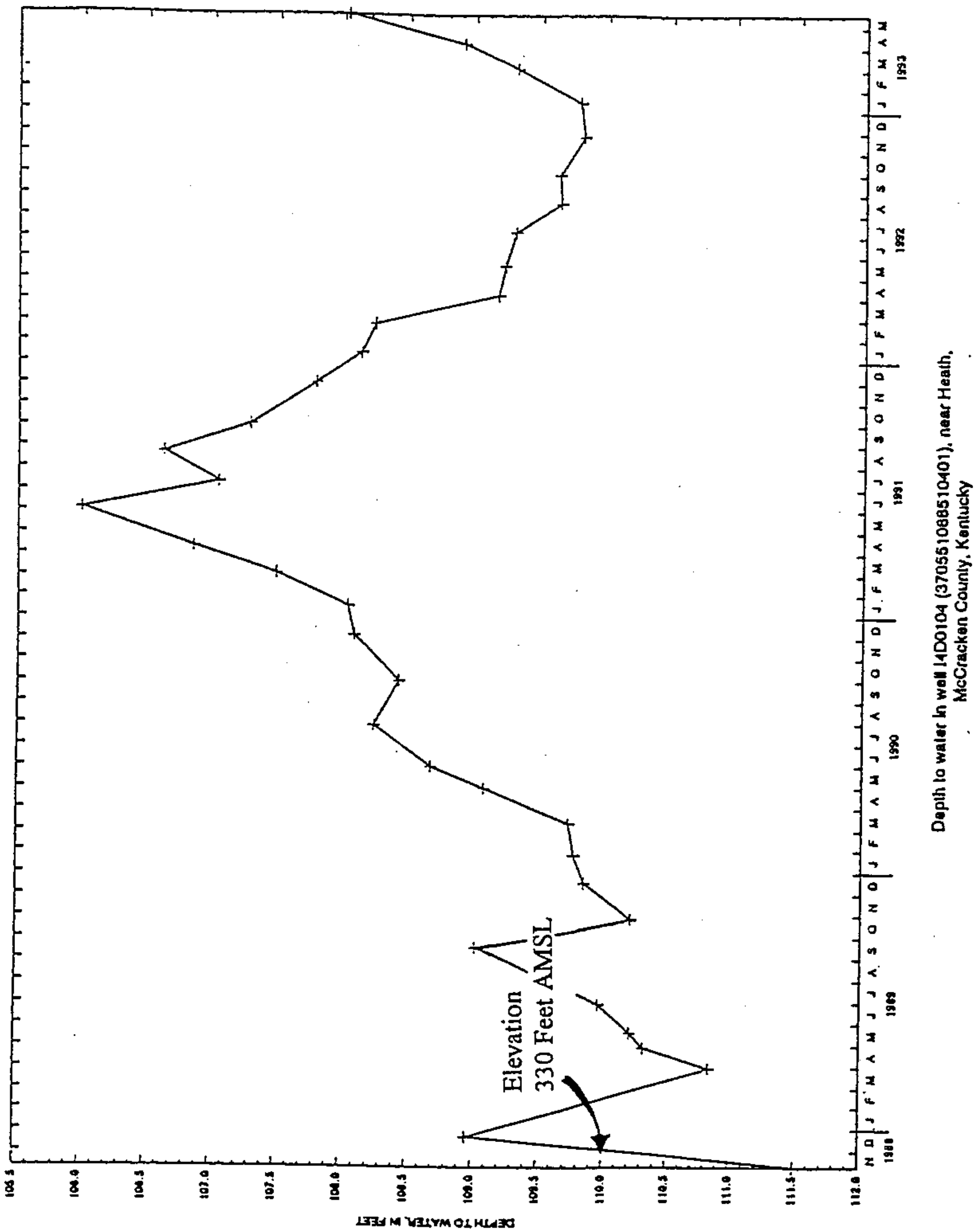


Figure 18. Water-level record of the Kentucky Ordnance Works well.

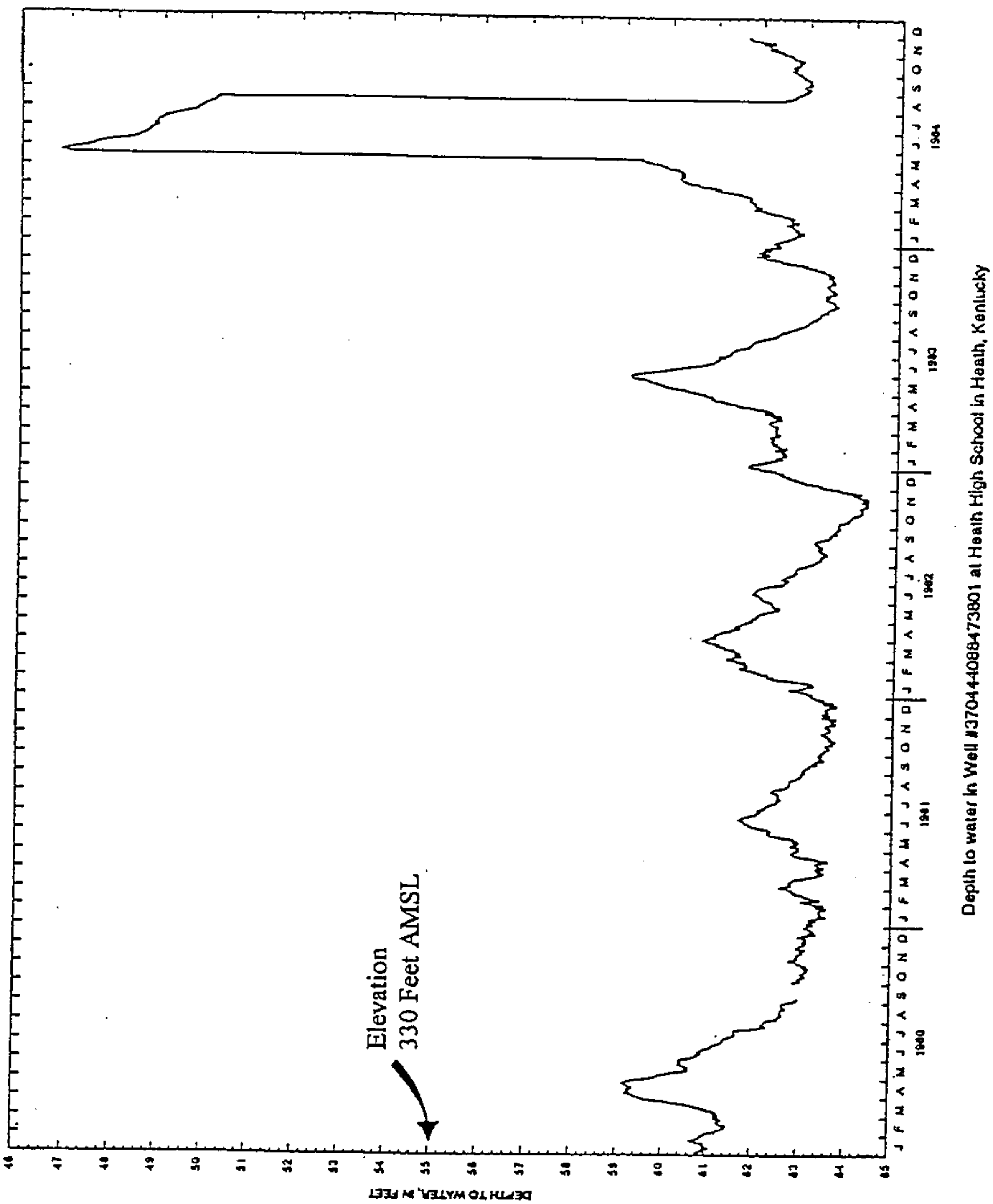
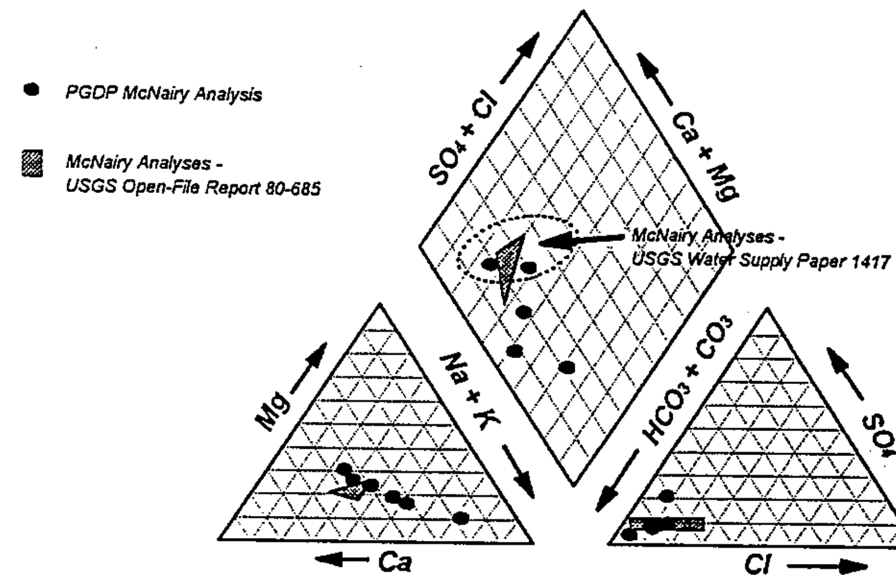


Figure 19. Water-level record of the Heath High School well.

McNairy Formation Groundwater Chemistry



RGA and Mississippian Groundwater Geochemistry

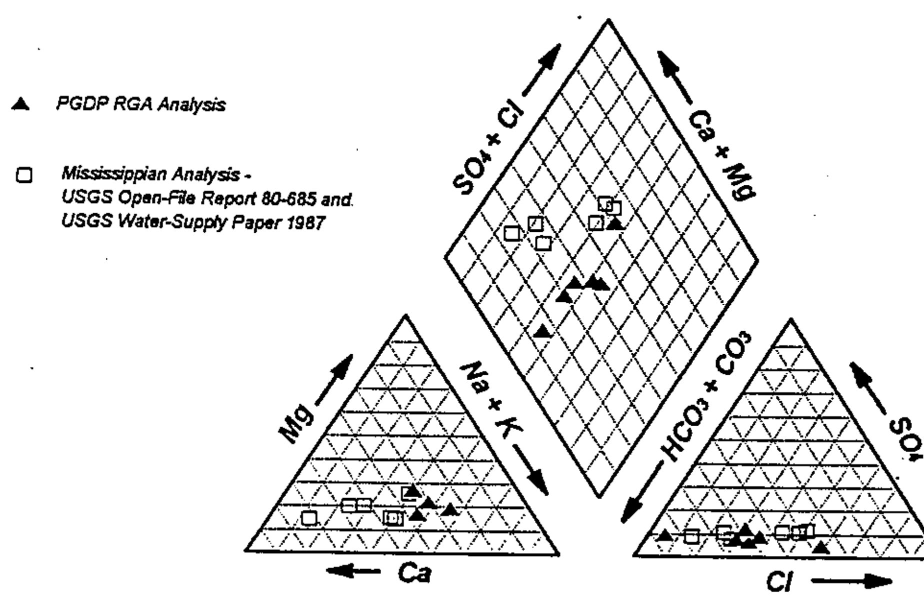
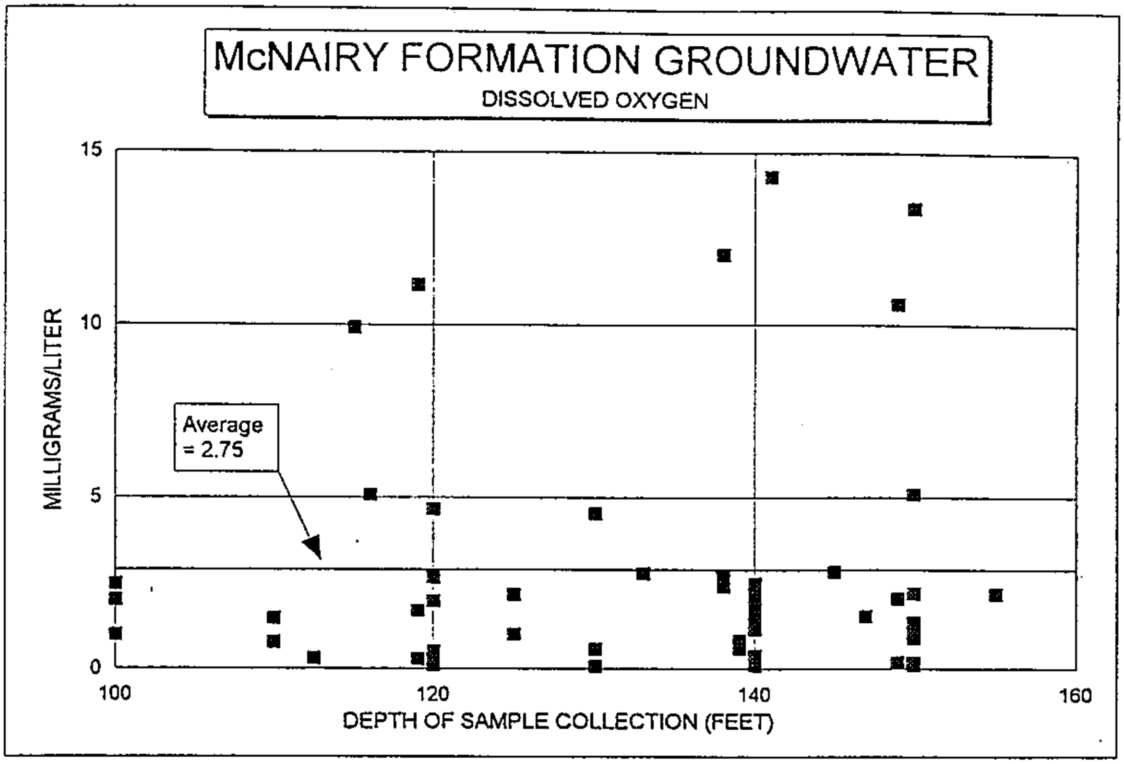


Figure 20. McNairy Formation, RGA, and Mississippian bedrock geochemistry.



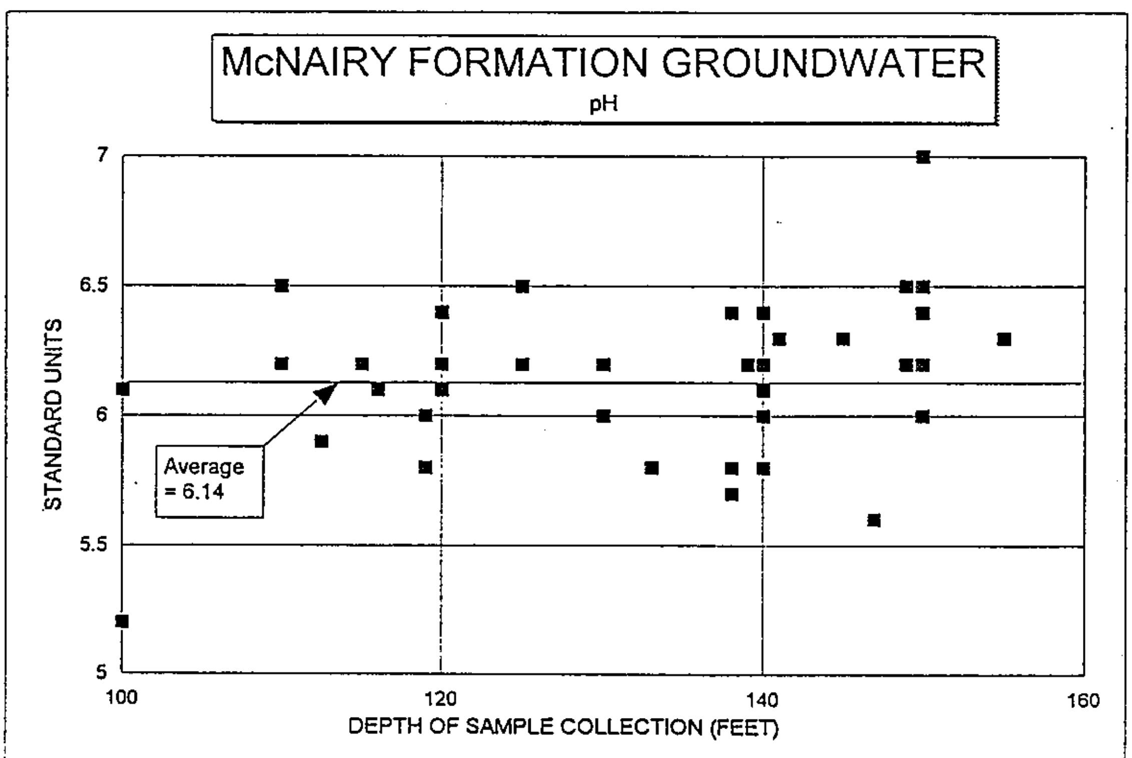


Figure 21. Acidity and dissolved oxygen content of McNairy groundwater.

The graph of cation distribution exhibits a distinct linear trend (Figure 20). Comparison of sodium and potassium percentage of the major cations versus elevation of well screen demonstrates a relationship of increasing sodium and potassium percentage with depth (Figure 22). This type trend is a typical result of mixing and suggests shallow groundwater with relatively high calcium concentration is mixing with sodium and potassium rich water at depth. An alternative explanation is that the trend defines the rate of cation exchange. In either case, it appears that groundwater from the Levings Member contains greater percentage of sodium and potassium than is typical of water producing zones of the McNairy Formation.

6.2 RGA AND MISSISSIPPIAN GEOCHEMISTRY

Analyses of water from RGA wells (located near the PGDP McNairy wells) and U.S. Geological Survey published analyses of water from Mississippian bedrock wells (Faust, Banfield, and Willinger, 1980; Davis, Lambert, and Hansen, Jr., 1973) allow comparison of the two potential recharge waters to the McNairy Formation in the PGDP area. In general, Mississippian bedrock water has a higher percentage of calcium as compared to the cation balance of RGA water. The range of major anion percentages is the same for both waters. RGA water is slightly acidic while Mississippian bedrock water is typically basic (Appendix H). Plots of the percentages of major ions of McNairy water, RGA water, and Mississippian bedrock water (Figure 20) demonstrate that water from McNairy wells in the region resembles water from Mississippian wells. However, McNairy groundwater from the PGDP wells more closely resembles RGA groundwater.

Neither candidate recharge source has a higher sodium and potassium percentage of the major cations to explain the trend of increasing alkaline cations with depth observed in the McNairy Formation. The hypothesis that the trend defines the chemical evolution of water moving vertically from the RGA into the McNairy Formation is consistent with groundwater flow direction determined by the vertical hydraulic gradient in the McNairy.

7. CONCEPTUAL GROUNDWATER FLOW MODEL

Infiltration in outcrop areas in southern Illinois and the eastern Jackson Purchase drives groundwater flow in the McNairy Formation towards discharge into the Ohio River. The Porters Creek Clay forms an upper confining unit to the McNairy flow system across most of the Jackson Purchase allowing lateral flow to predominate. Greater hydraulic potential in the RGA than in the McNairy immediately north of the Porters Creek Clay terrace results in an area of downward groundwater flow.

Groundwater in the RGA flows toward the Ohio River. The hydraulic gradient in the RGA is steeper than in the McNairy, resulting in upward hydraulic potential near the Ohio River. McNairy groundwater flows north in the PGDP area of Kentucky and south in adjacent areas of Illinois to discharge into the Ohio River.

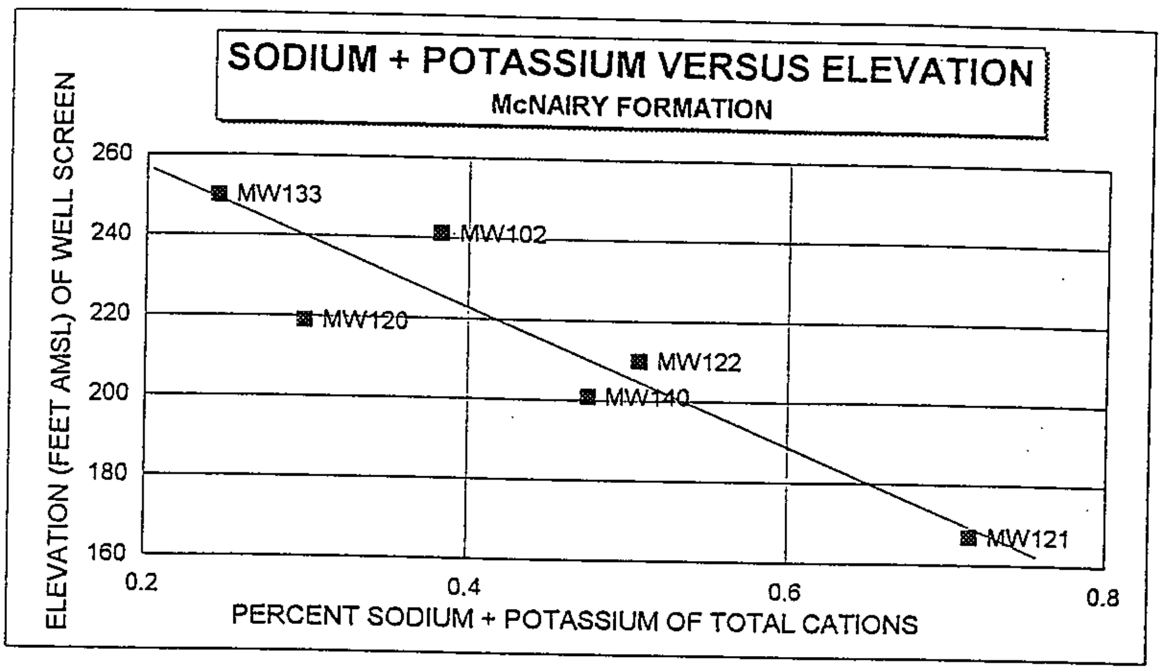


Figure 22. Sodium + potassium versus elevation, McNairy Formation.

Three lithologic members make up the McNairy Formation. The middle Levings Member of the McNairy locally functions as a confining layer in southern Illinois. Abrupt facies changes occur in the McNairy Formation in the vicinity of the Ohio River. At PGDP, subtle textural trends differentiate the upper and Levings Members of the McNairy. Both members contain interlensing units of sand, silt, and clay. The upper and Levings Members function together as a single hydrologic unit with a horizontal hydraulic conductivity of 6.30×10^{-6} cm/sec and a vertical hydraulic conductivity of 1.62×10^{-7} cm/sec. Porosity and storage remain nearly constant with depth in the McNairy Formation. Porosity is approximately 0.48 and specific storage is 8×10^{-8}/centimeter.

The lower McNairy member is a well-sorted, fine sand and should have a somewhat larger hydraulic conductivity than that of the upper and Levings Members. Facies changes to finer textures both east and west of PGDP create hydraulic conductivity barriers to flow paralleling the Ohio River.

Comparison of horizontal-to-vertical hydraulic conductivity (K) and gradient (i) in the upper McNairy members determines the vertical angle of the groundwater flow vector:

$$(K \times i)_{horizontal}/(K \times i)_{vertical} = 2.77 \times 10^{-9} \text{ cm/sec}/3.24 \times 10^{-9} \text{ cm/sec}$$

The ratio is the tangent of the angle of the flow vector, 41^0 to the horizontal. Greater hydraulic conductivity of the lower member results in a more lateral flow vector in the lower member.

The product of vertical hydraulic conductivity (K_v) and gradient (i_v)divided by porosity (θ) defines the vertical flow rate of groundwater:

$$1.62 \times 10^{-7} \text{ cm/sec } (K_v) \times 2 \times 10^{-2} (i_v)/0.48 (\theta) = 6.75 \times 10^{-9} \text{ cm/sec}$$

Thus, travel time for advective flow across the 125-foot thickness of the upper and Levings Members is 17,886 years.

A constant vertical hydraulic gradient across the entire thickness of the McNairy Formation indicates that the McNairy is hydraulically connected with the underlying Mississippian bedrock. A rubble zone derived from in situ weathering of the bedrock occurs immediately below the McNairy Formation in some boreholes. The rubble zone appears to have a much greater hydraulic conductivity than the lower McNairy member but is probably discontinuous.

8. SUMMARY

In the area of the PGDP, the McNairy Formation consists of three stratigraphic members. The upper and middle (Levings) members consist predominately of silt. These members function as a single hydrologic unit with a horizontal hydraulic conductivity (K_h) of 6.30×10^{-6} cm/sec and a vertical hydraulic conductivity of 1.62×10^{-7} cm/sec. Hydraulic conductivity of the basal McNairy sand member is untested but expected to be approximately 10^{-3} cm/sec (K_h). A single specific storage value of 8 x 10^{-8} applies to the entire McNairy sequence.

Regional hydraulic potential in the McNairy Formation drives groundwater flow towards the Ohio River. The overlying Porters Creek Clay confines the McNairy flow system over most of the Jackson Purchase. However, an erosional truncation of the Porters Creek Clay under PGDP allows interaction of shallow groundwater (the RGA) with the McNairy. Higher hydraulic potential in the RGA creates a vertical component of flow into the McNairy Formation at PGDP. Groundwater flow in the McNairy Formation at PGDP is northeast toward the river and downward.

The lateral hydraulic gradient is toward the Ohio River in both the RGA and the McNairy flow system. However, the lateral hydraulic gradient is steeper in the RGA than in the McNairy. Thus, the downward component of the hydraulic gradient decreases towards the Ohio River. The vertical hydraulic gradient is nearly absent at MW133, 1.5 miles northeast of PGDP. An upward component to the hydraulic gradient exists north of MW133, forcing McNairy groundwater to discharge into the Ohio River.

Although a downward component of groundwater flow exists in the McNairy Formation under PGDP, little potential exists for contamination in the RGA to migrate any significant distance through the McNairy Formation. Low permeability silts are characteristic of the upper and middle McNairy members beneath PGDP. The middle member contains abundant carbon and pyrite which readily bind and degrade the PGDP contaminants.

Faults are reported in outcrops of the McNairy Formation in Illinois, but faults have not been found at PGDP. The consistent hydraulic conductivity of the upper and middle McNairy members, as evidenced by the water level record of the PGDP wells, suggests faulting has not created preferential permeability pathways. In the absence of secondary permeability created by faulting, there appears little likelihood of contaminant migration in a dissolved phase or as DNAPL through the upper and middle McNairy members.

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APPENDIX A

REGIONAL MCNAIRY WELL AND BOREHOLE LOGS

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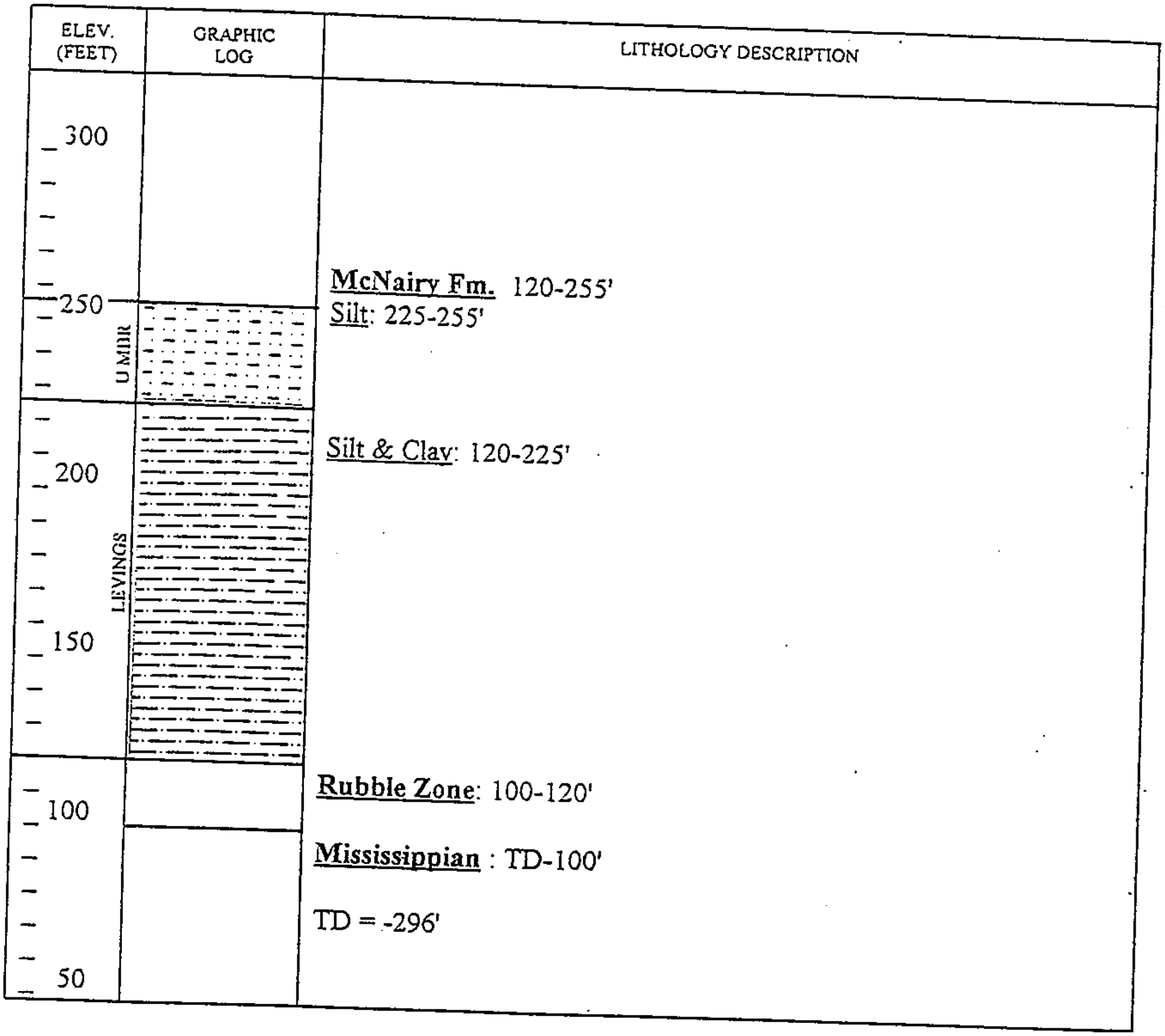
AEP Service Corp. Boreholes
Composite Formation Log



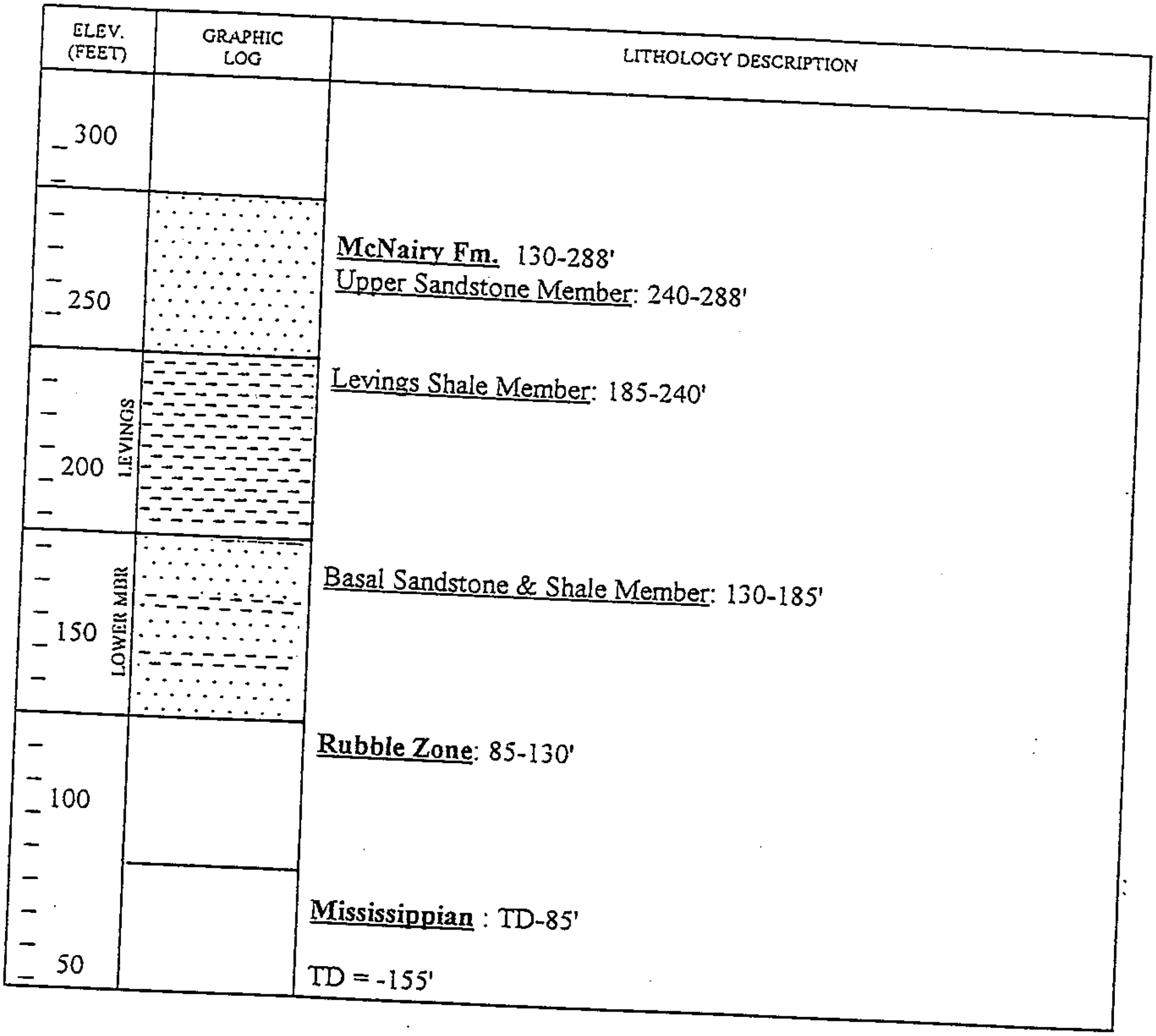
AEP SERVICE CORP. BORINGS
SUMMARY OF DETAILED SAMPLE STUDIES BY J.M. MASTERS

Elevations based on assumption of top of Levings member at 225' AMSL. Reported L.S. for AEP #1 = ± 345' AMSL, derived L.S. = 350' AMSL, reported L.S. for AEP #1A = ± 365' AMSL, derived L.S. = 362' AMSL, reported L.S. for AEP #2 = ± 345' AMSL, derived L.S. = 347' AMSL

ELEV. (FEET)	AEP SERVICE CORP. NO. 2	AEP SERVICE CORP. NO. 1	AEP SERVICE CORP. NO. 1A
250	McNAIRY FORMATION: TD-255' Silt: 230-255' sdy, cly, org-wht, some musc and hvy minerals. 225-230' m gry, some carbon wood frags	McNAIRY FORMATION: 121'-250' Silt: 233-250' m-c, cly, org-wht. 228-233' lt gry. 225-228' w/gv.	McNAIRY FORMATION: 125'-252' Silt: 225-252' some vf sd, tr graphite.
200	Silt & Clay: 195-225' m gry, some chert @ 210-215' 180-195' m gry w/ some carbon wood frags. 140-180' m gry.	Silt & Clay: 193-225' m gry. 143-193' musc. pyrite, poss graphite, dk gry, blk org frags.	Silt & Clay: 200-225' gry. 215-220' some carbon 195-200' abund musc. 190-195' calcareous. 185-190' wht, mic, slt laminations. 175-180' some vf sd.
150	115-140' musc, pyrite, carbon wood frags. TD = 115'.	121-143' musc, pyrite, poss graphite, dk gry, carbon wood frags.	155-160' f qtz sd & few gry chert pebbles. 135-155' carbon wood frags, pyrite.
100		TUSCALOOSA FORMATION: 100-121' gravel. MISSISSIPPIAN LIMESTONE: TD - 100'. TD = 93'.	Sand?: 125-135' fine, mod calcareous. TUSCALOOSA FORMATION: 97'-125' gravel. MISSISSIPPIAN LIMESTONE: TD - 125'. TD = -296'.

COMPOSITE FORMATION LOG:
- McNAIRY FORMATION:
  - upper silt member: 225-255' AMSL
  - Levings silt and clay member: 120-225' AMSL
- TUSCALOOSA FORMATION:
  - gravel: 100-120' AMSL
- MISSISSIPPIAN:
  - limestone: <-296-100' AMSL

Allied-Signal, Inc. Wells
Composite Formation Log



ALLIED SIGNAL, INC. WELLS
SUMMARY OF WELL DRILLERS LOGS

L.S. elevation is reported to be 373' for Process Well #1 and to be 367' AMSL for Process Well # 2. Assumed L.S. elevations are 370' AMSL for the Sanitary Well and Process Well #3 and 365' AMSL for the Gwin Drilling Co.Well.

ELEV. (FEET)	SANITARY WELL	PROCESS WELL #1	PROCESS WELL #2	PROCESS WELL #3	WELL DRILLED BY GWIN DRILLING CO.
250	<u>McNAIRY FM</u>:127?-278' SH: 270 - 278', sdy. SD & SH: 265-270'. SD: 230-265', brn.	<u>McNAIRY FM</u>: 131-288' SD, CL, & GV: 278-288', gry. SS: 251-278', brn-wht.	<u>McNAIRY FM</u>: 109-280' SS: 245-280', cgl.	<u>McNAIRY FM</u>: 127-279' SS: 270-279', lt tan. SS: 240-270', w/ SH interbed.	<u>McNAIRY FM</u>: 107-278' SS: 243-278', cgl, brn.
	SH: 210-230', dk.	SS: 238-251', w/CL interbed. CL: 236-238', gry. SH: 188-236', blu.	CL: 235-245', blu. SH: 181-235', dk.	SH: 200-240', dk gry.	CL: 233-243', blu.
200	SH & SD: 127-210'.				SH: 179-233', dk.
		SS: 161-188'		SS: 190-200', wht. SS: 170-190', w/SH interbed.	
150		SH: 131-161', blu.	SH: 162-181', w/SS interbed, dk. SS: 109-162', brn & gry	SH: 127-170', dk.	SH: 160-179', dk w/SS interbed. SS: 107-160', brn & gry.
100	<u>TUSCALOOSA FM?</u>: SD & LS: 125-127' SH, SD, & LS: 115-125' SD & LS: 100-115' SH, SD, & LS: 90-100'. LS & SS: 87-90'. <u>MISSISSIPPIAN</u> :TD-87'? TD = -38'.	<u>TUSCALOOSA FM?</u>: LS & SH: 81-131', broken rock.	<u>TUSCALOOSA FM?</u>: SS & LS: 107-109', broken <u>MISSISSIPPIAN</u>: TD - 107' TD = -153'.	<u>TUSCALOOSA FM?</u>: LS & SH: 100-127' broken	<u>TUSCALOOSA FM?</u>: SS & LS: 105-107' broken <u>MISSISSIPPIAN</u>: TD - 105' TD = -155'.
		<u>MISSISSIPPIAN</u>: TD - 81' TD = -82'.		LS & CHERT: 89-100' broken <u>MISSISSIPPIAN</u>: TD - 89' TD = -130'.	

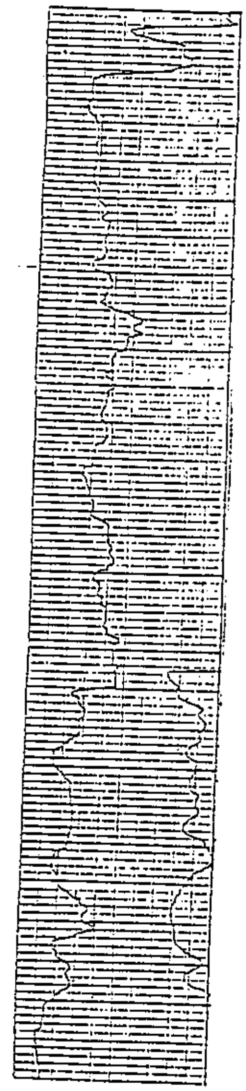
COMPOSITE FORMATION LOG:

McNAIRY FORMATION: upper sandstone member: 240-288' AMSL, Levings shale member: 185-240' AMSL, basal shale/sandstone member: 130-185' AMSL

TUSCALOOSA FORMATION: gravel: 85-130' AMSL

MISSISSIPPIAN: limestone: <-155'-85' AMSL

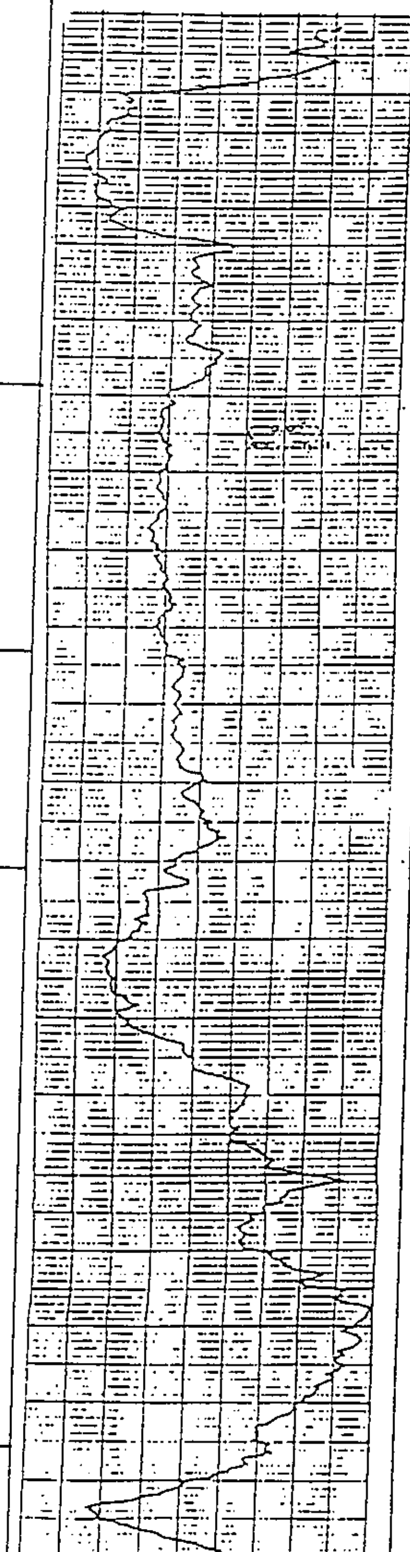
Daniel Gibbs #1
Land Surface = Approx. 341 Feet, AMSL

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION	GAMMA LOG
0, 50		**Loess & U. Cont. Dep.** 0-18' **L. Cont. Dep.** 18-70'	
100	UPPER MBR	**McNairy Fm.** 70-260' Silt: 70-78' Sand: 78-90' Silt: 90-116' Sand: 116-136'	
150, 200	LEVINGS	Silt: 136-150' Silt coarse up to Sand: 150-166' Unknown: 166-182' Silt: 182-194'	
200, 250	LOWER MBR	Sand: 194-202' Silt: 202-218' Sand: 218-232' Clay: 232-244' Sand: 244-250' Silt: 250-260'	
300		**Mississippian**: 260-TD TD = +280'	

Heath High School Well
Land Surface = approx. 385' AMSL

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION
0		**Loess & U. Cont. Dep.** 0-20'
		L. Cont. Dep. 20-58'
50		Porters Creek Clay 58-98'
100, 150	UPPER MBR	McNairy Fm 98-265' Sand: 98-168'
	LEVINGS	Silt: 168-197'
200	LEVINGS	Clay: 197-227' interbd w/slt
250		Sand: 227-238' f 238-265' m-c
300, 350	LOWER MBR	Clay: 265-382'
400		Mississippian: 382'-TD TD = 402'?

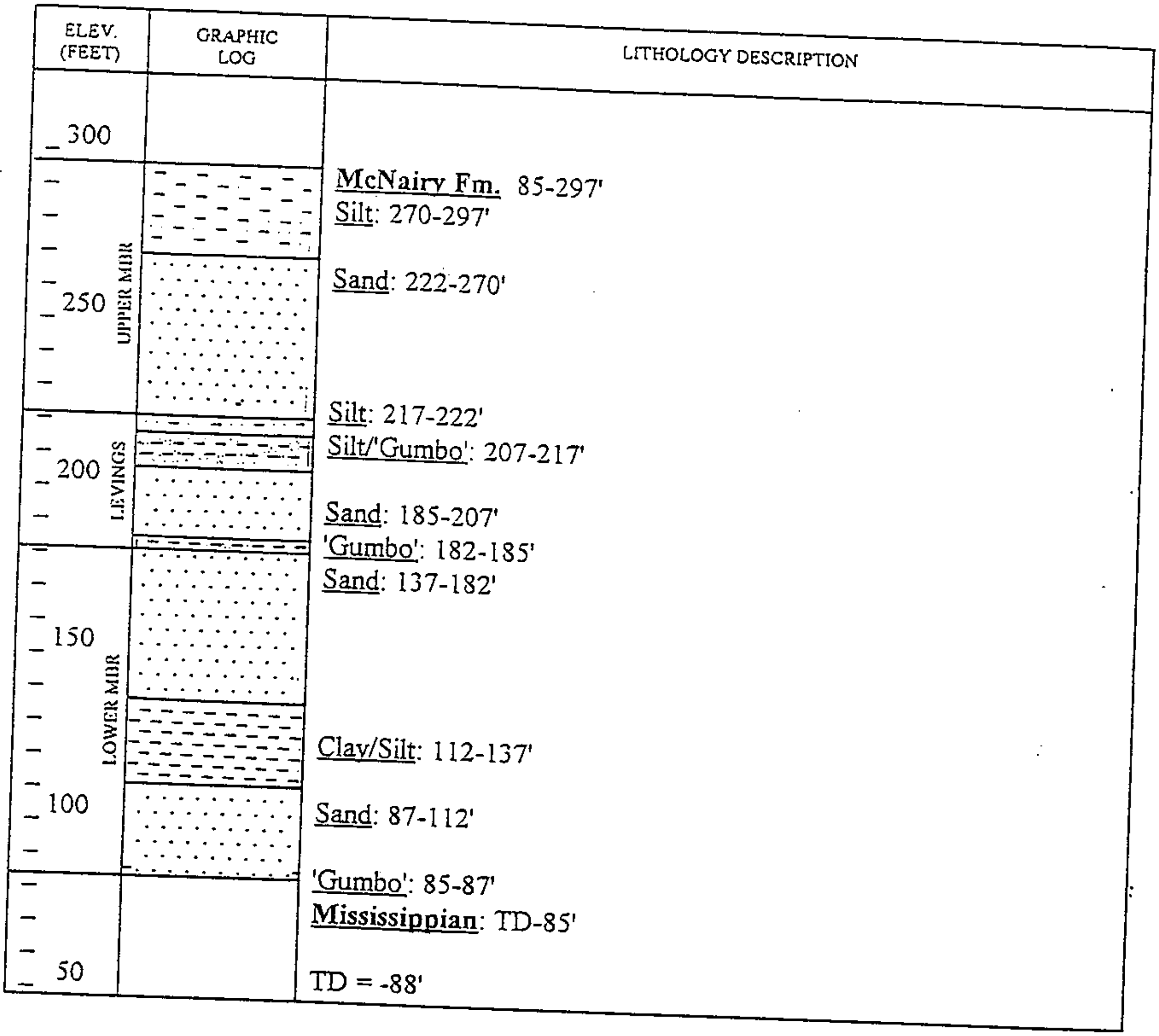
GAMMA LOG



McCracken County Board of Education
Well # 8840-3705-234 of USGS Water Supply Paper 1417
Land Surface = 330 ' AMSL
Drilled by R.B. Elrod, 1953

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION
0		<u>Loess</u>: 0-25'
50		<u>Porters Creek Clay</u>: 25-105'
100		
150		<u>McNairy Fm.</u> 105-345' <u>Sand</u>: 105-115' vf-f, slty, cly, brn. 115'-130' f-m, dk gry mic cl, brn 130-140' slty, cly, mic, brn <u>Clay</u>: 140-150' slty, sdy, mic, brn <u>Sand</u>: 150-155' f-m, dk gry cl, ironstone, lt brn. 155-160' slty, cly, mic, brn. 160-165' lam gry cl, lt brn. 165-180' slty, cly, mic, brn.
200		<u>Clay</u>: 180-225' slty, sdy, mic, brn. 225-235' lam w/ thin seams of f gry sd, brn. 235-245' slty, sdy, mic, brn.
250		<u>Sand</u>: 245-255' slty, cly, mic, carb matter, brn. <u>Clay</u>: 255-290' slty, mic & some sd, brn. 290-295' slty, small amt of pyrite, brn.
300		<u>Sand</u>: 295-300': f, slty, cly, some mica, brn. <u>Clay</u>: 300-315': slty, sdy, mic, brn. <u>Sand</u>: 315-330' f-m, slty, cly, mic, & carb matter, brn. 330-345' f, ang, qtz, carb matter, pyrite, gry. Pebs @ base 5'
350		**Record missing**: 345-351'
		<u>Mississippian</u> : 351'-TD TD = 353'

Metropolis Municipal Wells
Composite Formation Log



METROPOLIS MUNICIPAL WELLS

SUMMARY OF SAMPLE STUDIES BY M.P. MEYER (LUTH WELL) & L.E. WORKMAN (FULLER WELL) AND WELL DRILLER'S LOG (THORNE WELL)

L.S. for Luth Well and Fuller Well is reported to be 332' AMSL. Thorne Well L.S. is assumed to be 332' AMSL.

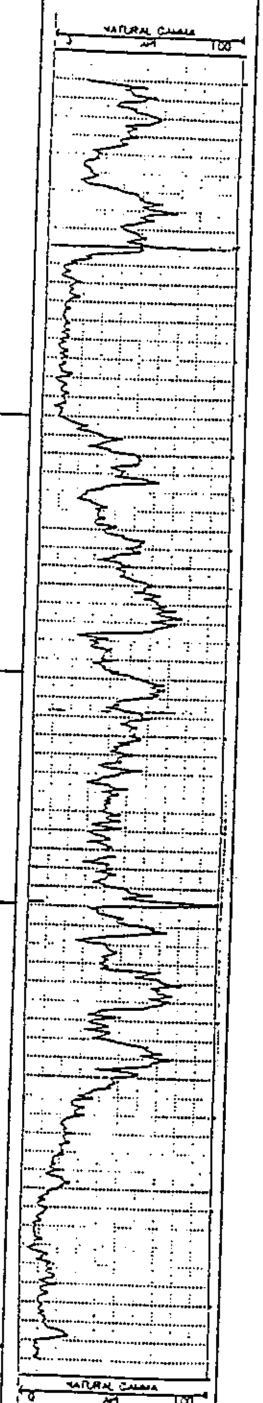
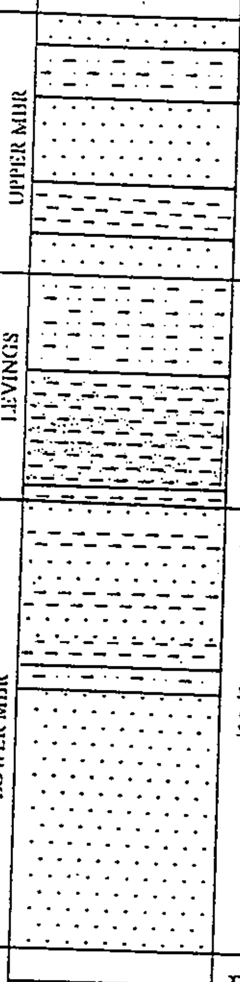
ELEV. (FEET)	DRILLED BY FRED M. LUTH 1924	DRILLED BY W.A. FULLER CO. 1925	DRILLED BY W.L. THORNE CO. 1928
300	**McNAIRY FORMATION: 85-275'** Silt: 270-275', cly, mic, brn. Sand: 222-270'	**McNAIRY FORMATION: 85-275'** Clay: 270-275', sdy, mic, red.	**McNAIRY FORMATION: -'** Gumbo: 277-297', blu-to-brn. Sand: 262-277', yel.
250	261-270' - slty, cly, mic, carbon, gry. 259-261' - f-m, pyrite. 249-259', f-m, mic, wht. 222-249', cly, slty, m-c, yel. Silt: 217-222', cly, mic, brn-gry.	Silt: 261-270', sdy, cly, mic, dk brn. Sand?: 259-261', f, pyrite. Sand: 249-259', m, angular, mic. Sand & Clay: 222-249', mic, yel. Silt: 217-222', sdy, mic, brn-gry.	Gumbo: 257-262', gry. Sand: 220-257', gry.
200	Gumbo: 207-217', blue. Sand: 185-207', f, mic, wht. Gumbo: 182-185', blk. Sand: 137-182' 167-182' - brn.	Silt as above?: 207-217'. Sand: 185-207', f, angular, mic, wht. Gumbo: 182-185', blk. Sand: 167-182', brn.	Gumbo: 215-220', blk. Sand: 187-215: gry. Gumbo: 177-187', pebbles, blk. Sand & Gumbo: 112-177', gry.
150	137-167' - f-m, mic, wht. Clay: 112-137', slty, mic, gry.	Sand: 137-167', f-m, lt gry. Silt: 112-137', sdy, mic, m gry.	
100	Sand: 87-112', f, wht. Gumbo: 85-87', blu. **TUSCALOOSA FM:** Sand: 64-85', f-c & gvl, chert, slty, wht.	Sand: 87-112', f, wht. Gumbo: 85-87', blu. **MISSISSIPPIAN :TD-85'** Weathering: 51-85'	Gumbo: 107-112'. Sand: 87-107', wht. Gumbo: 84-87'. **MISSISSIPPIAN :TD-84'**
50	Gravel: 51-64', c, chert, gry. **MISSISSIPPIAN :TD-51'** TD = -88'.	TD = -88'.	Limestone: 77-84', broken frags. TD = 36'.

COMPOSITE McNAIRY FORMATION LOG: upper member: 222-297', Levings member: 182-222', basal member: 85-182'

PGDP Well MW121
Land Surface = 372.43 ' AMSL
Drilled by Geotek Engineering in 1989-1990

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION
0 50		Loess & U. Cont. Dep. 0-52'
		L. Cont. Dep. 52-88'
100 150 UPPER MBR		McNairy Fm. 88'-TD Clay: 88-95.5' grysh-pink,intrbd w/ sd. 95.5-110' slty, mic, yellsh-brn Sand: 110-115' cly, yllsh-brn 115-130' well sort, w/slt, yellsh-brn-gry. 130-135' intrbd w/cl Silt: 135-165' olv blk, w/thin sd lens 165-170' intrbd w/f sd. wht
200 LEVINGS		170-200.5' olv blk w/thin sd lens Sand: 200.5'-TD vf, well sort, slty, lt gry TD = 211.5'

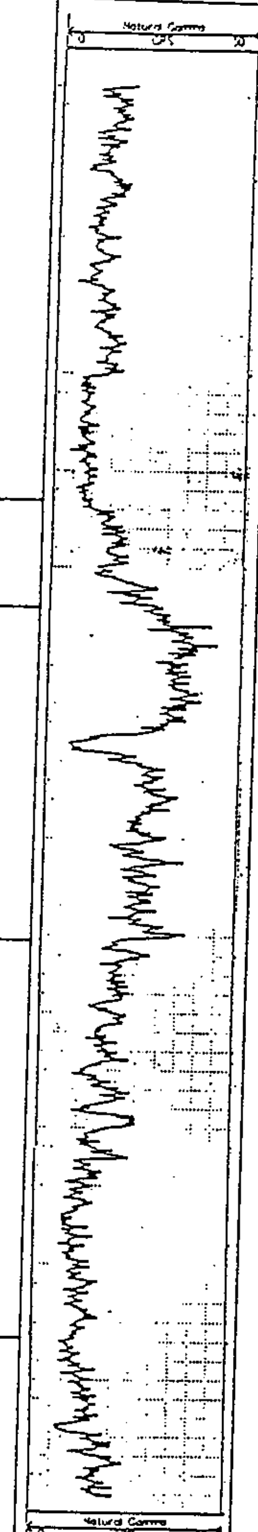
PGDP Boring P4-F08
Land Surface = 371.95' AMSL

DEPTH (FEET)		GRAPHIC LOG	LITHOLOGY DESCRIPTION	GAMMA LOG
0			**Loess & U. Cont. Dep.** 0-49'	
50			**L. Cont. Dep.** 49-90'	
100	UPPER MBR		**McNairy Fm.** 90-337' Sand: 90-98' Silt: 98-112' Sand & Silt: 112-134' Clay: 134-148', slty Sand: 148-159'	
150				
200	LEVINGS		Silt: 159-185', cly Silt: 185-215', sdy	
250	LOWER MBR		Clay & Sand: 215-263', interbd Silt: 263-269' Sand: 269-337'	
300				
350			**Rubble Zone**: 337-347' **Mississippian** : 347'-TD TD = 350'	

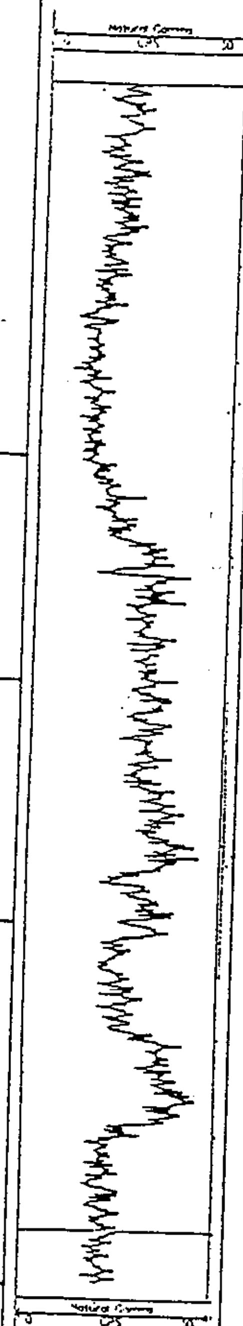
PGDP Boring Z12
Land Surface = 351.1' AMSL

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION
0, 50, 100		**Loess & U. Cont. Dep.** 0-75'
		L. Cont. Dep. 75-110'
	U MBR	**McNairy Fm.** 110-333' Sand: 110-129' Silt: 129-140'
150, 200	LEVINGS	Clay: 140-168' Sand: 168-175', gvly Silt: 175-229'
250, 300	LOWER MBR	Sand & Silt: 229-283' Sand: 283-333'
350		**Rubble Zone**: 333-348' **Mississippian** : 348'-TD TD = 369'

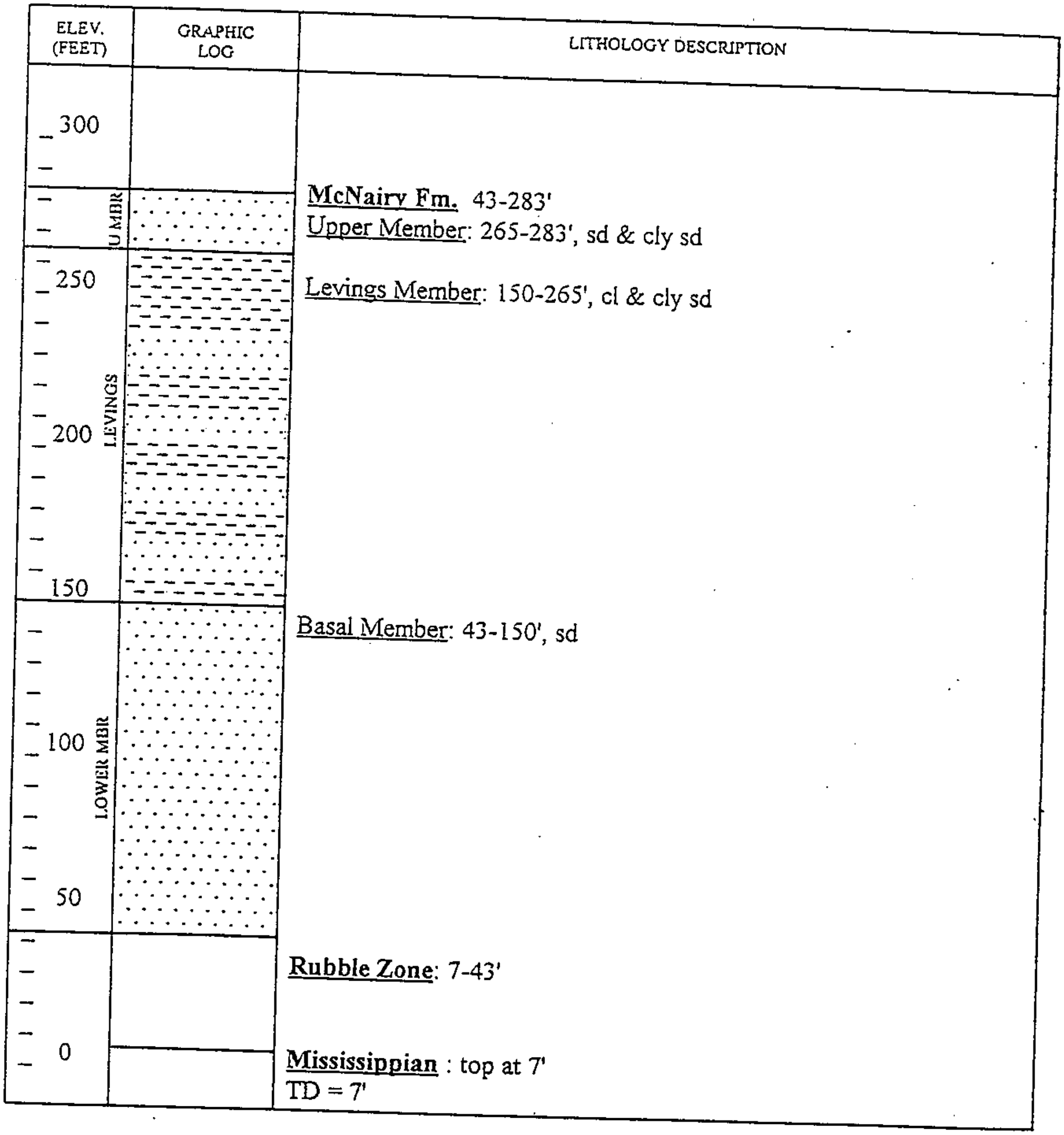
GAMMA LOG



PGDP Boring Z16
Land Surface = 370.9' AMSL

DEPTH (FEET)	GRAPHIC LOG	LITHOLOGY DESCRIPTION	GAMMA LOG
0, 50		Loess & U. Cont. Dep. 0-62'	
100		L. Cont. Dep. 62-101'	
150	UPPER MBR	McNairy Fm. 101-322' Sand: 101-122' Silt: 122-129' Sand: 129-131', gvly Silt, Sand, & Clay: 131-162' gvly	
200	LEVINGS	Silt, Sand, & Clay: 162-186' Clay & Silt: 186-207' Sand: 207-211' Silt & Clay: 211-224'	
250, 300	LOWER MBR	Sand: 224-248' Clay: 248-272' Sand: 272-322'	
350		Mississippian : 322'-TD TD = 356.5'	

TVA Shawnee Steam Plant Boreholes
Composite Formation Log



TVA SHAWNEE STEAM PLANT BOREHOLES
SUMMARY OF GRAPHIC LOGS
PRI TECHNICAL REPORT FILES, REPORT # 29-3#1, *GEOLOGY OF THE SHAWNEE STEAM PLANT SITE*

HOLE ID TAKEN FROM *GEOLOGIC QUADRANGLE MAP, JOPPA QUADRANGLE, KENTUCKY*, GQ-652

HOLE ID	#47	#48	#49	#50	#52	#53	#54	#55	#57	#58	#59	#60	#61
TOP OF UPPER MBR.	266'	267'	?	?	282'	276'	NA	?	276'	283'	279'	274'	NA
TOP OF LVNGS MBR.	258'	258'	?	?	265'	266'	265'	?	265'	270'	272'	268'	275'
TOP OF BASAL MBR.	<149'	<150'	<160'	<151'	<151'	<150'	<150'	152'	<152'	<189'	<149'	<176'	<152'

COMPOSITE FORMATION LOG:

McNAIRY FORMATION: upper sand member: 265-283', Levings member:150-265', lower sand member: 43-150'
RESIDUAL CHERT AND CLAY (HOLE #55): 7-43'
TOP OF MISSISSIPPIAN (HOLE #55): 7'

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APPENDIX B

MCNAIRY FORMATION GRAIN SIZE ANALYSES

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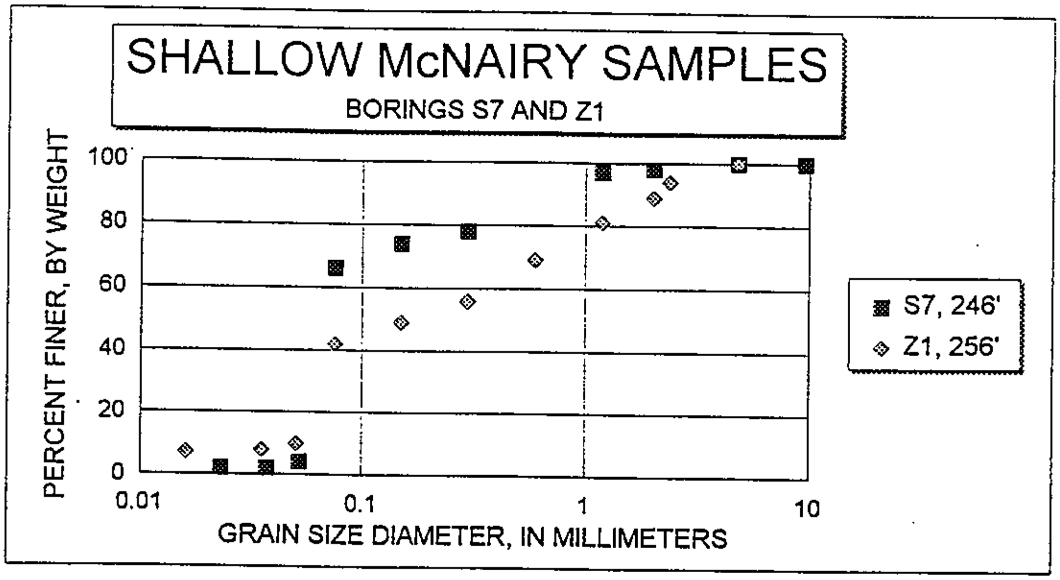
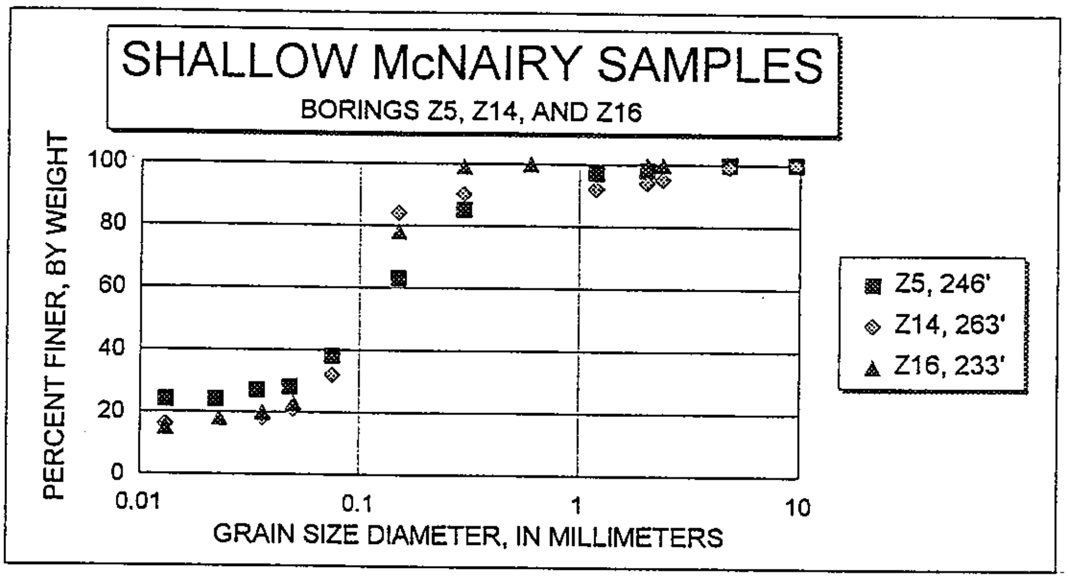
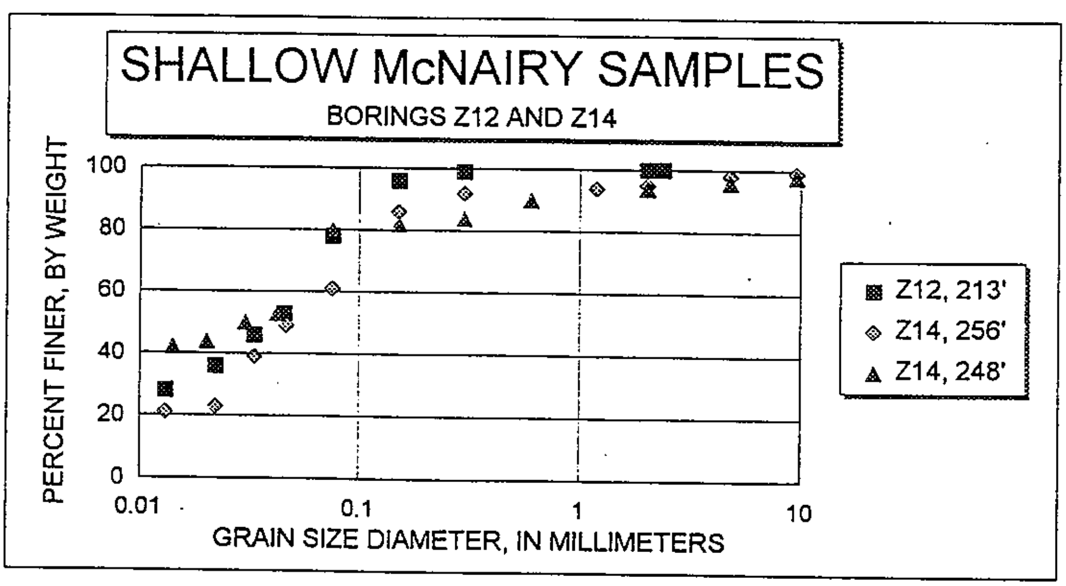
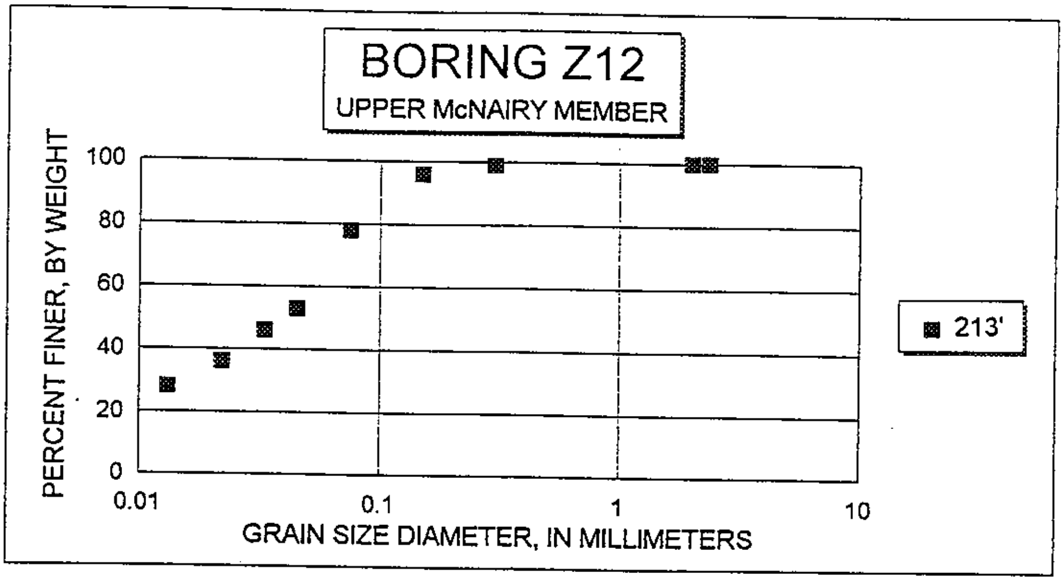
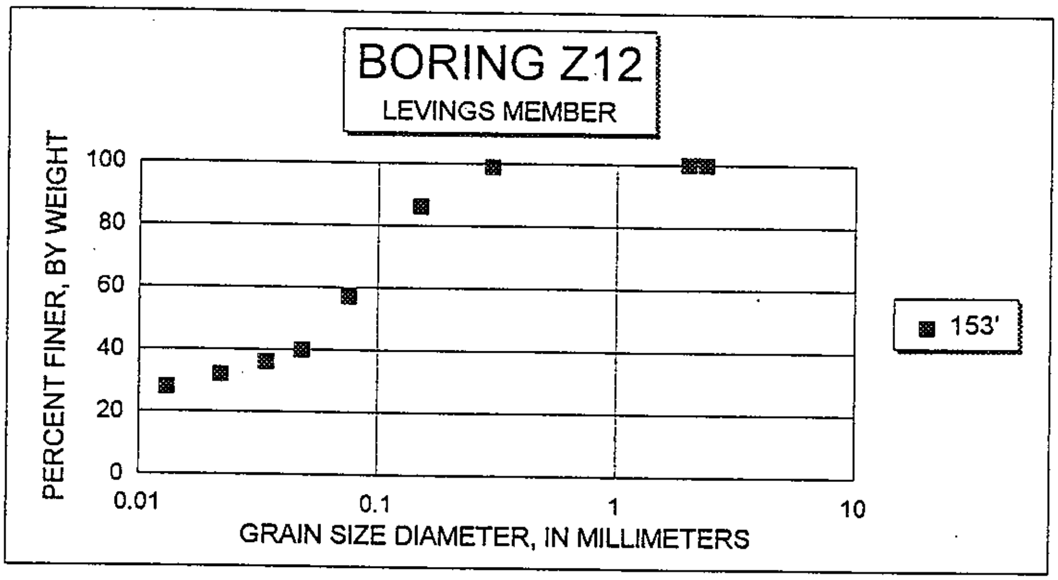
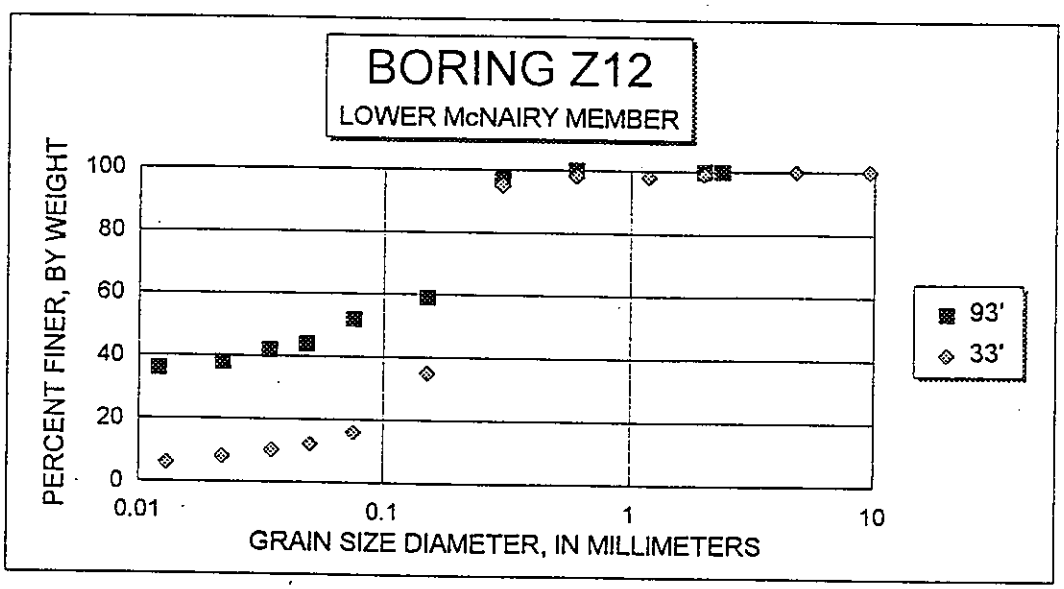

SHALLOW McNAIRY SAMPLES
BORINGS S7 AND Z1
PERCENT FINER, BY WEIGHT
0
20
40
60
80
100
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
S7, 246'
Z1, 256'

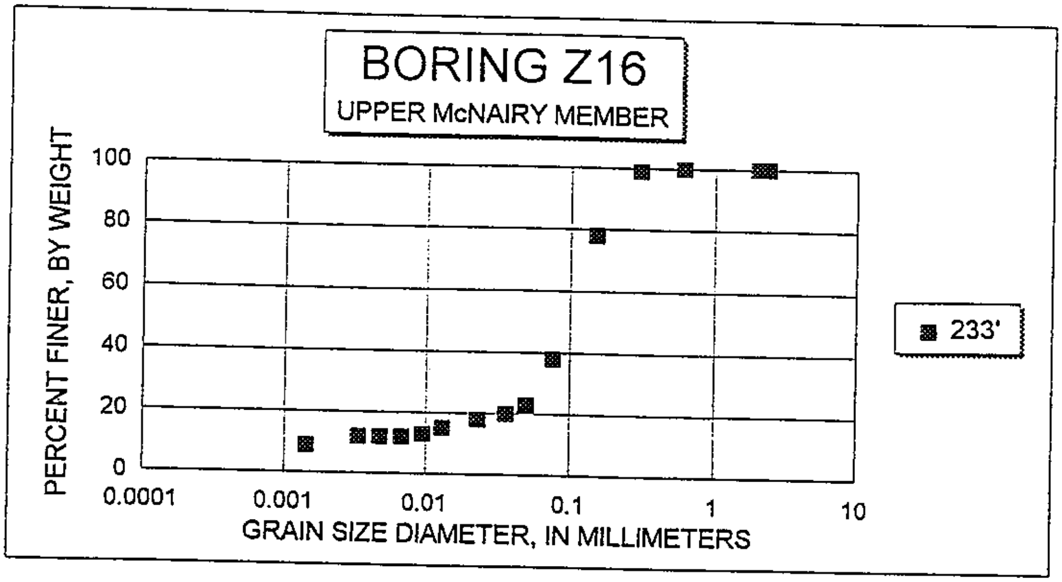

SHALLOW McNAIRY SAMPLES
BORINGS Z5, Z14, AND Z16
PERCENT FINER, BY WEIGHT
0
20
40
60
80
100
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
Z5, 246'
Z14, 263'
Z16, 233'

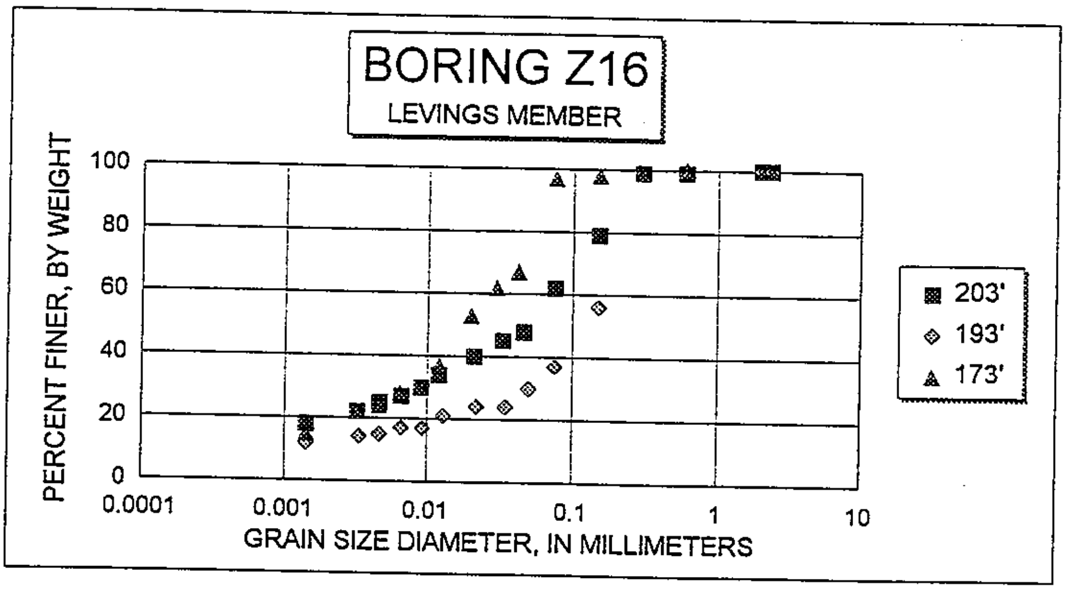

SHALLOW McNAIRY SAMPLES
BORINGS Z12 AND Z14
PERCENT FINER, BY WEIGHT
0
20
40
60
80
100
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
Z12, 213'
Z14, 256'
Z14, 248'

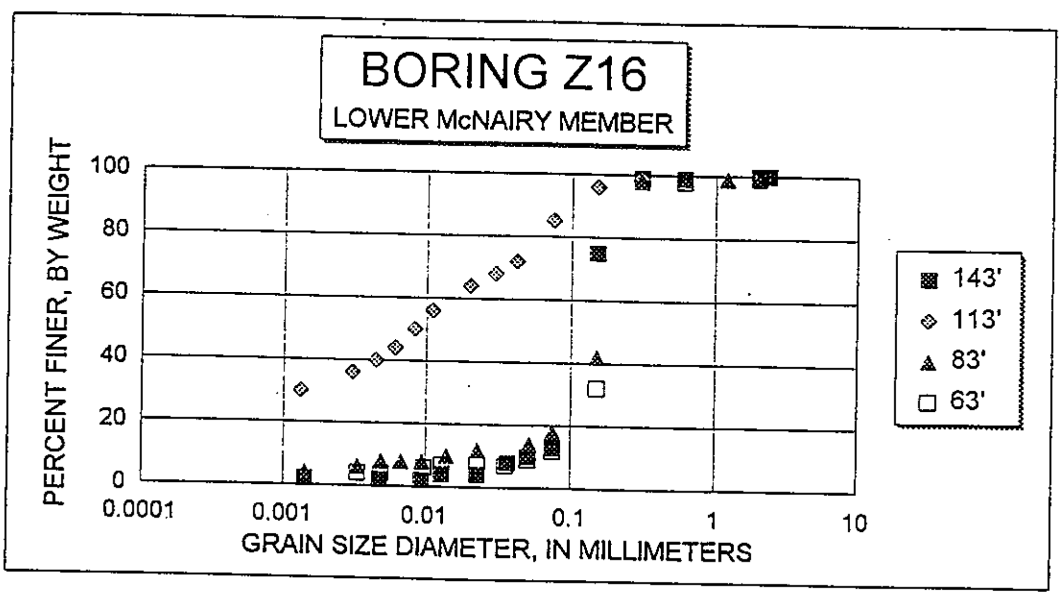

BORING Z12
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
213'

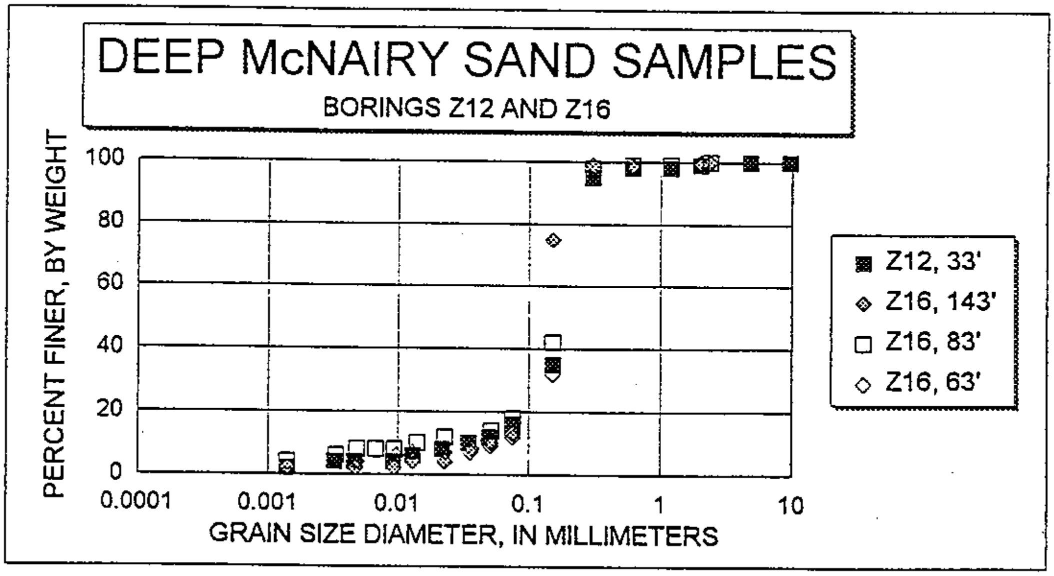

BORING Z12
LEVINGS MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
153'

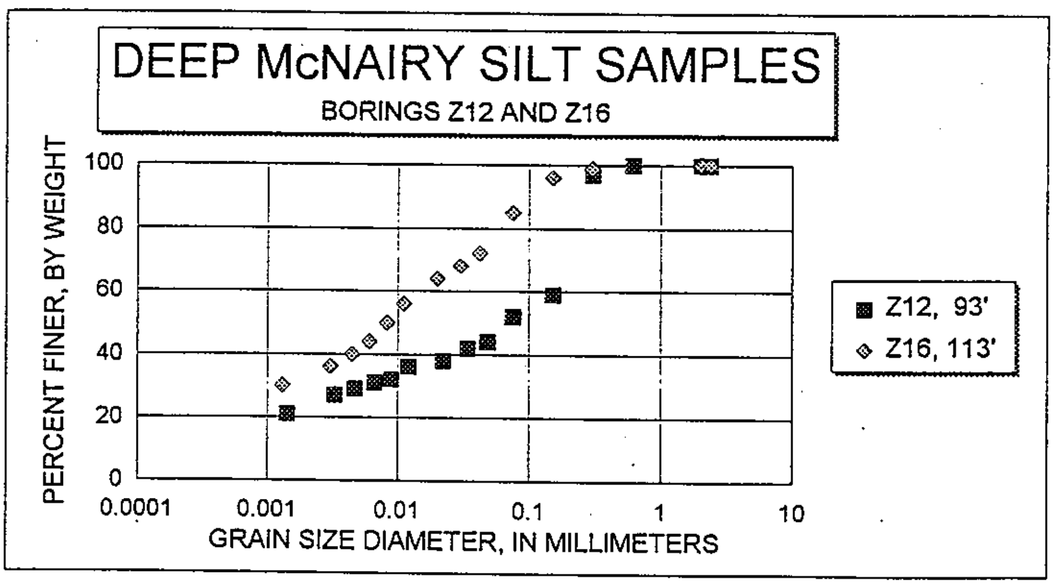

BORING Z12
LOWER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
93'
33'

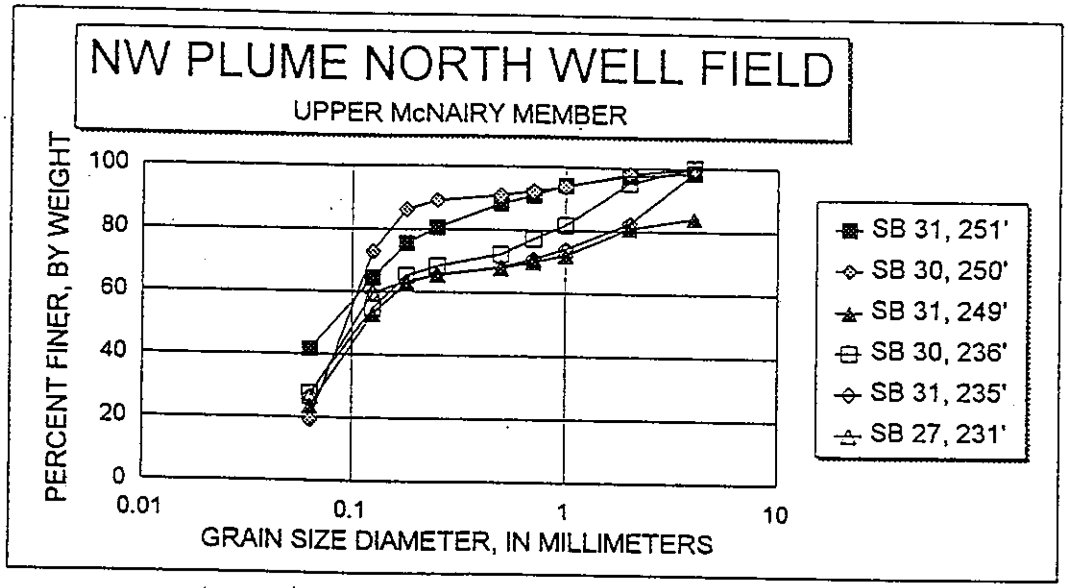

BORING Z16
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.0001
0.001
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
233'

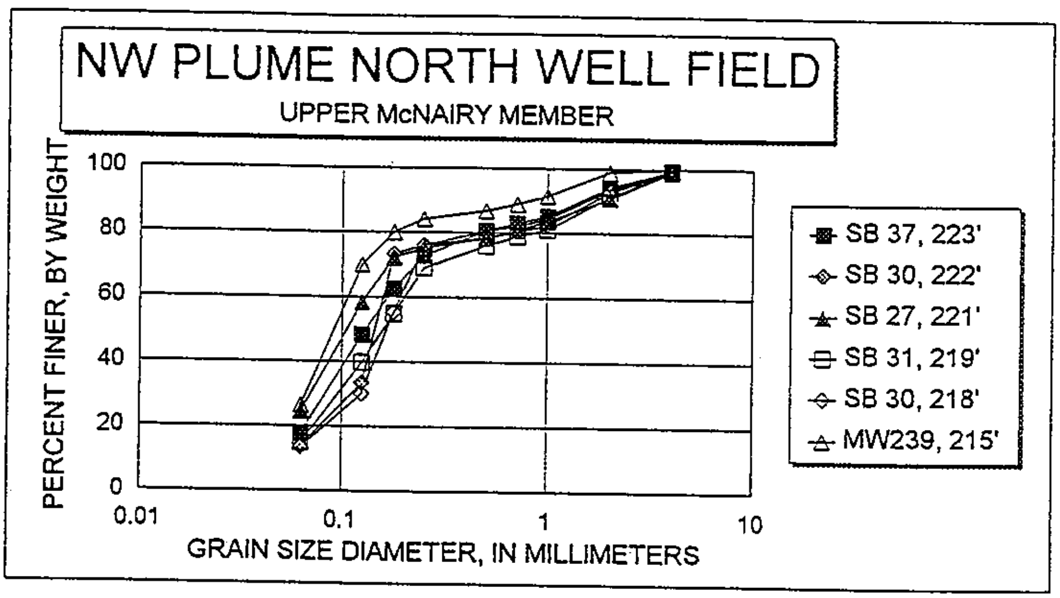

BORING Z16
LEVINGS MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.0001
0.001
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
203'
193'
173'

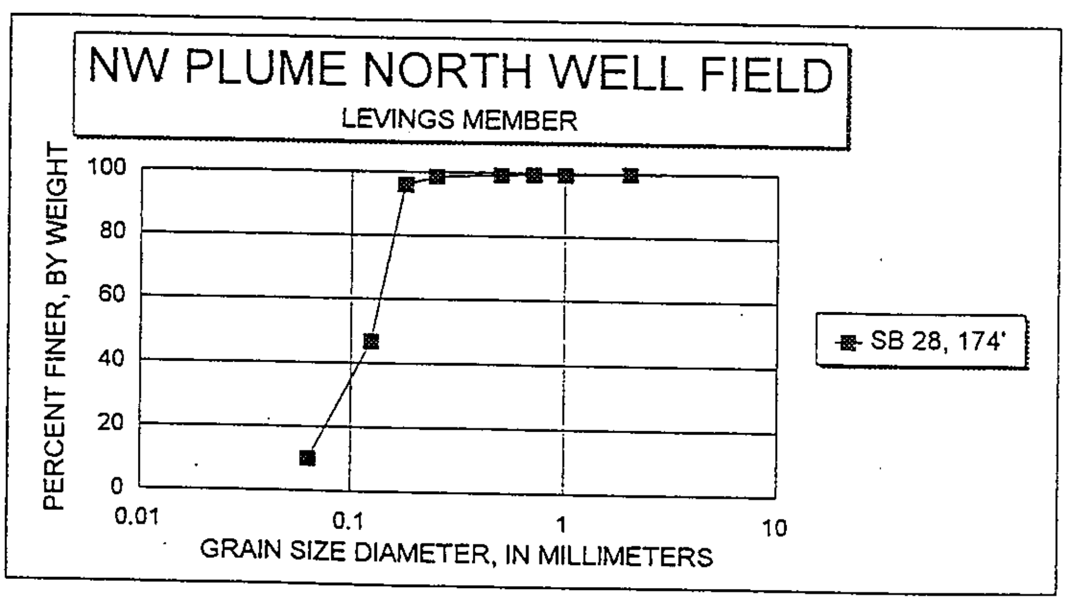

BORING Z16
LOWER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.0001
0.001
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
143'
113'
83'
63'

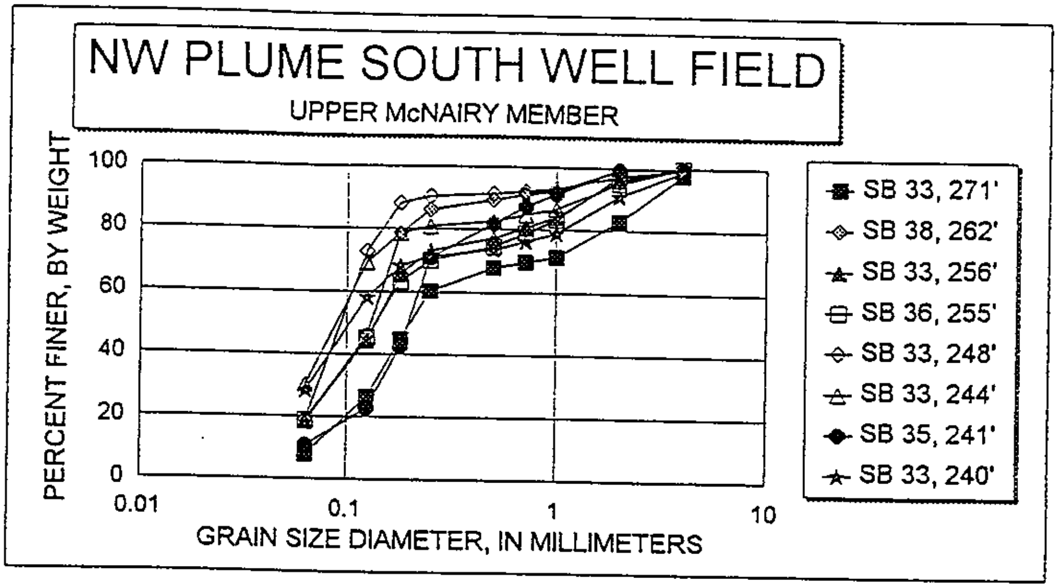

DEEP McNAIRY SAND SAMPLES
BORINGS Z12 AND Z16
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.0001
0.001
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
Z12, 33'
Z16, 143'
Z16, 83'
Z16, 63'

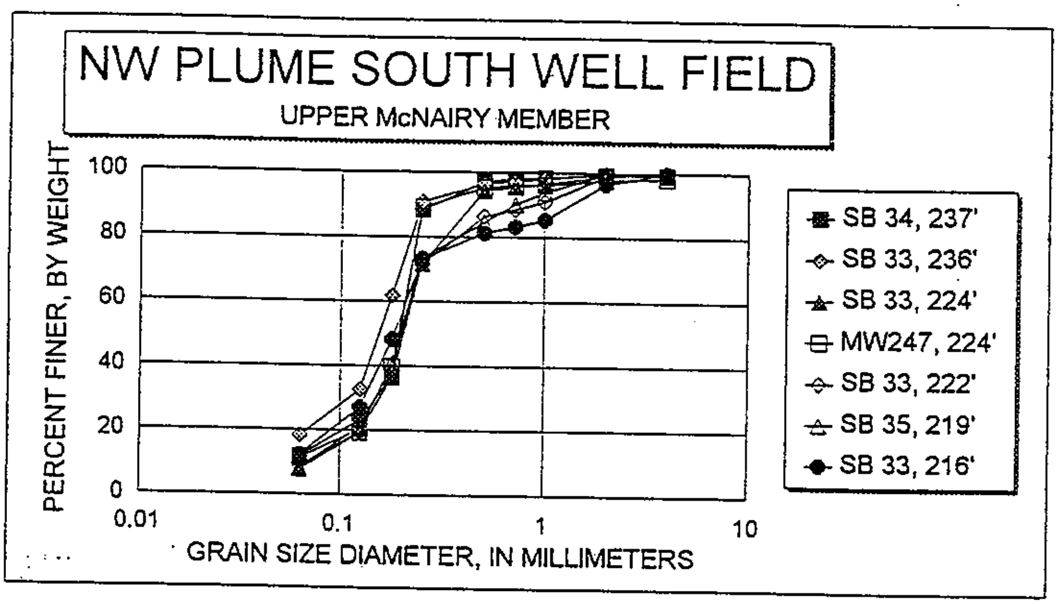

DEEP McNAIRY SILT SAMPLES
BORINGS Z12 AND Z16
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.0001
0.001
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
Z12, 93'
Z16, 113'

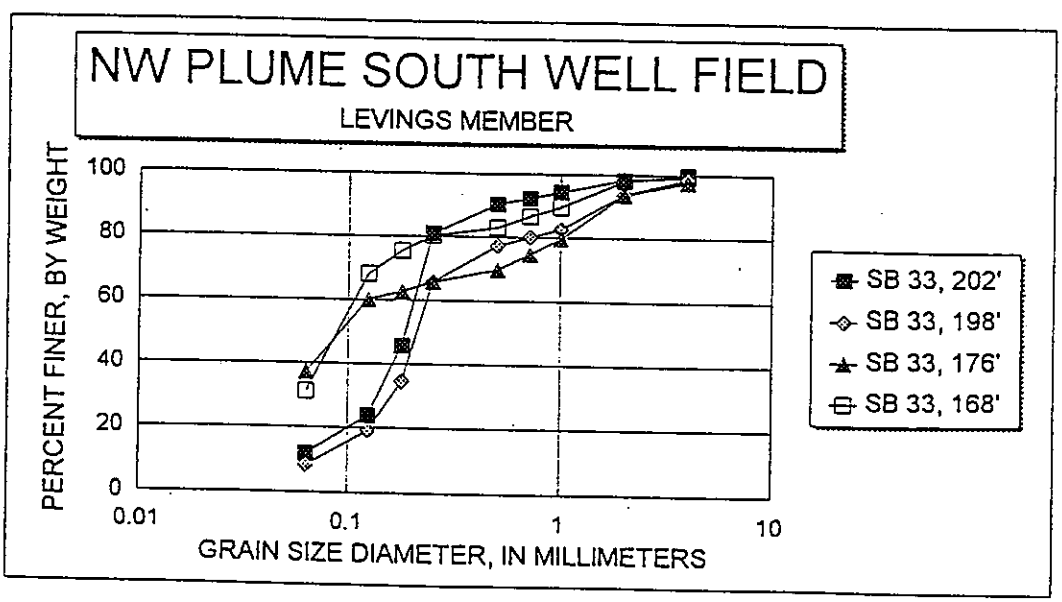

NW PLUME NORTH WELL FIELD
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 31, 251'
SB 30, 250'
SB 31, 249'
SB 30, 236'
SB 31, 235'
SB 27, 231'


NW PLUME NORTH WELL FIELD
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 37, 223'
SB 30, 222'
SB 27, 221'
SB 31, 219'
SB 30, 218'
MW239, 215'


NW PLUME NORTH WELL FIELD
LEVINGS MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 28, 174'


NW PLUME SOUTH WELL FIELD
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 33, 271'
SB 38, 262'
SB 33, 256'
SB 36, 255'
SB 33, 248'
SB 33, 244'
SB 35, 241'
SB 33, 240'


NW PLUME SOUTH WELL FIELD
UPPER McNAIRY MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 34, 237'
SB 33, 236'
SB 33, 224'
MW247, 224'
SB 33, 222'
SB 35, 219'
SB 33, 216'


NW PLUME SOUTH WELL FIELD
LEVINGS MEMBER
PERCENT FINER, BY WEIGHT
100
80
60
40
20
0
0.01
0.1
1
10
GRAIN SIZE DIAMETER, IN MILLIMETERS
SB 33, 202'
SB 33, 198'
SB 33, 176'
SB 33, 168'

APPENDIX C

DERIVATION OF EQUATION USED TO SOLVE FOR POROSITY

By assuming that the samples are completely saturated, the natural moisture content (by weight) is a measure of porosity. The conversion can be accomplished because the density of matrix - ρ_s (measured in the laboratory) and fluid - ρ_w (assumed to be 1 gram/centimeter^3) are known.

Porosity (θ) is the percentage of void space in the total volume of a soil sample. Thus, the porosity + percentage of volume occupied by the soil matrix = 1.

$$\text{Natural moisture content (m)} = \theta(\rho_w)/[\theta(\rho_w)+(1-\theta)(\rho_s)].$$

Solving for porosity:

$$\theta(\rho_w)-m(\theta)(\rho_w)+m(\theta)(\rho_s) = m(\rho_s)$$
$$\theta[\rho_w-m(\rho_w)+m(\rho_s)] = m(\rho_s)$$
$$\theta = m(\rho_s)/ [\rho_w-m(\rho_w)+m(\rho_s)].$$

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APPENDIX D

CALCULATION OF SPECIFIC STORAGE

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CALCULATION OF SPECIFIC STORAGE

DENSITY = 1.0 g/cm^3

1/COMPRESS = DEN(P-WAVE VEL)^2 - 4/3(DEN)(S-WAVE VEL)^2

POROSITY = 0.48

WATER COMPRESS = 4.4 X 10^-11 cm*s^2/g

ACCELERATION = 980 cm/s^2

SPECIFIC STORAGE = DEN*ACCELERATION(POROSITY*WATER COMPRESS+COMPRESSION)

DEPTH (ft)	ELEVATION (ft AMSL)	P-WAVE VELOCITY (cm/sec)	S-WAVE VELOCITY (cm/sec)	1/COMPRESS (g/(sec*cm^2)	COMPRESS ((sec*cm^2)/g)	SPECIFIC STORAGE (cm^3/cm^3/cm)
130	240.9	108373	42672	9.32E+09	1.07E-10	1.26E-07
140	230.9	203200	44196	3.87E+10	2.58E-11	4.60E-08
150	220.9	139337	45720	1.66E+10	6.01E-11	7.96E-08
160	210.9	135467	45720	1.56E+10	6.43E-11	8.37E-08
170	200.9	187569	38100	3.32E+10	3.01E-11	5.02E-08
180	190.9	182880	59436	2.87E+10	3.48E-11	5.48E-08
190	180.9	101600	65532	4.60E+09	2.18E-10	2.34E-07
200	170.9	166255	44196	2.50E+10	3.99E-11	5.98E-08
210	160.9	126124	45720	1.31E+10	7.62E-11	9.54E-08
220	150.9	215153	45720	4.35E+10	2.30E-11	4.32E-08
230	140.9	96253	45720	6.48E+09	1.54E-10	1.72E-07
240	130.9	812800	51816	6.57E+11	1.52E-12	2.22E-08
250	120.9	-203200	48768	3.81E+10	2.62E-11	4.64E-08
260	110.9	90311	71628	1.32E+09	7.60E-10	7.66E-07
270	100.9	103762	76200	3.02E+09	3.31E-10	3.45E-07
280	90.9	157316	57150	2.04E+10	4.90E-11	6.88E-08
290	80.9	113414	67056	6.87E+09	1.46E-10	1.63E-07
300	70.9	348343	58674	1.17E+11	8.57E-12	2.91E-08
305	65.9	243840	58674	5.49E+10	1.82E-11	3.86E-08

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APPENDIX E

DERIVATION OF EQUATION USED TO SOLVE FOR HYDRAULIC CONDUCTIVITY

$s_r = 2s_0 e^{-x[\text{square root of}(\pi S/tT)]}$

where:

s_r = range of groundwater stage,
s_0 = amplitude or half range of the surface-water stage,
x = distance from the monitoring well to the wave source,
S = coefficient of storage,
t = period of the wave fluctuation, and
T = coefficient of transmissibility.

$s_r/2s_0 = e^{-x[\text{square root of}(\pi S/tT)]} = e^{-1.77x[\text{square root of}(S/tT)]}$

$\log_{10}(s_r/2s_0) = -0.77x[\text{square root of}(S/tT)]$

$0.77[\text{square root of}(S/tT)] = -[\log_{10}(s_r/2s_0)]/x$

$s_r/2s_0$ = range of McNairy wave/range of RGA wave,
Solve by setting $s_r/2s_0 = 10$, then $\log_{10}(s_r/2s_0) = 1$ and the equation becomes:

$0.77[\text{square root of}(S/tT)] = -1/\Delta x$

where:

Δx = depth below RGA where $s_r = 10(2s_0)$

$0.59(S/tT) = 1/(\Delta x)^2$

$T = 0.59(\Delta x)^2 S/t$

$K_v = 0.59(\Delta x)^2 Ss/t$

$K_v = 0.59[(341')(12''/1')(2.54\ \text{cm}/1'')]^2(8 \times 10^{-8}/\text{cm})/(365.25\ \text{d})(24\ \text{hr/d})(60\ \text{min/hr})(60\text{s/min})$
$= 1.62 \times 10^{-7}$ cm/sec

$K_h = 39K_v = 6.30 \times 10^{-6}$ cm/sec

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APPENDIX F

WATER LEVEL DATA FOR MW71 (RGA WELL) AND MCNAIRY WELLS

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APPENDIX F

WATER LEVEL DATA FOR MW71 (RGA WELL) AND McNAIRY WELLS

	MW71	MW102	MW120	MW121	MW122	MW133	MW140
10/15/90	327.48		326.87	321.00	325.43	321.47	324.87
11/15/90	326.58		326.33	320.48	324.81	320.93	324.05
12/15/90	326.33		325.93	321.01	324.30	320.59	323.62
01/15/91	326.69		325.98	324.99	324.60	325.63	328.16
02/14/91	328.64		326.94	324.21	326.07	325.68	329.16
03/15/91	331.00		328.27	325.31	327.42	327.31	330.76
04/15/91	331.68		329.02	325.82	328.38	328.06	331.20
05/15/91	332.40		329.83	325.15	329.16	326.70	330.77
06/15/91	332.36		329.97	323.92	329.06	326.27	330.42
07/15/91	331.33		329.58	322.69	328.52	324.46	328.54
08/15/91	330.08		328.81	321.42	327.52	323.05	326.96
09/15/91	328.51		327.76	320.78	326.26	321.75	325.36
09/16/92	330.77		323.41	330.11			
10/15/92	330.54	325.55	323.13	329.92	323.25	322.97	320.57
11/12/92	330.36	325.49	323.16	330.31	323.16	320.27	320.57
12/16/92	330.73	325.47	323.01	330.96	323.23	320.86	321.56
01/14/93	330.72	325.77	323.12	332.29	323.49	321.80	322.39
02/17/93	331.91	327.00	323.82	332.14	324.58	322.86	323.10
03/18/93	333.19	327.99	324.54	333.90	325.40	324.83	324.22
04/15/93	335.72	330.25	325.77	335.28	326.96	327.50	325.85
05/12/93	337.39	331.79	326.96	335.53	328.28	327.96	326.49
07/14/93	337.24	332.32	327.63	333.97	328.53	325.38	324.96
08/17/93	336.22	331.63	327.22	385.22	328.01	325.26	
09/15/93	335.10	330.02	326.78	332.93	327.44	323.96	324.02
10/18/93	334.31	329.30	326.32	332.82	326.86	323.27	323.92
11/16/93	333.61	328.47	326.00	332.23	326.26	322.46	323.13
12/14/93	334.59	328.83	325.88	334.38	326.21	324.64	324.53
01/15/94	335.03	329.33	326.22	333.90	326.74	324.45	324.61
02/14/94	335.25	329.77	326.55	335.72	327.28	326.56	326.01
03/15/94	337.29	331.56	327.58	336.99	328.55	329.05	327.40
04/15/94	339.48	333.30	329.05	337.87	330.20	330.90	328.39
05/15/94	341.07	335.18	330.46	337.80	331.72	330.10	329.02
06/15/94	340.16	334.55	330.26	335.02	331.50	327.26	326.62
07/15/94	338.26	332.90	329.31	333.80	330.04	325.21	325.12
08/15/94	336.31	331.16	328.10	332.95	328.56	323.73	323.91
09/15/94	334.63	329.60	326.89	331.99	327.15	322.39	322.91
10/18/94	333.32	328.14	385.22	331.52	326.02	321.23	322.14
11/15/94	332.26	327.36	325.24	331.57	325.23	320.62	321.95
12/14/94	332.09	326.38	324.68	332.60	324.67	320.33	322.32
01/11/95	331.60	326.43	385.22	331.96	324.37	320.59	322.13
02/14/95	330.74	326.52	324.37	332.45	324.54	318.89	323.10
03/14/95	332.58	327.28	324.75	385.22	325.01	323.11	324.02
04/18/95	333.57	328.47	325.28	332.95	325.76	323.17	323.93
05/16/95	325.52	329.23	325.77	334.58	365.16	324.48	324.90
06/14/95		329.97	326.39	335.76	327.27	327.10	326.57

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APPENDIX G

CALCULATION OF VERTICAL GRADIENTS IN THE McNAIRY FORMATION

# OF MEASUREMENTS	41	41	40	40
WELL ID	MW121	MW123	MW122	MW126
HYDROGEOLOGIC UNIT	McN	RGA	McN	RGA
AVERAGE HYDRAULIC POTENTIAL (FT AMSL)	331.58	334.21	326.74	328.69
ELEVATION OF BASE OF RGA (FT AMSL)		284.43		302.90
ELEVATION OF MIDPOINT OF FILTER PACK (FT AMSL)	167.43		209.90	
AVERAGE McNAIRY GRADIENT (VERTICAL)	0.0225		0.0210	

# OF MEASUREMENTS	40	40	39	22	40
WELL ID	MW133	MW137	MW140	MW141	MW142
HYDROGEOLOGIC UNIT	McN	RGA	McN	RGA	RGA
AVERAGE HYDRAULIC POTENTIAL (FEET AMSL)	324.18	323.88	324.06	327.30	327.60
ELEVATION OF BASE OF RGA (FEET AMSL)		286.10		275.80	275.80
ELEVATION OF MIDPOINT OF FILTER PACK (FEET AMSL)	249.70		200.80		
AVERAGE McNAIRY GRADIENT (VERTICAL)	-0.0082		0.0432/0.0472		

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APPENDIX H

GROUNDWATER ANALYSES OF THE MCNAIRY FORMATION, THE REGIONAL GRAVEL AQUIFER, AND THE MISSISSIPPIAN BEDROCK

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USGS Open File Report 80-685										
McNAIRY GEOCHEMISTRY										
COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	HCO3 (MG/L)	SO4 (MG/L)	Cl (MG/L)
McCRACKEN										
	76	525	8.3	33	7.8	25	5.4	162	10	22
	94	210	7.6	39	9.8	20	4.1	185	14	14
	99	353	7.4	42	11	25	5.6	168	15	41
	119	174	6.5					132	6.8	4
	119	174	6.7	18	7.3	18	3.1	127	6.4	8
	123	61	6			39		104	28	98
BALLARD										
	47	244	7.6					205	10	12
	54	280	6.9					130	9.2	16
	56	116	7.9	32	9.5	20	3.6	187	16	3.2
	56	107	6.8					193	8.8	3
MISSISSIPPIAN GEOCHEMISTRY										
COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	HCO3 (MG/L)	SO4 (MG/L)	Cl (MG/L)
McCRACKEN										
	21	650	7.3	41	18	53	8.3	140	32	107
	21	650	6.8	55	10	52	7.6	146	34	104
	73	540	7.8					160	13	42
	90	460	7.6					159	13	45
USGS Water-Supply Paper 1987										
MISSISSIPPIAN GEOCHEMISTRY										
QUAD MAP	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	HCO3 (MG/L)	SO4 (MG/L)	Cl (MG/L)
PADUCAH EAST										
	177-58	333	7.7	43	8.7	44		134	26	72
	177-62	535	7.7	49	9.3	18	5.4	164	22	36
PADUCAH WEST										
	177-5	310	7.1	75	7.6	12	5.6	239	16	27
	177-8	353	7.4	42	11	25	5.6	168	15	41
	177-34	540	7.8					160	13	42

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McNAIRY GEOCHEMISTRY

COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca (MEQ/L)	Mg (MEQ/L)	Na (MEQ/L)	K (MEQ/L)	Na + K (MEQ/L)	HCO3 (MEQ/L)	SO4 (MEQ/L)	Cl (MEQ/L)
McCRACKEN										
	76	525	1.65	0.64	1.09	0.14	1.23	2.66	0.21	0.62
	94	210	1.95	0.81	0.87	0.10	0.97	3.03	0.29	0.39
	99	353	2.10	0.91	1.09	0.14	1.23	2.76	0.31	1.16
	119	174						2.16	0.14	0.11
	119	174	0.90	0.60	0.78	0.08	0.86	2.08	0.13	0.23
	123	61			1.70			1.71	0.58	2.76
BALLARD										
	47	244						3.36	0.21	0.34
	54	280						2.13	0.19	0.45
	56	116	1.60	0.78	0.87	0.09	0.96	3.07	0.33	0.09
	56	107						3.17	0.18	0.08

MISSISSIPPIAN GEOCHEMISTRY

COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca (MEQ/L)	Mg (MEQ/L)	Na (MEQ/L)	K (MEQ/L)	Na + K (MEQ/L)	HCO3 (MEQ/L)	SO4 (MEQ/L)	Cl (MEQ/L)
McCRACKEN										
	21	650	2.05	1.48	2.31	0.21	2.52	2.30	0.67	3.02
	21	650	2.74	0.82	2.26	0.19	2.46	2.39	0.71	2.93
	73	540						2.62	0.27	1.18
	90	460						2.61	0.27	1.27

USGS Water-Supply Paper 1987

MISSISSIPPIAN GEOCHEMISTRY

QUAD MAP	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca (MEQ/L)	Mg (MEQ/L)	Na (MEQ/L)	K (MEQ/L)	Na + K (MEQ/L)	HCO3 (MEQ/L)	SO4 (MEQ/L)	Cl (MEQ/L)
PADUCAH EAST										
	177-58	333	2.15	0.72	1.91		1.91	2.20	0.54	2.03
	177-62	535	2.45	0.77	0.78	0.14	0.92	2.69	0.46	1.02
PADUCAH WEST										
	177-5	310	3.74	0.63	0.52	0.14	0.67	3.92	0.33	0.76
	177-8	353	2.10	0.91	1.09	0.14	1.23	2.76	0.31	1.16
	177-34	540						2.62	0.27	1.18

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McNAIRY GEOCHEMISTRY

COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca % Cations	Mg % Cations	Na % Cations	K % Cations	Na + K % Cations	HCO3 % Anions	SO4 % Anions	Cl % Anions
McCRACKEN										
	76	525	0.47	0.18	0.31	0.04	0.35	0.76	0.06	0.18
	94	210	0.52	0.22	0.23	0.03	0.26	0.82	0.08	0.11
	99	353	0.50	0.21	0.26	0.03	0.29	0.65	0.07	0.27
	119	174						0.89	0.06	0.05
	119	174	0.38	0.25	0.33	0.03	0.37	0.85	0.05	0.09
	123	61						0.34	0.12	0.55
BALLARD										
	47	244						0.86	0.05	0.09
	54	280						0.77	0.07	0.16
	56	116	0.48	0.23	0.26	0.03	0.29	0.88	0.10	0.03
	56	107						0.92	0.05	0.02

MISSISSIPPIAN GEOCHEMISTRY

COUNTY	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca % Cations	Mg % Cations	Na % Cations	K % Cations	Na + K % Cations	HCO3 % Anions	SO4 % Anions	Cl % Anions
McCRACKEN										
	21	650	0.34	0.25	0.38	0.04	0.42	0.38	0.11	0.50
	21	650	0.46	0.14	0.38	0.03	0.41	0.40	0.12	0.49
	73	540						0.64	0.07	0.29
	90	460						0.63	0.07	0.31

USGS Water-Supply Paper 1987

MISSISSIPPIAN GEOCHEMISTRY

QUAD MAP	WELL ID	DEPTH TO BOTTOM OF SAMPLE INTERVAL (FEET)	Ca % Cations	Mg % Cations	Na % Cations	K % Cations	Na + K % Cations	HCO3 % Anions	SO4 % Anions	Cl % Anions
PADUCAH EAST										
	177-58	333	0.45	0.15	0.40	0.00	0.40	0.46	0.11	0.43
	177-62	535	0.59	0.19	0.19	0.03	0.22	0.65	0.11	0.24
PADUCAH WEST										
	177-5	310	0.74	0.12	0.10	0.03	0.13	0.78	0.07	0.15
	177-8	353	0.50	0.21	0.26	0.03	0.29	0.65	0.07	0.27
	177-34	540						0.64	0.07	0.29

Phase IV Groundwater Investigation							
P4-G1							
SAMPLE INTERVAL	DEPTH	pH	Ca	Mg	K	Na	Dissolved Oxygen
	(FEET)	(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
RGA-TOP	70	6.1	26.80	10.70	2.04	48.90	9.02
RGA-MID	80	5.9	34.20	13.00	2.33	45.70	10.44
RGA-BOTTOM	90	5.6	87.70	42.00	4.20	37.10	7.00
McNairy	100	5.2	6.30	2.94	2.20	11.20	0.99
McNairy	120	6.4					0.09
McNairy	150	6.0	16.40	13.60	14.30	15.30	0.18
P4-G12							
SAMPLE INTERVAL	DEPTH	pH	Ca	Mg	K	Na	Dissolved Oxygen
	(FEET)	(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
RGA-TOP	65	6.1	244.00	70.00	11.00	26.00	4.11
RGA-MID	80	5.9	26.00	11.00	2.00	31.00	7.20
RGA-BOTTOM	90	5.9	30.00	13.00	2.10	32.00	12.63
RGA-BOTTOM	100	6.1	51.00	31.00	20.00	31.00	1.50
McNairy	130	6.0	10.00	4.60	4.30	15.00	0.56

Phase IV Groundwater Investigation						
P4-G1						
SAMPLE INTERVAL	DEPTH	Ca	Mg	Na	K	Na + K
	(FEET)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)
RGA-TOP	70	1.34	0.88	2.13	0.05	2.18
RGA-MID	80	1.71	1.07	1.99	0.06	2.05
RGA-BOTTOM	90	4.38	3.46	1.61	0.11	1.72
McNairy	100	0.31	0.24	0.49	0.06	0.54
McNairy	120					
McNairy	150	0.82	1.12	0.67	0.37	1.03
P4-G12						
SAMPLE INTERVAL	DEPTH	Ca	Mg	Na	K	Na + K
	(FEET)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)
RGA-TOP	65	12.18	5.76	1.13	0.28	1.41
RGA-MID	80	1.30	0.91	1.35	0.05	1.40
RGA-BOTTOM	90	1.50	1.07	1.39	0.05	1.45
RGA-BOTTOM	100	2.54	2.55	1.35	0.51	1.86
McNairy	130	0.50	0.38	0.65	0.11	0.76

Phase IV Groundwater Investigation						
P4-G1						
SAMPLE INTERVAL	DEPTH	Ca	Mg	Na	K	Na + K
	(FEET)	%	%	%	%	%
		Cations	Cations	Cations	Cations	Cations
RGA-TOP	70	0.31	0.20	0.49	0.01	0.50
RGA-MID	80	0.36	0.22	0.42	0.01	0.43
RGA-BOTTOM	90	0.46	0.37	0.17	0.01	0.18
McNairy	100	0.30	0.23	0.47	0.05	0.52
McNairy	120					
McNairy	150	0.31	0.43	0.26	0.14	0.40
P4-G12						
SAMPLE INTERVAL	DEPTH	Ca	Mg	Na	K	Na + K
	(FEET)	%	%	%	%	%
		Cations	Cations	Cations	Cations	Cations
RGA-TOP	65	0.64	0.30	0.06	0.01	0.07
RGA-MID	80	0.37	0.25	0.38	0.01	0.39
RGA-BOTTOM	90	0.38	0.27	0.35	0.01	0.37
RGA-BOTTOM	100	0.39	0.40	0.21	0.08	0.29
McNairy	130	0.33	0.25	0.43	0.07	0.50

Phase IV Groundwater Investigation - McNairy

Boring ID	Depth (FT)	Dissolved Oxygen (PPM)	pH (SU)		Boring ID	Depth (FT)	Dissolved Oxygen (PPM)	pH (SU)
P4-A2	119	1.68	5.8		P4-D10	141	14.30	6.3
P4-A2	138	2.71	5.7		P4-D10	150	5.09	6.2
P4-A3	140	1.64	5.8		P4-D11	138	12.01	6.4
P4-B3	120	2.64	6.2		P4-D11	150	13.40	6.2
P4-B3	120	4.65	6.4		P4-D12	110	0.77	6.5
P4-B3	140	0.10	6.2		P4-D12	140	2.04	6.4
P4-B3	140	0.23	6.1		P4-D12	140	2.04	6.4
P4-B4	119	0.28	6.0		P4-D12	150	1.03	6.2
P4-C4	115	9.91	6.2		P4-E2	125	2.15	6.2
P4-C4	150	0.11	6.5		P4-E2	140	2.35	6.1
P4-C7	116	5.06	6.1		P4-E8	155	2.18	6.3
P4-C7	149	2.04	6.2		P4-F2	140	1.42	6.0
P4-C9	149	10.60	6.5		P4-F6	140	1.16	6.0
P4-C10	125	1.00	6.5		P4-F8	149	0.19	6.2
P4-C10	139	0.82	6.2		P4-G1	100	0.99	5.2
P4-D4	119	11.15	5.8		P4-G1	120	0.09	6.4
P4-D4	133	2.76	5.8		P4-G1	150	0.18	6.0
P4-D5	120	1.96	6.1		P4-G2	100	2.46	6.1
P4-D5	150	0.93	6.4		P4-G2	100	2.00	6.1
P4-D6	138	2.40	5.8		P4-G3	130	0.07	6.2
P4-D6	138	2.40	5.8		P4-G7	150	1.36	7.0
P4-D6	147	1.52	5.6		P4-G8	140	2.48	6.0
P4-D7	130	4.52	6.0		P4-G11	110	1.47	6.2
P4-D7	145	2.81	6.3		P4-G12	130	0.56	6.0
P4-D8	139	0.58	6.2		P4-H7	120	0.50	6.1
P4-D8	150	0.89	6.2		P4-H7	140	0.38	6.1
P4-D9	140	1.16	6.4		PZ-115	112.5	0.29	5.9
P4-D9	150	2.20	6.4					

Phase IV Groundwater Investigation - RGA

Boring ID	Depth (FT)	Dissolved Oxygen (PPM)	pH (SU)		Boring ID	Depth (FT)	Dissolved Oxygen (PPM)	pH (SU)
MW144	110	2.32	5.6		P4-E6	105	2.96	5.9
P4-A2	89	13.08	6.0		P4-E7	96	10.62	6.9
P4-A3	90	12.92	6.0		P4-E7	145	0.15	7.2
P4-B3	95	4.32	5.8		P4-E8	97	0.87	6.3
P4-B3	95	4.99	5.8		P4-F1	100	3.33	6.2
P4-B4	95	6.63	6.1		P4-F2	90	6.69	6.1
P4-B5	84	0.11	6.8		P4-F2	100	4.01	6.1
P4-C2	96	1.86	6.1		P4-F3	90	8.36	6.1
P4-C4		5.22	6.0		P4-F3	90	8.36	6.1
P4-C5	95	11.47	5.8		P4-F5	90	2.51	6.3
P4-C7	93	8.38	5.9		P4-F6	90	3.89	6.0
P4-C7	93	8.38	5.9		P4-F6	100	4.24	6.0
P4-C9	97	6.09	6.0		P4-F7	100	5.25	6.1
P4-C10	78	3.79	5.8		P4-G1	90	7.00	5.6
P4-D4	107	12.68	5.9		P4-G3	110	3.81	6.3
P4-D5	100	12.99	6.0		P4-G5	90	0.93	6.1
P4-D6	114	2.36	6.0		P4-G5	100	8.70	6.0
P4-D7	108	6.51	5.8		P4-G5	100	8.70	6.0
P4-D8	99	10.31	6.0		P4-G7	77	1.66	6.2
P4-D8	104	8.44	6.0		P4-G8	120	0.6	5.9
P4-D9	98	2.67	6.0		P4-G9	80	3.97	6.0
P4-D10	100	9.31	6.2		P4-G9	90	0.88	5.3
P4-D11	84.5	4.46	5.8		P4-G9	110	0.17	6.0
P4-D12	98	3.11	6.0		P4-G11	95	8.08	5.9
P4-D12	98	3.11	6.0		P4-G12	90	12.63	5.9
P4-E1	95	4.21	6.0		P4-G12	100	1.50	6.1
P4-E2	105	6.64	6.1		P4-H5	85	4.20	6.0
P4-E4	95	6.74	5.9		P4-H7	90	13.02	6.1
P4-E4	95	6.60			PZ-118	81	1.21	7.8

PGDP Analyses											
McNAIRY GEOCHEMISTRY											
WELL	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Dissolved Oxygen	Alkalinity	Calculated HCO3
MW102		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(PPM)	(MG/L CaCO3)	(MG/L)
	5174-93	6.10	19.26	6.51	18.00	4.38	25.00	9.00	0.90	95.00	
	5940-93	6.20	19.00	6.73	15.70	4.54	25.00	10.00	0.17	95.00	
	7295-93	6.00	19.10	6.49	16.80	5.83		11.00	2.40	92.00	
	4268-94	6.10	20.90	7.11	19.90	<2		9.00	0.19	93.00	
	5183-94	6.10	19.60	6.74	15.70	4.91		9.00	0.95	96.00	
	6022-94	5.90	19.50	8.06	18.30	7.66	26.20	7.60	0.73	95.00	
	6770-94	6.10	21.50	7.32	19.40	9.47	27.70	7.90	2.94	102.00	
	5619-95	6.20	21.20	6.90	21.60	13.10	27.50	7.60	0.83	99.00	
	6592-95	6.20	19.20	6.53	18.60		28.40	6.90	1.48	100.00	
	7467-95	6.20	18.20	6.23	15.20	<10.5	27.40	7.60	0.31	94.00	
	8285-95	6.30	19.20	6.56	18.90		28.80	7.10	0.27	100.00	
	AVERAGE	**6.13**	**19.70**	**6.83**	**18.01**	**7.13**	**27.00**	**8.43**	**1.02**	**96.45**	**118**
MW120											
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Dissolved Oxygen	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(PPM)	(MG/L CaCO3)	(MG/L)
	5088-93	6.60	24.90	8.46	13.80	6.37	12.00	10.00	0.29	127.00	
	5900-93	6.70	26.80	9.04	14.90	12.70	10.00	9.00	5.53	142.00	
	7065-93	6.80	29.62	9.45	18.23	9.66		11.00	0.33	121.00	
	4209-94	6.70	27.70	9.09	15.90	7.44		10.00	0.83	126.00	
	4991-94	6.70	25.30	9.61	15.50	9.41	14.00	11.00	0.52	127.00	
	6034-94	6.90	29.10	9.73	17.40	12.50	11.10	9.10	2.39	130.00	
	6928-94	6.50	30.00	10.00	16.00	6.70	10.90	9.30	1.80	127.00	
	5448-95	6.70	28.00	10.30	16.00	6.50	10.60	9.40	2.04	120.00	
	AVERAGE	**6.70**	**27.68**	**9.46**	**15.97**	**8.91**	**11.43**	**9.85**	**1.72**	**127.50**	**155**
MW121											
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Dissolved Oxygen	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(PPM)	(MG/L CaCO3)	(MG/L)
	5206-93		10.70	3.96	20.10	53.30					
	4864-94	**6.40**	**9.56**	**3.72**	**19.50**	**43.50**	**12.00**	**15.00**	**0.36**	**112.00**	**137**
	5452-95	9.90	5.50	2.30	26.00	101.00	9.60	14.50	2.73	151.00	
MW122											
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Dissolved Oxygen	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(PPM)	(MG/L CaCO3)	(MG/L)
	5246-93	6.40	18.65	5.10	22.07	16.06	8.00	5.00	2.08	145.00	
	4868-94	5.70	20.60	6.15	26.10	19.80	8.00	5.00	1.37	150.00	
	5456-95	6.70	22.00	6.60	26.00	21.00	7.30	3.30	3.08	142.00	
	6596-95	6.60	20.10	5.80	22.80		7.10	2.60	1.15	146.00	
	AVERAGE	**6.35**	**20.34**	**5.91**	**24.24**	**18.95**	**7.60**	**3.98**	**1.92**	**145.75**	**178**

PGDP Analyses

McNAIRY GEOCHEMISTRY

MW133

SMPID	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	SO4 (MG/L)	Cl (MG/L)	Dissolved Oxygen (PPM)	Alkalinity (MG/L CaCO3)	Calculated HCO3 (MG/L)
5282-93	6.50	39.30	15.80	22.03	4.03	13.00	31.00	2.97	205.00	
4761-94	**6.30**	**41.10**	**17.30**	**23.20**	**4.57**	**18.00**	**16.00**	**4.39**	**208.00**	**254**
5460-95	6.70	40.40	16.50	24.60	11.10	16.80	13.70	2.81	183.00	

MW140

SMPID	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	SO4 (MG/L)	Cl (MG/L)	Dissolved Oxygen (PPM)	Alkalinity (MG/L CaCO3)	Calculated HCO3 (MG/L)
6004-93	6.50	18.77	6.11	27.98	13.16	17.00	11.00	0.14	130.00	
6088-93	6.60	29.50	6.86	27.60	13.40	15.00	10.00	0.39	164.00	
7081-93	6.40	28.80	6.01	25.70	7.14		13.00	0.41	137.00	
4225-94	6.30	22.80	6.30	26.50	5.28		11.00	1.02	131.00	
5195-94	6.20	15.20	5.97	25.30	7.81		12.00	2.20	120.00	
6050-94	6.10	13.77	6.66	25.83	7.44	12.90	11.00	1.27	112.00	
6864-94	6.30	13.00	6.80	27.00	8.70	12.20	10.90	0.72	111.00	
AVERAGE	**6.34**	**20.26**	**6.39**	**26.56**	**8.99**	**14.28**	**11.27**	**0.88**	**129.29**	**158**

MW239

SMPID	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	SO4 (MG/L)	Cl (MG/L)	Dissolved Oxygen (PPM)
6043-95	5.70	4.90	3.20	17.00	< 10.5	17.20	21.20	0.58
6143-95	5.80	4.70	3.03	18.00	< 10.5	18.10	21.80	0.99
6366-95	5.80	4.19	2.72	15.10	< 10.5	17.80	21.80	5.80
6476-95	5.90	17.80	7.80	24.10		18.60	22.30	1.17
7106-95	6.10	4.55	2.82	15.30	< 10.5	19.70	22.20	0.31
7230-95	5.70	4.07	2.70	15.00	< 10.5	18.90	20.80	0.78
7920-95	5.90	4.21	2.74	15.00		17.80	21.80	0.23
8036-95	6.10	4.56	2.88	15.60		18.30	22.90	0.52
8165-95		5.14	3.25	-16.30		16.90	23.00	0.54
AVERAGE	**5.88**	**6.01**	**3.46**	**16.82**		**18.14**	**21.98**	**1.21**

MW247

SMPID	pH (SU)	Ca (MG/L)	Mg (MG/L)	Na (MG/L)	K (MG/L)	SO4 (MG/L)	Cl (MG/L)	Dissolved Oxygen (PPM)
6075-95	6.10	12.90	5.90	26.70	< 10.5	8.50	7.20	1.70
6175-95	6.20	1.70	0.78	3.30	< 10.5	12.00	8.50	0.27
6508-95	7.30	11.00	5.40	21.10		13.90	8.00	1.84
7138-95	6.20	12.20	5.70	22.00		14.40	8.50	0.82
7262-95	6.20	10.30	4.62	17.20	< 10.5	14.50	8.10	0.40
7393-95	6.30	11.80	5.17	20.90		14.80	8.40	0.23
8068-95	5.90	12.20	5.43	20.60	< 10.5	15.40	9.00	0.36
8197-95	6.10	11.80	5.33	24.60		17.20	8.80	11.50
5242-96		12.30	5.39	21.30	< 10.5			
AVERAGE	**6.29**	**10.69**	**4.86**	**19.74**		**13.84**	**8.31**	**2.14**

PGDP Analyses								
McNAIRY GEOCHEMISTRY								
WELL	Ca	Mg	Na	K	Na + K	SO4	Cl	HCO3
	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)
MW102	0.98	0.57	0.78	0.18	0.97	0.56	0.24	1.93
MW120	1.38	0.78	0.69	0.23	0.92	0.24	0.28	2.55
MW121	0.48	0.31	0.85	1.11	1.96	0.25	0.42	2.24
MW122	1.01	0.49	1.05	0.49	1.54	0.16	0.11	2.92
MW133	2.05	1.42	1.01	0.12	1.13	0.37	0.45	4.16
MW140	1.01	0.53	1.16	0.23	1.39	0.30	0.32	2.59

PGDP Analyses								
McNAIRY GEOCHEMISTRY								
WELL	Ca	Mg	Na	K	Na + K	SO4	Cl	HCO3
	%	%	%	%	%	%	%	%
	Cations	Cations	Cations	Cations	Cations	Anions	Anions	Anions
MW102	0.39	0.23	0.31	0.07	0.38	0.21	0.09	0.71
MW120	0.45	0.25	0.23	0.07	0.30	0.08	0.09	0.83
MW121	0.17	0.11	0.31	0.41	0.71	0.09	0.15	0.77
MW122	0.33	0.16	0.35	0.16	0.51	0.05	0.04	0.92
MW133	0.45	0.31	0.22	0.03	0.24	0.08	0.09	0.83
MW140	0.35	0.18	0.40	0.08	0.47	0.09	0.10	0.81

PGDP Analyses										
RGA GEOCHEMISTRY										
MW103										
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	5178-93	6.1	11.91	3.22	16.20	3.43	9.00	5.00	78.00	
	5944-93	6.1	0.03	0.01	0.32	<2	9.00	7.00	72.00	
	7299-93	5.8	10.90	3.01	13.70	2.59		7.00	69.00	
	4272-94	5.9	12.00	3.33	16.20	3.19		6.00	69.00	
	5187-94	6.0	11.90	3.51	15.20	3.90	9.00	6.00	71.00	
	6026-94	5.9	12.20	3.46	14.70	3.30	7.20	3.40	67.00	
	6774-94	6.1	11.70	3.34	14.40	3.12	6.50	3.90	69.00	
	5440-95	6.0	12.60	3.48	15.70	3.60	6.10	3.50	70.00	
	AVERAGE	**6.0**	**11.89**	**3.34**	**15.16**	**3.30**	**7.56**	**4.97**	**70.43**	**86**
MW71										
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	ALKALINITY	HCO3
	5194-93	5.7	28.60	11.80	48.70	<2	9.00	105.00	99.00	
	4340-94	5.7	33.90	13.40	55.30	<2	8.00	114.00	97.00	
	5432-95	5.8	32.70	14.50	56.80	<2	8.10	112.70	100.00	
	AVERAGE	**5.7**	**31.73**	**13.23**	**53.60**	**2.00**	**8.37**	**110.57**	**98.67**	**120**
MW123										
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	5294-93	6.5	20.08	6.77	32.52	10.16	11.00	33.00	123.00	
	4859-94	6.3	25.20	8.76	32.60	6.36	11.00	34.00	118.00	
	5623-95	6.3	18.00	7.20	43.00		11.00	39.00	104.00	
	6600-95	6.1	27.90	9.10	30.00		11.10	40.20	115.00	
	7471-95	6.2	25.90	7.75	28.60	< 10.5			119.00	
	8289-95	6.1	21.80	8.04	28.50		11.50	39.10	100.00	
	AVERAGE	**6.3**	**23.15**	**7.94**	**32.54**	**8.26**	**11.12**	**37.06**	**113.17**	**138**
MW126										
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	Calculated HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	5050-93	6.7	33.90	9.58	39.50	17.70	15.00	63.00		
	5051-93	6.0	18.90	7.63	39.80	4.72	12.00	44.00		
	5075-93	6.0	17.70	6.84	37.00	3.70	12.00	44.00		
	5082-93	6.2	18.00	7.21	38.80	4.39	12.00	44.00		
	5254-93	6.0	16.96	6.61	37.72	2.79	10.00	42.00	92.00	
	4883-94	6.3	18.10	7.82	43.10	3.64	10.00	41.00	97.00	
	5692-95	6.0	19.00	7.60	43.00		9.60	43.90	86.00	
	6612-95	6.0	16.40	6.80	36.20		9.40	44.20	93.00	
	7479-95	5.9	15.70	6.10	33.40	< 10.5			90.00	
	8093-95	6.2	16.10	6.41	37.30		9.90	43.00	88.00	
	AVERAGE	**6.1**	**17.43**	**7.00**	**38.48**	**3.85**	**10.61**	**43.26**	**91.00**	**111**

PGDP Analyses										
RGA GEOCHEMISTRY										
MW135										Calculated
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	5286-93	6.1	22.55	7.37	30.14	2.85	17.00	15.00	106.00	
	4769-94	6.1	21.70	7.66	32.20	2.55	14.00	31.00	18.00	
	5634-95	6.0	20.80	7.90	35.50		11.10	33.40	88.00	
	6624-95	5.9	19.50	7.85	31.00		11.70	34.60	96.00	
	7483-95	6.1	19.30	7.46	27.10	< 10.5	11.80	33.70	94.00	
	8301-95	5.9	19.30	7.65	31.40	< 10.5	11.40	33.20	93.00	
	AVERAGE	**6.0**	**20.53**	**7.65**	**31.22**	**2.70**	**12.83**	**30.15**	**82.50**	**101**
MW141										Calculated
	SMPID	pH	Ca	Mg	Na	K	SO4	Cl	Alkalinity	HCO3
		(SU)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)	(MG/L)
	6080-93	6.2	20.70	9.67	31.84	3.30	10.00	38.00	104.00	
	6092-93	6.2	22.10	10.40	27.50	4.25	8.00	40.00	93.00	
	7085-93	6.0	20.00	9.60	26.60	< 2		39.00	91.00	
	4229-94	6.0	22.30	10.60	31.50	< 2		39.00	92.00	
	5199-94	6.1	21.40	9.80	28.30	2.09		40.00	88.00	
	6054-94	6.1	23.27	10.73	30.56	2.13	9.30	42.90	90.00	
	6868-94	6.1	23.00	11.00	31.00	2.30	9.00	42.40	90.00	
	AVERAGE	**6.1**	**21.82**	**10.26**	**29.61**	**2.81**	**9.08**	**40.19**	**92.57**	**113**

PGDP Analyses

RGA GEOCHEMISTRY

WELL	Ca	Mg	Na	K	Na + K	SO4	Cl	HCO3
	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)	(MEQ/L)
MW71	1.58	1.09	2.33	0.05	2.38	0.17	3.12	1.97
MW103	0.59	0.27	0.66	0.08	0.74	0.16	0.14	1.41
MW123	1.16	0.65	1.42	0.21	1.63	0.23	1.05	2.26
MW126	0.87	0.58	1.67	0.10	1.77	0.22	1.22	1.82
MW135	1.02	0.63	1.36	0.07	1.43	0.27	0.85	1.65
MW141	1.09	0.84	1.29	0.07	1.36	0.19	1.13	1.85

PGDP Analyses

RGA GEOCHEMISTRY

WELL	Ca	Mg	Na	K	Na + K	SO4	Cl	HCO3
	%	%	%	%	%	%	%	%
	Cations	Cations	Cations	Cations	Cations	Anions	Anions	Anions
MW71	0.31	0.22	0.46	0.01	0.47	0.03	0.59	0.37
MW103	0.37	0.17	0.41	0.05	0.46	0.09	0.08	0.83
MW123	0.34	0.19	0.41	0.06	0.47	0.07	0.30	0.64
MW126	0.27	0.18	0.52	0.03	0.55	0.07	0.37	0.56
MW135	0.33	0.20	0.44	0.02	0.46	0.10	0.31	0.60
MW141	0.33	0.26	0.39	0.02	0.41	0.06	0.36	0.58

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