40-8102

EXXON MINERALS COMPANY

POST OFFICE BOX 2180 · HOUSTON, TEXAS 77001

Environmental and Regulatory Affairs
JAMES E. GILCHRIST - Manager

SF

February 24, 1982

Docket No. 40-8102
Tailings Basin Seepage Study for
Exxon's Highland Uranium Operations

RECEIVED
MAR 1 0 1982
U.S. Nuclear Regulatory Commission
WMUR
Mail Section

U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Attention: Mr. H. J. Pettengill, Section Leader,
Operating Facilities, Section II,
Uranium Recovery Licensing Branch

Gentlemen:

In accordance with license condition number 34 of renewed (February 10, 1982) Source Material License No. SUA-1139, enclosed are four copies of the "Highland Uranium Tailings Impoundment Seepage Study" report performed on the Highland Uranium Operations tailings basin. The seepage study was undertaken by Exxon in order to adequately respond to NRC questions relating to the impact of the tailings basin on the surrounding environment; these questions were initially put forth in your letter of June 18, 1980 (reference number 1--questions number 7, 8, and 9, see attachment), and referred to in the subsequent references in the attachment. These remaining questions are adequately answered in the enclosed report, and the study indicates that there is no significant impact on the environment due to continued operation of the Highland mill and its associated tailings basin.

The seepage study was initially contracted to Dames & Moore (see reference number 3) in July, 1980. However, we terminated our contract for this study with Dames & Moore, and reassigned it to Exxon Production Research Company (EPR) early in 1981. Exxon Production Research Company is an affiliate of Exxon Corporation with responsibility for research, development, and engineering studies relating to discovery and production of petroleum, oil shale, coal, and other minerals. The Company performs research application work for the operating affiliates of Exxon Corporation worldwide covering exploration (geology, geophysics, geochemistry), drilling, mining, production, pipelining, offshore operations, reservoir analysis, and arctic development. The EPR research center currently employs approximately 1,400 people.

20239

After you have reviewed this report and formulated questions Exxon (EPR and Highland staff members) will be available to come to your offices to make a presentation and answer your questions at a time convenient to all parties involved.

During the course of the study additional wells were drilled in order to obtain reliable and/or additional data. In light of this, along with the results of the seepage study, we are currently re-evaluating our groundwater monitoring program to determine which wells should be used and whether or not any additional wells are needed. We will submit our revised groundwater sampling system to you by June 1, 1982.

If you have questions concerning this matter, or wish to make arrangements for a presentation by Exxon, please contact Mr. H. Paul Estey (telephone number 713-895-1171) of my staff.

Sincerely,

James P. Gilbert

JEG:HPE:ms
Attachment (As Noted)
Enclosures (As Noted)

Attachment - References

1) June 18, 1980 letter from U. S. NRC (J. J. Linehan) to EMC (G. D. Ortloff).

2) July 3, 1980 letter from EMC (G. D. Ortloff) to U. S. NRC (J. J. Linehan).

3) September 8, 1980 letter from EMC (G. D. Ortloff) to U. S. NRC (J. J. Linehan).

4) October 16, 1980 letter from U. S. NRC (J. J. Linehan) to EMC (G. D. Ortloff).

5) November 10, 1980 letter from EMC (G. D. Ortloff) to U. S. NRC (J. J. Linehan).

EXXON PRODUCTION RESEARCH COMPANY
POST OFFICE BOX 2189 · HOUSTON, TEXAS 77001

MINING AND SYNTHETIC FUELS DIVISION

C.H. HEWITT
MANAGER

February 10, 1982

Mr. G.L. Wilhelm
Manager, U.S. Operations
Exxon Minerals Company
P.O. Box 3020
Casper, WY 82602

Attention: Mr. Steve Morzenti

Dear Sir:

Attached is a copy of research application report EPR 5ES.82 entitled "Highland Uranium Tailings Impoundment Seepage Study". This report addresses questions posed by the Nuclear Regulatory Commission regarding the amount and direction of seepage from the Highland Uranium tailings impoundment, the adequacy of the water-quality monitoring system near the impoundment, and seepage into North Fork Box Creek.

Seepage from the impoundment increases at a rate of about 19 gpm (gallons per minute) per year after 1975, and reaches a maximum rate of about 200 gpm in 1983. The mill is then shut down and, as the pond dries, seepage decreases at about 38 gpm per year. Seepage ceases in 1991 after all the water in the pond and tailings has either evaporated or drained into underlying formations.

Maximum lateral movement of the seepage front will occur west of the pond, reaching the northern edge of Pit 2 about the year 1992. The seepage front will move a maximum of 1300 feet southwest and 300 feet northwest of the impoundment. Migration of the acidic front is greatly attenuated. It only moves a maximum of about 500 feet from the pond.

Vertical migration of the seepage front and acidic front is limited. The seepage front will move vertically through the Tailings Dam and Upper Ore Body Sands, but will not enter the Middle Ore Body Sand. The acidic front will not migrate below the Tailings Dam Shale.

The existing water-quality monitoring system is adequate for detecting solute excursions from the impoundment. It is recommended that the results of this study continue to be compared to field data. The installation of three new water-quality monitoring wells would enhance the comparisons. Two wells, one completed in the Tailings Dam Sand and one completed in the Upper Ore Body Sand, should be located 1,500 feet south of Well XII. A third monitoring well should be completed in the Tailings Dam Sand about 2,000 feet northwest of Well IX.

Ground-water seepage into North Fork Box Creek was calculated to be about 25 gpm before the tailings impoundment was operational. Total seepage downstream of the dam is not expected to exceed 40 gpm anytime during pond operation.

We welcome any questions or comments you may have concerning this report.

Sincerely,

C. H. Hewitt

by H. Rodger Melton
H. R. Melton

HRM/smb

Exxon Production Research Company

Highland Uranium Tailings Impoundment Seepage Study

PROJECT COORDINATION: G. G. PETERS

LABORATORY PROGRAM: G. B. DREHER
E. M. SCHRAMM
R. E. KLIMENTIDIS
M. J. KLOSTERMAN
J. R. McGEE

GEOLOGIC MODELING: D. E. HAMILTON

FLOW MODELING: G. G. PETERS
T. J. CANNON
R. J. MITRO
E. M. SCHRAMM
D. E. TANG

FIELD PROGRAM: S. P. MORZENTI
G. L. ADAMS
G. M. GIBBS
C. A. KUHARIC

CORE ANALYSES: R. C. SOMMER
W. W. HARRIS

Mining and Synthetic Fuels Division
EPR.5ES.82
February 1982

The research information contained herein is FOR COMPANY USE ONLY. Address any correspondence concerning this report to Technical Information—Reports Room, Exxon Production Research Company, P. O. Box 2189, Houston, Texas 77001.

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ABSTRACT

This study addresses questions posed by the Nuclear Regulatory Commission regarding the amount and direction of seepage from the Highland Uranium tailings impoundment, the adequacy of the water quality monitoring system near the impoundment, and seepage into North Fork Box Creek.

The study consisted of three main endeavors: (1) a laboratory program to quantify the chemical interactions between the pond liquor and geologic strata underlying the impoundment, (2) a geologic modeling program to describe the structure and lithology of Highland, and (3) a solute transport modeling program to predict pond seepage and migration of solutes.

The laboratory program included batch (static) tests between tailings solution and rock samples, titration of tailings solution by calcium hydroxide solution to given pH levels, and a column flooding experiment of Tailings Dam Sand by tailings solution to determine the acid neutralization capacity of the sand. Mineralogical analyses were also performed to help characterize the sands and shales.

Geologic models of the Highland area were developed using Exxon Production Research Company's computer programs for two- and three-dimensional geologic mapping and modeling. The two-dimensional mapping program was used to construct geologic surfaces and to build those surfaces into a stratigraphic framework. The three-dimensional modeling program was used to interpolate measured resistivity values and relate those values to lithology.

A finite-difference solute transport model developed by Exxon Production Research Company was used to simulate seepage and solute movement through geologic strata underlying the tailings pond. Three cross-sectional models and one areal model were constructed and simulations were performed to predict the position of the seepage front and the position of each solute front to the year 2000. The model results for unattenuated solute movement and acid front movement were compared to water-quality data from monitoring wells.

The study showed very limited solute migration occurs from the tailings impoundment.

1.0. EXECUTIVE SUMMARY

1.1. GENERAL

This study was performed at the request of Exxon Minerals Company. The purpose of the study was to predict seepage and solute migration from the Highland Uranium Mill tailings impoundment in Converse County, Wyoming. The study results were used to address questions posed by the Nuclear Regulatory Commission regarding the amount and direction of seepage from the impoundment, the adequacy of the water-quality monitoring system near the impoundment, and seepage into North Fork Box Creek. The impoundment has been in continuous operation since October, 1972. It will become inactive following mill shutdown which is scheduled for December 1983.

The study consisted of three main endeavors: (1) a laboratory program to quantify the chemical interactions between the pond liquor and geologic strata underlying the impoundment, (2) a geologic modeling program to describe the structure and lithology of Highland, and (3) a solute transport modeling program to predict pond seepage and migration of solutes.

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A finite-difference solute transport model developed by Exxon Production Research Company was used to simulate seepage and solute movement through geologic strata underlying the tailings pond. Three cross-sectional models and one areal model were constructed and simulations were performed to predict the position of the seepage front and the position of each solute front to the year 2000. The model results for unattenuated solute movement and acid front movement were compared to water-quality data from monitoring wells.

The approach taken in this study to model solute movement has the following advantages:

1. Chemical attenuation is based on data obtained by actually contacting the pond liquor with aquifer rock.

2. The chemical attenuation experiments are linked directly to the flow calculations by means of the relative velocites.

3. A wide range of relative velocity fronts are tracked which provides the flexibility to track any solute front for which batch test data is available.

4. Flow is calculated using a finite-difference simulator, which has the capability to model two fluid phases, nonhomogeneous porous media, and transient boundary conditions.

As will be discussed in the body of the report, the study approach also has the following limitations:

1. Hydrodynamic dispersion is not calculated.

2. A simplified model (apparent distribution coefficient model) is used to account for the complex chemical reactions occurring between the pond liquor and the aquifer rock.

3. Radioactive decay and the generation of daughter products is only qualitatively considered.

4. The solution mine pilot is not modeled.

1.2. CONCLUSIONS

This section summarizes the principal findings of this study. The following subsections discuss a comparison of the model results to field data, pond seepage rates, lateral and vertical movement of seepage and acidic fronts, predicted movement of specific solutes, and seepage into North Fork Box Creek.

1.2.1. Comparison of Model Results to Field Data

To evaluate the accuracy of this study, areal model predictions of the seepage and acidic front positions were compared to field data. The seepage front was tracked by measuring calcium, magnesium, and chloride concentrations in monitoring wells. These solutes do not appear to react with any of the geologic units underlying the tailings impoundment and should move as fast as the seepage front. The acidic front was tracked using pH measurements.

The position of the seepage front predicted by the areal model is in good agreement with monitor well data north and south of the pond. East of the pond, where fluid seeps into North Fork Box Creek along the outcrop area, solute migration is sometimes underestimated due to the finite-difference gridding (discretization) of the areal model. Tracer concentrations in wells west of the pond indicate that the seepage front has traveled about 1300 feet further west than predicted. The presence of these solutes may be caused by high permeability streaks or vertical leakage near the tailings discharge spigot.

The predicted position of the acidic front is in good agreement with monitor well data north, west, and east of the pond. South of the pond the model appears to slightly overpredict acidic front migration.

1.2.2. Pond Seepage

Total seepage from the tailings impoundment rises to about 100 gpm (gallons per minute) within a year after the pond is put into operation. By 1974 seepage begins to decrease due to the buildup of low permeability tailings and reaches 50 gpm about 1975. Seepage then begins to increase as the water level rises and the cone of depression from surface mining lowers the water potential under the pond. The seepage rate increases at about 19 gpm per year until the maximum water level in the pond is obtained in 1983. The mill is then shut down and, as the pond dries, seepage decreases at about 38 gpm per year. Seepage ceases in 1991 after all the water in the pond and tailings has either evaporated or drained into underlying formations.

1.2.3. Predicted Lateral Movement of Seepage and Acidic Fronts

Maximum movement of the seepage front will occur west of the pond, reaching the northern edge of Pit 2 about the year 1992. The seepage front will move a maximum of 1300 feet southwest and 300 feet northwest of the pond. Migration of the acidic front is greatly attenuated. It only moves about 500 feet from the pond.

1.2.4. Predicted Vertical Movement of Seepage and Acidic Fronts

Vertical movement of the seepage and acidic fronts is limited. The seepage front will move vertically through the Tailings Dam and Upper Ore Body Sands, but will not enter the Middle Ore Body Sand. The acidic front will not migrate below the Tailings Dam Shale.

1.2.5. Solute Migration

The following 18 regulated solutes were considered in this study: Al, As, Cd, Cr, Cu, Fe, H (pH), Mn, Ni, Se, Th (total), U (total), Zn, SO_4^{-2}, Pb-210, Ra-226, Th-230, and U-238. The following paragraphs discuss their movement.

The radioactive solutes studied are U (total), Th (total), Pb-210, Ra-226, U-238, and Th-230. All of these substances are strongly attenuated by the Tailings Dam Sand and Shale. Vertical migration will not extend below the Tailings Dam Shale. Maximum horizontal movement is estimated to be less than 100 feet from the pond.

The concentrations of As, Cd, Mn, Ni, and Zn in the pond liquor exceed regulatory limits in acidic solutions, but not in basic solutions. Therefore, migration of the acidic front is an important factor in determining where these solutes exceed regulatory standards.

The acidic front moves vertically to near the bottom of the Tailings Dam Shale but stops short of entering the Upper Ore Body Sand. Maximum horizontal movement occurs west and southwest of the pond with maximum excursions of about 800 feet. The concentrations of Cd, Mn, and Zn are controlled by pH. Their concentrations in the acidic zone are expected to be approximately the same as they are in the tailings pond. Those concentrations are 30 ppm, 45 ppm, and 3.2 ppm for Cd, Mn, and Zn, respectively.

Nickel is attenuated by the Tailings Dam Shale but not by any of the other formations. It is anticipated that Ni will move areally through the Tailings Dam Sand the same as Cd, Mn, and Zn, but will not penetrate vertically into the Tailings Dam Shale. The concentration of Ni behind the acidic front should be about 1.4 ppm.

Arsenic is strongly attenuated by all geologic units considered in this study. It will not move below the Tailings Dam Shale and maximum horizontal migration will be about 175 feet to the west and southwest.

Aluminum, Cr, Cu, Fe, and Se exceed the most stringent regulatory limits in both acidic and basic solutions. Chromium, Fe, and Se are very strongly attenuated by both the sands and shales. Essentially no vertical or horizontal solute migration is expected. Copper, which is less strongly attenuated by the geologic materials, is not expected to migrate below the Tailings Dam Shale, and maximum horizontal movement will be less than 600 feet to the west. Aluminum was not attenuated by the Tailings Dam or Ore Body Sands. However, it was strongly attenuated by the Tailings Dam and Ore Body Shales. A very conservative estimate of Al migration indicates maximum horizontal movement of about 1200 feet southwest of the pond.

1.2.6. Seepage into North Fork Box Creek

Seepage into North Fork Box Creek was calculated by the areal model. The results showed ground-water seepage downstream of the dam to be about 25 gpm before the tailings pond was operational. During the first few years of pond operation, seepage increased from 25 to 33 gpm as a result of seepage through the area where the Tailings Dam Sand was in direct contact with the pond bottom. As the buildup of tailings on the contact area reduced the effective vertical permeability of the Tailings Dam Sand, and the surface mine intercepted regional flow, seepage downstream of the dam

decreased to less than 20 gpm. Seepage increases from 20 gpm to 40 gpm as the water level in the pond increases between 1977 and 1983. After 1983, seepage decreases as the pond dries and the tailings drain, reaching a minimum value of about 7 gpm. About 1993 the seepage begins to increase as regional flow is re-established.

Maximum westward solute migration occurs about the year 1992. By 1995 regional flow has been re-established and the solutes are swept eastward towards North Fork Box Creek at a velocity of about 35 feet per year. The pH beneath the pond will rise as regional ground water reinvades the strata underlying the pond. The rise in pH will precipitate many solutes from solution. The concentration of some solutes will also decrease due to continued adsorption onto the aquifer rocks.

Solutes that remain in solution will eventually be discharged into North Fork Box Creek. The discharged solutes may; (1) move slowly downstream towards Box Creek, (2) be left behind as solids due to evaporation along the seepage face, or (3) seep downward into outcropping sands and shales.

1.3. RECOMMENDATIONS

It is recommended that the predictions made by the areal model continue to be compared to field data. To enhance the comparisons, three new water-quality monitoring wells should be installed. Two wells, one completed in the Tailings Dam Sand and one completed in the Upper Ore Body Sand, should be located 1,500 feet south of Well XII. These wells will be beyond the maximum extent of the seepage front predicted by the areal model. Background concentrations of the tracer solutes (Ca, Mg, and Cl) in these wells will help verify that the areal model predicted maximum solute migration.

A third monitoring well should be completed in the Tailings Dam Sand about 2,000 feet northwest of Well IX. This well, which will also be beyond the maximum extent of the predicted seepage front, will help determine whether pond-level concentrations of solutes detected in Wells IX and X result from tailings being discharged west of the pond or from high premeability streaks.

No additional modeling studies are recommended. The close agreement between the areal model predictions and monitor well data indicate that the chemical transport model adequately described solute movement.

Solute movement into North Fork Box Creek should be evaluated using the modeling results in conjunction with surface and ground-water monitoring data. However, it is unlikely that solute migration from the pond will have a significant impact on North Fork Box Creek.

2.0. INTRODUCTION

The objective of this study was to simulate historic and future seepage and solute transport from the Highland uranium mine tailings impoundment. The study results were used to address questions posed by the Nuclear Regulatory Commission regarding the amount and direction of seepage from the impoundment, the adequacy of the water-quality monitoring system near the impoundment, and seepage into North Fork Box Creek. To conduct this study, familiarity with the facility operations (mine, mill, and tailings impoundment), regional and local geology, and the hydrologic setting was essential. The remainder of the introduction will give an overview of each of these topics.

2.1. FACILITY OPERATIONS

In 1968, Exxon Minerals Company (then the Minerals Department of Humble Oil and Refining Company) discovered a significant uranium deposit in Converse County, 35 miles north of Douglas, Wyoming. The site of this discovery became known as Exxon's Highland property. Recovery of uranium ore at Highland has primarily been by surface and underground mining. Some uranium has also been recovered by a pilot solution mine.

The surface mine was the first mine to be developed on the Highland property. Overburden removal (stripping) began in September, 1970 with the first ore being recovered in October, 1972. The surface mine has been in operation continually since 1970 and is scheduled for shutdown in December, 1983.

In 1973, sinking of the Buffalo Shaft for access to underground mining began. In 1976, the lateral development of two levels was initiated. The track drift, located at a depth of 600 feet, was used for rail haulage and water control. Trackless development in ore occurred at a depth of 550 feet. Ore production commenced at the underground mine in 1977 and was continued until shutdown in January, 1982 (Moe, 1979).

An in situ solution mine pilot was initiated in 1972 and expanded in 1979. The solution mine had relatively little effect on the hydrologic system compared to the surface and underground mining operations, and therefore was not considered in the study.

Highland's uranium mill uses a conventional acid leach-solvent extraction process based on metallurgical technology widely accepted and practiced in the uranium industry. The mill began production of yellowcake in October 1972, processing ore at a rate of 2,200 tons per day. In 1974, the milling capacity was increased to 3,000 tons per day. The mill is scheduled for shutdown in December, 1983, when the surface mining operation is completed.

The primary waste from the mill is called "tailings" which consist of leached solids and liquid wastes. The tailings solids are composed mainly of the sand, silt and clay particles which originally formed the ore rock. Since uranium constitutes a small fraction of the ore, the amount of tailings solids generated by the mill is nearly equal to the amount of ore processed. The tailings at Highland are acidic with a pH value of about 2.

A typical method of tailings disposal has been to slurry them into a natural depression which has been dammed at one end. At Highland, an erosional feature called North Fork Box Creek is used to store the tailings. This facility is commonly referred to as the "Highland Uranium Tailings Pond".

Once tailings are discharged to the pond the solid material sinks to the bottom relatively quickly. Some particle size segregation occurs because the fine-grained materials (slimes) are carried further from the discharge spigots than the sand-sized materials (sands). To conserve water and reduce the water level in the pond, some of the pond liquid (liquor) is decanted and reused for mill process water. In addition to mill tailings, the pond is used to store water from the mine dewatering wells, mine seepage, and solution mine wastes.

When the mill closes in December of 1983, reclamation of the tailings pond will begin. The first reclamation objective will be to enhance evaporation of the pond liquor. This will be accomplished by sprinklers within the pond area. Final reclamation of the pond will begin when the tailings have been dried sufficiently to support earth-moving equipment.

2.2. GEOLOGIC SETTING

The geology of the Powder River Basin is described by Langen and Kidwell (1970):

2.2.1. Physical Setting

"The Powder River Basin includes an area of some 12,000 square miles in northeastern Wyoming (Figures 1 and 2). It is a broad basin both structurally and topographically, which is bounded on the west by the Big Horn Mountains and Casper Arch, on the south by the Laramie Mountains and Hartville Uplift, and on the east by the Black Hills and less structural features. To the north, it passes into Montana where it gradually terminates.

"The terrain near Highland is typical of the Powder River Basin as a whole. Topographically, the region has moderate relief consisting of sagebrush cover, rolling hills between flattopped highlands, and wide gentle drainages. Elevations generally range from about 4,500 to 5,500 feet, with the exception of the Pumpkin Buttes which rise to an elevation of 6,000 feet in the central part of the basin.

"Drainage in the western and northern parts of the basin is northward through the Powder River and its tributaries and is essentially along the structual basinal axis. In the southern part of the basin drainage is to the east, normal to the structure, and by way of the Cheyenne River and its tributaries. The Highland deposit is located on the north side of eastward flowing Box Creek, which is a tributary of Lance Creek."

2.2.2. Regional Geology

"The Powder River Basin is an asymmetric syncline with the axis displaced several miles west of the basin center. Also, the trace of the basin axis on the Precambrian basement lies to the east of the axis in the surface rocks. The Highland deposit is approximately parallel to the surface axis and about two miles east of it.

"Dips are generally less than 3 degrees on the east side of the basin but become steep on the southwest and west sides near the basin margin. Local small-scale faulting has been recognized in the mineralized areas near Pumpkin Buttes, Monument Hill, and Box Creek, but no widespread extensive faulting is known to occur. The mountain axes and major folds of Wyoming started to develop late in the Cretaceous and were well defined by the Paleocene."

2.2.3. Local Geology

The Highland uranium mine and associated tailings impoundment are located in the southern Powder River Basin, Converse County, Wyoming. The Highland operation is contained in sections 17, 19, 20, 21, 22, 27, 28, 29, and 30 of T36N., R72W., and sections 23 and 24 of T36N., R73W. as illustrated in Figure 3. The geologic sequence of the Powder River Basin is shown in Figure 4. The rock units of interest in this area lie in the upper Fort Union Formation. They are composed of interbedded fine-to-coarse grained sandstone, siltstone, claystone and lignite. The streams which deposited this material flowed northward into the basin and derived sediment from Mesozoic, Paleozoic, and Precambrian rocks of the Laramie and Granite mountains and from wind-blown volcanic debris of the Absarokas to the west.

The Highland ore sands are, for this study, referred to as the Upper, Middle and Lower Ore Body Sands. These sands are laterally continuous in the area of the tailings pond and mine pits but break up or "shale out" to the north and east. Each ore sand has been interpreted to represent the migration of a large individual point bar system across the meander belt. A neck cutoff then returned the river to the center of the basin where the process was repeated. The three ore sands are separated by several feet of siltstones, claystones and lignites deposited in upper point bar, natural levee, and flood plain environments. In places this separating material has been removed due to channel scour and the ore sands are in vertical contact.

The most consistent rock stratum encountered at Highland is located directly above the Upper Ore Body Sand at an elevation of approximately 5,120 feet near the tailings dam. This stratum is a shale and is referred to at Highland as the "Tailings Dam Shale". It outcrops in the valley floor at and downstream of the dam. This shale was reported to be in all borings that extended down to at least this elevation. As illustrated in Figures 5 through 9, the Tailings Dam Shale member is continuous throughout the area except where it has been eroded in the creek bottom.

The first major sand immediately above the ore sands is referred to as the "Tailings Dam Sand". This sand was probably deposited by the same mechanism that deposited the Ore Body Sands. However, the Tailings Dam Shale, which separates the Tailings Dam Sand from the Upper Ore Sand, is more laterally continuous than the material separating the individual ore sands. Channel scour has not connected the Tailings Dam Sand and Upper Ore Sands in the study area.

Several other sand bodies lie above and below the four sands just described but are of little importance to the present study. Directly above the Tailings Dam Sand are several small discontinuous sands of the Fort Union Formation, and higher in the section is a major sand of the Wasatch Formation which is called the Fowler Sand at the Highland mine. Below the Lower Ore Sand are two sand units both of which are less continuous than the ore sands.

2.3. HYDROLOGIC SETTING

2.3.1. Climate

The Highland property is in an area which has a semi-arid and cool climate. Total precipitation averages about 12 inches per year with snowfall ranging between 35 and 65 inches per year. Average summer temperatures are in the high 60's and low 70's and average winter temperatures are in the mid 20's. Extreme temperatures may exceed 100° in the summer and -40° in the winter. The average growing season is approximately 120 days. The prevailing winds are estimated to be from the southwest about 24 percent of the time with an average wind speed of about 13-14 miles per hour. The average evaporation rate is about 48 inches per year.

2.3.2. Recharge and Discharge

Recharge and discharge studies of natural hydrologic systems are commonly based on a model proposed by Hubbert (1940) in which topographically high areas are "recharge zones" and low areas are "discharge zones". Water level data from the Highland area and regional studies by Hagmaier (1971) indicate Hubbert's model is valid in the Powder River Basin. Toth (1963) expanded Hubbert's model by superimposing local, intermediate, and regional flow systems to better account for the effects of topographic changes. The three types of flow systems are dif-

ferentiated by the lengths of the ground-water flow paths. Local systems have flow paths ranging in length from a few thousand feet to several thousand feet, intermediate systems range from several thousand feet to several miles, and regional systems range from several miles to several tens of miles. Figure 10 illustrates the superposition of these three types of flow systems.

Regional flow through the upper Cretaceous Parkman Sandstone is shown in Figure 11. Although the Parkman Sandstone underlies the Fort Union Formation, it is likely that regional flow directions would be similar in overlying formations. Note that regional flow is to the northeast in the Highland area.

Intermediate flow in the Highland vicinity is from Blizzard Heights to the North Fork Box Creek area as shown on Figure 12. Blizzard Heights is a topographically high area about 5,600 feet above mean sea level and located about nine miles west of the tailings pond. North Fork Box Creek is directly east of the tailings pond (the upper reach of North Fork Box Creek was dammed to form the tailings pond) and is at approximately 5,150 feet. Figure 12 shows a generalized flow net construction between Blizzard Heights and North Fork Box Creek which represents premining ground-water flow.

It is assumed that the potentiometric levels in the Tailing Dam Sandstone, Ore Body Sandstones, and interspaced shale layers were equal in the predevelopment flow system. The flow net is in reasonable agreement with premining potentiometric water levels reported by Hagmaier (1971) and Dames and Moore (1972). In a semi-arid region like Highland, it would be expected that the potentiometric surface would be a significant distance below the elevation of the recharge area and very close to the elevation of the discharge area. The flow net is consistent with this expectation. It predicts the potentiometric surface to be 150 feet below the elevation of Blizzard Heights. Also, it shows the water table at the discharge area to be at nearly the same elevation as the ground surface (average elevation of about 5,050 to 5,100 feet).

There may be a local flow system between Highland Flats and North Fork Box Creek (see Figure 12). Highland Flats is about two and a half miles north of the tailings pond at an elevation of about 5,400 feet. However, the close proximity of Highland Flats to the 5,100 foot topographic contour to the east and Gumbo Draw to the southeast indicates that it would have little if any effect on the intermediate flow system.

2.3.3. Infiltration

The stratified nature of the sediments near the Highland Mine complicates the estimation of infiltration. The most expedient and accurate method of estimating infiltration at Highland is to use a numerical model. By modeling assumed (and physically reasonable) ground-water recharge and discharge rates it should be possible to reproduce potentiometric data measured in the field. This exercise was undertaken by Dames and Moore (1980a) in the local recharge system between

Highland Flats and the Highland mine - North Fork Box Creek area. They reported infiltration rates of 0.8 inches per year in the Highland Flats area above elevations of 5,400 feet and 0.4 inches per year elsewhere. Since the climate does not change within the intermediate flow system, and the geologic materials have similiar characteristics, the infiltration rates cited by Dames and Moore should be applicable between Blizzard Heights and North Fork Box Creek.

2.3.4. **Field Program**

An extensive field program was conducted by Exxon Minerals Company at Highland. The program was aimed at obtaining geologic and hydrologic site descriptions and water-quality data.

The geologic program consisted of core analysis, geophysical logging, and geologic interpretation of the area. The hydrologic program was designed to obtain hydraulic properities of the aquifiers and an understanding of regional ground-water flow. Hydraulic properties were obtained by pump testing, packer testing, and core analyses. The regional flow was determined by measuring water levels in observation wells.

The water-quality monitoring program consisted of a network of monitoring wells from which water samples were obtained, analyzed, and correlated.

A complete description of the field program is given in Appendix C.

3.0. GENERAL APPROACH

The complexities of solute interaction with geologic formations and the difficulties associated with describing ground-water flow in hydrologic systems precludes exact analysis of solute transport. However, by exercising judgment and using simplified models of complex physical systems, reasonable estimates of solute movement can be obtained. When available, field data is used to check the accuracy of the model results.

This chapter provides an overview of the mechanisms affecting solute transport at Highland and describes the methods and approximations used in this study.

3.1. MECHANISMS AFFECTING SOLUTE MOVEMENT AT HIGHLAND

There are three contaminant transport mechanisms that will affect the movement of solutes at Highland. These mechanisms are advection, hydrodynamic dispersion, and chemical and biochemical attenuation.

Advection (sometimes called convection) is the mechanism by which solutes are moved through the porous media by flowing ground water. The rate of movement of solutes by advection is equal to the average linear ground-water velocity. To determine solute movement by advection, the flow regime must be known. Analytical solutions are available for very simple flow situations. However, when attempting to calculate flow in a complex geologic environment, like Highland, numerical (finite difference or finite element) methods must be employed. A general purpose finite-difference reservoir simulator developed by Exxon Production Research Company was used in this study. The simulator has the capability to solve one-, two-, or three-dimensional flow for one, two, or three fluid phases. In this analysis it was used in a two-dimensional, two phase mode.

Hydrodynamic dispersion is the phenomenon which causes a spreading of the contaminant front. Hydrodynamic dispersion is caused by both dynamic dispersivity and molecular diffusion. Dynamic dispersivity is a result of small-scale heterogeneities in the porous media which cause some ground water to move faster and some slower than the average linear velocity. Molecular diffusion is the result of collisions between molecules and may be an important mode of solute transport in low-velocity flow regimes frequently associated with low-permeability materials. Commonly, a measure of both the dynamic dispersivity and molecular diffusion is incorporated in a parameter called the coefficient of hydrodynamic dispersion or the effective dispersion coefficient.

Although many contaminant transport studies consider hydrodynamic dispersion, there is frequently a fundamental flaw in their calculations. That flaw is well stated by Anderson (1979):

"It is well known that the magnitude of the measured dispersivity changes, depending on the scale to which the measurements are taken. Laboratory experiments designed to measure dispersivity yield values in the range of 10^{-2} to 1 centimeter, while dispersivities of 10 to 100 meters have been obtained for field problems."

In other words, the dispersion coefficient depends on the flow path length. Modeling studies are often conducted using a dispersion coefficient that was obtained for some arbitrary flow length, and has no real signficance for the situation being analyzed.

The approach taken in this study was to postpone the calculation of hydrodynamic dispersion and first consider advection and attenuation mechanisms. Had the results of this study indicated that dispersion was important, it would have been incorporated into later modeling studies. The advantage of this strategy is that after analyzing the flow, we had a knowledge of the pertinent flow path lengths and, if required, could have designed dispersion coefficient field tests accordingly. The results of the flow analysis, which are described in Chapter 6, indicate that modeling hydrodynamic dispersion was not necessary because solute movements from the pond was areally restricted.

There are six major categories of chemical and biochemical reactions that can alter solute concentrations in ground water, namely adsorption-desorption reactions (including ion exchange), acid-base reactions, solution-precipitation reactions, oxidation-reduction reactions, ion pairing or complexation, and microbial cell synthesis. The large number of possible reactions combined with the myriad of chemical constituents found in waste ponds and natural ground water can make the chemical analysis of contaminant transport problems extremely difficult.

To circumvent such difficulties, a relatively simple laboratory test is frequently employed. The test measures the chemical reactions taking place between the solutes and the aquifer rock. The test is conducted by equlibrating known quantities of liquid (pond liquor) with aquifer rock and measuring the concentration of each solute in the pond liquor before and after contact with the rock. It is assumed that any solute concentration reduction in the pond liquor was caused by the solute adsorbing onto the aquifer rock and any solute concentration increase was caused by the solute desorbing from the aquifer rock. The results of such an experiment are commonly expressed as an apparent distribution coefficient which is the ratio of the mass of a solute on the rock to the mass of a solute in the liquid. Distribution coefficients, together with the bulk density and porosity of the aquifer rock, are used to calculate the velocity of a specific solute concentration front relative to the average linear velocity of the fluid leaving the tailings pond. Therefore, the chemical attenuation and advection components of solute movement can be calculated once the apparent distribution coefficients and the flow field (and hence, the fluid velocity field) in the vicinity of the pond are known.

Finally, one additional attenuation mechanism is radioactive decay. One must be concerned with possible concentration reductions of radioactive solutes originally in the pond liquor and the generation and subsequent decay of daughter products.

The radioactive constituents of interest in this study are uranium-238, thorium-230, radium-226, lead-210, and polonium-210. Uranium-238, radium-226, and thorium-230 have half-lives of 4.5 billion years, 80,000 years, and 1622 years respectively. Since these half-lives are long compared to the length of the study, radioactive decay will not affect the concentration of these isotopes and they are treated in the same manner as stable elements.

Lead-210 has a half-life of 22 years and is a daughter product of radium-226. Lead-210 decays to a series of short-lived (fraction of a second to days) daughter products and eventually forms polonium-210 which has a half-life of 138.4 days. Over the simulation period the concentrations of lead-210 and polonium-210 will not change, since they are in secular equilibrium with the uranium series. The daughter product of polonium-210 is lead-206, which is stable. Its concentration will increase as the polonium-210 decays. Figure 13 illustrates the uranium--238 radioactive series.

3.2. STUDY APPROACH

Having briefly described the important contaminant transport mechanisms considered for Highland, the following text describes the calculation procedure used to quantify solute movement.

The basis of the solute movement calculations will be the flow calculations performed by the finite-difference reservoir simulator. In addition to calculating flow rates, the simulator uses a point tracking scheme to account for solute movement.

Point tracking is a method which uses calculated flow rates and water saturations to simulate the movement of mathematical points through an aquifer. By defining a line of these points along the bottom of the seepage pond at the beginning of a simulation, the position of the mean relative concentration (one-half the pond concentration) front of a solute can be determined at any time by connecting the mathematical points. The point tracking scheme actually predicts piston-displacement type flow. The assumption that hydrodynamic dispersion causes the contaminant concentration to be symmetrically distributed about the mean concentration allows us to state that we are tracking the mean relative concentration front. Dispersion will cause concentrations of solutes less than one-half the pond concentration to be ahead of the mean relative concentration front. This study does not calculate the positions of these lower concentration fronts.

It is well known that the mean relative concentration front of many solutes does not move as fast as the average linear velocity of the pond liquor. This "retardation" is due to chemical reactions occurring between the solutes, the aquifer rock, and the native ground water. It is also recognized that the advance of many solutes depends strongly upon the solution acidity. Most solutes move much further in acidic environments than in neutral or basic environments. It is, therefore, important to determine the ability of the rock underlying the pond to buffer the acidic tailings pond solution. This buffering capacity will control the velocity and migration of various solute fronts relative to the pond liquor.

The determination of the buffering capacity of the aquifer rock and the apparent distribution coefficients for various solutes were measured in an experimental laboratory program. First, the buffering capacity of the Tailings Dam Sand was determined by column flooding rock samples with pond liquor. Second, apparent distribution coefficients for dissolved solids under acidic and neutral conditions were determined using the procedure previously described. Finally, the apparent distribution coefficients were used to calculate the relative velocity values of various solute species.

The buffering capacity of the aquifer and the relative velocity values for the solutes are used with the flow rates calculated by the flow simulator to predict the position of the mean relative concentration fronts of the chemically reactive solutes as a function of time. This is a two step procedure. First, the titration data are combined with flow rates to determine how much of the underlying stratum was acidified by pond leakage. This area will represent the practical excursion boundary for many solutes which are efficiently removed from solution once they leave the acidified zone. Having determined the movement of the acidic zone under the pond, the appropriate apparent distribution coefficients can be selected (based upon whether the zone is acidic, neutral, or basic) and relative velocities calculated. The relative velocities can then be incorporated into the flow simulator's point tracking scheme. This is done by multiplying the average linear fluid velocity by the relative velocity of a solute concentration front before the mathematical point is moved through the aquifer. Since the relative velocities of many of the solutes are nearly the same, a series of relative velocity values were used which reflected the values of individual solutes. This reduced the number of moving points without sacrificing accuracy. At any time during the simulation the points can be connected to provide the mean relative concentration front's position.

The approach taken in this study to model solute movement has the following advantages:

1. Chemical attenuation is based on data obtained by actually contacting the pond liquor with aquifer rock.

2. The chemical attenuation experiments are linked directly to the flow calculations by means of the relative velocities.

3. A wide range of relative velocity fronts are tracked which provides the flexibility to track any solute front for which batch test data is available.

4. Flow is calculated using finite-difference simulator, which has the capability to model two fluid phases, nonhomogeneous porous media, and transient boundary conditions.

As mentioned previously, the study approach also has the following limitations:

1. Hydrodynamic dispersion is not calculated.

2. A simplified model (apparent distribution coefficient model) is used to account for the complex chemical reactions occurring between the pond liquor and the aquifer rock.

3. Radioactive decay and the generation of daughter products is only qualitatively considered.

Having outlined the strategy of this study, the following three chapters will be devoted to the technical details of the laboratory program, the geologic modeling effort, and the flow simulation work.

4.0. LABORATORY PROGRAM

Laboratory studies of some of the chemical interactions which take place between Highland tailings solution and four rock units, namely the Tailings Dam Sandstone, Tailings Dam Shale, Ore Body Sandstone, and Ore Body Shale, which underlie the tailings pond were performed. The studies included batch (static) tests between tailings solution and rock samples, titrations of tailings solution by calcium hydroxide solution to given pH levels, and a column-flooding experiment of Tailings Dam Sandstone by tailings solution. Mineralogical analyses were also performed to help characterize the sands and shales.

The batch tests were designed to determine the attenuation of various elements in the tailings solution by each of the four rock types, and whether equilibrium of the attenuation reactions appear to have been reached during the particular batch test.

The major cause of attenuation at Highland is believed to be the buffering action of the rock samples which results in increased pH and simultaneous precipitation from the tailings solution. To study this, titrations of tailings solution by 0.015 M $Ca(OH)_2$ were made to pH 3.5, 5, and 8, and resulting solutions were analyzed for the cations and anions of interest.

The final step in the laboratory program was to monitor the change in column effluent pH as tailings solution was pumped slowly through a column packed with disaggregated Tailings Dam Sandstone. This test provided an estimate of the capacity of this sandstone to neutralize tailings solution.

4.1. FLUID AND ROCK SAMPLES

Samples of the Tailings Dam Sandstone and Tailings Dam Shale were taken from Surface Mine 4 (Pit 4), Ore Body Sandstone and Ore Body Shale from Surface Mine 3 (Pit 3), and tailings solution from the discharge tube just prior to entering the tailings pond (see Figure 3).

The results of inorganic analyses of the as-received rock materials and Highland tailings solution are given in Table 1. Elemental and oxide concentrations are given for the major (Al, Ca, Fe, K, Mg, Na, Si) and minor (Mn) constituents of the rock samples. Elemental concentrations were determined by atomic absorption spectrometry. The relatively high silica concentrations in the rock samples were determined by subtracting the sum of all other major and minor rock constituents from 100 percent. There may be some calcite (calcium carbonate) present in the rock samples that is not detectable by x-ray diffraction analysis, but the error involved in not accounting for calcite is small. All the other major and minor elements probably occur in aluminosilicates or quartz.

The as-received tailings solution has a pH of 2.4 and an Eh of 846 mv. The total milliequivalents of cations is 6% lower than the total milliequivalents of anions on a relative basis. An error of this magnitude might be accounted for in experimental error of analysis. However, at the tailings solution pH there may be some bisulfate present (10% or less of the sulfate) which would have the effect of decreasing the total milliequivalents of anions from 158 to about 138. The determination of iron is for total iron with no regard for oxidation state. In the charge balance calculation all iron was considered as ferric iron, but there may have been some ferrous iron present. The effect of ferrous iron is to decrease the number of milliequivalents of cations in the charge balance. The closeness of the charge balance indicates that the analysis was relatively complete and accurate. It appears that all major components of the tailings solution have been accounted for.

In the batch tests, when the oven dried shales were used, the samples were initially quite hard, and could be disaggregated only with the aid of a mortar and pestle. The sandstones, on the other hand, were easily disaggregated. After a day or two of exposure to the tailings solution, the shale samples disintegrated to form beds of finely divided materials in the bottoms of the flasks. The sandstones did not behave in this manner. Their average particle size was much larger than that of the shales. There was a notable decoloration of the solution in each flask, especially in the flasks containing shales. The color changed from straw yellow to almost clear.

4.2. BATCH EXPERIMENTS

Batch experiments were conducted in which 25 grams of rock sample was exposed to 100 ml of tailings solution for up to 30 days. Subsamples of each of the four rock types (Tailings Dam Sandstone, Tailings Dam Shale, Ore Body Sandstone, Ore Body Shale) were crushed to -1/4" size before drying in an oven at 110°C for 5 to 6 hours. After drying, the samples were stored in desiccators over calcium chloride.

The batch-test solutions were analyzed by atomic absorption spectrometry to determine cation concentrations and by ion chromatography for sulfate ion. Results of these analyses are given in Tables 2 through 5 and Figure 14. In the batch tests the pH changed from 2.4 in the as-received tailings solution to between 3 and 3.5 after 30 days of exposure to the various rock samples. Note that the concentrations of aluminum and silicon increased in the solutions above the sandstones but decreased in the solutions above the shales with increasing exposure time. The concentrations of calcium, magnesium, and strontium in solution increased with increasing exposure time. The concentration increases of these three cations probably arise as a result of ion exchange reactions on clay minerals in which these cations are replaced by hydrogen ion.

Some cations were removed from solution. The concentration of iron, which probably precipitates as ferric hydroxide, decreased from 775 ppm in the as-received tailings solution to between 25 and 125 ppm after 30 days exposure. The solutions over the shales lost iron more rapidly than those over the sandstones. Chromium and copper decreased in all solutions.

Calcium and strontium seem to have reached saturation levels in solution. Strontium concentrations decreased sharply between 15 and 30 days of exposure. This observation may be the expression of coprecipitation of strontium sulfate with gypsum.

4.3. ACID-BASE TITRATIONS

The buffering action of the rocks, resulting in simultaneous change in pH and precipitation is thought to be the prevalent mechanism in altering the concentrations of the various constituents of the tailings solution. To study this, titrations of the tailings solution by 0.015M calcium hydroxide were made. The calcium hydroxide solution was prepared by dissolving 1.11 grams of $Ca(OH)_2$ in deionized water in a one liter volumetric flask and was standardized with HCl solution. Aliquots of tailings solution were titrated in triplicate to pH 3.5, 5, and 8 by the standard $Ca(OH)_2$ solution. After stable pH values were attained at the predetermined levels, the solutions were filtered through 0.45μm Teflon® filters, then acidified with HNO_3. The solutions were stored in acid-washed polyethylene bottles. The filtered and acidified solutions from the titrations were analyzed by atomic absorption spectrometry. Results of these analyses are shown in Table 6 and Figure 15.

Table 6 shows two columns of data for each pH level. In each case, the first column lists concentrations of cations in the diluted tailings solution sample after titration to the given pH. The second column lists the cation concentrations in tailings solution as if the pH of the tailings solution had been changed without dilution in order to approximate the result of buffering the tailings solution by rock. In the calculations no attempt was made to account for possible precipitation reactions or other removal mechanisms which are concentration dependent.

Magnesium, sodium, and potassium form somewhat stable ion pairs with sulfate, which if not dissociated, cause low determinations of these cations in high sulfate solutions. For the analyses, a 50 ml aliquot of the titrated tailings solution was transferred to a polyethylene bottle and 5 ml of 10% lanthanum chloride solution and 1 ml of nitric acid were added. Lanthanum chloride is added to the solutions because lanthanum forms a more stable ion pair with sulfate thereby releasing the other cations for analysis. During the progress of the titrations the sulfate ion concentration was decreased by dilution and by precipitation as gypsum. At each stopping point an aliquot of fixed volume was withdrawn from the reaction vessel, and to this aliquot a given volume of lanthanum chloride solution was added. A greater proportion of sulfate ion was combined in ion pairs with lanthanum as the sulfate concentration decreased. This resulted in apparent increases in magnesium, sodium and potassium with increasing pH in the undiluted tailings solution.

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In addition, ionization of sodium and potassium in the atomic absorption flame may also occur as in the following reaction:

$$Na^0 = Na^+ + e^-$$

When ionization occurs, the population of ground state atoms in the flame decreases, thereby masking the ions from determination.

None of the regulated elements determined in the titrated tailings solution were initially present at concentrations lower than the most stringent water quality standards which are described in Section 7.1 and listed in Table 22. At pH 3.5 arsenic and zinc concentrations decreased to a level below the limits. At pH 8 manganese, nickel, and cadmium concentrations were at or below the limits. No limits have been established for potassium, magnesium, sodium, silicon, or strontium. Aluminum, iron, chromium, copper and selenium remained at concentrations above the limits at pH 8.

A discussion of the analytical methods used for determining element concentrations is given in Appendix A.

4.4. COLUMN FLOODING EXPERIMENT

A column flooding test was performed to provide an estimate of the capacity of the Tailings Dam Sand to neutralize tailings solution. The test was conducted in a lucite cylinder with threaded end caps. The cylinder was prepared to contain a one inch diameter by six inch long column of disaggregated Tailings Dam Sandstone. Each end cap had fittings for directing solution flow through the sandstone column.

The sandstone was disaggregated and packed in the column in a slurry to exclude air. Table 7 lists the physical characteristics of the sandstone column. Distilled water was pumped through the column at 0.1 ml/min, using a Waters Associate Model 45 liquid chromatography pump, until the effluent pH was stable (pH = 8.5). The influent stream was changed from distilled water to tailings solution without introduction of air. Influent flow rate, pressure drop across the column, and effluent pH were monitored throughout the leaching test. Pressure and flow rate data were output to a Digitec Model 3000 Datalogger and pH was continuously recorded on a strip chart recorder. A flow-through pH cell was constructed by sealing a micro-combination pH electrode in a sidearm of a 1/4" Nylon union-T fitting.

Figure 16 shows the dependence of effluent pH on volume of tailings solution passed through the column of Tailings Dam Sandstone. The effluent pH stream was 7.7 after one pore volume of tailings solution had passed through the column, and 3.8 after passage of 4 pore volumes. There was a gradual decrease of pH to 3.2. These results indicate that the Tailings Dam Sand has the capability to buffer the tailing solution.

At the end of the column leach there was a coating of what appears to be ferric hydroxide on the sand grains throughout the length of the column. Some fine-grained material, which had segregated to one end of the column during packing, had no observable yellow coating. There was no measurable pressure drop across the core during the leaching experiment despite the formation of the coating on the sand grains.

4.5. MINERALOGY

Samples of undried and oven-dried sandstones and shales in their as-received conditions and samples of sandstones and shales after exposure to the tailings solution in the batch experiments for three and thirty days were submitted for mineralogical analyses.

No mineralogical differences were found between the undried and oven-dried shales other than dehydration of expandable clays upon drying, and subsequent collapse of the expandable clay matrices. The quantities of clay-sized material increased significantly upon drying.

Results of the mineralogical analyses are shown in Tables 8 and 9. Quartz, kaolinite, and mica were detected in all the bulk composition shale samples. Smectite was detected in all samples except the bulk undried sandstones and shales. Smectite was detectable in the bulk dried samples because the concentration of the clay material increased upon water loss. Gypsum was detected in the shale samples that had been exposed to tailings solution, but not in the as-received shale samples. The weight percentage of gypsum in the samples was estimated by assuming that all sulfur detected was present as gypsum. In the few samples analyzed there was an increase in gypsum concentration with exposure time. The tailings solution evidently became saturated with calcium due to alteration of mineral species or ion exchange, and gypsum began to precipitate from solution.

The sandstone samples underwent a general decrease in average grain size. Rock fragments originally present were broken down to individual mineral constituents. A yellow clay-like coating was gradually deposited on the grains. There was more of the coating on 30-day exposure samples than on 3-day samples, but there were lower concentrations of uranium, calcium, and potassium in the coating of the 30-day samples than the 3-day samples. The yellow coating on the grains had silicon, iron, and aluminum as the major cations, generally in the order Si > Fe > Al. Minor amounts of magnesium, potassium, calcium, sulfur, and titanium were detected at different times.

There was the appearance of abundant silt-sized "clay clumps" consisting either of single crystals (i.e., quartz, feldspar, hornblende, muscovite) or poorly formed oxides (iron) and clays. There was also a gradual alteration of iron- and magnesium-rich minerals to oxides and/or clays, and a gradual loss of feldspars through grain size reduction to silt, or alteration to clays.

A discussion of the methods used for mineralogical analyses is given in Appendix A.

4.6. INTERPRETATION OF LABORATORY RESULTS

The laboratory work shows that the four rock types analyzed have capacity to buffer the Highland tailings solution and thereby cause the bulk of its dissolved solids burden to precipitate.

When tailings solution first comes into contact with geologic units underlying the pond, the dissolved solids burden will be quickly reduced due to the increase in pH. Continued flow of tailings solution into this zone will cause the pH to decrease with the possible dissolution of portions of the precipitate, and alteration of sandstone constituents. The species brought into solution at this zone will be carried forward to the next zone of higher pH and be reprecipitated. There will be a general retardation in the migration of the original dissolved solids burden behind the pH front. When the flow of tailings liquor has ceased and native ground water reinvades the formations underlying the pond, the pH of the acidic area will increase, and dissolved solids will precipitate.

5.0. GEOLOGIC MODELING

An accurate and complete geologic description of the Highland area was an essential prerequisite to the flow calculations. There were two aspects of the geology which were extremely important to predicting solute movement: structure and stratigraphy.

The structure of the area has a significant impact on solute movement. The beds generally dip to the northwest at between one and three degrees (two and five percent). These dips are in the same range as the premining potentiometric surface which decreased from west to east at horizontal hydraulic gradients of between one and six percent. Since the Tailings Dam Sand will be unconfined near the outcrops, tailings pond, and surface mine during parts of the simulation, the local geologic structure could significantly affect horizontal ground water movement.

The stratigraphy of the sand and shale layers will clearly control vertical solute movement. For example, the tailings impoundment is not in direct contact with any of the Ore Body Sands. To predict whether solutes move into the Ore Body Sands, an accurate description of the Tailings Dam Shale and the interspaced Ore Body Shales was required. In addition to flow impedance considerations, the sands and shales have different attenuation and neutralization characteristics. Knowledge of the thickness and continuity of the individual layers will enhance the prediction of solute migration.

Geologic models of the Highland uranium mine were constructed using Exxon Production Research Company's computer programs for two- and three-dimensional geologic mapping and modeling. The two-dimensional mapping program is used to construct geologic surfaces and to build those surfaces into a stratigraphic framework. Input to the two-dimensional program are coordinate locations at intersections between drill holes and the various rock units. The resulting surfaces can be displayed as structural contour maps or cross sections.

The three-dimensional modeling program is used to interpolate any characteristic that has been measured along a drill hole,shaft, or working face. Resistivity values were used at Highland. A variety of interpolation techniques are available which can be used in either layered or isotropic situations or any mixture of the two. The resulting models can be displayed in plan and cross section as well as evaluated for volume and tonnage.

5.1. PROCEDURE

Two geologic models were constructed; a fine-grid model (100-foot square grid blocks) in the area of the pond and pits, and a coarse-grid model (500-foot square grid blocks) for the area within several miles of the mine site. Two models were required because the flow simulator is a variable-sized block modeling program and the geologic mapping and modeling programs are not. To model the detail needed by the flow

simulator near the pond and yet cover the area of interest would require a three-dimensional geologic model many millions of cells in size. By building two reasonably sized models, one coarse and one fine, the entire area was modeled at the detail required.

Geologic model development involved data collection, construction of the two-dimensional stratigraphic model, and construction of the three-dimensional lithologic model. The following text describes each of these steps.

5.2. Geologic Data

The data used in constructing the geologic models came from contour maps and drill hole geophysical logs (see Appendix C).

The information digitized from the contour maps included the pre-mining topography (1:2000), the base of Pit 1 (1:500), the base of Pit 2 (1:500), and the present day topography (1:500)

Interpretation of electrical resistivity curves from 230 holes provided the 'tops' picks for the various lithologic units of interest. The geologic picks were made at Highland and checked for errors using computer displays from the two-dimensional program. Lithologic units used in the modeling were the Tailings Dam Sand; the Tailings Dam Shale; the Upper, Middle, and Lower Ore Body Sands; and the interspaced Ore Body Shales.

Electrical resistivity curves from 77 of the 230 logs were digitized at two-foot increments. The digitized curves provided the downhole lithology information used in constructing the three-dimensional models. Single point resistivity values were recorded downhole. The magnitude of the resistivity readings varied from one hole to the next because the measurements were uncalibrated. Due to these variations all the logs were normalized to a resistivity range between 0 and 100. A value of 0 was assumed to represent a pure shale and a value of 100 a clean sand. The cutoff value between a sand and shale was set at 45 which was the average normalized resistivity value of all intervals in all holes.

5.3. CONSTRUCTION OF THE TWO-DIMENSIONAL STRATIGRAPHIC MODEL

The Highland stratigraphic model consists of a series of two-dimensional surfaces (grids) each representing the top or base of a stratigraphic unit. A two-dimensional surface was constructed by overlaying a grid on the original tops picks for a unit. The original tops data surrounding each grid intersection were used in an inverse distance squared interpolation to estimate the value for the intersection. The resulting grid represents that particular geologic surface.

Prior to constructing the grids, nine additional "dummy" picks were added for each surface in the data set. These picks were required to control the gridding process as it progressed away from the data. During gridding the first intersections to be assigned values are those near data

points. As the gridding continues, intersections progressively farther from the data are assigned values. Because of this, a trend at the edge of the data going either up or down, although only a local feature, may be erroneously extrapolated to the edge of the grid. The addition of supplementary picks which reflect the regional trend minimize false extrapolations.

The final geologically acceptable stratigraphic model was constructed by operating the individual preliminary grids against each other. The unrefined grids were not geologically sensible because they were constructed independently and sometimes crossed each other. To prevent this, each grid was operated against neighboring grids to produce properly onlapped, truncated, or conformable surfaces.

One additonal geologic control placed on the grids during construction was to maintain a ten foot thickness of the Tailings Dam Shale throughout the area. This control is based on the geologists' understanding of the unit and was applied to prevent unrealistic pinch outs caused by data extrapolation. The ten foot minimum shale thickness was in good agreement with wellbore data (see Figure 5).

5.4. CONSTRUCTION OF THE THREE-DIMENSIONAL LITHOLOGIC MODEL

A three-dimensional model of electrical resistivity was constructed using the lithology simulator. The simulator adds the third dimension by generating a stack of blocks at each grid cell of the two-dimensional model. Resistivity values are then assigned to all blocks by interpolating and extrapolating well resistivity data using the inverse distance weighting method. No values were assigned to blocks greater than 2.5 miles from a hole. Those blocks were assigned the resistivity characteristic of the particular stratigraphic unit in which they were located. For example, cells beyond the search limit and in a shale unit would be assigned a low resistivity and those in a sand unit a high resistivity.

The three-dimensional model of resistivity was converted to lithology by designating all blocks having resistivity values less than 45 as shales and those greater than or equal to 45 as sands.

Models of premining and present day lithology were obtained by superimposing the topographic surfaces of the premining and present day situations on the results of the three-dimensional lithology simulator.

5.5. USE OF GEOLOGIC MODELS

Geologic models greatly enhanced our capability to evaluate the Highland geology, select representative cross sections, and construct flow models. The stratigraphic and lithologic models were used to define formation structure and rock characteristics in the cross-sectional and areal flow models. The geologic displays that were generated are described in the following paragraphs.

5.5.1. Cross-Sectional Flow Models

Several cross sections passing through a common point in the center of the tailings pond were generated from the geologic models. These cross sections were anaylzed and three were selected as being representative of Highland. The representative cross sections, shown in Figures 17 - 20, had orientations of west-east, 45 degrees west of north, and 45 degrees east of north. These sections demonstrate the limited range of structure, formation thickness, and lithology seen in the study area.

Three displays were generated for each cross section. They consisted of the coarse model premining topography and geology, fine model premining topography and geology, and the fine model present day topography and geology. The coarse model displays were only used in the portions of the sections not covered by the more detailed fine model. The fine model displays covered the entire area of pits and pond and thus eliminated the need for a present day coarse model display.

The stratigraphic models were used to establish a grid for the cross-sectional flow models, as will be discussed in Section 6.1.2. Each horizontal grid followed a separate geologic unit and varied in thickness and depth from block to block. (See Figures 18 - 20).

The lithologic models were used to determine the sand and shale content of each block so average porosity and permeability values could be calculated.

5.5.2. Areal Flow Model

The areal flow model considered only the Tailings Dam Sand as will be discussed in Section 6.2.1. The stratigraphic and lithologic models were used to describe that unit over an area of approximately 30 square miles.

The stratigraphic fine- and coarse-grid models provided contour maps of the Tailings Dam Sand's structural top, structural base, and thickness. These maps were used to input formation thickness and depth into the flow simulator.

The lithologic model provided contour maps of the thickness of sand and shale lenses in the Tailings Dam Sand unit. These maps were used to calculate average porosity and permeability values.

6.0. FLOW MODELING

The prediction of solute movement in this study uses the distribution coefficient approach to model geochemical reactions. The model relates laboratory adsorption/ desorption results to the velocity of a solute front relative to the advective movement of ground water, as previously discussed in Chapter 3. A finite-difference simulator was used to calculate ground-water movement. The simulator calculated ground-water potentials and fluid fluxes in the vicinity of the tailings pond and tracked mathematical points by converting the fluxes to fluid velocities. Several sets of points were tracked simultaneously with each set being retarded a different amount to account for geochemical reactions. The retardation (relative velocity) factors were chosen based on results of the laboratory program.

This chapter discusses flow modeling at Highland. The chapter is divided in two main sections: cross-sectional modeling and areal modeling. The sections describe the purpose, the location and grid construction (discretization) the fluid and rock properties, the simulation strategy, and the results of the cross-sectional and areal models, respectively.

6.1. CROSS SECTIONAL MODELS

6.1.1. Purpose

The purpose of the cross-sectional models was fourfold:

1. To evaluate the vertical movement of solutes from the tailings impoundment to the underlying sands,

2. To calculate the horizontal movement of solutes between the pond and the surface and underground mines,

3. To estimate pond seepage as a function of time, and

4. To evaluate possible vertical communication of solutes between sand units via the backfilled surface mine.

One of the important issues this study addressed was whether solutes would move through the Tailings Dam Shale and enter one or more of the Ore Body Sands. To accurately determine the extent of vertical solute migration, the cross-sectional models included all of the stratigraphic layers from above the maximum water level in the pond to at least the shale underlying the Lower Ore Sand. Although this approach required modeling up to 16 different geologic layers, it provided sufficient detail to allow accurate simulation of vertical gradients caused by the impounded tailings liquor and surface and underground mines.

It was also necessary to determine maximum horizontal migration. A preliminary assessment of solute movement at Highland indicated that maximum ground-water gradients would exist between the pond and the mines and between the pond and the sand outcrops east of the tailings dam. It was also hypothesized that although a distorted radial flow field would best describe water movement away from the pond, the flow field would be essentially linear between the tailings pond and the surface and underground mines. Figure 21 is a sketch of anticipated flow patterns through the Tailings Dam Sand near the tailings impoundment during mining. By judicial selection of cross-sections, horizontal flow from the pond to the mines could be simulated using a linear flow model. Since part of the dam is constructed through the Tailings Dam Sand, water in that unit will flow around the dam's wings. The cross-sectional models will not correctly predict flow around the dam in the Tailings Dam Sand because of the curved flow lines. The linear flow assumption requires that the flow lines be straight (this limitation is overcome by the areal flow model, as discussed in Section 6.2.1.). However, the calculated movement of solutes in all underlying formations will be physically realistic. The models will provide valuable insight regarding maximum horizontal solute movement between the pond and the mines in all geologic formations, and solute movement between the pond and the outcrop for the units underlying the Tailings Dam Sand.

Calculating seepage from the tailings impoundment is complicated by partially saturated conditions, nonhomogeneous underlying formations, and transient boundary conditions at the mines. To address unsaturated flow, the flow simulator was used in a two phase mode for the cross-sectional calculations. Laboratory analyses were conducted to determine the relative permeability and capillary pressure characteristics of the various geologic units. The nonhomogeneity was addressed by defining each geologic unit as a separate layer in the models and maintaining a relatively fine (250-foot) grid spacing near the tailings pond and mines. The lithology model was used to assign average sand and shale permeabilities and porosities to each finite-difference block in the flow model. Finally, the historical and anticipated mining operations were incorporated in the cross-sectional models to insure the boundary conditions were accurately simulated.

It was anticipated that the greatest solute movement would occur towards the surface mine. If solutes migrated as far as the backfilled portions of the surface mine, they could possibly move down through the backfill and eventually enter an underlying sand. To study this, backfilling and reinvasion of the pits by regional ground-water flow was simulated.

In summary, the cross-sectional models were used to calculate vertical and horizontal solute movement, determine seepage rates emanating from the pond, and evaluate possible solute movement through the surface mine backfill. The following text describes details of the cross-sectional models.

6.1.2. Location and Discretization

The three-dimensional lithology model was used to generate cross sections at angle increments of 22.5 degrees. These cross sections were used to determine similarities and differences between cross sections as a function of orientation. Generally, the stratigraphy and lithology of the cross sections were similar regardless of orientation.

Three cross sections were selected which were oriented roughly parallel to anticipated ground-water flow paths between the tailings pond and the mines. The cross-section orientations were; west-east (W-E), 45 degrees west of north (NW-SE), and 45 degrees east of north (SW-NE). The orientation and extent of the cross-sections are illustrated in Figure 17. The SW-NE and W-E cross sections intersect the surface mine where early and late years of mining were conducted, respectively. The NW-SE cross section intersects the underground mine.

Figure 17 also shows the coordinate system used for this study. The origin is located at the center of the tailings pond. Length units of feet were used with X-direction coordinate values increasing from west to east and Y-coordinate values increasing from south to north. The W-E, NW-SE, and SW-NE cross sections had the following end point coordinates:

W-E	(-37,750; 0)	; (7,750; 0)
NW-SE	(-16,970; 16,970)	; (10,600; -10,600)
SW-NE	(-17,325; -17,325)	; (11,125; 11,125)

The extent of each cross section was based on characteristics of the intermediate flow system. East of the pond the cross sections terminated near the outcrop of the Tailings Dam Sand. West of the pond they terminated a distance estimated to be beyond the maximum extent of the surface mine's effect on the potentiometric surface.

The radius of influence of the surface mine was estimated by two methods. First, average yearly seepage rates into the surface mine (577 gpm) and average aquifer properties were input to an unconfined, steady-state flow equation. This method indicated a 1.7 mile radius of influence. Second, a mass balance was done in which the seepage rate in the pit equaled the product of the infiltration rate and an area available for infiltration. This method indicated a radius of influence of about 3.7 miles.

Both of these methods were very approximate, but gave physically reasonable results. Based on these results the cross-sectional models were extended at least three miles west of the surface mine. Constant potential boundary conditions were specified at both ends of each cross-sectional model. The ground-water potential east of the pond was set equal to the Tailings Dam Sand outcrop elevation. The potential west of the pond was obtained by locating the end point of the cross section on the intermediate flow net (Figure 12) and interpolating between equipotential lines.

Figures 18 - 20 show the cross sections and the finite-difference grids which were superimposed to construct the flow models. Note that the lithology and stratigraphy of the cross sections are similar. The horizontal grid spacing was kept at 250 feet near the tailings pond and the surface mines. Increased grid spacings (500-2000 feet) were used away from the pond. Vertical grid spacing was varied at each block to best represent the thickness of individual geologic units. Each main sand and shale unit was gridded as a separate layer.

6.1.3. Fluid and Rock Properties

One of the most challenging tasks in modeling hydrologic systems is extending fluid and rock properties obtained from laboratory and field tests to represent a large, complex physical system. Fluid properties of interest include density, viscosity, and compressibility. Rock properties include porosity, permeability, relative permeability, capillary pressure, and compressibility. The remainder of this section will discuss the results of the tests performed for Highland and state the fluid and rock properties used in the study.

The movement of air, water, and tailings fluid were modeled at Highland. The properties of air and water are well documented in the literature and testing was not required. The tailings fluid was sufficiently dilute to assume it had the same properties as the ground water. Viscosities at standard conditions were used for air (.0179 centipoise) and water (1 centipoise). The density of air was input as a function of pressure based on the ideal gas law. The water density was kept constant at 1 g/cc (gram/cubic centimeter). The relatively low pressures and moderate pressure changes considered in the simulation justify the use of the above pressure-volume relationships.

The compressibility of a confined aquifer is generally expressed as a specific storage value or a confined storage coefficient. The specific storage is the volume of water released from storage per unit aquifer volume per unit pressure head decline. The confined storage coefficient is the specific storage multiplied by the aquifer thickness.

Specific storage values for the sand and shale units were calculated using typical rock and water compressibilities. This study used a specific storage of 7.3×10^{-6} (1/ft) for sands and 2.2×10^{-6} (1/ft) for shales. The difference in the specific storage values reflects differences in sand and shale porosities.

The specific storage value calculated for the sand units can be compared to storage coefficient values measured in the field by considering the formation thickness. Where the sand thickness was not reported, a 50-foot thickness was assumed. Table 10 compares the specific storage value calculated by EPR to values obtained from well tests.

TABLE 10

Comparison of Specific Storage and
Storage Coefficient Values for Highland Sands

Specific Storage (1/ft)	Storage Coefficient (dimensionless)	Formation Thickness (ft.)	Reference	Geologic Unit
7.3×10^{-6}	3.6×10^{-4}*	50	EPR calculated	-
1.5×10^{-6}	2.5×10^{-4}	165	Golder Assoc. (1979)	Ore Body Sand (multiple completion)
4.1×10^{-7}	6.3×10^{-5}	155	Golder Assoc. (1979)	Ore Body Sand (multiple completion)
2.0×10^{-7}*	1.0×10^{-5}	50	Dames & Moore (1980)	Ore Body Sand (completion unknown)
2.0×10^{-5}	1.9×10^{-4}	9.5	Exxon(Well VI-1)	Middle Ore Body Sand
1.9×10^{-5}	4.8×10^{-4}	25	Exxon(Well VII-3)	Tailings Dam Sand

*assumes a 50-foot sand thickness

Several types of tests were used to determine the rock properties including laboratory core tests and field pumping and packer tests. The following paragraphs describe the results of these tests for the main geologic units and state the values used in the models.

6.1.3.1. Tailings Dam and Fowler Sands

Permeability values for the Tailings Dam and Fowler Sands were measured by pump tests, packer tests, and core analyses. The locations of the wells and boreholes are shown in Figure 22. The results of three drawdown tests and a recovery test performed by Exxon Minerals Company (see Figures 23 - 26) conducted in Wells XXI (Tailings Dam Sand), XII (Tailings Dam Sand), and VII (Tailings Dam Sand - drawdown and recovery) indicate permeabilities of 1190, 2220, 7930, and 7420 md (millidarcies)[1], respectively. Packer tests conducted by Dames and Moore (1980) in the near surface material along the dam indicate permeabilities of 2220 md and 1280 md at a depth of 19.8 feet in boring 12; 1630 md at a depth of 9.7 feet in boring 13; 7500 md at depth of 11.8 feet in boring 8; and 1800 md at a depth of 19.5 feet in boring 9. Dames and Moore did not specify the geologic units in which the packer tests were performed.

[2] For the conditions at Highland, a permeability of 1 md is equivalent to a hydraulic conductivity of about 1×10^{-6} cm/sec or 1 ft/yr.

Core tests were performed by ERCO Petroleum Services to determine porosity, horizontal and vertical permeabilities, air-water relative permeabilities, and capillary pressure characteristics. The results of porosity and permeability tests conducted on Tailings Dam Sand cores are summarized in Table 11.

TABLE 11

Laboratory Measurements of Porosity, Permeability, and Grain Density for the Tailings Dam Sand

Core		Depth(feet)	Porosity (%)	Permeability (md) (gas flood) Horiz.	Vert.	Grain Density(g/cc)
VIII	a	112.9-113.2	29.4	372	3177	2.60
	b		35.4			
XII	a	127.4-127.8	31.7	2804	2992	2.65
	b		34.5			
	c		35.8			
XX	a	122.7-123.1	22.1	6390	5522	2.39

The lab analyses agree closely with results obtained in the field. Note that the horizontal and vertical permeabilities are nearly the same in cores XII and XX. This indicates that the Tailings Dam Sand may be isotropic. Visual inspection of the cores indicate that the Fowler and Tailings Dam Sands are very fine- to medium-grained sands with varying amounts of silt and clay. Based on the above data, an isotropic permeability of 2000 md was used in the models for the Fowler and Tailings Dam Sands.

Figures 27 - 30 show the results of ERCO's air-water relative permeability analyses for Tailings Dam Sand Cores VIII, XII, and XX. Differences in the curves are probably attributable to varying amounts of clay in the samples which could affect the overall core wettability. The presence of clay is supported by greatly decreased permeability measurements when water, instead of gas, was used to flood the cores. The following decreases in permeability occurred:

TABLE 12

Comparison of Tailings Dam Sand Permeability Measured by Gas and Water Floods

Permeability (md)

Core	Gas flood	Water flood
VIII (vertical)	3177	63
XII (horizontal)	2804	1525
XII (vertical)	2992	230
XX (vertical)	5522	757

Permeability reductions of approximately one order of magnitude or more occurred in all cores except Core XII (horizontal). This indicates that Core XII (horizontal) was most representative of a clean sandstone. Therefore, the air-water relative permeability curve measured for that core was used to represent model blocks which were predominately sandstone.

Figure 31 shows the results of ERCO's air-water capillary pressure tests for Cores VIII (horizontal), XII (horizontal), and XX (horizontal). The results of Core XII (horizontal) were taken to be representative of a clean sand because the core (1) showed the least permeability reduction when flooded with water, and (2) had a permeability to water close to the value selected to represent a clean sand in the models (1525 md vs. 2000 md).

6.1.3.2. Ore Body Sands

Permeability, porosity, and grain density values for the Ore Body Sands were measured by pump tests and core analyses. Pump tests were performed in Wells XX and VI which were completed in the Upper and Middle; and Middle Ore Body Sands, respectively. Results of these tests, shown in Figures 32 and 33, indicate permeabilities of 2060 and 6260 md, respectively.

Appendix B lists core analysis data taken at one-foot intervals through the Ore Body Sands in seven core holes near the solution mine. The data indicate that permeabilities of individual cores range from millidarcies to tens of thousands of millidarcies. The variation is probably due to differences in the degree of cementation and the clay and silt content of the samples. However, when the permeabilities were arithmetically averaged over the entire core depth the following values were obtained:

TABLE 13

Summary of Porosity, Permeability, and Grain Density for the Ore Body Sands

Core	Depth (feet)	Porosity (%)	Permeability (md)		Grain Density (g/cc)
			Horiz.	Vert.	
2700-0505	384-411	30.9	1672	3450	2.63
0865-0875	353-361	30.0	1036		
0815-4950	695-764	25.6	2236		
2700-2310	650-704	25.9	3079		
4260-0940	627-659	30.0	3235		
4260-0940	745-795	26.9	3103		
2650-0320	367-400	31.0	2288	1687	2.61
0600-0810	633-667	25.6	834	626	

Since these results are very similar to those obtained for the Tailings Dam and Fowler Sands, a single set of properties were used to represent all clean sands in the study. Those properties are listed in Table 14:

TABLE 14

Properties of the Tailings Dam, Fowler, and Ore Body Sands Used in the Cross-Sectional Models.

Horizontal permeability	= 2000 md
Vertical permeability	= 2000 md
Porosity	= 34 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.72 g/cc
Specific Storage	= 7.3×10^{-6}(1/ft)
Relative permeability	= Figure 28
Capillary pressure	= Figure 31 - Core XII (horizontal)

6.1.3.3. Shales

Permeability, porosity, and grain density values for the Tailings Dam Shale were measured by core analysis. The Tailings Dam Shale has very low permeabilities and long term pump tests would have been required to obtain field permeability measurements. The results of the core analyses can be summarized as follows (see Figure 22 for core locations):

TABLE 15

Summary of Porosity, Permeability, and Grain Density for the Tailings Dam Shale

Core	Depth (Feet)	Porosity (%)	Permeability (md) Air	Permeability (md) Water	Grain Density (g/cc)	Reference
1	60.5		3.6			Dames & Moore (1980b)
1	75.5			1.0		Dames & Moore (1980b)
1	80.5			9.3		Dames & Moore (1980b)
1	85.5			0.10		Dames & Moore (1980b)
4	35.5			0.15		Dames & Moore (1980b)
4	40.5			0.03		Dames & Moore (1980b)
XX	169.9-170.3	14.0			2.49	ERCO (1981)
XXa	169.0-169.5	10.9				Exxon Prod. Research
b		20.3				Exxon Prod. Research
c			2.59			Exxon Prod. Research
d			.0009			Exxon Prod. Research
e		11.0				Exxon Prod. Research
f			4.53	0*		Exxon Prod. Research

* Core plug XXf was saturated with filtered tailings pond liquor. Permeability to the liquor was measured at an injection pressure of 225 psig, and at atmospheric outlet pressure. The permeability measured over the first 24 and 48 hours was 0.003 and 0.004 md, respectively. No fluid flow occurred for the next 10 days.

The permeability of the shale samples ranged from impermeable to over 9 md. This range is probably caused by differing amounts of sand and clay in the shale. Tables 16 and 17 describe the lithology of sections of Cores XII and XX, respectively. Sections within the "shale" units include clay, claystones, silt, very-fine to coarse sand, and gravel. A representative permeability value for the shale units would consist of an average permeability of the materials composing them.

Two well accepted permeability averaging techniques are used depending on lithology and flow direction. Assuming the individual layers are areally extensive, arithmetic averaging would be used for horizontal permeabilities and harmonic averaging for vertical permeabilities. Note that the use of harmonic averaging generally results in an average permeability relatively close in value to the lowest permeability in the series.

This study assumed an isotropic shale permeability of 1 md for both the Tailings Dam and Ore Body Shales. This is probably a high estimate of the vertical permeability.

ERCO Petroleum Services performed relative permeability and capillary pressure tests on a Tailings Dam Shale sample taken between 169.9 and 170.3 feet from Core XX. Although several plugs were cut from the core, they all cracked during testing. The cracks invalidated the test results.

To overcome this difficulty, relative permeability and capillary pressure data reported by Battelle Northwest Labs (1980a) for shales at Morton Ranch were used in the Highland Study. These data are shown on Figures 34 and 35. The Morton Ranch site is located approximately four miles south of Highland. The geologic units tested at Morton ranch were from the Wasatch Formation which directly overlies the Fort Union Formation. The saturated permeability of the Morton Ranch sample was reported to be 1.3 md, which is very similar to the value used for Highland (1.0 md). It was assumed that the shale relative permeability and capillary pressure data obtained by Battelle for Morton Ranch would represent shales at Highland.

The shale properties used in the cross-sectional models are summarized in Table 18.

TABLE 18

Properties of the Tailings Dam, Fowler, and Ore Body Shales Used in the Cross-Sectional Models

Horizontal permeability	= 1 md
Vertical permeability	= 1 md
Porosity	= 10 percent
Grain density	= 2.60 g/cc
Bulk density	= 2.34 g/cc
Specific storage	= 2.2×10^{-6}(1/ft)
Relative permeability	= Figure 31
Capillary pressure	= Figure 32

6.1.3.4. Surface Mine Backfill Material

At the time of model construction the properties of the surface mine backfill had not been measured. Since vertical migration of solutes through the backfill was of primary concern, high values of vertical and horizontal permeabilities were assumed. It was also assumed that the backfill would be loosely compacted (compared to geologic formations) and have a high porosity consisting of relatively large pores. The large pores would result in very weak capillary forces and promote segregation of air and water. To account for the segregated flow, relative permeability pseudofunctions were used. The pseudofunctions accounted for the change in transmissibility due to water level fluctuations. The pseudo-relative permeability and capillary pressure curves used for the backfill are shown in Figure 36.

The properties assumed for the backfill material are summarized in Table 19.

TABLE 19

Properties of the Surface Mine Backfill Material Used in the Cross-Sectional Models

Horizontal permeability	= 2000 md
Vertical permeability	= 2000 md
Porosity	= 35 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.69 g/cc
Specific storage	= 7.5×10^{-6} (1/ft)
Relative permeability	= Figure 36
Capillary pressure	= Figure 36

After the models were completed, an unconfined pump test was conducted in the backfill. The results of that test, shown in Figure 37, indicate a permeability of 40 md. This low permeability will greatly reduce any migration of solutes through the backfill predicted by the flow models.

6.1.3.5. Tailings

Four permeability tests were performed on tailings samples obtained from the mill discharge pipe. The tailings were slurry packed into a Soiltest Compaction Permeameter. Filtered pond liquor with a pH of 2.3 was used in all tests. The results of the first two tests indicate permeabilities of 10.5 md and 11.0 md.

The second two tests were designed to study the effect of solute precipitation on permeability. The permeameter was sealed for about three weeks to allow the tailings and pond liquor to react. Permeability tests were run again and yielded values of 8.9 md and 6.7 md. These values indicate permeability reductions of 15 and 39 percent, respectively.

Upon disassembly of the permeameter a yellow precipitate, probably iron hydroxide, was observed. The permeability reductions were probably caused by plugging of pore space in the tailings and the porous stone in the permeameter by the precipitate. It is anticipated that this phenomenon will occur near the bottom of the tailings impoundment and reduce seepage. However, because of the difficulty in quantifying long term permeability reductions, precipitate plugging was not considered. A tailings permeability value of 10 md was used in the study.

6.1.3.6. Property Averaging

The rock properties described in this section represent a single type of material (sand, shale, or backfill). In some model blocks two or more materials exist. The following paragraph describes the averaging procedure employed for nonhomogeneous blocks.

Each flow model block was evaluated for sand, shale, and backfill content based on the lithologic model. The porosity and permeability of the blocks were then averaged using the typical material properties. Both horizontal and vertical average permeabilities were calculated. Generally, arithmetic and harmonic averages were used for horizontal and vertical permeabilities, respectively. Porosities were averaged arithmetically.

6.1.4. Simulation Strategy

This section describes methods and approximations used to simulate the initial and boundary conditions, the effects of the surface and underground mines, the tailings pond, and the movement of the solute fronts with point tracking.

6.1.4.1. Initial and Boundary Conditions

The regional and intermediate premining flow systems are shown in Figures 11 and 12, respectively. As previously described, the intermediate flow system was used to determine the boundary conditions of the cross-sectional models by the following procedure.

The end points of each cross section were located on the flow net. The ground-water potential east of the pond was set equal to the Tailings Dam Sand outcrop elevation. The potential west of the pond was obtained by interpolating between equipotential lines on the flow net. Source-sink terms incorporated at the ends of the models would inject or produce fluid if the block potential decreased or increased, respectively. The amount of fluid injected or produced depended on the pressure drop in the block and the transmissibility of the block.

The cross-sectional models were initialized to a level potentiometric surface. The source-sink terms then injected or produced fluid until they reached their specified potentials. The NW-SE model was run

until the maximum pressure change in all blocks became negligible. After premining regional flow was established, simulation of the tailings pond and underground mine was initiated.

Pond and surface mine simulation was initiated in the W-E and SW-NE models without first establishing premining flow. This was done because the surface mine was present near the beginning of both simulations and dominated the flow field. Premining flow would have relatively little effect on solute transport compared to potential gradients caused by the surface mine. The proper boundary conditions were established early in the simulation allowing ground water reinvasion of the backfilled surface mine to be modeled.

6.1.4.2. Surface and Underground Mines

The effect of the open pits was simulated by defining source-sink terms in all blocks representing the surface mine. The source-sink terms produced sufficient fluid to maintain atomspheric air pressure in each block representing the mine . To simulate backfilling, the source-sink terms were eliminated allowing water to reinvade the blocks. Backfill properties listed in Table 19 were used in all blocks representing the backfilled pits.

The underground mine was modeled in a similar manner except the pressure was specified above atmospheric. This prevented the need to simulate air movement into the underground mine. This approximation should have little, if any, effect on the calculation of solute movement.

6.1.4.3. Tailings Impoundment

To accurately calculate pond seepage and solute movement it was necessary to model the areal extent and depth of the pond liquor and the thickness of the tailings as a function of time. The areal extent and depth of the pond liquor determined the area available for seepage and the driving force for fluid flow, respectively. The tailings depth was important because it provided most of the resistance to flow leaving the pond.

The areal extent and elevation of the pond liquor was obtained from annual contour maps prepared by Exxon Minerals Company. The rate of increase in pond depth was used to calculate pond elevations from 1981 till mill shutdown in December 1983.

To estimate the water level in the pond after mill shutdown a water balance was performed. The water balance considered precipitation, surface water runoff, natural evaporation, enhanced evaporation by sprinklers, and seepage. Calculations indicate that it will take about five years for the pond to dry.

After the standing pond liquor is gone the tailings must drain. The total quantity of water in the tailings was estimated by multiplying the volume of tailings by a 35 percent drainable porosity. Pond seepage was simulated until all the water drained from the tailings.

The tailings thickness was derived from two contour maps of the tailings prepared in 1972 and 1980. The 1972 tailings elevations were subtracted from the 1980 elevations to obtain a tailings isopach map. The tailings thicknesses in intermediate years were then determined as follows. Tailings were assumed to be evenly distributed in the impoundment. The tailings build-up was then prorated by the ratio of the yearly mill tonnage to the total mill tonnage over the eight year period. The tailings and pond liquor were assumed to build up at a constant rate from 1979 through 1983 when the mill is scheduled to shutdown. The tailings and pond liquor levels for each cross-sectional model are shown in Figure 38.

Pond seepage was modeled using source terms. The quantity of fluid injected into the formations underlying the pond was a function of water potential values and resistance factors specified for the source terms. The potential value reflected the depth of the pond liquor. The resistance factor accounted for the tailings thickness and the fluid flow geometry. A separate source term was specified for each 250-foot block underlying the pond. The potential value and resistance factor for each source term were respecified yearly to reflect changing pond conditions.

The high vertical permeability of the Tailings Dam Sand made it desirable to model the area where it was in direct contact with the bottom of the tailings pond. The easiest way of accomplishing this was to have the cross sections pass through the contact area. However, if all the cross sections passed through the contact area they would no longer be parallel to the flow lines between the pond and the pits. As discussed previously, the linear flow constraint requires that the cross sections and flow lines be parallel.

To resolve this dilemma the contact area was accounted for by modifying the lithology of some blocks underlying the tailings pond in the W-E and SW-NE cross sections. The NW-SE cross section passed through the contact area, therefore, its lithology did not need adjustment.

The W-E and SW-NE cross sections were adjusted by extending the Tailings Dam Sand up to the pond bottom where thinning of the overlying shale was evident. This approximation provided seepage rates into the sand and shale units for each 250-foot finite-difference block.

The seepage rates calculated by the cross-sectional models were used to obtain total pond seepage by the following procedure. The area of the pond and tailings dam beach were calculated as a function of time. The total area was then divided into two categories depending on whether the formation exposed on the pond bottom was Tailings Dam Sand or Fowler Sand and Shales.

Each cross sectional model block was identified as a "Tailings Dam Sand" or "Fowler" block based on the formation that block represented. The average yearly seepage rates for the Tailings Dam Sand blocks were summed and divided by the total area of those blocks. This provided an average seepage rate per unit area into the Tailings Dam Sand. The unit seepage rates were multiplied by the total exposed area of the Tailings Dam Sand to obtain total seepage into the sand. The same procedure was repeated for the Fowler Formation.

The unit seepage rates for the Tailings Dam Sand and Fowler Formation are shown in Figure 39 for the W-E, NW-SE, and SW-NE cross sections. The difference in the average rates can be attributed to differences in lithology, rate of tailings build-up, and proximity to mining operations.

6.1.4.4. Solute Front Movement

Chapter 3 discussed in detail the methodology used to track solute fronts. Briefly, tailings fluid and rock are put in a container and allowed to reach equilibrium. Analyses are performed to determine distribution coefficients which are the ratio of the solute concentration on the rock to the solute concentration in the liquid. Any solute not in the liquid is assumed to have adsorbed on the rock, even though it may have been removed from solution by precipitation or other reactions. The distribution coefficient, porosity, and bulk density of the rock are used to calculate the ratio of the solute front velocity to the average fluid velocity.

Table 20 lists the distribution coefficients and relative velocities of solutes at Highland for the Tailings Dam Sand, Tailings Dam Shale, Ore Body Sand, and Ore Body Shale. The values listed for lead-210 and radium -226 were obtained by Battelle (1980b) for the Wasatch Formation at Morton Ranch. Because Battelle used Highland tailings liquor in their analyses and the Wasatch and Fort Union Formations are similar, it is assumed that the distribution coefficients and relative velocities will be applicable to Highland.

Negative distribution coefficients were calculated for several elements when tailings solution was equilibrated over sedimentary materials. A negative coefficient results when the equilibrium concentration of a solute is higher than the initial fluid concentration. This could be caused by experimental error, particularly when concentration levels are near the solute's detection limit. In some cases the negative distribution coefficients indicate dissolution of solutes by the tailings solution. This appears to be the case for aluminum from sandstones; calcium, magnesium, and strontium from all rocks; and thorium and uranium from the Ore Body Sand.

The solute transport model used in this study does not address solutes being desorbed or dissolved from rocks. The calculation of a relative velocity using a negative distribution coefficient leads to ludicrous results. The model would predict the solute front moving in the opposite direction of ground-water flow. Physically, negative distribution coefficients indicate that the solute front moves as fast as the ground water and may have solute concentrations above the tailings pond concentration due to dissolution. A relative velocity of 1.0 was assigned to solutes with negative distribution coefficients.

The wide range of relative velocities calculated for the solutes made it impractical to track a set of points for each different relative velocity. Instead, six sets of points were defined with relative velocities of 1.0, 0.50, 0.30, 0.20, 0.10, and 0.05. These relative velocity values were typical of those calculated for the solutes (See Table 20).

Since the actual relative velocities of the solutes were not used, solute fronts will be described in terms of the typical values. For example, potassium has a relative velocity of 0.062 in the Tailings Dam Sand. Although a relative velocity of 0.062 was not tracked, the potassium front will be located between the 0.10 and 0.05 relative velocity contours. Those contours are sufficiently close to make this approximation well within the uncertainty of the data.

Each set of points was initially located under the entire length of the tailings pond. Two points were defined in shale blocks and four points in sand blocks. Point density was greater in sand blocks because larger seepage rates were anticipated to occur through the sand. The number of points varied in each cross-sectional model. Typically about forty points were tracked for each relative velocity value.

6.1.5. Results

As stated in the beginning of this chapter, the cross-sectional models were designed to address the following issues:

1. Evaluation of the vertical movement of solutes from the tailings impoundment to the underlying sands,

2. Calculation of the horizontal movement of solutes between the pond and the surface and underground mines,

3. Evaluation of possible vertical communication of solutes between sand units via the backfilled surface mine, and

4. Estimation of pond seepage as a function of time.

This section will present the cross-sectional model results and discuss each of the above items.

6.1.5.1. Solute Movement

Figures 40 - 42 show unattenuated solute movement for the W-E, SW-NE, and NW-SE cross sections, respectively. Note that the topography under the pond has been modified to indicate where direct contact between the tailings pond and the Tailings Dam Sand has been superimposed into the cross section.

The unattenuated vertical movement results under the pond are very similar in all three cross sections. They indicate solutes move through the Tailings Dam Shale and into the Upper Ore Body Sand. Vertical movement essentially stops in the shale separating the Upper and Middle Ore Body Sands. For example, between the years 1987 and 2000 the solutes move a maximum of about 10 feet vertically. By the year 2000 the pond has completely drained and regional flow is re-established. Thus, it is unlikely that further vertical migration will occur.

The W-E and SW-NE cross sections predict significant vertical movement near the western end of the pond. This probably reflects the influence of the surface mine. The same trend is predicted by the NW-SE section, but it is probably caused by increased seepage where the tailings pond and Tailings Dam Sand are in contact.

The results show that the pond acts as a ground-water divide causing horizontal solute movement away from the pond in both directions. As discussed previously, horizontal movement towards the outcrop in the Tailings Dam Sand will not be accurately predicted by the cross-sectional models but will be accounted for by the areal model.

The W-E model predicts unattenuated solutes will reach a backfilled portion of Pit 2 about the year 1995. By that time the pond will be dry and regional flow re-established. It is unlikely that solutes will migrate to lower sand formations. Unattenuated solute movement to the northwest and southeast is limited to a few hundred feet of the pond.

Figures 43 - 45 show solute movement attenuated at a velocity fraction of 0.3 for the W-E, SW-NE, and NW-SE cross sections, respectively. The 0.3 velocity fraction is significant since it represents a conservative estimate of acidic front migration. The estimate is conservative because although the acidic front moves at a somewhat higher velocity fraction in the Tailings Dam and Ore-Body Sands (0.485 and 0.423, respectively), it moves at a much lower velocity fraction in the Tailings Dam and Ore Body Shales (0.085 and 0.141, respectively).

The results of all three cross-sections are again very similar. They indicate that the acidic front will not migrate below the Tailings Dam Shale. Horizontal migration is limited to the area directly under the pond. The significance of the acidic front position on the movement of specific solutes will be discussed in the next chapter.

Figures 46 - 51 show solute movement attenuated at velocity fractions of 0.20 and 0.10 for the W-E, SW-NE, and NW-SE cross sections, respectively. It is evident that very little solute migration occurs at these small velocity fractions.

6.1.5.2. Seepage

The procedure used to calculate total seepage from the pond using the results of the cross-sectional models was described earlier in this chapter. Figure 52 shows the results of those calculations. The total seepage rates were in close agreement. They all peaked in 1983 when the tailings pond was at its maximum depth. Maximum seepage ranged from 180 gpm for the W-E model to 225 gpm for the NW-SE model. The models show decreasing seepage after 1983 as the pond water level decreases due largely to evaporation.

The SW-NE model shows a 110 gpm peak in seepage about 1973 which was not calculated by the other models. This probably results from the SW-NE cross section intersecting the early years of surface mining. The surface

mine would cause a drop in potential under the pond resulting in high vertical seepage rates. The rate decrease is likely a result of a rapid decrease in effective vertical permeability due to tailings build-up.

The seepage appeared to be distributed over the entire area of the pond. It was anticipated that most of the seepage would occur through the Tailings Dam Sand contact area. However, this area was covered by a significant amount of relatively low permeability tailings which greatly decreased the effective vertical permeability of the sand.

Figure 52 also shows the seepage rates used in the areal model. The areal model rates were generally the average of the rates calculated by the three cross-sectional models. However, from 1972-1976 seepage rates calculated by the SW-NE model were used. This was done because the SW-NE model results best described seepage during the early years of surface mining.

Figure 39 shows area normalized seepage rates into the Fowler Sands and Shales and the Tailings Dam Sand for the W-E, NW-SE, and SW-NE cross sections. Seepage rates into the Fowler Sands and Shales range between 0.25 and 2.0 gpm per acre. Note that the cross-section results are fairly consistent.

A much larger variation exists for seepage into the Tailings Dam Sand. The SW-NE cross section shows normalized seepage rates above 8 gpm per acre early in the pond life. As previously discussed, this is probably due to the effect of Pit 1 and the lack of tailings build-up during the early years of pond operation. After 1977 the normalized seepage rate drops to between 1 and 2 gpm per acre. These rates are consistent with those calculated for the NW-SE cross section (1-3 gpm per acre).

The W-E cross-sectional model predicted normalized seepage rates of between 6 and 7 gpm per acre from 1978 to 1985. These higher values are likely a result of fewer shale stringers in the finite-difference blocks representing the Tailings Dam Sand in the W-E model. Note that although the W-E model generally had the highest normalized seepage rate into the Tailings Dam Sand, it had the lowest total seepage rate of the three cross-sectional models (Figure 39). This is because the W-E cross section predicted lower normalized seepage rates for the Fowler Sands and Shales. Since most of the pond area is composed of these units, a majority of the seepage occurs through them.

6.2. AREAL MODEL

The cross-sectional models provided insight to vertical and horizontal solute movement, solute migration in the backfilled mines, and pond seepage. They indicated that unattenuated solutes would not reach any sands underlying the Upper Ore Body Sand, that horizontal solute movement was areally restricted, and that some unattenuated solutes might reach the backfilled surface mine. Maximum seepage from the pond was calculated to be between 180 and 225 gpm and occurred over the entire pond.

While the above results are encouraging, it is worthwhile to review some of the limitations of the cross-sectional models. The orientations of the models were selected based upon an estimate of flow paths between the pond and the mines (Figure 21). Since each cross-sectional model simulated flow along a streamline, the radial flow could be approximated with an areally linear model. However, errors in the assumed flow paths could lead to incorrect predictions of horizontal solute movement. Also, the cross-sectional models could not follow the curved flow paths between the pond and the outcrop area in the Tailings Dam Sand, thus invalidating flow calculations east of the pond in that geologic unit.

Another uncertainty is the assumption that the Tailings Dam Shale has an average vertical permeability of 1 md. Available data indicate that this is probably a high average value. Assigning this vertical permeability to the Tailings Dam Shale will result in overprediction of vertical solute movement. However, if the shale has a significantly lower average permeability or is impermeable, fluid leaving the pond would be forced to move horizontally rather than vertically. This could result in the cross-sectional models underpredicting horizontal solute movement in the Tailings Dam Sand.

Finally, the W-E and SW-NE cross-sectional models only simulated operation of the surface mine when it intersected the cross sections. This does not fully account for the complex effect the surface mine has on the flow field as the mine progresses northwestward.

An areal model was used to overcome these limitations. The following text describes the purpose, the location and discretization, the fluid and rock properties, the simulation strategy, and the results of the areal model.

6.2.1. Purpose

The purpose of the areal model was twofold:

1. To predict the maximum horizontal movement of solutes and,

2. To overcome limitations of the cross-sectional models resulting from the linear flow assumption.

The prediction of maximum horizontal solute movement was accomplished by assuming that all seepage calculated by the cross-sectional models entered directly into the Tailings Dam Sand and the overlying and underlying shales were impermeable. The cross-sectional models showed that some fluid leaving the pond entered sand stringers above the Tailings Dam Sand. These stringers were not areally extensive and the shale surrounding them would serve to trap solutes. Also, over much of the pond any fluid reaching the Tailings Dam Sand would first have to migrate through shale. Since the shales effectively adsorbed many solutes, this fluid would be much cleaner than the pond liquor.

By assuming the overlying and underlying shales were impermeable, all fluid entering the Tailings Dam Sand was forced to move horizontally away from the pond, since it could not move downward to underlying formations. This would lead to overprediction of horizontal movement.

The areal model provided greater flexibility than the cross-sectional models for simulating the surface mine and the outcrop area. Changing flow paths could be simulated as surface mining progressed. Also, the simulation could be conducted over the entire life of the mine. The ability of the areal model to calculate flow around the dam provided estimates of seepage into North Fork Box Creek.

6.2.2. Location and Discretization

The location and extent of the areal model, shown in Figure 53, was based on the geology and intermediate flow system at Highland. The eastern model boundary was the Tailings Dam Sand outcrop. The western model boundary was a north-south equipotential line. The location and potential of this line was estimated by interpolating between the 5266- and 5300-foot equipotential lines shown in Figure 12. The north and south model boundaries were specified 16,500 and 13,500 feet from the pond, respectively. The boundaries were sufficiently far from the pond and surface mine to avoid affecting flow patterns.

A variable-spaced grid, shown in Figure 53, was used for the areal model. A relatively fine grid of 500 feet was used in the vicinity of the pond and surface mine. Larger grid spacings of between 1000 and 2000 feet were used towards the model boundaries.

6.2.3. Fluid and Rock Properties

A detailed description of the fluid and rock properties used for the Highland study were given in the cross-sectional modeling section. The horizontal permeability, porosity, grain density, bulk density, and specific storage values used in the cross-sectional models were also used in the areal model.

The relative permeability curve used in the areal model for the Tailings Dam Sand and surface mine backfill, is shown in Figure 54. It accounted for reductions in transmissivity due to unconfined flow rather than apparent permeability reductions due to partially saturated flow. Use of these relationships is justified for two reasons. First, the vertical permeabilities of the Tailings Dam Sand and mine backfill material are high, causing vertical drainage to occur relatively quickly. Such rapid drainage will result in segregated flow of the air and water phases. Second, the cross-sectional models have already accounted for the unsaturated zone beneath the pond in determining seepage rates. The seepage rates calculated by the cross-sectional models were used for the areal model. Knowing the pond seepage rates as a function of time eliminated the need to use partially saturated flow relative permeability curves under the pond in the areal model. The relative permeability functions were more effectively used to account for unconfined, segregated flow.

A similar argument can be made for the capillary pressure curves. The relatively large pores in the Tailings Dam Sand result in weak capillary forces. As shown in Figure 31, most of the pores have drained only two feet (1 psi) above the water table. Rather than simulate actual capillary forces, the capillary pressure term in the flow equations was used to account for gravity drainage between blocks of equal elevation. This was accomplished by assuming segregated flow and relating grid-block saturations to the fractional height of the free water surface in the block. By knowing the thickness of the grid block the saturation could be related to a gravity driving force, as shown in Figure 55. Thus, gravity flow for blocks of equal elevation would be initiated by differences in block saturations. Note that gravity flow between blocks of different elevations but equal saturations is already incorporated in the gravity term of the total fluid potential.

Properties of the Tailings Dam Sand and surface mine backfill material are listed in Table 21.

TABLE 21

Properties of the Tailings Dam Sand and Surface Mine Backfill Material Used in the Areal Model

Tailings Dam Sand

Horizontal permeability	= 2000 md
Porosity	= 34 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.72 g/cc
Specific storage	= 7.3×10^{-6} (1/ft)
Relative permeability	= Figure 54
Capillary pressure	= Figure 55

Surface Mine Backfill Material

Horizontal permeability	= 2000 md
Porosity	= 35 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.69 g/cc
Specific storage	= 7.5×10^{-6} (1/ft)
Relative permeability	= Figure 54
Capillary pressure	= Figure 55

6.2.4. Simulation Strategy

This section describes methods and approximations used to simulate the initial and boundary conditions, the surface and underground mines, the tailings pond, and the movement of the solute fronts with point tracking.

6.2.4.1. Initial and Boundary Conditions

The initial and boundary conditions for the areal model were determined from the intermediate flow system, shown in Figure 12. The model was initialized to a uniform potential of 5160 feet above mean sea level. Potential specified source-sink terms were then used to establish boundary conditions. The western boundary of the model was kept at a uniform potential of 5280 feet. This value was obtained from Figure 12 by interpolating between the 5266- and 5300-foot equipotential lines to estimate the potential of the north-south trending equipotential line. Source-sink terms were also located along the Tailings Dam Sand outcrop east of the pond. The potential of each source-sink term was set to the outcrop elevation of the Tailings Dam Sand.

The model was run for 500 days to establish regional flow. The maximum grid-block pressure change was monitored during this period. Regional flow was considered to be established when the maximum pressure change became negligible.

The north and south boundaries were specified sufficiently far from the pond and surface mine to avoid having an effect on flow patterns. Since the north and south model boundaries were roughly parallel to the west-east flow lines, they were defined as no-flow boundaries.

6.2.4.2. Surface and Underground Mines

The open pits were simulated by defining source-sink terms in all blocks representing the surface mine. The source-sink terms produced fluid at a constant rate of about one percent of the grid block's initial water content until the block reached residual water saturation. The source-sink term would then maintain that saturation. The locations of active source-sink terms were adjusted yearly to simulate the progression of the surface mine. To simulate backfilling, use of the source-sink terms was discontinued and water reinvaded the block. Backfill properties were used in all blocks representing the surface mine.

It was not necessary to simulate the underground mine in the areal model. Grout was used to seal the Tailings Dam Sand from the vertical shaft, thus preventing the shaft from acting as an atmospheric boundary condition. The lateral workings were all completed below the Tailings Dam Shale, and that unit was assumed impermeable. It is believed that the underground mine had relatively little effect on ground-water flow in the Tailings Dam Sand.

6.2.4.3. Tailings Impoundment

In the areal model it was assumed that all seepage entered the Tailings Dam Sand uniformly over the entire pond area. The seepage rate was estimated using the results of the cross-sectional models, as previously described. After surface mine shutdown in December, 1983, the seepage rate was allowed to decrease in a manner similar to that calculated by the cross-sectional models. The seepage rate used to simulate the tailings impoundment is compared to the cross-sectional model results in Figure 52.

6.2.4.4. Solute Front Movement

The methodology used to track solute fronts for the cross-sectional models was described earlier in this chapter. The same methodology was used for the areal model. Sets of points with relative velocities of 1.0, 0.50, 0.30, 0.20, 0.10, and 0.05 were specified around the tailings pond. Each set contained fifty individual points. By connecting these points the approximate location of different solute fronts could be determined.

6.2.5. Results

This section presents results of the areal model. Specific topics discussed are predictions of maximum horizontal movement of solutes and seepage rates in North Fork Box Creek.

6.2.5.1. Solute Movement

Figure 56 shows areal solute movement from 1972-1992 for a velocity fraction of 1.0. The areal model predicts that maximum unattenuated solute movement will occur west of the pond. Solutes will reach the northern edge of Pit 2 about 1992. This is similar to the results of the W-E cross-sectional model which predicted arrival about the year 1995.

Unattenuated solutes are predicted to move a maximum of 1300 feet southwest and 300 feet northwest of the pond. These predictions are greater than the predictions of the cross-sectional models which showed little, if any areal movement past the pond boundary in those directions.

The areal and cross-sectional models show very similar trends regarding the direction of solute movement. This is most apparent in the prediction of westward solute movement. The areal and W-E cross-sectional models both calculated the same extent of solute migration. The areal model predicted solute arrival at Pit 2 about three years earlier than the W-E cross-sectional model. This is expected considering the conservative assumptions used in the areal model.

Figures 57 - 60 show areal solute movement for velocity fractions of 0.5, 0.3, 0.2, and 0.1, respectively. As expected, the areal model predicts greater horizontal solute movement than the cross-sectional models at these lower velocity fractions.

Figure 61 shows unattenuated solute movement from 1995-2010. By 1995 regional flow has been re-established and the solutes are swept eastward towards the outcrop area at a velocity of about 35 feet per year.

The pH beneath the pond will rise as regional ground water reinvades the strata underlying the pond. The rise in pH will remove many solutes from solution. The concentration of solutes will also decrease due to continued adsorption onto the aquifer rocks.

Solutes that remain in solution will eventually be discharged into North Fork Box Creek. The discharged solutes may; (1) move slowly downstream towards Box Creek, (2) be left behind as solids due to evaporation along the seepage face, or (3) seep downward into outcropping sands and shales. Attempts will be made to determine the fate of these solutes as more water quality data is obtained in North Fork Box Creek.

6.2.5.2. Seepage into North Fork Box Creek

The results of the flow models indicate that preferential solute movement occurs westward towards the pits and eastward towards the North Fork Box Creek outcrop area. In support of the latter, seeps can be observed along the sides of North Fork Box Creek. Wet conditions along the bottom of the creek are evidenced by vegetation which includes cattails near the dam. An objective of the modeling study was to calculate seepage into North Fork Box Creek before, during, and after pond operation.

Figure 62 shows calculated seepage rates into North Fork Box Creek as a function of time. Ground-water seepage was calculated to be about 25 gpm before the pond was operational. During the first few years of pond operation the seepage increased from 25 to 33 gpm as a result of relatively high seepage through the Tailings Dam Sand contact area. As the build up of tailings on the contact area reduced the effective permeability of the Tailings Dam Sand, and the cone of depression from surface mining intercepted regional flow, seepage decreased to below 20 gpm.

Seepage into North Fork Box Creek increased from 20 gpm to 40 gpm as the water level in the pond increased. Note that there is a slight lag time (about six months) between maximum pond water level and maximum seepage into North Fork Box Creek.

Seepage decreases as the pond dries and the tailings drain, reaching a minimum value of about 7 gpm. The seepage then slowly increases after 1993 as regional flow is re-established.

Seepage probably occurs further along the outcrop than is indicated by Figures 56 - 61. The apparent seepage face along a narrow portion of North Fork Box Creek predicted by the areal model is a result of space discretization in the model. In reality seepage probably occurs in an elongated band parallel to the outcrop.

7.0. DISCUSSION

Previous chapters have described Highland's geology and hydrology, laboratory studies designed to quantify geochemical interactions between selected solutes and geologic materials, and ground-water flow modeling to determine the subsurface movement of tailings pond seepage. The purpose of this chapter is to use this information to describe the migration of specific solutes. The significance of this migration will be discussed in relation to regulatory standards. The remainder of this chapter will discuss the following topics:

1. Ground-water regulations pertinent to Highland,
2. Categories of solutes,
3. Migration of solutes, and
4. Comparison of predicted solute migration to field data

7.1. GROUND-WATER REGULATIONS PERTINENT TO HIGHLAND

Table 22 summarizes standards described by the draft Environmental Protection Agency (EPA)/Nuclear Regulatory Commission (NRC) Uranium Mine Tailings Control Act, the EPA drinking water standards, the Wyoming Department of Environmental Quality (WY DEQ) ground water standards, and the United States Code of Federal Regulations (CFR) pertinent to water quality. The ranges of solute concentrations permitted by the various standards are also listed. All subsequent comparisons to the regulations will refer to the lowest permissible concentration in those ranges.

Of the 38 solutes and parameters listed, the following 18 were selected for consideration at Highland: Al, As, Cd, Cr, Cu, Fe, pH, Mn, Ni, Se, Th (total), U (total), Zn, SO_4^{-2}, Pb-210, Ra-226, Th-230, and U-238. In addition, six unregulated solutes were also studied: Ca, K, Mg, Na, Si, and Sr. It was felt that consideration of these 23 solutes and pH would provide an adequate understanding of solute movement from the tailings impoundment. However, the study was formulated so that movement of any other solute could be calculated if batch and neutralization tests were performed. No additional flow modeling would be required.

7.2. SOLUTE CATEGORIES

The solutes studied for Highland can be categorized according to regulatory status, attenuation properties when in contact with sand and shales, and ability to remain dissolved in acidic and basic solutions. Figure 63 categorizes the solutes studied for Highland.

The solutes were divided into two main categories: regulated and nonregulated. The regulated solutes were further subdivided depending on whether they exceeded regulatory standards in both acidic and basic solutions or in acidic solutions only. The relative velocities of the solutes exceeding the regulatory standards were then compared to the relative velocity of the acidic front. Note that the acidic front relative velocity of 0.30 was assumed to be an average front movement through both sands and shales. The batch tests indicated that the acidic front moved through the sands at a higher (.42-.49) relative velocity and the shales at a lower (.09-.14) relative velocity.

Although the areal model only simulates flow in the Tailings Dam Sand, most seepage entering the sand must first flow through Fowler Sands and Shales. Contact with shales in the Fowler Formation justifies the use of a relative velocity that reflects sand and shale attenuation properties to track the acidic front. Furthermore, a comparison of Figures 57 and 58 shows that there is little difference between front positions calculated using a relative velocity of 0.30 (which reflects flow through sands and shales) and a relative velocity of 0.50 (which reflects flow through sands only).

7.3. SOLUTE MIGRATION

This section discusses the movement of the 23 solutes considered in this study. The solutes will generally be discussed as groups based on the categorization scheme illustrated in Figure 63. An exception will be the radioactive solutes which will be discussed as a separate group.

7.3.1. Unregulated Solutes (Ca, K, Mg, Na, Si, Sr)

The incentive for studying unregulated solutes was to identify tracer elements that could be used to verify the flow modeling results with field data. The appropriateness of using these solutes in the field verification program will be discussed later in the chapter.

The unregulated solutes considered in the study generally are not attenuated by any of the geologic materials. Exceptions are K and Si which are strongly attenuated by sands and shales, respectively. Figures 40, 41, and 42 show unattenuated movement in the W-E, NW-SE, and SW-NE cross sections, respectively. All four unattenuated solutes (Ca, Mg, Na, Sr) will move through the Upper Ore Body Sand and be stopped by the underlying shale. Figure 56 illustrates the maximum horizontal movement predicted by the areal flow model.

Because K is strongly attenuated by the Tailings Dam Sand, it is unlikely that it will migrate any significant distance outside the Fowler Formation. Silicon is attenuated by shales and therefore will only enter the Tailings Dam Sand where it is in direct contact with the pond bottom. Although Si will migrate within the Tailings Dam Sand, very little movement will occur into overlying or underlying shales.

7.3.2. Radioactive Solutes[2] (U, Th, Pb-210, Ra-226, U-238, Th-230)

As shown in Figure 63 and Table 14, all of the radioactive substances considered in this study are strongly attenuated by the Tailings Dam Sand and Shale. The highest relative velocity reported for any of the radioactive solutes is 0.104 for U-238 in the Tailings Dam Sand. Figures 49, 50, and 51 show that vertical solute migration for a relative velocity of 0.10 is limited to the upper half of the Tailings Dam Shale.

Figure 60 shows horizontal solute movement for the same velocity fraction. The greatest horizontal migration is westward where solutes move a total of about 400 feet from 1972-1992. At this time the solutes reverse direction and move towards the outcrop. Note that most of the radioactive solutes will move only a small fraction of the distances shown in the above figures.

7.3.3. Solutes that Exceed Regulatory Limits in Both Acidic and Basic Environments (Al, Cr, Cu, Fe, Se)

Three of the five solutes in this cateogry, Cr, Fe, and Se, are strongly attenuated by both the sands and the shales. The relative velocities of these solutes are less than or equal to 0.02 for all geologic units. Solute migration is expected to be less than one-fifth the distances shown in Figures 49, 50, 51, and 60.

Cu is attenuated by all geologic materials studied for Highland. It has relative velocities of 0.156, 0.008, 0.088, and 0.010 in the Tailings Dam Sand, Tailings Dam Shale, Ore Body Sands, and Ore Body Shales, respectively. Figures 46, 47, and 48 show the results of the cross-sectional models for a velocity fraction of 0.20. The migration of Cu is expected to be considerably less than the region enclosed by the 0.20 velocity fraction contour. As shown, Cu is not expected to migrate below the Tailings Dam Shale.

Figure 59 illustrates areal solute movement for a velocity fraction of 0.20. Again, the 0.20 relative velocity contour bounds the region of Cu migration. The figure shows that maximum migration occurs to the west with the solute moving a total of about 600 feet from 1972-1992.

Aluminum is expected to move further than the other solutes in this category. The batch tests indicated that Al was not attenuated by the Tailings Dam or Ore Body Sands. However, it was strongly attenuated by the Tailings Dam and Ore Body Shales (relative velocities of 0.005 and 0.023, respectively).

Figures 40, 41, and 42 show vertical solute movement for a relative velocity of 1.0. Because of high attenuation in the Tailings Dam Shale it is unlikely that Al will move through it. Therefore, Al should be confined to the Tailings Dam and Fowler Sands.

[2] The predicted migration of Pb-210, Ra-226, U-238, and Th-230 is based on analyses performed by Battelle (1980b) on the Wasatch Formation at Morton Ranch.

Horizontal movement of Al is difficult to predict. Although Al is not attenuated by the Tailings Dam Sand, most pond seepage occurs through the Fowler Sands and Shales. Much of the pond fluid entering the Tailings Dam Sand will have been cleansed of Al by the overlying Fowler Shales. Figure 56 shows an extremely conservative estimate of Al migration. The laboratory program predicts Al concentrations of 18 mg/l in the neutralized zone which exceeds the 5.0 mg/l EPA and WY DEQ water standards for livestock.

7.3.4. Solutes that Exceed Regulatory Limits in Acidic Environments But Not in Basic Environments (pH, As, Cd, Mn, Ni, Zn)

Migration of the acidic front is an important factor in relating the movement of solutes in this category to regulatory standards. Several solutes (Cd, Mn, and Zn) are not attenuated by any of the geologic units. However, when pond water moves past the acidic front, the concentrations of these solutes drop below the regulatory limits. Thus the acidic front bounds the region where the solute concentrations exceed ground-water regulations.

Figures 43, 44, and 45 illustrate movement of the acidic front calculated by the cross-sectional models, assuming the front moves at an average relative velocity of 0.30. The acidic front moves vertically to near the bottom of the Tailings Dam Shale but stops short of entering the Upper Ore Body Sand. The cross-sectional models show limited horizontal movement.

Figure 58 shows areal movement of the acidic front. Maximum movement occurs west and southwest of the pond with maximum excursions of about 800 feet. The above figures also denote where Cd, Mn, and Zn exceed regulatory limits. The concentrations of these solutes within the acidic zones are expected to be similar to those in the tailings pond. Those concentrations are 30 ppm, 45 ppm, and 3.2 ppm for Cd, Mn, and Zn, respectively.

Nickel is attenuated by the Tailings Dam Shale (relative velocity of 0.066) but not by any of the other formations. It is anticipated that Ni will move areally through the Tailing Dam Sand the same as Cd, Mn, and Zn, but will not penetrate vertically into the Tailings Dam Shale. The concentration of Ni behind the acidic front should be about 1.4 ppm.

Arsenic is strongly attenuated by all geologic units considered in this study. It is expected to move at a velocity fraction less than 0.05 in all formations. Figures 49, 50, 51, and 60 show solute movement for a relative velocity of 0.10. Arsenic will migrate less than half the distances shown, resulting in a total maximum horizontal movement of about 175 feet by 1992.

7.4. COMPARISON OF PREDICTED SOLUTE MIGRATION TO FIELD DATA

It is desirable to compare predicted solute migration with field data. Such comparisons indicate the validity of the model used to predict solute transport and the appropriateness of data input to the model. The following text compares the results of this study to field data and provides a foundation for future comparisons.

Two relative velocity fronts are of special interest; the 1.0 front, which describes unattenuated solute movement, and the 0.30 front, which predicts the position of the acidic zone. The acidic front is easily tracked by monitoring the pH in observation wells. The pond pH (2.4) is considerably lower than the pH of the ground water (above 7.0).

The unattenuated front is more difficult to track. It is necessary to find a tracer which; (1) is not attenuated by the porous media, (2) has a significantly higher concentration in the pond than in the ground water, and (3) is not dependent on pH.

Table 23 lists 11 solutes that were considered as tracers for the 1.0 relative velocity front. Cadmium, Mn, Sr, Zn, and Si were eliminated from consideration because their concentrations were pH dependent. Potassium and sulfate were eliminated because they had relative velocities other than 1.0. Sodium was eliminated because there was relatively little difference between its concentration in the pond and the local ground water. The remaining candidates were Ca, Mg, and Cl. Although Cl analyses were not done for the batch tests it is generally a very good tracer.

The results of the batch tests indicate that Ca and Mg are not attenuated by any of the geologic units underlying the pond. Also, the concentration of Mg only changed from 375 to 340 ppm when the tailings solution was titrated to a pH of 8. This indicates that the concentration of Mg is relatively insensitive to pH changes. The pH dependency of Ca could not be determined from the neutralization experiments since $Ca(OH)_2$ was used to titrate the tailings liquor. Despite the uncertainties regarding Cl and Ca, it appears that, along with Mg, they are the best tracers for unattenuated solute movement.

Extensive water quality data has been taken at Highland over the past few years. However, many of the water-quality monitoring wells were completed in two or more zones and "grab" samples were obtained for analysis. Multiple well completions and the sampling technique make it difficult to interpret the data.

An ambitious program was undertaken at Highland in 1981 to upgrade the water-quality monitoring program. Well completions were verified using down-hole viewers, new monitor wells were drilled, and a geochemical consultant was retained to recommend proper sampling techniques. This new sampling program became operational in October, 1981 (see Appendix C). The remainder of this section compares the results of the areal model to water-quality data obtained from the sampling program during the last quarter of 1981.

A conclusive comparison would require data over a relatively long period of time. However, this preliminary comparison, which is limited to two months of data, gives an indication of the accuracy of the model predictions and serves as an example of how the model results and field data can be compared.

Figure 64 shows the areal model results for 1982 overplotted on the Ca water-quality data for the Tailings Dam Shale and all overlying formations. Based on the limited data, the model appears to predict unattenuated solute movement north and south, of the pond accurately. East of the pond the model underpredicts solute movement near the outcrop. This is probably caused by describing the outcrop area as discrete blocks in the finite-difference model. Because of discretization, the model predicts water will seep from two points near the upstream end of North Fork Box Creek. Actually, seepage is more spead out along the outcrop.

West of the pond the areal model predicts background concentrations in Wells IX (Tailings Dam Sand) and X (Fowler Formation). Measured Ca concentrations in these wells are 601 and 489 ppm, respectively. These concentrations are very similar to the pond concentration of 584 ppm. This indicates that the areal model underpredicted unattenuated solute movement west of the pond.

Figure 65 displays the unattenuated areal model results with measured concentrations of Mg in the Tailings Dam Shale and overlying formations. Data in Wells VII (Tailings Dam Sand), XIX (Fowler Formation), XXI (Tailings Dam Sand), and XII (Tailings Dam Sand), are in close agreement with the areal model predictions. Data in Wells IX (Tailings Dam Sand) and X (Fowler Formation) have concentrations of 267 and 151 ppm, respectively. These concentrations are between the background (1.5-15 ppm) and pond (375 ppm) concentrations. Data in Wells IX and X indicate that the areal model underpredicts unattenuated solute movement west of the pond.

Figure 66 compares the areal model results for unattenuated solutes to measured Cl concentrations in the Tailings Dam Shale and overlying formations. The comparison is favorable north and south of the pond. East of the pond the well data again indicate seepage is spread out along the outcrop area.

West of the pond the concentrations measured in Tailings Dam Sand Well IX (26 ppm) and Fowler Well X (300 ppm) differ significantly. This difference could be accounted for by Cl attenuation by the Fowler Formation or errors in sampling or analysis. After more data is collected, Cl concentrations west of the pond will be better understood.

There are two likely reasons for the high Ca, Mg, and Cl concentrations in wells near the western end of the pond. First, tailings have been discharged in the western part of the pond from 1972 to 1977. The high concentrations may be a result of vertical leakage of liquor to underlying formations near the discharge spigot.

Second, a high permeability streak may exist in the Tailings Dam and Fowler Sands which causes increased fluid flow west of the pond. Note that the surface mine would intersect such high permeability streaks and prevent extensive fluid migration due to the low permeability of the backfill. Although the areal model may underpredict westward solute migration, the surface mine will limit solute excursions in that direction.

Figures 67 - 69 compare the areal model results to Ca, Mg, and Cl concentrations measured in the Upper and Middle Ore Body Sands, respectively. Note that the background levels for these solutes were assumed to be the same as for the Tailings Dam Sand. Concentrations of all three solutes measured in the Ore Body Sands indicate that background concentrations in the Tailings Dam Sand are representative of background concentrations in the Ore Body Sands.

The areal model predictions are in good agreement with the measured concentrations of all three solutes. The only area where the water-quality measurements indicate that solutes have exceeded model predictions is near the outcrop. Again, this is probably due to space discretization in the areal model.

Figures 70 and 71 show the areal model predictions of acidic front movement (relative velocity of 0.30) and measured pH values for the formations above the Tailings Dam Shale and the Ore Body Sands, respectively. The only well completed above the Tailings Dam Shale that the model predicts will be within the acidic zone is Well XII, which is near the southern edge of the pond. Measurements in Well XII indicate a pH of 7.6 which is in the range of background values. This indicates that the areal model is overpredicting acidic front movement southwest of the pond.

In summary, areal model predictions of unattenuated solute and acidic front movement are in good agreement with monitor well data north and south of the pond. East of the pond where fluid seeps into North Fork Box Creek, solute migration is sometimes underestimated due to discretization of the areal model. However, seepage does not seem to be extensive based on field data.

Calcium, Mg, and Cl concentrations, similar to those in the pond, were measured in Well X (Fowler Formation). Calcium and Mg were at pond concentrations in Well IX (Tailings Dam Sand), and Cl was at background concentration. These data show that unattenuated solutes have traveled about 1300 feet further west than predicted by the areal model for 1982. The presence of these solutes may be caused by high permeability streaks in the Tailings Dam and Fowler Sands or vertical leakage near the tailings discharge spigot. Calcium, Mg, and Cl were not detected in the Ore Body Sands west of the pond.

Measurements of pH in Well XII (Tailings Dam Sand) indicate that the areal model overpredicted migration of the acidic front south of the pond. However, overall predictions of acidic front movement are generally in good agreement with monitor well data.

8.0. SUMMARY

This study was performed at the request of Exxon Minerals Company. The purpose of the study was to predict seepage and solute migration from the Highland Uranium Mill tailings impoundment in Converse County, Wyoming. The study results were used to address questions posed by the Nuclear Regulatory Commission regarding the amount and direction of seepage from the impoundment, the adequacy of the water-quality monitoring system near the impoundment, and seepage into North Fork Box Creek. The impoundment has been in continuous operation since October, 1972. It will become inactive when mill shutdown occurs in December 1983.

The study consisted of three main endeavors: (1) a laboratory program to quantify the chemical interactions between the pond liquor and geologic strata underlying the impoundment, (2) a geologic modeling program to describe the structure and lithology of Highland, and (3) a flow modeling program to calculate pond seepage and the migration of solutes.

The laboratory program included batch (static) tests between tailings solution and rock samples, titration of tailings solution by calcium hydroxide solution to given pH levels, and a column flood of Tailings Dam Sandstone by tailings pond liquid. Mineralogical analyses were also performed to help characterize the sands and shales.

Geologic models of the Highland area were developed using Exxon Production Research Company's computer programs for two- and three-dimensional geologic mapping and modeling. The two-dimensional mapping program was used to construct geologic surfaces and to build those surfaces into a stratigraphic framework. The three-dimensional modeling program was used to interpolate measured resistivity values and relate those values to lithology.

A finite-difference flow model developed by Exxon Production Research Company was used to simulate seepage and solute movement through geologic strata underlying the tailings pond. Three cross-sectional models and one areal model were constructed and simulations were performed to the year 2000. The model results for unattenuated solute movement and acidic front movement were compared to water-quality data from monitoring wells.

The approach taken in this study to model solute movement has the following advantages:

1. Chemical attenuation is based on data obtained by actually contacting the pond liquor with aquifer rock.

2. The chemical attenuation experiments are linked directly to the flow calculations by means of the relative velocities.

3. A wide range of relative velocity fronts are tracked which provides the flexibility to track any solute front for which batch test data is available.

4. Flow is calculated using a finite-difference simulator capable of modeling two fluid phases, nonhomogeneous porous media, and transient boundary conditions.

As mentioned previously, the study approach also has the following limitations:

1. Hydrodynamic dispersion is not calculated.

2. A simplified model (apparent distribution coefficient model) is used to account for the complex chemical reactions occurring between the pond liquor and the aquifer rock.

3. Radioactive decay and the generation of daughter products is only qualitatively considered.

4. The solution mine pilot is not modeled.

8.1. RESULTS AND CONCLUSIONS

The results and conclusions obtained from the laboratory, geologic modeling, and flow modeling programs can be summarized as follows:

8.1.1. Laboratory Program

8.1.1.1. Batch Tests

Results of the batch tests are given in Figure 14 and Tables 2 - 5.

1. Significant decreases occurred in the concentrations of As, Cr, Cu, Fe, and Se after 30 days of contact with Tailings Dam Sand, Tailings Dam Shale, Ore Body Sand, and Ore Body Shale.

2. The concentrations of K, Mn, Na, and Zn were not significantly affected by contact with the four geologic materials.

3. The concentrations of Mg, Ca, and Cd increased after contact with the four geologic materials.

4. The concentration of Si increased when contacted with Tailings Dam Sand and decreased when contacted with the other geologic materials.

5. The concentration of Ni decreased when contacted with the Tailings Dam Shale and increased when contacted with the other geologic materials.

6. The concentration of Sr increased significantly when contacted with the Tailings Dam Shale and remained about the same when contacted with the other geologic materials. Increases in Sr concentration were noticed after 3, 7, and 15 days of contact, but decreased between 15 and 30 days of contact.

7. The concentration of Al decreased when contacted by the shales and increased when contacted by the sands.

8. Thorium and uranium concentrations increased when contacted with the Ore Body Sand and decreased when contacted with the other geologic materials.

9. The concentration of sulfate increased slightly when contacted with the Ore Body Sand and decreased when contacted with the other geologic materials.

10. The pH of the tailing solution increased from 2.4 to between 3.2 and 3.5 after 30 days of contact with the geologic materials.

11. The Eh decreased from 846 mv (millivolts) to between 618 and 712 mv after 30 days of contact with the geologic materials.

8.1.1.2. Titration Experiments

Results of the titration experiments are given in Figure 15 and Table 6.

1. The concentrations of As, Ni, Zn, Al, Fe, Mn, Si, and Cd decreased significantly when the tailings solution was titrated to a pH of 8.0.

2. The concentrations of Cr and Cu were relatively insensitive to increasing pH.

3. The concentrations of Sr, K, Mg, and Na appeared to increase with increasing pH. The apparent increases of K, Mg, and Na may have been caused by masking of these cations by the high concentration of sulfate in the tailings solution. During the progress of the titrations, the sulfate ion concentration was decreased by dilution and by precipitation as gypsum. The decreases in sulfate concentration may have resulted in apparent increases in K, Mg, and Na concentrations.

8.1.1.3. Column Flooding Experiment

Results of the column flooding experiment are given in Figure 16.

1. The Tailing Dam Sand has the capacity to neutralize tailings solution.

2. When tailings solution at pH 2.4 was pumped through a column of disaggregated Tailings Dam Sand, effluent pH was 7.7, 5.8, 4.2, and 3.8 after passage of 1, 2, 3, and 4 pore volumes of tailings solution, respectively.

8.1.1.4. Mineralogical Analyses

Results of the mineralogical analyses are given in Tables 8 and 9.

1. No mineralogical differences were found between undried and oven-dried shales other than dehydration of expandable clays upon drying, and subsequent collapse of the expandable clay matrices.

2. After being in contact with the geologic materials, the tailings solution evidently became saturated with calcium due to alteration of mineral species or ion exchange, and gypsum began to precipitate from solution.

3. Contact with tailings solution caused a general decrease in average grain size in the sandstone samples. Rock fragments originally present were broken down to individual mineral constituents.

4. During the batch tests a yellow clay-like coating was gradually deposited on sand grains. There was more of the coating on 30-day exposure samples than on 3-day samples, but there were lower concentrations of U, Ca, and K in the coating of the 30-day samples than the 3-day samples. The coating had Si, Fe, and Al as the major cations, generally in the order Si >Fe >Al. Minor amounts of Mg, K, Ca, S, and Ti were detected at different times.

5. During the batch tests there was a gradual alteration of iron- and magnesium-rich minerals to oxides and/or clays, and a gradual loss of feldspars through grain size reduction to silt, or alteration to clays.

8.1.2. Geologic Modeling

1. The Tailings Dam Shale is continuous around the pond except where it has been eroded in North Fork Box Creek.

2. Three representative cross sections, which were orientated west-east, 45 degrees west of north, and 45 degrees east of north, demonstrated the limited range of structure, formation thickness, and lithology seen in the study area.

8.1.3. Flow Modeling

8.1.3.1. Cross-Sectional Models

The results of the cross-sectional models are shown in Figures 40 - 52.

1. The pond acts as a ground-water divide causing horizontal solute movement away from the pond in all directions.

2. Unattenuated solutes will move vertically through the Tailings Dam and Upper Ore Body Sands, but will not enter the Middle Ore Body Sand.

3. The farthest migration of unattenuated solutes will occur west of the pond where they will reach the northern edge of Pit 2 about the year 1995. By that time the pond will be dry and regional flow re-established. It is unlikely that solutes will migrate to lower sand formations through the backfilled pit.

4. Unattenuated solute movement to the northwest and southeast is limited to within a few hundred feet of the pond.

5. The acidic front (velocity fraction of 0.30) will not migrate below the Tailings Dam Shale.

6. Horizontal migration of the acidic front is limited to within 100 feet of the pond.

7. Very little solute movement occurs at velocity fractions below 0.20.

8. Total seepage from the tailings impoundment rises to about 100 gpm (gallons per minute) within a year after the pond is put into operation. By 1974 seepage begins to decrease due to the buildup of low permeability tailings and reaches 50 gpm about 1975. Seepage then begins to increase as the water level rises and the cone of depression from surface mining lowers the water potential under the pond. The seepage rate increases at about 19 gpm per year until the maximum water level in the pond is attained in 1983. The mill is then shut down and, as the pond dries, seepage decreases at about 38 gpm per year. Seepage ceases in 1991 after all the water in the pond and tailings has either evaporated or drained into underlying formations.

8.1.3.2. Areal Model

The results of the areal model are shown in Figures 56 - 62.

1. Maximum unattenuated solute movement will occur west of the pond, reaching the northern part of Pit 2 about the year 1992.

2. Unattenuated solutes will move a maximum of 1300 feet southwest and 300 feet northwest of the pond.

3. The acidic front moves a maximum of about 500 feet from the pond.

4. By 1995 regional flow will be re-established and the solutes will be swept eastward towards North Fork Box Creek at a velocity of about 35 feet per year.

5. The pH beneath the pond will rise as regional ground water reinvades the strata underlying the pond. The rise in pH will remove many solutes from solution. The concentration of some solutes will also decrease due to continued adsorption onto the aquifer rocks.

6. Solutes that remain in solution will eventually be discharged into North Fork Box Creek. The discharged solutes may; (1) move slowly downstream towards Box Creek, (2) be left behind as solids due to evaporation along the seepage face, or (3) seep downward into outcropping sands and shales.

7. Ground-water seepage into North Fork Box Creek was about 25 gpm before the tailings pond was operational. During the first few years of operation seepage increased from 25 to 33 gpm as a result of relatively high seepage where the Tailings Dam Sand was in direct contact with the pond bottom. As the build up of tailings on the contact area reduced the effective vertical permeability of the Tailings Dam Sand, and the surface mine intercepted regional flow, seepage decreased to below 20 gpm. Seepage increases from 20 gpm to 40 gpm as the water level in the pond increases between 1977 and 1983. After 1983, seepage decreases as the pond dries and the tailings drain, reaching a minimum value of about 7 gpm. About 1993 the seepage begins to increase as regional flow is re-established.

8.1.4. Solute Migration

1. The solutes studied for Highland can be categorized according to regulatory status, attenuation properties when in contact with sand and shales, and ability to remain dissolved in acidic and basic solutions. The categories used for this study are: unregulated solutes, radioactive solutes, solutes that exceed regulatory limits in both acidic and basic environments, and solutes that exceed regulatory limits in acidic environments but not in basic environments.

2. The unregulated solutes are Ca, K, Mg, Na, Si, and Sr. These solutes generally are not attenuated by any of the geologic units underlying the pond. Exceptions are K and Si which are strongly attenuated by sands and shales, respectively.

   All four unattenuated solutes (Ca, Mg, Na, Sr) will move through the Upper Ore Body Sand and be stopped by the underlying shale. Maximum horizontal movement will be about 1200 feet west and southwest of the pond.

   Because K is strongly attenuated by the Tailings Dam Sand, it is unlikely that it will migrate any significant distance outside the Fowler Formation. Silicon is attenuated by shales and therefore will only enter the Tailings Dam Sand where it is in direct contact with the pond bottom. Although Si will migrate within the Tailings Dam Sand, very little movement will occur into overlying or underlying shales.

3. The radioactive solutes are U (total), Th (total), Pb-210, Ra-226, U-238, and Th-230. All of these substances are strongly attenuated by the Tailings Dam Sand and Shale. Vertical migration will not extend below the Tailings Dam Shale. Maximum horizontal movement is estimated to be less than 100 feet from the pond.

4. The solutes that exceed regulatory limits in both acidic and basic environments are Al, Cr, Cu, Fe, and Se.

   Chromium, Fe, and Se are very strongly attenuated by both the sands and shales. Essentially no vertical or horizontal solute migration is expected.

   Copper is attenuated by all geologic materials studied for Highland. It is not expected to migrate below the Tailings Dam Shale, and maximum horizontal movement will be less than 600 feet to the west.

   Aluminum is not attenuated by the Tailings Dam or Ore Body Sands. However, it is strongly attenuated by the Tailings Dam and Ore Body Shales. Most of the fluid seeping from the pond will be cleansed of Al as it moves through the Fowler Shales (assuming the Fowler Shale adsorbs Al as do the Tailings Dam and Ore Body Shales). A very conservative estimate of Al migration indicates maximum horizontal movement of about 1200 feet southwest of the pond. The laboratory program predicts Al concentrations of 18 mg/l in neutral ground water. This exceeds the 5.0 mg/l EPA and WY DEQ water standards for livestock.

5. The solutes that exceed regulatory limits in acidic but not in basic environments are H (pH), As, Cd, Mn, Ni, and Zn.

   Migration of the acidic front is an important factor in relating the movement of solutes in this category to regulatory standards. Several solutes (Cd, Mn, and Zn) are not attenuated by any of the geologic units. However, when pond water moves past the acidic front, the concentrations of these solutes drop below the regulatory limits. Thus, the acidic front bounds the region where the solute concentrations exceed ground-water regulations.

   The acidic front moves vertically to near the bottom of the Tailings Dam Shale but stops short of entering the Upper Ore Body Sand. Maximum horizontal movement occurs west and southwest of the pond with maximum excursions of about 800 feet. The concentrations of Cd, Mn, and Zn within the acidic zone are expected to be approximately the same as they are in the tailings pond. Those concentrations are 30 ppm, 45 ppm, and 3.2 ppm for Cd, Mn, and Zn, respectively.

   Nickel is attenuated by the Tailings Dam Shale but not by any of the other formations. It is anticipated that Ni will move areally through the Tailings Dam Sand the same as Cd, Mn, and Zn, but will not penetrate vertically into the Tailings Dam Shale. The concentration of Ni behind the acidic front should be about 1.4 ppm.

   Arsenic is strongly attenuated by all geologic units considered in this study. It will not move below the Tailings Dam Shale and maximum horizontal migration will be about 175 feet to the west and southwest.

6. To evaluate the accuracy of this study, areal model predictions of the seepage and acidic front positions were compared to field data. The seepage front was tracked by measuring calcium, magnesium, and chloride concentrations. These solutes do not appear to react with any of the geologic units underlying the tailings impoundment and should move fast as the seepage front. The acidic front was tracked using pH measurements.

   The position of the seepge front predicted by the areal model was in good agreement with monitor well data north and south of the pond. East of the pond, where fluid seeps into North Fork Box Creek along the outcrop area, solute migration is sometimes underestimated due to the finite-difference gridding (discretization) of the areal model. Tracer concentrations in wells west of the pond indicate that the seepage front has traveled about 1300 feet further west than predicted.

   The predicted position of the acidic front was in good agreement with monitor well data north, west, and east of the pond. South of the pond the model appears to slightly overpredict acidic front migration.

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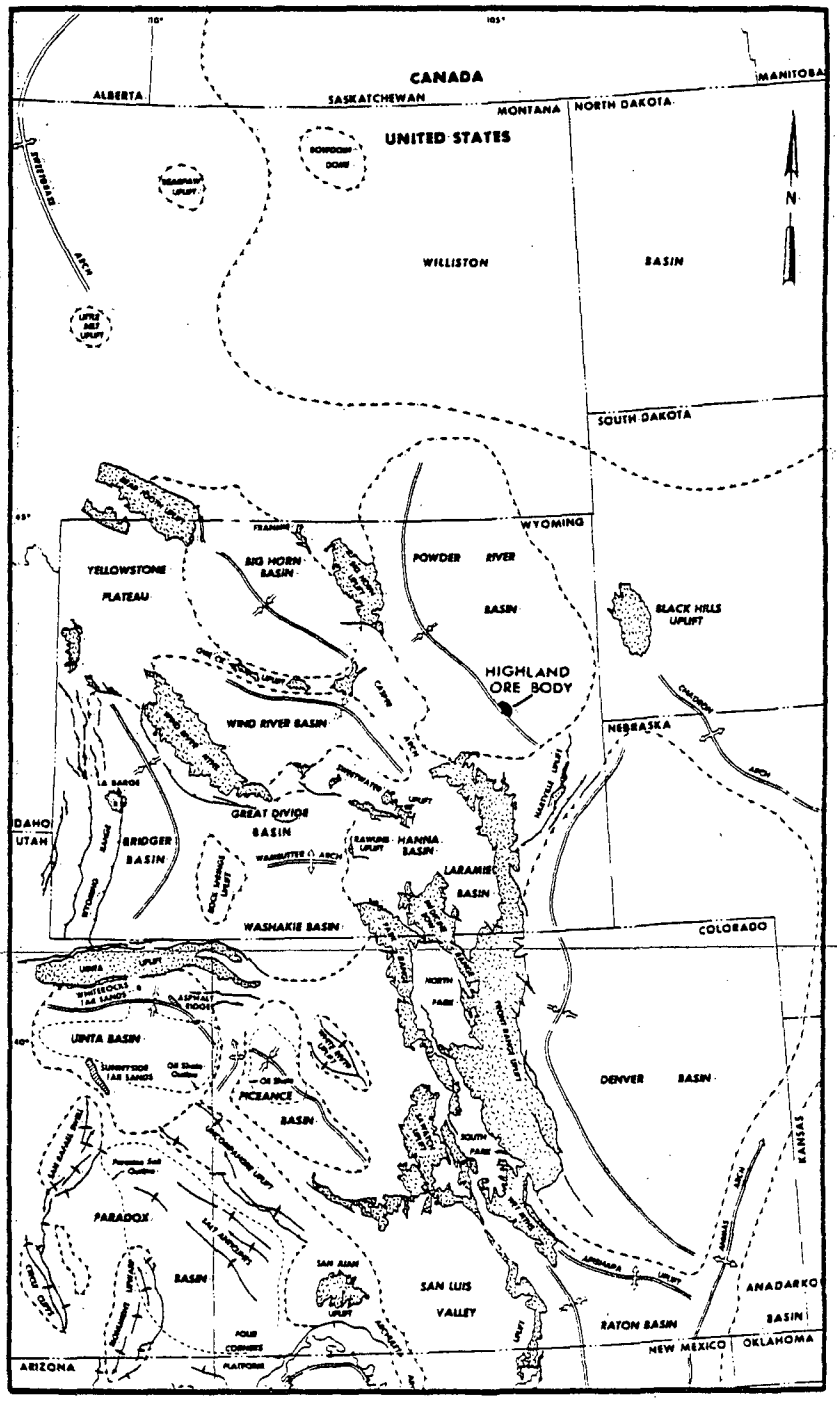


0 100
MILES

FIG. 1 REGIONAL POSITION OF POWDER RIVER BASIN
(FROM LANGEN AND KIDWELL, 1970)

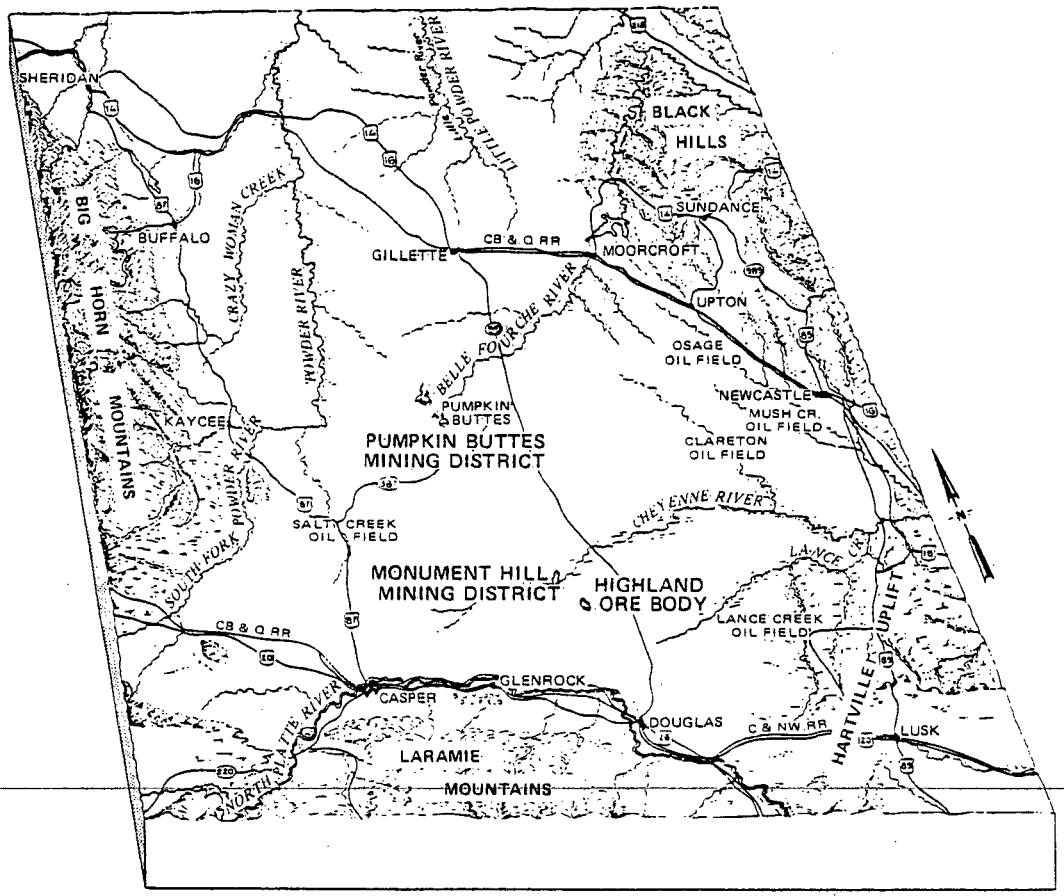


FIG. 2 RELIEF MAP OF POWDER RIVER BASIN, WYOMING AND ADJACENT MOUNTAINS
(FROM WYOMING GEOLOGICAL ASSOC. GUIDEBOOK, 1958)

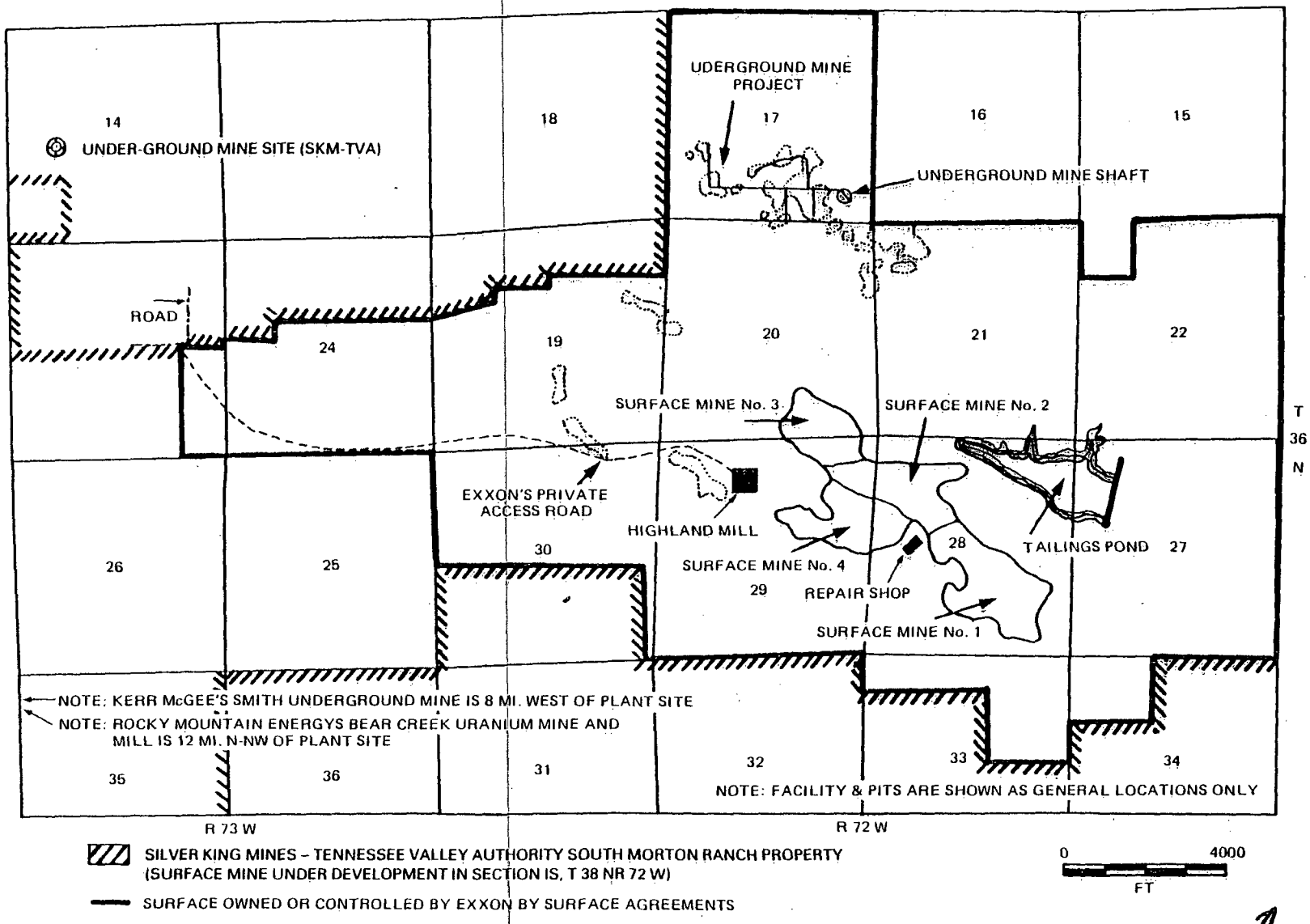


FIG. 3 LOCATION AND LAYOUT OF THE HIGHLAND URANIUM OPERATIONS (FROM EXXON COMPANY, USA: 1973)

Regional flow to NE

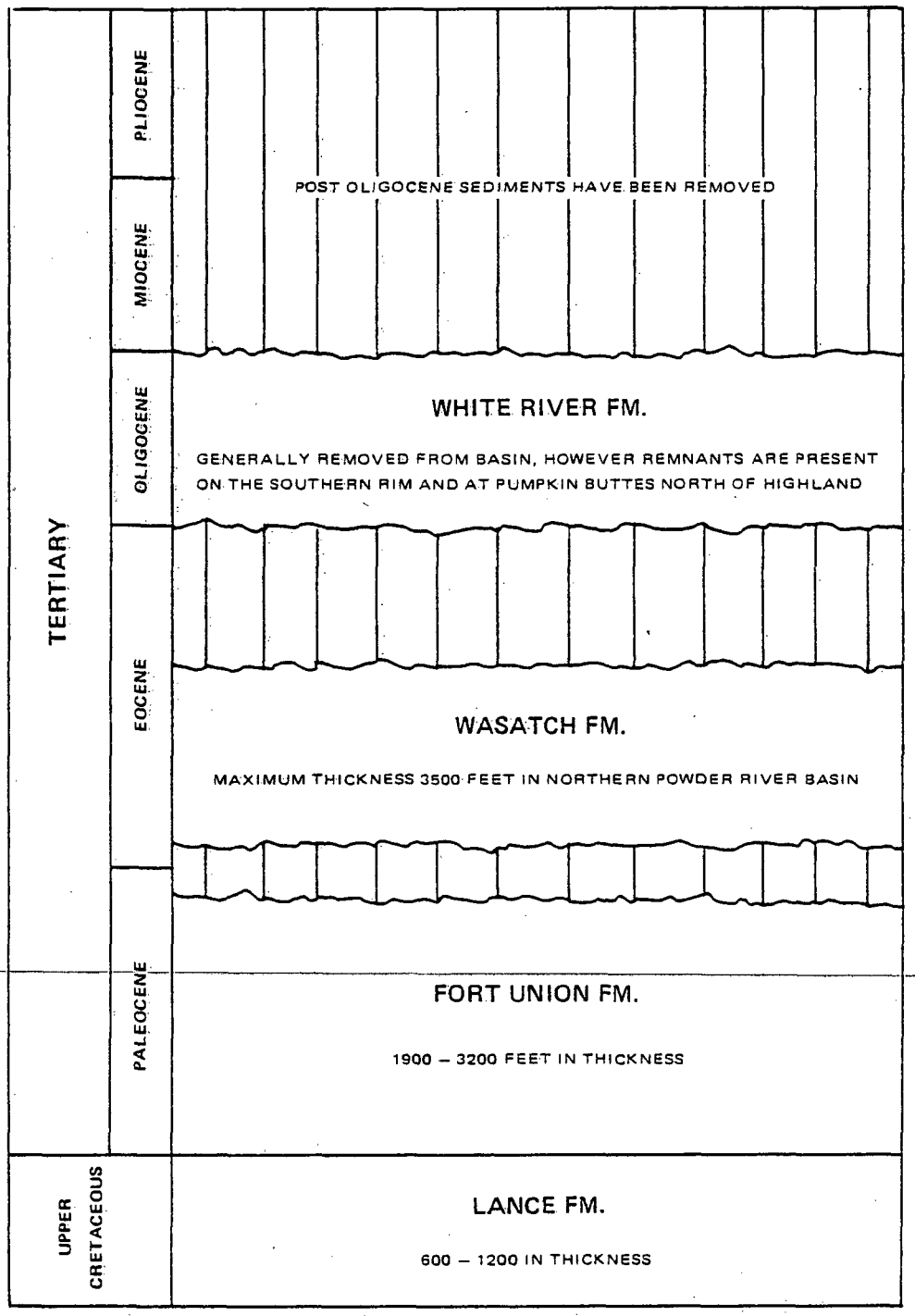


FIG. 4 GEOLOGIC SEQUENCE OF THE POWDER RIVER BASIN
(FROM LANGEN AND KIDWELL, 1970)

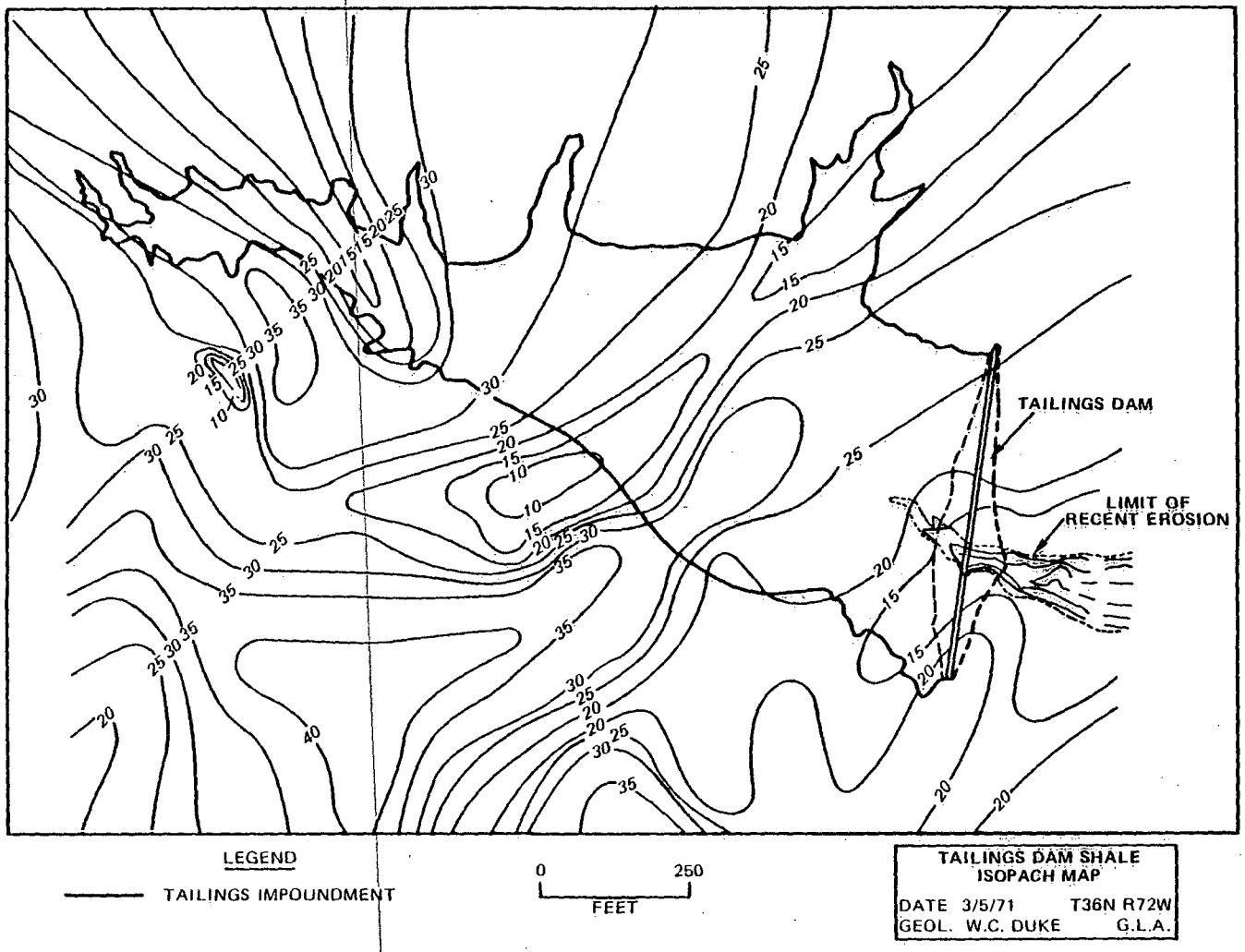
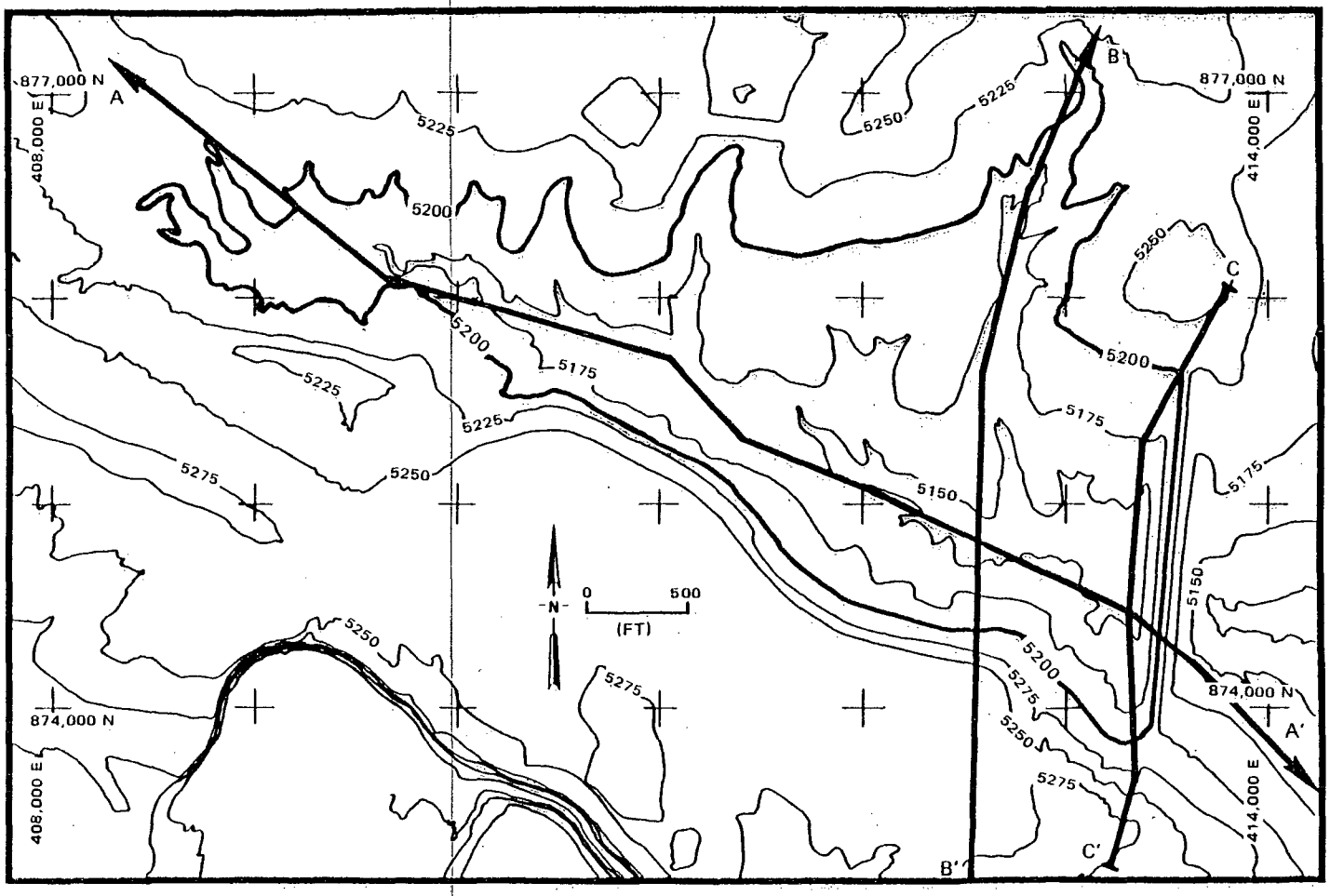


FIG. 5 TAILINGS DAM SHALE ISOPACH MAP
(FROM EXXON COMPANY, USA; 1973)



5200 – FOOT CONTOUR APPROXIMATES PROJECTED MAXIMUM POND EXTENT

FIG 6 LOCATIONS OF CROSS SECTIONS A-A', B-B', AND C-C'
(FROM EXXON COMPANY, USA; 1973)

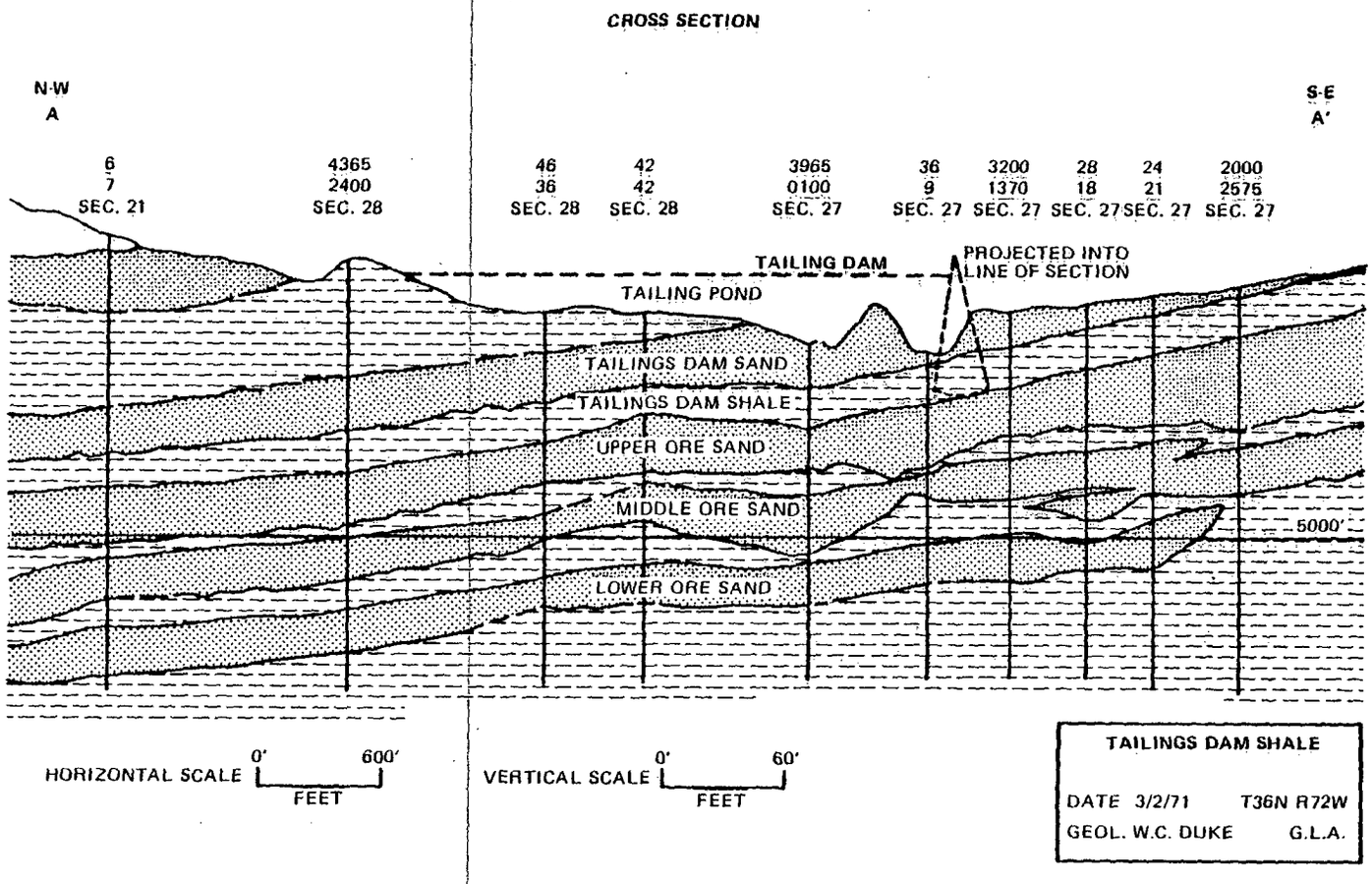


FIG 7 CROSS SECTION A-A'
(FROM EXXON COMPANY, USA; 1973)

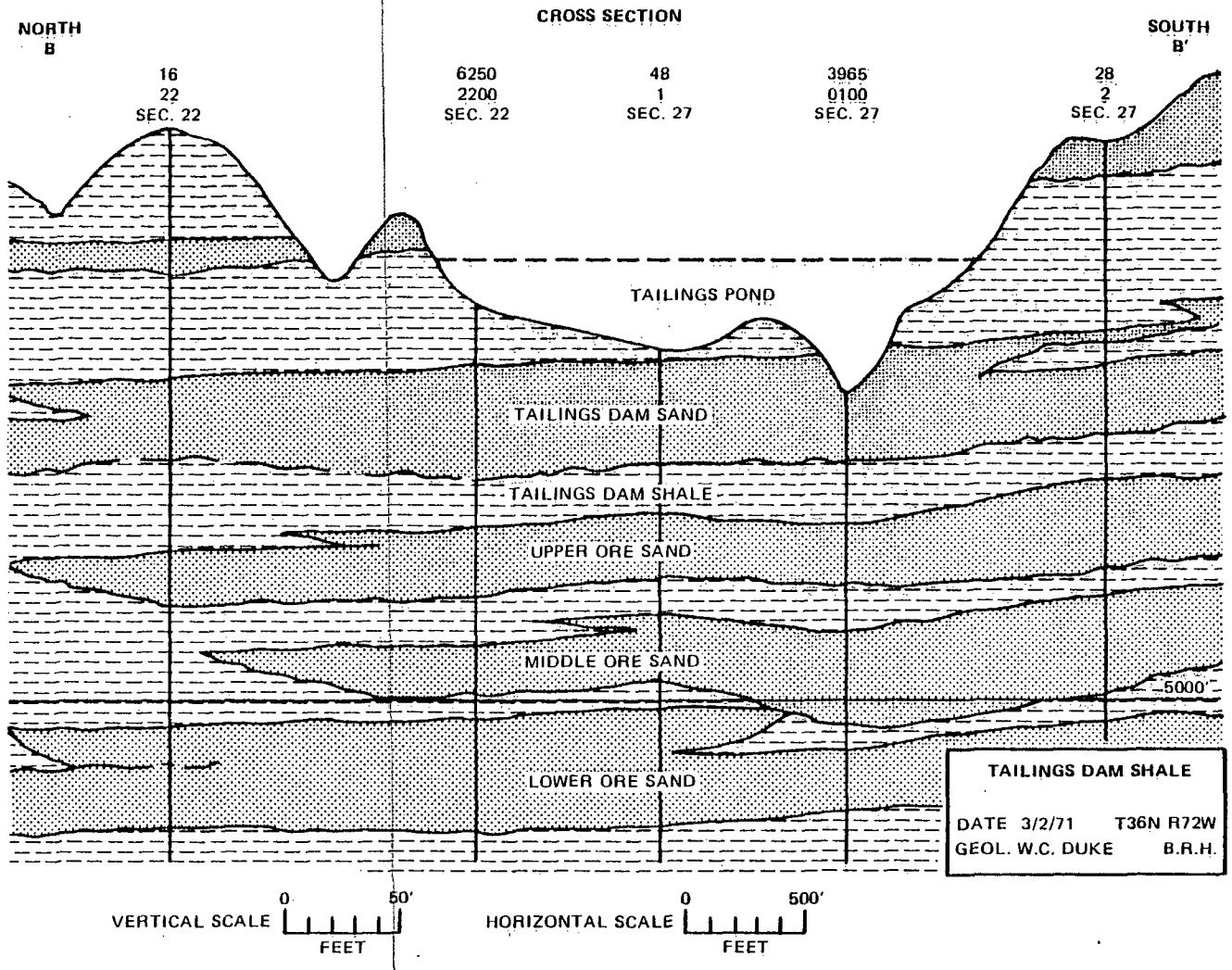


FIG 8 CROSS SECTION B-B'
(FROM EXXON COMPANY, USA; 1973)

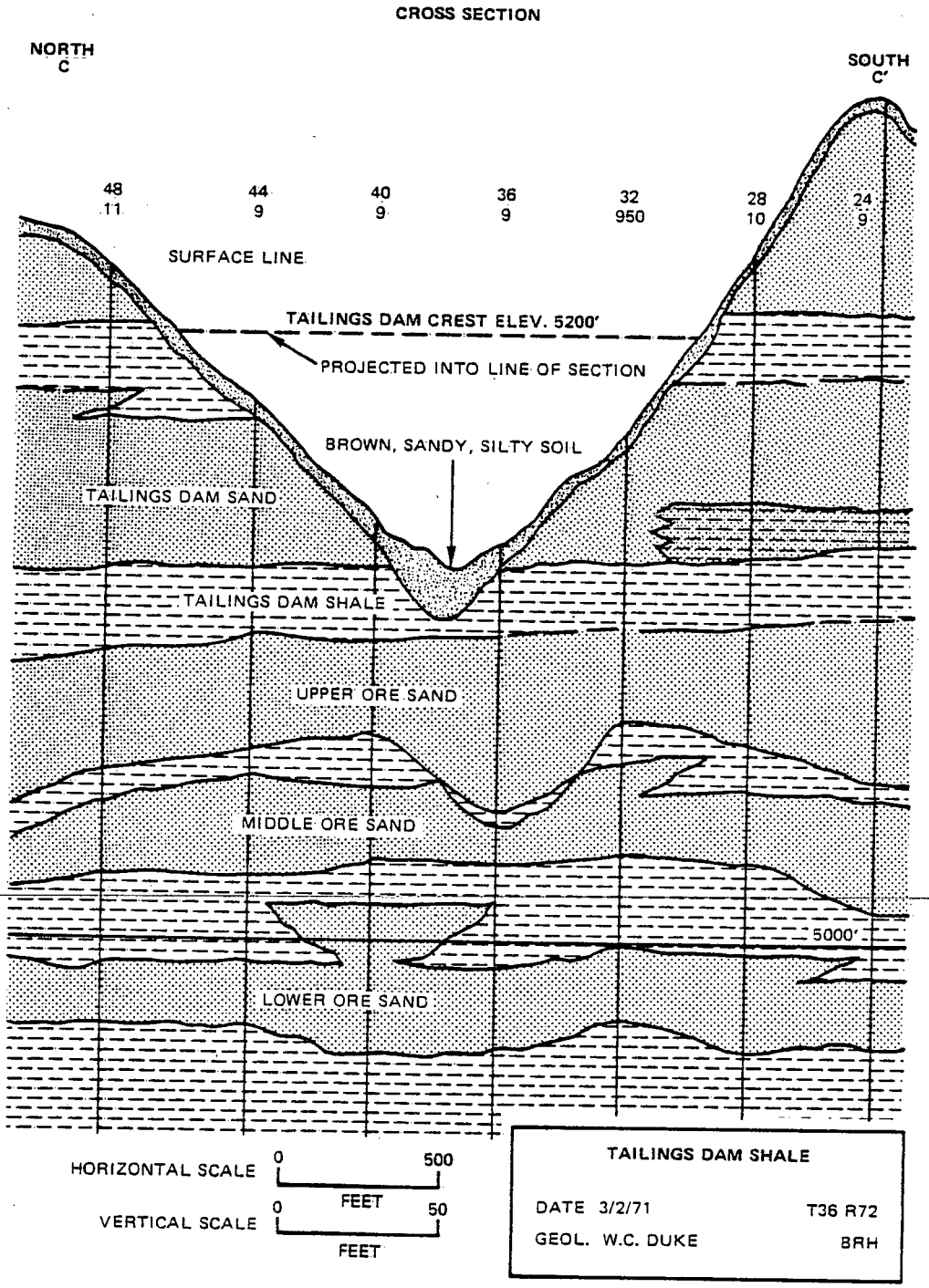
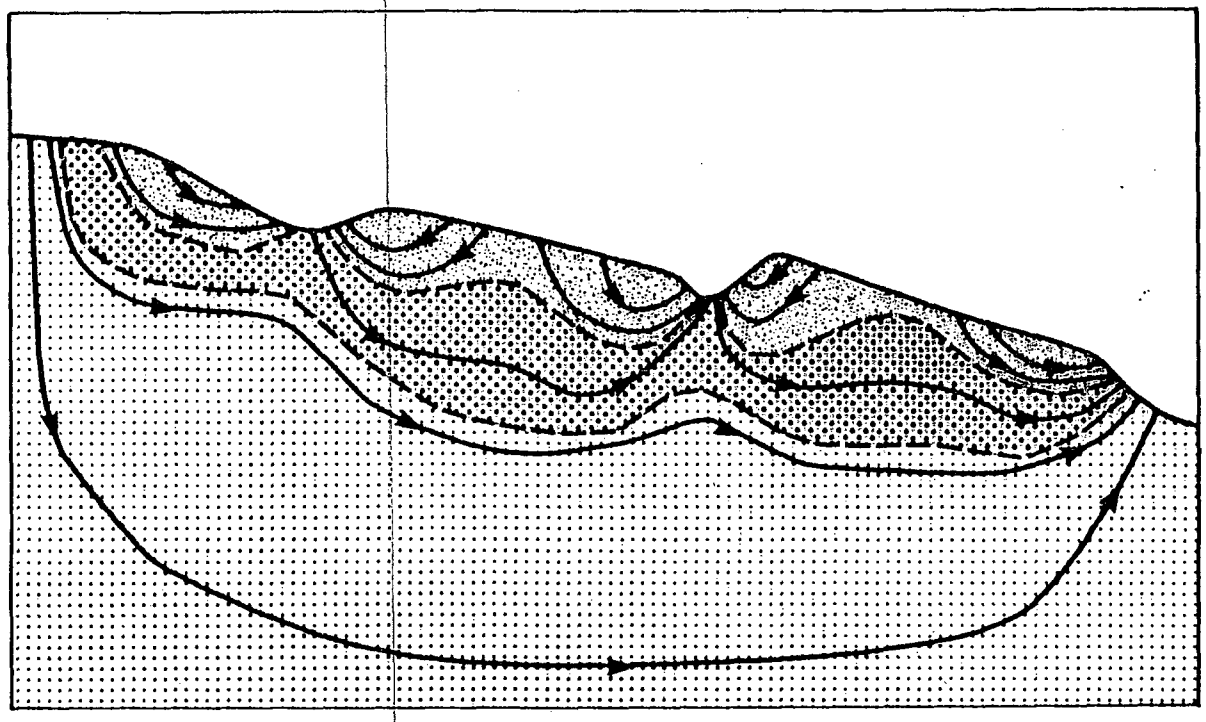


FIG 9 CROSS SECTION C-C'
(FROM EXXON COMPANY, USA; 1973)



REGION OF LOCAL SYSTEM OF GROUND-WATER FLOW

REGION OF INTERMEDIATE SYSTEM OF GROUND-WATER FLOW

REGION OF REGIONAL SYSTEM OF GROUND-WATER FLOW

FIG. 10 LOCAL, INTERMEDIATE, AND REGIONAL GROUND-WATER FLOW SYSTEMS

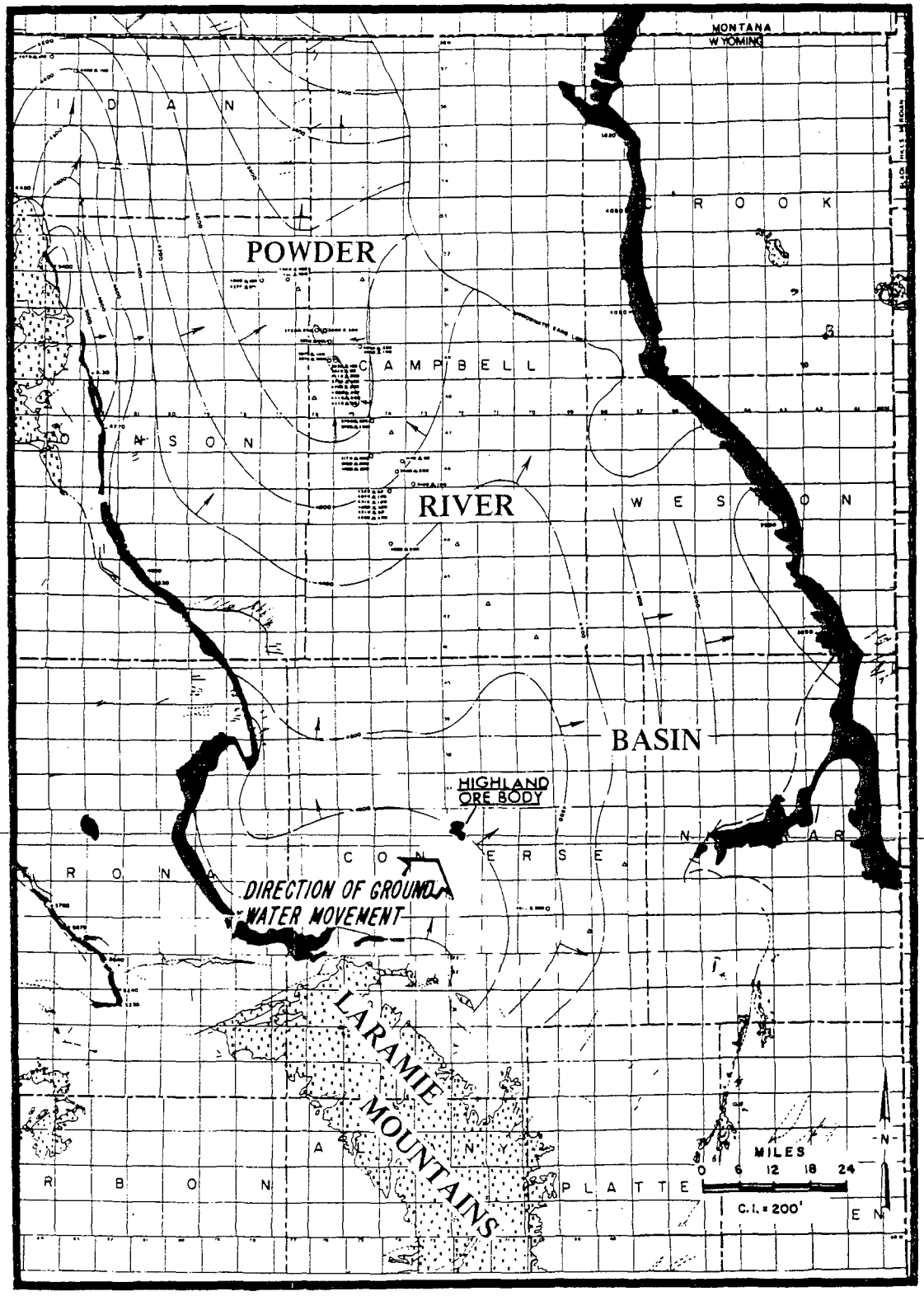


FIG. 11 REGIONAL FLOW SYSTEM IN THE UPPER CRETACEOUS PARKMAN SANDSTONE (FROM PETROLEUM RESEARCH CORP.)

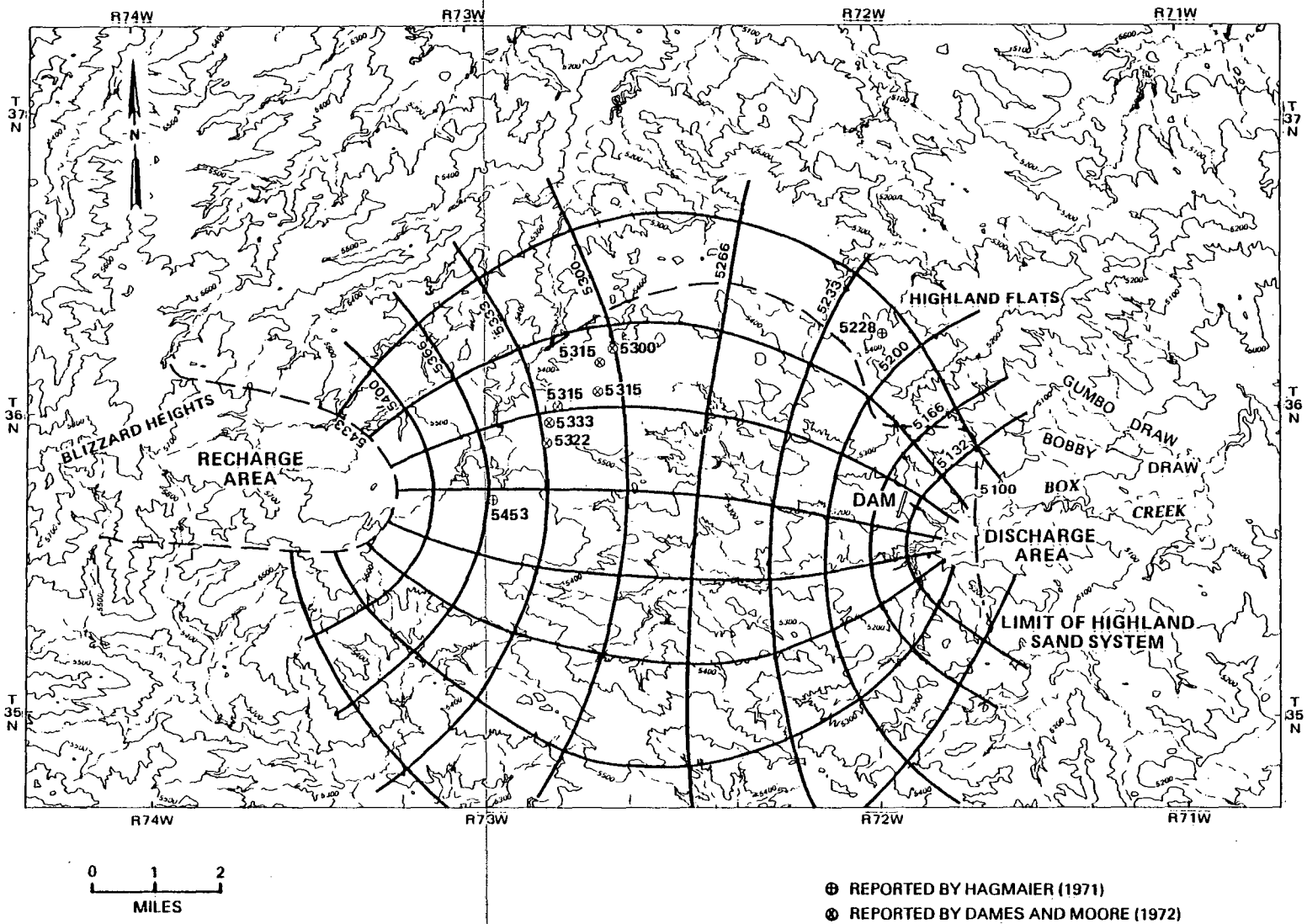


FIG. 12 INTERMEDIATE FLOW SYSTEM IN THE VICINITY OF THE HIGHLAND MINE

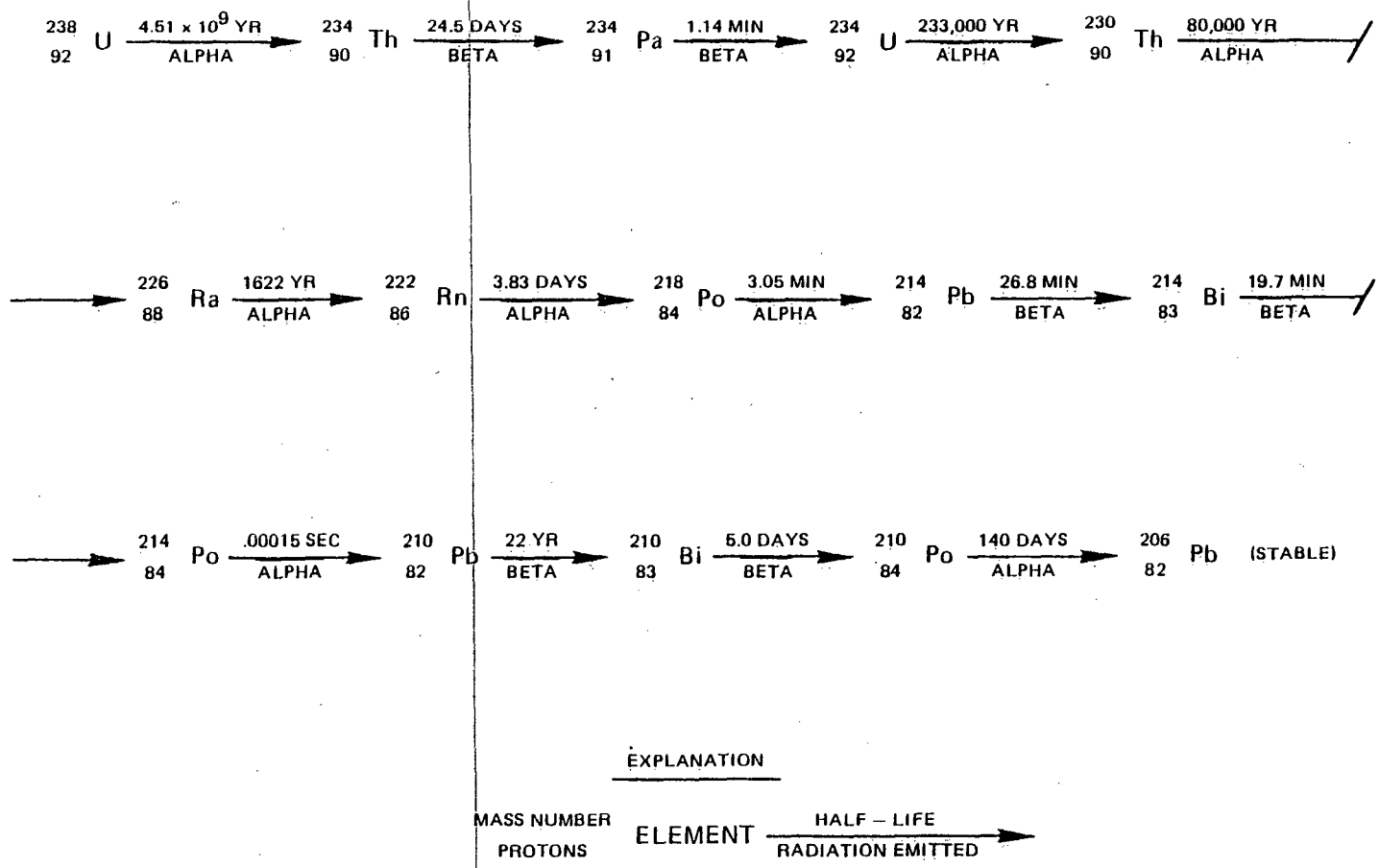


FIG. 13 URANIUM-238 RADIOACTIVE DECAY SERIES

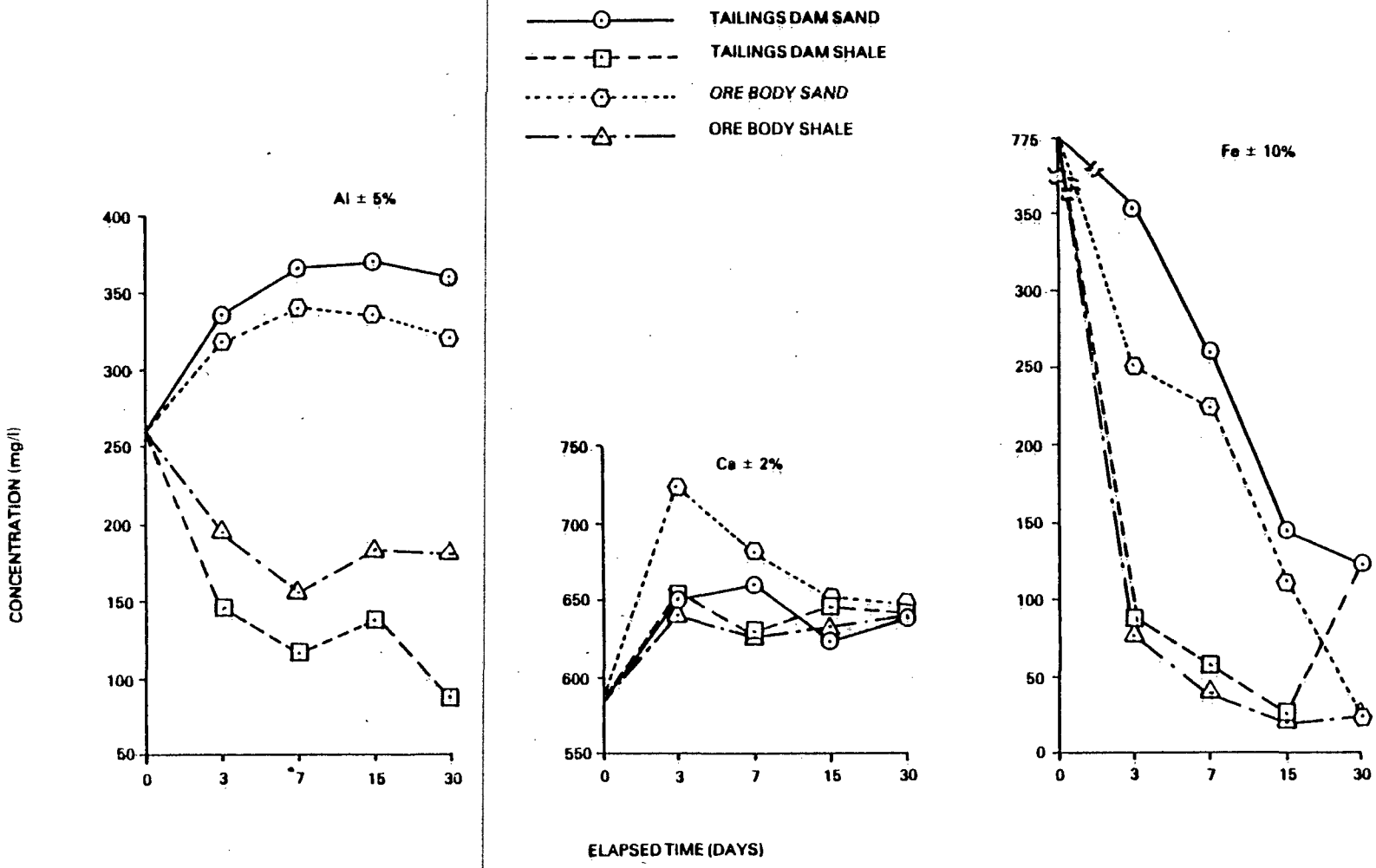


FIG. 14 CONCENTRATIONS OF VARIOUS ELEMENTS, pH AND Eh VERSUS ELAPSED TIME IN DAYS FROM BATCH TESTS OF TAILINGS SOLUTION OVER FOUR ROCK TYPES

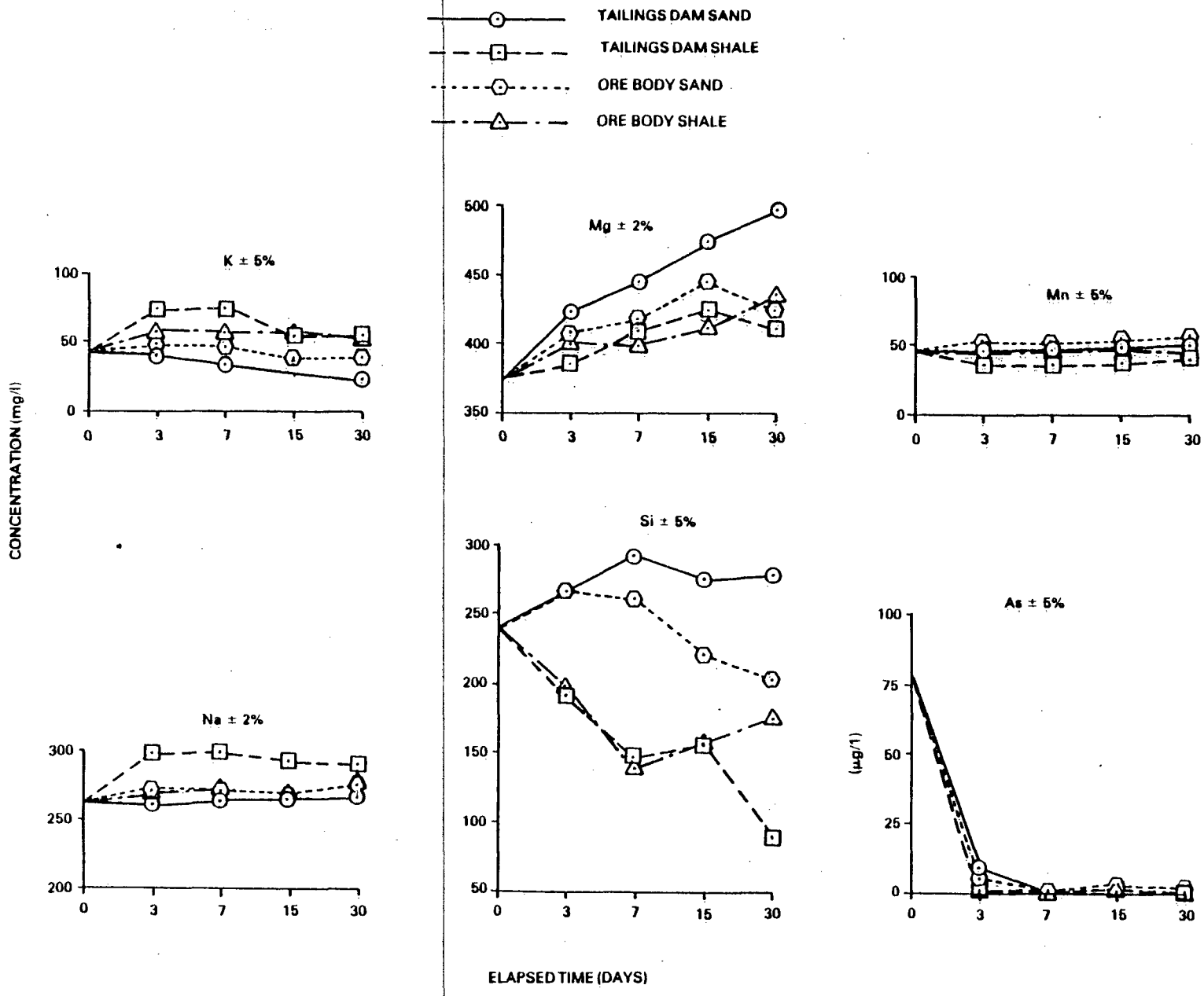
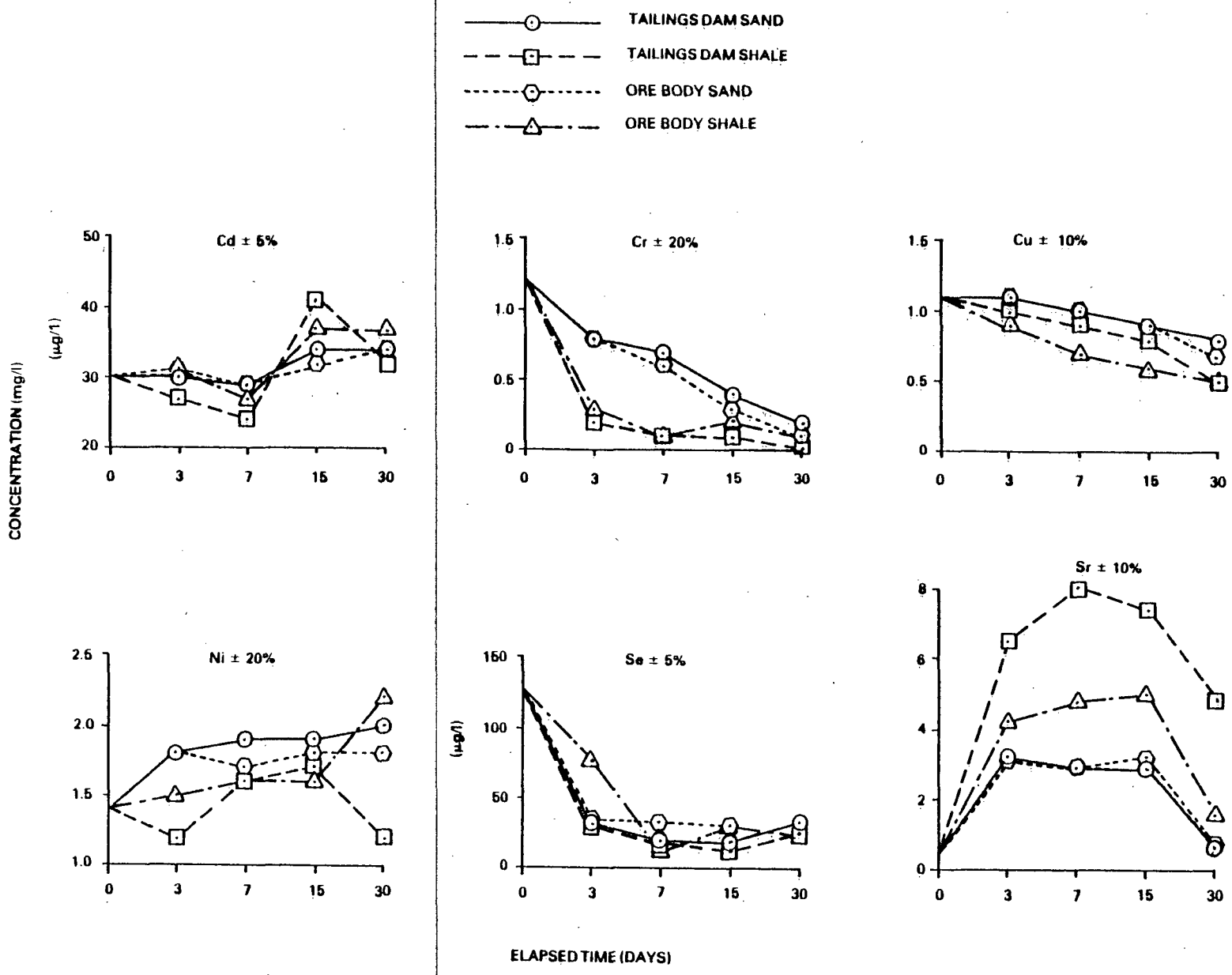


FIG. 14 (CONTINUED)



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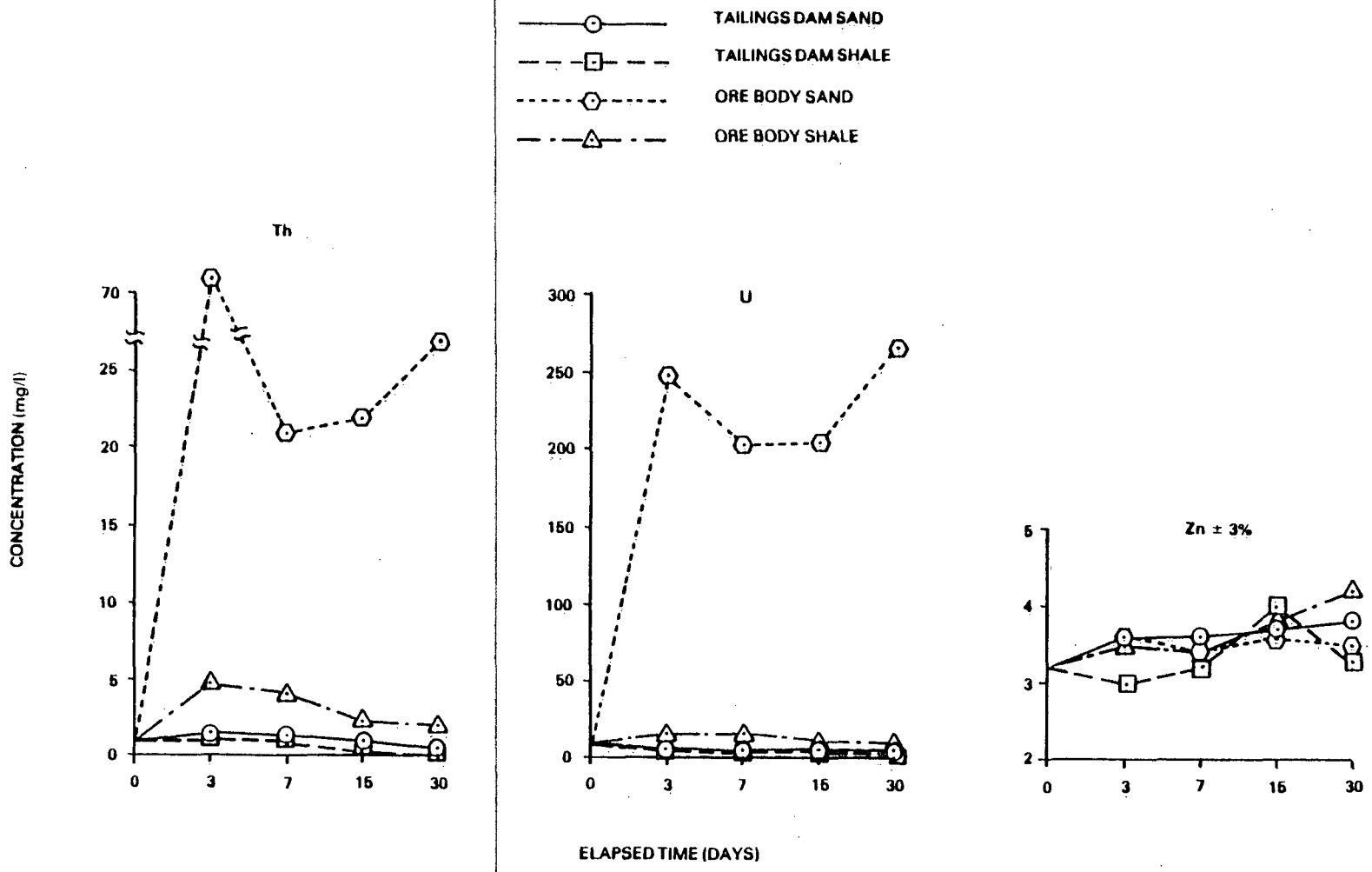


FIG. 14 (CONTINUED)

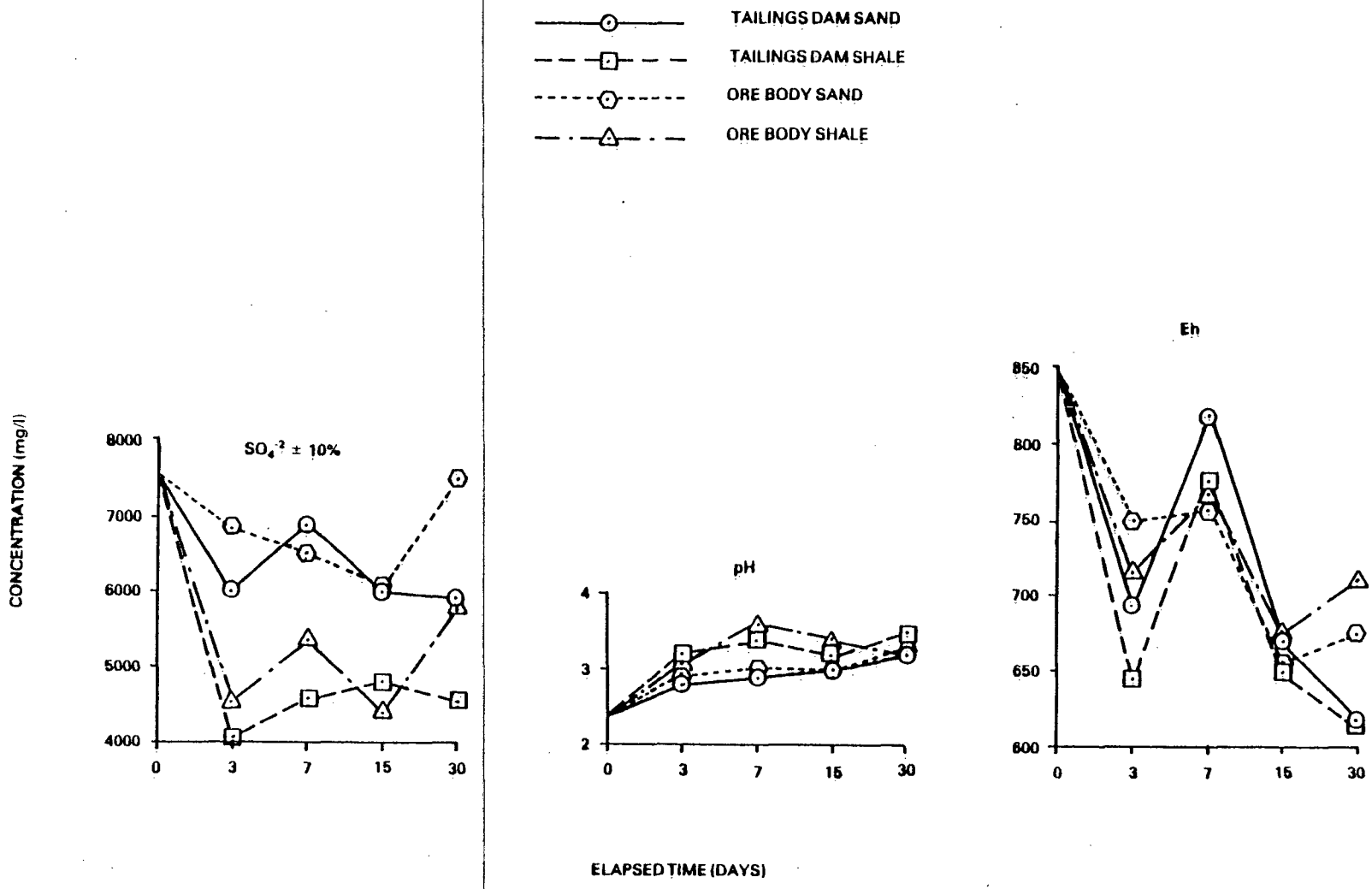


FIG. 14 (CONTINUED)

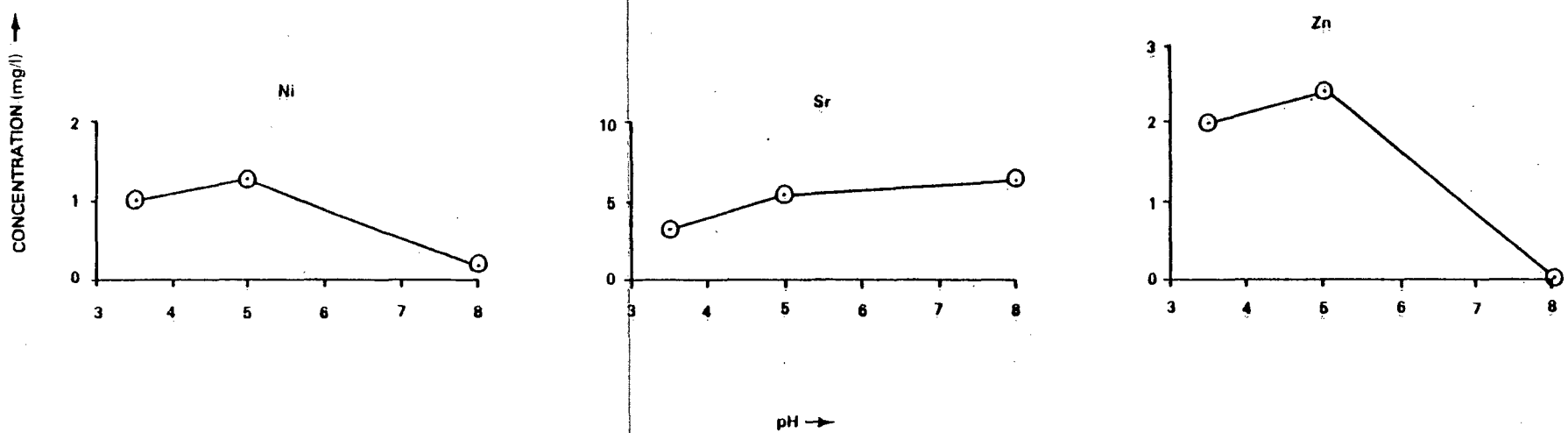


FIG. 15 TITRATIONS OF HIGHLAND TAILINGS SOLUTION BY 0.015M $Ca(OH_2)$

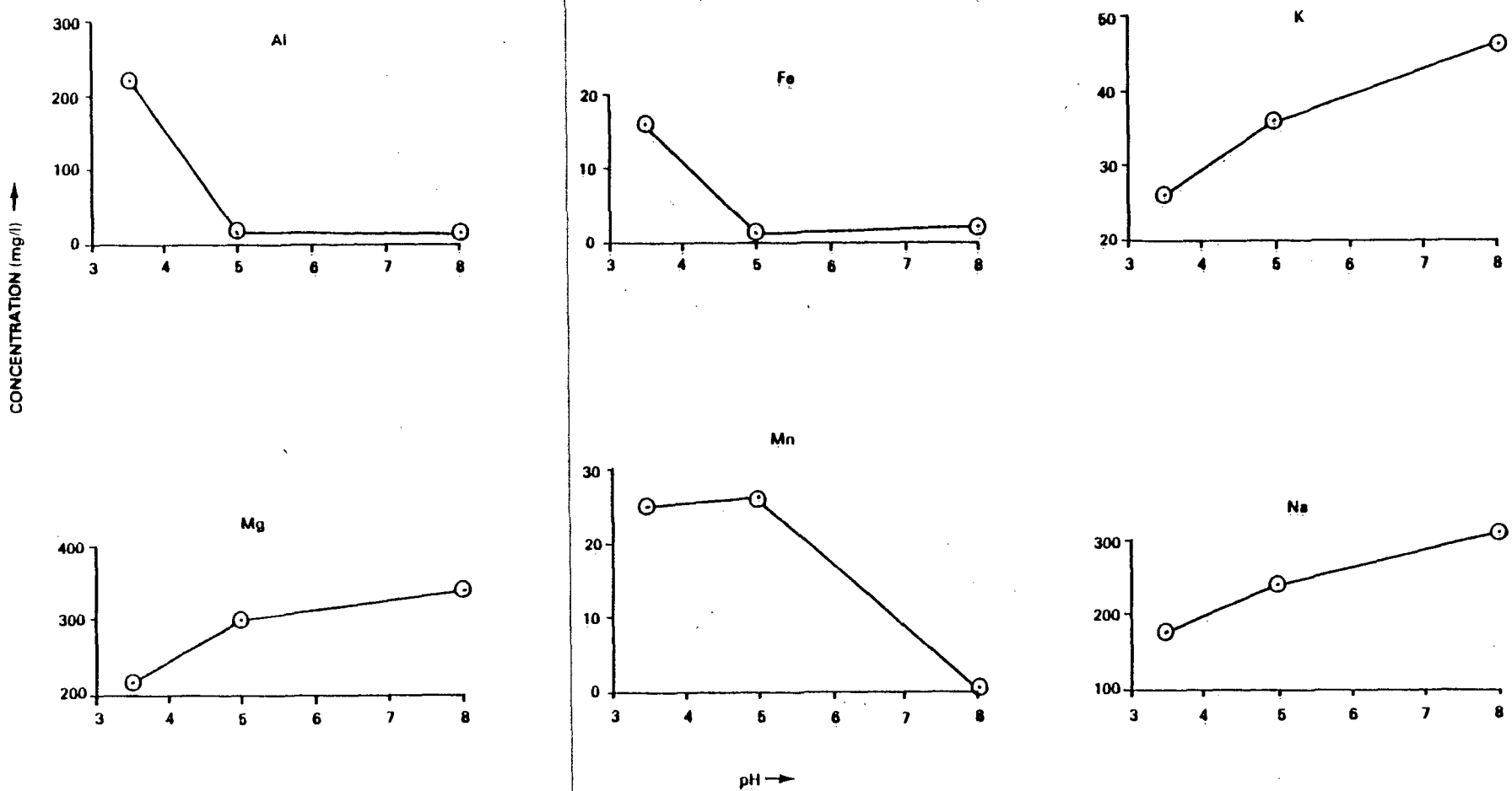


FIG. 15 (CONTINUED)

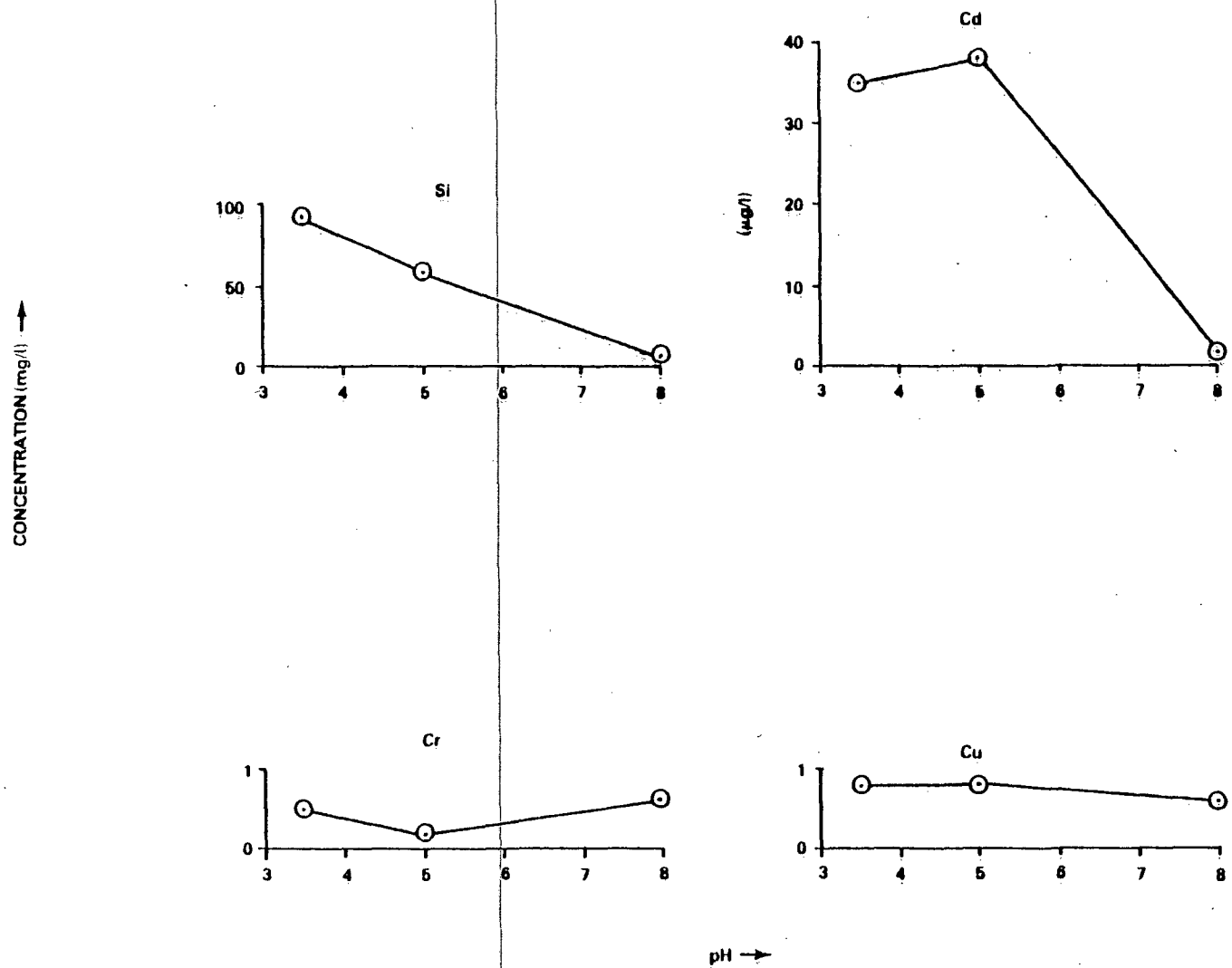


FIG. 15 (CONTINUED)

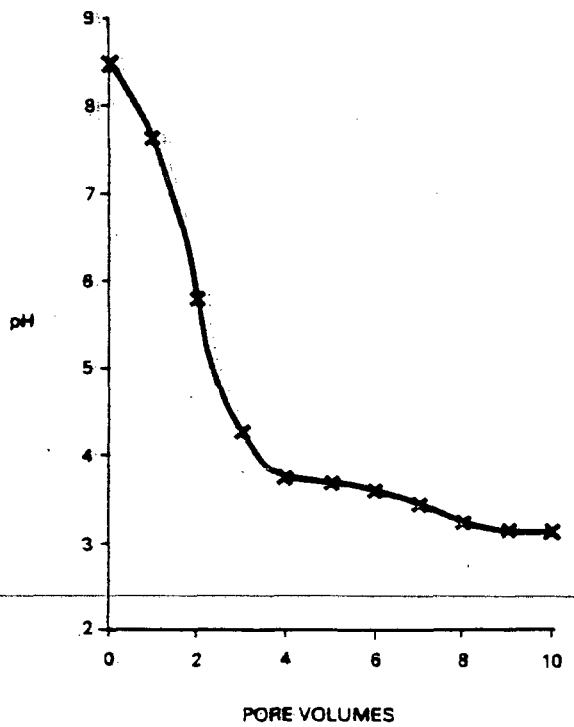


FIG. 16 pH VERSUS PORE VOLUMES OF TAILINGS SOLUTION PASSED THROUGH TAILINGS DAM SANDSTONE

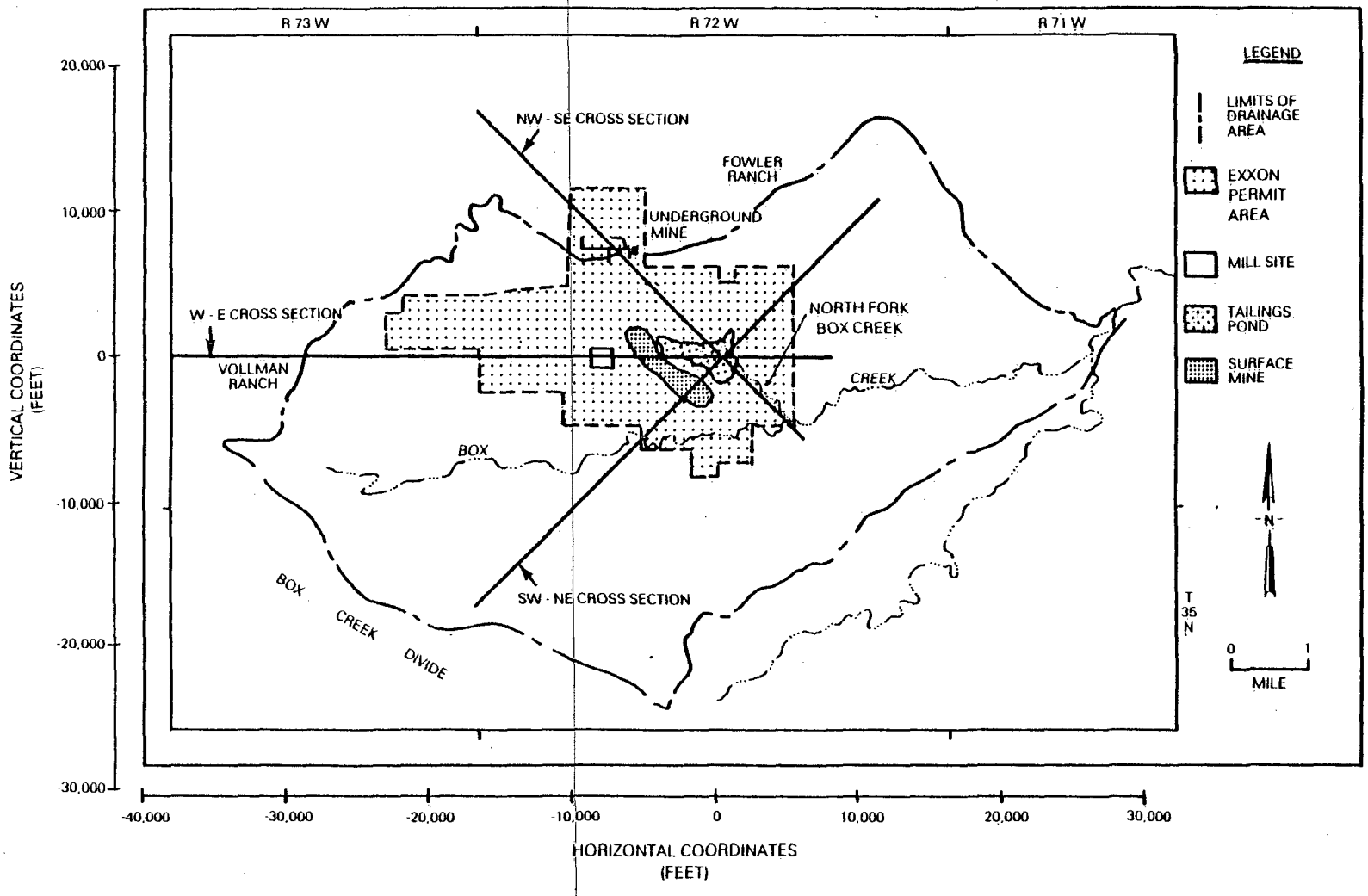
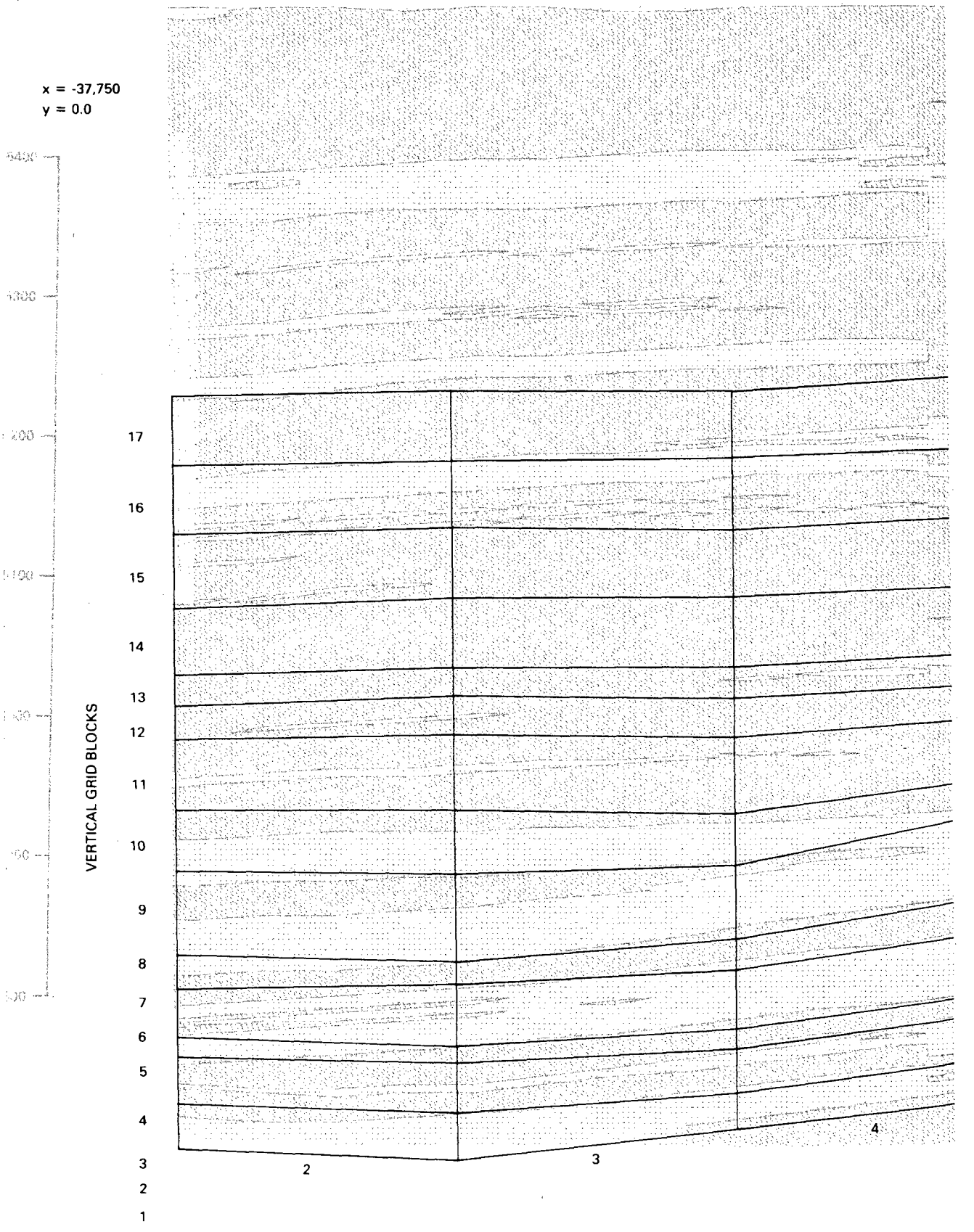


FIG. 17 ORIENTATIONS AND COORDINATE SYSTEM USED FOR THE CROSS-SECTIONAL MODELS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y = 0.0
VERTICAL GRID BLOCKS
17
16
15
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13
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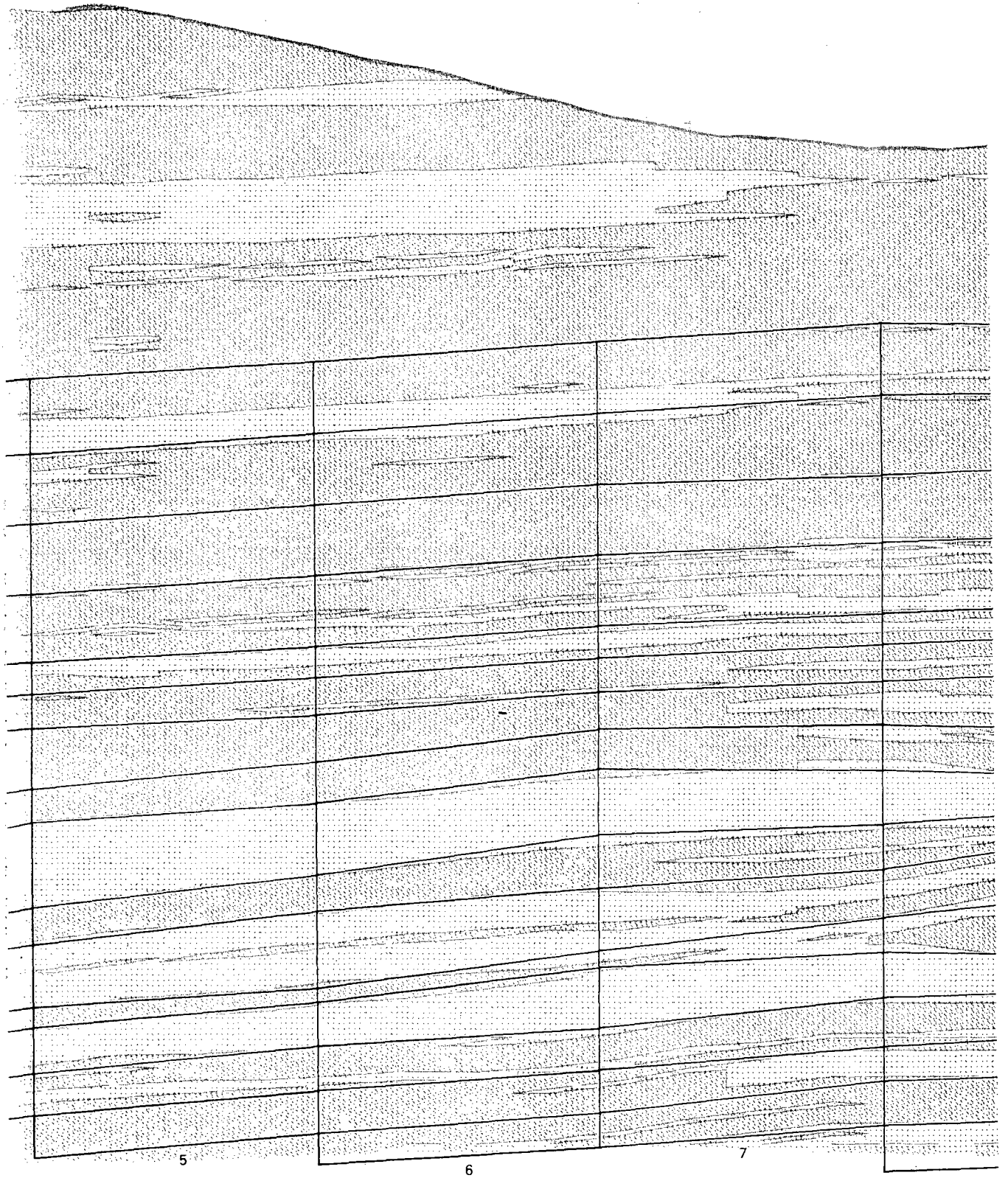
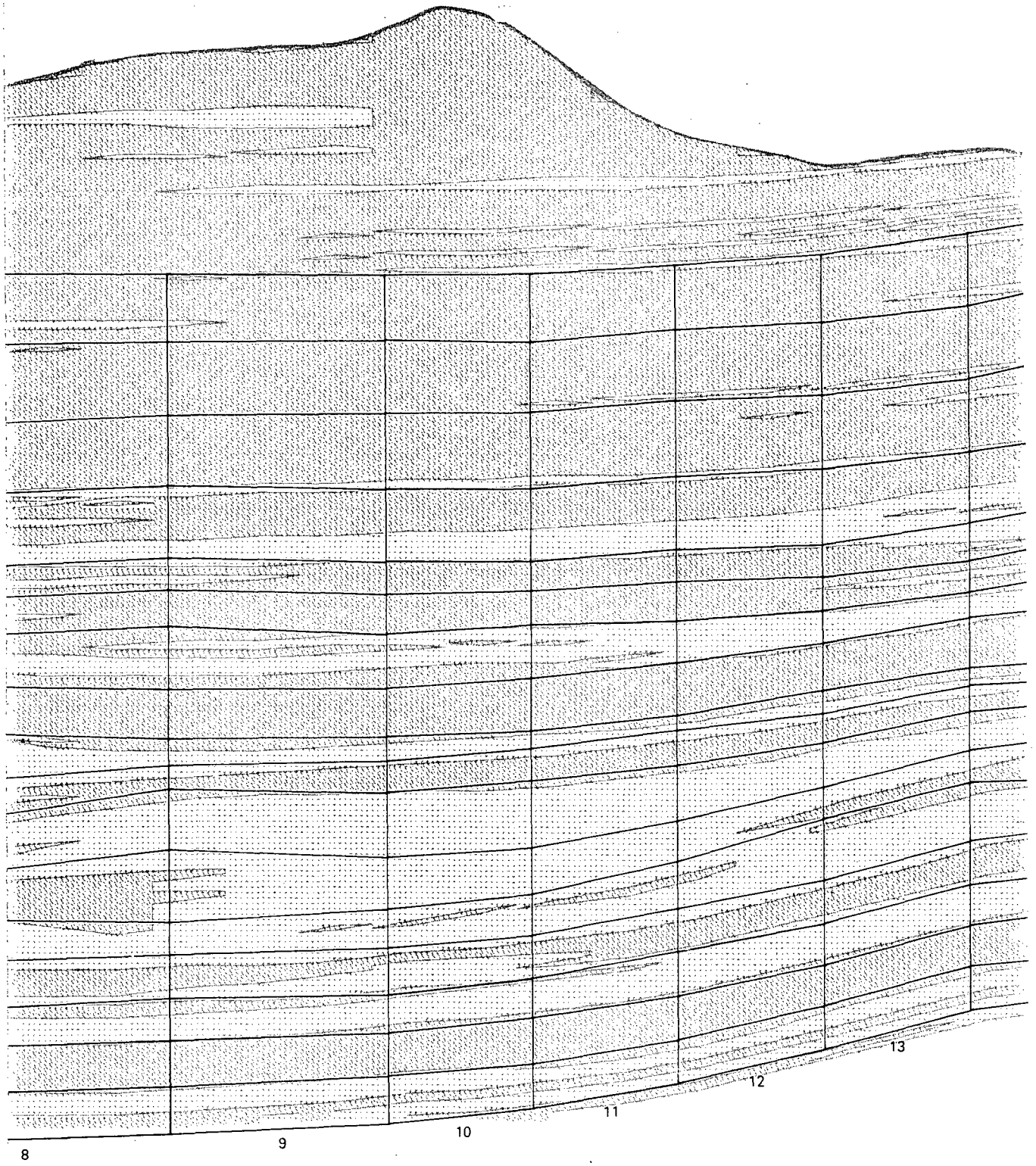
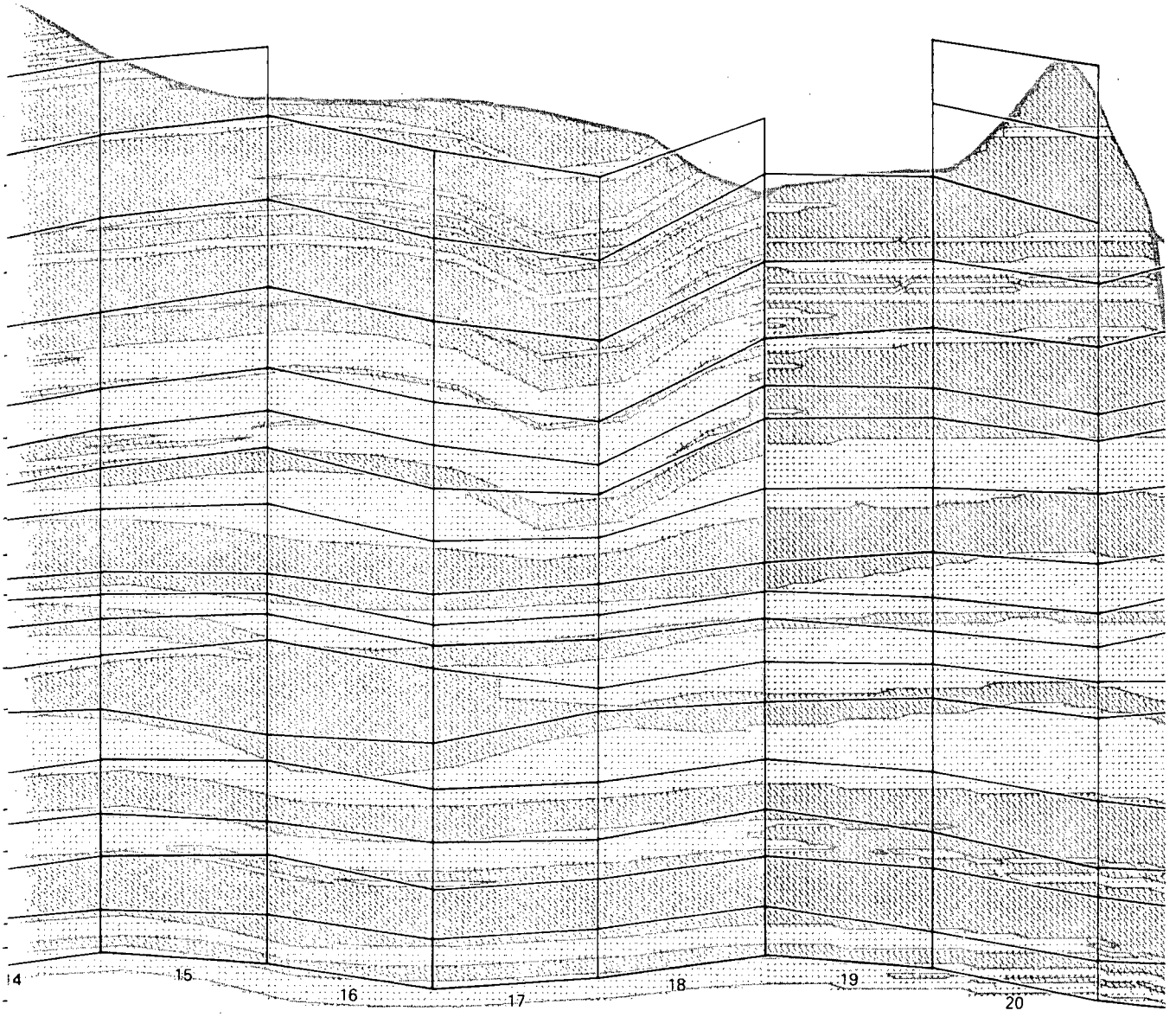
8
7
6
5
4
3
2
1
2
3
4


5
6
7



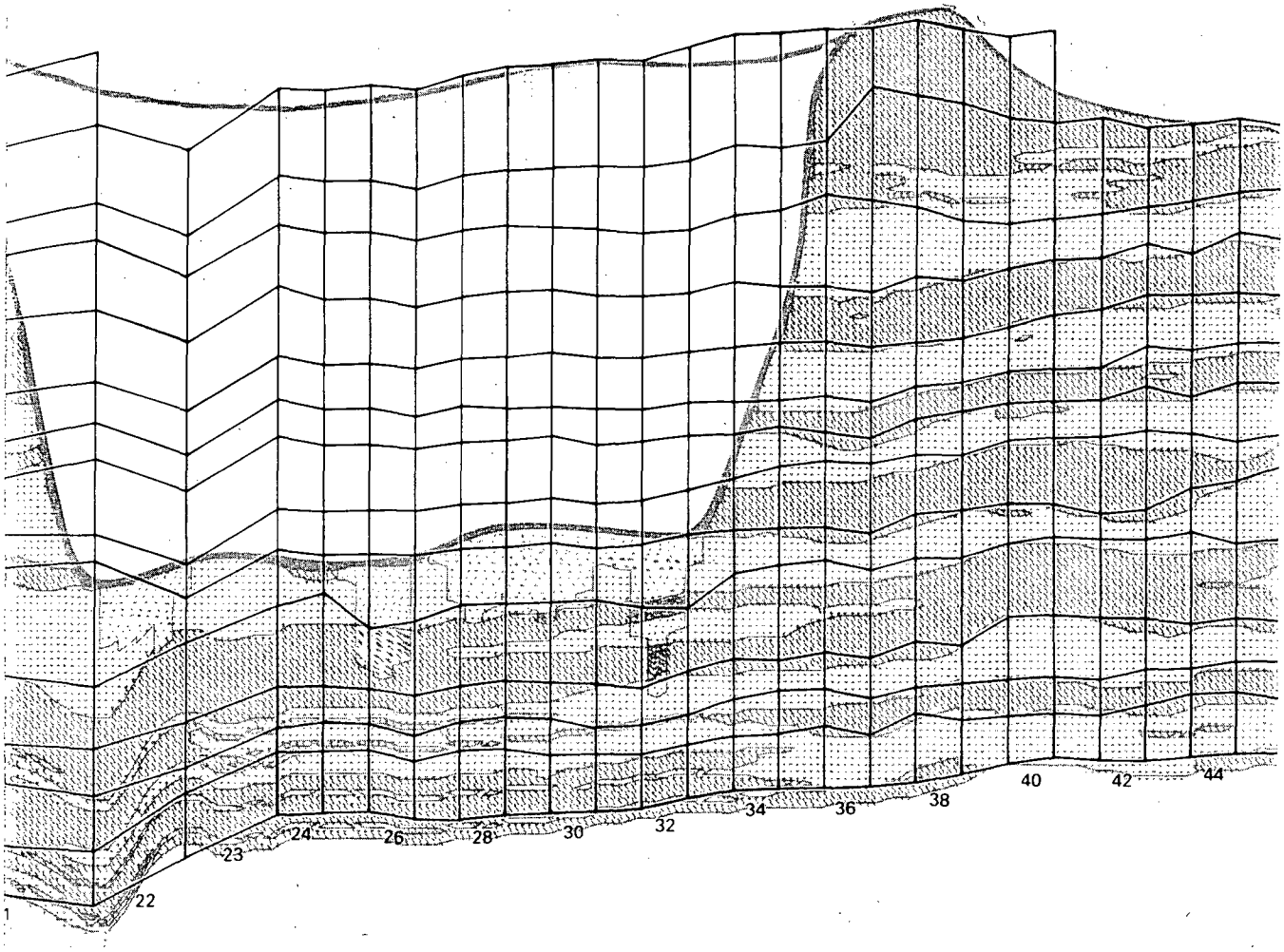
HORIZO

FIG. 18 GEOLOGY AND DISCRETIZ



ITAL GRID BLOCKS

ATION OF THE WEST-EAST CROSS SECTION


22
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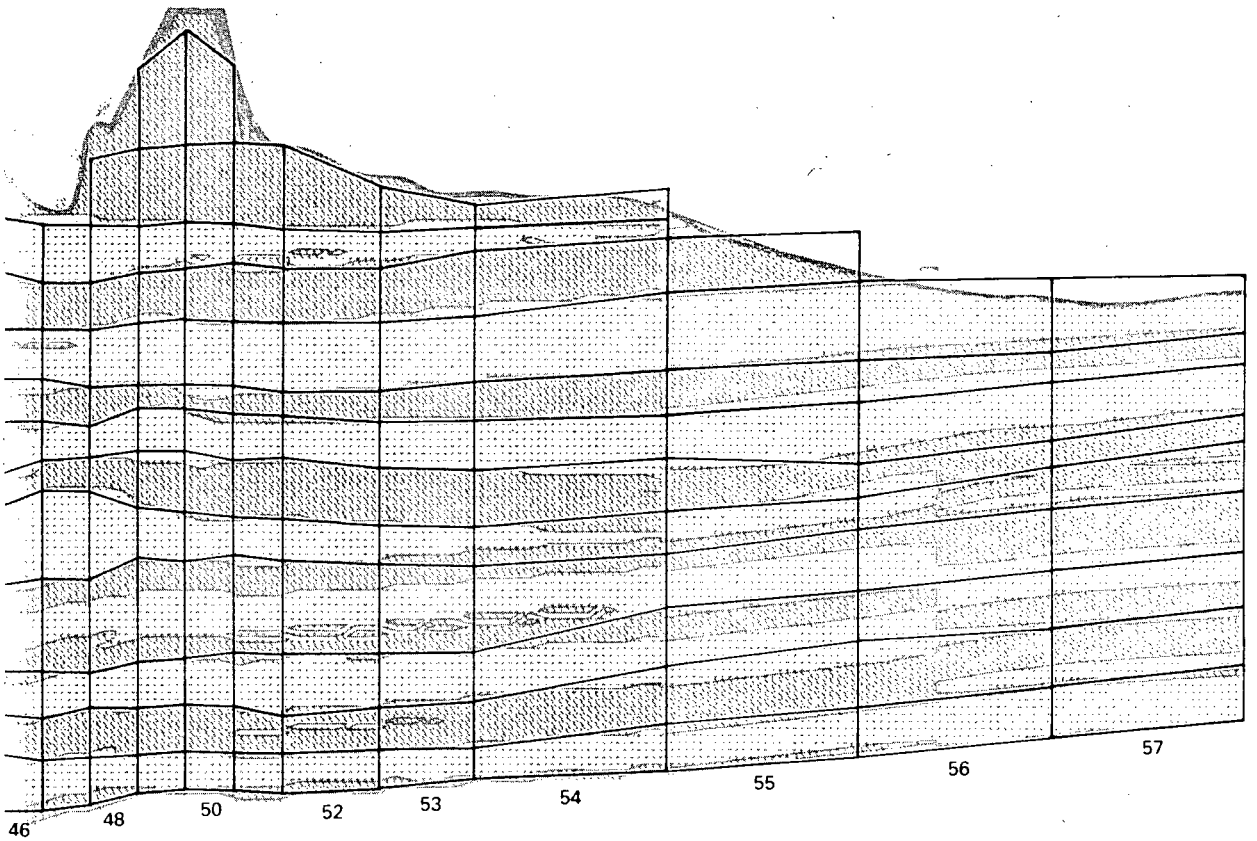

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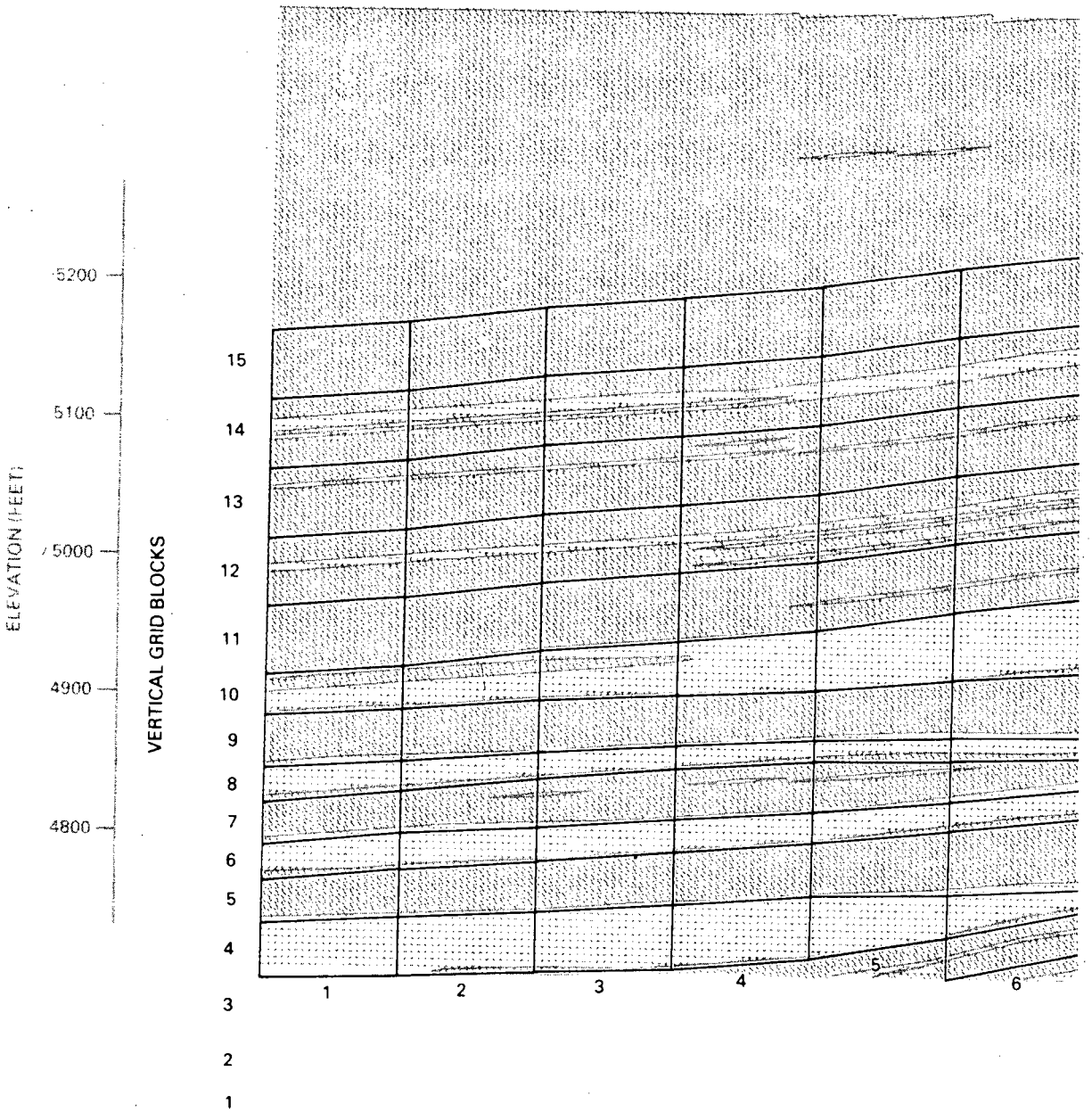
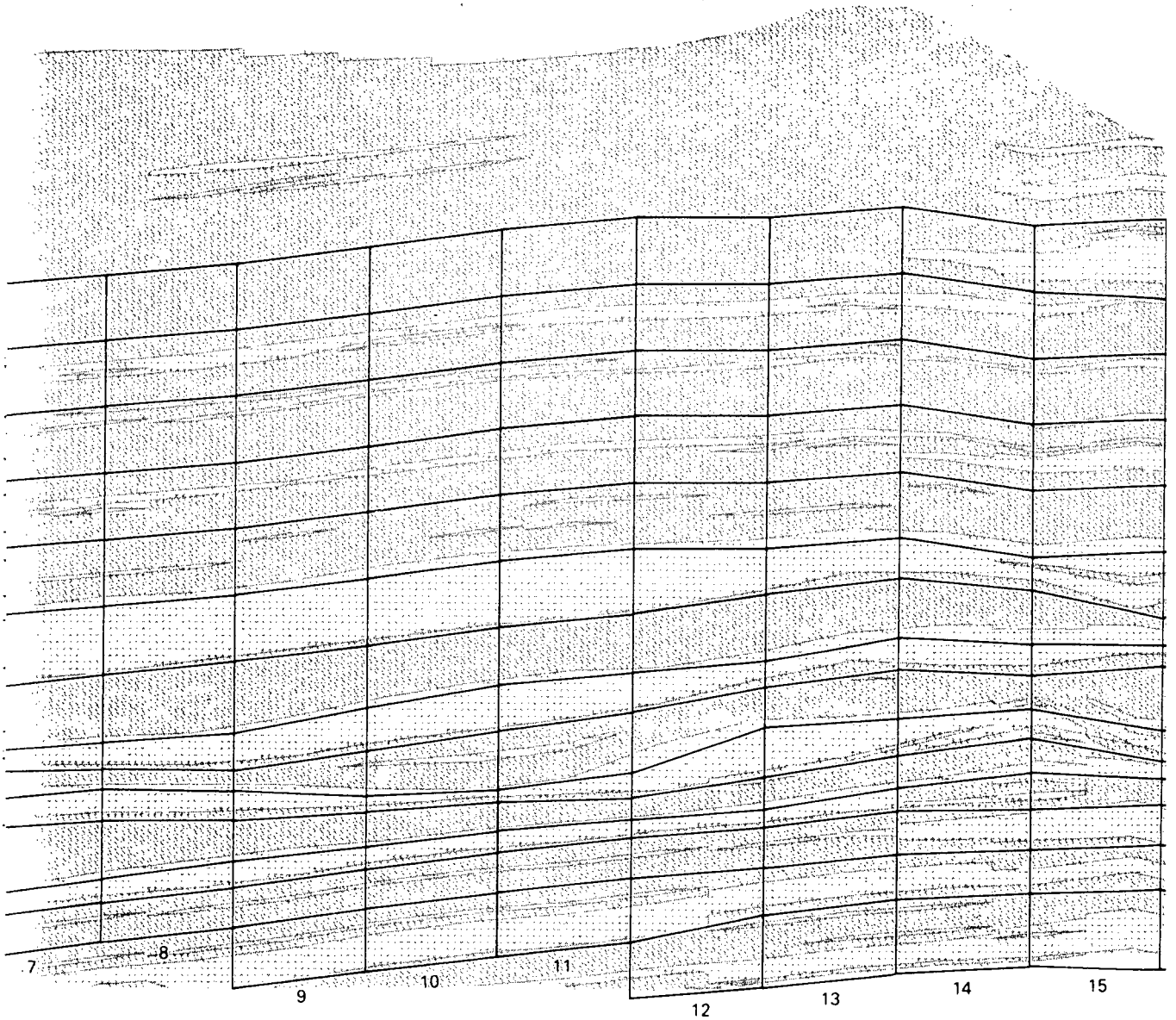
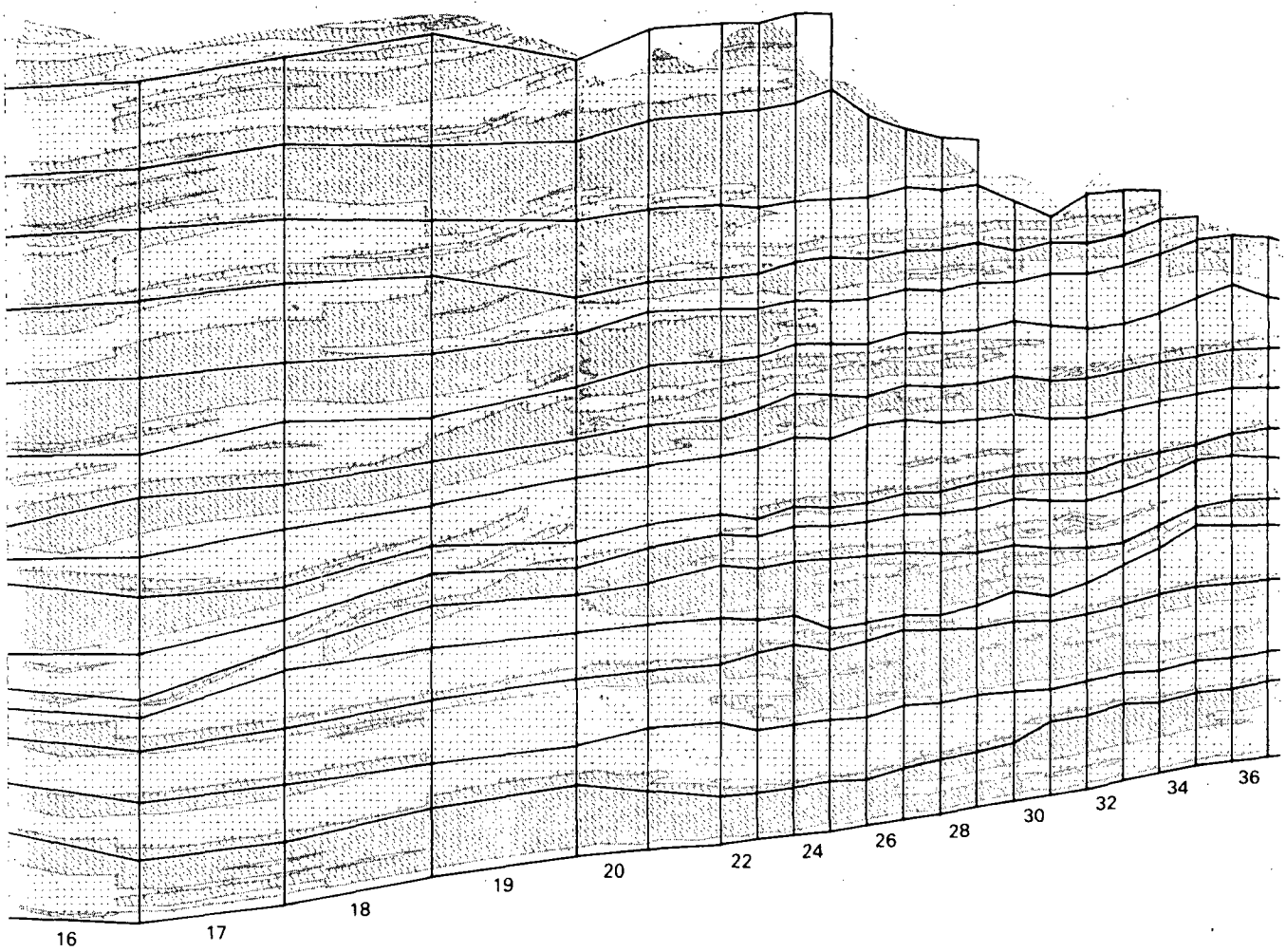
y = 16,970





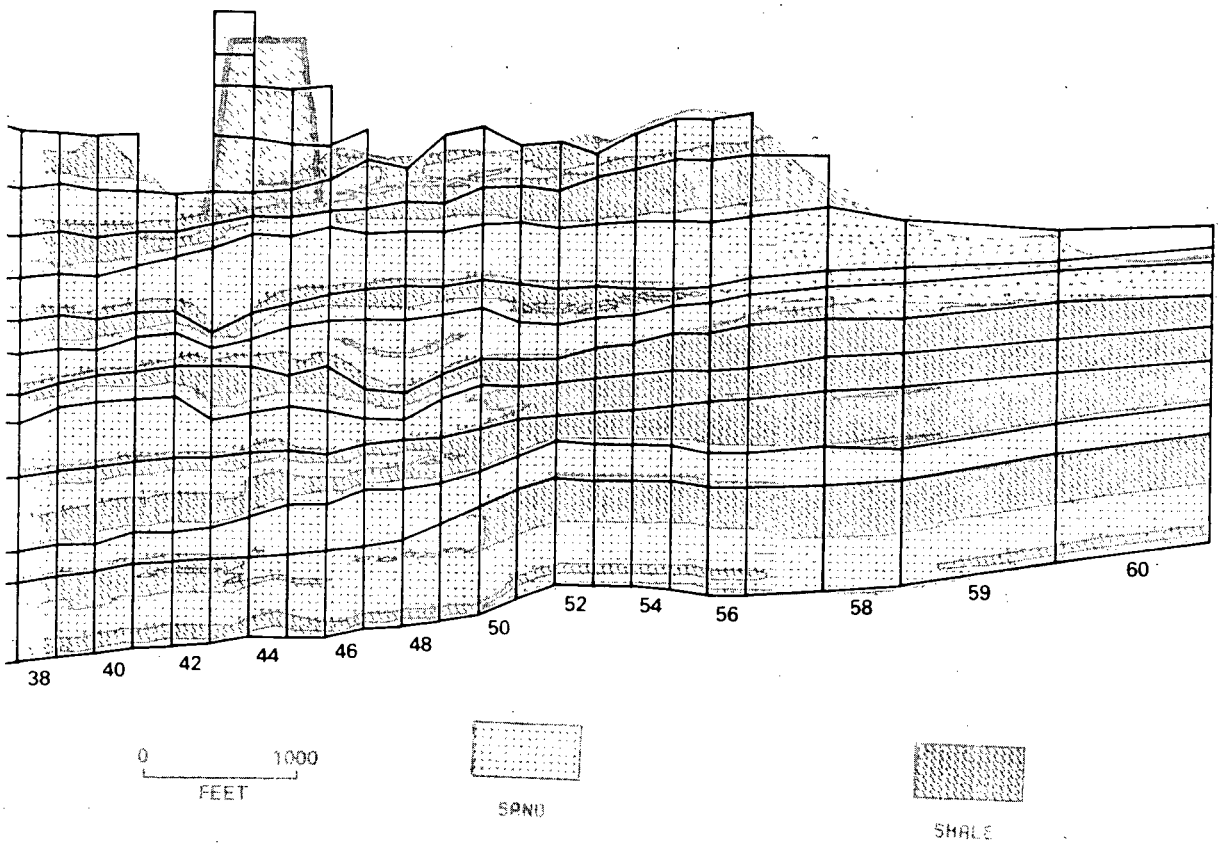
HORIZONTAL GRID BLOCK

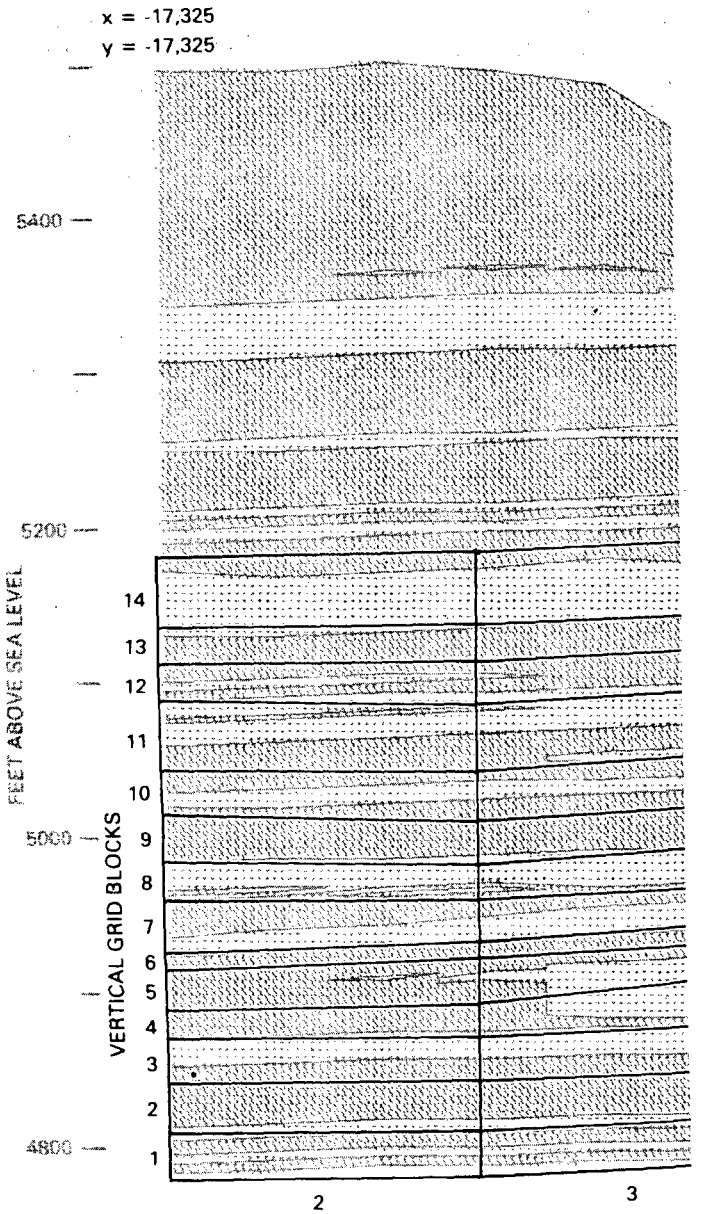
FIG. 19 GEOLOGY AND DISCRETIZATION OF THE NORTH

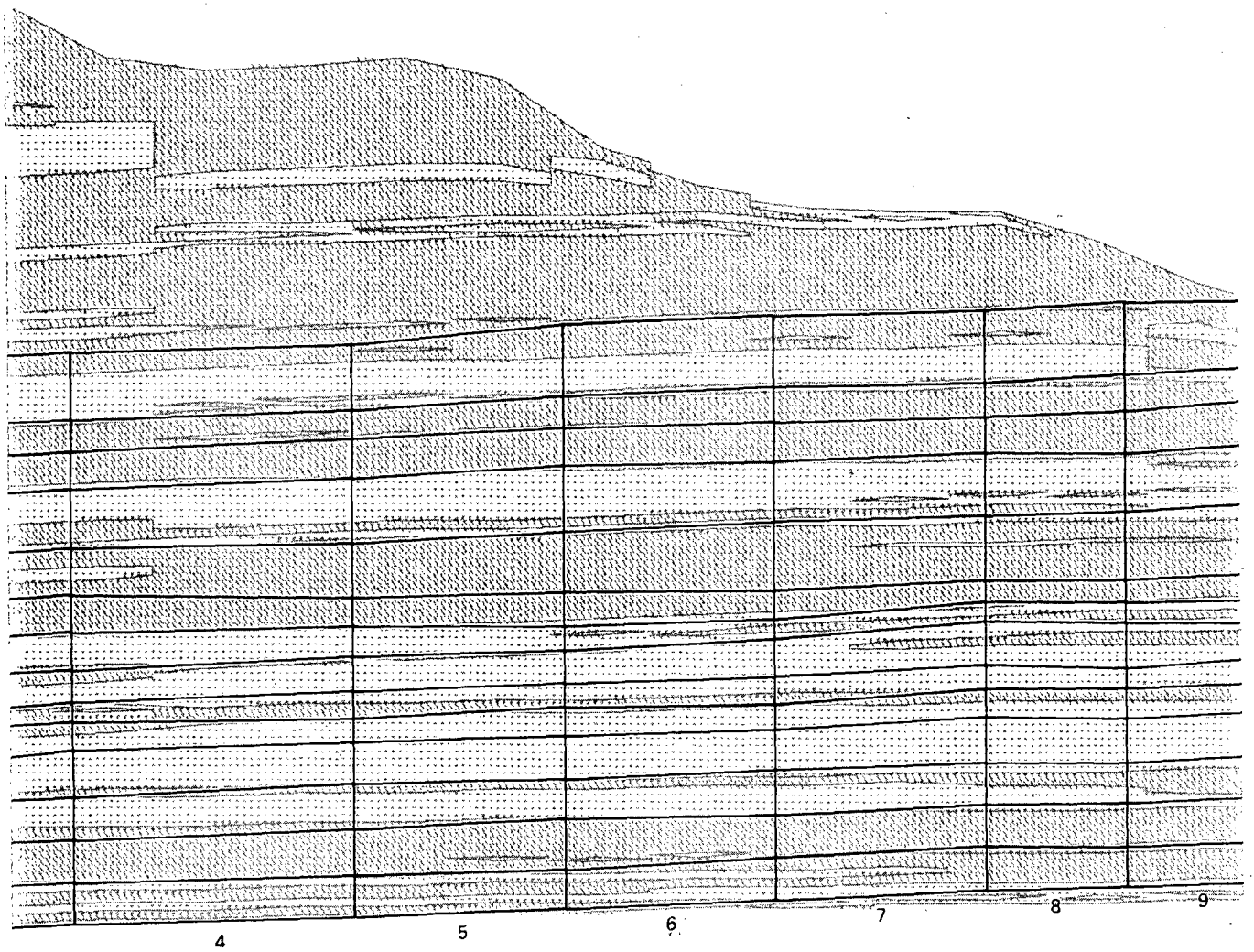


IWEST-SOUTHEAST CROSS SECTION

x = 5,600
y = -5,600




x = -17,325
y = -17,325
5400
5200
5000
4800
FEET ABOVE SEA LEVEL
VERTICAL GRID BLOCKS
14
13
12
11
10
9
8
7
6
5
4
3
2
1
2
3


4
5
6
7
8
9

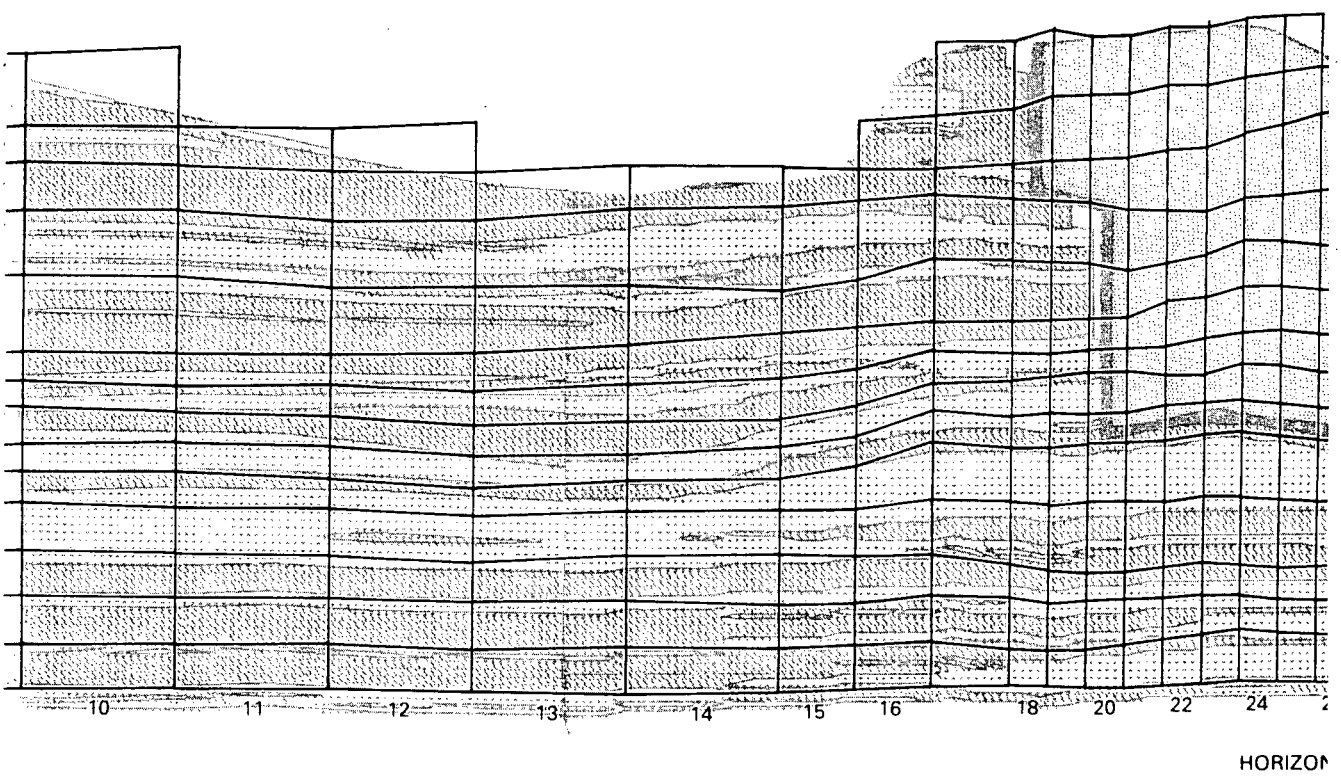
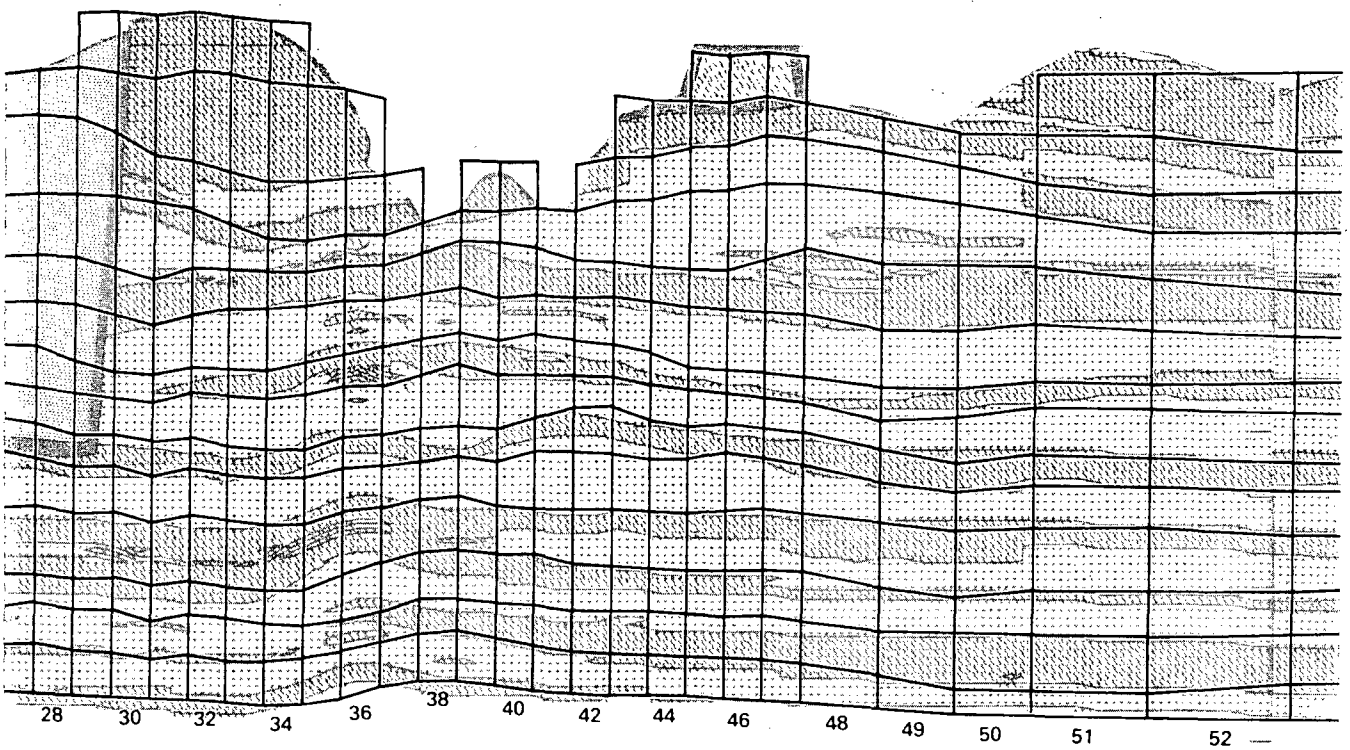


FIG. 20 GEOLOGY AND DISCRETIZATION (

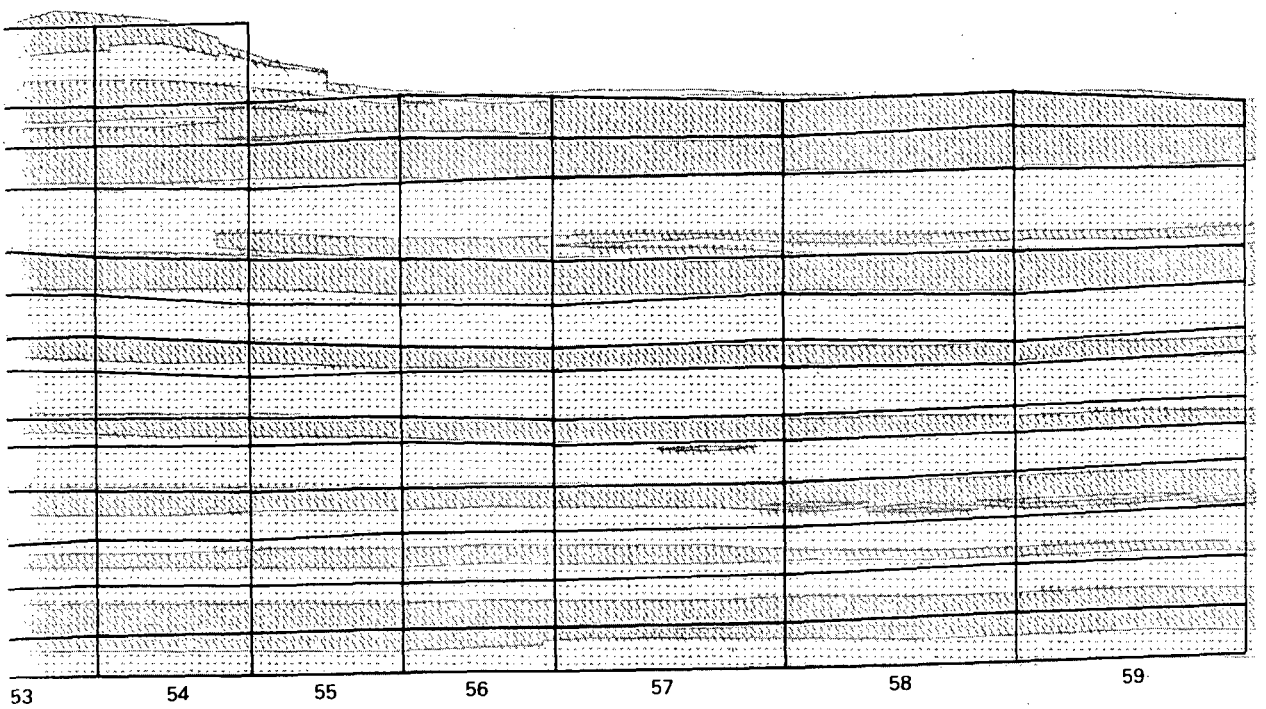


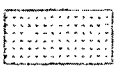
L GRID BLOCKS

0 1000
FEET

THE SOUTHWEST-NORTHEAST CROSS SECTION

x = 11,125
y = 11,125





SAND

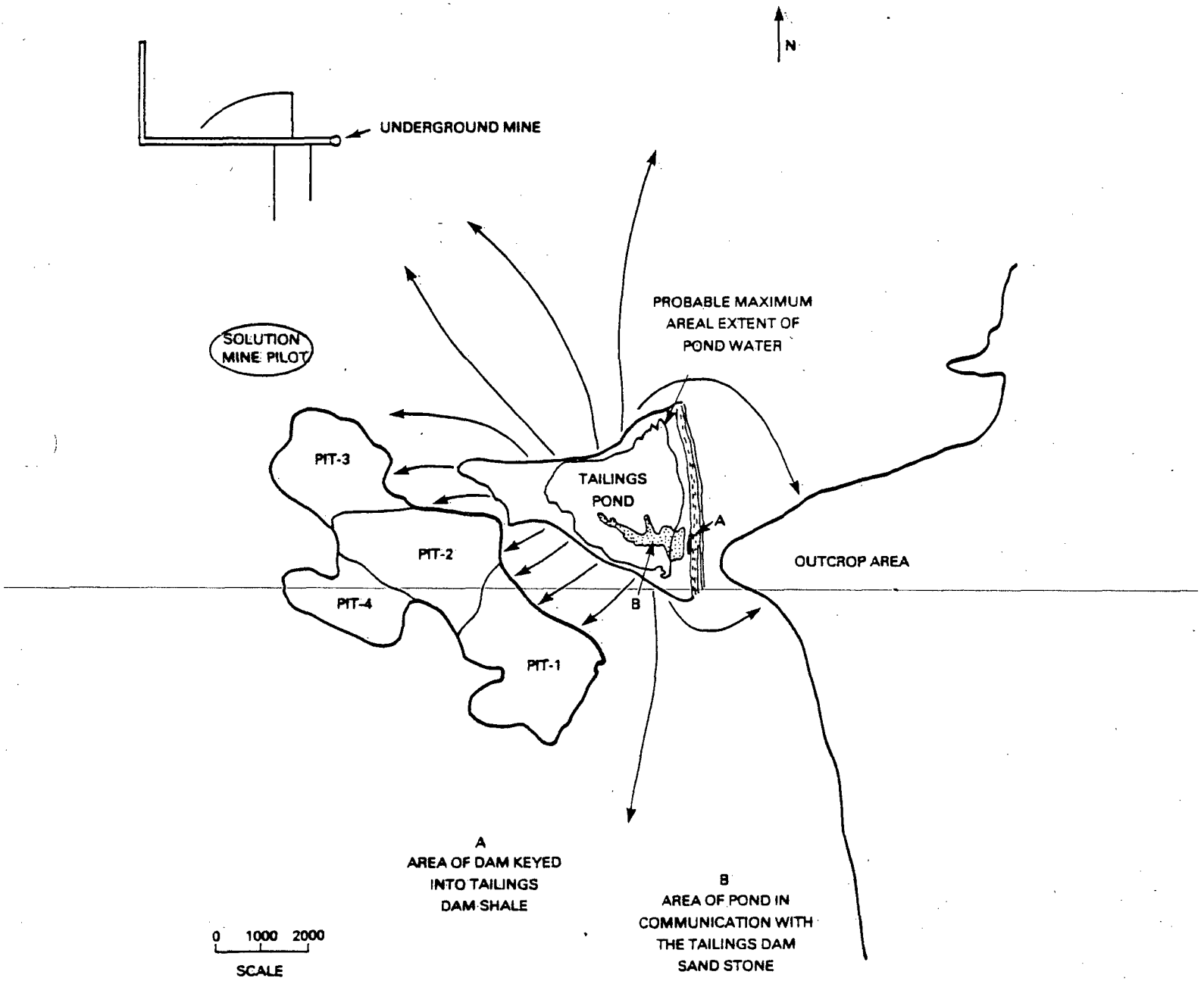


FIG. 21 ANTICIPATED FLOW PATTERNS NEAR TAILINGS IMPOUNDMENT DURING MINING

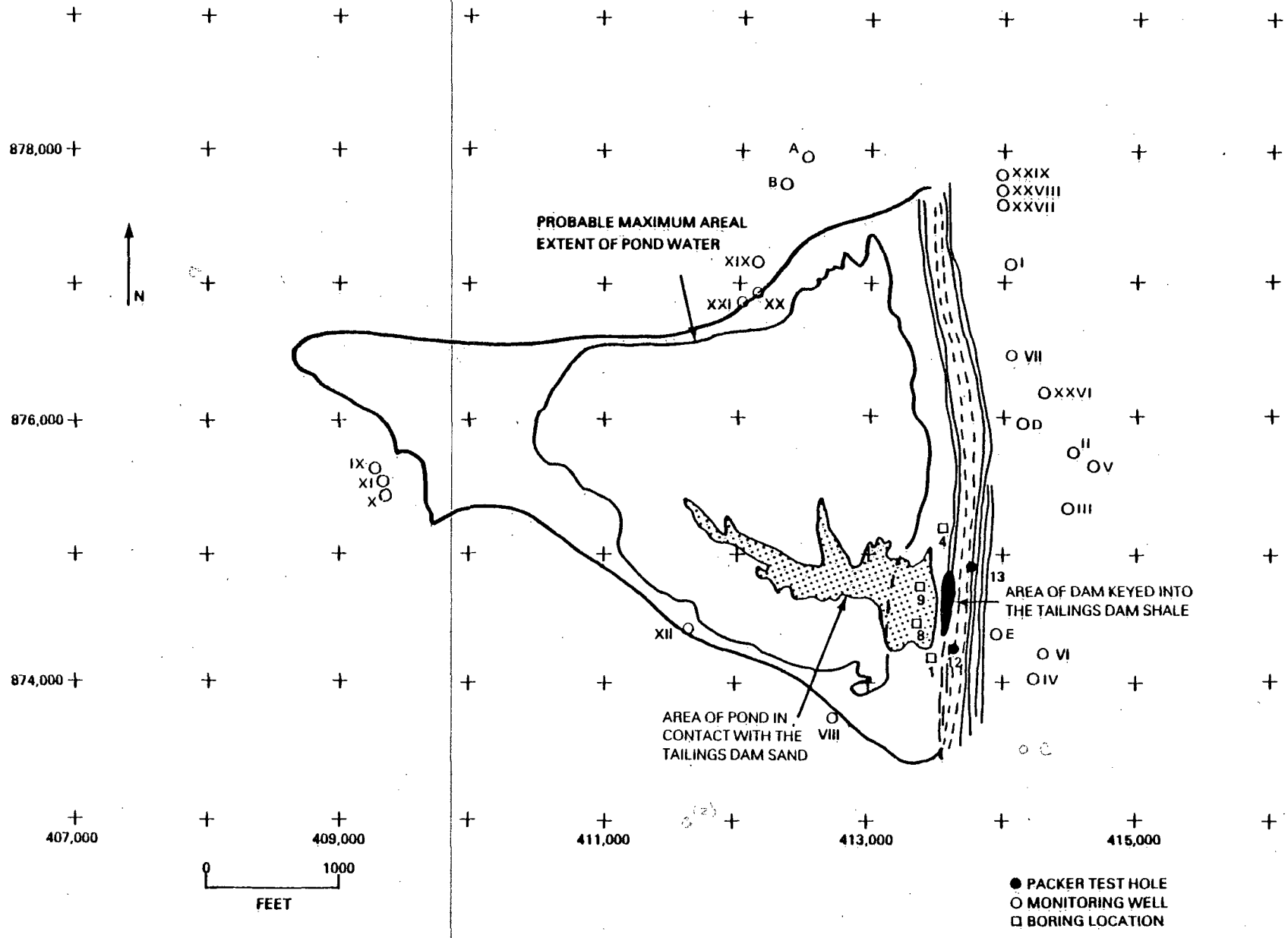


FIG. 22 LOCATIONS OF WELLS AND BORINGS

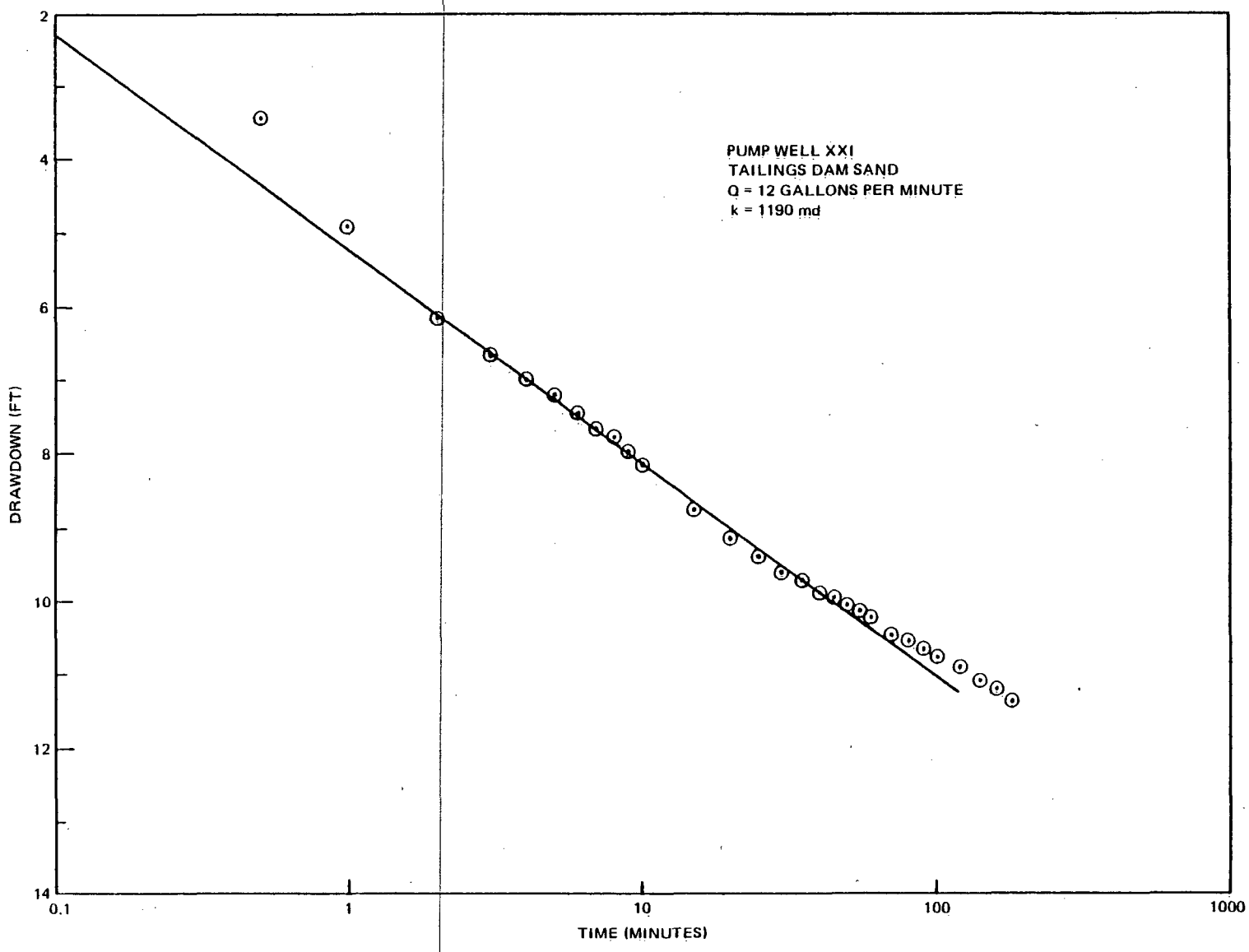


FIG. 23 PUMPING TEST CONDUCTED IN THE TAILINGS DAM SAND AT WELL XXI

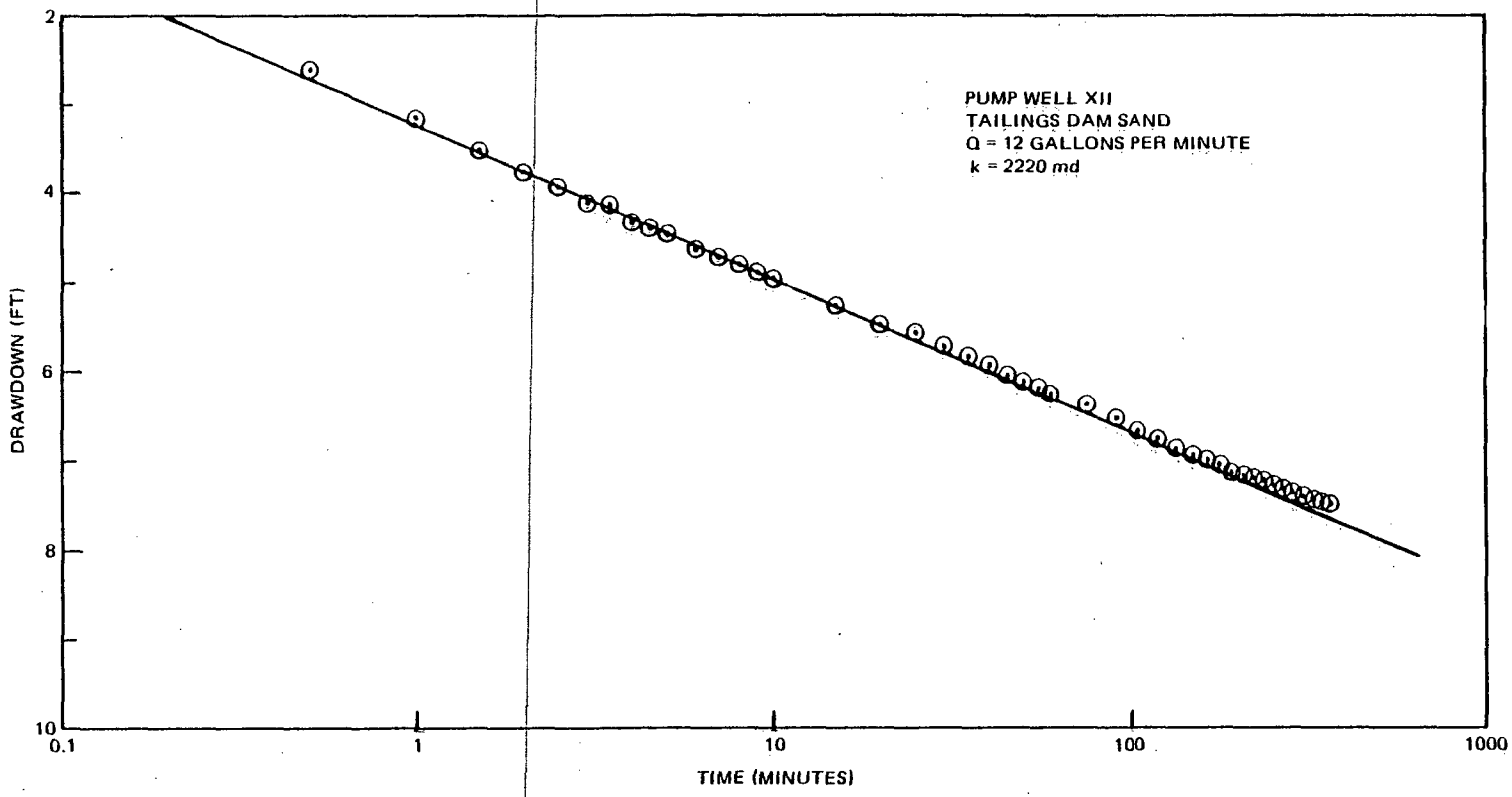


FIG. 24 PUMPING TEST CONDUCTED IN THE TAILINGS DAM SAND AT WELL XII

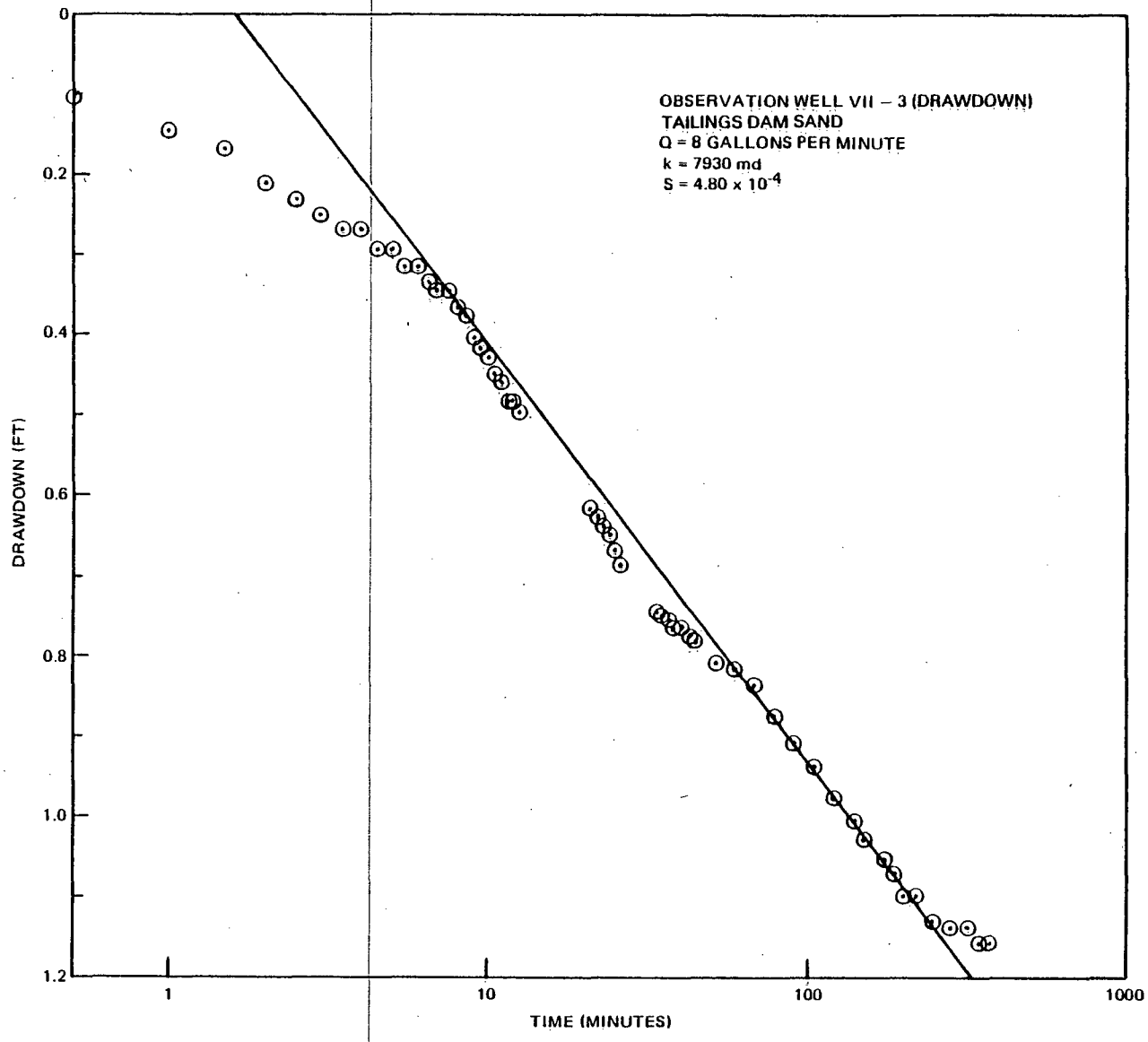


FIG. 25 PUMPING TEST CONDUCTED IN THE TAILINGS DAM SAND AT WELL VII

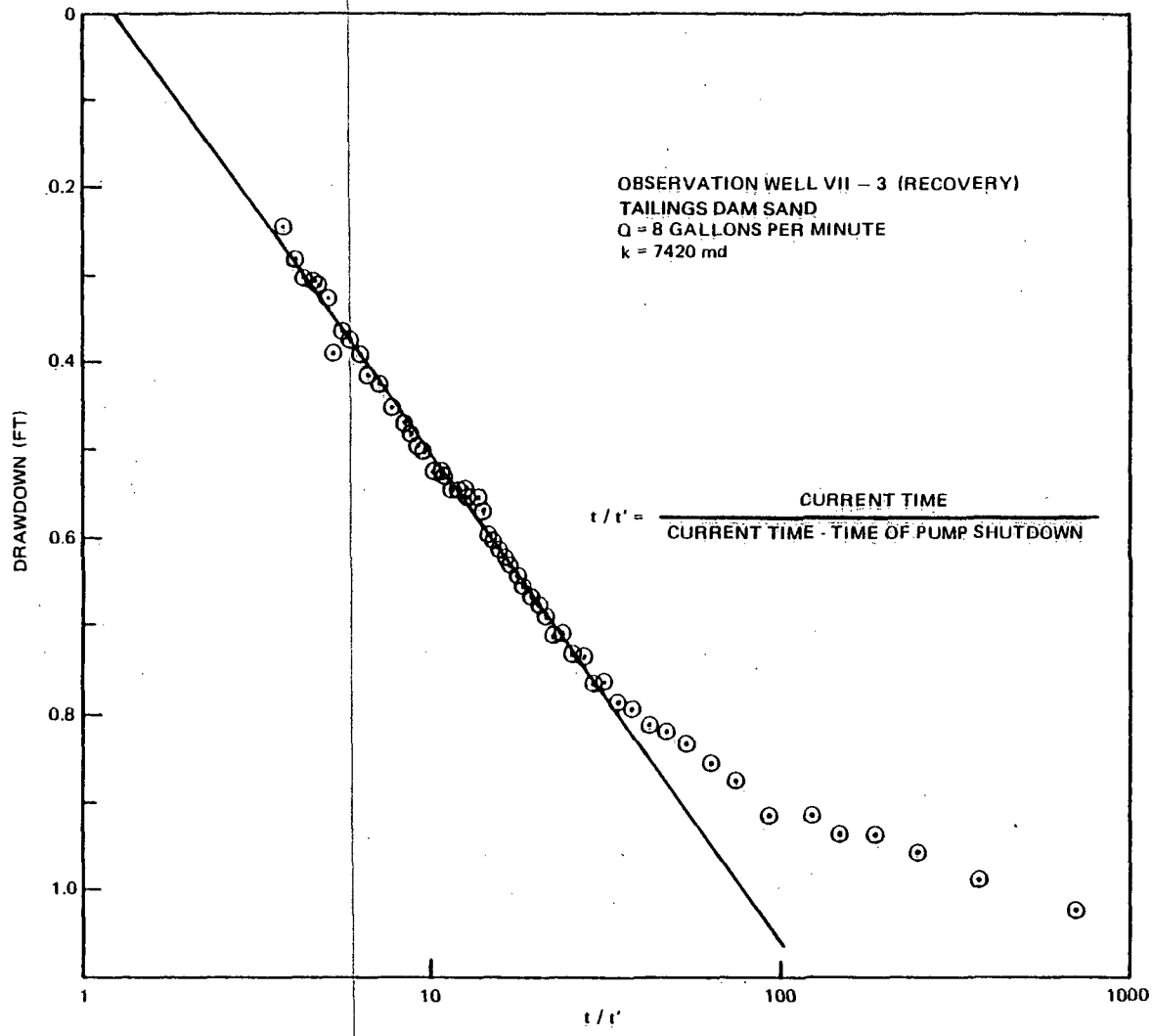


FIG. 26 RECOVERY TEST CONDUCTED IN THE TAILINGS DAM SAND AT WELL VII

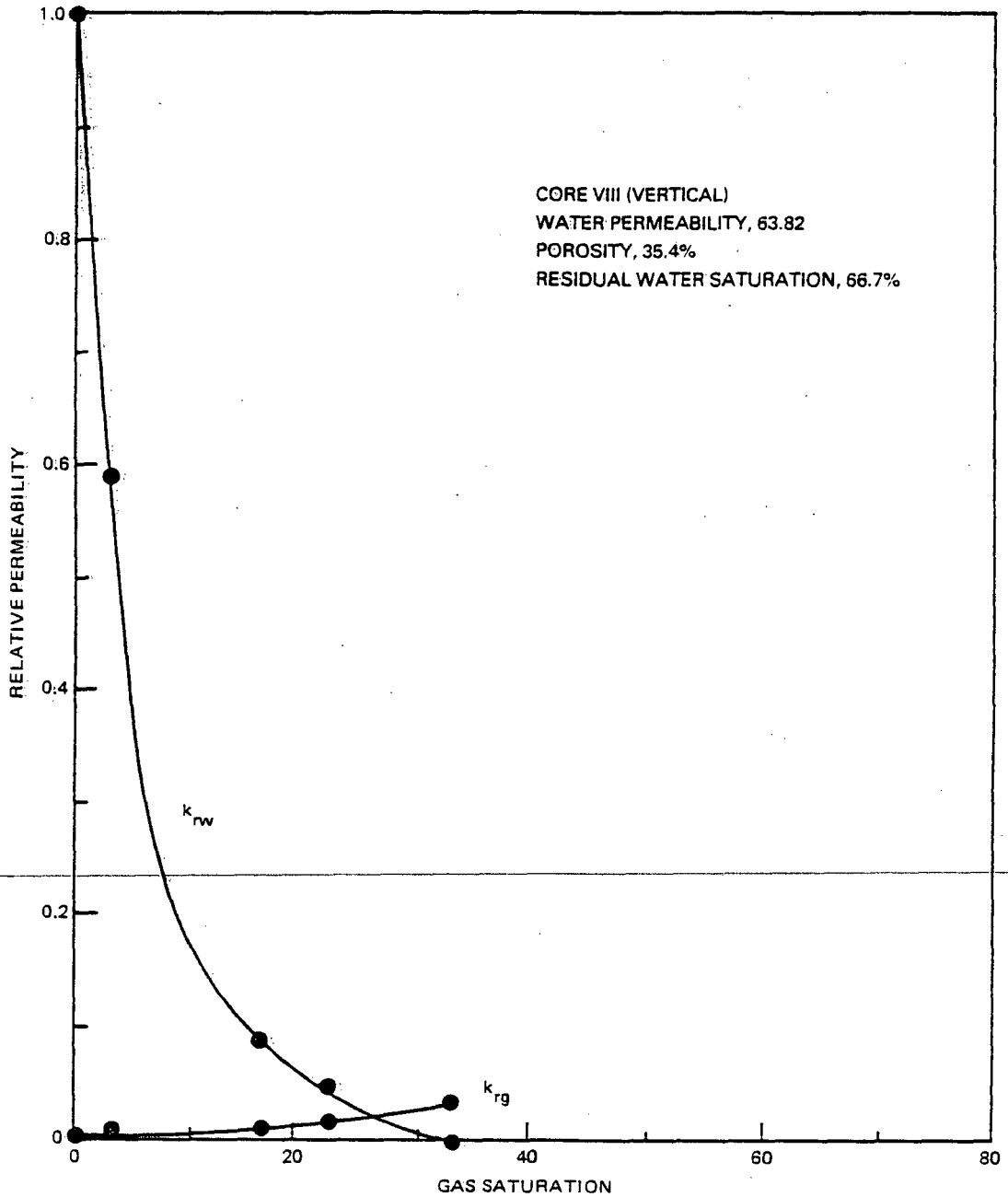


FIG. 27 AIR-WATER RELATIVE PERMEABILITY DATA FOR TAILINGS DAM SAND CORE VIII (VERTICAL)

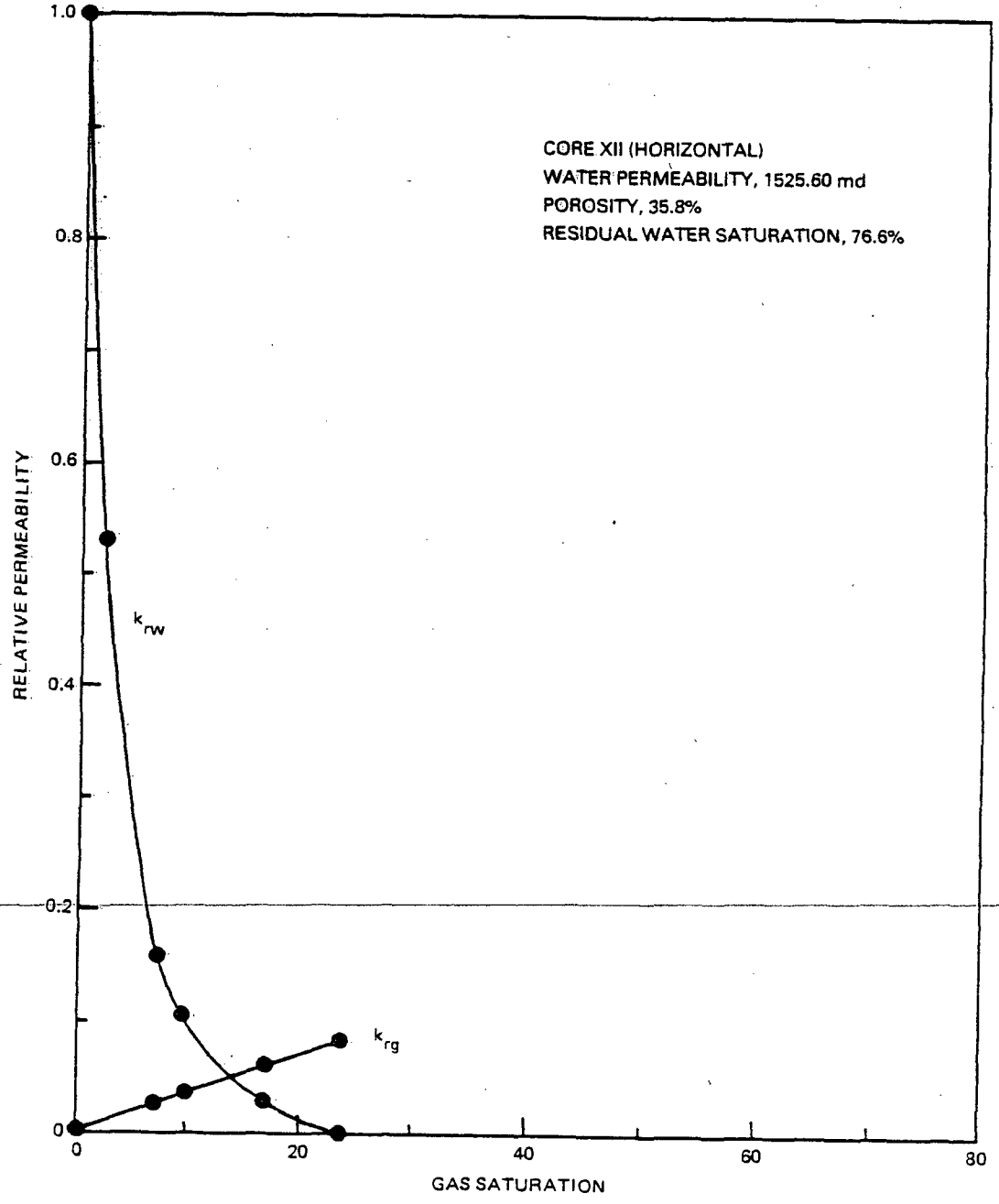


FIG. 28 AIR-WATER RELATIVE PERMEABILITY DATA FOR TAILINGS DAM SAND CORE XII (HORIZONTAL)

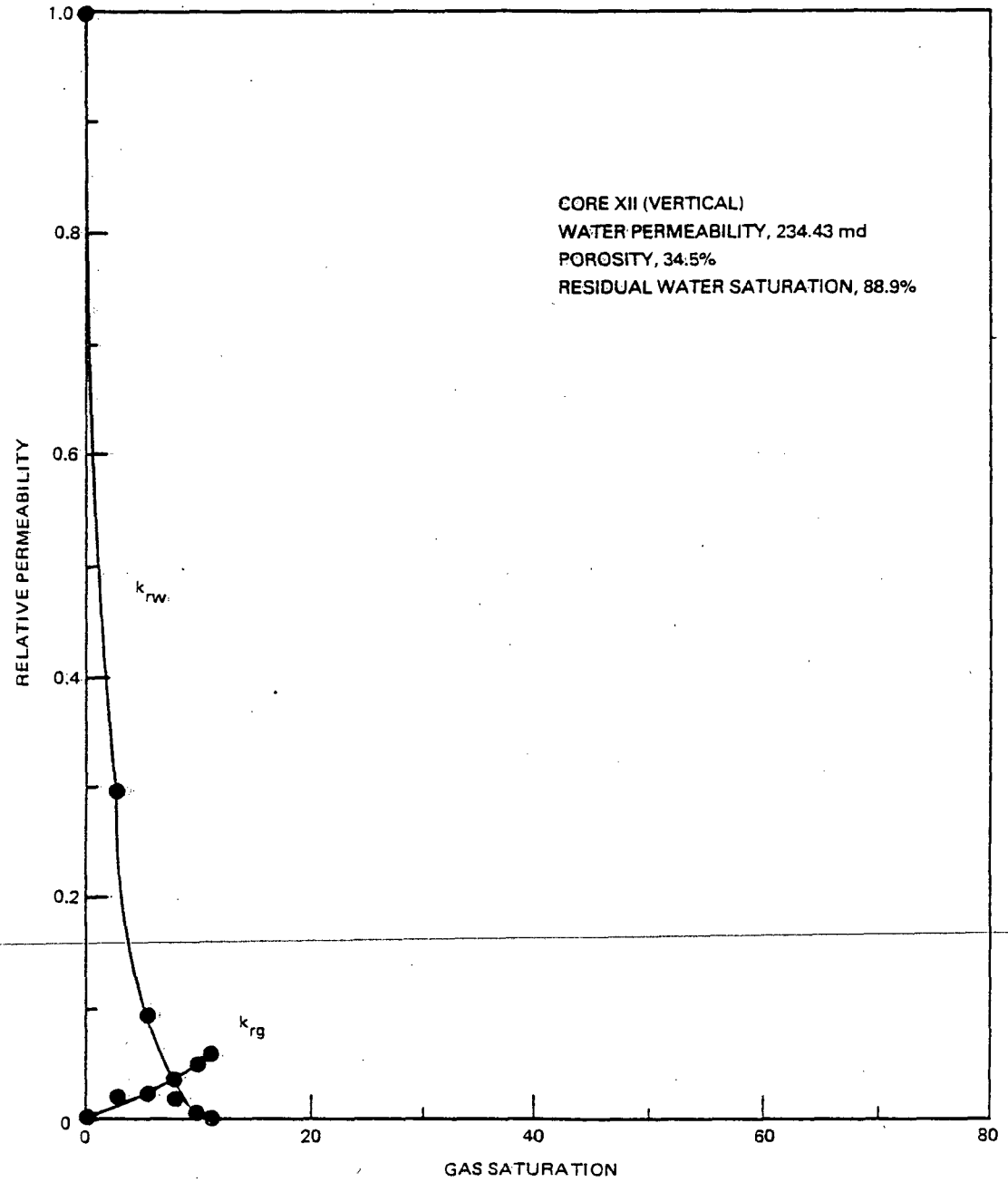


FIG. 29 AIR-WATER RELATIVE PERMEABILITY DATA FOR TAILINGS DAM SAND CORE XII (VERTICAL)

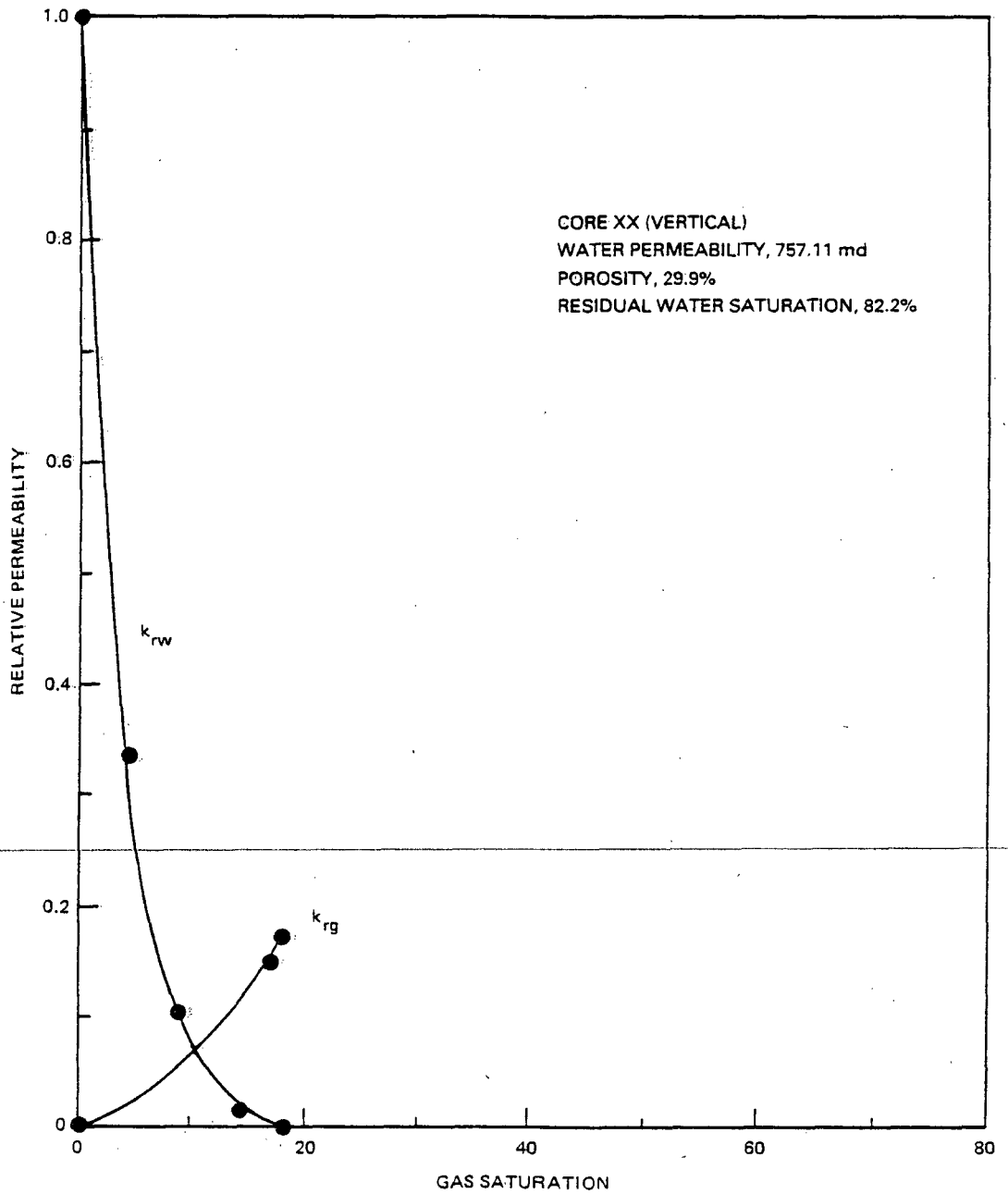


FIG. 30 AIR-WATER RELATIVE PERMEABILITY DATA FOR TAILINGS DAM SAND CORE XX (VERTICAL)

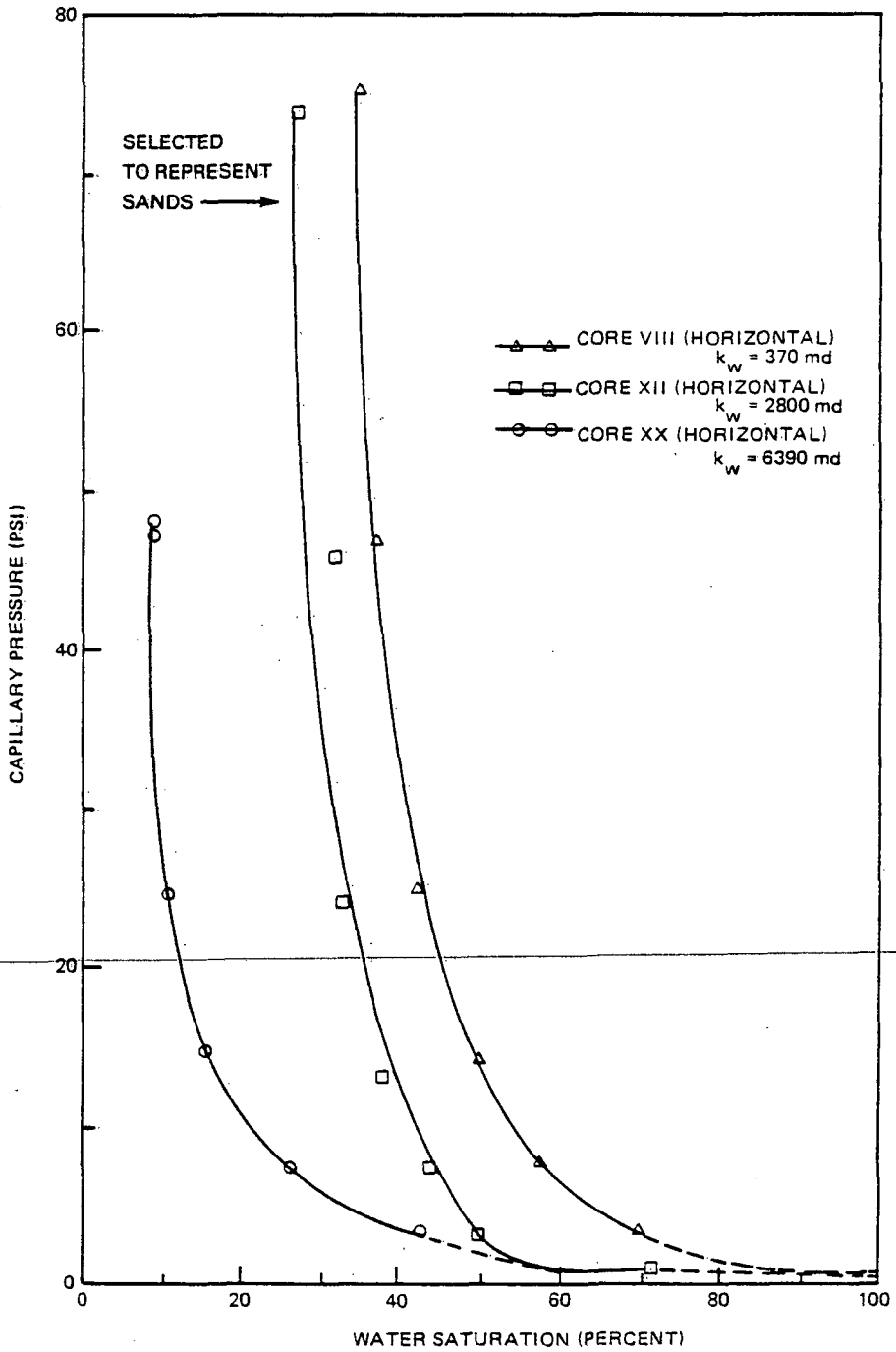


FIG. 31 AIR-WATER CAPILLARY PRESSURE CURVES FOR TAILINGS DAM SAND CORES VIII (HORIZONTAL), XII (HORIZONTAL), AND XX (HORIZONTAL)

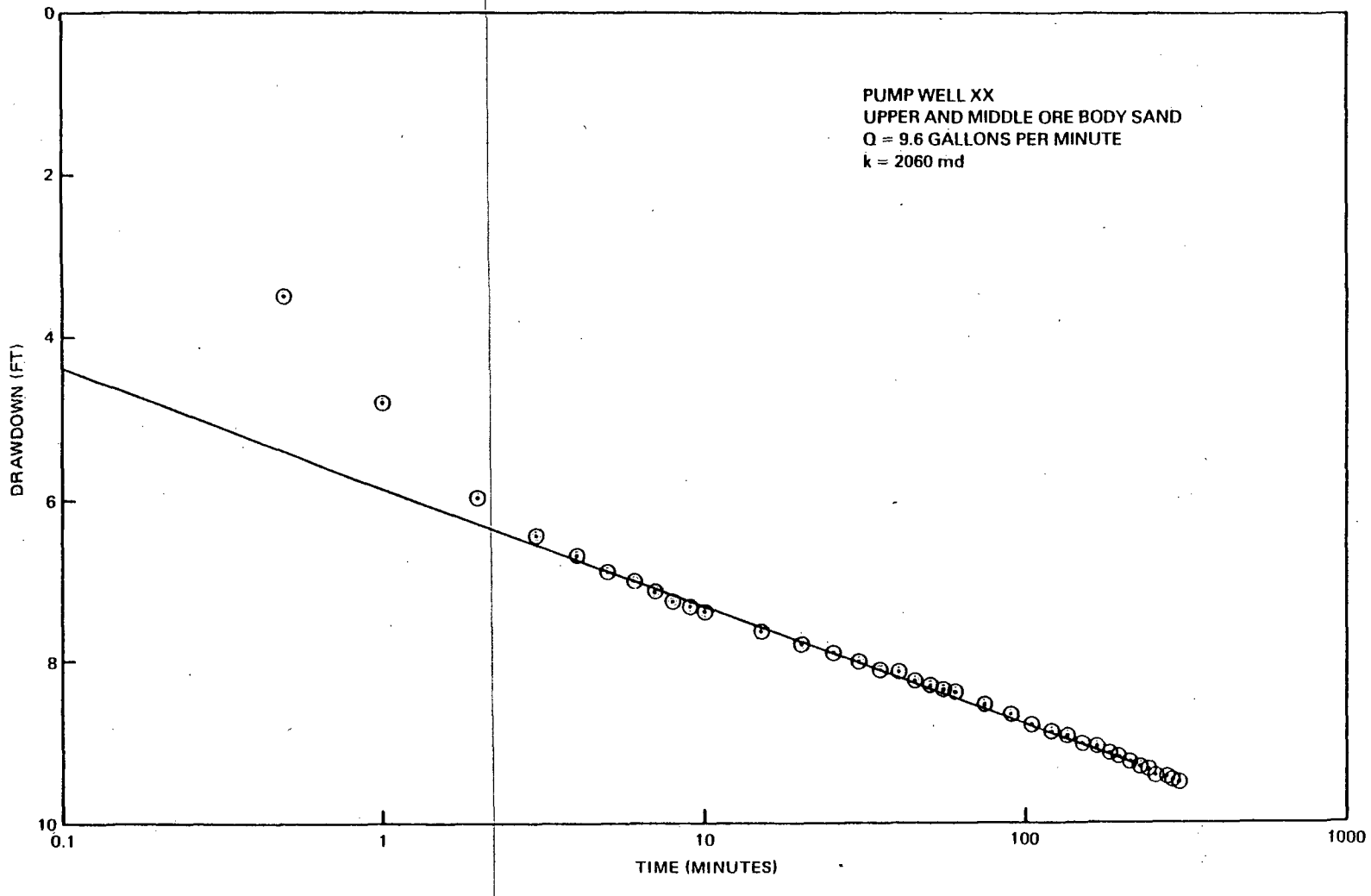


FIG. 32 PUMPING TEST CONDUCTED IN THE UPPER AND MIDDLE ORE BODY SAND AT WELL XX

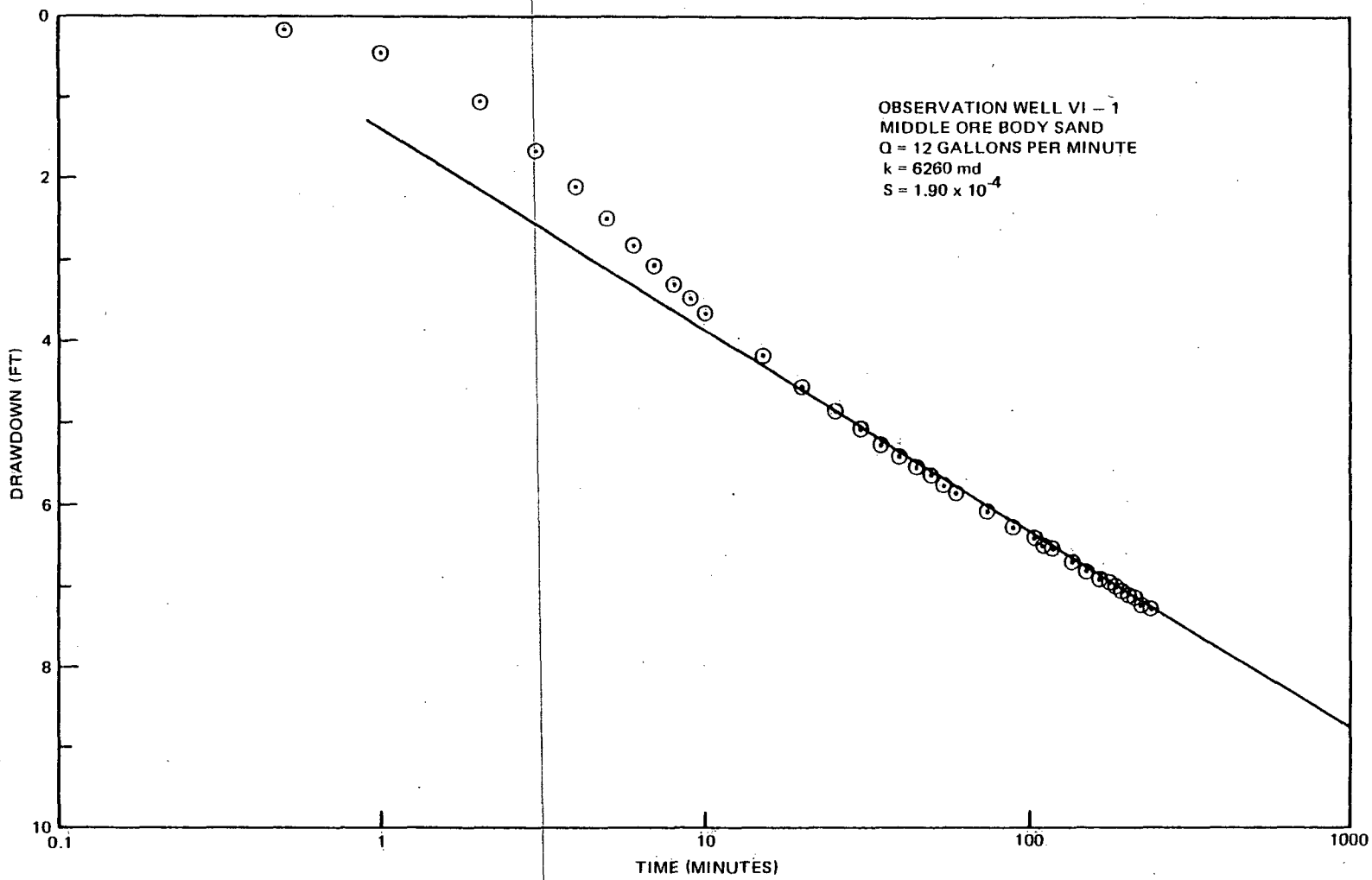


FIG. 33 PUMPING TEST CONDUCTED IN THE MIDDLE ORE BODY SAND AT WELL VI

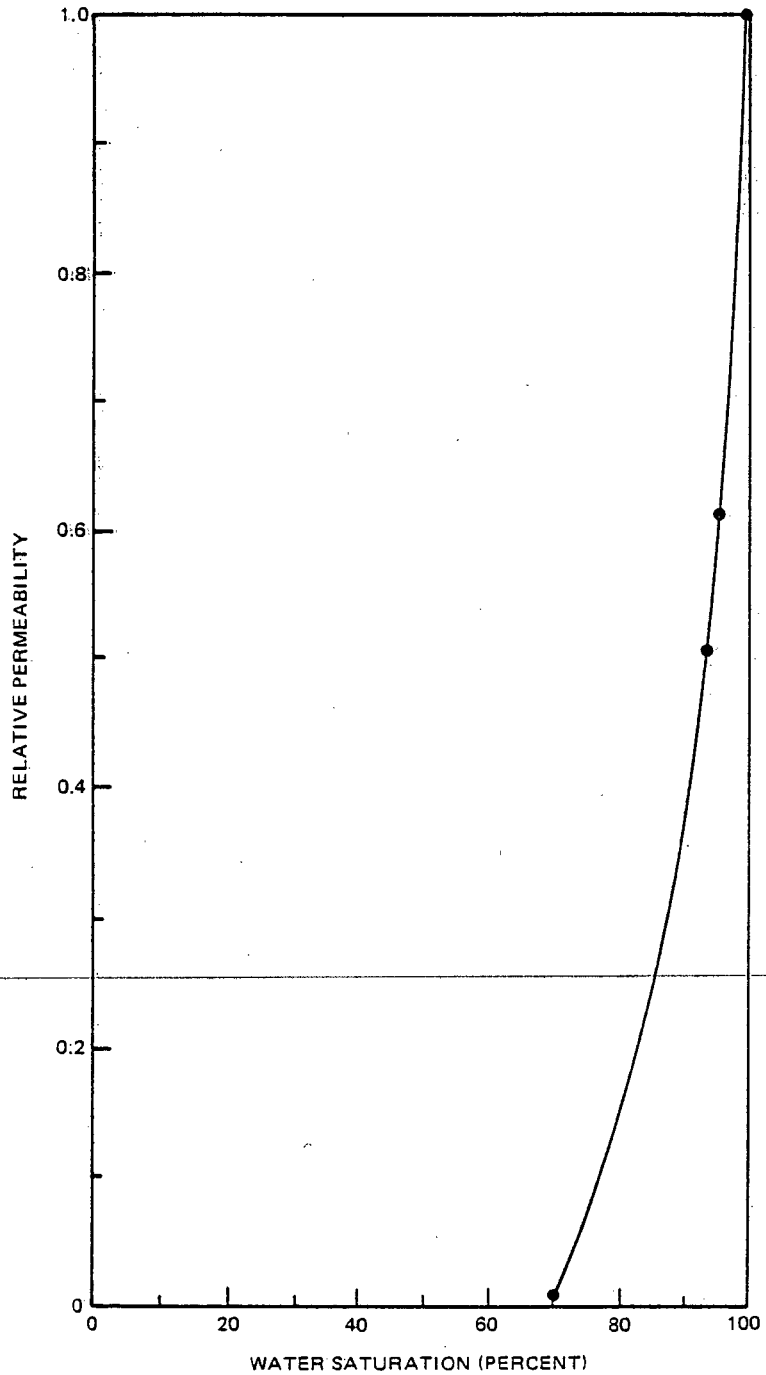


FIG. 34 SHALE RELATIVE PERMEABILITY DATA
(FROM BATTELLE; 1980a)

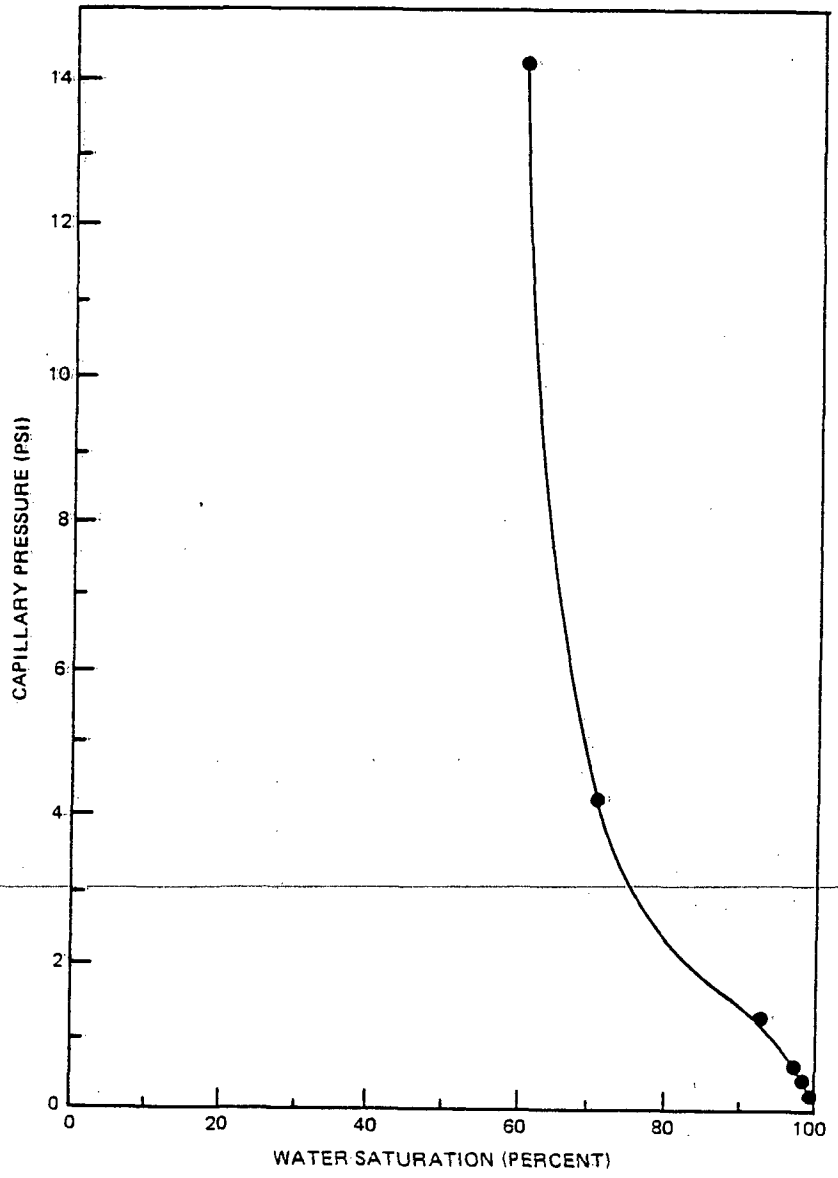
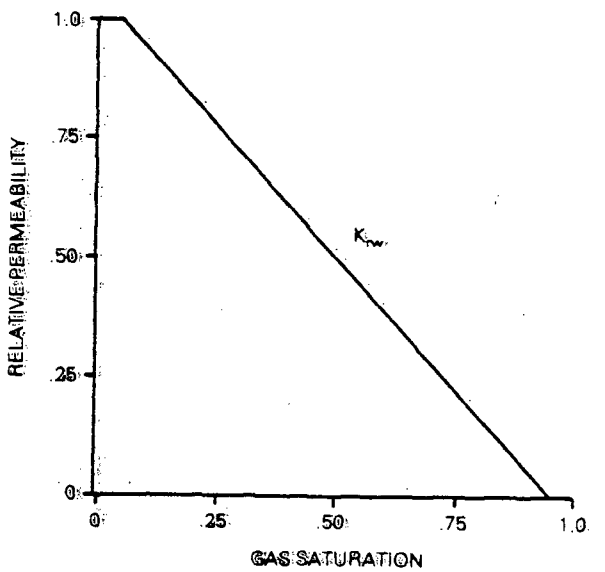


FIG. 35 SHALE CAPILLARY PRESSURE DATA
(FROM BATTELLE; 1980a)



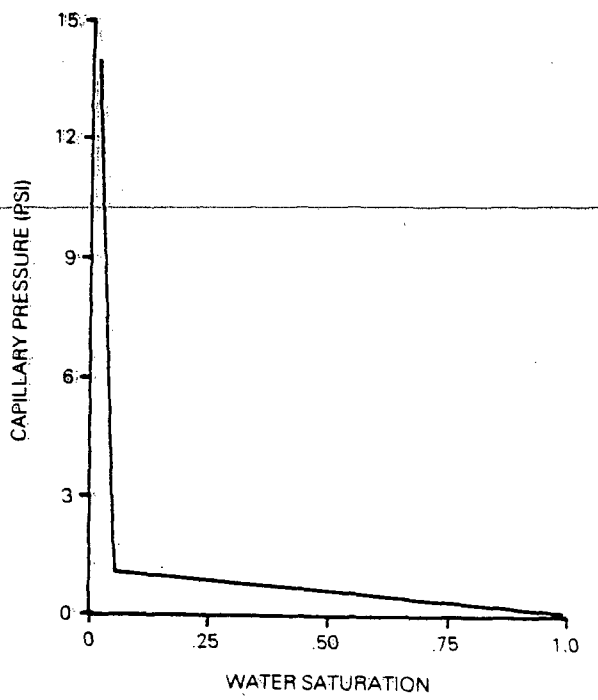


FIG.36 PSEUDO-RELATIVE PERMEABILITY AND PSEUDO-CAPILLARY PRESSURE CURVES USED FOR THE SURFACE MINE BACKFILL IN THE CROSS SECTIONS

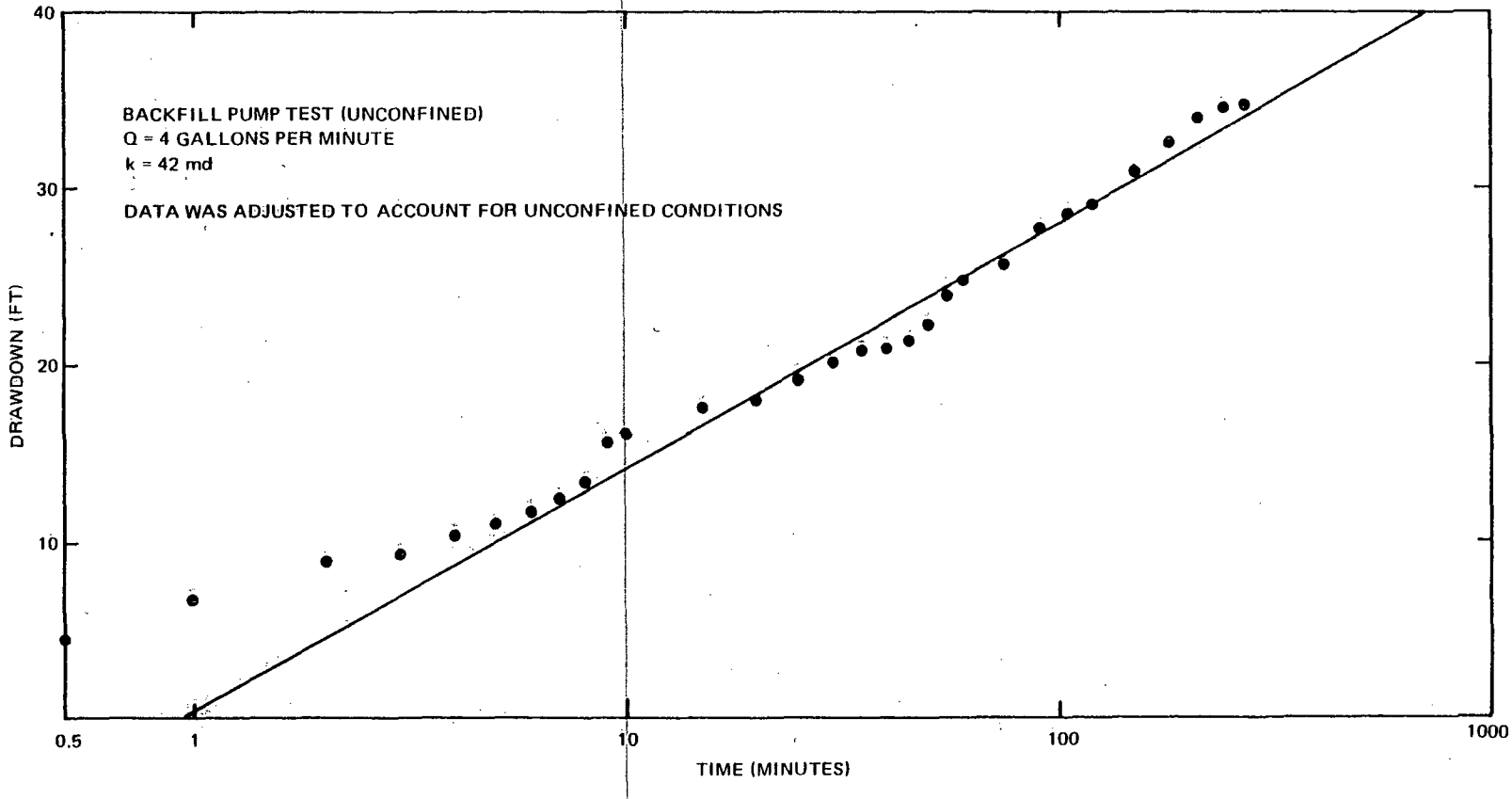
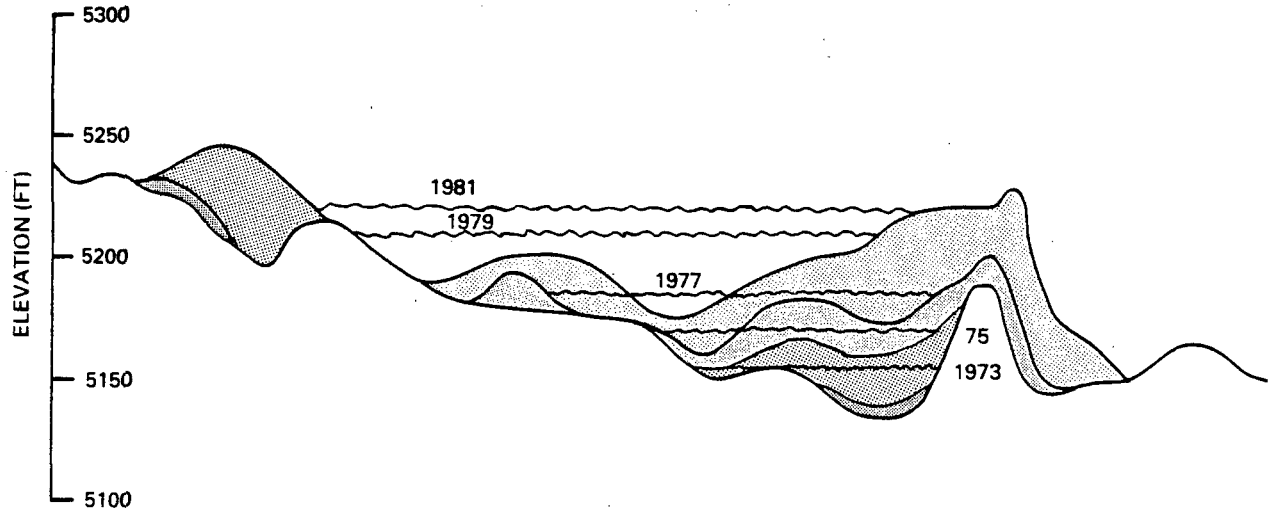
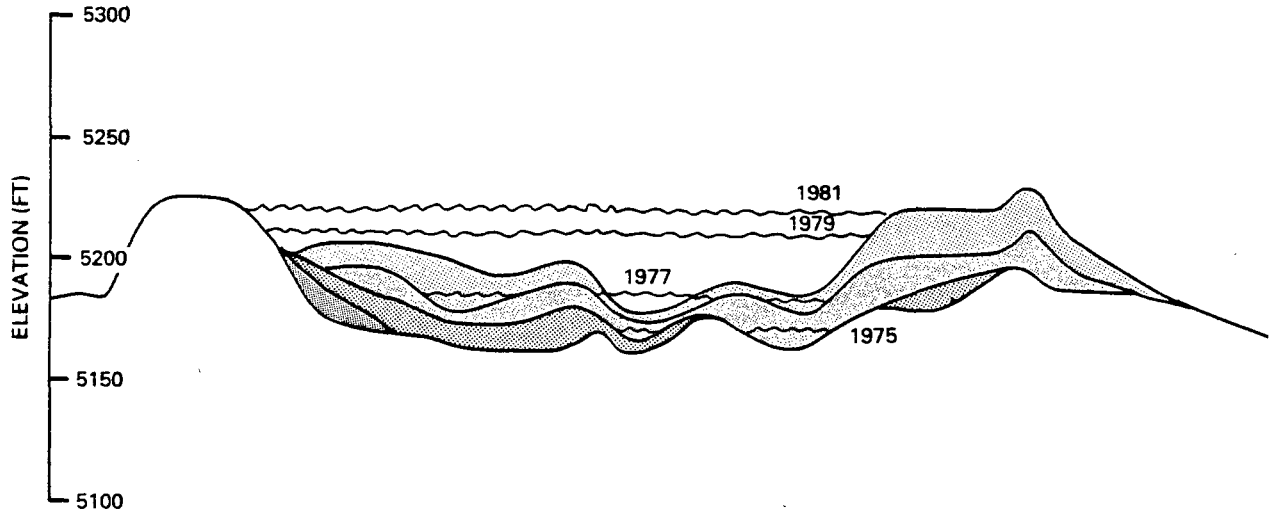


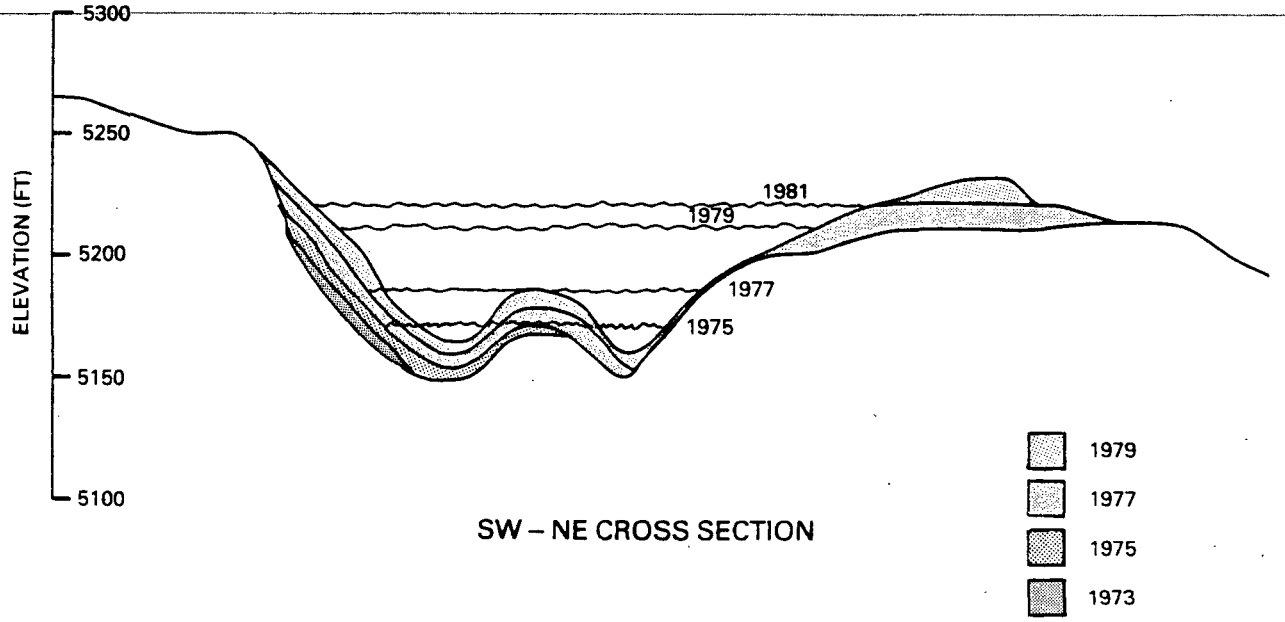
FIG. 37 PUMPING TEST RESULTS FROM A WELL COMPLETED IN THE SURFACE MINE BACKFILL



NW – SE CROSS SECTION

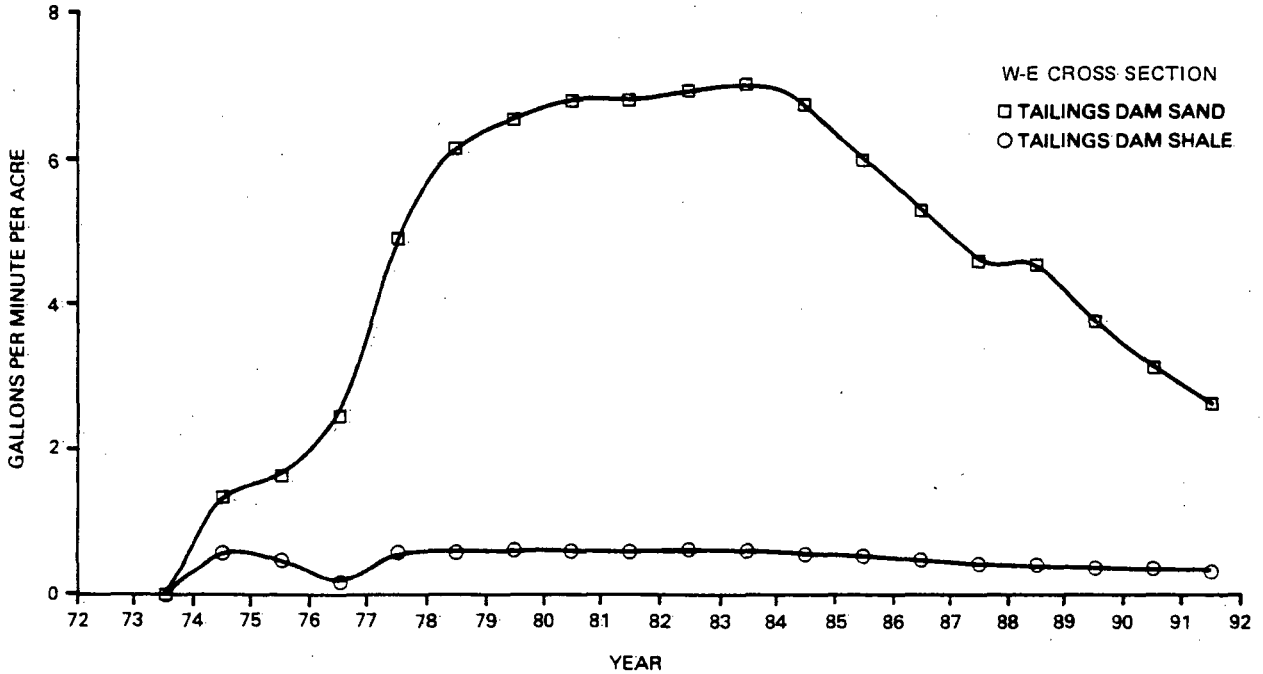


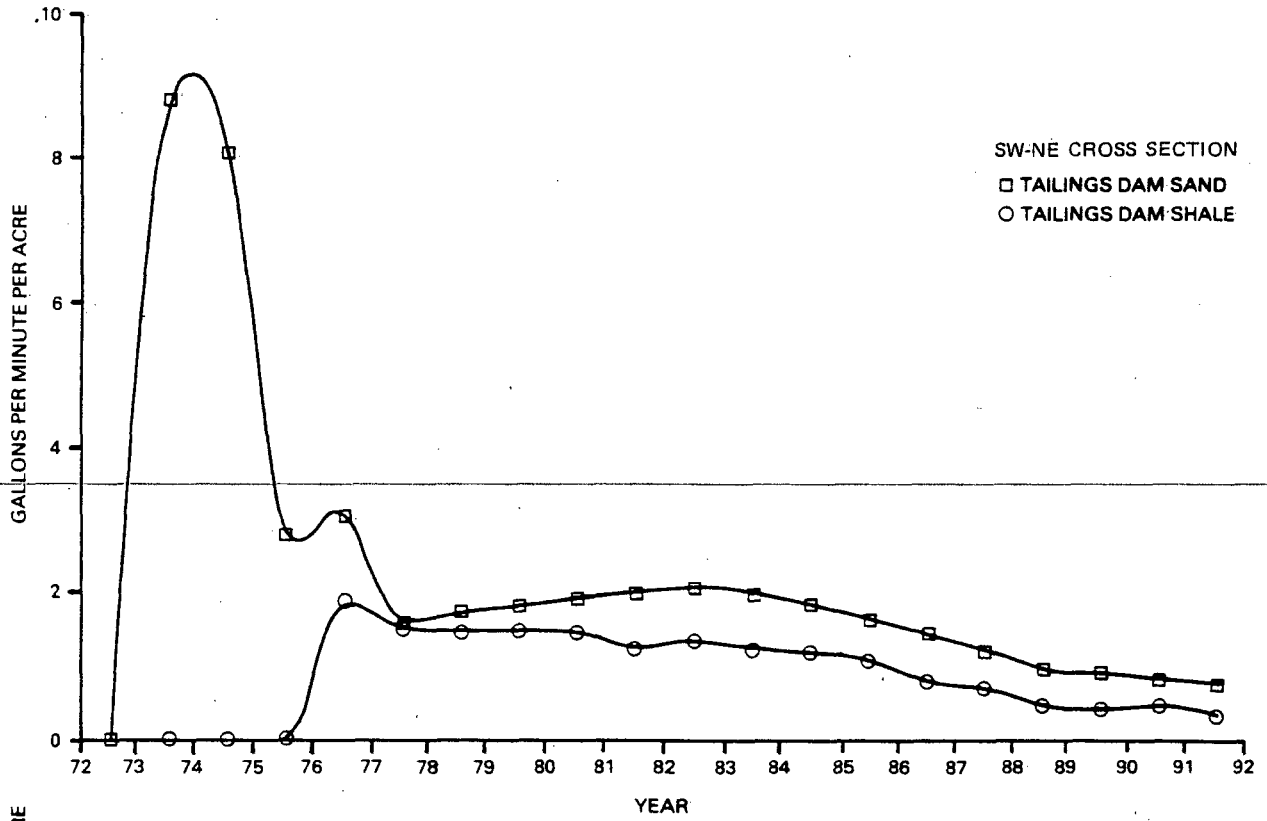
W – E CROSS SECTION



SW – NE CROSS SECTION

FIG. 38 TAILINGS AND POND LIQUOR BUILD-UP IN THE CROSS SECTIONS





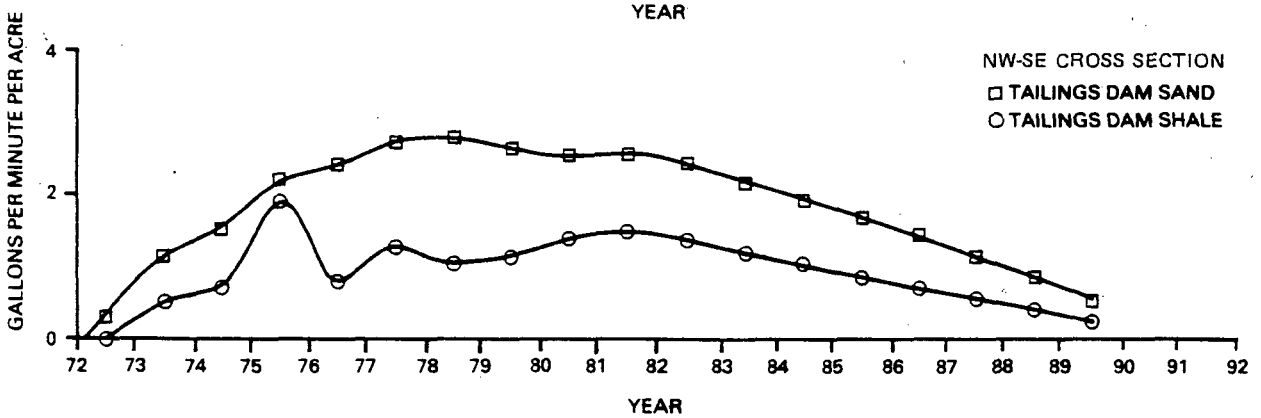


FIG. 39 AREA-NORMALIZED PREDICTED POND SEEPAGE FROM THE CROSS SECTIONS (GALLONS PER MINUTE PER ACRE)

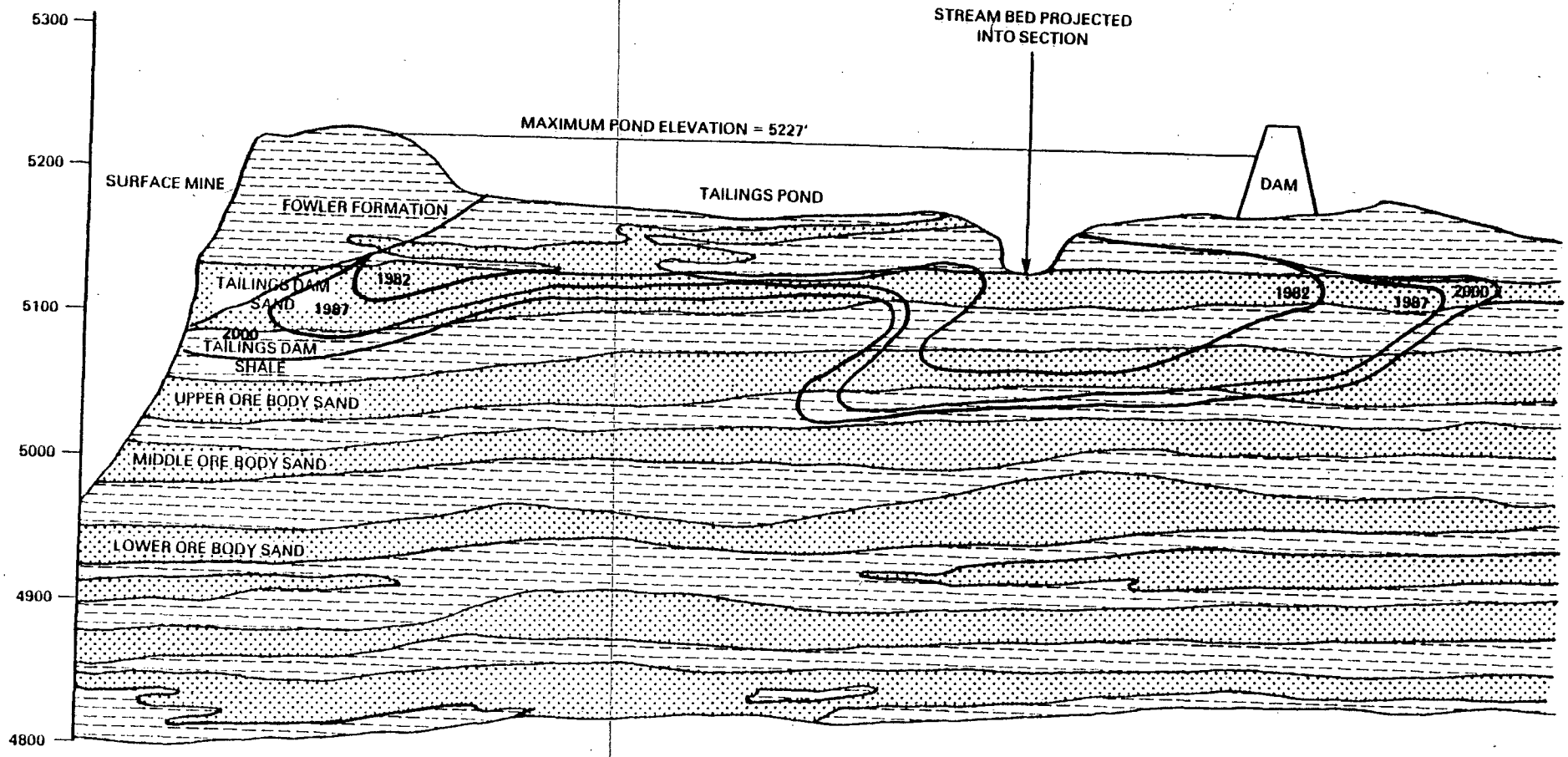


FIG. 40 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 1.0
WEST-EAST CROSS SECTION

0 100
FEET
VERTICAL SCALE

0 500
FEET
HORIZONTAL SCALE

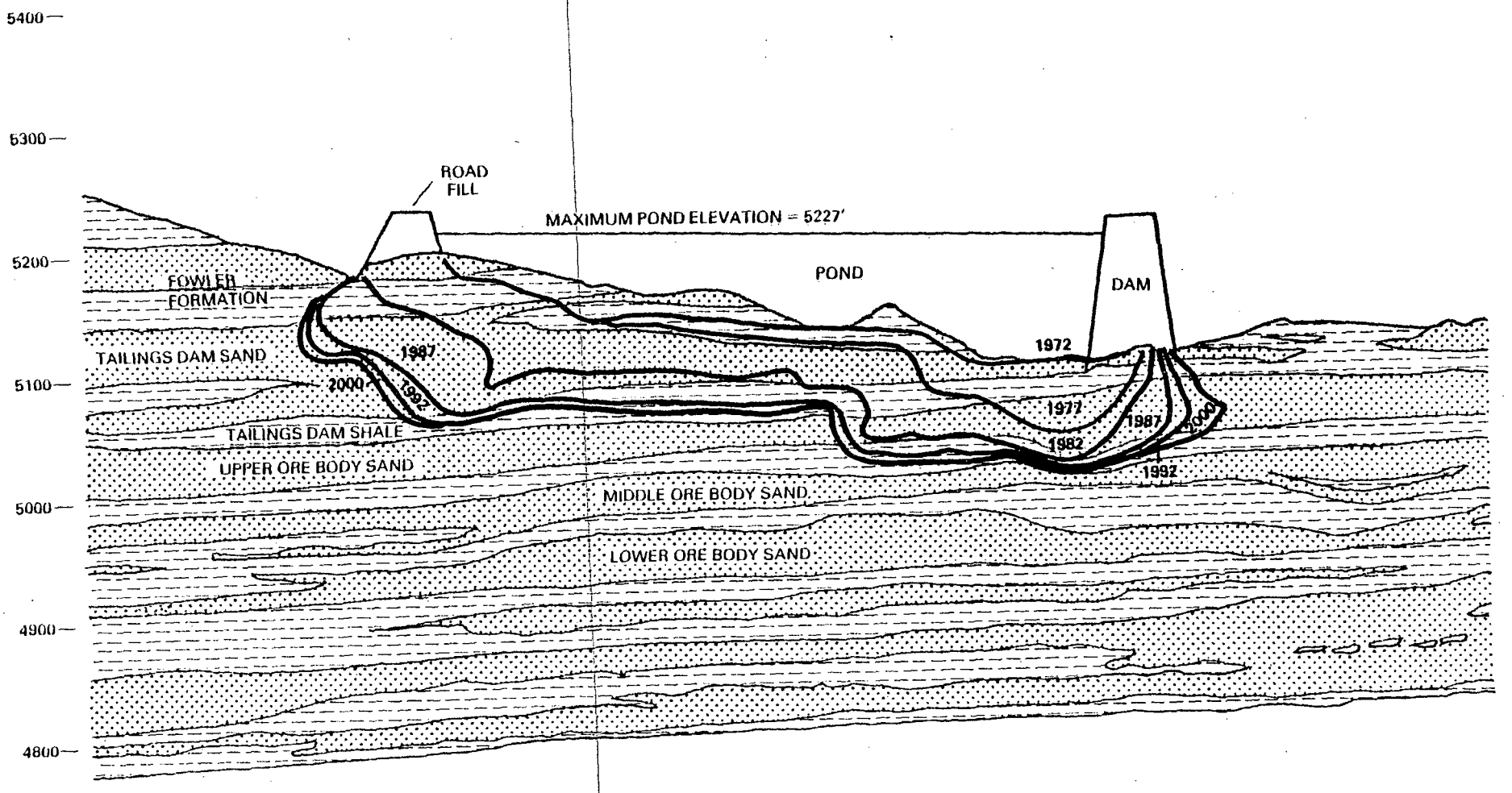


FIG. 41 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 1.0
NORTHWEST-SOUTHEAST CROSS SECTION

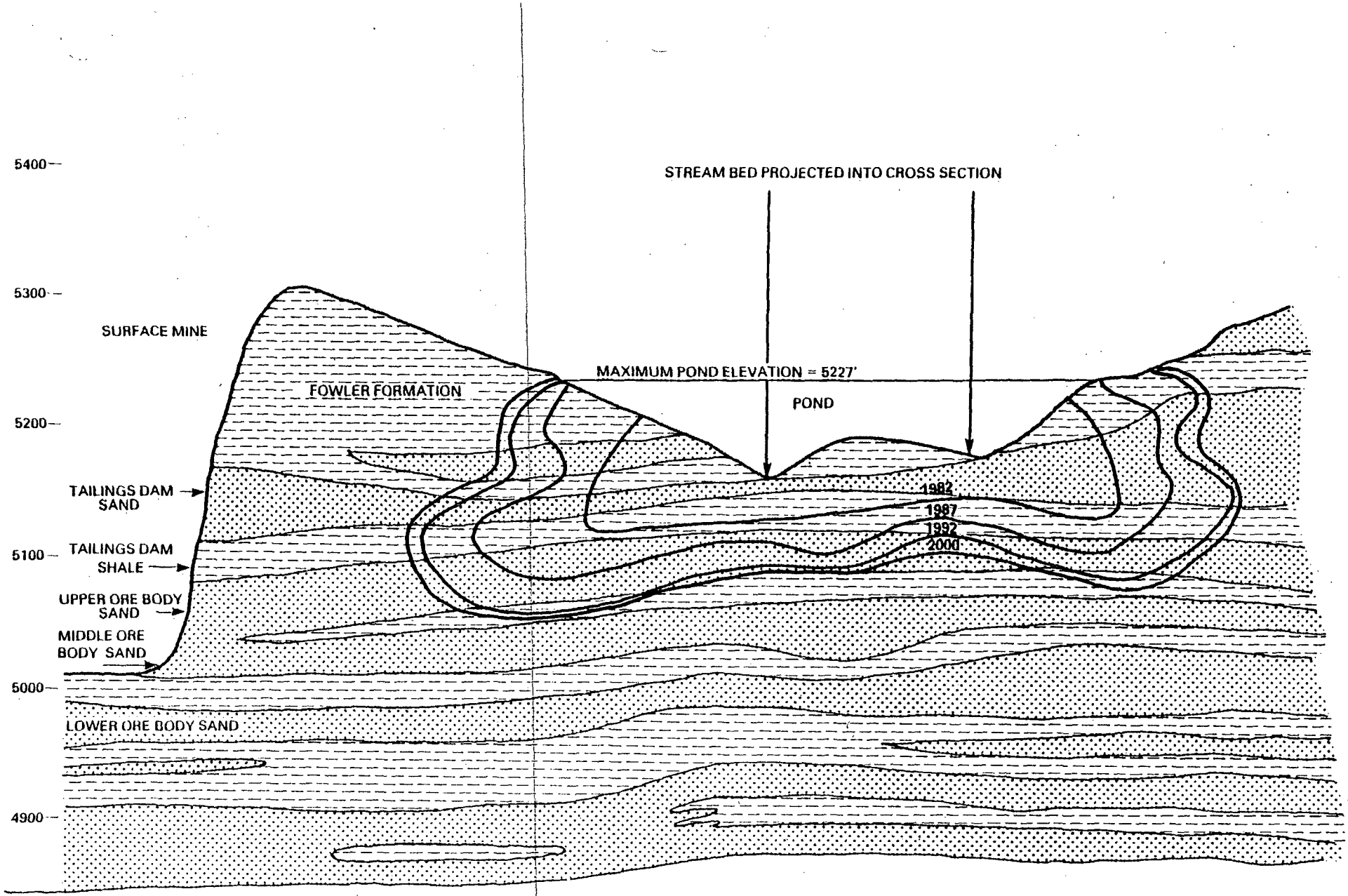


FIG. 42 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 1.0
SOUTHWEST-NORTHEAST CROSS SECTION

VERTICAL SCALE 0 100 FEET

HORIZONTAL SCALE 0 500 FEET

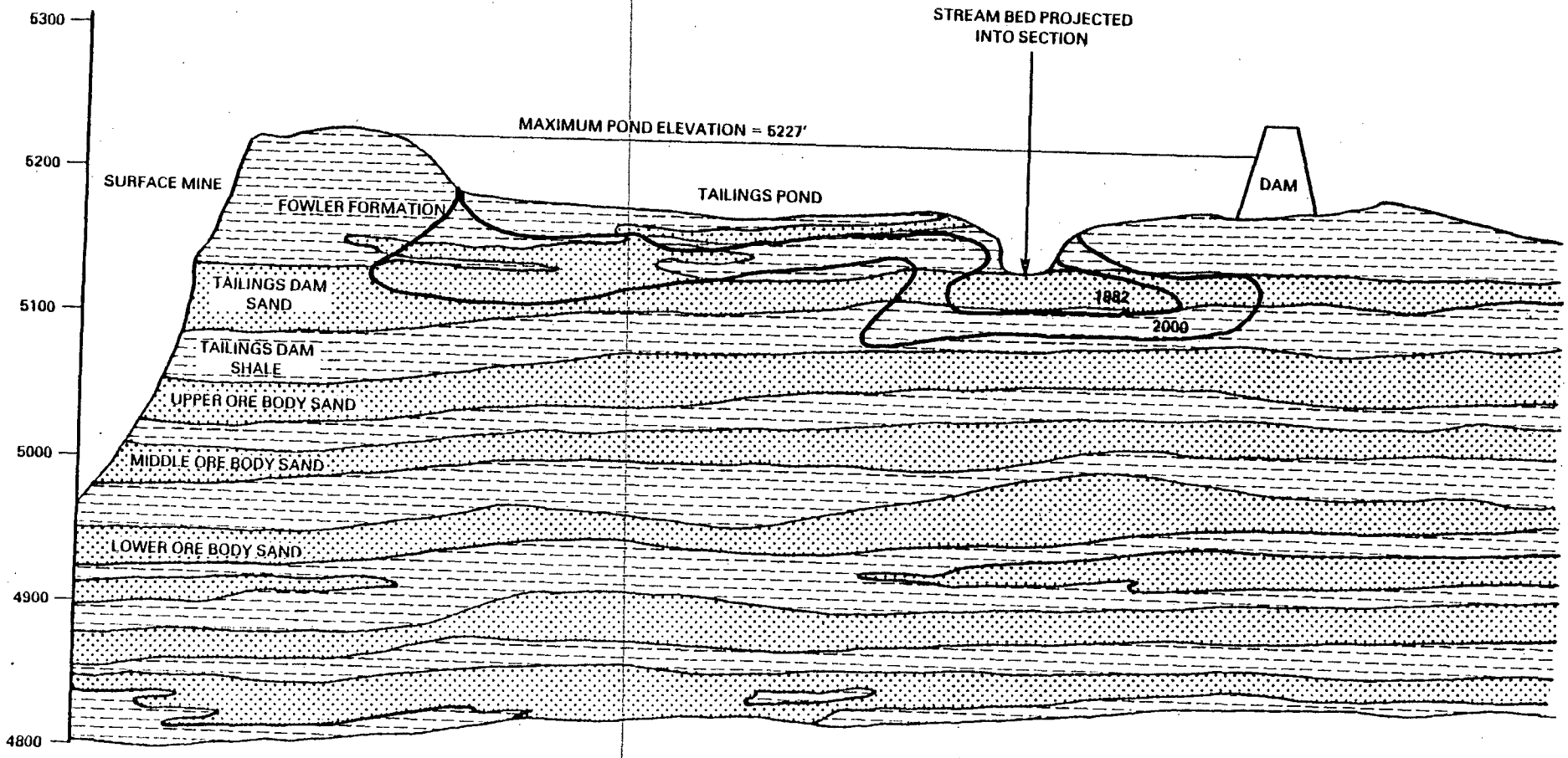


FIG. 43 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.30
WEST-EAST CROSS SECTION

0 100 FEET VERTICAL SCALE

0 500 FEET HORIZONTAL SCALE

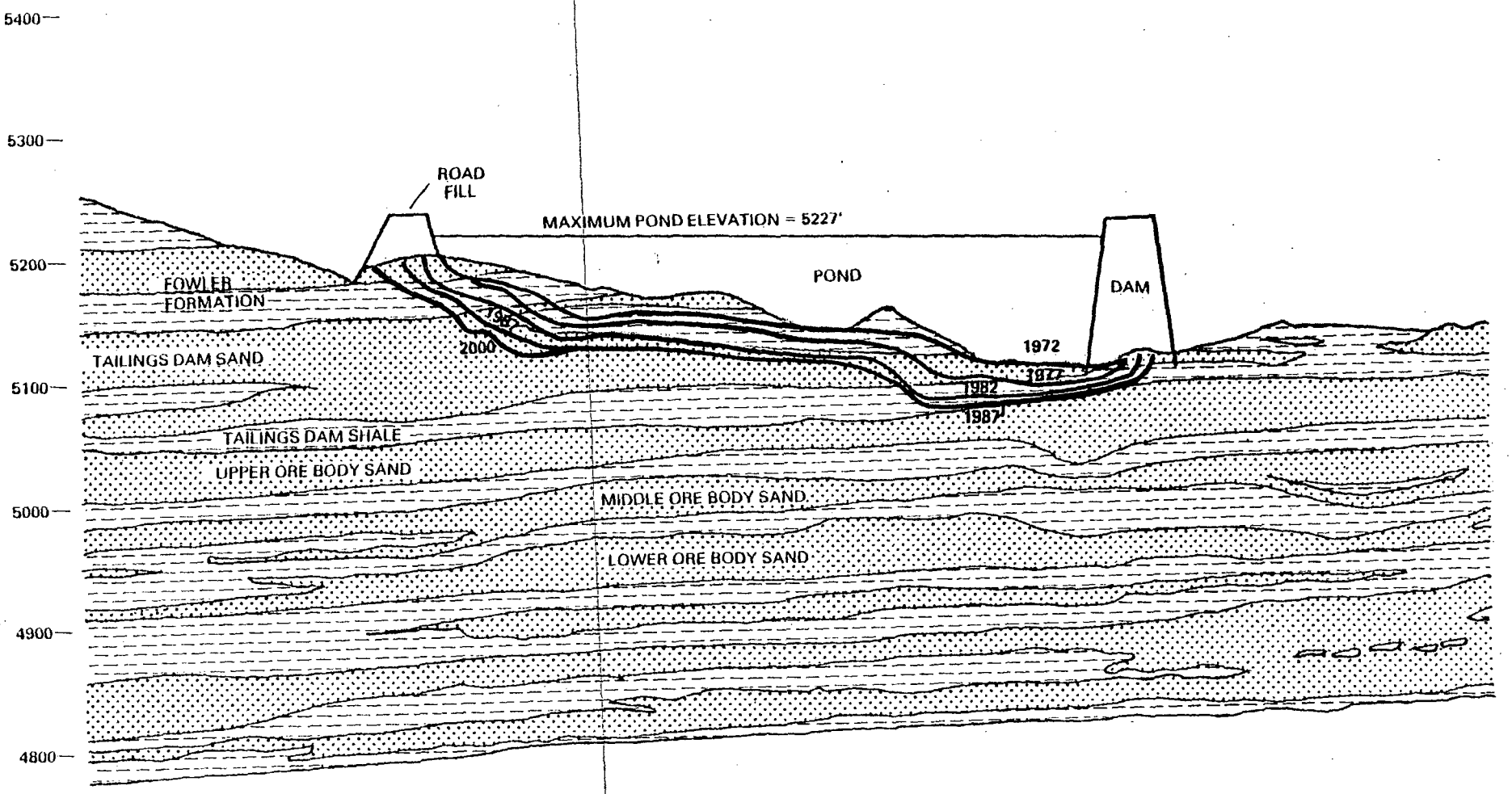


FIG. 44 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.30 NORTHWEST-SOUTHEAST CROSS SECTION

0 100
FEET
VERTICAL SCALE

0 500
FEET
HORIZONTAL SCALE

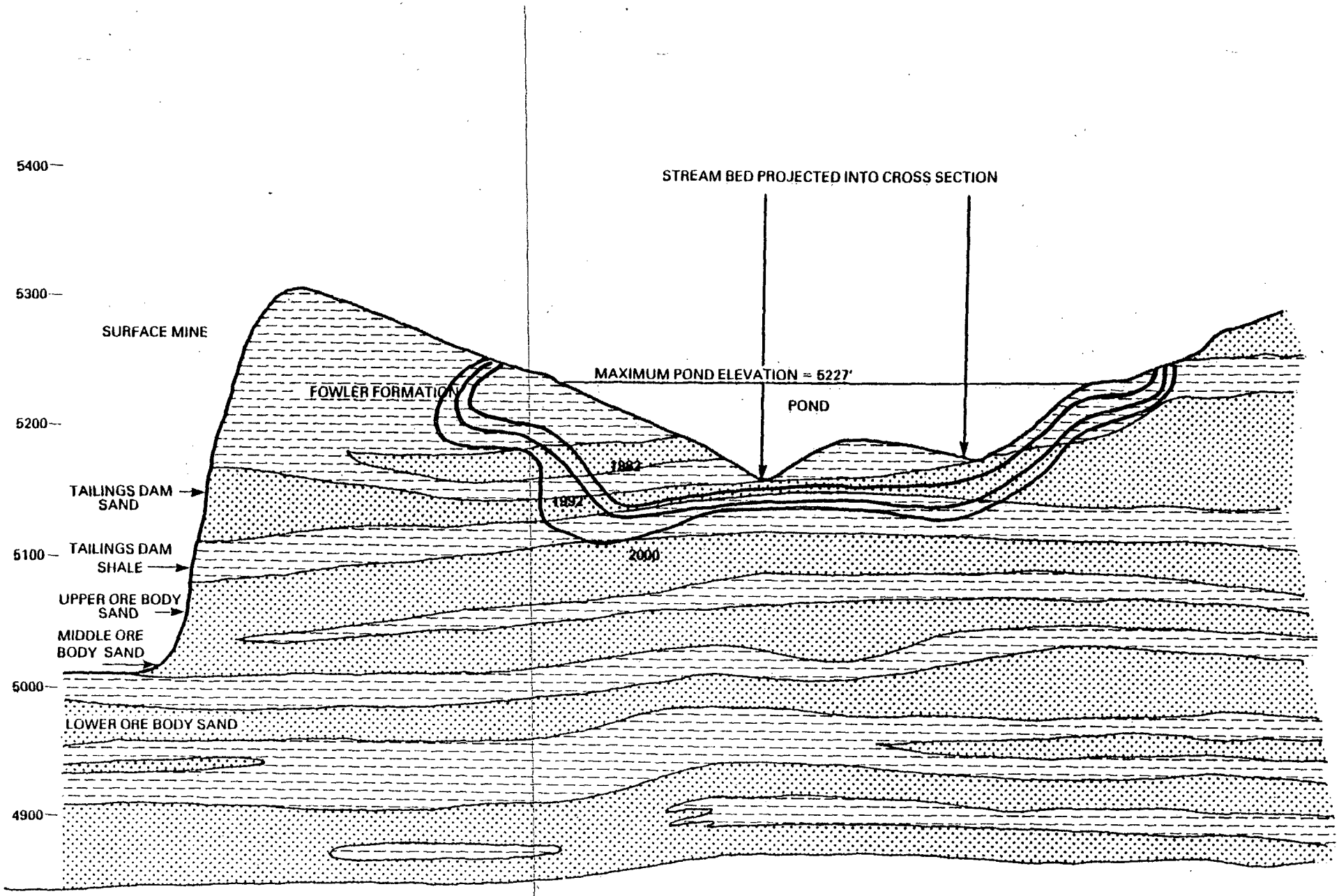


FIG. 45 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.30
SOUTHWEST-NORTHEAST CROSS SECTION

VERTICAL SCALE 0 100 FEET

HORIZONTAL SCALE 0 500 FEET

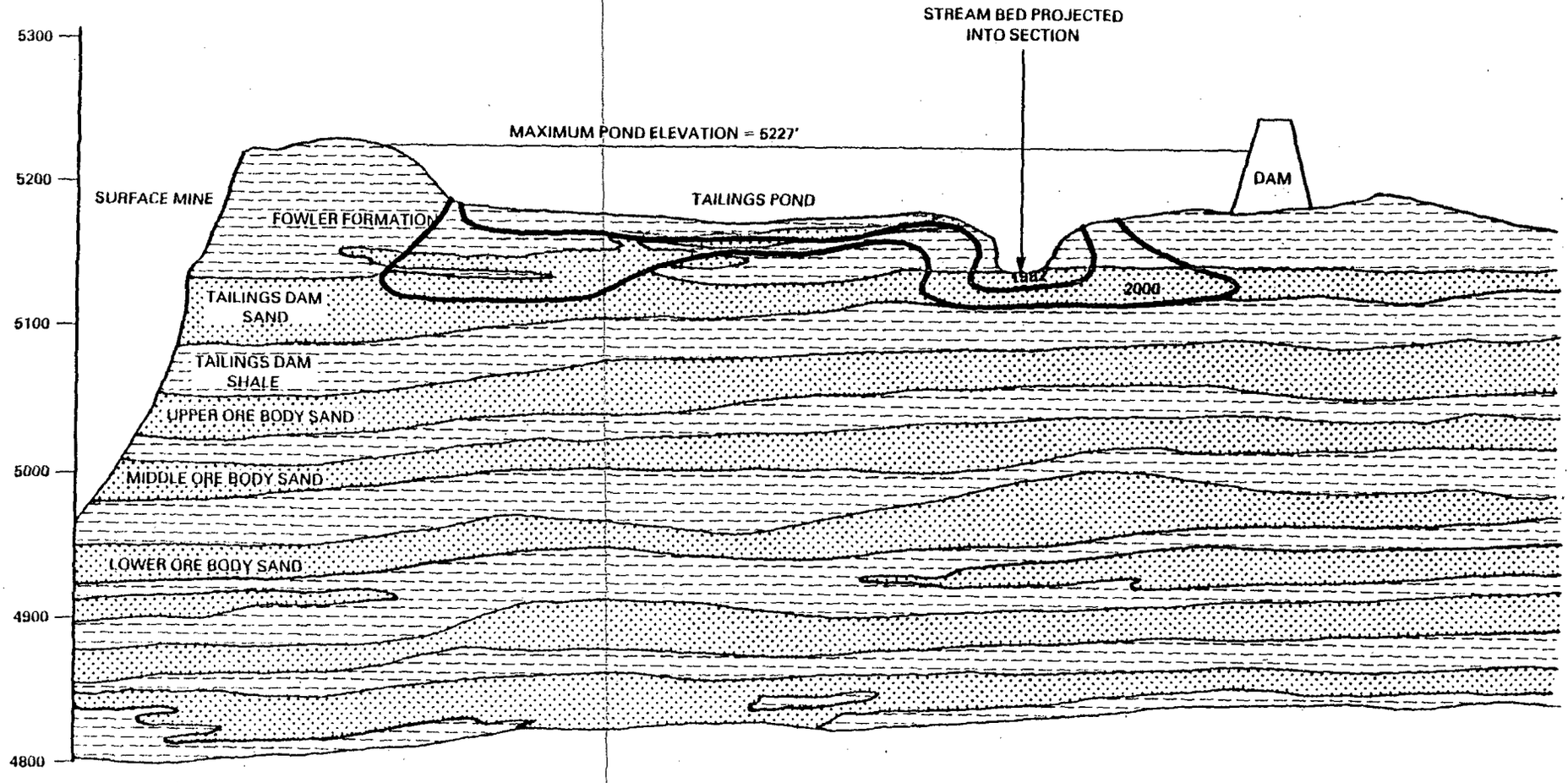


FIG. 46 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.20
WEST-EAST CROSS SECTION

0 100
FEET
VERTICAL SCALE

0 500
FEET
HORIZONTAL SCALE

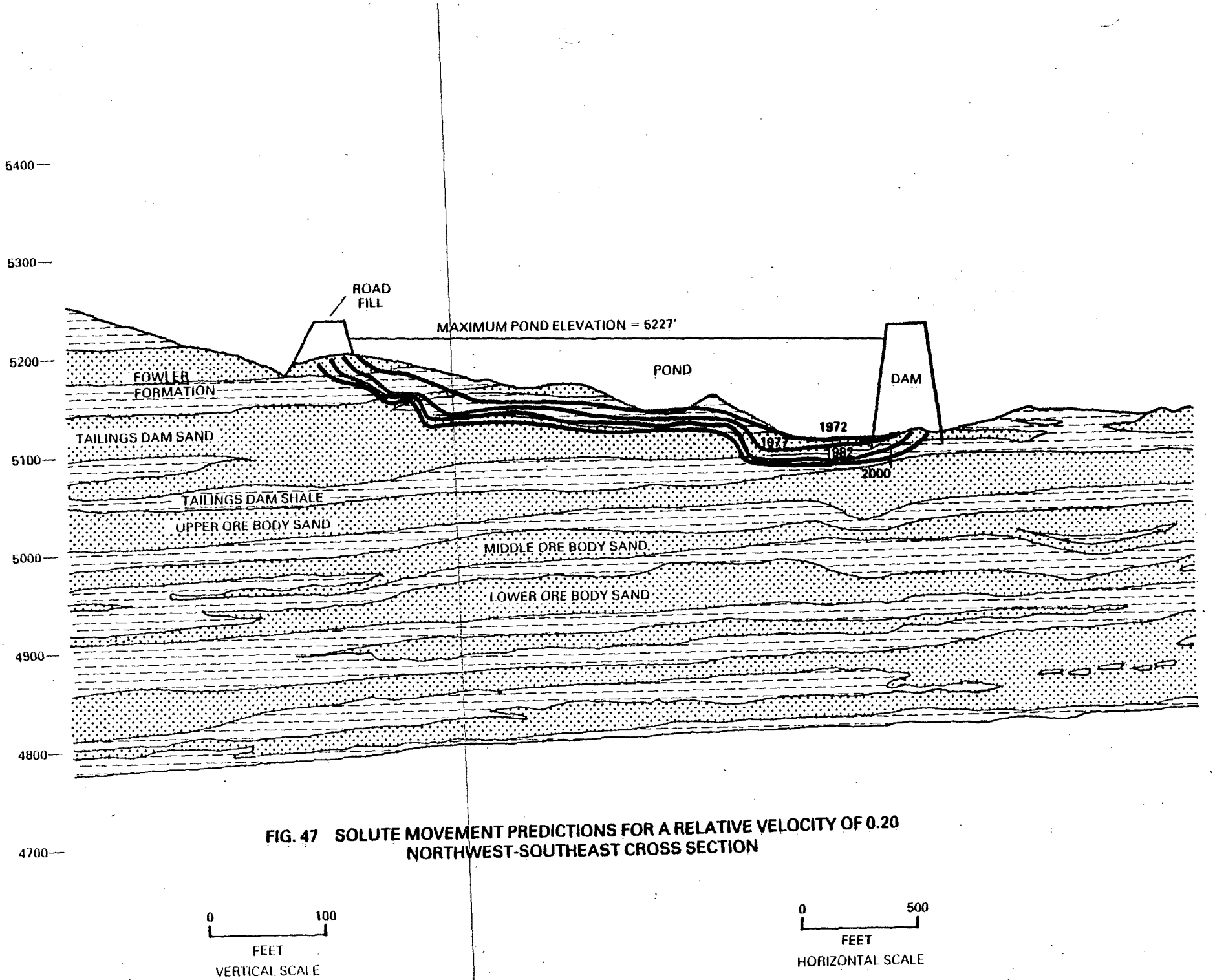


FIG. 47 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.20
NORTHWEST-SOUTHEAST CROSS SECTION

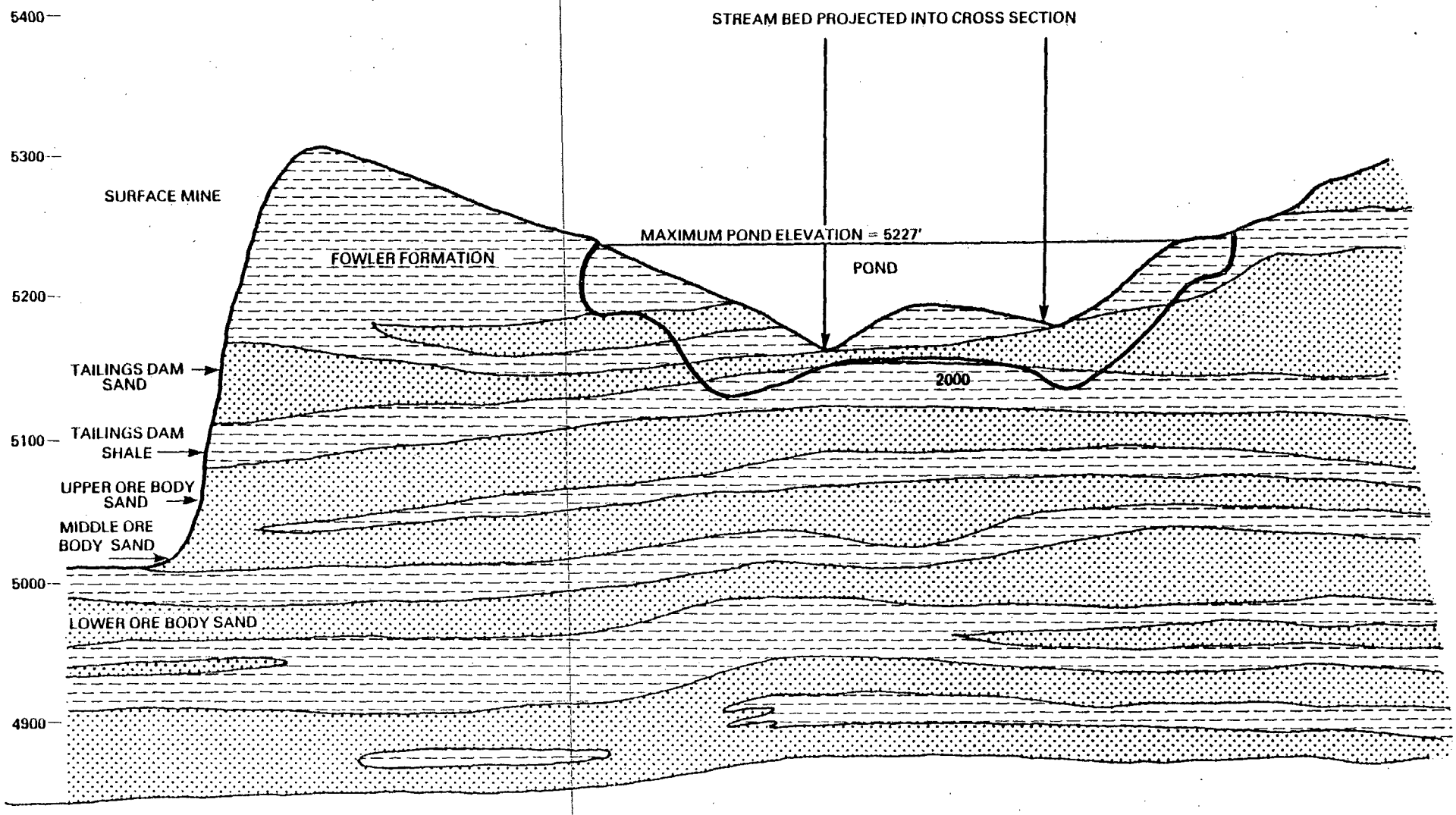


FIG. 48 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.20
SOUTHWEST-NORTHEAST CROSS SECTION

VERTICAL SCALE 0 100 FEET

HORIZONTAL SCALE 0 500 FEET

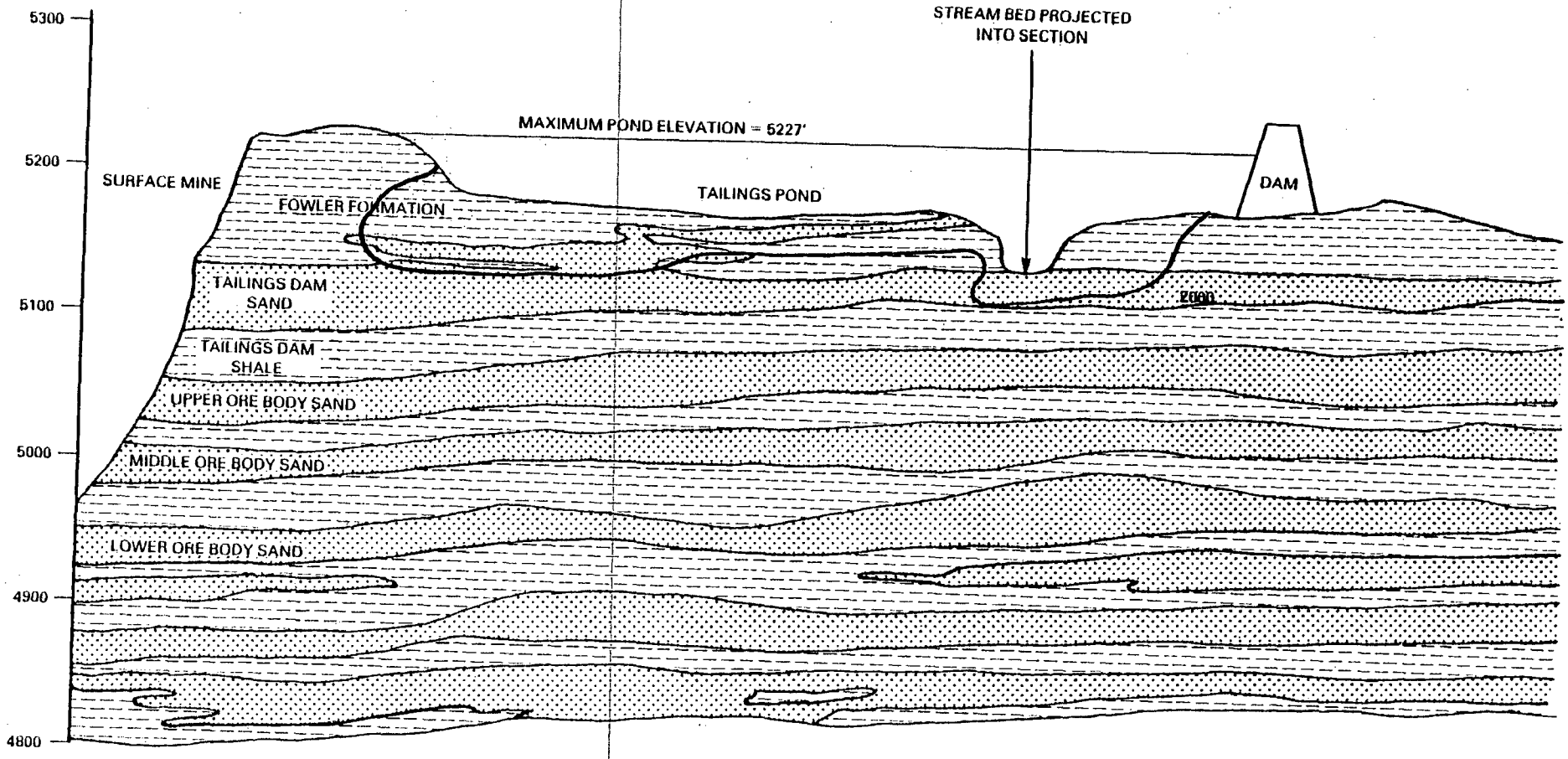


FIG. 49 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.10
WEST-EAST CROSS SECTION

0 100 FEET VERTICAL SCALE

0 500 FEET HORIZONTAL SCALE

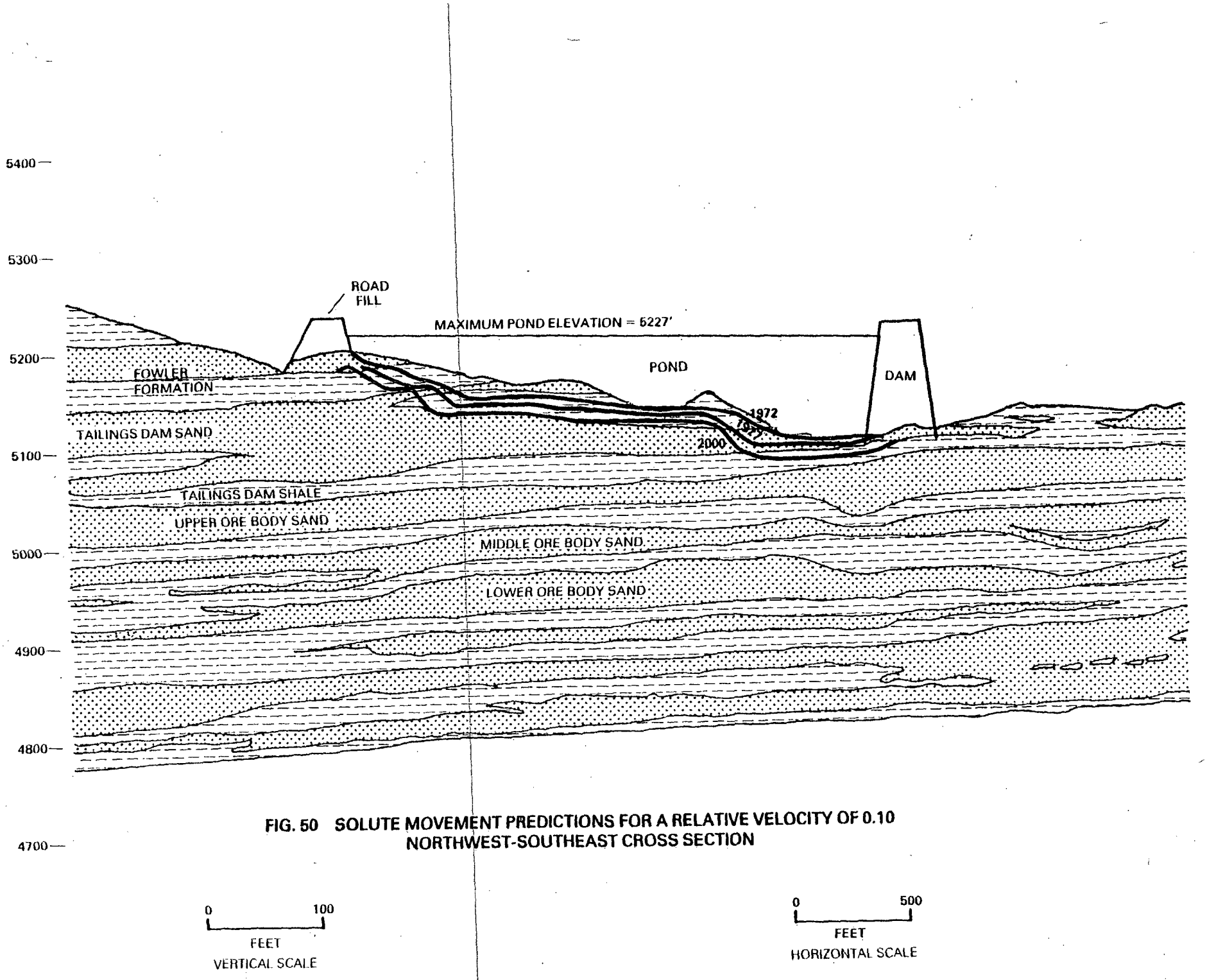


FIG. 50 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.10
NORTHWEST-SOUTHEAST CROSS SECTION

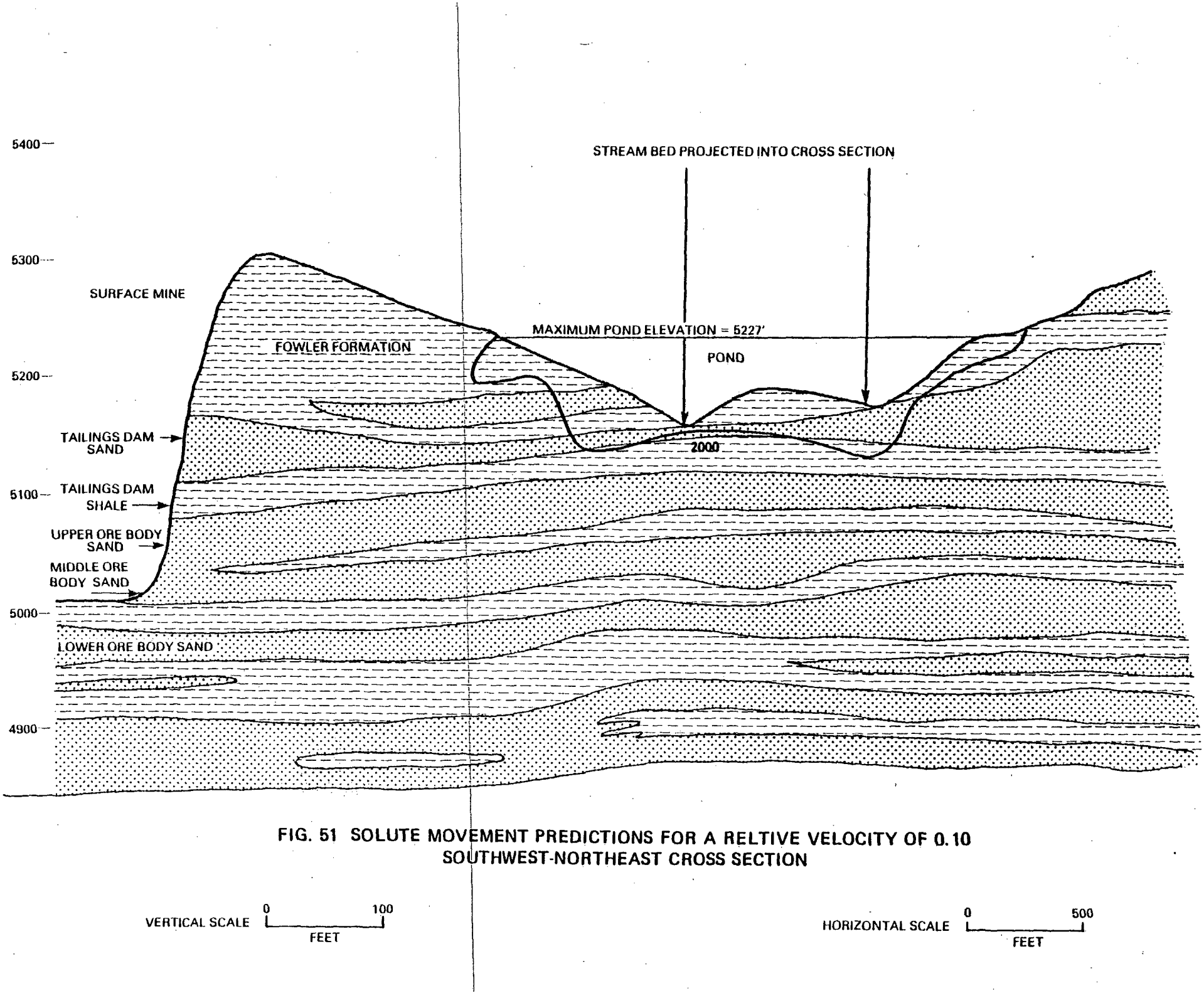


FIG. 51 SOLUTE MOVEMENT PREDICTIONS FOR A RELTIVE VELOCITY OF 0.10
SOUTHWEST-NORTHEAST CROSS SECTION

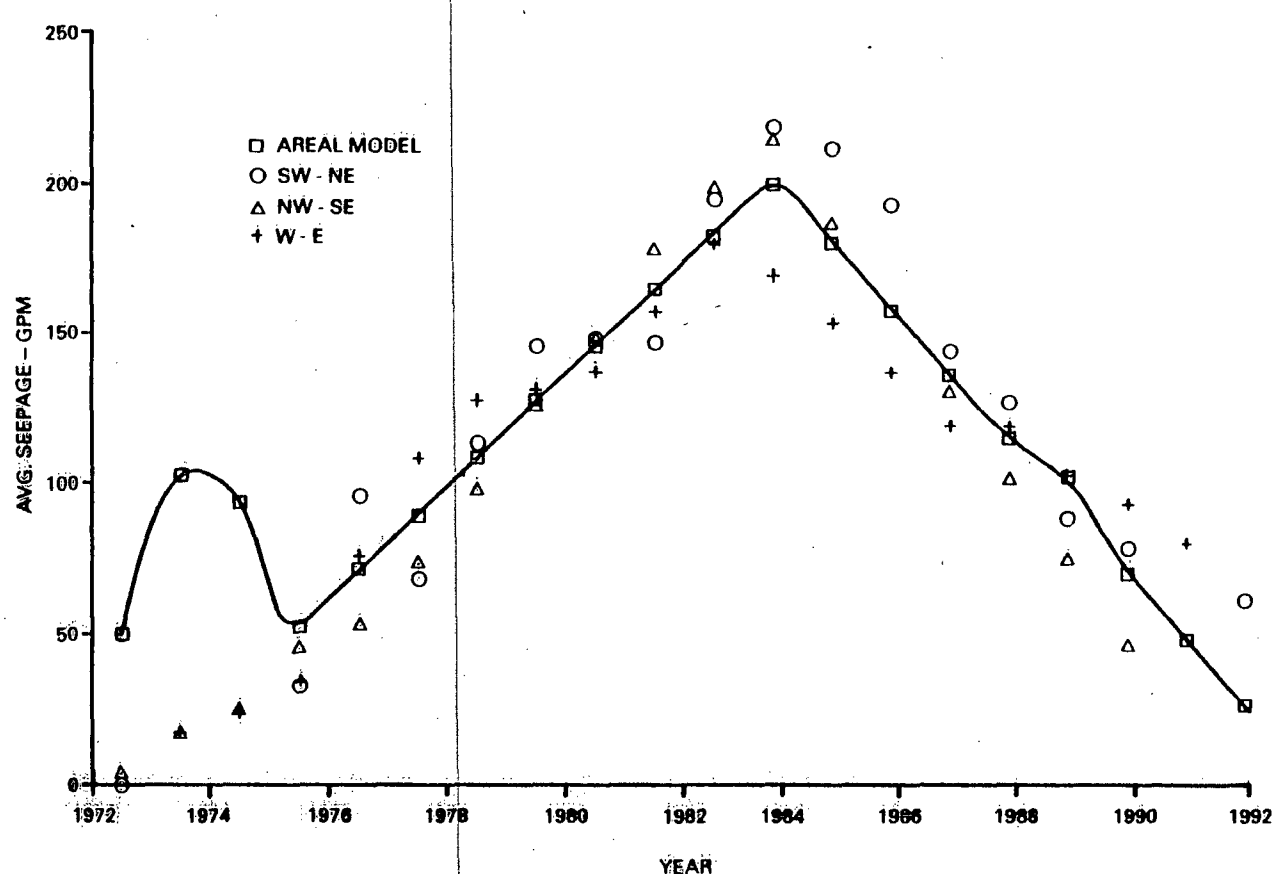


FIG. 52 POND SEEPAGE RATES CALCULATED BY THE CROSS-SECTIONAL MODELS AND INPUT TO THE AREAL MODEL

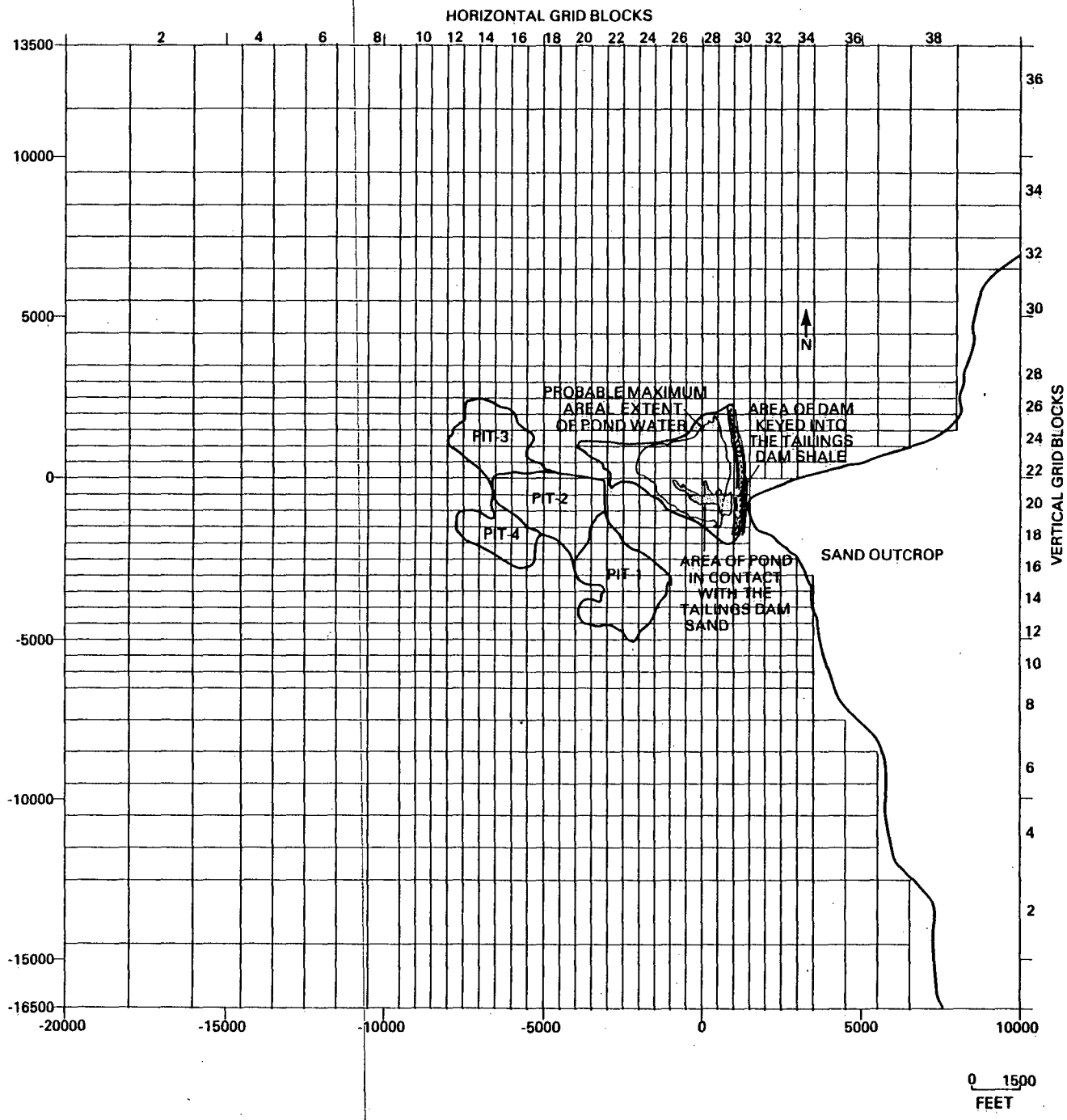


FIG. 53 EXTENT AND DESCRETIZATION OF THE AREAL MODEL

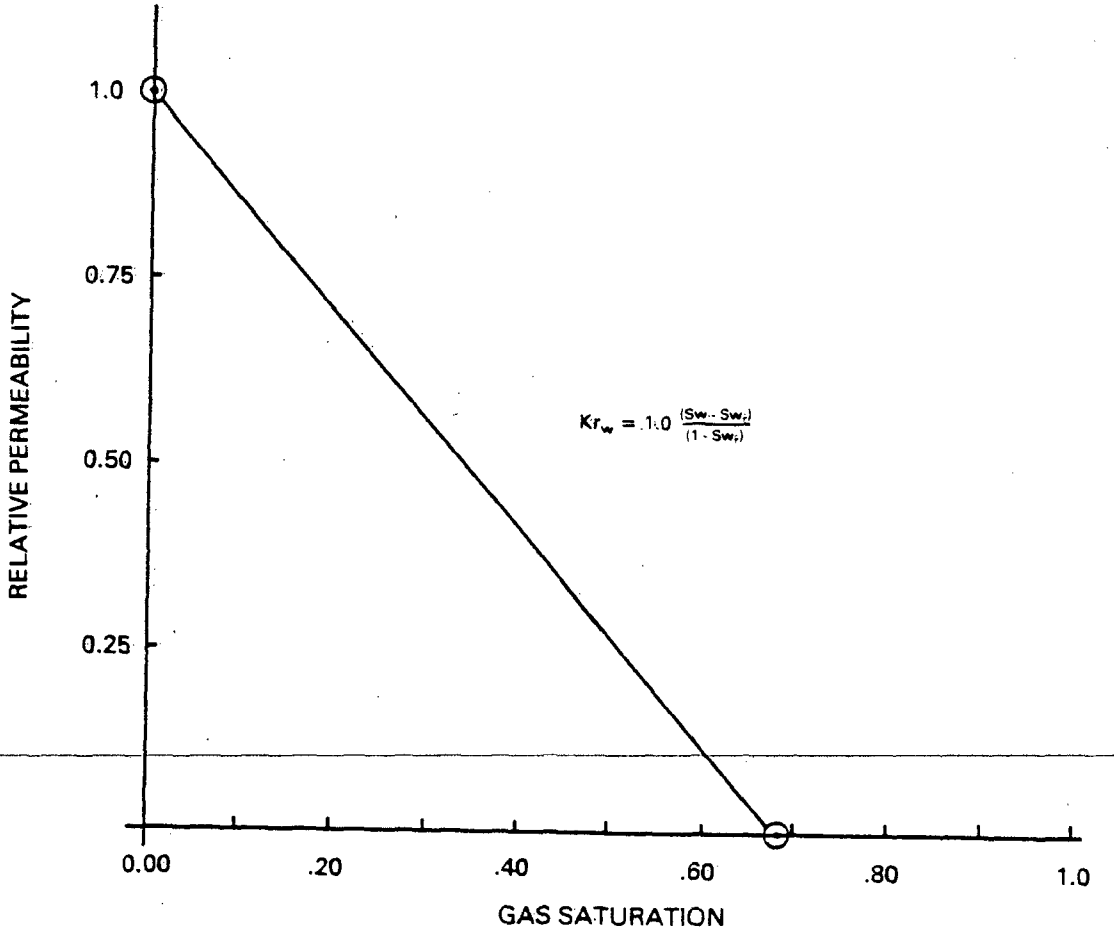
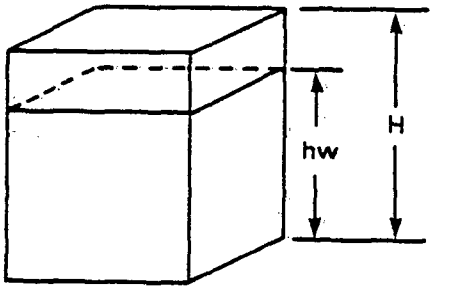


FIG. 54 PSEUDO-RELATIVE PERMEABILITY CURVE USED TO ACCOUNT FOR UNCONFINED FLOW IN THE TAILINGS DAM SAND AND THE SURFACE MINE BACKFILL IN THE AREAL MODEL



$$\hat{P}_c = H[(\frac{S_w - S_{wr}}{1 - S_{wr}}) - 1/2]\,\rho_w g$$

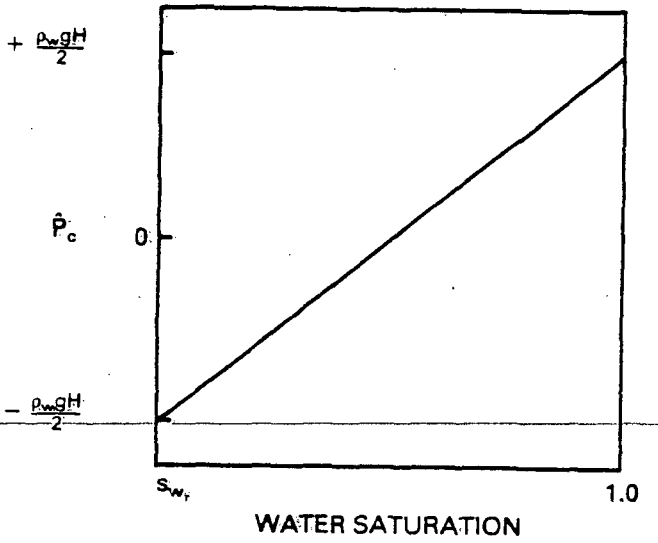


FIG. 55 PSEUDO-CAPILLARY PRESSURE CURVES USED TO ACCOUNT FOR GRAVITY DRAINAGE BETWEEN BLOCKS OF EQUAL ELEVATION IN THE AREAL MODEL

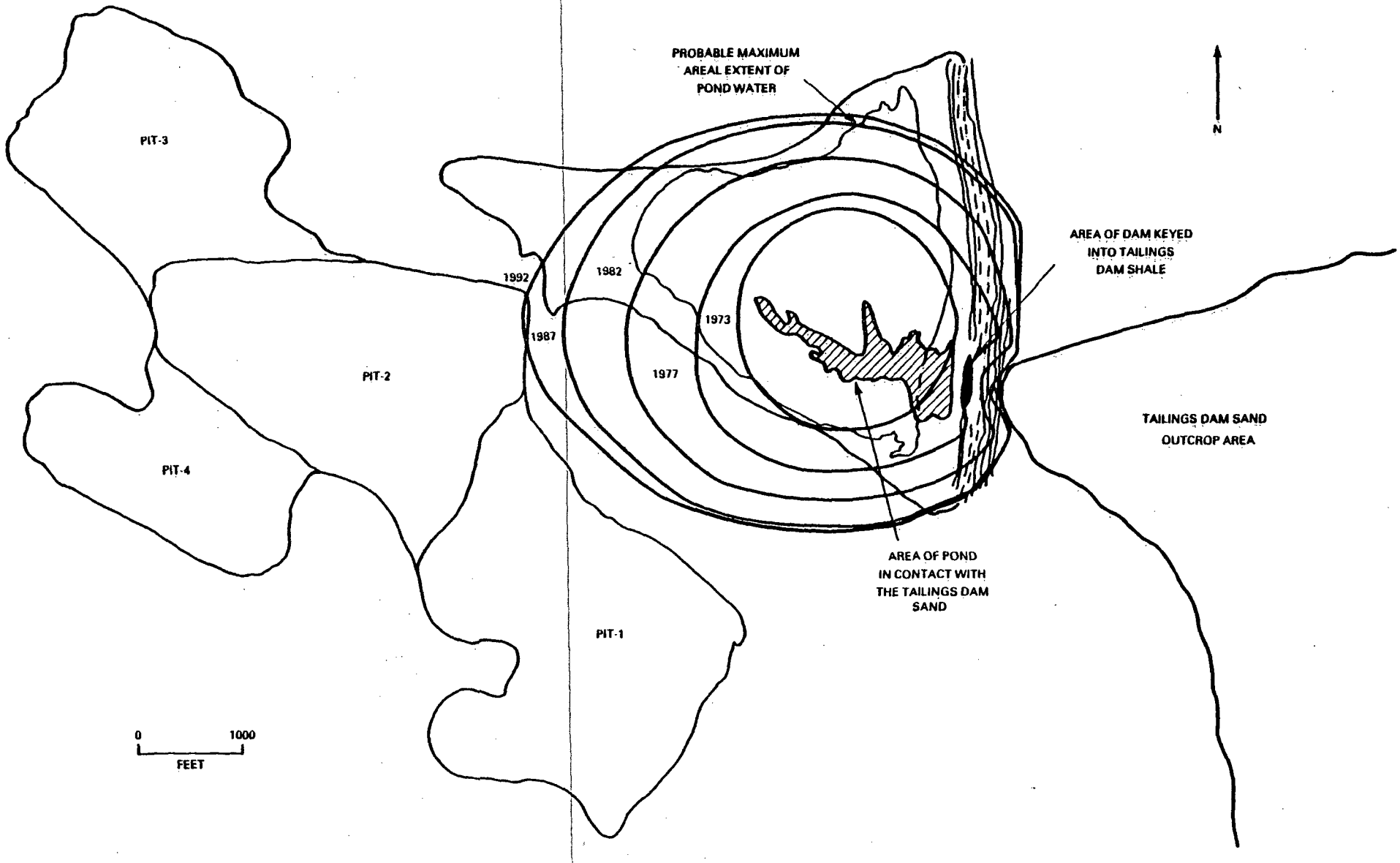


FIG. 56 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 1.0
AREAL MODEL

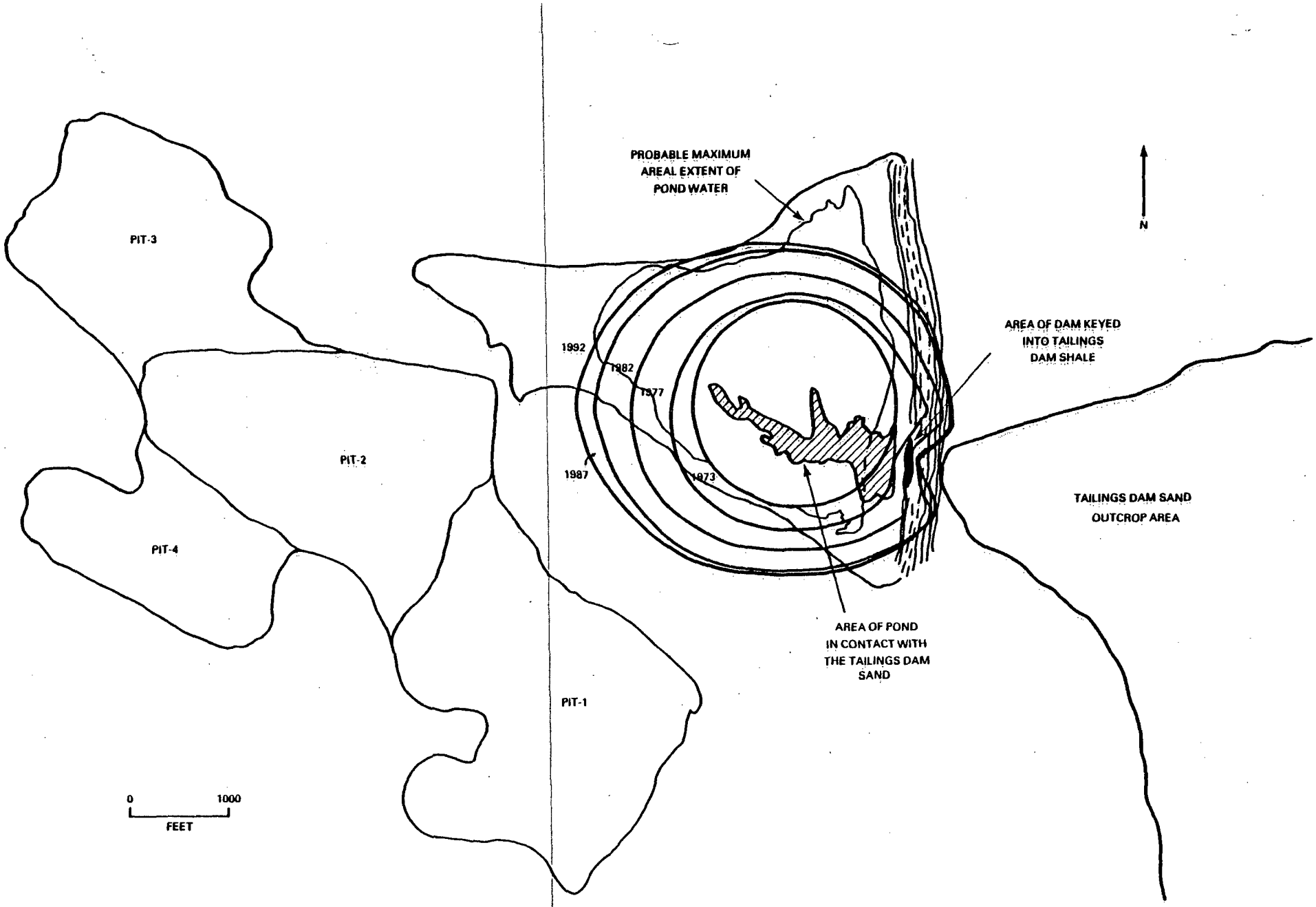


FIG. 57 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.50
AREAL MODEL

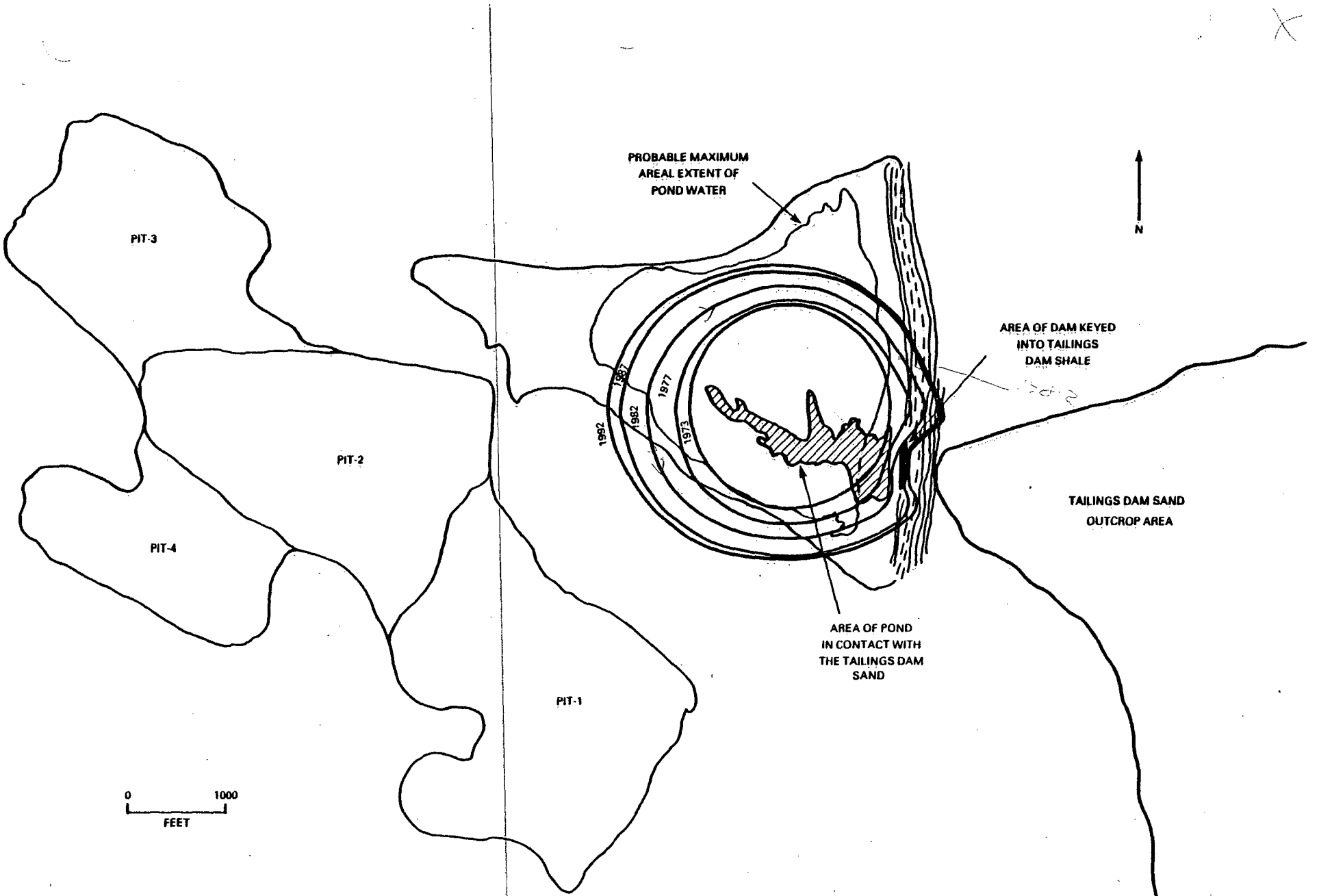


FIG. 58 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.30
AREAL MODEL

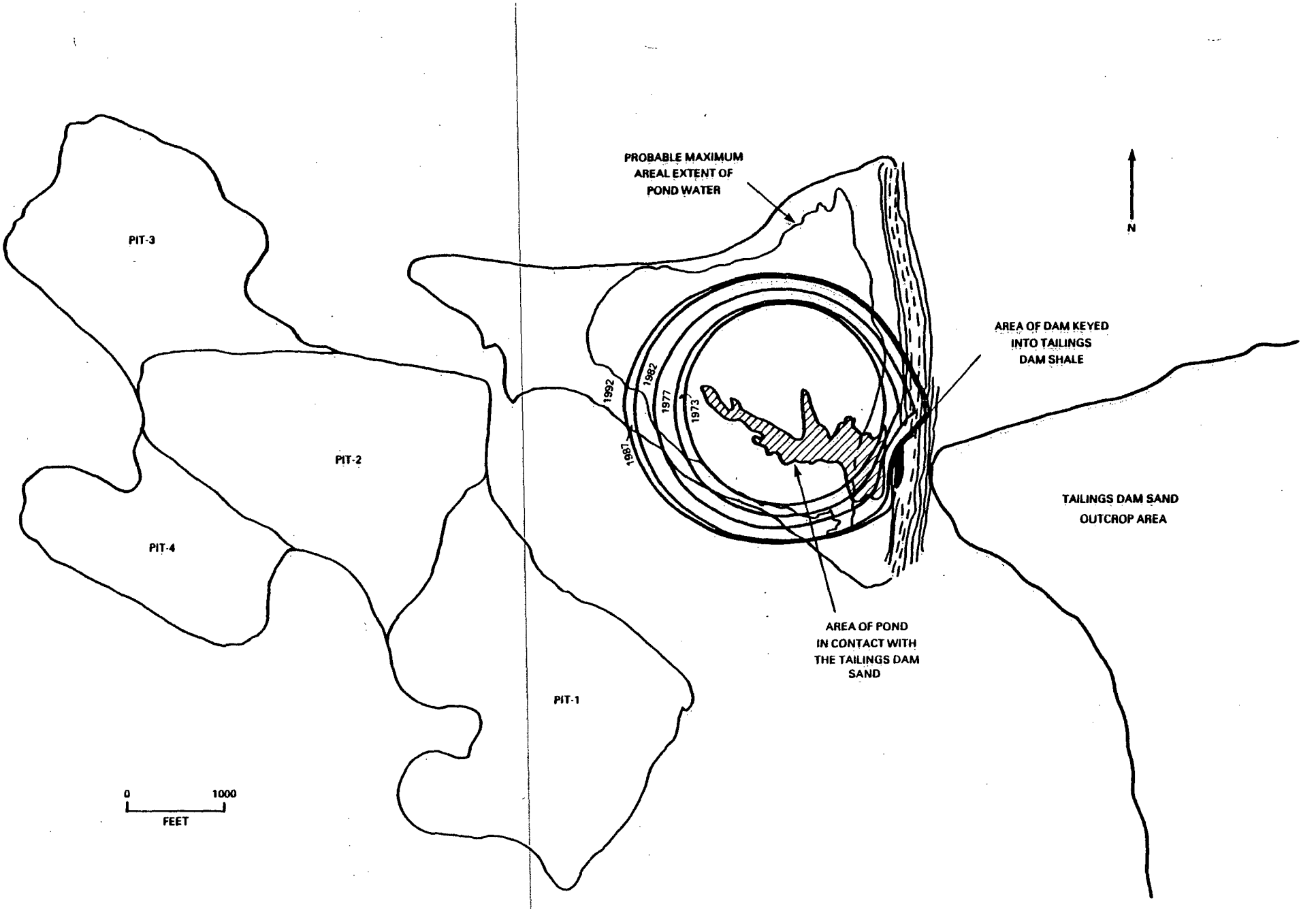


FIG. 59 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.20
AREAL MODEL

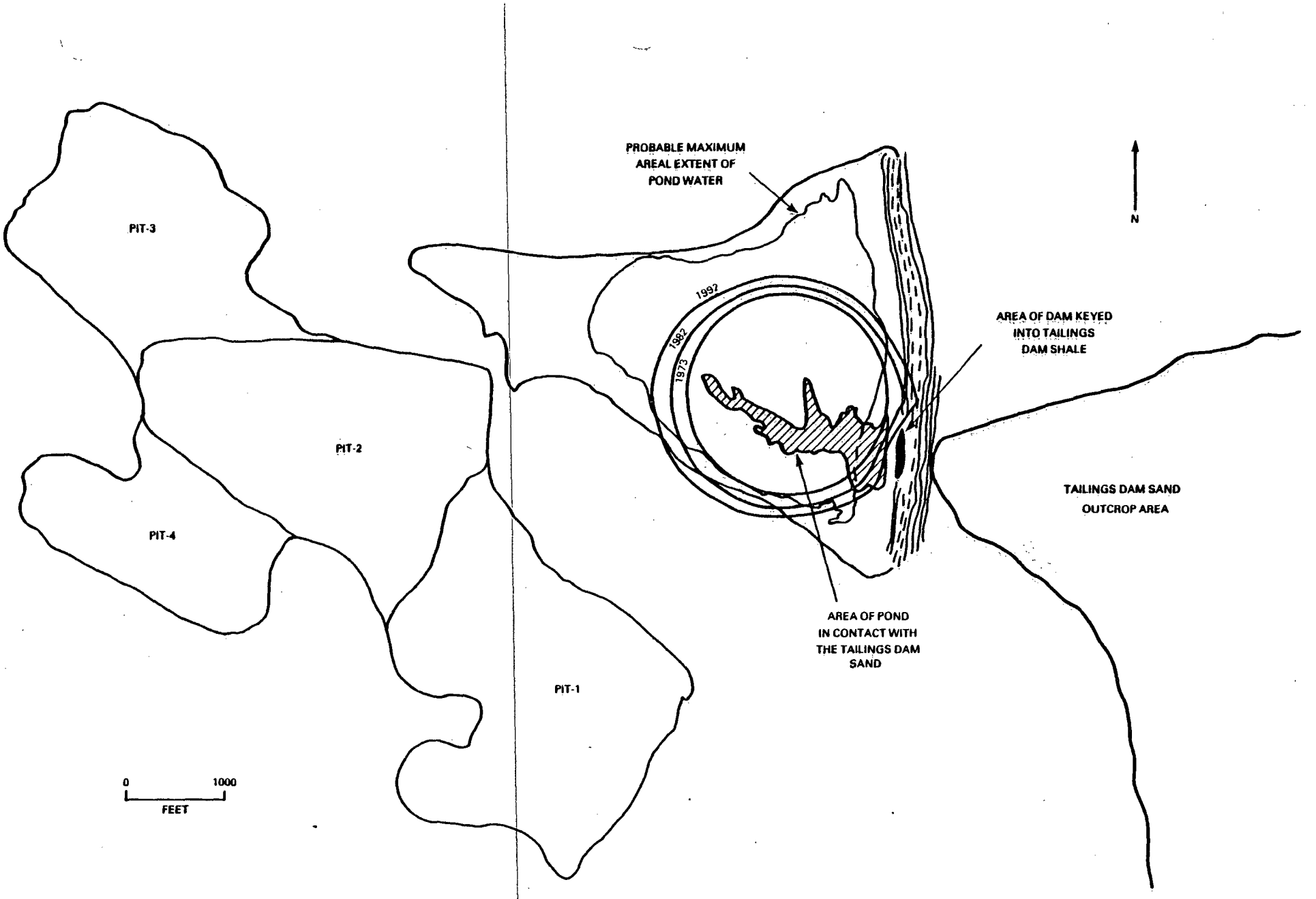


FIG. 60 SOLUTE MOVEMENT PREDICTIONS FOR A RELATIVE VELOCITY OF 0.1
AREAL MODEL

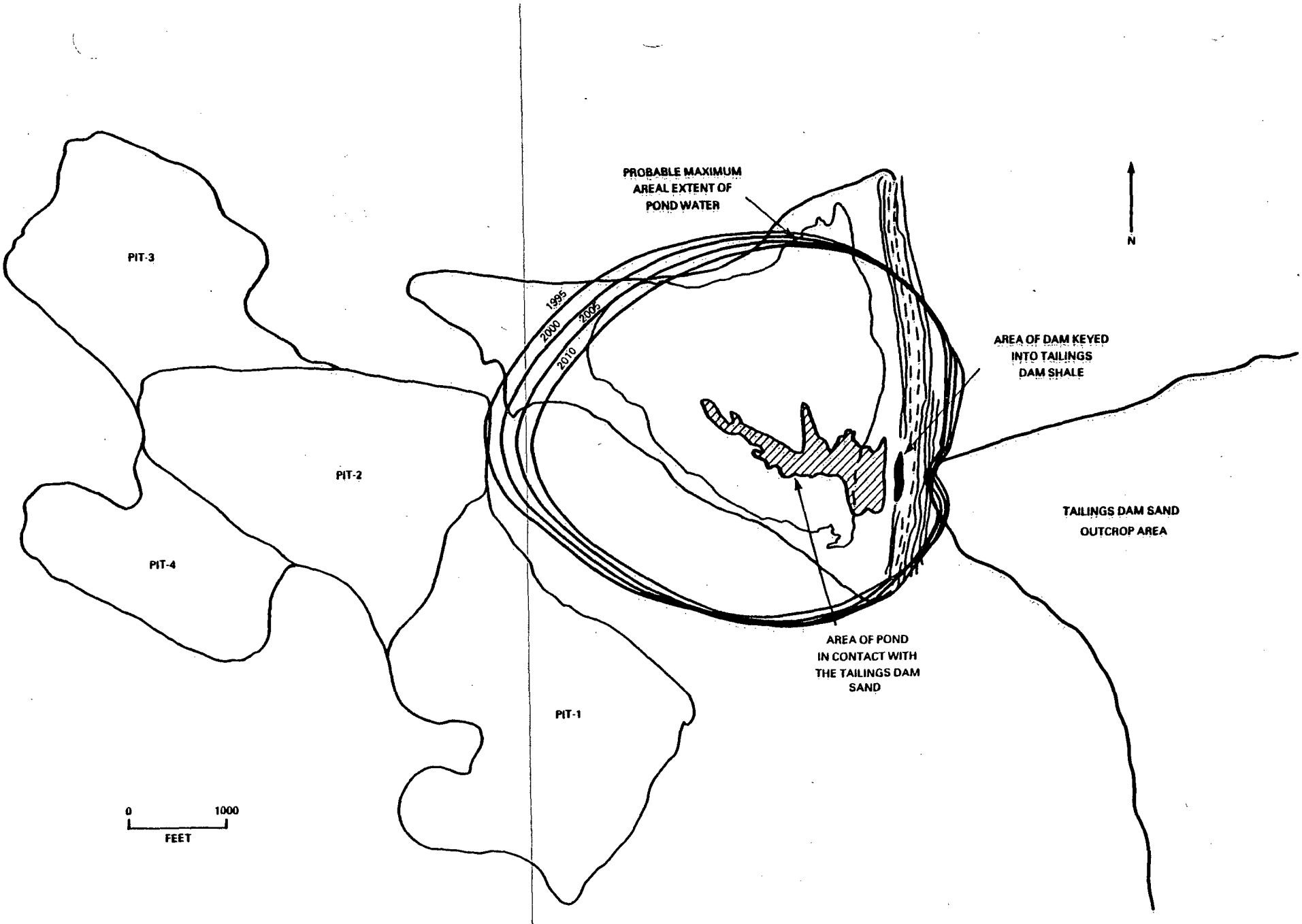


FIG. 61 SOLUTE MOVEMENT TOWARD THE OUTCROP AFTER REGIONAL FLOW IS RE-ESTABLISHED FOR A RELATIVE VELOCITY OF 1.0 – AREAL MODEL

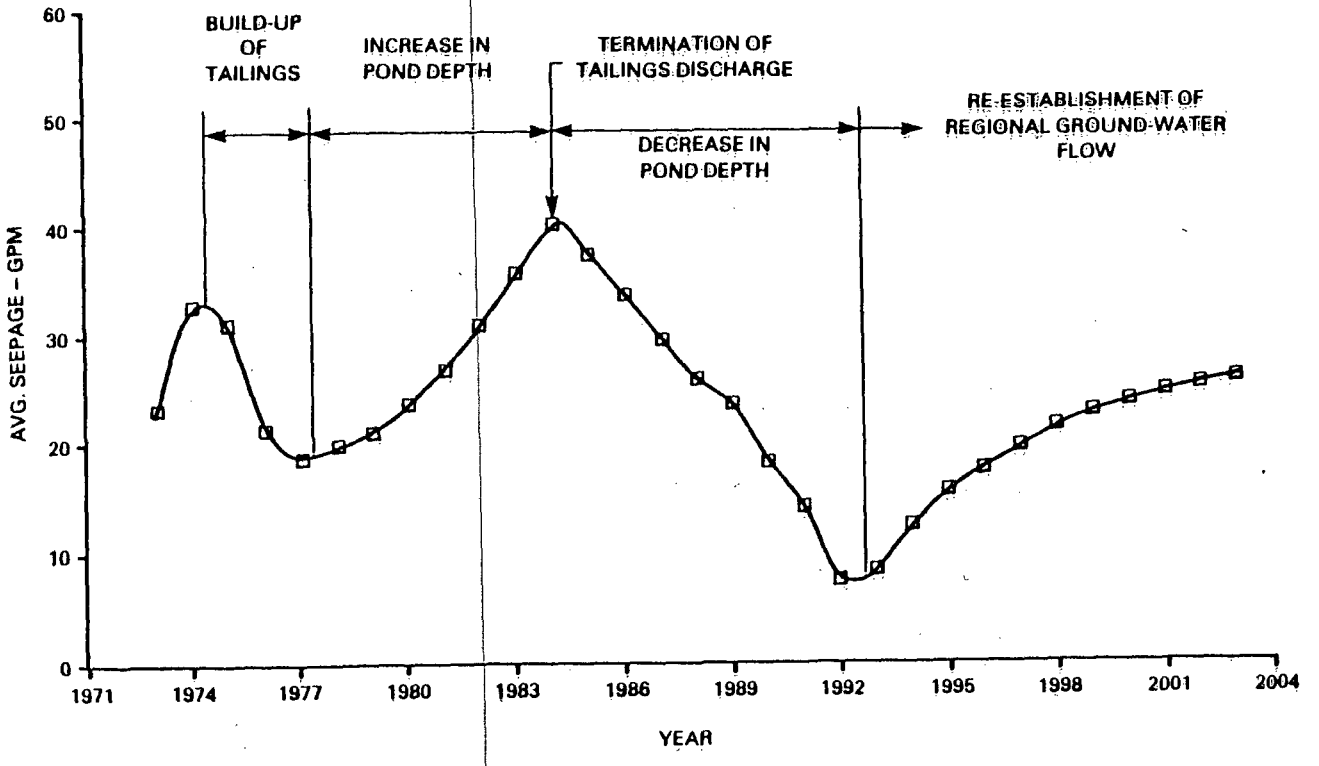


FIG. 62 TOTAL PREDICTED SEEPAGE INTO BOX CREEK – AREAL MODEL

ABOVE LIMI

E

RELA

SAND

$\frac{V_s}{V_f} = 0.30$

(ASSUMED pH FRONT RELATIVE

FASTER

Al

SO_4

SLOW

$0.30 > \frac{V_s}{V_f}$

$0.20 > \frac{V_s}{V_f} >$

$0.10 > \frac{V_s}{V_f}$ Cr

$\frac{V_s}{V_f}$ $\frac{\text{VELOCITY OF THE SOLL}}{\text{VELOCITY OF THE FLUID}}$

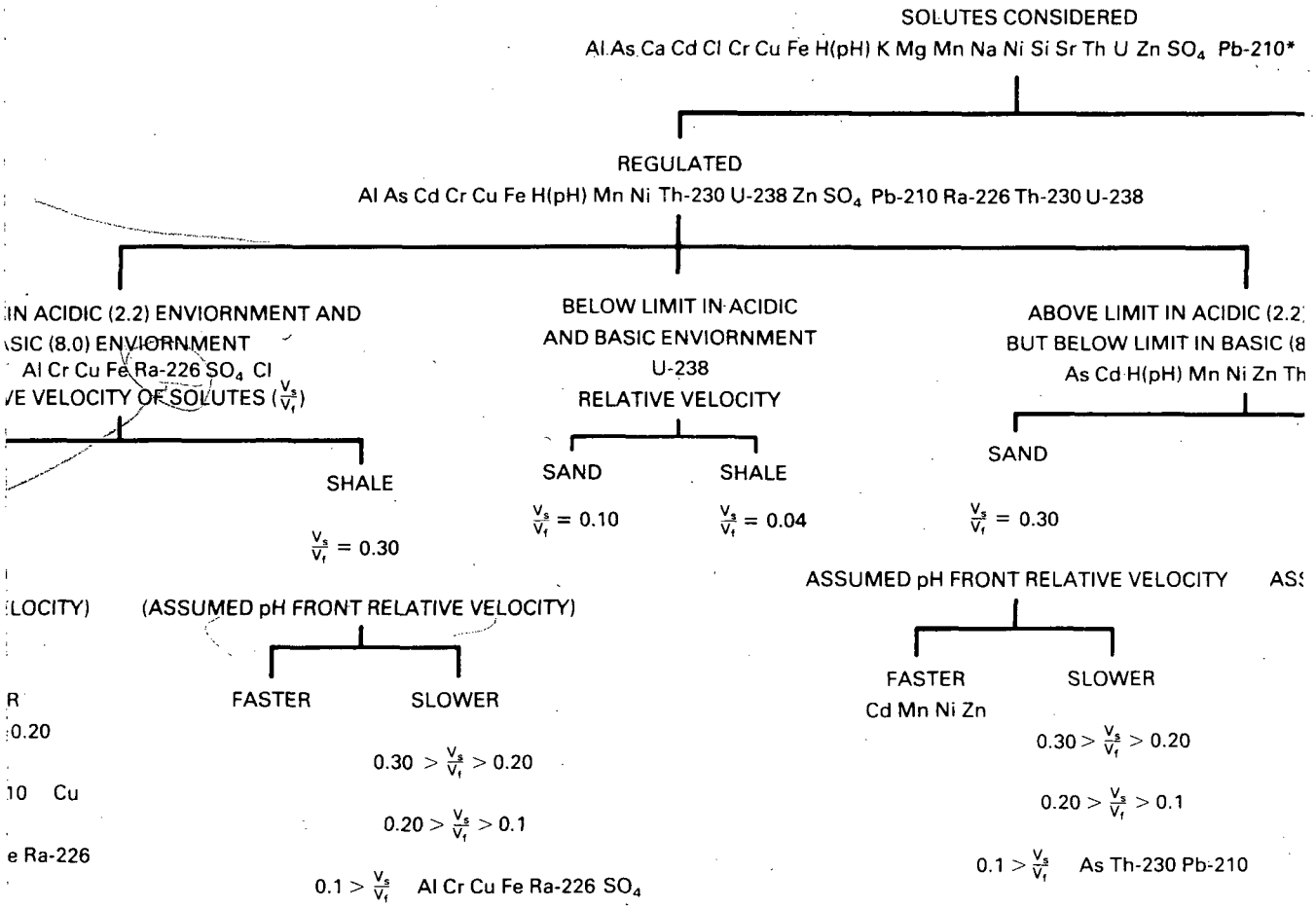


FIG. 63 CATEGORIES OF HIGHLAND SOLUTES WITH RELAT
FRONT MOVEMENT AND THE MOST STRINGENT REGULAT

ı-226* Th-230* U-238*

NOT REGULATED
Ca K Mg Na Si Sr
RELATIVE VELOCITY OF SOLUTES ($\frac{V_s}{V_f}$)

SAND

$\frac{V_s}{V_f} = 1.0$ Ca Mg Na Si Sr

$1.0 > \frac{V_s}{V_f} > 0.30$

$0.30 > \frac{V_s}{V_f} > 0.20$

$0.20 > \frac{V_s}{V_f} > 0.1$

$0.1 > \frac{V_s}{V_f}$ K

SHALE

$\frac{V_s}{V_f} = 1.0$ Ca K Mg Na Sr

$1.0 > \frac{V_s}{V_f} > 0.30$

$0.30 > \frac{V_s}{V_f} > 0.20$

$0.20 > \frac{V_s}{V_f} > 0.1$

$0.1 > \frac{V_s}{V_f}$ Si

:NVIRONMENT
) ENVIRONMENT
·30* Pb-210*

SHALE

$\frac{V_s}{V_f} = 0.30$

!MED pH FRONT RELATIVE VELOCITY

FASTER

Cd Mn Zn

SLOWER

$0.30 > \frac{V_s}{V_f} > 0.20$

$0.20 > \frac{V_s}{V_f} > 0.1$

$0.1 > \frac{V_s}{V_f}$ As Ni Th-220 Pb-210

*BASED ON RESULTS BY BATTELLE (1980b) FOR WASATCH FORMATION AT MORTON RANCH

IN TO ACIDIC
RY STATUS

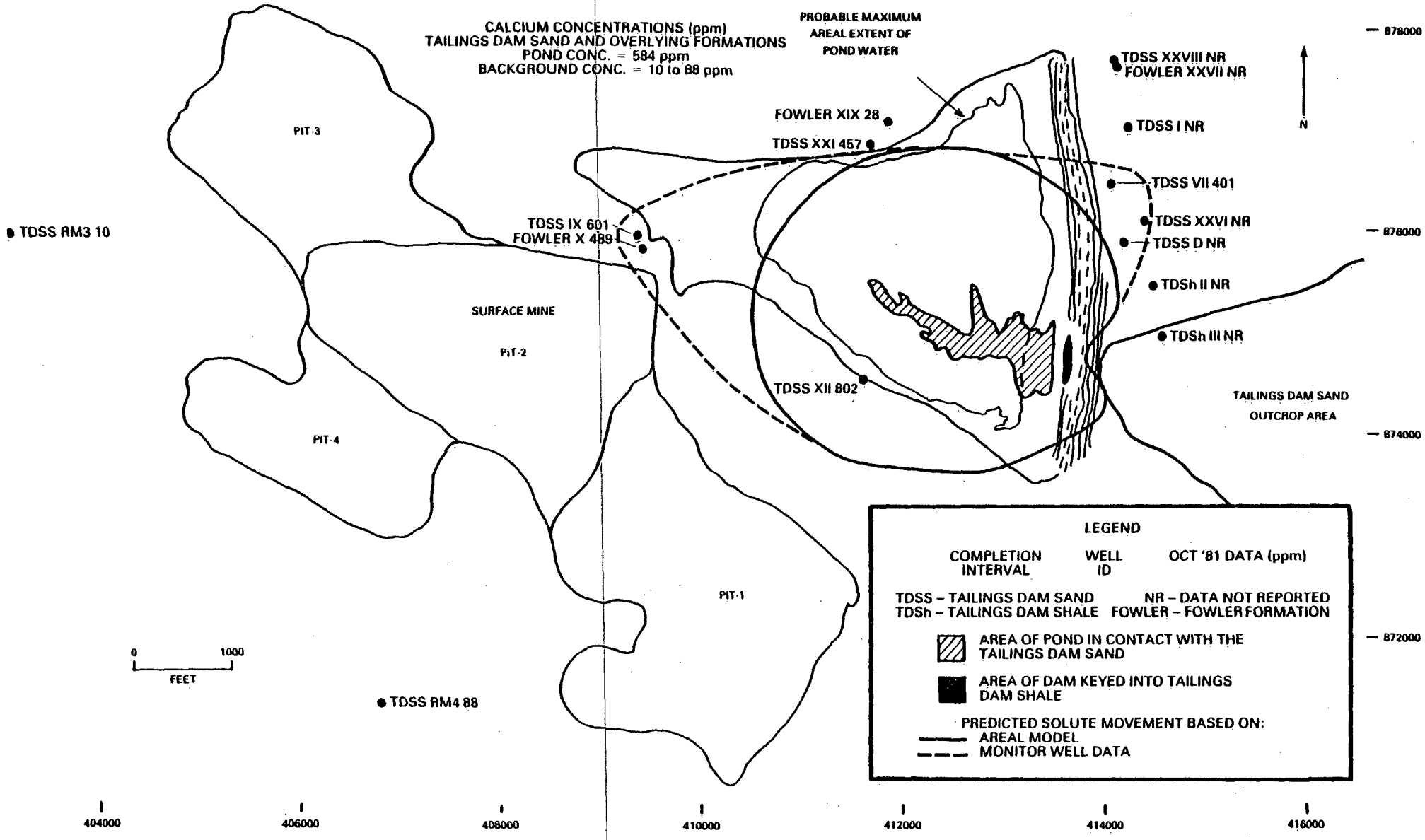


FIG. 64 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO CALCIUM CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE TAILINGS DAM SHALE AND OVERLYING FORMATIONS

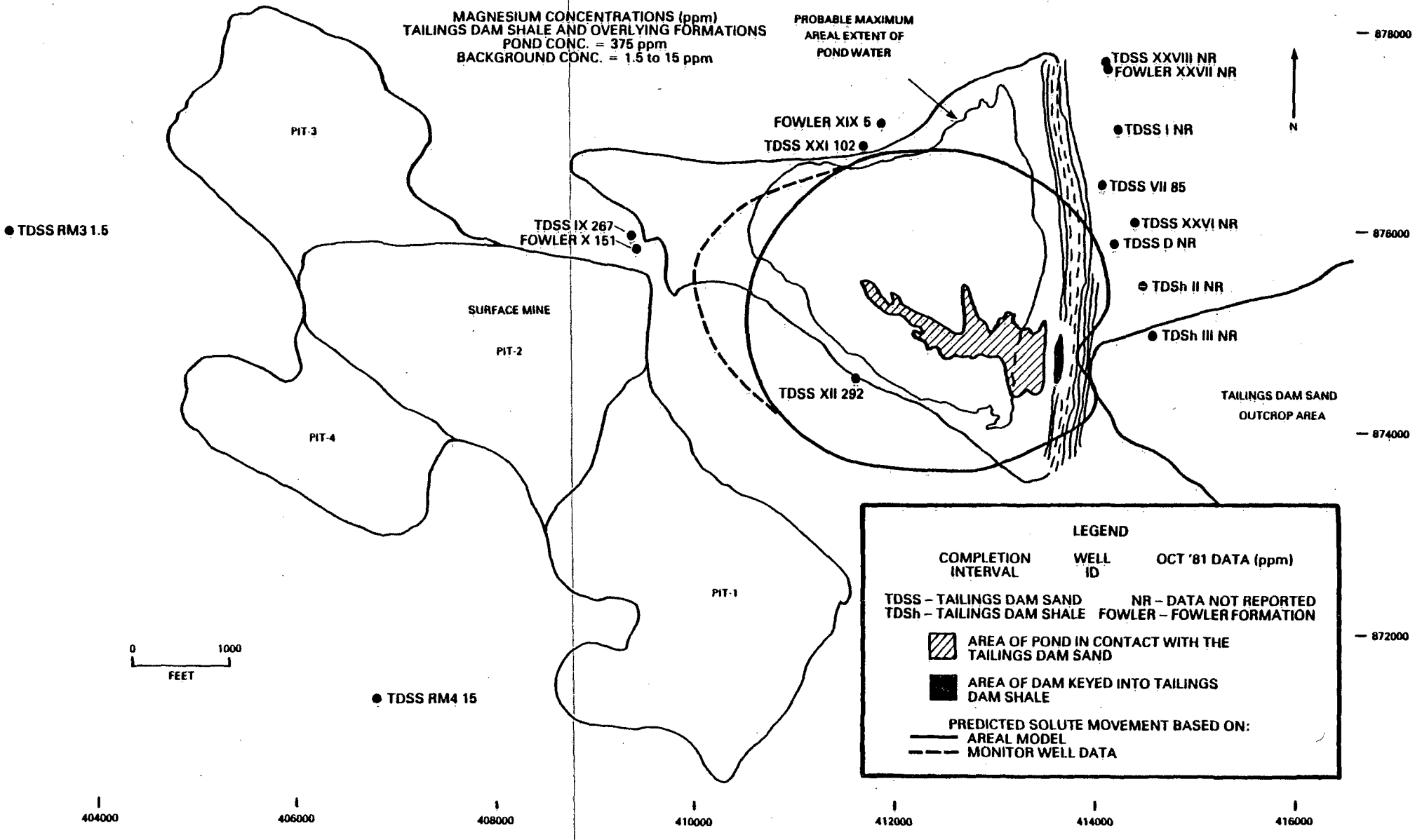


FIG. 65 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO MAGNESIUM CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE TAILINGS DAM SHALE AND OVERLYING FORMATIONS

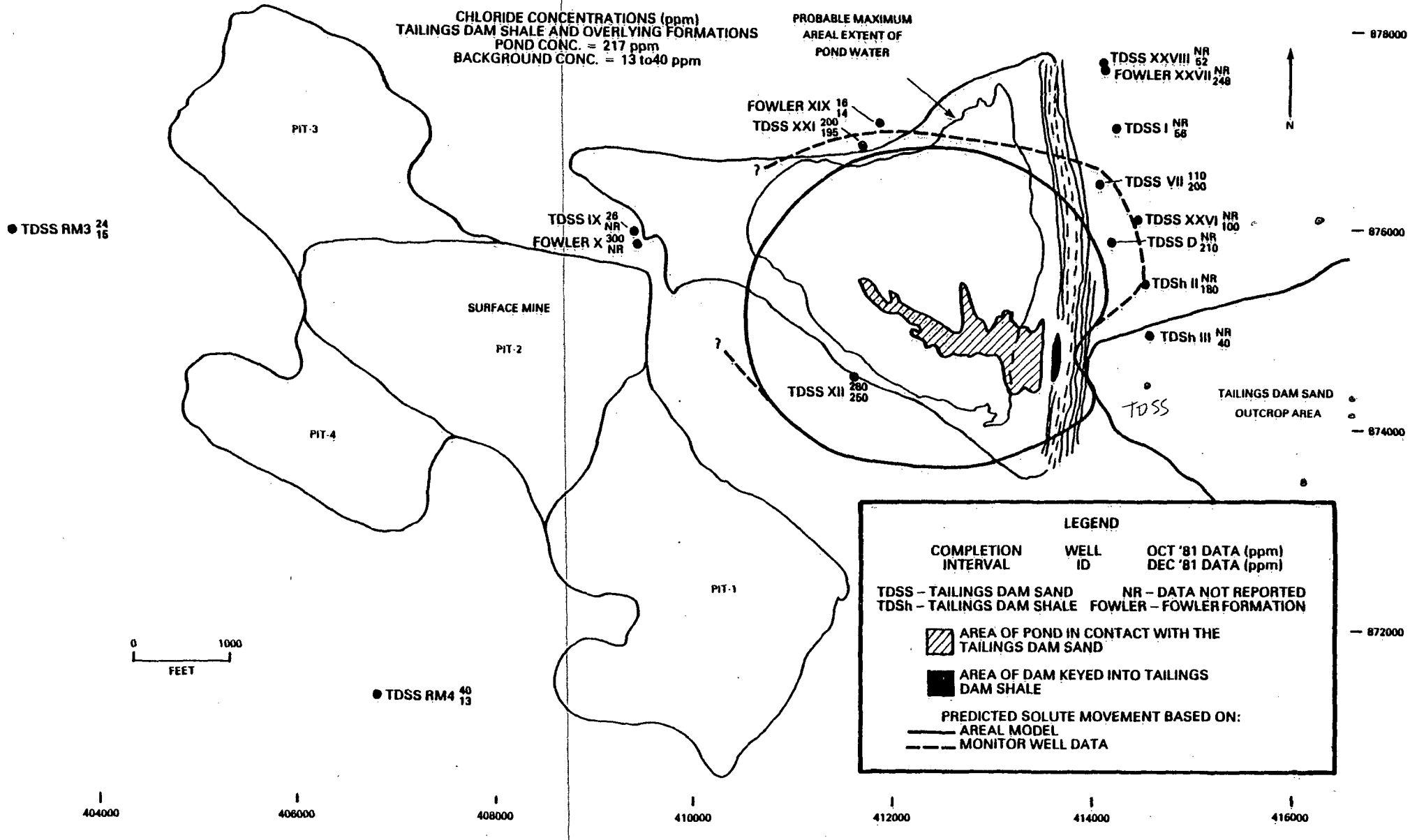


FIG. 66 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO CHLORIDE CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE TAILINGS DAM SHALE AND OVERLYING FORMATIONS

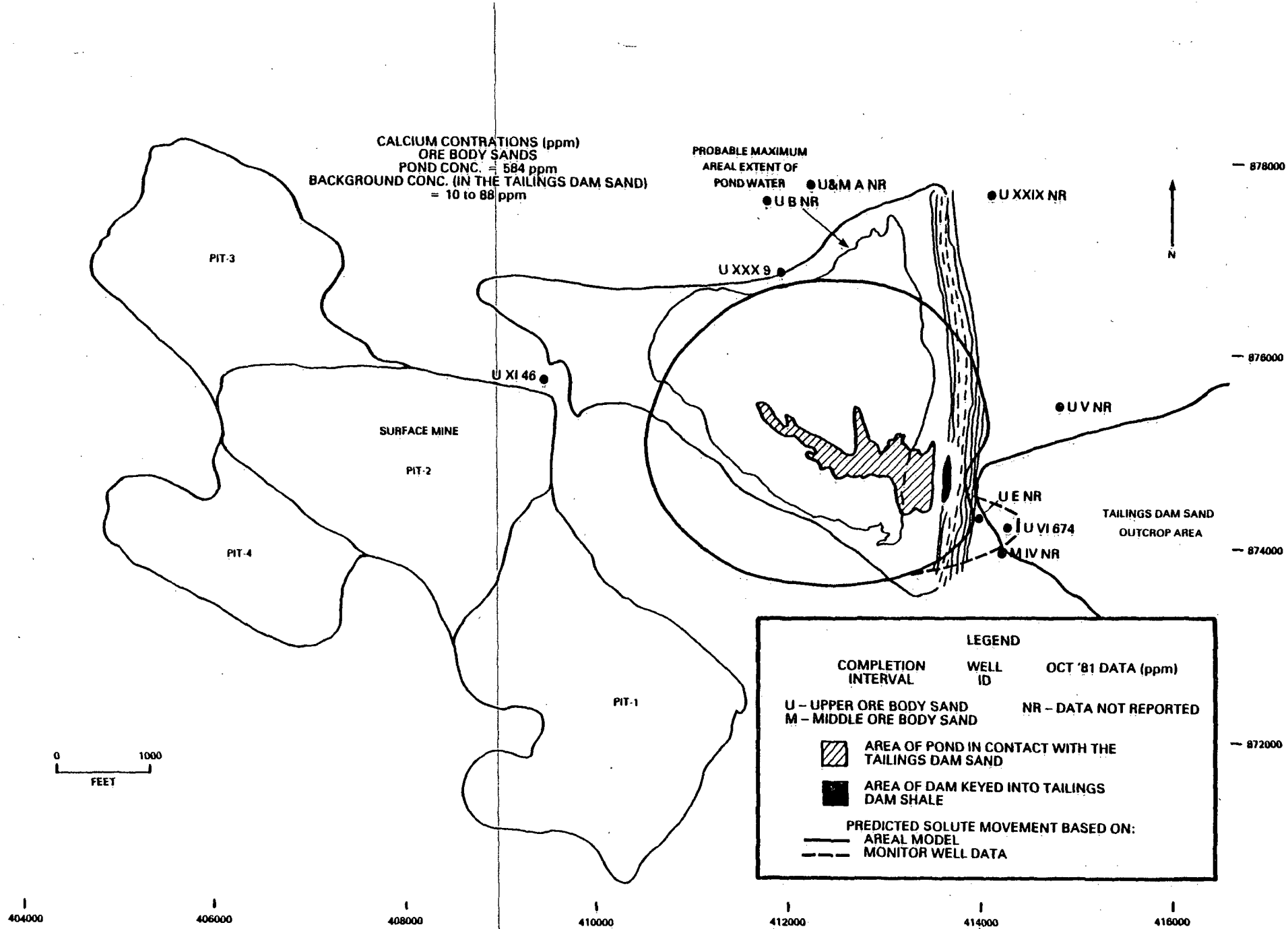


FIG. 67 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO CALCIUM CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE ORE BODY SANDS

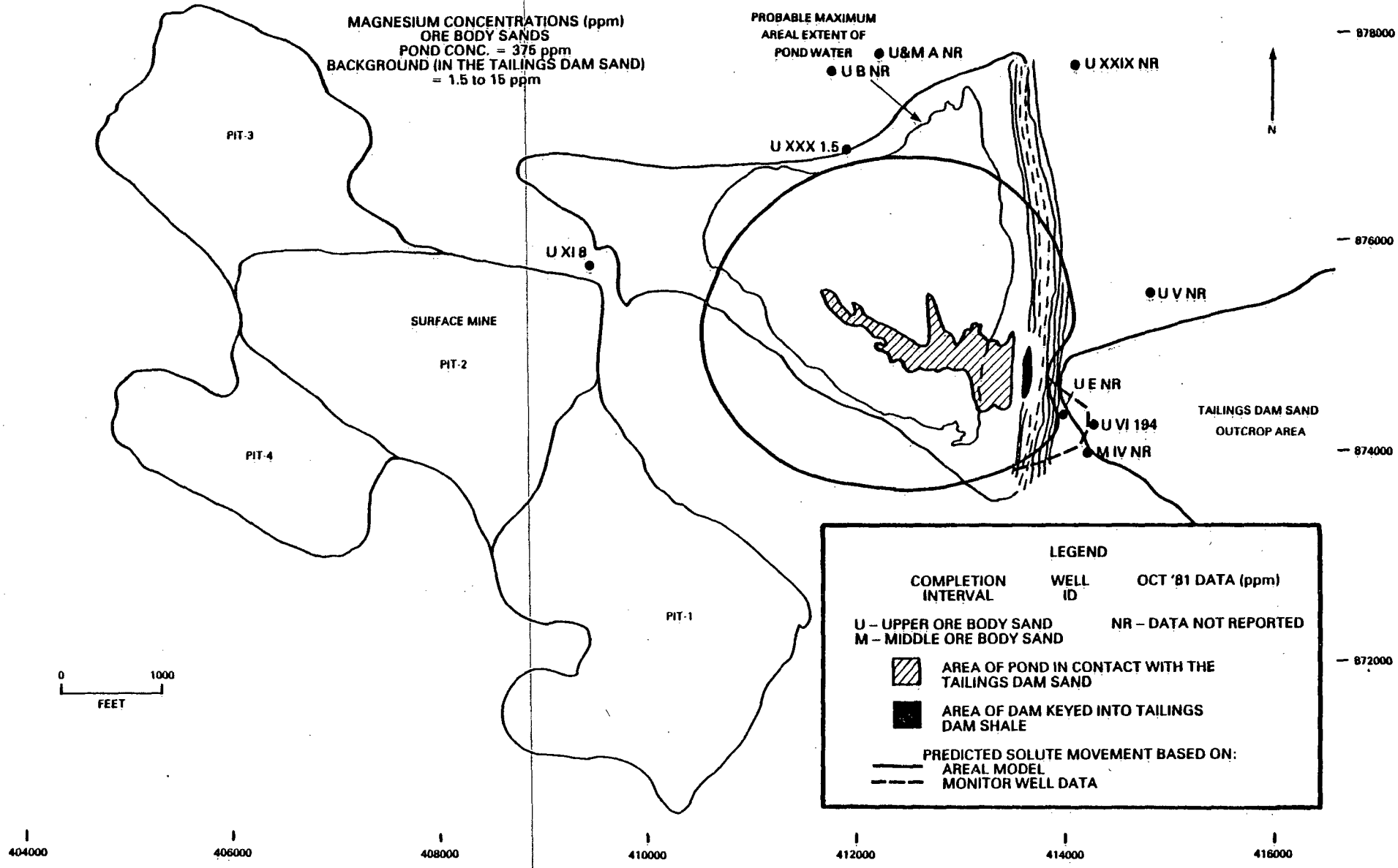


FIG. 68 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO MAGNESIUM CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE ORE BODY SANDS

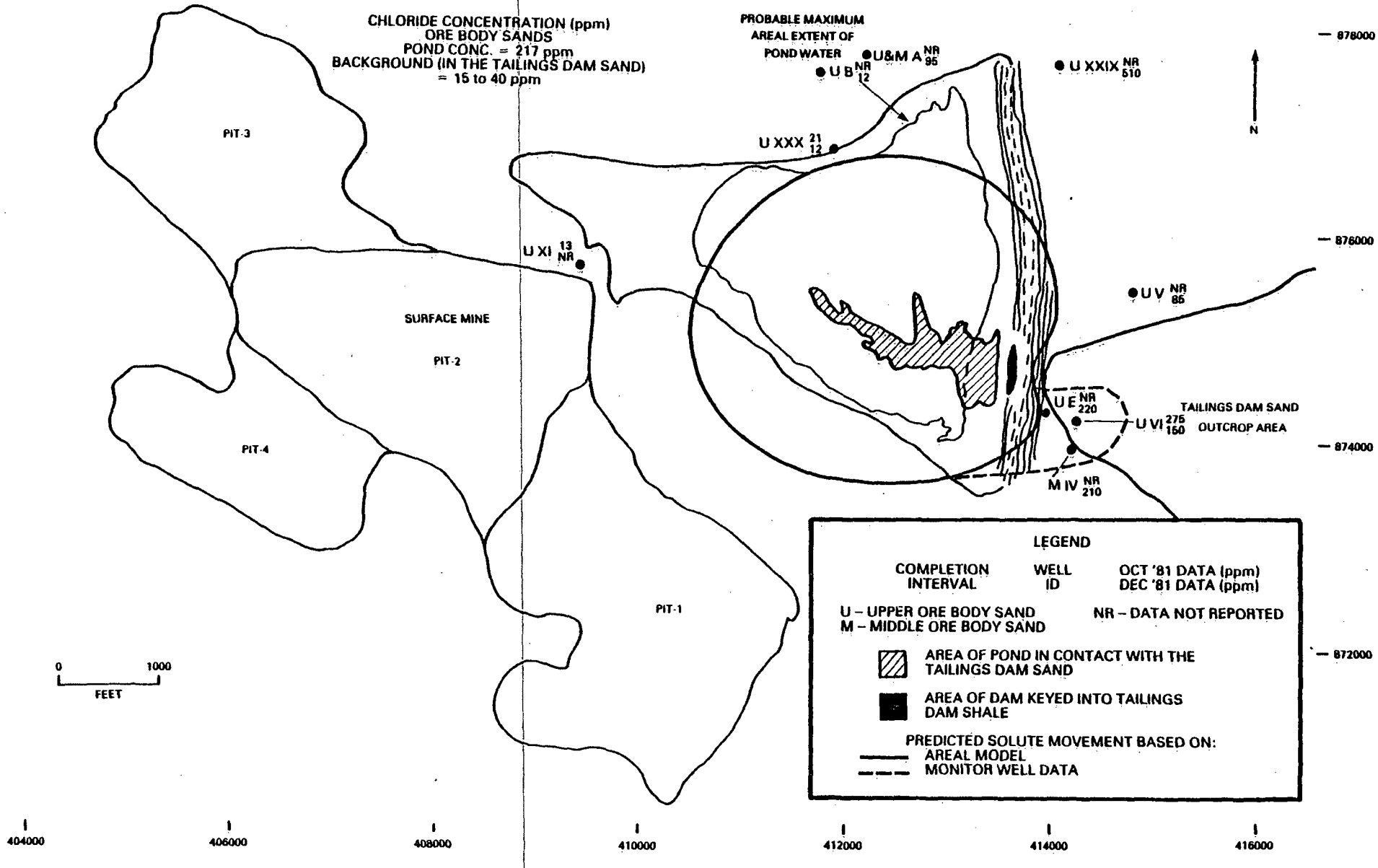


FIG. 69 COMPARISON OF THE 1982 UNATTENUATED SOLUTE FRONT POSITION PREDICTED BY THE AREAL MODEL TO CHLORIDE CONCENTRATIONS MEASURED IN MONITOR WELLS COMPLETED IN THE ORE BODY SANDS

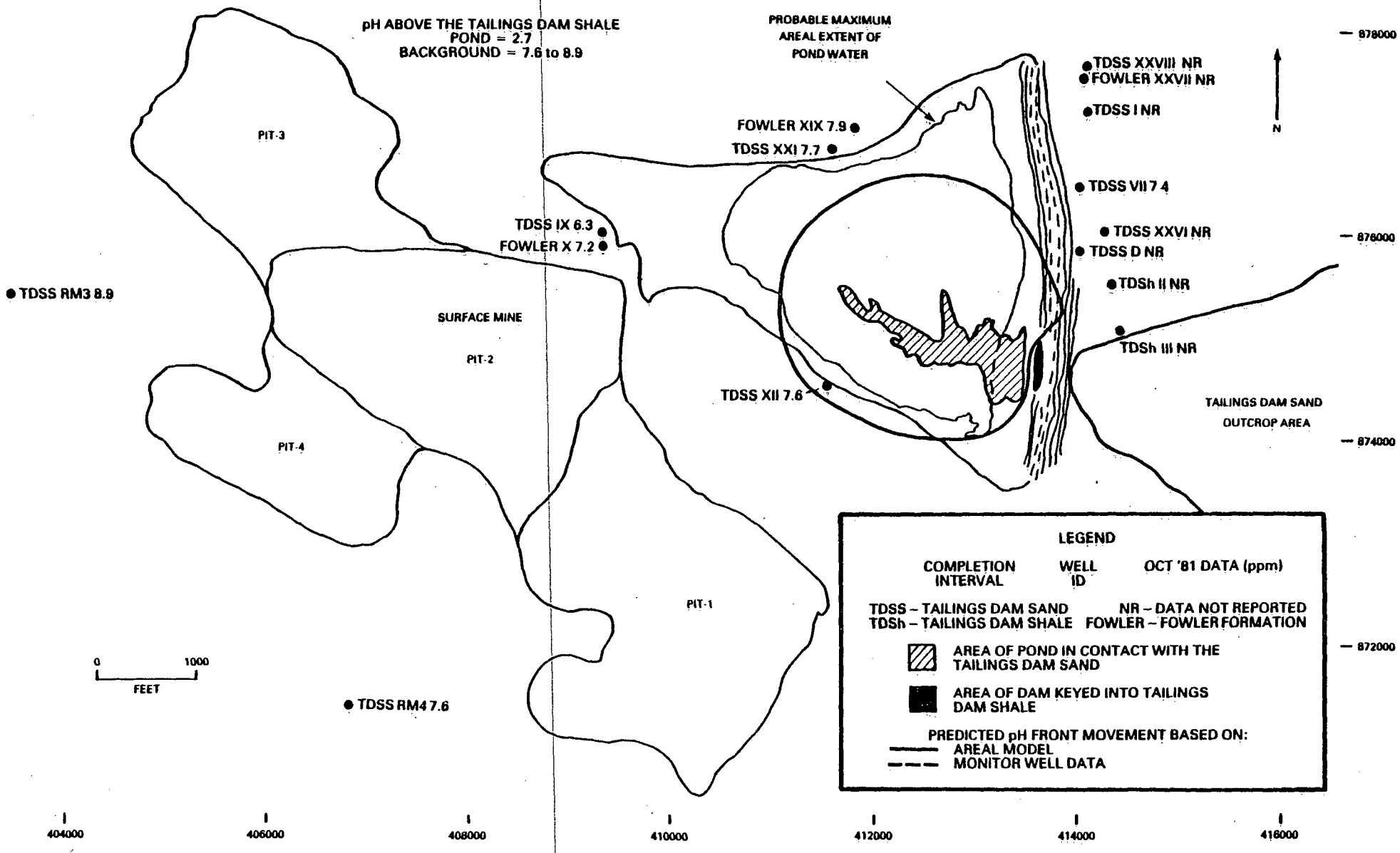


FIG. 70 COMPARISON OF THE 1982 ACIDIC FRONT POSITION PREDICTED BY THE AREAL MODEL TO pH MEASUREMENTS IN THE MONITOR WELLS COMPLETED IN THE TAILINGS DAM SHALE AND OVERLYING FORMATIONS

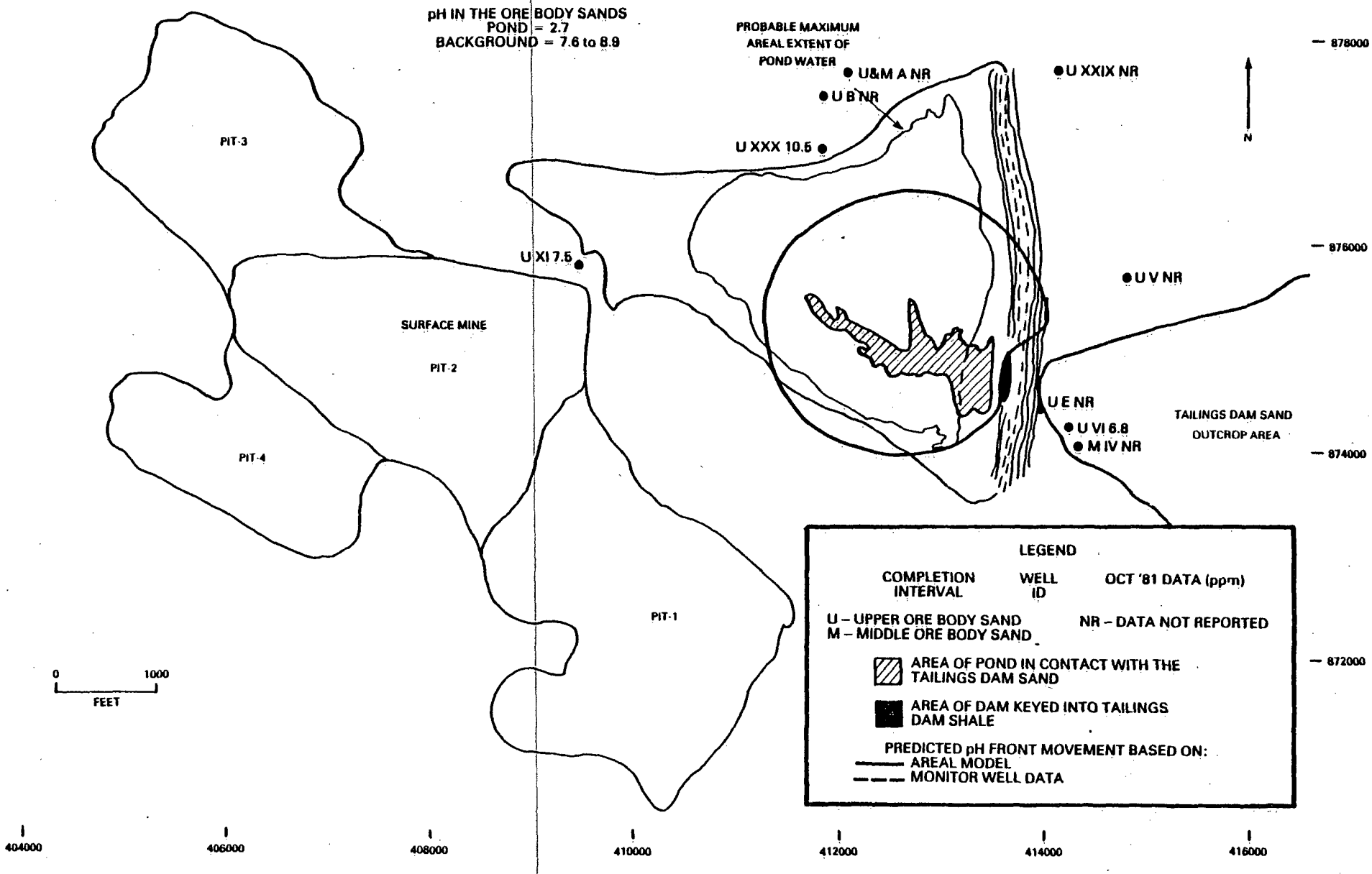


FIG. 71 COMPARISON OF THE 1982 ACIDIC FRONT POSITION PREDICTED BY THE AREAL MODEL TO pH MEASUREMENTS IN MONITOR WELLS COMPLETED IN THE ORE BODY SANDS

TABLE 1
Concentrations of Major, Minor and Trace Elements
in As Received Materials
(Concentrations in ppm unless otherwise noted)

ELEMENT	TAILINGS DAM SANDSTONE		TAILINGS DAM SHALE		HIGHLAND SANDSTONE		HIGHLAND SHALE		HIGHLAND TAILINGS SOLUTION	MOST STRINGENT WATER QUALITY STANDARDS (SEE TABLE 22)
	Elemental	Oxide	Elemental	Oxide	Elemental	Oxide	Elemental	Oxide		
Al	6.15%	11.62%	8.80%	16.63%	5.95%	11.25%	3.98%	7.52%	261	5.0
Ca	0.88%	1.23%	0.52%	0.73%	1.26%	1.76%	0.34%	0.48%	584	No Limit
Fe	3.04%	4.35%	2.16%	3.09%	3.28%	4.69%	1.28%	1.83%	775	0.3
K	2.26%	2.72%	1.60%	1.92%	1.94%	2.34%	1.88%	2.26%	42	No Limit
Mg	0.82%	1.36%	0.66%	1.09%	1.10%	1.82%	0.44%	0.73%	375	No Limit
Mn	0.020%	0.026%	0.008%	0.010%	0.040%	0.052%	0.010%	0.013%	45	0.05
Na	1.90%	2.56%	1.00%	1.35%	1.82%	2.45%	0.48%	0.65%	262	No Limit
Si*	35.08%	75.03%	74.18%	34.68%	33.63%	71.94%	39.00%	83.42%	240	No Limit
As	9.7		1.5		8.8		0.9		78. ppb	50. ppb
Cd	0.3 ppb		0.4 ppb		0.1 ppb		0.1 ppb		30. ppb	10. ppb
Cr	52		82		56		40		1.2	0.05
Cu	12		48		8		14		1.1	0.20
Ni	3		5		2		2		1.4	0.2
Se	0.3		0.7		0.2		1.0		126. ppb	10. ppb
Sr	98		40		104		55		0.50	No Limit
Th	10		10		-		10		0.82	2,000. pCi/l
U	103		10		-		10		9.1	5.
Zn	31		80	26	45		3.2			2.0
Cl									217.5	100.
SO_4^{-2}									7580.	200.
Loss on Ignition		1.1%		1.0%		3.7%		3.1%		
Total		100.00%		100.00%		100.00%		100.00%		
pH									2.4	6.5-8.5
Eh									846.mv	No Limit
Meq. Cations									149	
Meq. anions									158	

TABLE 2

Concentrations of Inorganic Constituents
In Solution After Batch Tests of Highland
Tailings Solution With Tailings Dam Sandstone
(All Concentrations in ppm Unless Otherwise Noted)

Element	Initial Concentration	3 day	7 day	15 day	30 day	Most Stringent Water Quality Standards (see Table 22)
Al	261.	336.	367.	370.	361.	5.0
Ca	584.	651.	660.	624.	638.	No Limit
Fe	775.	354.	261.	146.	124.	0.3
K	42.	41.	34.	--	24.	No Limit
Mg	375.	423.	445.	474.	497.	No Limit
Mn	45.	45.	47.	49.	50.	0.05
Na	262.	260.	263.	264.	266.	No Limit
Si	240.	265.	292.	274.	279.	No Limit
As (ppb)	78.	9.5	0.6	>0.5	--	50. ppb
Cd (ppb)	30.	30.	29.	34.	34.	10. ppb
Cr	1.2	0.8	0.7	0.4	0.2	0.05
Cu	1.1	1.1	1.0	0.9	0.8	0.2
Ni	1.4	1.8	1.9	1.9	2.0	0.2
Se (ppb)	126.	31.	19.	18.	32.	10. ppb
Sr	0.5	3.2	2.9	2.9	0.6	No Limit
Th	0.82	1.5	1.3	1.0	0.4	2000 pCi/l
U	9.1	6.5	5.1	6.2	5.4	5.0
Zn	3.2	3.6	3.6	3.7	3.8	2.0
SO_4^{-2}	7580.	6030.	6880.	6000.	5940.	200.
pH	2.4	2.8	2.9	3.0	3.2	6.5-8.5
Eh (mv)	846.	694.	818.	670.	618.	No Limit

--Not determined

TABLE 3

Concentrations of Inorganic Constituents
In Solution After Batch Tests of Highland
Tailings Solution With Tailings Dam Shale

Element	Initial Concentration	3 day	7 day	15 day	30 day	Most Stringent Water Quality Standards (see Table 22)
Al	261.	146.	117.	138.	87.	5.0
Ca	584.	656.	630.	646.	641.	No Limit
Fe	775.	89.	58.	27.	124.	0.3
K	42.	74.	75.	55.	55.	No Limit
Mg	375.	386.	409.	424	411.	No Limit
Mn	45.	36	36.	38.	40.	0.05
Na	262.	297.	298.	293.	290.	No Limit
Si	240.	191.	147.	156.	90.	No Limit
As (ppb)	78.	1.2	<0.5	1.6	< 0.5	50. ppb
Cd (ppb)	30.	27.	24.	41.	32.	10. ppb
Cr	1.2	0.2	0.1	0.1	0.02	0.05
Cu	1.1	1.0	0.9	0.8	0.5	0.2
Ni	1.4	1.2	1.6	1.7	1.2	0.2
Se (ppb)	126.	29.	17.	12.	24.	10. ppb
Sr	0.5	6.5	8.0	7.4	4.8	No Limit
Th	0.82	1.0	0.8	0.3	<0.05	2000 pCi/l
U	9.1	3.6	1.9	3.2	1.8	5.0
Zn	3.2	3.0	3.2	4.0	3.3	2.0
SO_4^{-2}	7580.	4030.	4580.	4810.	4570.	200.
pH	2.4	3.2	3.4	3.2	3.5	6.5-8.5
Eh (mv)	846.	645.	777.	650.	614.	No Limit

TABLE 4

Concentrations of Inorganic Constituents
In Solution After Batch Tests of Highland
Tailings Solution With Ore Body Sandstone
(All Concentrations in ppm Unless Otherwise Noted)

Element	Initial Concentration	3 day	7 day	15 day	30 day	Most Stringent Water Quality Standards (see Table 22)
Al	261.	318.	340.	336.	321.	5.0
Ca	584.	724.	682.	651.	646.	No Limit
Fe	775.	252.	225.	111.	23.	0.3
K	42.	48.	46.	38.	39.	No Limit
Mg	375.	408.	418.	445.	424.	No Limit
Mn	45.	52.	51.	54.	56.	0.05
Na	262.	272.	270.	267.	274.	No Limit
Si	240.	265.	261.	222.	203.	No Limit
As (ppb)	78.	5.5	0.9	3.	2.6	50. ppb
Cd (ppb)	30.	31.	29.	32.	34.	10. ppb
Cr	1.2	0.8	0.6	0.3	0.1	0.05
Cu	1.1	1.1	1.0	0.9	0.7	0.2
Ni	1.4	1.8	1.7	1.8	1.8	0.2
Se (ppb)	126.	35.	32.	29.	--	10. ppb
Sr	0.5	3.1	2.9	3.2	0.7	No Limit
Th	0.82	71.	21.	22.	27.	2000 pCi/l
U	9.1	247.	203.	205.	267.	5.0
Zn	3.2	3.6	3.4	3.6	3.5	2.0
SO_4^{-2}	7580.	6830.	6510.	6090.	7510.	200.
pH	2.4	2.9	3.0	3.0	3.3	6.5-8.5
Eh (mv)	846.	749.	757.	656.	676.	NO Limit

--Not determined

TABLE 5

Concentrations of Inorganic Constituents
In Solution After Batch Tests of Highland
Tailings Solution With Ore Body Shale
(All Concentrations in ppm Unless Otherwise Noted)

Element	Initial Concentration	3 day	7 day	15 day	30 day	Most Stringent Water Quality Standards (see Table 22)
Al	261.	195.	157.	183.	181.	5.0
Ca	584.	640.	625.	633.	642.	No Limit
Fe	775.	76.	40.	21.	25.	0.3
K	42.	58.	57.	59.	54.	No Limit
Mg	375.	400.	399.	412.	436.	No Limit
Mn	45.	44.	46.	45.	46.	0.05
Na	262.	269.	270.	270.	274.	No Limit
Si	240.	197.	138.	157.	175.	No Limit
As (ppb)	78.	<0.5	0.7	1.1	<0.5	50. ppb
Cd (ppb)	30.	31.	27.	37.	37.	10. ppb
Cr	1.2	0.3	0.1	0.2	0.1	0.05
Cu	1.1	0.9	0.7	0.6	0.5	0.2
Ni	1.4	1.5	1.6	1.6	2.2	0.2
Se (ppb)	126.	77.	11.	29.	25.	10. ppb
Sr	0.5	4.2	4.8	5.0	1.6	No Limit
Th	0.82	4.7	4.1	2.3	2.0	2000 pCi/l
U	9.1	16.	16.	11.	10.	5.0
Zn	3.2	3.5	3.4	3.8	4.2	2.0
SO_4^{-2}	7580.	4570.	5380.	4420.	5800.	200.
pH	2.4	3.1	3.6	3.4	3.2	6.5-8.5
Eh (mv)	846.	717.	768.	676.	712.	No Limit

TABLE 6

Concentrations of Cations in Highland Tailings Solution After Titration by 0.015M ($Ca(OH)_2$ Solution. The "Diluted" Columns List Concentrations in the Aliquots Taken for Analysis. The "Corrected" Columns List Concentrations After Correcting for Dilution By The Titrant. (All Concentrations Are Shown in ppm Unless Otherwise Noted).

Element	Initial Concentration	pH 3.5 Diluted	pH 3.5 Corrected*	pH 5 Diluted	pH 5 Corrected	pH 8 Diluted	pH 8 Corrected	Most Stringent Water Quality Standard (see Table 22)
Al	261	109	220	4.2	17	2.8	18	5.0
Fe	775	7.7	16	0.4	1.5	0.3	2.1	0.3
K	42	13	26	8.7	36	7.0	46	No Limit
Mg	375	110	220	73	300	52	340	No Limit
Mn	45	12	25	6.3	26	≤0.01	≤0.6	0.05
Na	262	88	180	59	240	46	310	No Limit
Si	240	45	92	14	60	1.3	8.7	No Limit
As (ppb)	78	0.6	1.2	≤0.5	≤2.	1.1	7.5	50.ppb
Cd	30	17	35	9.2	38	≤0.3	≤1.8	10. ppb
Cr	1.2	0.3**	0.5	0.05**	0.2	0.09**	0.6	0.2
Ni	1.4	0.4	1.0	0.3	1.3	0.04	0.2	0.2
Se (ppb)	126.	1.1	2.3	≤0.5	≤4.	1.7	11.	10. ppb
Sr	0.5	1.6	3.3	1.3	5.5	1.0	6.6	No Limit
Zn	3.2	1.0	2.0	0.6	2.4	≤0.02	≤0.13	2.0

*Correct = Concentration of element in diluted sample x (volume of original sample + volume of titrant)/volume of original sample (i.e. $c(V_0 + V_T)/V_0$

**Determined concentration is near detection limit

TABLE 7

Physical Characteristics of
Tailings Dam Sandstone Column

Diameter	2.2 cm (0.875 in)
Length	15.2 cm (6 in)
Weight of Sand	85.105 g
Bulk Density	1.47 g/cm^3
Grain Density	2.51 g/cm^3
Porosity	0.42
Pore Volume	24.07 cm^3

TABLE 8

X-ray diffraction results of bulk and clay mineralogy of shale samples used in batch experiments. Constituents are listed in order of decreasing abundance

	TAILINGS DAM SHALE				ORE-BODY SHALE			
	undried	dried	3-day	30-day	undried	dried	3-day	30-day
Bulk Composition	qtz, kaol, mica	qtz, smect, kaol, mica	qtz, smect, gyps, mica kaol	qtz, gyps, smect, mica, kaol	qtz, feld, mica, kaol	qtz, feld, smect, mica kaol	qtz, feld, gyps, smect, mica, kaol	qtz, feld, gyps, smect, mica, kaol
Clay Fraction (less than 5μm)	smect, kaol, mica	smect, kaol, mica	smect, kaol, mica	smect, kaol, mica, feld	smect, kaol, mica	smect, kaol, mica, feld	smect, kaol, mica, feld	smect, kaol, mica, feld
Weight % Clay fraction (estimate)	-	89.1%	84.8%	76.5%	-	31%	33%	35.1%
Weight % gypsum (estimate)	-	-	1.5%	2.8%	-	-	2.0%	2.2%

	TAILINGS DAM SANDSTONE (undried)	ORE-BODY SANDSTONE (undried)
Bulk Composition	qtz, feld, mica,	qtz, feld, kaol
Clay Fraction (less than 5μm)	smect, kaol mica	smect, kaol mica
Weight % Clay fraction (estimate)	2.9%	12.4%

qtz = quartz
smect = smectite
kaol = kaolinite
mica = mica
feld = feldspar
gyps = gypsum

TABLE 9

Results of Petrographic Analysis of Sandstone Samples (As Percent of Total Measured on Sample)

Minerals	Tailings Dam Sandstone	*Tailings Dam Sandstone Rock Fragments	Ore Body Sandstone	*Ore Body Sandstone Rock Fragments
Quartz	24	35	43	34
K-feldspar	15	21	6	7
Plagioclase	6	11	8	19
Rock Fragments*	44		28	
Mica	1		1	
Clay	9	27	13	38
Chert		3		1
Biotite		2		
Opaques	1		1.5	
Clino-pyroxenes		1	0.3	1

TABLE 10

Comparison of Specific Storage and
Storage Coefficient Values for Highland Sands

Specific Storage (1/ft)	Storage Coefficient (dimensionless)	Formation Thickness (ft.)	Reference	Geologic Unit
7.3×10^{-6}	3.6×10^{-4}*	50	EPR calculated	-
1.5×10^{-6}	2.5×10^{-4}	165	Golder Assoc. (1979)	Ore Body Sand (multiple completion)
4.1×10^{-7}	6.3×10^{-5}	155	Golder Assoc. (1979)	Ore Body Sand (multiple completion)
2.0×10^{-7}*	1.0×10^{-5}	50	Dames & Moore (1980)	Ore Body Sand (completion unknown)
2.0×10^{-5}	1.9×10^{-4}	9.5	Exxon(Well VI-1)	Middle Ore Body Sand
1.9×10^{-5}	4.8×10^{-4}	25	Exxon(Well VII-3)	Tailings Dam Sand

*assumes a 50-foot sand thickness

TABLE 11

Laboratory Measurements of Porosity, Permeability, and Grain Density for the Tailings Dam Sand

Core		Depth(feet)	Porosity (%)	Permeability (md) (gas flood) Horiz.	Permeability (md) (gas flood) Vert.	Grain Density(g/cc)
VIII	a	112.9-113.2	29.4	372	3177	2.60
	b		35.4			
XII	a	127.4-127.8	31.7	2804	2992	2.65
	b		34.5			
	c		35.8			
XX	a	122.7-123.1	22.1	6390	5522	2.39

TABLE 12

Comparison of Tailings Dam Sand Permeability
Measured by Gas and Water Floods

Core	Permeability (md) Gas flood	Water flood
VIII (vertical)	3177	63
XII (horizontal)	2804	1525
XII (vertical)	2992	230
XX (vertical)	5522	757

TABLE 13

Summary of Porosity, Permeability, and Grain Density for the Ore Body Sands

Core	Depth (feet)	Porosity (%)	Permeability (md)		Grain Density (g/cc)
			Horiz.	Vert.	
2700-0505	384-411	30.9	1672	3450	2.63
0865-0875	353-361	30.0	1036		
0815-4950	695-764	25.6	2236		
2700-2310	650-704	25.9	3079		
4260-0940	627-659	30.0	3235		
4260-0940	745-795	26.9	3103		
2650-0320	367-400	31.0	2288	1687	2.61
0600-0810	633-667	25.6	834	626	

Since these results are very similar to those obtained for the Tailings Dam and Fowler Sands, a single set of properties were used to represent all clean sands in the study. Those properties are listed in Table 14:

TABLE 14

Properties of the Tailings Dam, Fowler, and Ore Body Sands Used in the Cross-Sectional Models.

Horizontal permeability	= 2000 md
Vertical permeability	= 2000 md
Porosity	= 34 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.72 g/cc
Specific Storage	= 7.3×10^{-6}(1/ft)
Relative permeability	= Figure 28
Capillary pressure	= Figure 31 - Core XII (horizontal)

TABLE 15

Summary of Porosity, Permeability, and Grain Density for the Tailings Dam Shale

Core	Depth (Feet)	Porosity (%)	Permeability (md)		Grain Density (g/cc)	Reference
			Air	Water		
1	60.5		3.6			Dames & Moore (1980b)
1	75.5			1.0		Dames & Moore (1980b)
1	80.5			9.3		Dames & Moore (1980b)
1	85.5			0.10		Dames & Moore (1980b)
4	35.5			0.15		Dames & Moore (1980b)
4	40.5			0.03		Dames & Moore (1980b)
XX	169.9-170.3	14.0			2.49	ERCO (1981)
XXa	169.0-169.5	10.9				Exxon Prod. Research
b		20.3				Exxon Prod. Research
c			2.59			Exxon Prod. Research
d			.0009			Exxon Prod. Research
e		11.0				Exxon Prod. Research
f			4.53	0*		Exxon Prod. Research

* Core plug XXf was saturated with filtered tailings pond liquor. Permeability to the liquor was measured at an injection pressure of 225 psig, and at atmospheric outlet pressure. The permeability measured over the first 24 and 48 hours was 0.003 and 0.004 md, respectively. No fluid flow occurred for the next 10 days.

Table 16

Shale Lithology
Core XII 0 - 120.0 Feet

DEPTH	DESCRIPTION	
0-15'	Brown silty clay	moist
15-20'	Grey silty clay	"
20-25'	Grey-green silty clay	
25-30'	Grey-green silty clay	"
30-40'	Brown clayey fine sand to silt	
40-43'	Brown clayey sand	
43-48.5'	Core lost	
?-1.3'	Brown clayey silt to fine sand	"
.6'	Grey claystone	
51.9-56.6'	Grey claystone	
56-60'	Alternating fine sandstones and claystones	
60-63.4	Grey to black carbonsceous	
67.2-68.8	Grey silty claystone w/carbonsceous steaks	
68.8-72.8'	Grey silty claystone to siltstone at base	
72.8-86.8	Grey to green claystone and silty claystone	
87-90'	Very porous, weakly indurated feldspathic medium sandstone	
90-100'	Grey clay	moist
100-115	Grey and brown silty clay and clayey silt - moist	
115-120'	Gray and brown silty clay and clayey silt - moist	

Table 17

Shale Lithology

CORE XX 125.0 to 167.5

DEPTH	DESCRIPTION
125-130	Silty Claystone
130-135	Clayey sand to very coarse sand to gravel
135-140	Clayey very coarse sand to gravel
140-155	Silty grey clay
155-160	Grey clay
161-162.9	Gray claystone
162.9-165	Core loss
165-169.9	Grey to grey green claystone

TABLE 18

Properties of the Tailings Dam, Fowler, and Ore Body Shales Used in the Cross-Sectional Models

Horizontal permeability	= 1 md
Vertical permeability	= 1 md
Porosity	= 10 percent
Grain density	= 2.60 g/cc
Bulk density	= 2.34 g/cc
Specific storage	= 2.2×10^{-6} (1/ft)
Relative permeability	= Figure 31
Capillary pressure	= Figure 32

TABLE 19

Properties of the Surface Mine Backfill Material Used in the Cross-Sectional Models

Horizontal permeability	= 2000 md
Vertical permeability	= 2000 md
Porosity	= 35 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.69 g/cc
Specific storage	= 7.5×10^{-6} (1/ft)
Relative permeability	= Figure 36
Capillary pressure	= Figure 36

TABLE 20

Distribution Coefficients and Relative Velocities for Solutes at Highland Resulting from Contact with the Tailings Dam Sand, Tailings Dam Shale, Ore Body Sands, and Ore Body Shales.

	Distribution Coefficient $\left(\frac{ml}{g}\right)$				Relative Velocity $\left(\frac{\text{solute front velocity}}{\text{fluid velocity}}\right)$			
Solute	Tailings Dam Sand	Tailings Dam Shale	Ore-Body Sand	Ore-Body Shales	Tailings Dam Sand	Tailings Dam Shale	Ore-Body Sands	Ore-Body Shales
Al	-1.09	7.99	-1.09	1.82	1.00	0.005	1.00	0.023
As	4.00	776.	116.	776.	0.048	$5x10^{-5}$	0.002	$5x10^{-5}$
Ca	-0.34	-0.36	-0.38	-0.36	1.00	1.00	1.00	1.00
Cd	-0.47	-0.25	-0.47	-0.76	1.00	1.00	1.00	1.00
Cr	20.5	320.	39.0	37.9	0.010	$1x10^{-4}$	0.005	0.001
Cu	1.07	5.46	2.05	4.12	0.156	0.008	0.088	0.010
Fe	20.9	118.	129.	119.	0.009	$4x10^{-4}$	0.002	$3x10^{-4}$
H	0.21	0.46	0.27	0.26	0.485	0.085	0.423	0.141
K	3.00	-0.97	0.29	-0.88	0.062	1.00	0.405	1.00
Mg	-0.96	-0.35	-0.42	-0.56	1.00	1.00	1.00	1.00
Mn	-0.43	-0.45	-0.81	-0.13	1.00	1.00	1.00	1.00
Na	-0.06	-0.38	-0.17	-0.16	1.00	1.00	1.00	1.00
Ni	-1.09	0.60	-0.72	-1.24	1.00	0.066	1.00	1.00
Se	11.8	17.0	13.4	16.2	0.016	0.003	0.014	0.003
Si	-0.38	6.62	0.72	1.57	1.00	0.006	0.215	0.026
Sr	-0.68	-3.56	-1.04	-2.68	1.00	1.00	1.00	1.00
Zn	-0.62	-0.66	-0.28	-0.89	1.00	1.00	1.00	1.00
SO_4^{-2}	0.87	1.59	0.034	0.94	0.185	0.026	0.85	0.043
Th	5.33	61.6	-3.80	-2.37	0.036	$7x10^{-4}$	1.00	1.00
U	2.70	17.5	-3.77	-0.25	0.068	0.002	1.00	1.00
Pb-210*	68.	13.	68.	13.	0.003	0.003	0.003	0.003
Ra-226*	18.	10.	18.	10.	0.011	0.004	0.011	0.004
Th-230*	1.9	1.1	1.9	1.1	0.094	0.037	0.094	0.037
U-238*	1.7	1.0	1.7	1.0	0.104	0.041	0.104	0.041
pH**	3.2	3.5	3.3	3.3				
Eh**	619.	614.	676.	712.				

* Distribution coefficients obtained by Battelle (1980b) for Morton Ranch
**Value after 30 days contact period

TABLE 21

Properties of the Tailings Dam Sand and Surface Mine Backfill Material Used in the Areal Model

Horizontal permeability	= 2000 md
Porosity	= 34 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.72 g/cc
Specific storage	= 7.3×10^{-6} (1/ft)
Relative permeability	= Figure 54
Capillary pressure	= Figure 55

Surface Mine Backfill Material

Horizontal permeability	= 2000 md
Porosity	= 35 percent
Grain density	= 2.60 g/cc
Bulk density	= 1.69 g/cc
Specific storage	= 7.5×10^{-6} (1/ft)
Relative permeability	= Figure 54
Capillary pressure	= Figure 55

TABLE 22

APPLICABLE GROUNDWATER STANDARDS AND CONCENTRATION LEVELS OF INTEREST

Species	Draft EPA/NRC UMTCA (mg/l) Inactive Sites	APPLICABLE DRINKING WATER STANDARDS (mg/l) EPA Drinking Water Standards Primary	Secondary	Livestock	WY DEQ Proposed GW Standards Domestic	Agric	Livestock	USNRC 10 CFR Part 20	Groundwater Concentration Levels (mg/l) Of Interest
Aluminum (Al)	-	-	-	5.0	-	5.0	5.0	-	5.0
Ammonia (NH_3)	-	-	-	-	0.5	-	-	-	0.5
Arsenic (As)	0.05	0.05	-	0.2	0.05	0.1	0.2	-	0.05-0.20
Barium (Ba)	1.0	1.0	-	-	1.0	-	-	-	1.0
Beryllium (Be)	-	-	-	-	-	0.1	-	-	0.1
Boron (B)	-	-	1.0	5.0	0.75	0.75	5.0	-	0.75-5.0
Cadmium (Cd)	0.01	0.01	-	0.05	0.01	0.01	0.05	-	0.01-0.05
Chromium (Cr)	0.05	0.05	-	1.0	0.05	0.10	0.05	-	0.05-1.0
Cobalt (Co)	0.05	-	-	-	-	0.05	1.0	-	0.05-1.0
Copper (Cu)	-	-	1.0	0.5	1.0	0.20	0.50	-	0.20-1.0
Cyanide (CN)	-	0.05	-	-	0.2	-	-	-	0.05-0.20
Fluoride (F)	-	1.4-2.4	-	2.0	1.4-2.4	-	-	-	1.4 -2.4
Hydrogen Sulfide (H_2S)	-	-	-	-	0.05	-	-	-	0.05
Lithium (Li)	-	-	-	-	-	2.5	-	-	2.5
Lead (Pb)	0.05	0.05	-	0.1	0.05	5.0	0.10	-	0.05-5.0
Mercury (Hg)	0.002	0.002	-	0.01	0.002	-	-	-	0.002-0.01
Molybdenum (Mo)	1.0	-	-	-	-	-	-	-	1.0
Nickel (Ni)	0.2	-	-	-	-	0.2	-	-	0.2
Nitrate (as N)	10.0	10.0	-	-	10.1	-	-	-	10.0
Nitrite (as N)	-	-	-	-	1.0	-	10.1	-	1.0-10.0
Selenium (Se)	0.01	0.01	-	0.05	0.01	0.02	0.05	-	0.01-0.05
Silver (Ag)	0.05	0.05	-	-	0.05	-	-	-	0.05
Vanadium (V)	-	-	-	-	-	0.1	0.1	-	0.10
Zinc (Zn)	-	-	5.0	25.0	5.0	2.0	25.0	-	2.0-25.0
Chloride (Cl)	-	-	250.0	2000.0	250.0	100.0	2000.0	-	100.0-2000.0
Iron (Fe)	-	-	0.3	-	0.3	5.0	-	-	0.3-5.0
Manganese (Mn)	-	-	0.05	-	0.05	0.2	-	-	0.05-0.2
Ph	-	-	6.5-8.5	-	6.5-8.5	4.5-9.0	6.5-8.5	-	4.5-9.0
Sulfate (SO_4)	-	-	250.0	3000.0	250.0	200.0	3000.0	-	200.0-3000.0
TDS	-	-	500.0	-	500.0	2000.0	5000.0	-	500.0-5000.0
Uranium (U)	-	-	-	-	5.0 mg/l	5.0 mg/l	5.0 mg/l	44.3 mg/l	5 mg/l, 44.3 mg/l
Ra-226,228	5.0 pCi/l	5.0 pCi/l	-	-	5.0 pCi/l	5.0 pCi/l	5.0 pCi/l	30.0 pCi/l	5-30 pCi/l
Gross α	15.0 pCi/l	15.0 pCi/l	-	-	15.0 pCi/l	15.0 pCi/l	15.0 pCi/l	-	15 pCi/l
Thorium-230	-	-	-	-	-	-	-	2000.0 pCi/l	2000 pCi/l
Gross β	-	30.0 pCi/l	-	-	-	-	-	-	30 pCi/l
Lead-210	-	-	-	-	-	-	-	-	-

Table 23

SOLUTES CONSIDERED FOR USE AS TRACERS FOR THE 1.0 RELATIVE VELOCITY FRONT

Solute	Pond Concentration mg/l	Background Concentration mg/l	Relative Velocity				Measured Concentration at pH=8
			Tailings Dam Sand	Tailings Dam Shale	Ore Body Sand	Ore Body Shale	
Ca	584.	10 - 88	1.0	1.0	1.0	1.0	?
Cd	.030		1.0	1.0	1.0	1.0	.0018
Mg	375.	1.5 - 14	1.0	1.0	1.0	1.0	340.
Mn	45.		1.0	1.0	1.0	1.0	0.06
Na	262.	114 - 194	1.0	1.0	1.0	1.0	310.
Sr	0.50		1.0	1.0	1.0	1.0	6.6
Zn	3.2		1.0	1.0	1.0	1.0	0.13
Cl	218.	15 - 40	ND	ND	ND	ND	279.
K	42.	7 - 10	0.062	1.00	0.405	1.00	46.
Si	240.		1.00	0.006	0.215	0.026	8.7
SO_4^{-2}	7580.	150 - 500	0.185	0.026	0.85	0.043	7580.

APPENDIX A

Methods Used for Determining Element Concentrations and Performing Mineralogical Analyses

I. Analytical Methods for Determining Element Concentrations

A. Atomic Absorption Spectrometry

The following elements were determined in the filtrates and controls from the batch tests and titrations, the as-received tailings solution, and the rock samples: Al, Ca, Fe, K, Mg, Mn, Na, Si, As, Cd, Cr, Cu, Ni, Se, Sr, Th, U, and Zn. All elements, except Th and U were determined by atomic absorption spectrometry (AAS), using a Perkin-Elmer Model 5000 spectrometer for flame and hydride determinations and a Perkin-Elmer Model 703 spectrometer for heated graphite atomizer (HGA) determinations. Arsenic and selenium were determined as hydrides, and cadmium was determined using the heated graphite atomizer. Thorium and uranium were determined by Analytical Consulting Services, Houston, Texas using a d.c. plasma emission spectrometer.

The major (Al, Ca, Fe, K, Mg, Na, Si) and minor (Mn) element concentrations were determined in accordance with Standard Method D3682 of the American Society of Testing and Materials (ASTM), "Standard Test Method for Major and Minor Elements in Coal and Coke Ash by Atomic Absorption." In the procedure, 0.1 gram of rock sample was fused with one gram of lithium tetraborate ($Li_2B_4O_7$). After fusion the fusion cake was dissolved in 5% HCl solution prior to atomic absorption analysis. Lanthanum chloride solution was added to release some elements, for example, magnesium, from ion pair formation.

For trace elements (As, Cd, Cr, Cu, Ni, Se, Sr, Th, U, and Zn) the ASTM "Standard Test Method for Trace Elements in Coal and Coke Ash by Atomic Absorption," D3683, was followed. In this method, 0.2 gram of a rock sample was dissolved in a small volume of hydrofluoric, hydrochloric, and nitric acids in a sealed linear polyethylene bottle. After the dissolution, boric acid solution was added to complex excess hydrofluoric acid.

Analytical standards for major and minor elements were prepared in 10^{-3}M H_2SO_4 to approximate the tailings solution matrix, however, trace element standards were prepared in 1% HNO_3 solution. Nitric acid was used for trace element standards because the solutions used for analyses were dilute enough that H_2SO_4 effects were not significant.

A summary of the analytical wavelengths and flame types used is given in Table A-1.

B. Ion Chromatography

Sulfate concentrations in each of the batch test and titration filtrates were determined by ion chromatography using a Dionex Model 16 Ion Chromatograph. The eluent stream was 0.0024M $NaHCO_3$ plus 0.003M Na_2CO_3.

II. Mineralogical Analyses

A. Petrography

Random samples of each sandstone were impregnated with clear epoxy and thin sectioned for examination on a standard petrographic microscope. Two hundred point counts were made on each of two thin sections cut from the Tailings Dam Sandstone and Highland Sandstone after no tailings solution treatment, 3-day treatment, and 30-day treatment, using a petrographic microscope to note qualitative differences (such as texture, grain size, mineralogy, and grain preservation) between these samples and the as-received sandstones.

B. X-ray Diffraction

The as-received sandstones and shales, and the dry, 3-day treatment, and 30-day treatment Tailings Dam and Highland shales were analyzed by x-ray diffraction spectrometry. Each sample was scanned for bulk composition. The less than 5μm clay fractions of the shale samples were separated from suspension by gravity sedimentation. An estimate of weight percent clay was obtained by weighing both settled and suspended fractions. Samples were prepared on glass slides for examination by x-ray diffraction using Cu Kα radiation. These mounts were then heated to 550°C and re-examined by x-ray diffraction to confirm the presence of kaolinite and the absence of chlorite. Another set of mounts were treated with ethylene glycol to detect the expandable smectite clay minerals.

C. Energy Dispersive X-ray Fluorescence Elemental Analysis

Chemical analysis on scanning electron microscope is performed by measuring the energy and intensity distribution of the x-ray signal generated by a focused beam of electrons. The energy-dispersive spectrometer measures x-ray energy directly, producing a spectrum of relative intensity versus energy. The spectrum produced is used for qualitative analysis.

TABLE A-1

Summary of Atomic Absorption Wavelengths and Flame Types Used for Analysis of Highland Tailings Solutions.

Element	Wavelength (nm)	Flame
Al	309.3	N_2O/C_2H_2
Ca	422.7	Air/C_2H_2
Fe	248.3	Air/C_2H_2
K	766.5	Air/C_2H_2
Mg	285.2	Air/C_2H_2
Mn	279.5	Air/C_2H_2
Na	589.0	Air/C_2H_2
Si	251.6	N_2O/C_2H_2
As	193.7	hydride
Cd	228.8	HGA*
Cr	357.9	Air/C_2H_2
Cu	324.8	Air/C_2H_2
Ni	232.0	Air/C_2H_2
Se	196.0	hydride
Sr	460.7	Air/C_2H_2
Zn	213.9	Air/C_2H_2

*HGA = heated graphite atomizer

APPENDIX B

Summary of Core Analysis Data for the Highland Ore Body Sands

Permeability, porosity, and grain density data were obtained for eight Ore Body Sand cores at Highland. The locations of those cores are shown in Figure B-1. The core analysis data are summarized in Tables B-1 through B-8.

The data show that permeability varies from less than one millidarcy to over ten darcies. This variation is probably caused by shale stringers and differing amounts of clay and silt in the sands. Arithmetically averaged permeabilities are between 0.6 and 3.4 darcies. The sands appear to be isotropic.

Porosity varies from less than 10 percent to over 40 percent. Again, this variation is probably due to differing amounts of shale, clay, and silt in the sands.

Measured grain densities showed little variation and were generally about 2.65 grams per cubic centimeter.

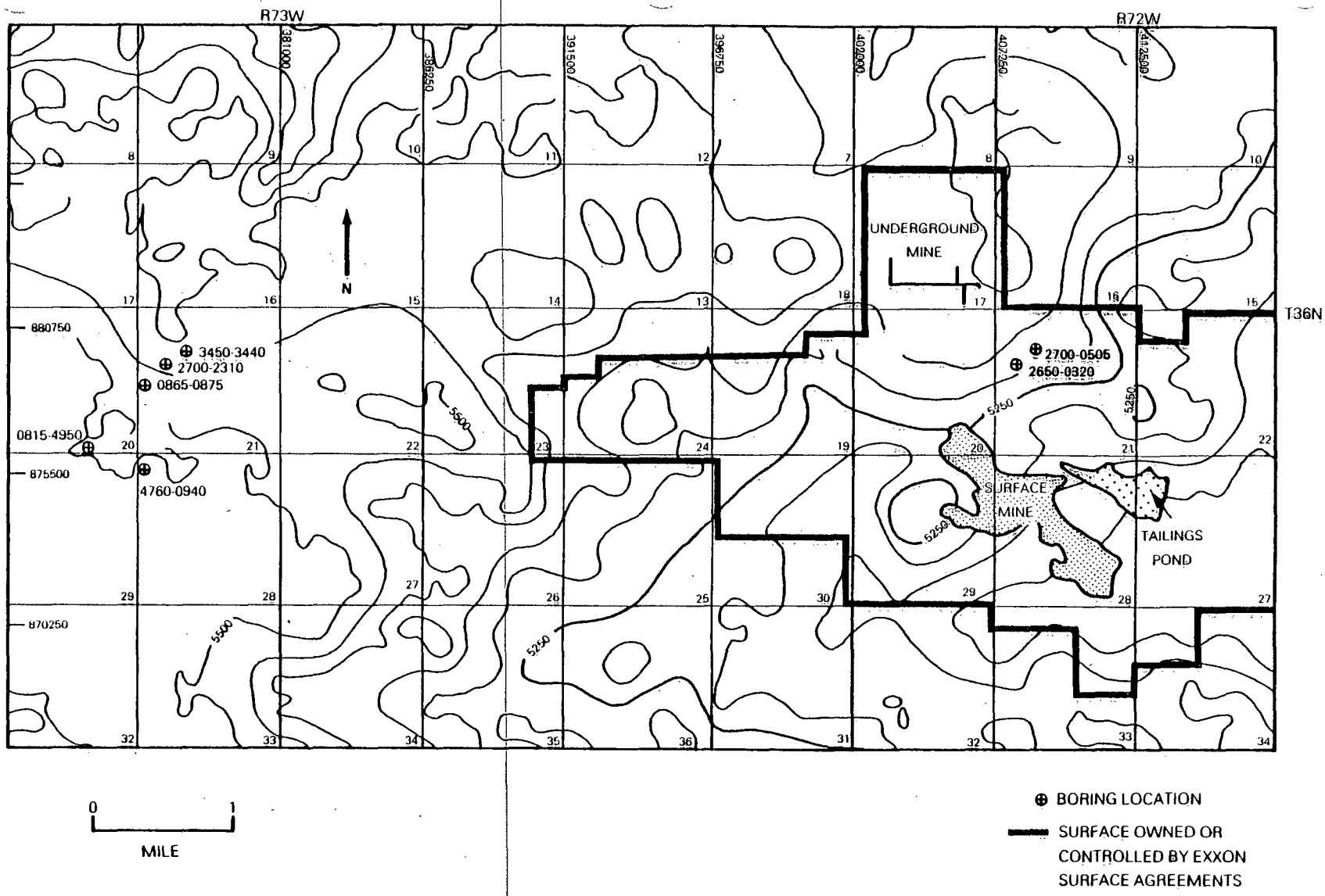


FIG. B-1 LOCATIONS OF BORINGS USED TO DETERMINE PERMEABILITY, POROSITY, AND GRAIN DENSITY OF THE HIGHLAND ORE BODY SAND

Table B-1

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 2700-0505 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
384-85	3.72	9.98	25.6	2.65
385-86	7.57	4.38	27.1	2.66
386-87	242.	29.	34.1	2.65
387-88	328.	137.	32.2	2.65
388-89	1623.	885.	34.1	2.63
389-90	1216.	1110.	33.3	2.64
390-91	355.	1295.	30.3	2.64
391-92	1992.	1688.	33.0	2.64
392-93	1725.	835.	33.5	2.64
393-94	5576.	6020.	31.9	2.63
394-95	3031.	12369.	35.2	2.63
395-96	3353.	6639.	30.7	2.62
396-97	4938.	10648.	30.0	2.62
397-98	8465.	8839.	30.0	2.63
398-99	1553.	21524.	33.4	2.63
399-400	645.	401.	33.0	2.65
400-01	2065.	693.	32.1	2.64
401-02	215.	20.	23.6	2.60
402-03	43.	217.	29.4	2.61
403-04	1109.	403.	32.0	2.62
404-05	3958.	61.	33.0	2.60
405-06	26.	533.	29.1	2.62
406-07	1255.	328.	30.7	2.62
407-08	518.	1576.	31.1	2.63
408-09	316.	16830.	30.6	2.59
409-10	582.	36.	24.8	2.65
410-11	20.	1.44	29.3	2.67
Arithmetic Average	1672.	3450.	30.9	2.63

Table B-2

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 0815-C-4950 SECTION 20 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
695-96	7.80		21.8	
696-97	150.		29.0	
697-98	1225.		31.3	
698-99	1250.		31.4	
699-700	1500.		29.4	
700-01	1600.		32.1	
701-02	1850.		31.7	
702-03	2000.		33.0	
703-04	230.		25.9	
704-05	1650.		27.1	
705-06	245.		26.1	
706-07	690.		20.2	
707-08	1950.		26.4	
708-09	1110.		32.2	
809-10	1790.		29.1	
710-11	1075.		31.0	
711-12	2700.		31.9	
712-13	2800.		30.7	
713-14	2100.		35.1	
714-15	2540.		31.0	
715-16	U.T.		33.4	
716-17	U.T.		32.1	
717-18	4000.+		33.0	
718-19	4000.+		28.7	
719-20	0.30		7.5	
720-21	2850.		27.9	
721-22	25.		23.3	
722-23	2.85		18.0	
723-24	1.26		13.8	
724-25	0.95		15.0	
725-26	1.60		14.2	

Note: U.T. = Unsuitable for testing

Table B-2
Continued

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 0815-C-4950 SECTION 20 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
726-27	1.80		14.8	
727-28	2.50		21.1	
728-29	-		29.7	
729-30	-		26.1	
730-31	308.		27.9	
731-32	4000.+		26.1	
732-33	4000.+		21.2	
733-34	2950.		27.1	
734-35	3300.		27.2	
735-36	3850.		28.1	
736-37	3140.		24.2	
737-38	1225.		18.3	
738-39	1045.		26.2	
739-40	4000.+		27.2	
740-41	4000.+		28.3	
741-42	4000.+		27.5	
742-43	-		27.8	
743-44	4000.+		24.7	
744-45	3450.		22.2	
745-46	3100.		21.6	
746-47	4000.+		26.1	
747-48	4000.+		28.9	
748-49	4000.+		25.1	
749-50	4000.+		24.0	
750-51	4000.		29.1	
751-52	4000.+		30.3	
759-60	4000.+		23.6	
760-61	4000.+		23.6	
761-62	4000.+		19.3	
762-63	4000.+		21.6	
763-64	4000.+		21.8	
764-64	0.60		11.7	

Table B-3

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 2700-C2310 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
650-51	4000.+		34.2	
651-52	1766.		31.7	
652-53	2548.		31.9	
653-54	3657.		30.8	
654-55	3950.		28.7	
655-56	4000.+		26.9	
656-57	4000.+		25.9	
657-58	4000.+		28.9	
658-59	4000.+		26.7	
659-60	4000.+		25.2	
660-61	4000.+		26.9	
661-62	3716.		21.8	
662-63	U.T.		U.T.	
663-64	U.T.		U.T.	
664-65	4000.+		22.5	
665-66	3849.		20.6	
666-67	1233.		23.1	
667-68	4000.+		23.7	
668-69	4000.+		25.7	
669-70	4000.+		22.7	
670-71	4000.+		21.9	
671-72	4000.+		20.8	
672-73	4000.+		21.4	
673-74	U.T.		U.T.	
674-75	U.T.		U.T.	
675-76	1405.		17.3	
676-77	35.		13.0	
677-78	4000.+		27.6	
678-79	4000.+		26.6	
679-80	4000.+		23.8	

Note: U.T. = Unsuitable for testing

Table B-3
Continued

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 2700-2310 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
680-81	3940.		29.4	
681-82	2062.		28.0	
682-83	2566.		29.4	
683-84	1471.		27.2	
684-85	2144.		26.8	
685-86	752.		23.2	
686-87	2144.		27.1	
687-88	4000.+		24.7	
688-89	4000.+		31.0	
689-90	4000.+		26.9	
690-91	2.50		8.2	
691-92	2029.		32.3	
692-93	3047.		29.9	
693-94	2472.		32.8	
694-95	4000.+		31.9	
695-96	2655.		31.0	
696-97	1390.		29.2	
697-98	75.		17.1	
698-99	4000.+		34.0	
699-700	4000.+		28.8	
700-01	U.T.		U.T.	
701-02	U.T.		U.T.	
702-03	3809.		20.3	
703-04	U.T.		U.T.	
Arithmetic Average			25.9	

Note: U.T. = Unsuitable for testing

Table B-4

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 4260-0940 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
627-28	1464		31.5	
628-29	302.		30.5	
629-30	U.T.		35.5	
630-31	4000.+		31.7	
631-32	4000.+		34.2	
632-33	4000.+		32.5	
633-34	4000.+		32.9	
634-35	3805.		31.2	
635-36	4000.+		31.9	
636-37	4000.+		34.9	
637-38	4000.+		31.9	
638-39	4000.+		32.4	
639-40	4000.+		32.1	
640-41	U.T.		U.T.	
641-42	U.T.		U.T.	
642-43	4000.+		25.4	
643-44	4000.+		25.7	
644-45	U.T.		U.T.	
645-56	U.T.		U.T.	
646-47	U.T.		U.T.	
647-48	U.T.		U.T.	
648-49	4000.+		30.8	
649-50	U.T.		U.T.	
650-51	U.T.		U.T.	
651-52	4000.+		29.1	
652-53	U.T.		U.T.	
653-54	U.T.		U.T.	
654-55	2510.		25.6	
655-56	4000.+		22.6	
656-57	3850.		21.6	
657-58	8.90		28.5	
658-59	2.82		26.9	

Note: U.T. = Unsuitable for testing

Table B-4
Continued

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 4260-0940 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
745-46	1598		29.7	
746-47	4000.+		32.0	
747-48	1116.		30.9	
748-49	1652.		30.5	
749-50	4000.+		32.5	
750-51	4000.+		30.9	
751-52	4000.+		26.8	
752-53	2.41		7.7	
753-54	U.T.		U.T.	
754-55	U.T.		U.T.	
755-56	4000.+		31.3	
756-57	4000.+		27.6	
757-58	4000.+		28.7	
758-59	4000.+		32.3	
759-60	4000.+		27.4	
760-61	4000.+		27.4	
761-62	4000.+		26.5	
762-63	4000.+		27.6	
763-64	4000.+		27.6	
764-65	4000.+		27.0	
765-66	4000.+		30.9	
766-67	4000.+		29.7	
767-68	4000.+		29.4	
768-69	894.		23.4	
769-70	4000.+		24.9	
770-71	4000.+		27.9	
771-72	4000.+		26.5	
772-73	4000.+		26.5	

Note: U.T. = Unsuitable for testing

Table B-4
Continued

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 4260-0940 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
773-74	3140		26.2	
774-75	4000.+		24.4	
775-76	2062.		20.9	
776-77	2566.		24.0	
777-78	1917.		26.2	
778-79	U.T.		U.T.	
779-80	U.T.		U.T.	
780-81	U.T.		U.T.	
781-82	U.T.		U.T.	
782-83	U.T.		U.T.	
783-84	4000.+		27.8	
784-85	3688.		28.0	
785-86	4000.+		28.3	
786-87	4000.+		29.6	
787-88	4000.+		29.2	
788-89	1249.		29.9	
789-90	245.		21.8	
790-91	U.T.		U.T.	
791-92	U.T.		U.T.	
792-93	0.71		19.6	
793-94	2.30		17.3	
794-95	U.T.		U.T.	

Note: U.T. = Unsuitable for testing

Table B-5

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 2650-C-0320 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
367-68	318.	144.	24.0	2.64
368-69	5.13	2.28	22.2	2.64
369-70	84.	2.83	23.2	2.65
370-71	8.33	6.0	27.0	2.63
371-72	238.	32.	26.7	2.65
372-73	519.	317.	33.3	2.65
373-74	708.	403.	33.9	2.63
374-75	1267.	1266.	34.2	2.63
375-76	1652.	1204.	33.7	2.63
376-77	1638.	855.	33.9	2.62
377-78	2202	1433.	34.3	2.64
378-79	2511.	1123.	35.5	2.64
379-80	2808.	1906.	36.5	2.64
380-81	6047.	3393.	41.0	2.60
381-82	5527.	4712.	40.1	2.62
383-84	11705.	15.3	39.8	2.58
384-85	5061.	6770.	36.3	2.62
385-86	5592.	1957.	38.1	2.62
386-87	156.	63.	27.7	2.63
387-88	2275.	1875.	32.2	2.62
388-89	1524.	1091.	31.4	2.63
389-90	3040.	3377.	32.6	2.63
390-91	3027.	3686.	32.7	2.64
391-92	4177.	4177.	33.0	2.63
392-93	2286.	3515.	33.7	2.64
393-94	4560.	3505.	34.6	2.63
394-95	34.	42.	27.1	2.63
395-96	1457.	2986.	33.1	2.64
396-97	2048.	3791.	32.6	2.63
397-98	2901.	1062.	32.1	2.61
398-99	142.	961.	29.8	2.63
399-400	0.94	0.23	16.9	2.71
Arithmetic Average	2288.	1687.	31.0	2.61

Table B-6

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 0865-0875 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
353-54	720.		29.1	
354-55	875.		31.7	
355-56	1470.		30.8	
356-57	1233.		31.3	
357-58	1510.		31.8	
358-59	970.		30.8	
359-60	775.		26.5	
360-61	733.		27.9	
Arithmetic Average	1036.		30.0	

Table B-7

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 0600-0810 SECTION 24 T36N R73W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
633-34	U.T.	U.T.	U.T.	
634-35	U.T.	U.T.	U.T.	
635-36	U.T.	U.T.	U.T.	
636-37	80.	55.	25.0	
637-38	208.	200.	26.6	
638-39	164.	144.	28.0	
655-56	820.	751.	23.6	
656-57	1493.	843.	24.1	
657-58	538.	247.	23.4	
658-59	280.	130.	20.7	
659-660	1659.	1436.	24.7	
660-61	527.	477.	28.6	
661-62	831.	682.	25.4	
662-63	U.T.	U.T.	U.T.	
663-64	U.T.	U.T.	U.T.	
664-65	1936.	1564.	29.9	
665-66	741.	673.	24.0	
666-67	1567.	936.	28.3	
Arithmetic Average	834.	626.	25.6	

Note: U.T. = Unsuitable for testing

Table B-8

PERMEABILITY, POROSITY, AND GRAIN DENSITY DATA
OBTAINED BY CORE ANALYSIS OF THE HIGHLAND ORE BODY SAND

CORE 3450-3440 SECTION 21 T36N R72W

Core Depth (Feet)	Air Permeability, md Horizontal	Air Permeability, md Vertical	Porosity (Percent)	Grain Density (gm/cc)
652-53	28.	U.T.	28.5	
653-54	40.	U.T.	29.6	
654-55	0.50	0.46	8.5	
655-56	0.15	0.05	8.8	
656-57	58.	8.60	27.3	
657-58	U.T.	U.T.	16.5	
666-67	U.T.	U.T.	29.3	
667-68	U.T.	U.T.	28.6	
668-69	U.T.	U.T.	27.9	
669-70	35.	14.	26.5	
670-71	59.	29.	28.6	
671-72	80.	U.T.	30.0	
672-73	U.T.	U.T.	25.8	
673-74	38.	43.	25.1	
674-75	15.	U.T.	28.6	
675-76	U.T.	U.T.	26.8	
676-77	80.	20.	29.6	
677-78	28.	8.50	19.8	

Note: U.T. = Unsuitable for testing

APPENDIX C

HIGHLAND FIELD PROGRAM

C.1. Purpose and Scope of the Field Program 1972-1979

C.2. Original Water Quality Monitoring Network

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C.2.3. Sampling

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C.2.4. Deficiencies and Additional Data Required

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C.2.4.2. Sampling
C.2.4.3. Analytical Techniques
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C.3 1980-81 Field Program

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C.3.4.7. Bulk Samples of Geologic Units

C.3.5. Field Program Summary

C.1 Purpose and Scope of the Field Program 1972-1979

Background

Potential seepage from the Highland Tailings Impoundment has been a concern to Exxon Minerals Company (formerly Minerals Department, Humble Oil & Refining Company) since 1970 when design work on the tailings dam was underway. (Dames & Moore, 1970).

A formal ground water monitoring program was proposed in 1971 and subsequently incorporated into the Final Environmental Statement for "The Highland Uranium Mill" (U.S. AEC, 1973). Monitoring of the original four wells began in 1972 prior to the deposition of tailings in the basin in October, 1972. A fifth monitor well was installed in 1974. In 1977, five additional wells were completed around the tailings impoundment to monitor potential seepage, bringing the monitoring network to ten wells. Figure 22 has locations of the monitor wells and Table C-1 summarizes location data.

Purpose and Scope

The purpose of the above mentioned wells was to monitor potential seepage from the tailings impoundment:

- through the toe of the tailings dam
- through the dam abutments and sides of the reservoir
- through the Tailings Dam Shale and into lower sands. (Exxon, 1977)

The scope of the work included the completion of the wells at discrete intervals above and below the Tailings Dam Shale, which is considered to be the major seepage control feature in the local stratigraphy. Also included in the program was periodic sampling of the wells for possible seepage and the analysis of the collected data.

The descriptions of the well completions, sampling techniques, and data evaluation are discussed in subsequent sections of this report.

C.2. Original Water Quality Monitoring Network

C.2.1. Well Locations

Two of the first five Tailings Dam Monitor (TDM) wells, A and B, were drilled north of the tailings impoundment and three of the first five TDM wells were drilled on the downstream side of the tailings dam. TDM-E was drilled very close to the channel of the impounded intermittent stream. TDM-C was drilled near the south abutment of the tailings dam and TDM-D was drilled nearly opposite the center of the tailings dam. TDM's I through V were drilled downstream of the tailings dam to fill in gaps in the original network of five wells. The locations are shown on Figure 22.

C.2.2. Well Completion Information

To verify the screened interval data of the ten original TDM wells, the eight TDM wells with 4" casing were TV camera logged in 1980. Two TDM's, A and B, had 2" casing and could not be TV camera logged. The camera logs provided depths from the collar to the screened intervals and the total well depth or the depth to fill or sediment in the casings.

During the 1981 field program, probe holes were drilled and very carefully geophysically logged in five areas near the other TDM wells downstream from the tailings dam. All probe holes and TDM wells were surveyed to establish collar elevation. Geologic formations were correlated between probe holes and then correlated to the eight TDM wells nearby that had been TV camera logged. The projected elevations of the contacts of the geologic formations were compared to the elevations of the screened intervals in the 1972, 1974, and 1977 TDM wells to determine which geologic formations were screened in each well.

Cross sectional drawings of the eight original TDM wells that were camera logged are attached in Figures C-1 to C-8.

TDM wells C and D were screened above the Tailings Dam Shale and TDM well E was screened below the Tailings Dam Shale. The intent of these wells, and wells A and B, was to detect seepage above or below the floor of the tailings impoundment in multiple screened wells that penetrated all geologic formations that had reasonable potential to carry seepage.

TDM wells I through V were intended to be screened in a single geologic formation. The amount of fill or sediment in the wells makes the total screened interval difficult to determine. TDM II is screened 2 feet or more into the Tailings Dam Shale, and extends upward to the lower contact of the Tailings Dam Sandstone. Since the shales transmit only very small amounts of water, the water produced in TDM II is most likely coming from the Tailings Dam Sandstone. TDM IV is screened up to the lower contact of the 45 Shale as well as in the intended completion in the 40 Sandstone.

C.2.3. Sampling

C.2.3.1. Sampling Procedures

Procedures for sampling monitor wells prior to June, 1981, involved obtaining a grab sample from the well by two methods. Most of the monitor wells were sampled with a bail. The bail consisted of two-inch black iron pipe with a capped bottom end. The well was bailed until sufficient sample was obtained. The second method involved the use of an air compressor to air lift the wells with small casing diameters. In both methods, a one gallon sample was collected from the well and taken to the laboratory. At the lab the water was filtered through #40 Whatman paper and preserved for the required analyses.

Due to inconsistency in the records, the sampling frequency of the monitor wells is difficult to determine for early years of tailings disposal. Since 1977, sampling has followed a specific schedule. TDM wells A, B, D, E, and I required monthly radium-226, thorium-230 and total uranium analysis. TDM wells II through V required monthly radium-226 and total uranium with thorium-230 being analyzed only once a year. All wells were sampled quarterly for major anions/cations and trace metals. These parameters usually included pH, sodium, potassium, calcium, magnesium, sulfate, chloride, bicarbonate, T.D.S., arsenic and selenium. After 1977 the Wyoming DEQ, LQD required analysis of pH, T.D.S., total iron, nitrate, sulfate, molybdenum, total uranium, and radium-226 twice a year. Those parameters not already sampled on a more frequent basis were incorporated into the bi-annual sampling schedule.

C.2.3.2. Summary of Data

Baseline data is on file for TDM's A, B, and E. Sampling of these TDM's began in July, 1972, and tailings disposal did not begin until October, 1972. This data consists of anion/cation and radiological analyses. These files are maintained at Highland.

The hydrology data base on the Highland Uranium Operations' HP-3000 computer includes water quality data from April, 1974 through June, 1980. It is currently being expanded to include baseline 1972 to 1974 data and June, 1980 to present data. Once the hydrology data base is updated, it will facilitate evaluation of all water quality data and summary statistics, time vs. concentration graphs, and other statistical analyses of these data will be possible.

For each sampling site the major ions, trace constituents, and radionuclides are reported. An example listing from TDM A (sample site 9) from 1974 is included in Table C-2. Elements not analyzed in a specific month are flagged with an asterisk; those below limits of detection are flagged with a "¢". The example shows radionuclide analyses monthly and major and trace constituent analyses performed quarterly.

C.2.4. Deficiencies and Additional Required Data

The original ten TDM wells served their purpose as "early warning indicators" of seepage but were not adequate for a detailed hydrological study of the tailings impoundment and the geologic formations that might be affected.

C.2.4.1. Well Construction

The multiple screened TDM wells and the TDM wells screened all the way to the contact with another geologic formation could not be used to construct potentiometric maps for the several geologic formations of interest. The water levels in these wells were a composite of the two or more geologic formations open to the well screens. Also, the water samples collected from these wells were a composite of the water qualities of the two or more geologic formations open to the well screens.

The first five TDM wells were cased with steel pipe and the second five TDM wells were cased with PVC pipe. All of these TDM wells were constructed with slotted pipe for well screen with no gravel pack. The fill or sediment observed in TV camera logs of these wells indicates that the slots were too coarse and that the geologic formations were not as well consolidated as they were thought to be.

C.2.4.2. Sampling

Water quality samples collected from the original TDM wells were of questionable value for a detailed hydrologic study. The problem of composite water samples has already been discussed. The effect of fill or sediment in the bottom of the wells was unknown but leaching of minerals from the fill was possible. The steel well casings rusted and contributed to the iron content of water samples.

Finally, the water sampling methods cast doubt on the water sample analyses. TDM's A and B had to be air lifted since the 2" casings were too small for any other method of sampling. Air lifting has the potential of oxidizing elements in the water sample and changing the water sample's chemical composition. The remaining eight TDM wells were sampled with a bailer made from a piece of steel pipe and a rope. The bailer and rope were not rinsed between wells and were usually dropped on the dirt beside the well after the sample was poured from the bailer. This introduced surface soils into the wells with unknown impact on water quality.

C.2.4.3. Analytical Technique

Prior to 1977 all water analyses were performed by a contract laboratory. Highland started in-house radiological assays for total uranium, radium-226, and thorium-230 in 1977; however, a Quality Assurance (Q.A.) program was not started until 1979. It was not until 1981 that an approved Q.A. program was finalized. With the Q.A. program, we can demonstrate the accuracy of our methods.

C.2.4.4. New Data Needed

An accurate assessment of the hydrologic and hydrogeochemical systems in the tailings basin area required a network of wells screened in single geologic formations. These single zone completion wells would provide accurate information to determine water levels, potentiometric maps and hydrogeochemical data for each geologic formation of interest. Also, these new wells could be pump tested by a portable submersible turbine pump to allow calculation of the permeability of the water bearing formations which were needed to calculate ground water velocities.

C.3. 1980-81 Field Program

C.3.1. Purpose of 1980-81 Field Program

The primary objective of the 1980-81 field program was to collect site-related field data required to characterize the tailings basin hydrology and related seepage. The program goals were to:

- o develop both regional and local field data required for modeling
- o obtain samples for laboratory testing
- o expand and modify the existing ground water monitoring system with its identified deficiencies.
- o expand knowledge of the geology detail in the tailings basin region.

To meet these goals, the following general activities were conducted:

- o drilled regional hydrology wells to determine potentiometric surfaces for each aquifer
- o drilled additional water quality monitor wells around the tailings basin to provide solute-transport information for each aquifer
- o ran pump tests and packer tests to determine hydrologic parameters of the various aquifers
- o made geophysical logs of the drill holes to provide detailed geology and correlations and insure hole completions in the proper aquifers
- o sampled soil types to determine chemical and hydrologic parameters
- o sampled tailings and tailings solutions to determine physical and chemical characteristics
- o coring to provide drill core samples for laboratory determination of hydrologic parameters and chemical testing
- o bulk field sampling of each geologic unit for laboratory determination of fluid-rock chemical interactions
- o established an adequate long term monitoring program

This extensive field program required field work in Fall 1980 and Summer 1981 to complete. We believe that the data collected during these two drilling programs satisfies the stated objectives of the field program and provides high quality input data for the laboratory and modeling studies.

C.3.2. Water Quality Monitor Wells

In 1980 and 1981, a well drilling and data collection program was completed to correct the deficiencies in the original TDM well network. These new wells provided the needed water level and permeability data and were designed with 5" casing to permit easy pumping with a standard 3-3/4" submersible pump for water quality samples.

C.3.2.1. TDM Well Location Rationale

The well drilling and data collection program concentrated on monitoring water bearing geologic formations downstream of the tailings dam and on the perimeter of the tailings impoundment. The locations of the new TDM wells are shown on Figure 22, main text. The wells were located in areas judged to be most likely for seepage to occur. Table C-1 summarizes the locations of the 1980 and 1981 tailings dam monitor wells.

C.3.2.2. Well Completion Specifications

TDM wells VI, VII, VIII and IX, X, XI, XII, XIX, XX, and XXI were designed and drilled in 1980 by a contractor geotechnical firm. Figures C-9 through C18 show the completion intervals of these wells. These wells have 5" PVC well screen with 0.02 inch slots and 5" PVC well casing. The gravel pack used was uniform grain size #10 silica sand with a particle size of approximately 1/10 inch. Bentonite pellets were placed above the gravel pack as a formation water seal. A cement and bentonite grout was then pumped behind the casing from the top of the bentonite seal to a minimum of 30 feet above the completion interval. The well casings were cut off 3-1/2 feet above the ground and an 8" steel pipe was set over the PVC casing and cemented into the ground to protect the PVC casing. All wells were set with vented, removeable PVC caps. Observation wells were similarly constructed with 2 inch casing. Four observation wells are at site VII and one is at site VIII. Figure C-33 diagrams the completion specifications of these wells.

TDM wells D (replacement), VI (replacement) XXX (replaces XX), XXIII, XXIV, XXV, XXVI, XXVII, XXVIII and XXIX were designed and drilled in 1981 by Exxon. Figures C-19 through C-28 show the completion intervals in these wells. All of these wells except XXIV, XXVI, XXVII, RM-3 and RM-4 have 5" PVC well screen with 0.02 inch slots adapted to 4-1/2 inch fiberglass well casing. The other wells have 5" PVC well casing. The gravel packs used in the 1981 field program were the same as that used in the TDM wells drilled in 1980. The bentonite

seal and grout used along with the above ground well protection were similar to that used in the prior year. Observation wells with 2 inch casing were installed at VI, XXIII, XXIV, XXVII, XXVIII, and XXIX. Figure C-34 diagrams the completion specifications of these 5 inch and 2 inch wells.

To complete the 1981 field drilling program, four regional monitor (RM) wells were installed to determine regional groundwater gradients in the Highland Operations area. These wells were completed in the Tailings Dam Sandstone, and this data was used in the seepage study. Figures C-28 through C-32 show the completed intervals for these wells.

C.3.3. Regional Hydrologic Data

In order to model ground water flow in the tailings basin, the formation permeabilities, recharge and discharge areas had to be determined.

C.3.3.1. Permeabilities

Five of the holes drilled for TDM wells had packer tests run on the bore hole before screen and casing were installed. These packer tests provided a good general idea of geologic formation permeabilities and are summarized in Table C-3.

In addition to the packer tests, rock cores taken from holes drilled for TDM wells were sent to testing laboratories to measure formation permeabilities under controlled conditions. These data are in Chapter 6, Flow Modeling.

Finally, in-place, long-term formation permeabilities were measured by pumping tests run in the TDM and RM wells. The pumping tests in the water bearing formations resulted in calculated permeabilities of 2 darcies or about 36.4 gallons per day per square foot. The other permeability measurements generally agreed with the pumping test permeabilities. No pumping test was possible in the Tailings Dam Shale. A relatively high and conservative permeability of 0.0001 darcies or about 0.0018 gallons per day per square foot was selected from core permeability data. The pump test results are summarized in Chapter 6, Flow Modeling.

C.3.3.2. Recharge/Discharge Areas

Intensive geologic mapping and drill hole log data established the outcrop area of the geologic formations important to this study. The formations outcrop very close to the downstream side of the tailings dam as shown in Figures 40 through 51, main text. This outcrop area is the regional discharge area for the Highland ore sandstones and the Tailings Dam Sandstone.

The recharge area for the same geologic formations was determined to be the topographic high west of the mining area and known as Blizzard Heights. This determination was based on site experience and accepted ground water flow system theory along with work by Dames & Moore (1980) and Haigmaier (1971).

Flow net analysis based on the above information indicates quantities, flow directions and water levels consistent with actual water levels measured in the field. This flow net is depicted in Figure 12.

C.3.4. Other Sampling

A major part of the field program centered around the water quality and regional hydrology sampling discussed in Section C.3.1. and C.3.2. In addition, information on the soils, tailings, drill cores, drill cuttings, geologic drill hole logs, geophysical drill hole logs, and bulk samples of each rock unit were collected as input for the seepage study laboratory and modelling work.

C.3.4.1. Soils and Soil Tests

The subsurface soil, embankment, tailings and ground water conditions in the area of the tailings basin were explored during two investigations by Dames & Moore in 1970 and 1977. The 1977 investigation consisted of drilling two exploration borings, three survey borings, and three field permeability borings. The borings were drilled to depths ranging from 4 to 11 feet. Fourteen test pits were also excavated to depths ranging from 4 to 11 feet. The borings and test pits were located from 1000 feet south to 3000 feet north of the tailings dam (Dames & Moore, 1977).

Six single packer permeability tests were run in these borings to determine near-surface soil permeabilities. These data have been used in the flow modeling.

Soil samples from these borings and test pits were analyzed in the laboratory for soil type, moisture, density, liquid limit, plasticity limit, compaction, and permeability. These results are tabulated in the Dames & Moore studies and were used in the seepage study.

C.3.4.2. Tailings Samples

Two borings in the tailings basin, Q-1 and R-1, were drilled to provide samples of tailings and tailings fluid at various depths. The locations are shown in Figure 22 of the text. A total of 37 undisturbed tailings samples from 2 feet to 86.5 feet in depth were collected. Table C-4 lists the samples and depths. Additionally, tailings were obtained from the mill discharge pipe for laboratory permeameter testing. The samples are referenced in Chapter 6 of the report.

C.3.4.3. Core Samples

During the 1980 drill program, 366.1 feet were sampled with 3 inch cores for laboratory permeability tests and geologic logging. These cored intervals are summarized below:

Monitor Well Number	Footage Cored	Total Depth
VI	65.6	85.6
VII-2	58	78
VIII	71	130
X	41.4	101.4
XII	51.9	150.6
XX	78.2	235
	366.1	780.6

These cored intervals of the total drill hole were selected to provide samples in all shale and sandstone units. The cores were stored in plastic bags and sealed steel cans. Table C5 lists the core sample data. The laboratory data from these cores are contained in Chapter 6, Flow Modeling.

C.3.4.4. Cuttings

Samples of drill cuttings were collected from all drilled monitor and observation wells. Samples were taken for every 5 foot interval and stored in plastic bags. These samples were used principally for geologic logging and sample description to correlate with geophysical drill logs. The grab samples also provided a physical record of the geology which will be retained until completion of the seepage analysis. These cutting intervals are detailed in Table C-6.

C.3.4.5. Geologic Drill Hole Logs

Based on the sampled cuttings, geologic drill hole logs at a scale of 1 inch = 2.5 feet for each monitor and observation well were prepared to include rock type, sample color, texture, and grain size. For cored intervals, similar logs were made to include hardness and structure. These logs were used with the geophysical drill hole logs to correlate rock units from hole to hole and to select proper completion intervals.

C.3.4.6. Geophysical Drill Hole Logs

A Century Compu-Logger logging tool was used to log drill holes in the immediate vicinity of all the monitor wells. The Century logs provide a high quality record which were used to correlate stratigraphy throughout the tailings basin area, to tie the geology back into the detailed mine geology to the west, to make proper geologic unit picks, and to insure well completions in the desired geologic units. The Century Geophysical logging records provided the basic geology framework that was needed for the Geologic Modeling described in Chapter 5.

C.3.4.7. Bulk Samples of Geologic Units

Bulk samples of the geologic units were needed for the fluid-rock interaction chemistry analyses. Tailings Dam Sand and Tailings Dam Shale samples were collected in March, 1981, in the Pit 4 area during the stripping of these rocks from off of the underlying ore sands. Samples of Ore Body Sands and Ore Body Shales were collected in March, 1981, in the Pit 3 mining area. These samples have been used in the Laboratory Program discussed in Chapter 4.

C.3.5. Field Program Summary

From the initial seepage monitoring of the tailings basin area in 1972, the scope of the program has been significantly expanded and improved. This has resulted in improved understanding of the tailings basin hydrology, and additional data with which to quantitatively characterize and model ground water solute transport.

The current monitor system provides high quality water chemistry data from each aquifer. The sampling program was upgraded in 1977 as discussed in section C.2.3. Since completion of the 1980 and 1981 monitor well network, an expanded sampling program was started and will continue. Analytical techniques have been improved and our laboratory is now participating in an approved quality assurance program.

Collection of water quality information from around the Highland Uranium Operation tailings basin will be continued and will provide additional data to more fully characterize area hydrology.

REFERENCES

Dames & Moore, 1979; "Report of Tailings Dam Study, Highland Uranium Mine near Casper, Wyoming, for Humble Oil & Refining Company".

Humble Oil & Refining Company, 1971; "Applicant's Environmental Report, Highland Uranium Mill, Converse County, Wyoming".

U.S. Atomic Energy Commission, 1973; "Final Environmental Statement Related to Operation of the Highland Uranium Mill by the Exxon Company, U.S.A. (Formerly Humble Oil & Refining Company) Docket No. 40-8102".

Exxon Company, U.S.A., 1977; "Applicant's Response to NRC Questions, Modifications to Tailings Dam Centerline Design, Amendment to Source Material License, SUA 1139, Docket No. 40-8102".

Dames and Moore, 1977; Proposal for Phase I Detailed Site Selection, Future Tailings Pond, for Exxon Company, U.S.A.

Dames and Moore, 1980; Hydrologic evaluation, Pit 5 Lake Reclamation, Highland Uranium Mine, Converse County, Wyoming, for Exxon Minerals Company.

Hagmaier, J.L., 1971; Groundwater flow, hydrogeochemistry, and uranium deposition in the Powder River Basin, Wyoming, Univ. of North Dakota Ph.D. dissertation.

FIGURE C-1

TDM WELL NUMBER E

6-25-72

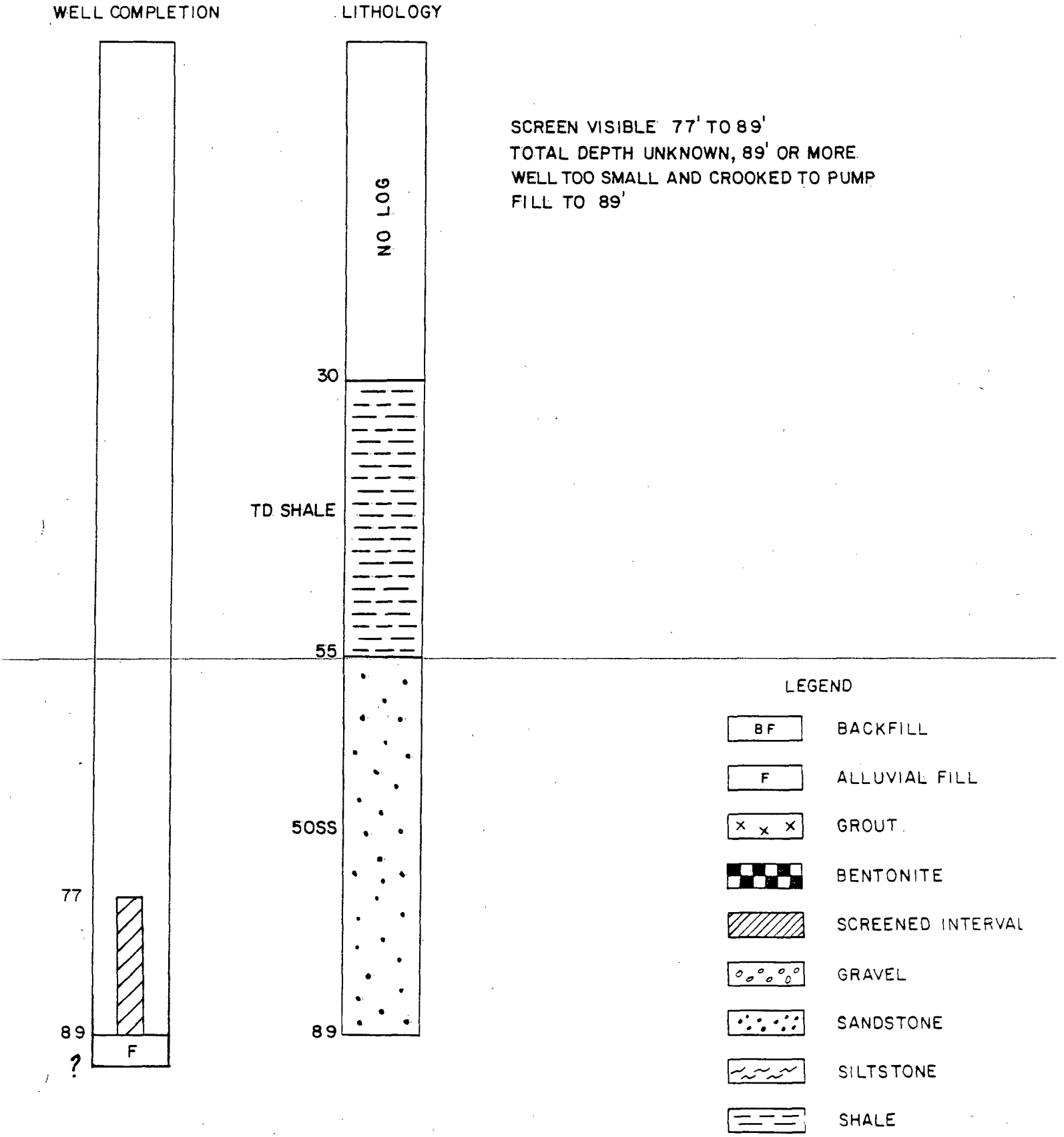


FIGURE C-2

TDM WELL NUMBER D

12-6-74

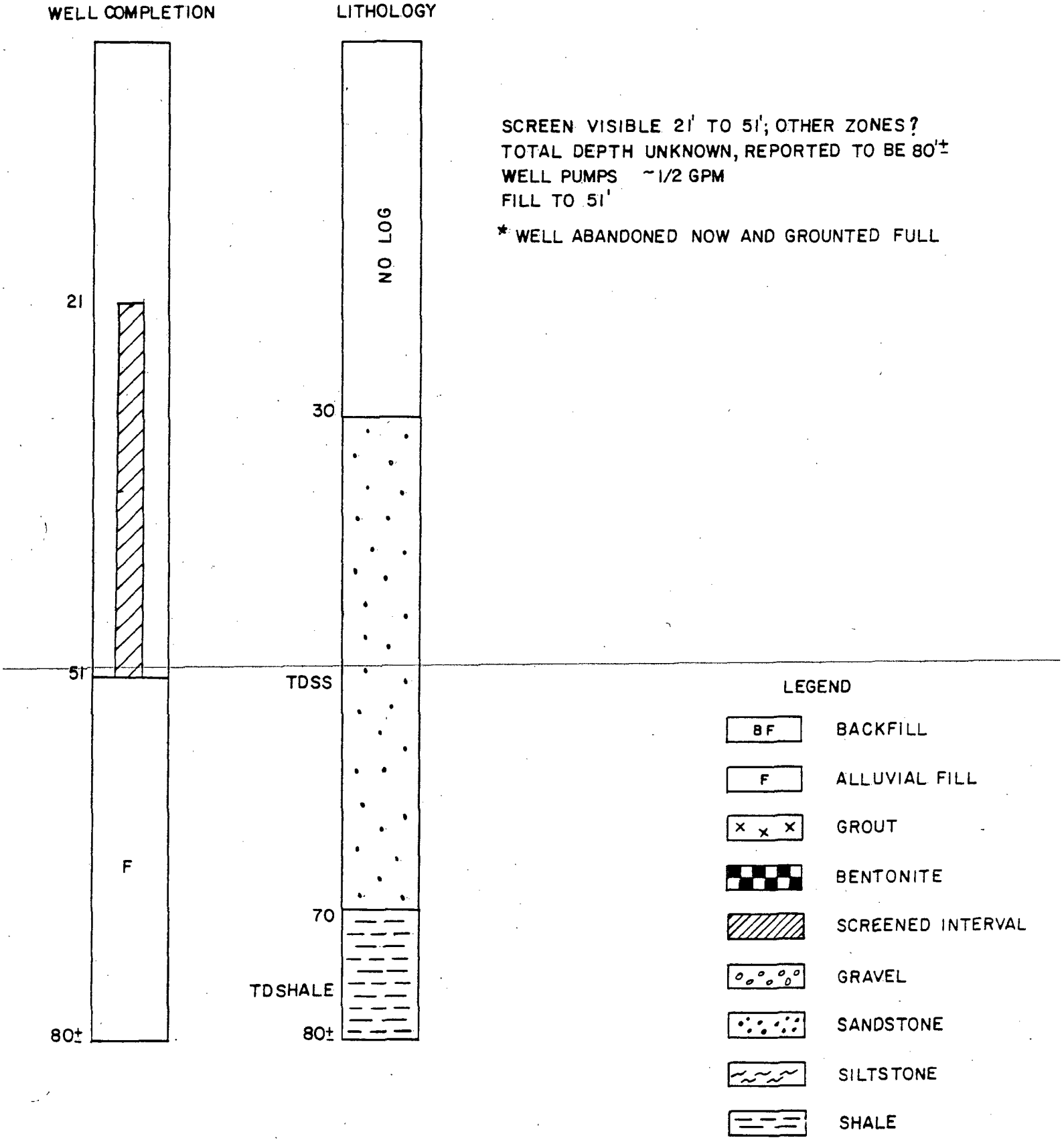


FIGURE C-3

TDM WELL NUMBER C

12-15-74

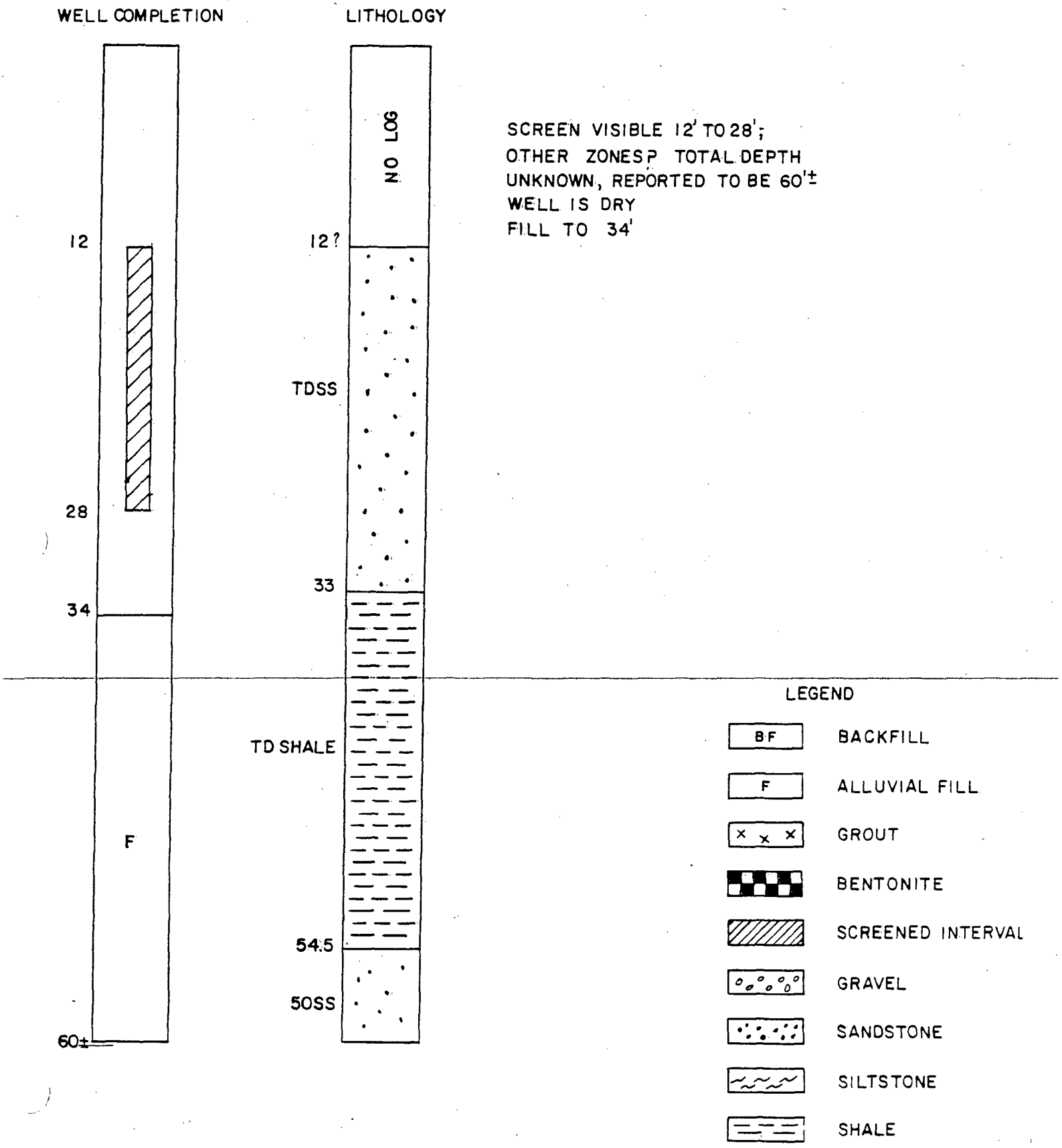


FIGURE C-4

TDM WELL NUMBER I

9-3-77

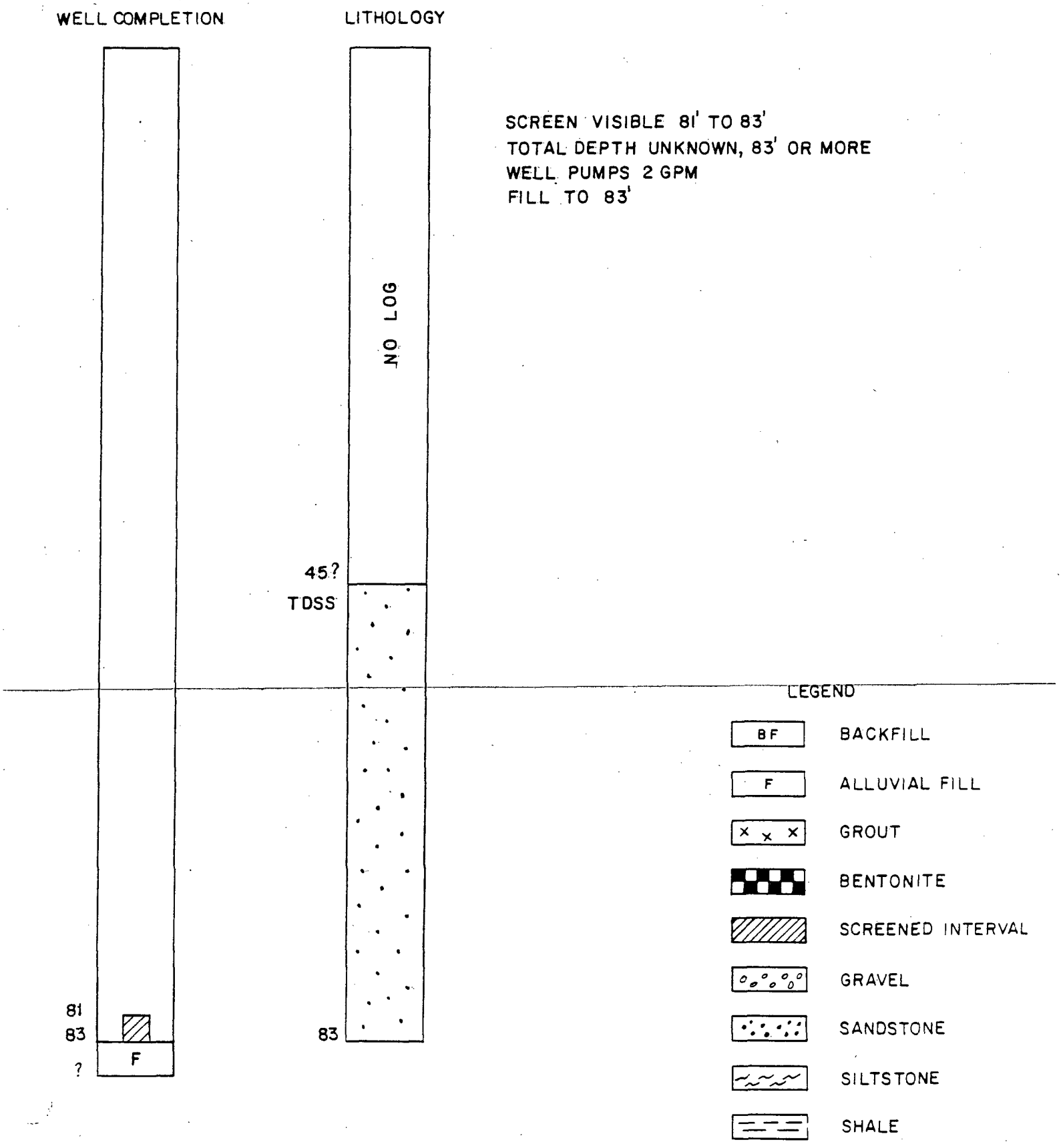


FIGURE C-5

TDM WELL NUMBER II

9-3-77

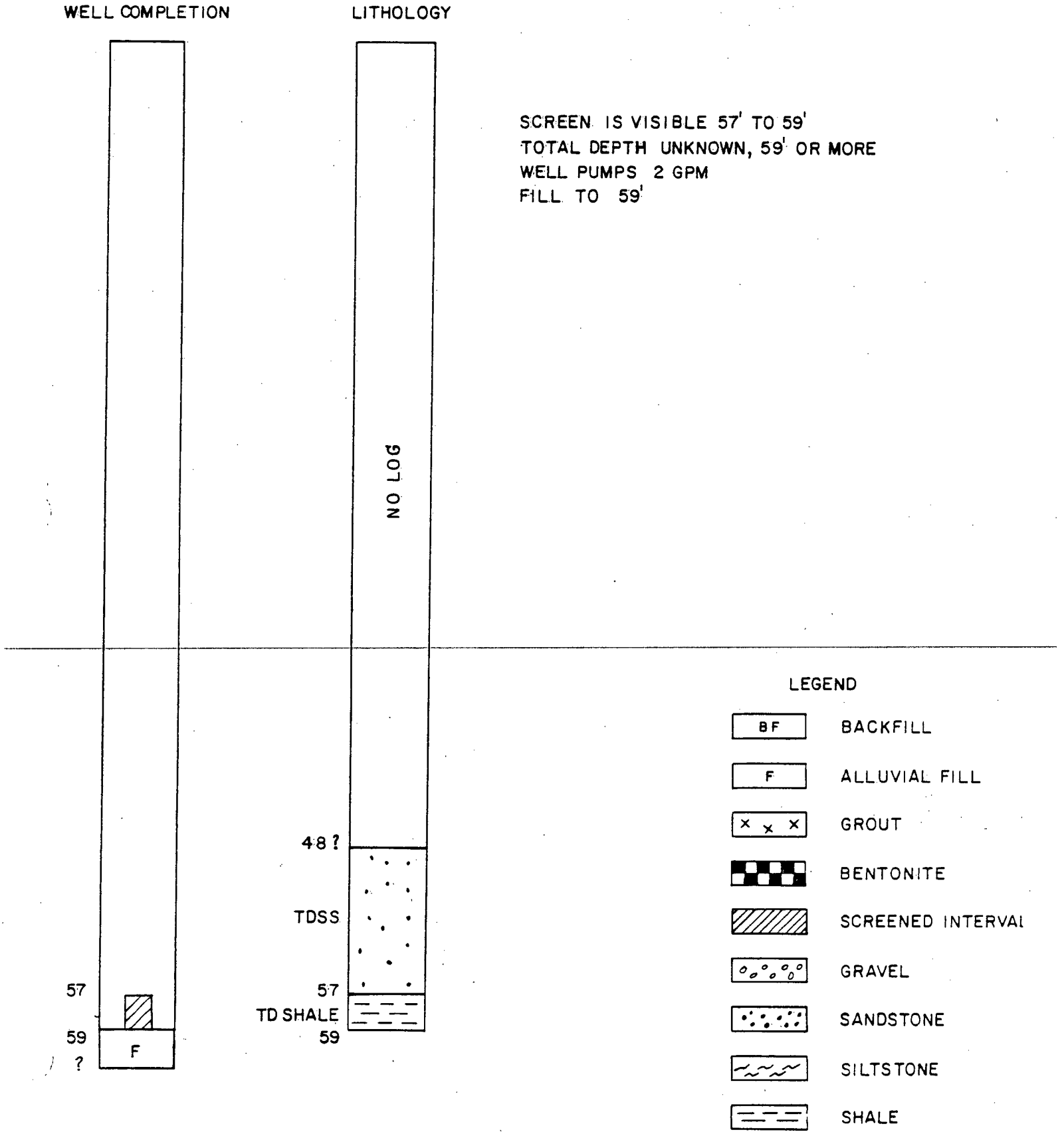


FIGURE C-6

TDM WELL NUMBER III

9-3-77

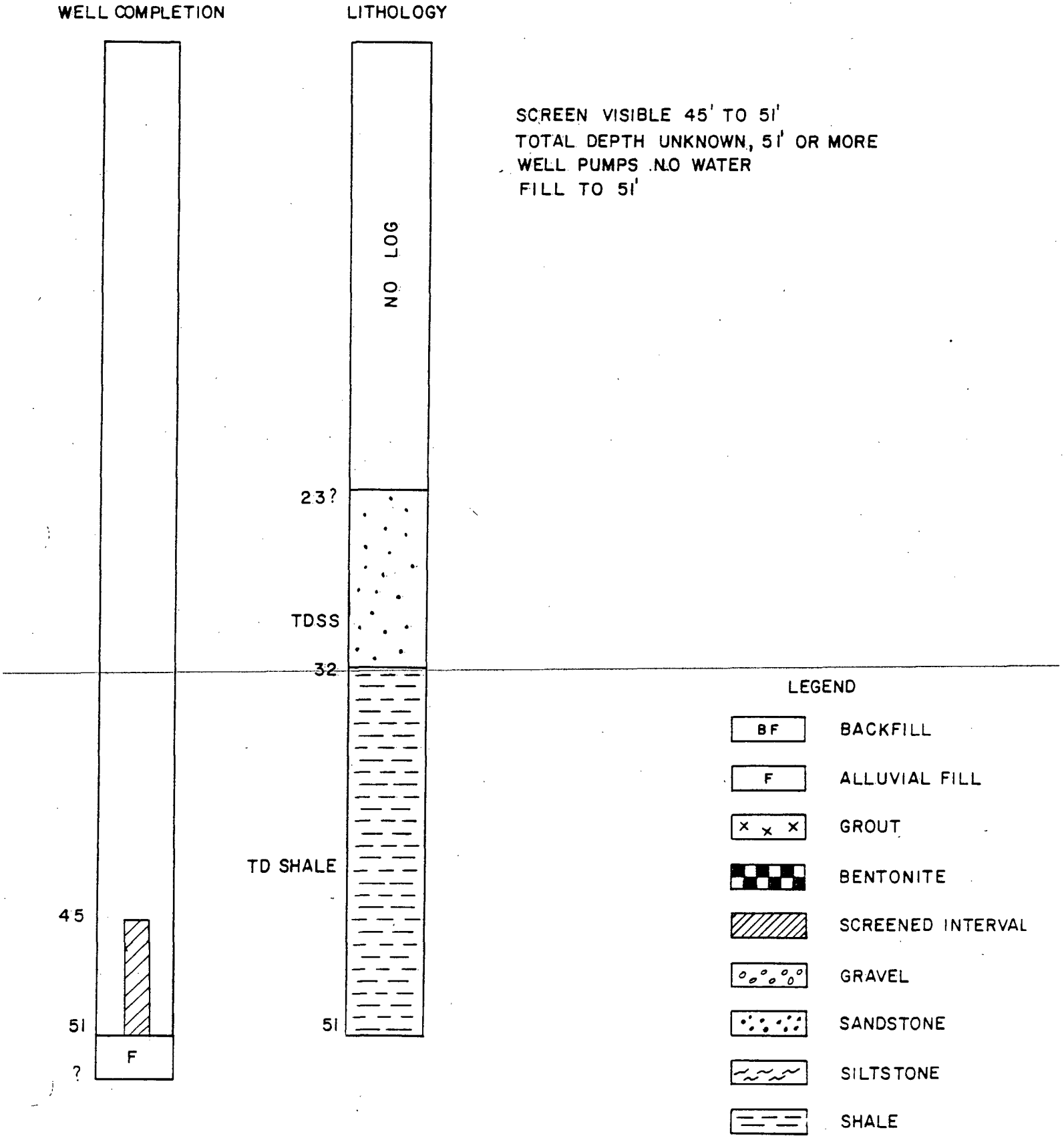


FIGURE C-7

TDM WELL NUMBER IV

9-3-77

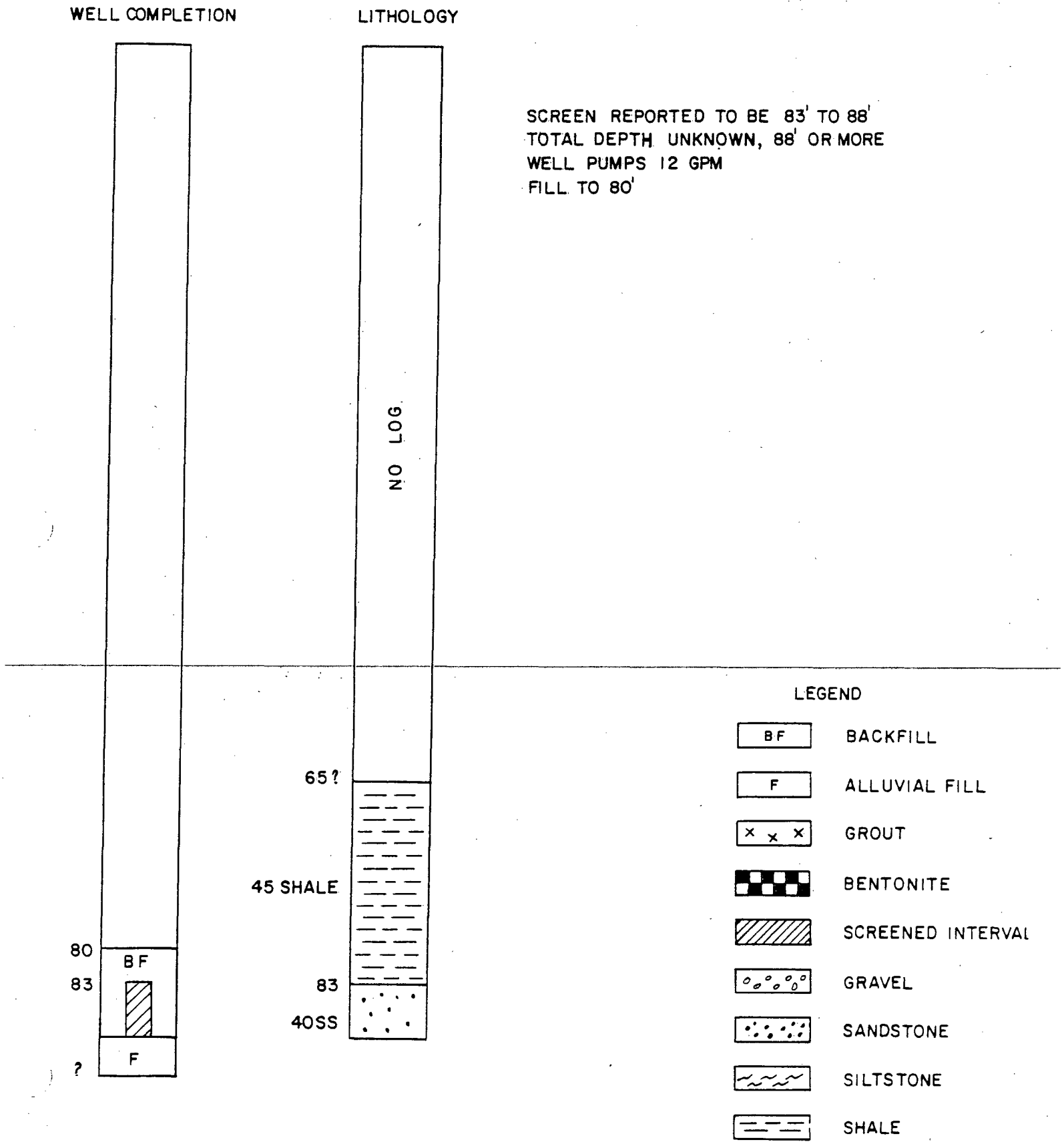


FIGURE C-8

TDM WELL NUMBER V

9-3-77

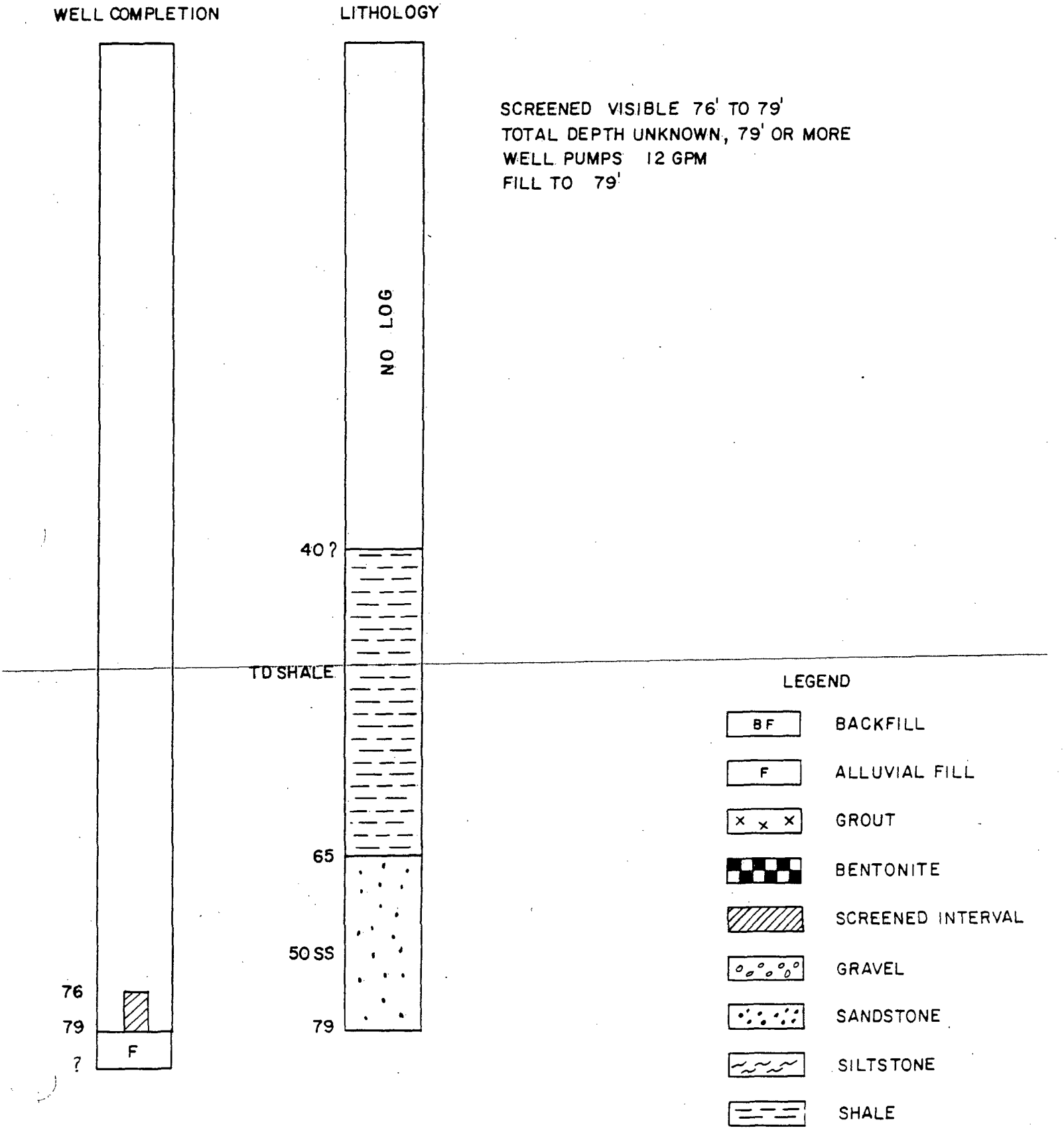


FIGURE C-9

TDM WELL NUMBER VI

9-18-80

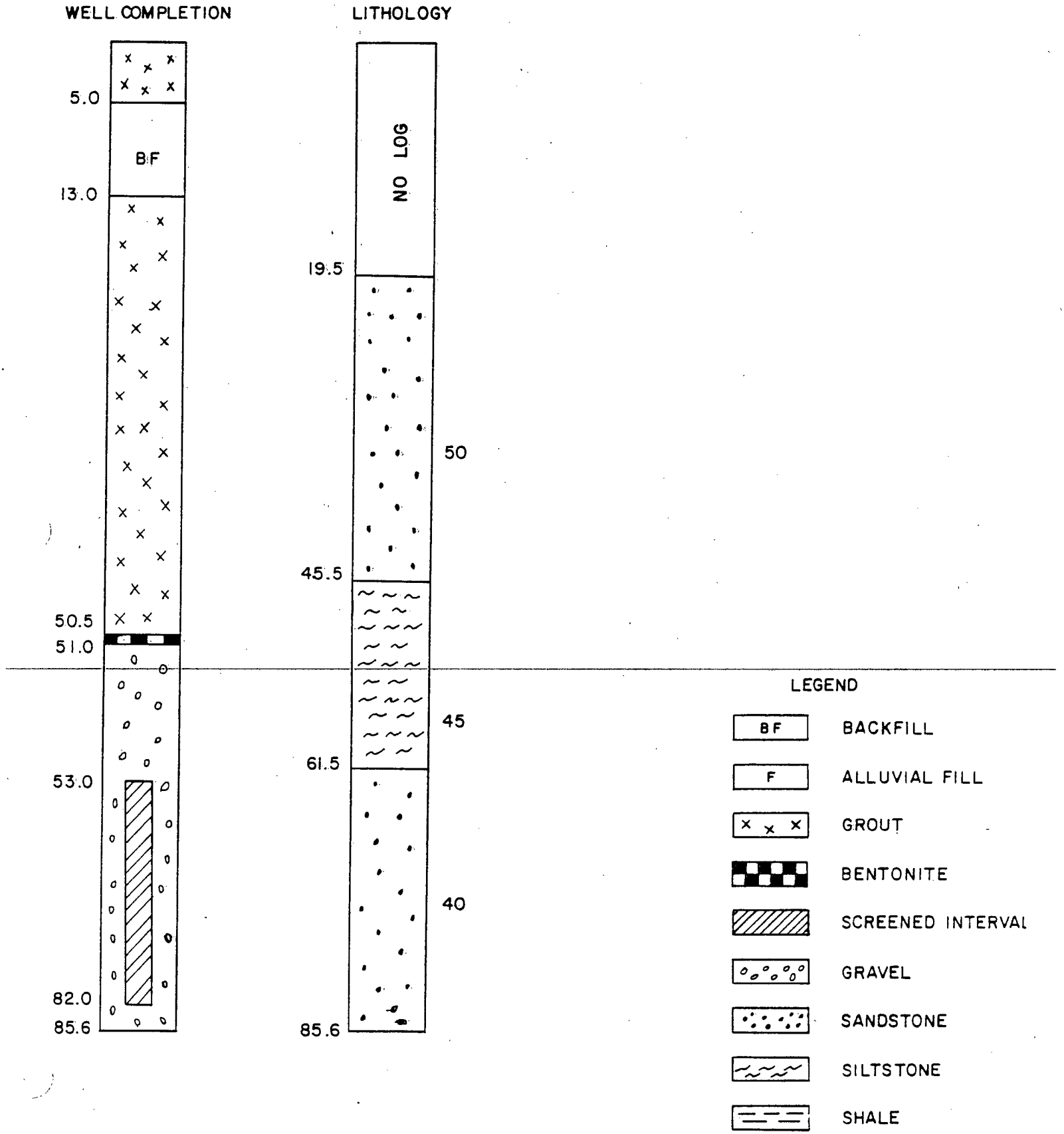


FIGURE C-10

TDM WELL NUMBER VII

10-22-80

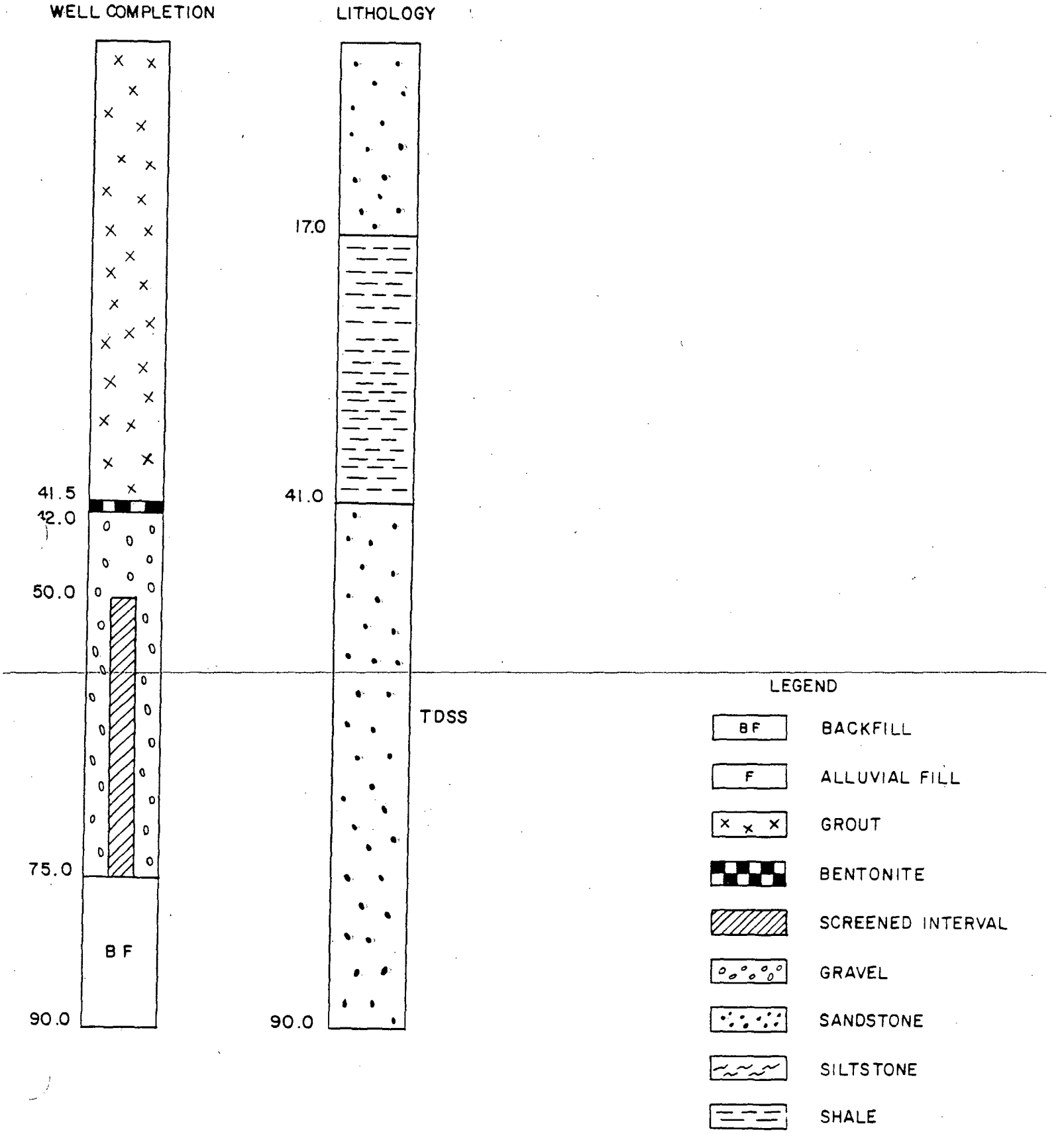


FIGURE C-11

TDM WELL NUMBER VIII

9-23-80

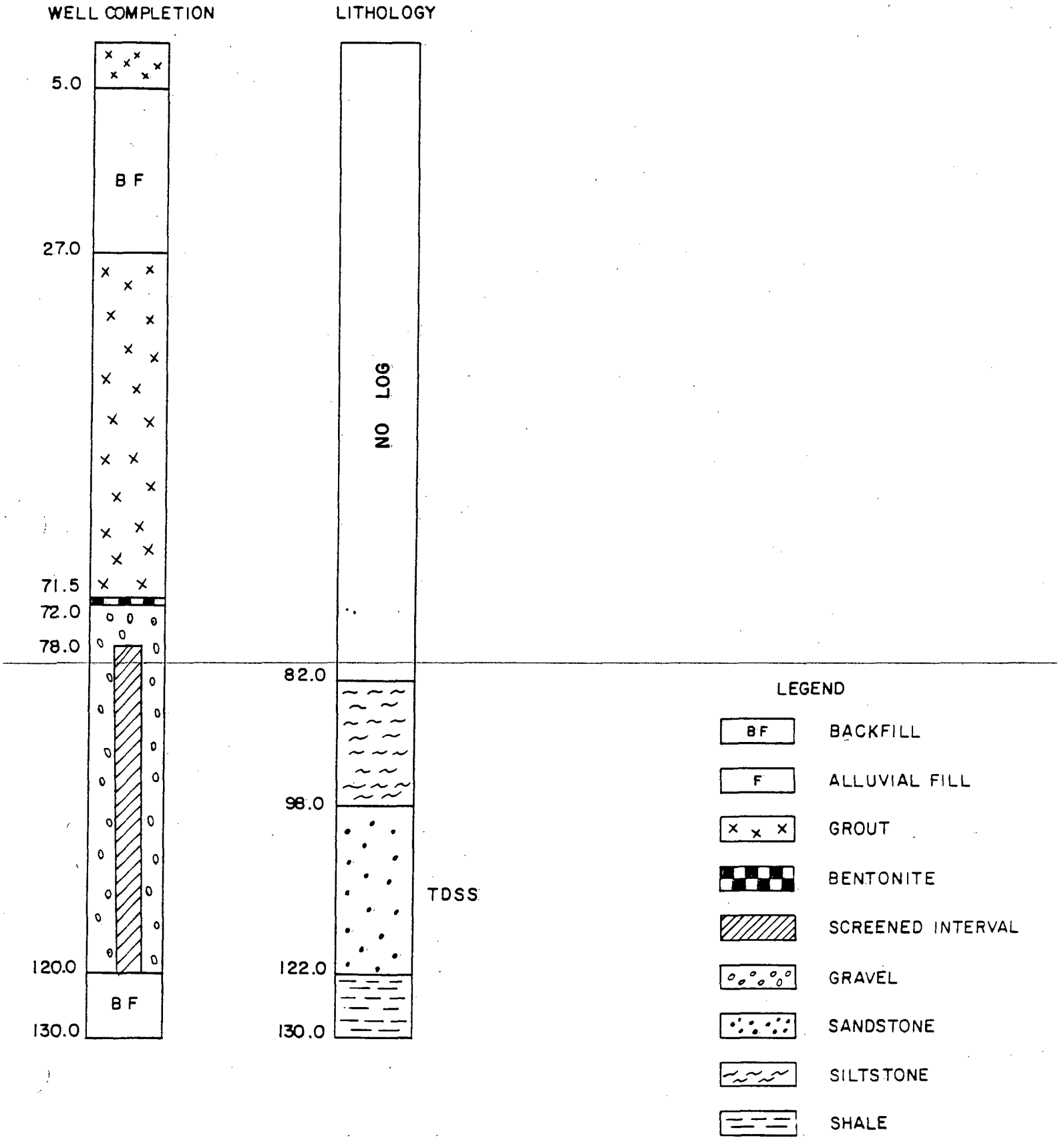


FIGURE C-12

TDM WELL NUMBER IX

10-27-80

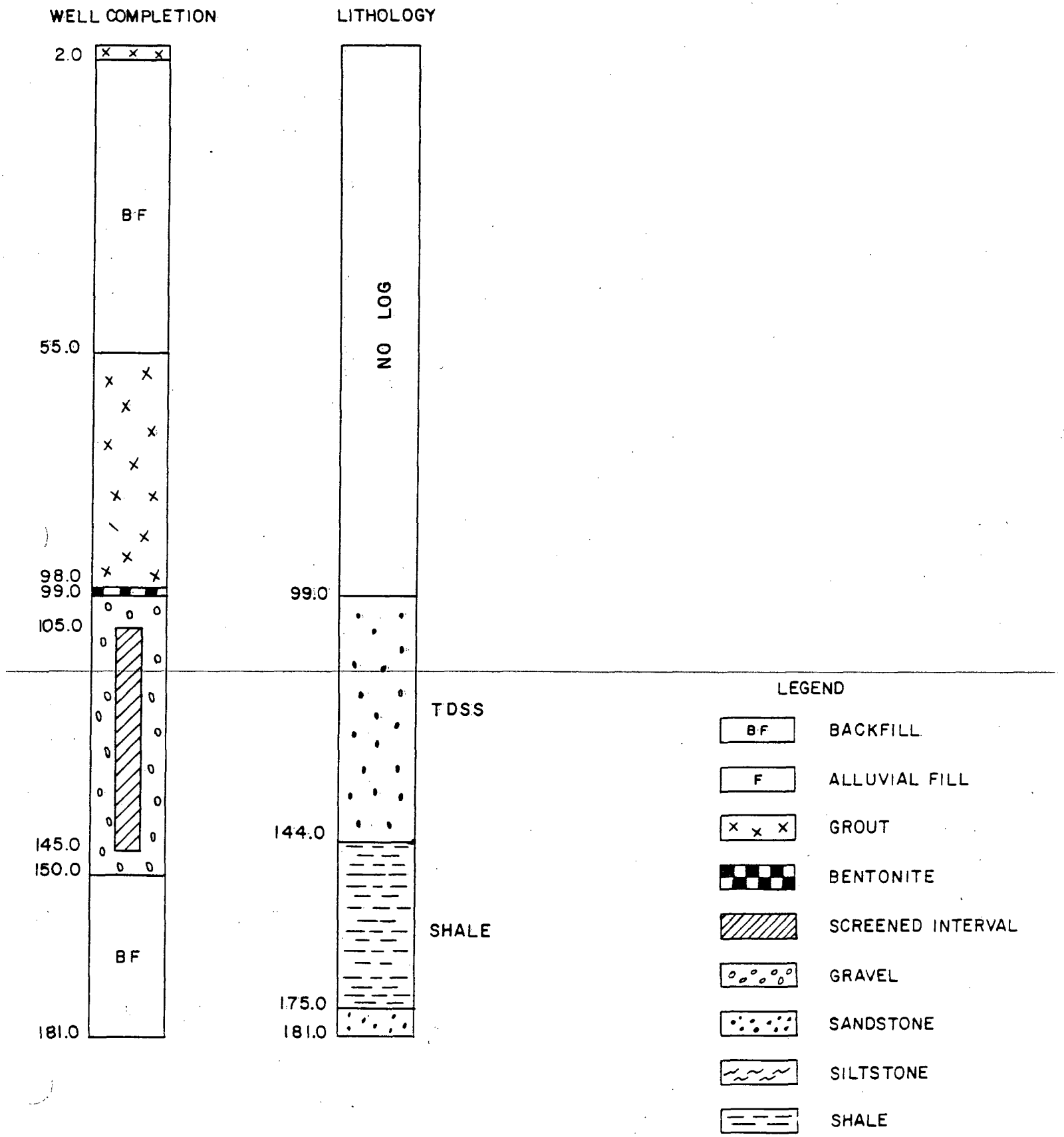


FIGURE C-13

TDM WELL NUMBER X

10-3-80

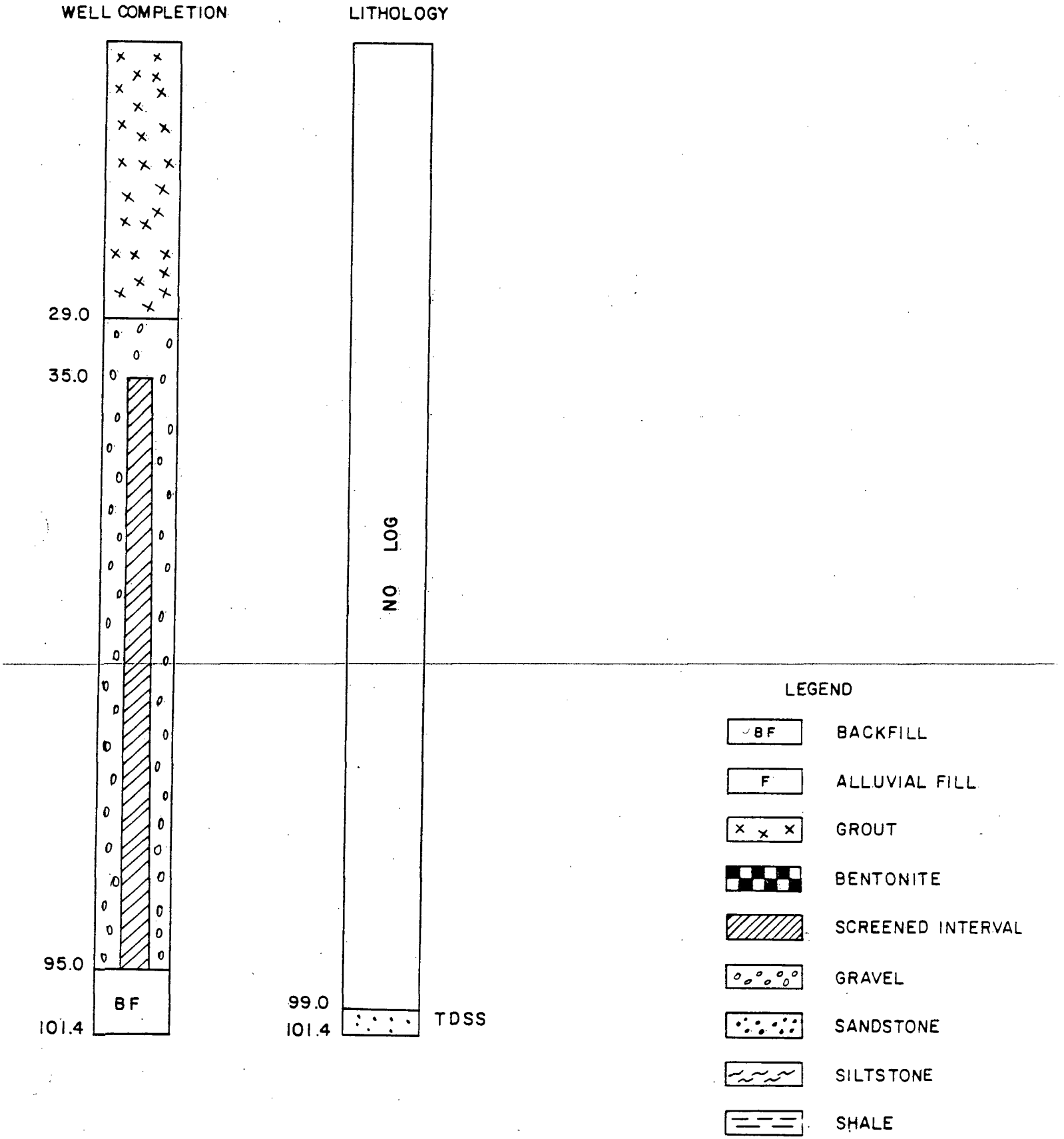


FIGURE C-14

TDM WELL NUMBER XI

10-29-80

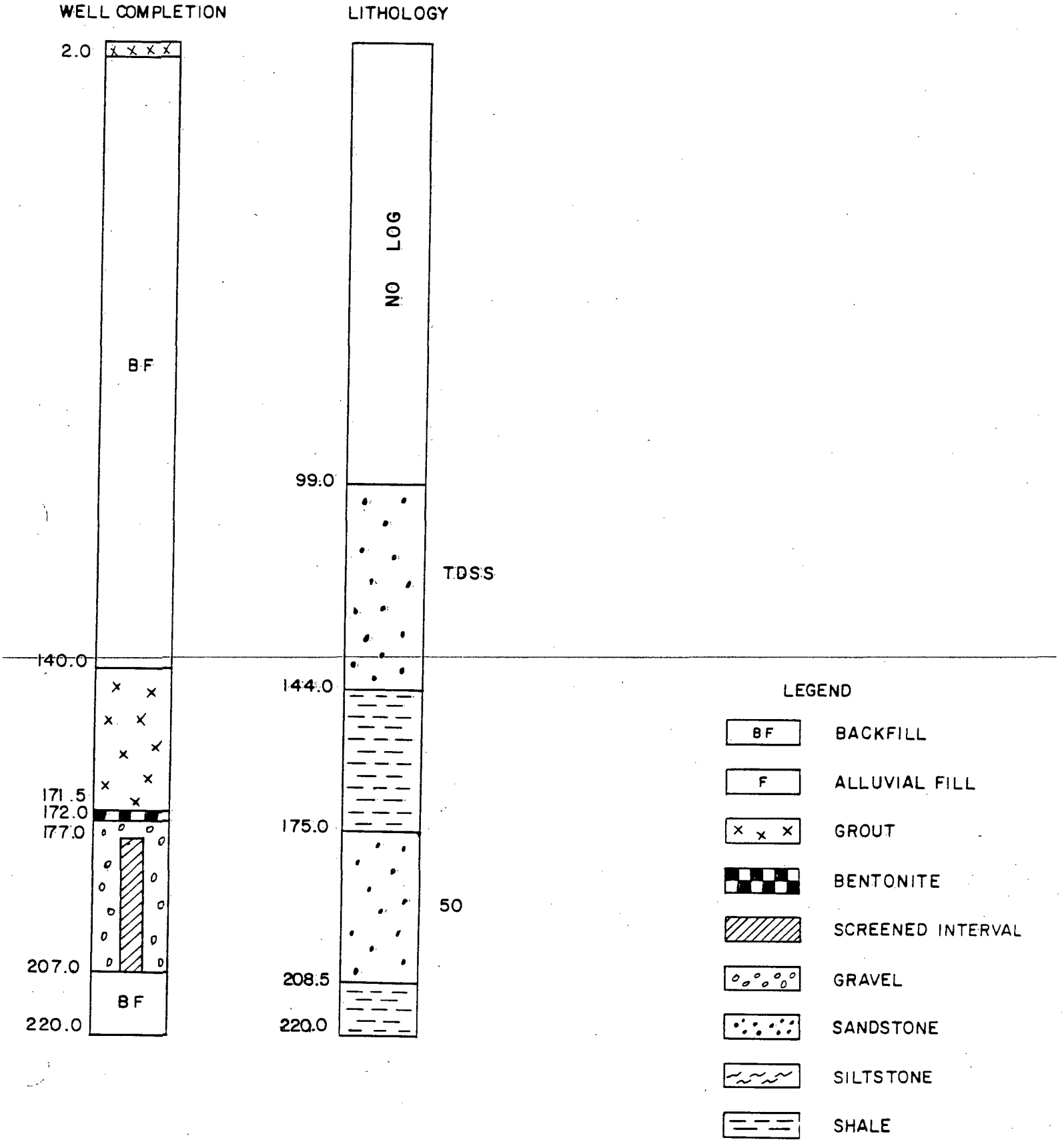


FIGURE C-15
TDM WELL NUMBER XII

9-29-80

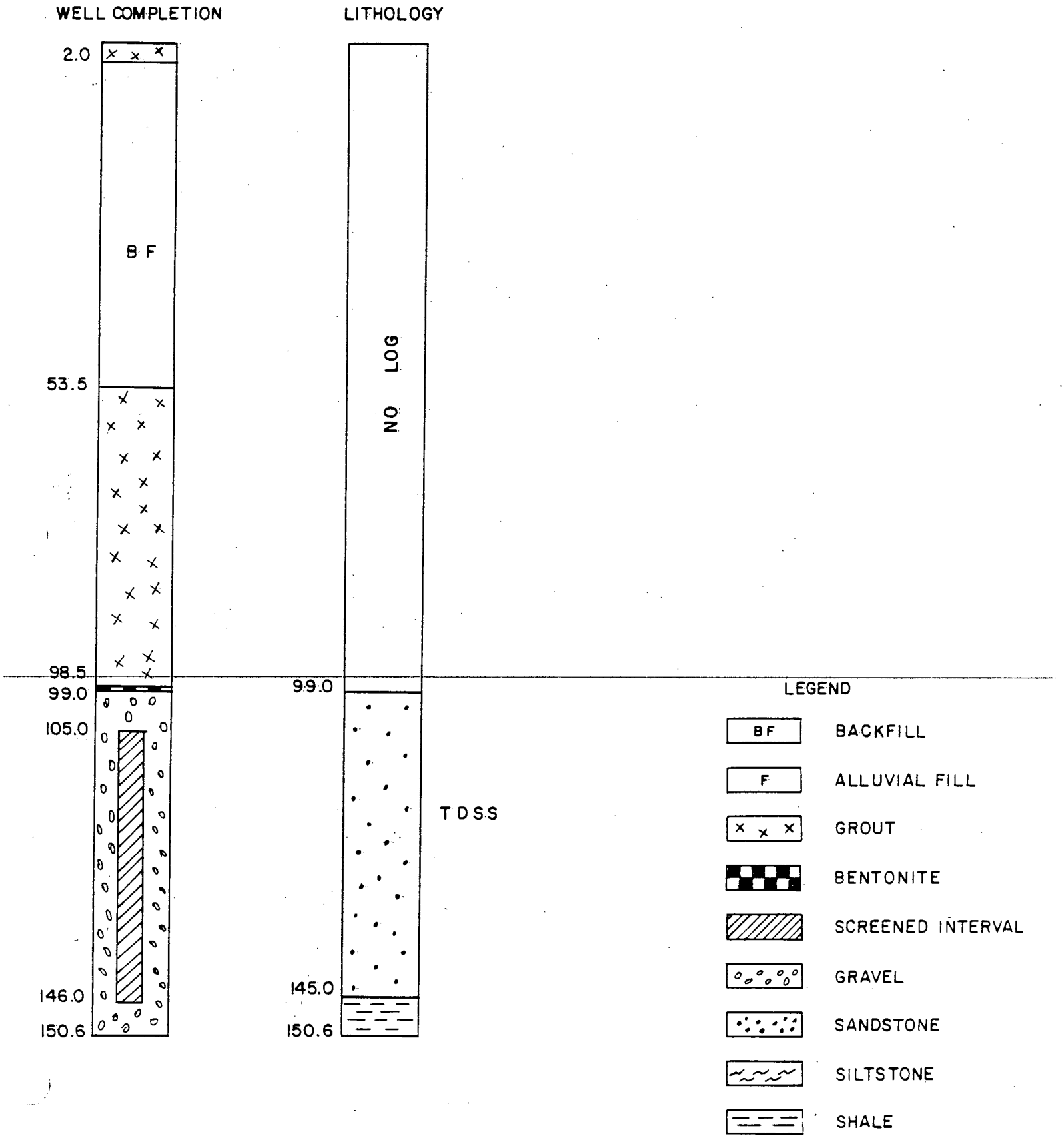


FIGURE C-16

TDM WELL NUMBER XIX

10-15-80

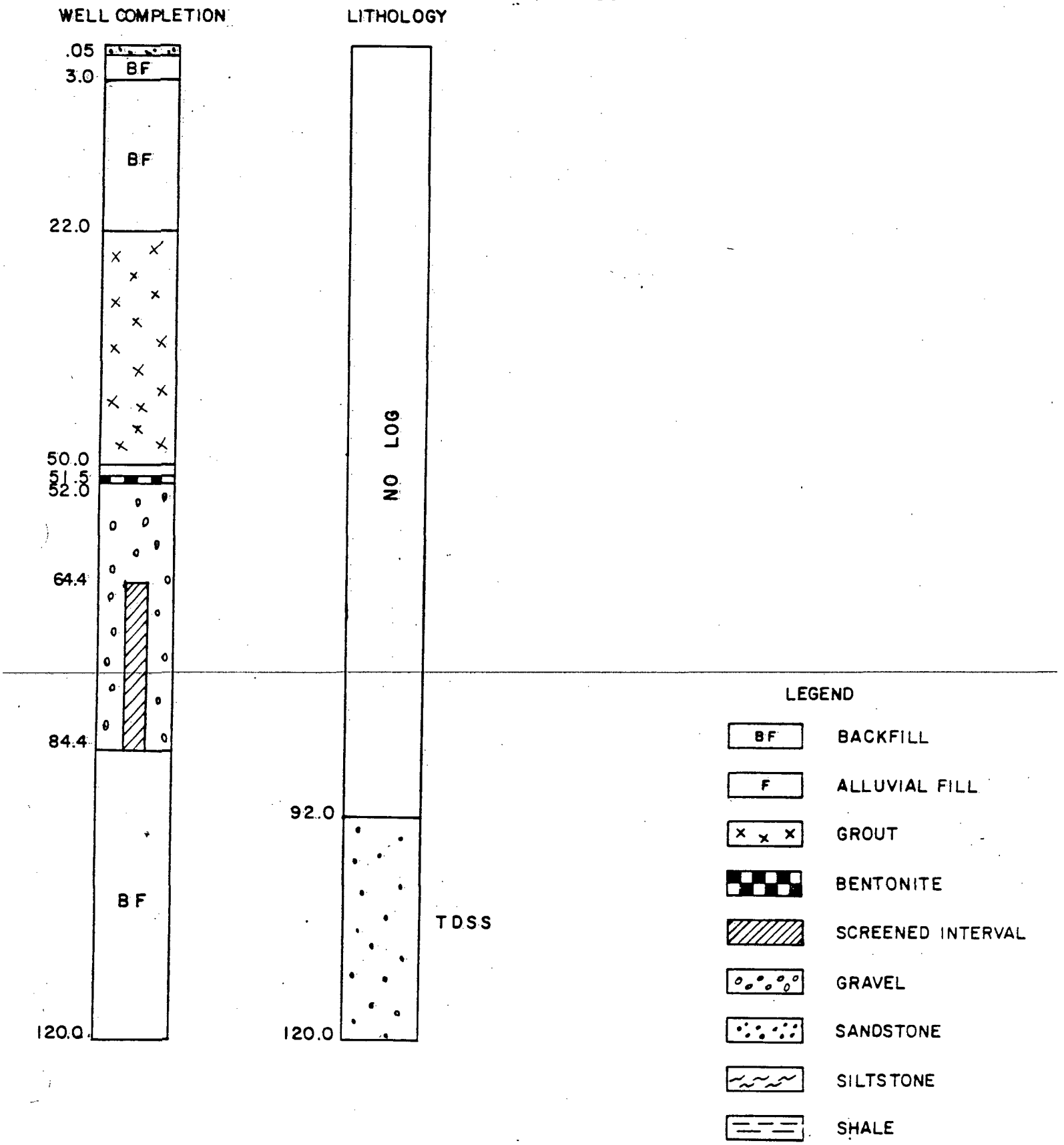


FIGURE C-17

TDM WELL NUMBER XX

10-8-80

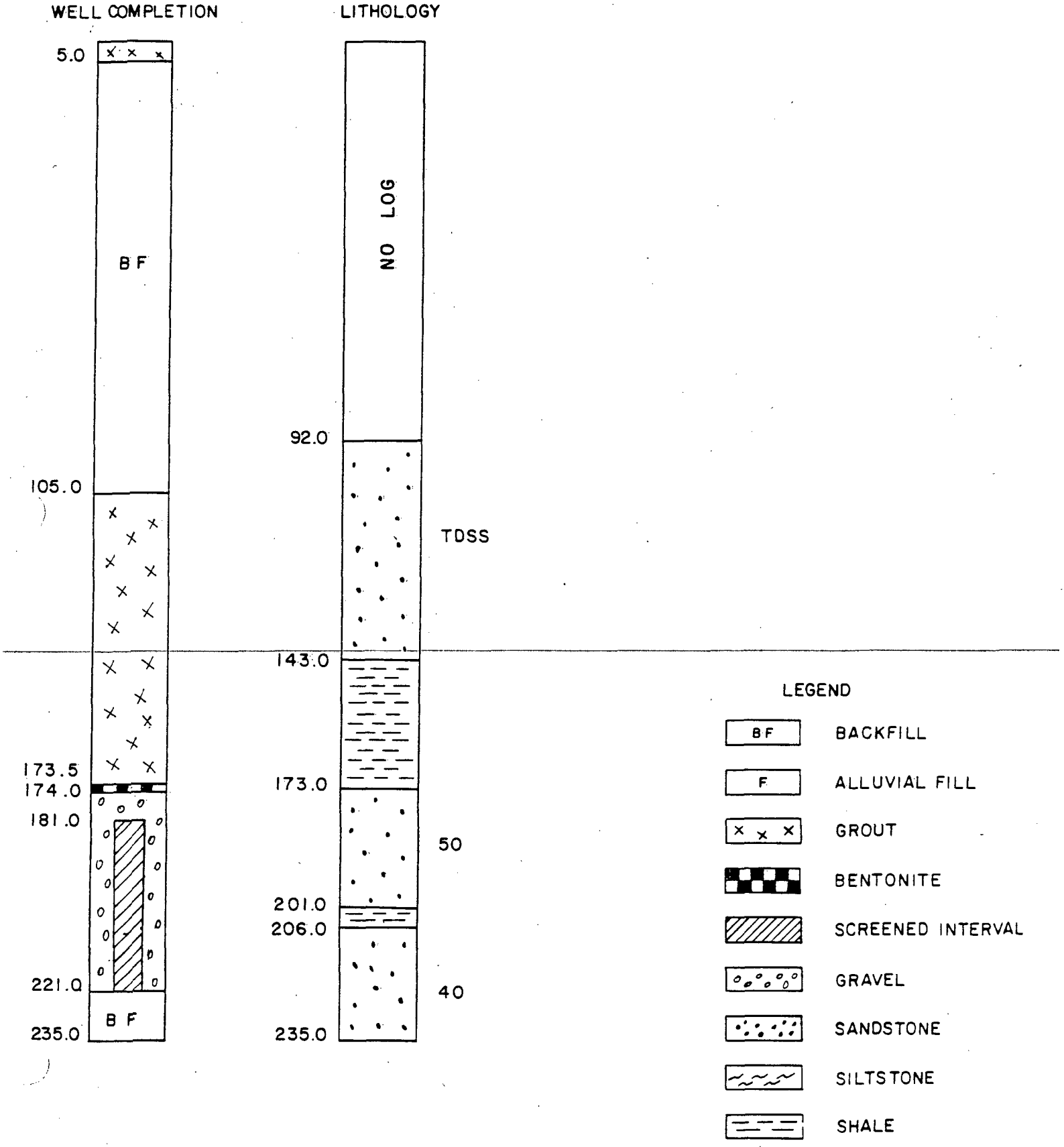


FIGURE C-18

TDM WELL NUMBER XXI

10-14-80

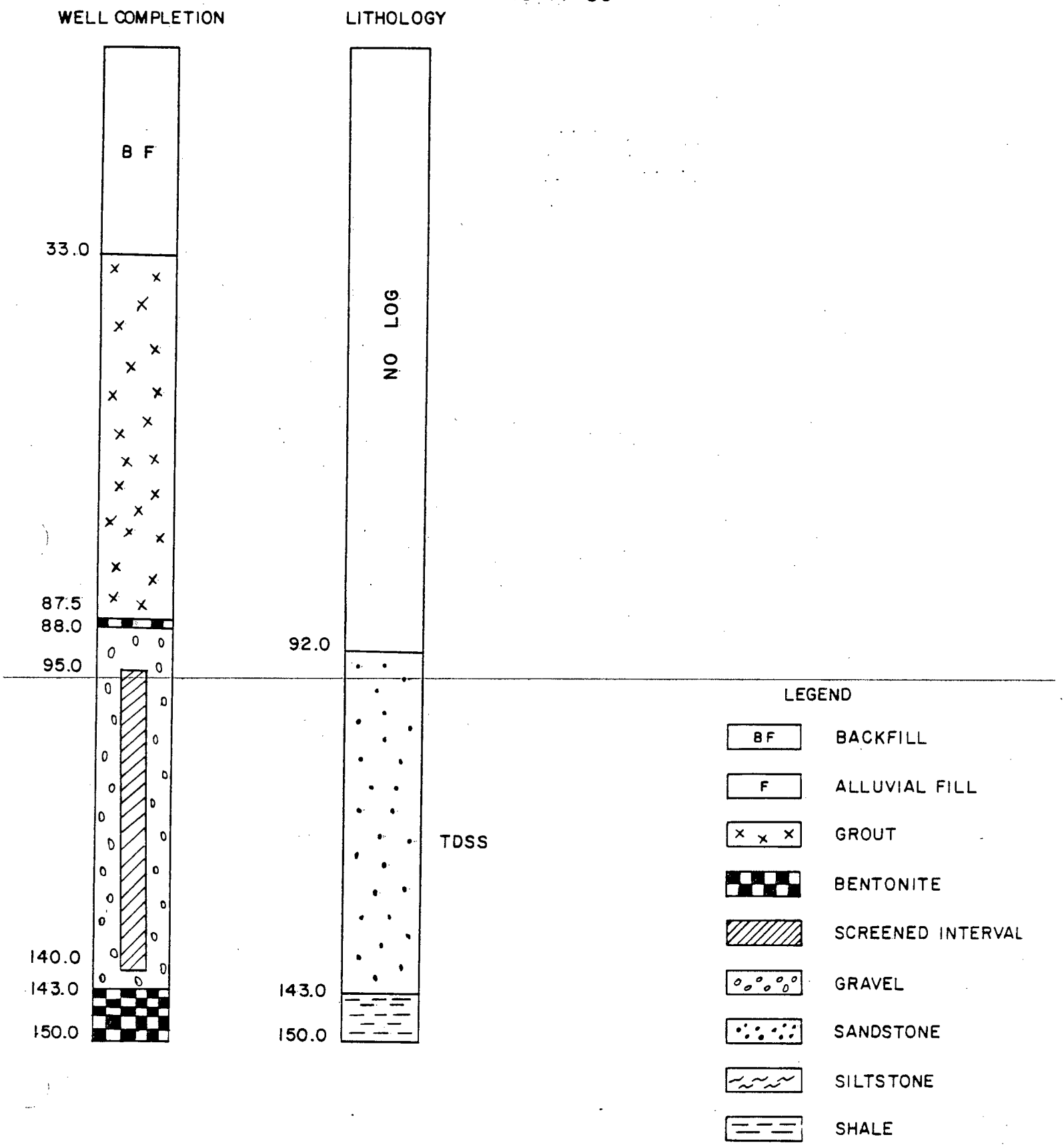
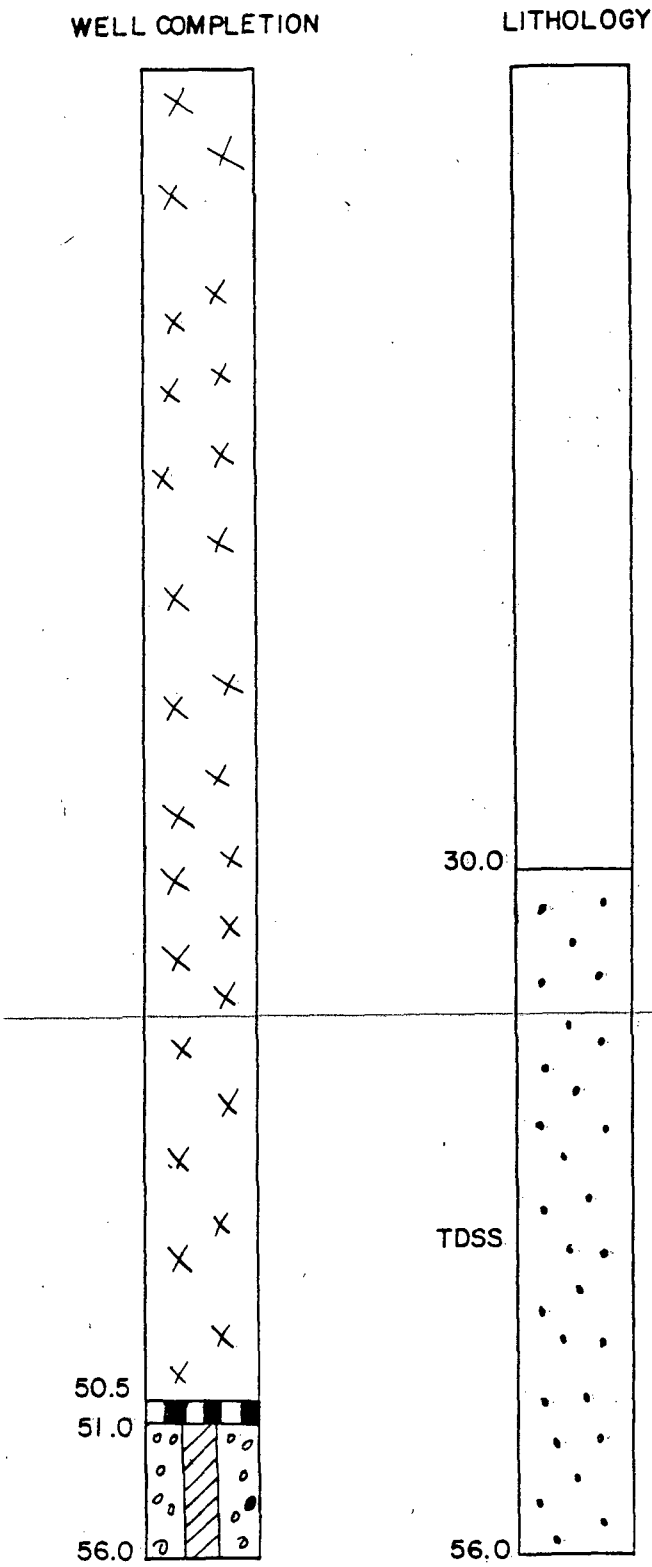


FIGURE C-19

TDM WELL NUMBER D REPLACEMENT

8-18-81



SCREEN INSTALLED AND GRAVEL PACKED 51' TO 56'
TOTAL DEPTH IS 56'
WELL PUMPS 12 GPM
NO FILL

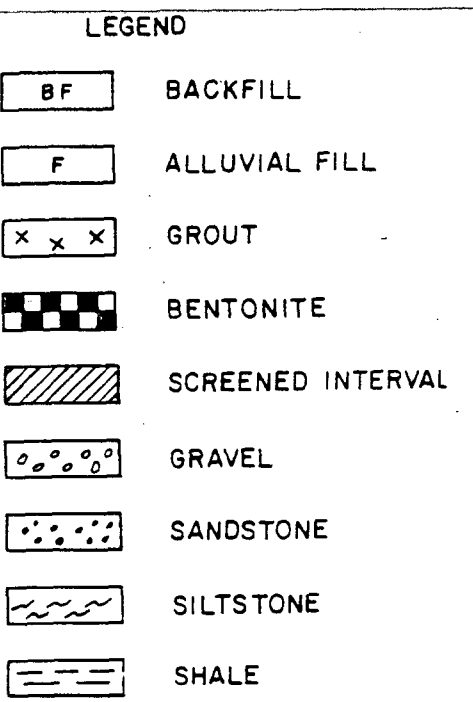


FIGURE G-20

TDM WELL NUMBER VI REPLACEMENT

8-10-81

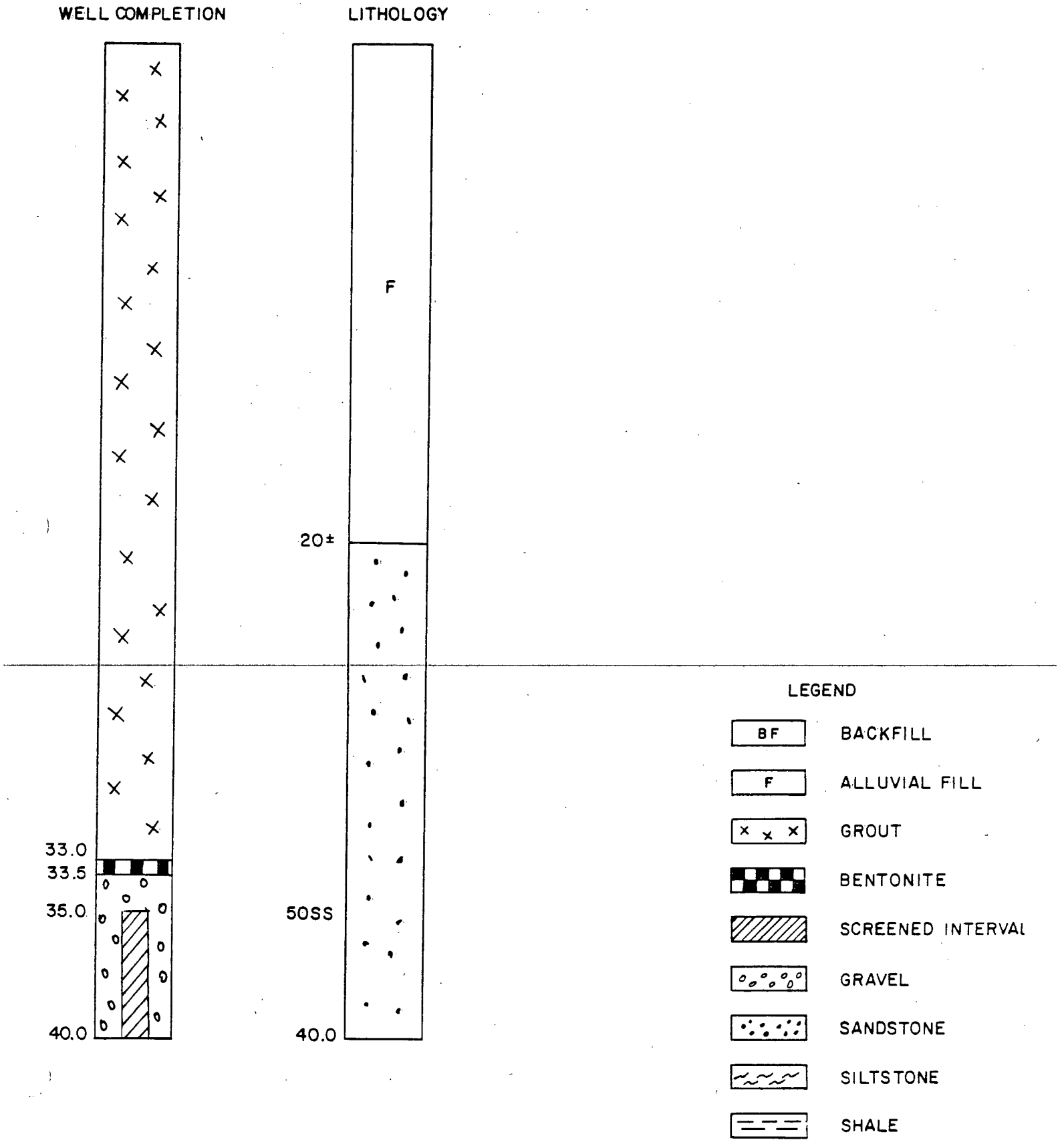


FIGURE C-21

TDM WELL NUMBER XXIII

8-6-81

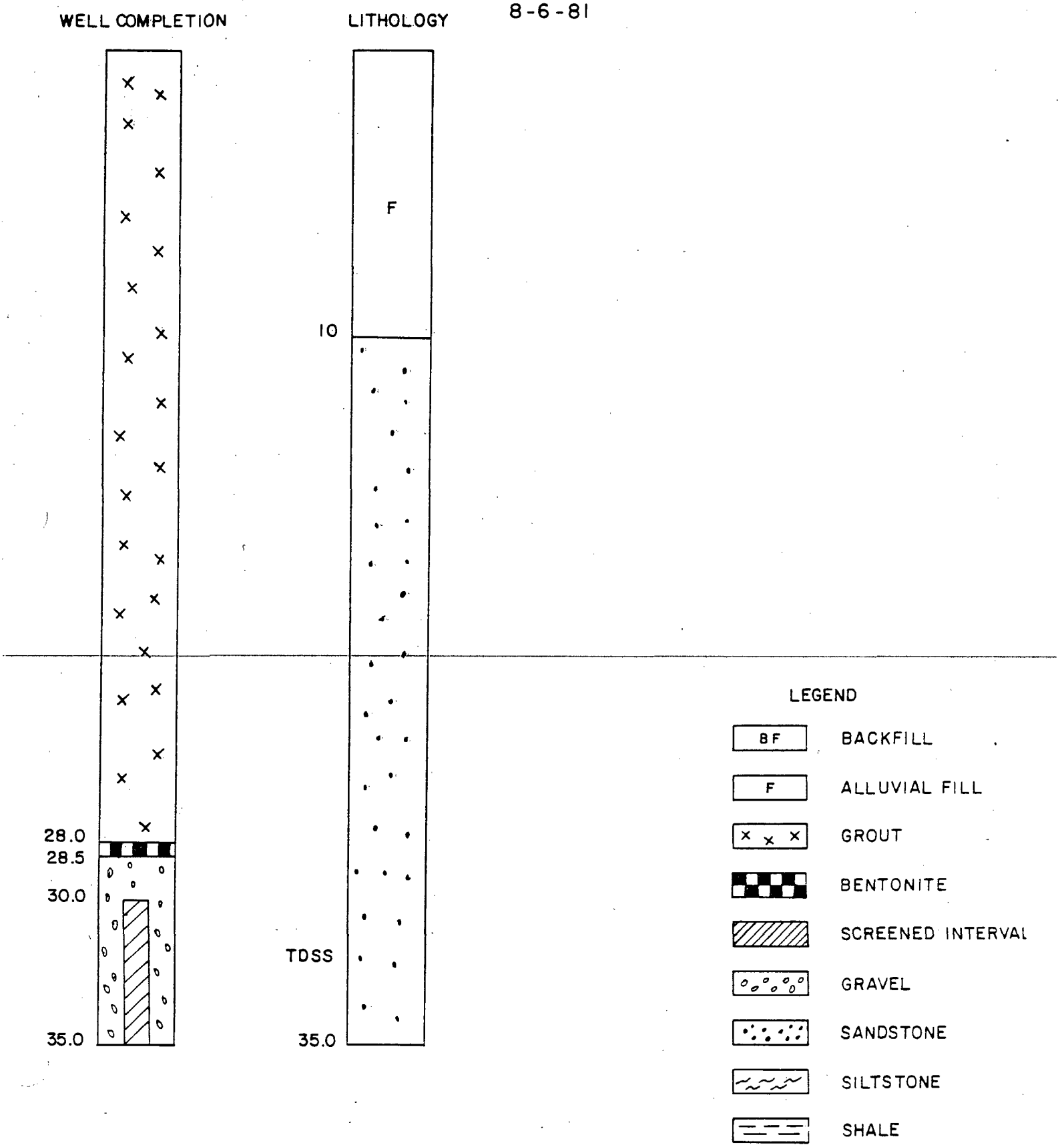


FIGURE C-22

TDM WELL NUMBER XXIV

8-6-81

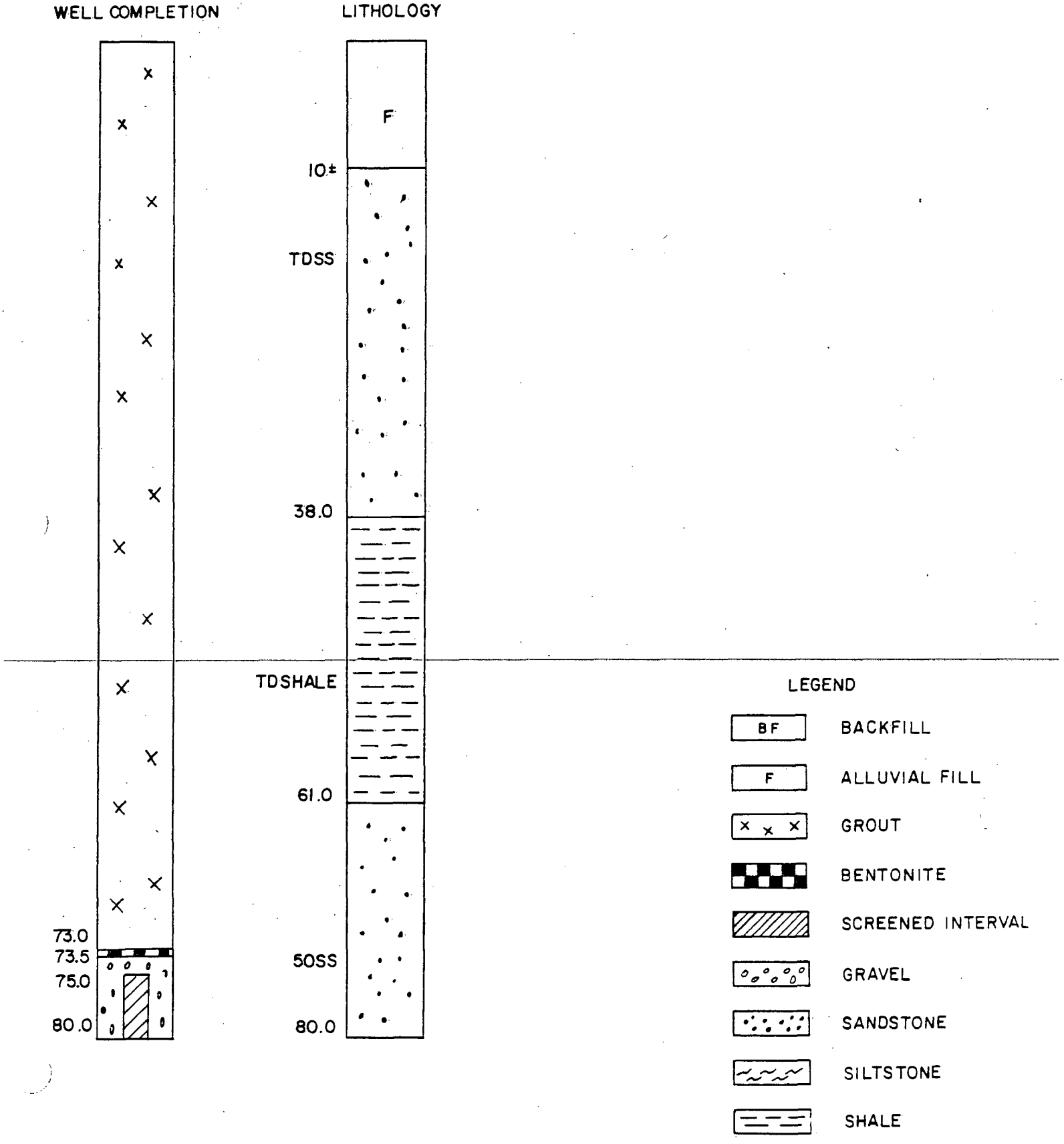


FIGURE C-23

TDM WELL NUMBER XXV

8-10-81

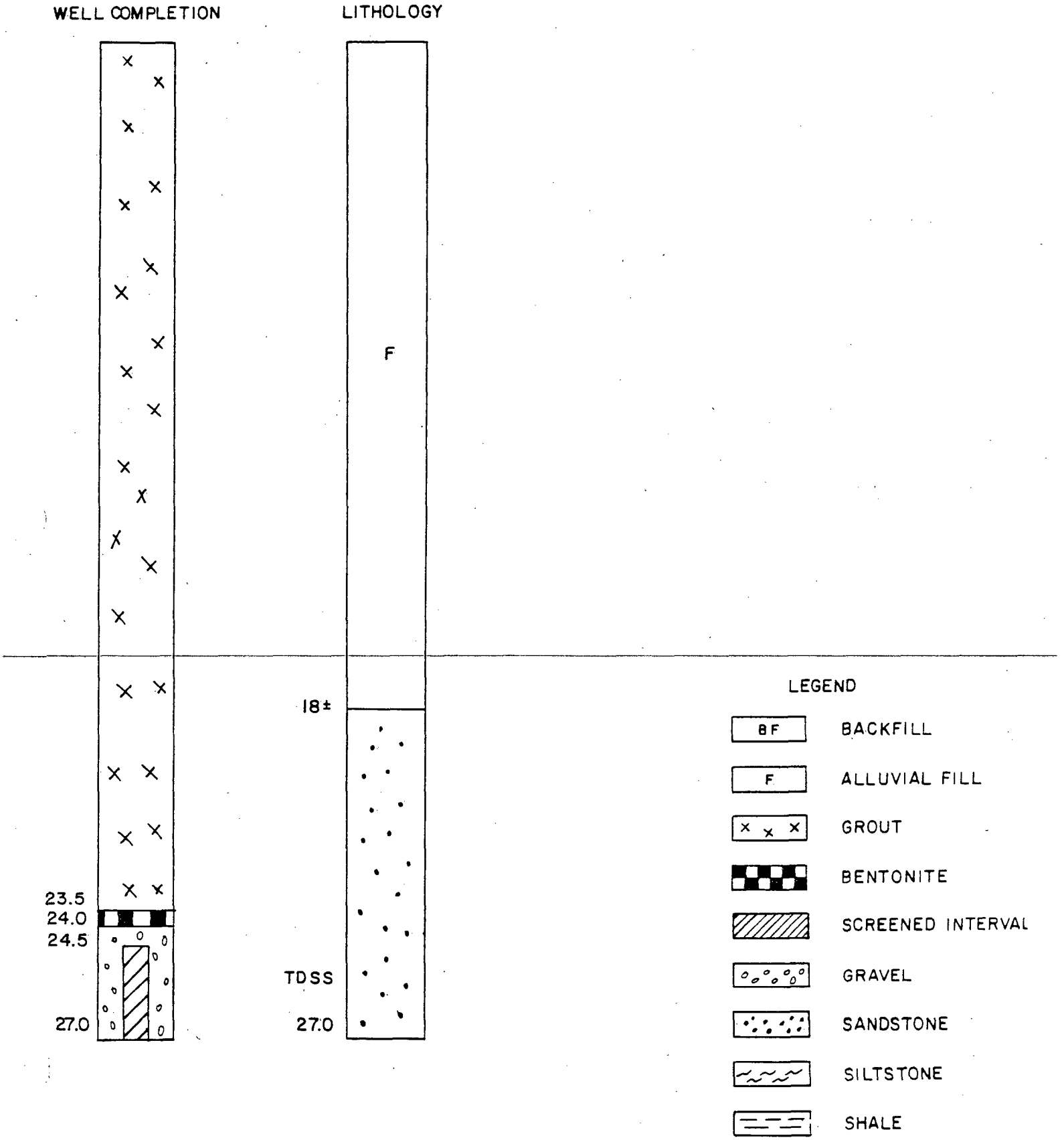


FIGURE C-24

TDM WELL NUMBER XXVI

8-11-81

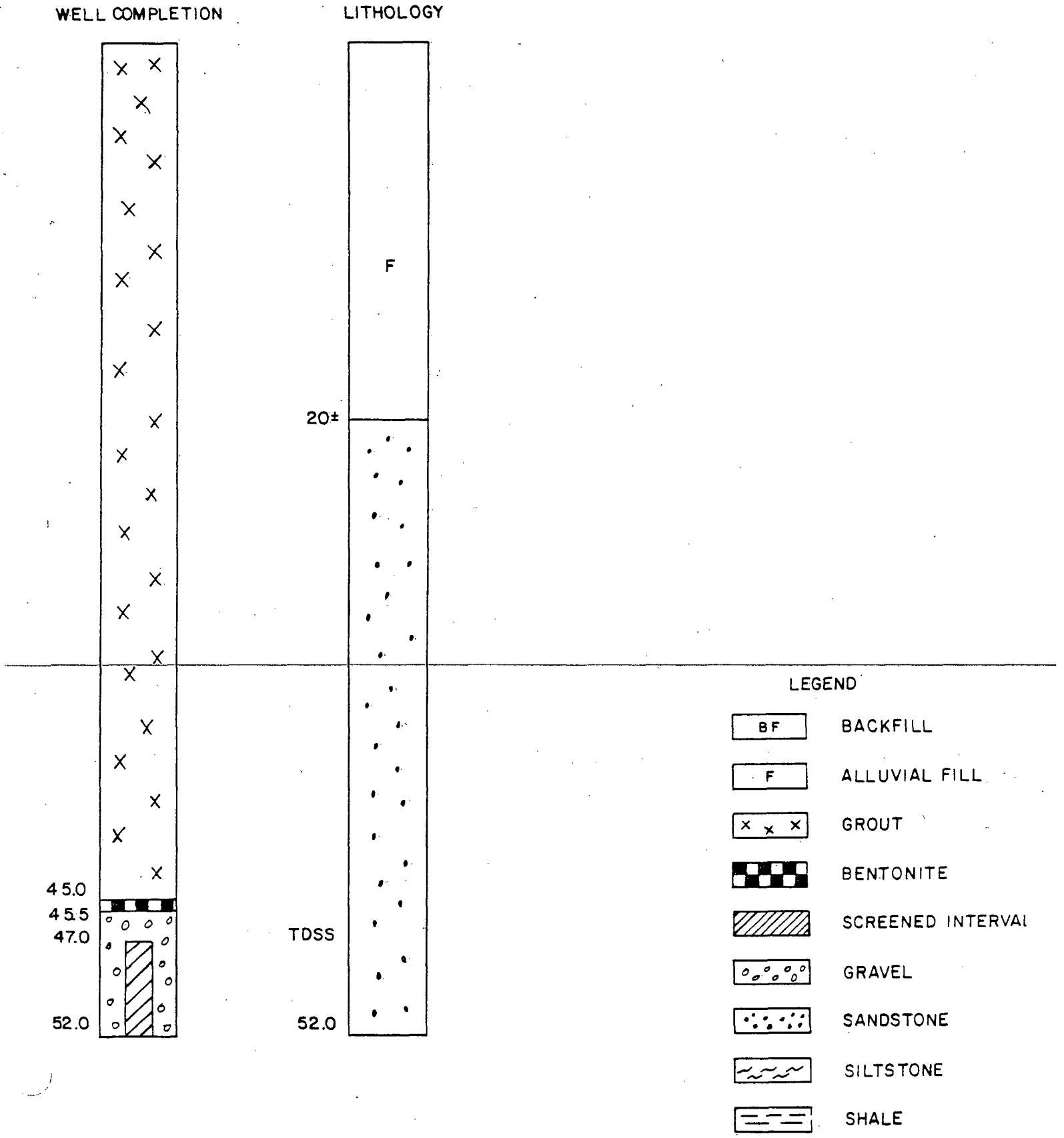


FIGURE C-25

TDM WELL NUMBER XXVII

8-14-81

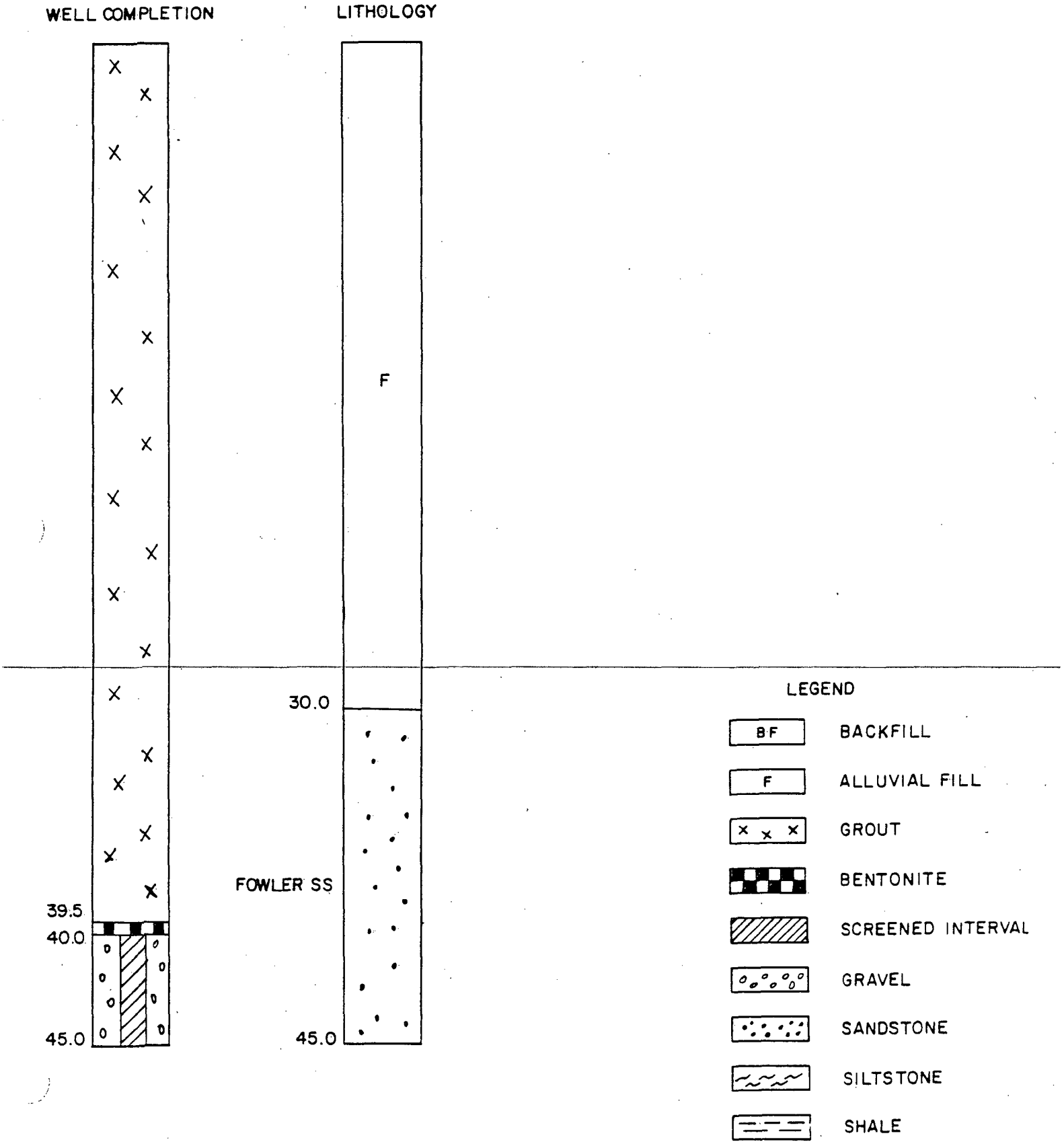


FIGURE C-26

TDM WELL NUMBER XXVIII

8-13-81

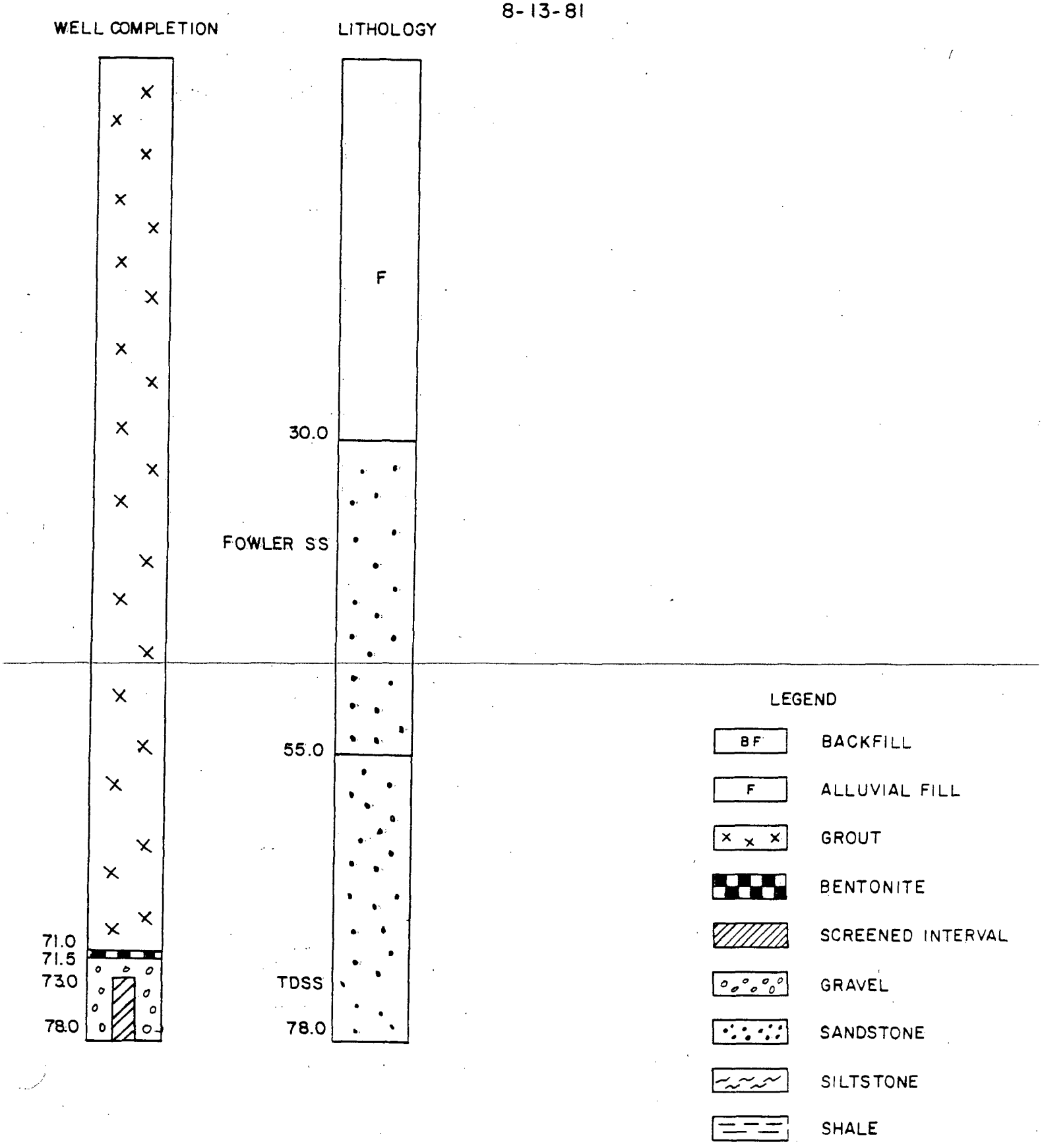


FIGURE C-27

TDM WELL NUMBER XXIX

8-12-81

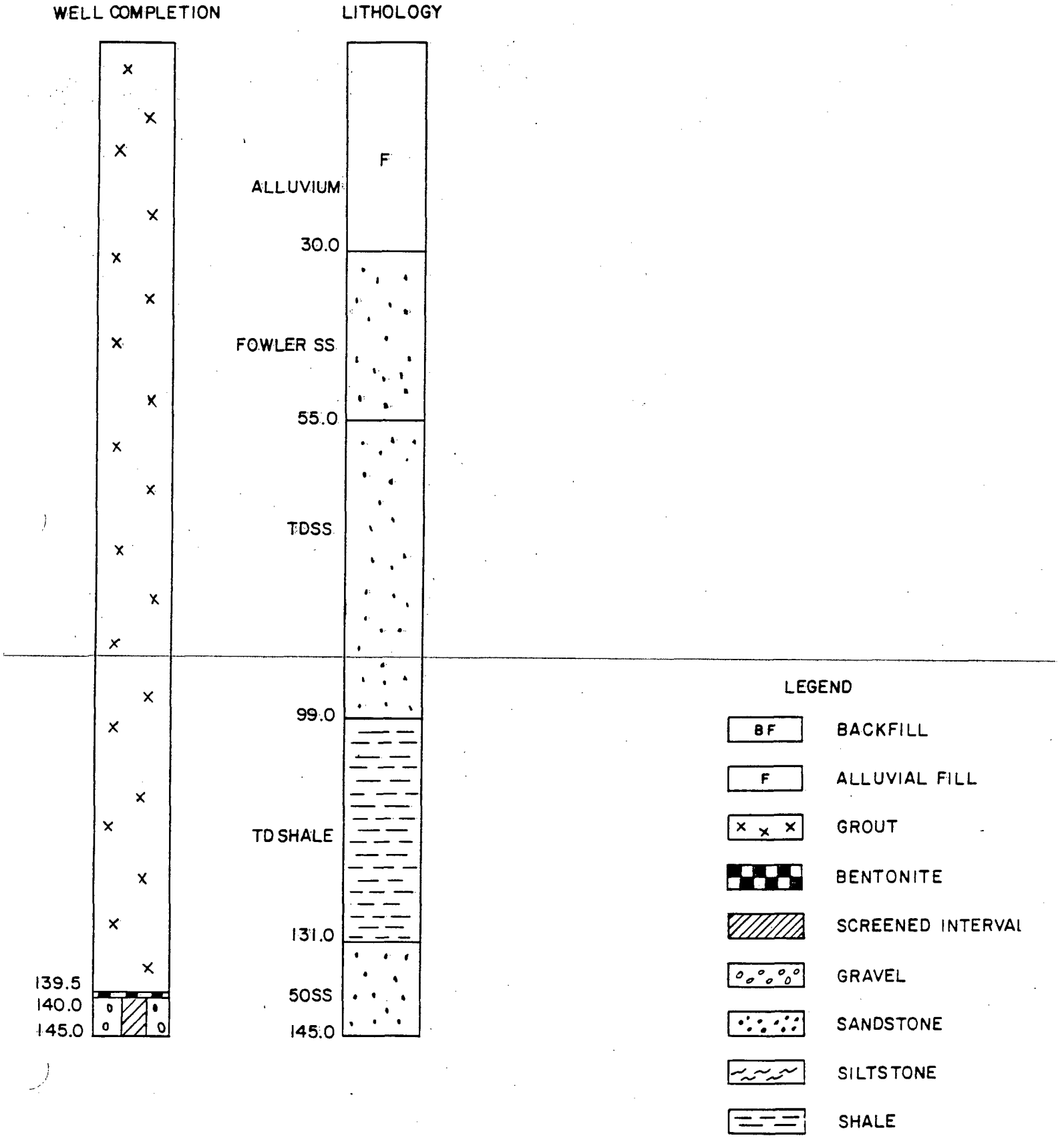


FIGURE C-28

TDM WELL NUMBER XXX

8-20-81

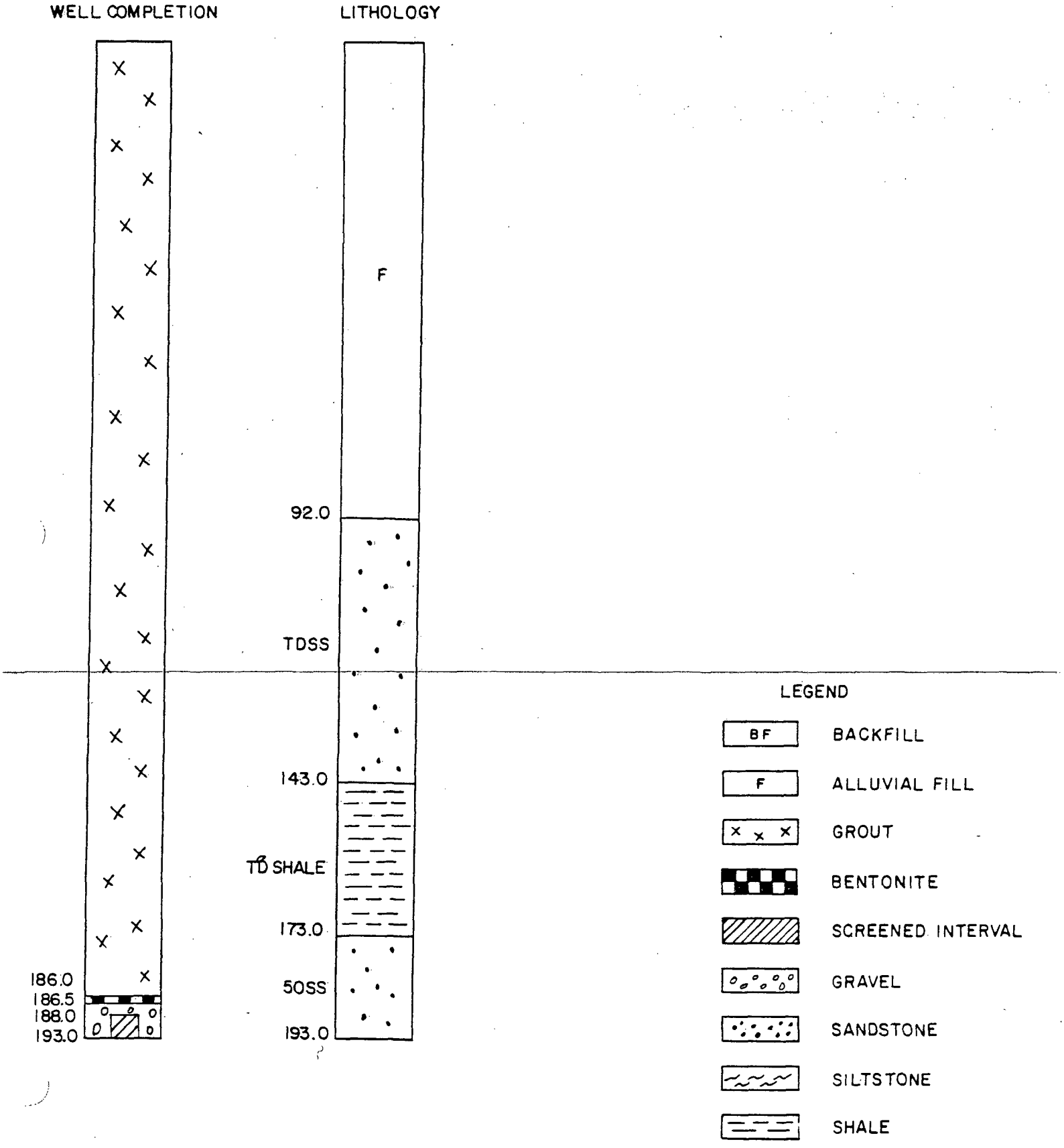


FIGURE C-29

TDM WELL NUMBER RM-1

8-3-81

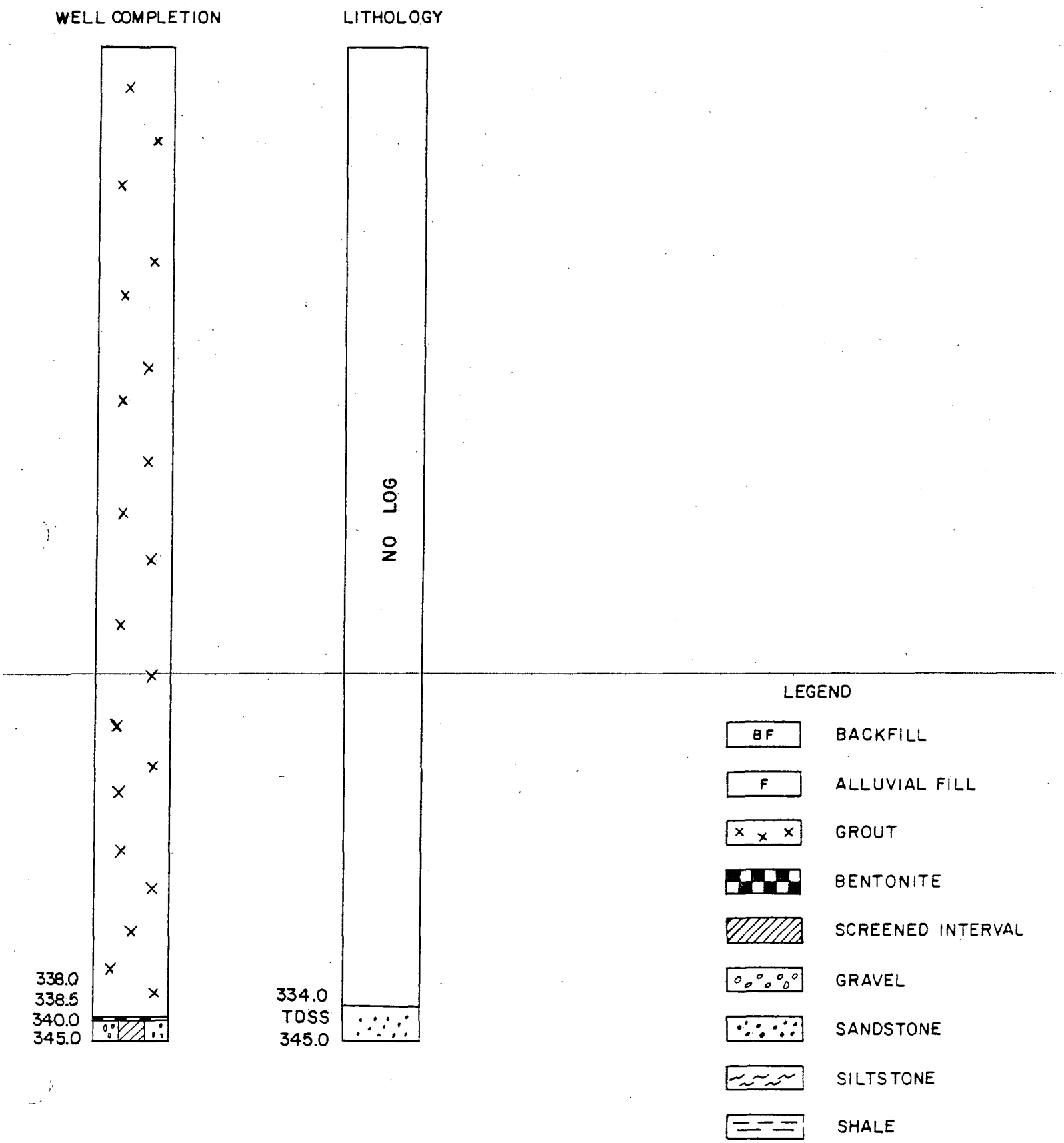


FIGURE C-30
TDM WELL NUMBER RM-2

8-5-81

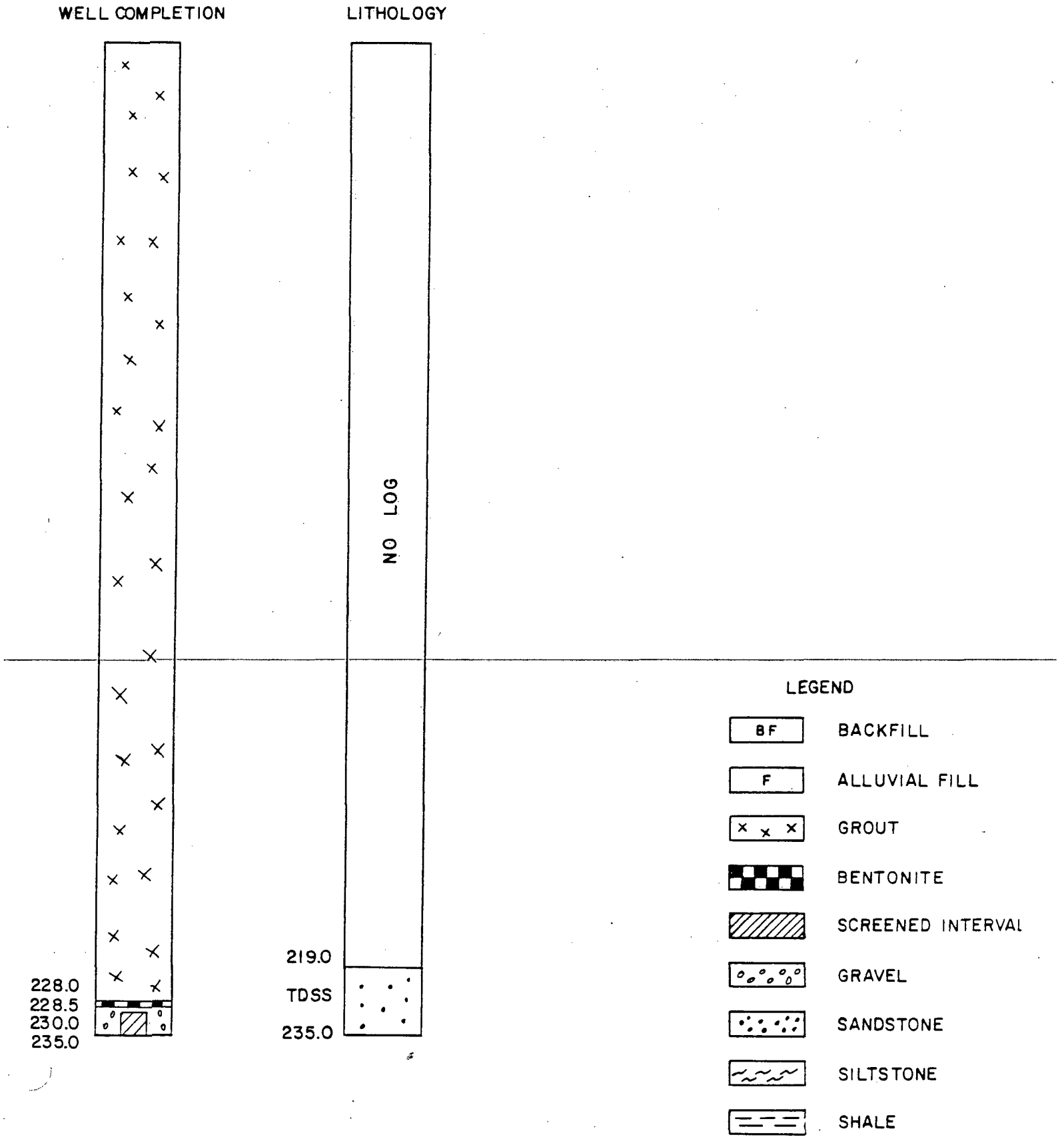


FIGURE C-31
TDM WELL NUMBER RM-3

7-23-81

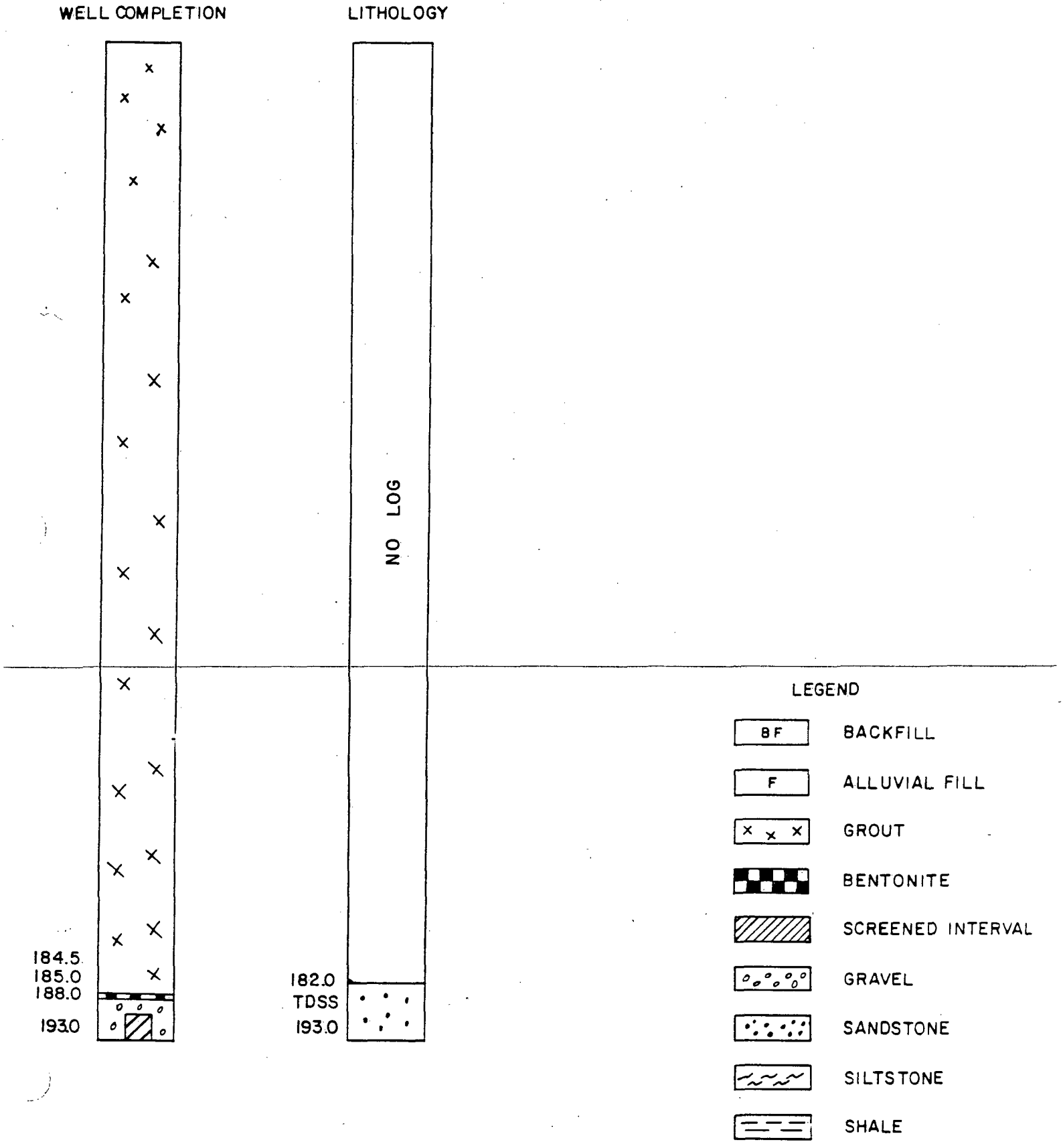


FIGURE C-32

TDM WELL NUMBER RM-4

7-22-81

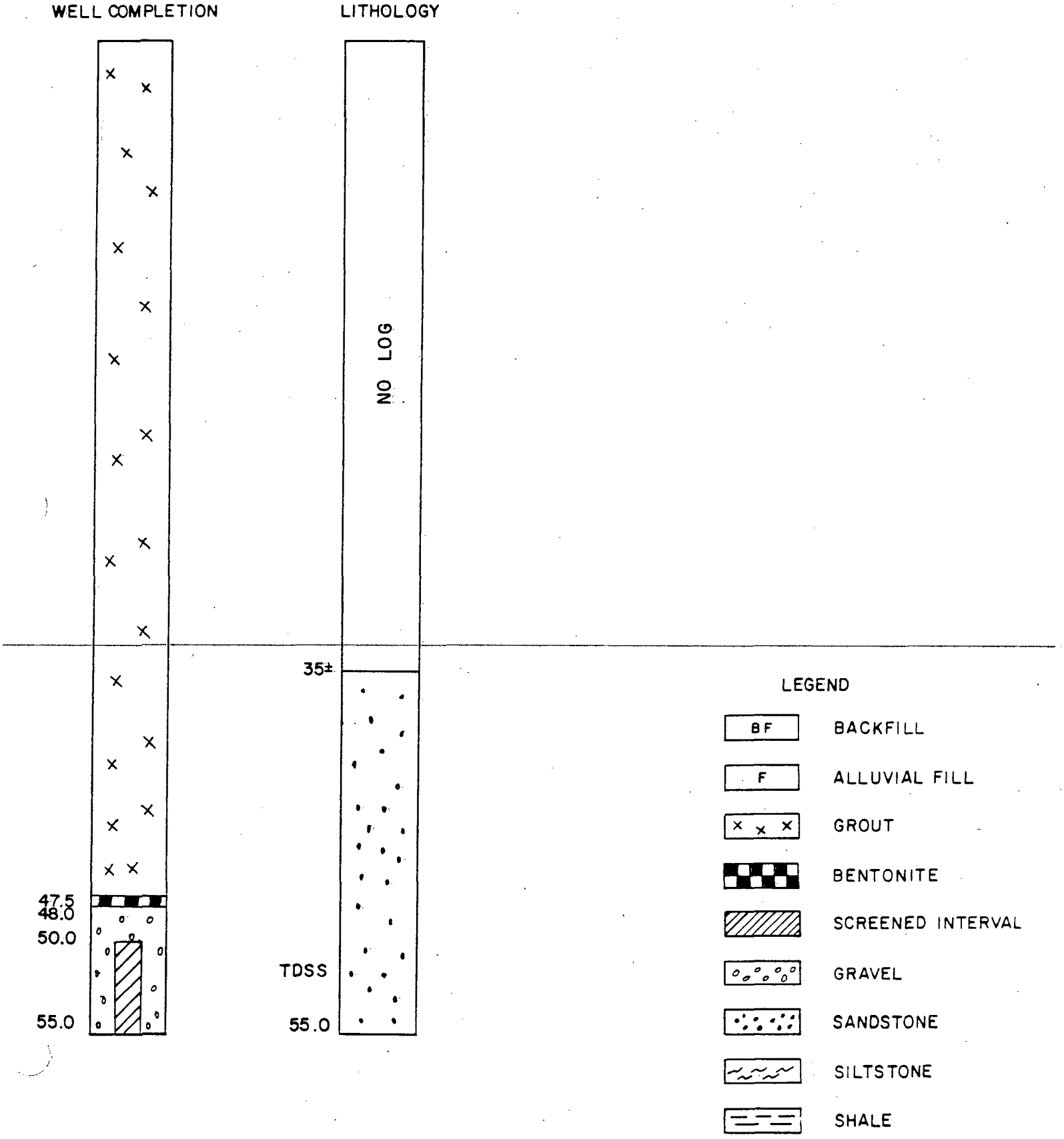
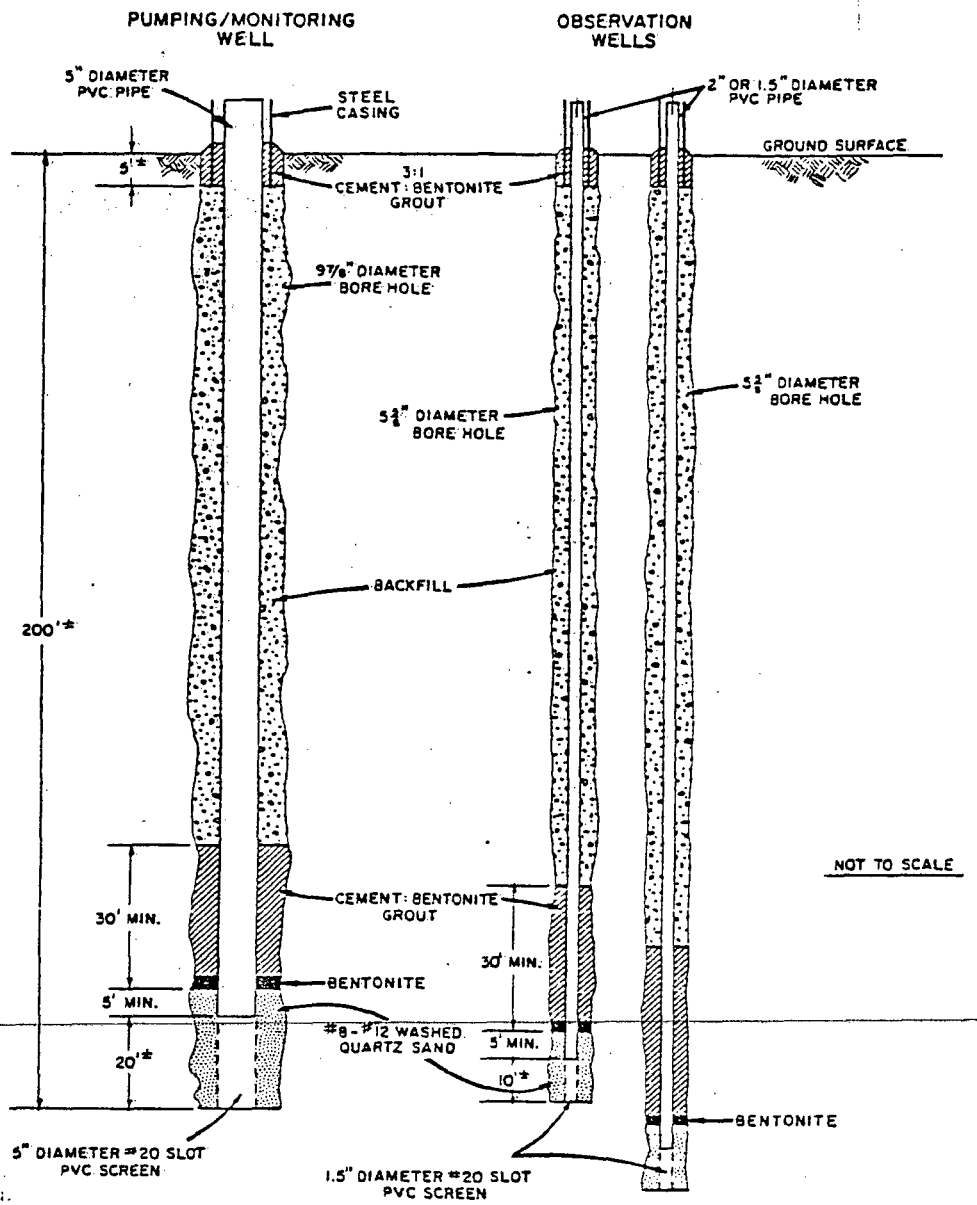
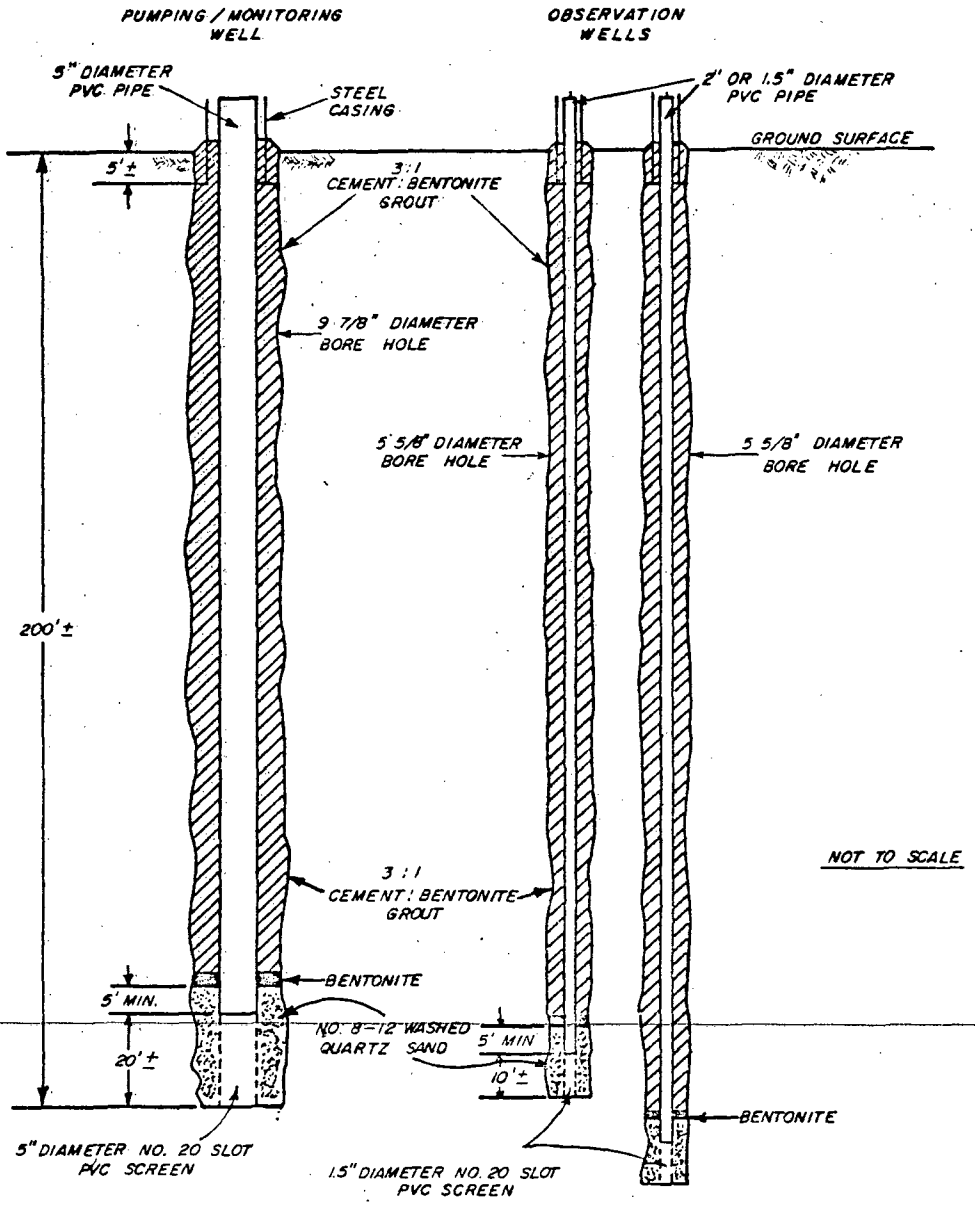


FIGURE C-33



TYPICAL PUMPING/MONITORING WELL AND OBSERVATION WELL CONSTRUCTION

FIGURE C-34



TYPICAL PUMPING / MONITORING WELL AND OBSERVATION WELL CONSTRUCTION

TABLE C-1

SUMMARY OF TAILINGS DAM MONITOR WELLS

WELL NAME	DATE DRILLED	TOTAL DEPTH	COLLAR EVEVATION	NORTHING	EASTING	FORMATION COMPLETED IN	OBSERV. WELLS	OLD NAME
TDM A	1972	310	5285	877971	411977	TDSS		9
TDM B	1972	290	5196	878026	412196	TDSS		10
TDM E	1972	105	5170	874421	413838	50 SS		11
TDM D	1972	80	5177	876008	414178	TDSS		15
TDM C	1974	80	5176	873488	414174	TDSS		16
TDM I	1977	80	5193	876775	414310	TDSS		17
TDM II	1977	60	5173	875370	414530	TDSH/TDSS		18
TDM III	1977	40	5148	874700	414620	TDSH, 50 SS?		19
TDM IV	1977	90	5150	874090	414170	40 SS		20
TDM V	1977	80	5144	875406	415003	50 SS		21
TDM VI	1980	85.6	5115	874195	414445	40 SS	VI-1,2,3	
TDM VII	1980	90	5184	876520	414181	TDSS	VII-1,2,3,4	
TDM VIII	1980	130	5261	873777	412814	TDSS	VIII-1	
TDM IX	1980	181	5230	875580	410121	TDSS, TDSH		
TDM X	1980	101.4	5230	875630	410100	Above TDSS		
TDM XI	1980	220	5230	875600	410102	50 SS		
TDM XII	1980	150.6	5263	874254	411750	TDSS		
TDM XIX	1980	120	5238	876929	412049	Above TDSS		
TDM XX	1980	235	5236	876955	412086	50 and 40 SS		
TDM XXI	1980	150	5237	876950	412068	TDSS		
TDM D Repl.	1981	56	5177	876008	414183	TDSS		
TDM VI Repl.	1981	40	5113	874176	414440	50 SS		
TDM XXIII	1981	35	5180	873271	414264	TDSS	XXIII-1	
TDM XXIV	1981	80	5179	873262	414365	50 SS	XXIV-1	
TDM XXV	1981	27	5161	875165	415138	TDSS		
TDM XXVI	1981	52	5168	876129	414594	TDSS		
TDM XXVII	1981	45	5200	877255	414254	Fowler	XXVII-1	
TDM XXVIII	1981	78	5200	877262	414255	TDSS	XXVIII-1	
TDM XXIX	1981	145	5201	877279	414251	50 SS	XXIX-1	
TDM XXX	1981	193	5237	876922	412068	50 SS		
RM-1	1981	345	5341	878459	400395	TDSS		
RM-2	1981	235	5289	877037	401325	TDSS		
RM-3	1981	193	5256	875999	402001	TDSS		
RM-4	1981	55	5154	871161	406802	TDSS		

Fowler = Fowler Sandstones and Shale
TDSS = Tailings Dam Sandstone
TDSH = Tailings Dam Shale
50 SS = 50 Sandstone, Upper Ore Sand
40 SS = 40 Sandstone, Middle Ore Sand

TABLE C-2

Example Water Quality Data Sheet

WELL ID.		W 9	W 9	W 9	W 9	W 9	W 9	W 9
DATE		OCT-74	SEP-74	AUG-74	JUL-74	JUN-74	MAY-74	APR-74
MAJOR IONS (MG/L EXCEPT AS NOTED)								
TOTAL HARDNESS	(HARD.)	* 0.00	32.50	* 0.00	* 0.00	14.00	* 0.00	* 0.00
BICARBONATE	(HCO3)	* 0.00	61.00	* 0.00	* 0.00	61.00	* 0.00	* 0.00
CALCIUM	(CA)	* 0.00	8.00	* 0.00	* 0.00	4.00	* 0.00	* 0.00
CARBONATE	(CO3)	* 0.00	60.00	* 0.00	* 0.00	24.00	* 0.00	* 0.00
CHLORIDE	(CL)	* 0.00	12.00	* 0.00	* 0.00	12.00	* 0.00	* 0.00
HYDROXIDE	(OH)	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00
MAGNESIUM	(MG)	* 0.00	3.00	* 0.00	* 0.00	1.00	* 0.00	* 0.00
POTASSIUM	(K)	* 0.00	7.00	* 0.00	* 0.00	5.00	* 0.00	* 0.00
SODIUM	(NA)	* 0.00	104.00	* 0.00	* 0.00	85.00	* 0.00	* 0.00
SODIUM CHLORIDE	(NACL)	* 0.00	277.00	* 0.00	* 0.00	202.00	* 0.00	* 0.00
SULPHATE	(SO4)	* 0.00	.96	* 0.00	* 0.00	94.00	* 0.00	* 0.00
OBSERVED PH	(PH)	* 0.00	9.00	* 0.00	* 0.00	8.50	* 0.00	* 0.00
OBS. RESISTANCE	(O-OHMS)	* 0.00	28.00	* 0.00	* 0.00	29.00	* 0.00	* 0.00
CAL. RESISTANCE	(C-OHMS)	* 0.00	22.00	* 0.00	* 0.00	28.50	* 0.00	* 0.00
TOT. DIS. SOLIDS	(TDS)	* 0.00	320.00	* 0.00	* 0.00	255.00	* 0.00	* 0.00
DISSOLVED SOLIDS (SUM OF MAJOR IONS)		0.000	255.960	0.000	0.000	286.000	0.000	0.000
TOTAL MAJOR CATIONS (MEQ/L)		0.00	5.35	0.00	0.00	4.11	0.00	0.00
TOTAL MAJOR ANIONS (MEQ/L)		0.00	3.39	0.00	0.00	4.13	0.00	0.00
CHARGE BALANCE		0.00	22.40	0.00	0.00	-.26	0.00	0.00
TRACE CONSTITUENTS (MG/L EXCEPT AS NOTED)								
ARSENIC (PPB)	(AS)	* 0.00	13.00	* 0.00	* 0.00	¢ 10.00	* 0.00	19.00
HYDRO. SULFIDE	(H2S)	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00
IRON	(FE)	* 0.00	.10	* 0.00	* 0.00	14.60	* 0.00	* 0.00
LITHIUM	(LI)	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00	* 0.00
SELENIUM (PPB)	(SE)	* 0.00	¢ 5.00	* 0.00	* 0.00	¢ 5.00	* 0.00	¢ 5.00
RADIONUCLIDES								
ALPHA (PCI/L)	(ALPHA)	6.60	.60	5.60	2.10	2.60	2.40	1.80
PRECISION +-	( )	2.00	1.20	2.20	1.00	1.10	1.40	1.00
BETA (PCI/L)	(BETA)	11.00	18.00	4.00	9.00	6.40	* 0.00	5.60
PRECISION +-	( )	10.00	10.00	10.00	7.00	6.80	12.00	6.00
RADIUM (PCI/L)	(RA-226)	.20	.80	.40	.20	1.20	.40	.70
PRECISION +-	( )	.30	.70	1.90	¢ .50	.60	.40	1.40
THORIUM (PCI/L)	(TH-230)	.70	* 0.00	12.00	* 0.00	.40	* 0.00	* 0.00
PRECISION +-	( )	1.80	.80	3.00	2.30	.80	1.50	4.20
URANIUM	(U-NAT.)	2.60	¢ 1.00	7.50	.50	¢ .50	¢ .50	¢ 1.50

TABLE C3

SUMMARY OF PACKER TEST RESULTS

Well No.	Interval (ft)	Permeability (ft/yr)
VI-1	45 - 55	0.*
	55 - 65	0.*
	65 - 75	< 2.6
	75 - 85	< 2.4
VII	35 - 45	0.*
	45 - 55	7.9
	55 - 65	14.
	65 - 75	12.
	74 - 84	3.9
VIII-1	35 - 45	0.*
	50 - 60	.87
	60 - 70	0.*
	100 - 110	.15
	110 - 120	0.*
XIX	40 - 50	0.*
	93 - 120	.93
	105 - 120	.52
IX	55 - 65	18.
	65 - 75	2.6
	75 - 85	0.*
	85 - 95	0.*

* No measurable inflow during test

TABLE C4

UNDISTURBED TAILINGS SAMPLES

Boring	Sample No.	Depth (ft)
Q-1	1	2
	2	5
	3	7.5
	4	10
	5	12.5
	6	17.5
	7	20
	8	22.5
	9	25.0
	10	27.5
	11	30.0
	12	32.5
	13	35.0
	14	37.5
	15	43.0
	16	45.0
	17	49.0
	18	51.5
	19	55.0
R-1	1	8
	2	10
	3	15
	4	20
	5	25
	6	30
	7	35
	8	40
	9	45
	10	50
	11	55
	12	60
	13	65
	14	70
	15	75
	16	80
	17	85
	18	86.5

TABLE C5

UNDISTURBED CORE SAMPLES IN PLASTIC CONTAINERS

Well No.	Sample No.	Interval
VI	1	45.2 - 45.7
	2	46.8 - 47.2
	3	47.8 - 48.3
	4	50.0 - 50.4
	5	49.8 - 50.2
	6	71.7 - 72.1
	7	72.3 - 72.7
	8	72.9 - 73.2
VII-2	1	44.6 - 45.0
	2	53.4 - 53.9
	3	56.2 - 56.7
	4	61.2 - 61.7
	5	65.3 - 65.8
VIII	1	34.1 - 34.6
	2	34.6 - 35.0
	3	38.8 - 39.1
	4	43.9 - 44.4
	5	50.7 - 51.2
	6	69.7 - 70.2
	7	76.0 - 76.5
	8	107.2 - 107.7
	9	114.2 - 114.6
	10	122.3 - 122.7
X	1	61.0 - 61.5
	2	62.2 - 62.7
	3	69.1 - 69.6
XII	1	56.3 - 56.8
	2	61.9 - 62.4
	3	79.5 - 80.0
	4	120.8 - 121.2
	5	131.3 - 131.8
	6	149.7 - 150.2
	7	66.7 - 67.2
	8	140.2 - 140.7

Continued

TABLE C5 (Continued)

UNDISTURBED CORE SAMPLES IN PLASTIC CONTAINERS

Well No.	Sample No.	Interval
XX	1	23.4 - 23.9
	2	37.0 - 37.5
	3	21.0 - 21.5
	4	35.8 - 36.2
	5	113.8 - 114.3
	6	118.5 - 119.0
	7	162.9 - 163.4
	8	166.0 - 166.5
	9	171.1 - 171.6
	10	179.4 - 179.9
	11	182.0 - 182.5
	12	187.2 - 187.5
	13	190.0 - 190.5

TABLE C5 (Continued)

CORE SAMPLES IN CORE BOXES

Well No.	Interval (ft)
VI	20.0 - 46.7
	46.7 - 70.6
	70.6 - 85.6
VII	20.0 - 28.0
	28.0 - 44.0
	44.0 - 56.7
	56.7 - 70.0
	70.0 - 78.0
	81.1 - 125.0
VIII	0.0 - 38.7
	38.7 - 48.2
	48.2 - 58.2
	58.2 - 68.2
	68.2 - 78.0
	80.0 - 114.0
	114.0 - 130.0
X	0.0 - 72.0
	72.0 - 82.0
	82.0 - 92.0
	92.3 - 101.4
XII	0.0 - 57.9
	57.9 - 70.8
	70.8 - 81.1
	125.0 - 138.7
XX	0.0 - 30.5
	30.5 - 40.3
	40.3 - 116.3
	116.3 - 126.3
	169.5 - 182.5
	182.5 - 194.8
	194.8 - 235.0

TABLE C5 (Continued)

DISTURBED CORE SAMPLES IN SEALED STEEL CONTAINERS

Well No.	Sample No.	Interval
VI	1	41.2 - 41.5
	2	46.2 - 46.6
	3	52.6 - 53.0
	4	65.0 - 65.3
	5	70.6 - 71.1
	6	84.9 - 85.3
VII	1	30.1 - 30.4
	2	42.0 - 42.4
	3	52.5 - 52.7
	4	62.3 - 62.5
	5	65.0 - 65.5
	6	72.7 - 73.0
VIII	1	33.8 - 34.2
	2	38.7 - 38.8
	3	62.2 - 62.6
	4	65.8 - 66.2
	5	101.3 - 102.6
	6	118.0 - 118.7
X	1	60.0 - 61.0
	2	61.5 - 62.2
	3	66.0 - 66.9
XII	1	55.0 - 55.4
	2	66.0 - 66.7
	3	120.0 - 120.8
XX	1	25.2 - 26.1
	2	28.1 - 28.8
	3	43.7 - 44.5
	4	111.0 - 112.0
	5	160.0 - 161.0
	6	171.6 - 172.4
	7	178.4 - 179.4
	8	181.0 - 182.0
	9	187.5 - 188.5
	10	189.6 - 190
		190.5 - 191.2

TABLE C6

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
VI-1	0
	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
VII	0
	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
	90

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
VII-1	0
	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
VII-3	0
	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
VII-4	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
	90
	95
	100
	105
	110
	115
	120
	125
	130
	135
	140
	145
	150
	155
	160
	165
	170

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
IX	0
	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
	90
	95
	100
	105
	110
	115
	120
	125
	130
	135
	140
	145
	150
	155
	160
XI	0
	5
	10
	15
	20
	25
	30

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
XI	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
	90
	95
	100
	105
	110
	115
	120
	125
	130
	135
	140
	145
	150
	155
	160
	165
	170
	175
	180
	185
	190
	195
	200
	205
	210
	215
	220

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
XIX	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
XXI	5
	10
	15
	20
	25
	30
	35
	40
	45
	50
	55
	60
	65
	70
	75
	80
	85
	90
	95
	100
	105
	110
	115
	120
	125

Continued

TABLE C6 (Continued)

CUTTING SAMPLES IN PLASTIC BAGS

Well No.	Depth (ft)
XXI	130
	135
	140
	145
	150

TDM VIR	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	0.76	0.67	1.06			1.57
Th-230 pCi/L	1.26		comp. 3.46			<1.12 0.00
Uranium pCi/L	140		201			6.9
pH	6.3	6.6	6.7			6.7
Conductivity umho/cm²	3150	3410	3020	TDM VLR		3130
TDS mg/L	4754		4568			556
$SO_4^=$ mg/L	1850		2110		~~TDM VI~~	267
Cl^- mg/L	275		200			184
NO_3 mg/L	0.09		0.38			1.5
As mg/L	<.002		<0.002			
Se mg/L	<.002		<0.002			
Al mg/L	< 0.10					

TDM VII	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.02	0.76	1.06			0.54
Th-230 pCi/L	0.61		comp. 4.87			<1.12 (-0.28)
Uranium pCi/L	-5.6	13	15			0.8
pH	7.2	7.0	7.0			7.8
Conductivity µmho/cm²	2090	2260	2110			2150
TDS mg/L	2676		2766			4924
$SO_4^=$ mg/L	1350		1250			2666
Cl^- mg/L	110		150			123
NO_3 mg/L	0.14		0.21			2
As mg/L	<0.002		<0.002			
Se mg/L	<0.002		<0.002			
Al mg/L	<0.10					

TDM IX	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.40				2.14	Comp. 3.44
Th-230 pCi/L			Comp. 0.51			<1.12 0.10 Comp
Uranium pCi/L	-24				5.5	0.27
pH	6.0				* pH-probe out of order. ~6.0	6.2
Conductivity umho/cm²	3400				3270	3230
TDS mg/L	5162					1304
$SO_4^=$ mg/L	2600					654
Cl^- mg/L	26					239
NO_3 mg/L	0.11					1.5
As mg/L	<0.002					
Se mg/L	<0.002					
Al mg/L	<0.10					

TDM X	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.27				5.99	Comp 1.03
Th-230 pCi/L	1.40		Comp. 7.08			<1.12 0.98 Comp.
Uranium pCi/L	423				33	12
pH	6.8				* pH. Probe out of order ~6.8	7.2
Conductivity umho/cm²	3190				2880	2750
TDS mg/L	3664					3686
$SO_4^=$ mg/L	1250					2037
Cl^- mg/L	300					183
NO_3 mg/L	8.8					3
As mg/L	<0.002					
Se mg/L	<0.002					
Al mg/L	<0.10					

TDM XL	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L.	3.14				4.56	comp. 1.55
Th-230 pCi/L	0.79		comp. 2.63			<1.12 0.45 comp
Uranium pCi/L	-18				3.0	2
pH	7.4				pH. Probe out of order 7.0	7.4
Conductivity umho/cm²	3670				417	400
TDS mg/L	380					5304
$SO_4^=$ mg/L	115					2812
Cl^- mg/L	13					15
NO_3 mg/L.	0.14					<1
As mg/L.	<0.002					
Se mg/L.	<0.002					
Al mg/L.	<0.10					

TDM XII	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.95	1.69	1.53			3.17
Th-230 pCi/L	6.15		Comp. 5.42			<1.12 (0.05)
Uranium pCi/L	451	787	580			
pH	6.7	6.8	6.3			6.6
Conductivity umho/cm²	3670	3770	3720			3440
TDS mg/L	6142		5332			2892
$SO_4^=$ mg/L	2550		2400			1741
Cl^- mg/L	280		250			234
NO_3 mg/L	0.23		0.27			1.5
As mg/L	<0.002		<0.002			
Se mg/L	<0.002		<0.002			
Al mg/L	<0.10					

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TDM XIX	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.62	2.21	1.75			
Th-230 pCi/L	0.05		comp. 2.75			<1.12 0.51
Uranium pCi/L	-25	34	4.4			0.3
pH	8.5	8.0	8.2			7.7
Conductivity umho/cm²	550	547	599			658
T.D.S mg/L	506		504			4756
$SO_4^=$ mg/L	190		211			2383
Cl^- mg/L	16		14			5
NO_3 mg/L	0.19		0.17			2
As mg/L	<0.002		<0.002			
Se mg/L	<0.002		<0.002			
Al mg/L	<0.10					

TDM XX	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L						1.04
Th-230 pCi/L						1.21
Uranium pCi/L						
pH						7.4
Conductivity $\mu mho/cm^2$						524
TDS mg/L						862
$SO_4^=$ mg/L						121
Cl^- mg/L						2
NO_3 mg/L						2.5
As mg/L						
Se mg/L						
Al mg/L						

TDM XXI	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	2.80	1.77	1.56			3.87
Th-230 pCi/L	0.42		Comp. 0.79 EDL			1.67
Uranium pCi/L	21	33	28			
pH	6.8	7.4	7.1			7.3
Conductivity $\mu mho/cm^2$	2000	1905	1962			1938
TDS mg/L	2392		2492			3304
$SO_4^=$ mg/L	1300		1110			1494
Cl^- mg/L	200		195			166
NO_3 mg/L	0.21		0.17			1.5
As mg/L	<0.002		0.0025			
Se mg/L	<0.002		<0.002			
Al mg/L	<0.10					

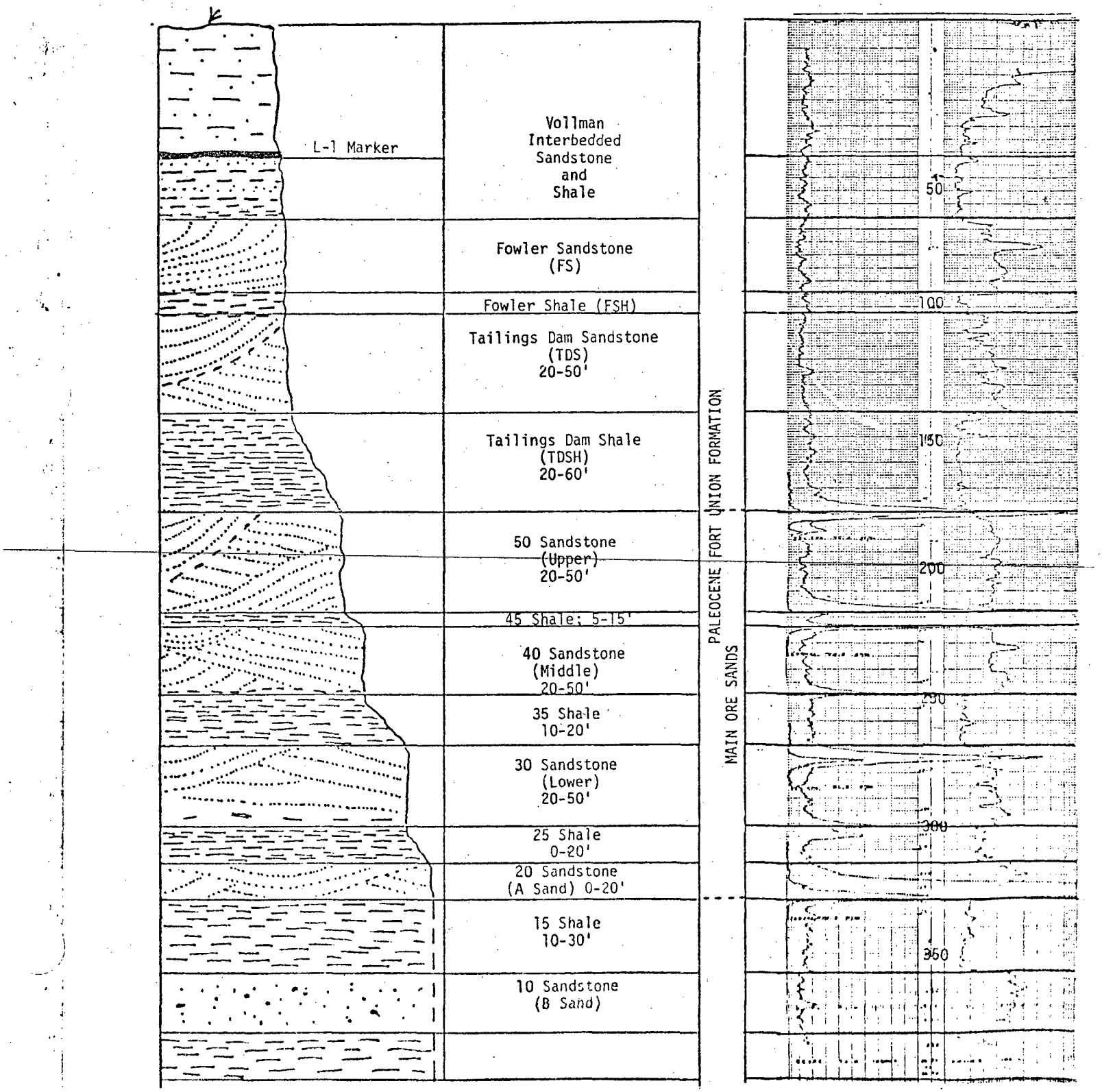
TDM XXII	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	0.14					
Th-230 pCi/L	0.23		(Comp.) 1.0			
Uranium pCi/L	16					
pH	6.7					
Conductivity umho/cm²	2980					
TDS mg/L	3686					
$SO_4^=$ mg/L	1850					
Cl^- mg/L	205					
NO_3 mg/L	0.95					
As mg/L	<0.002					
Se mg/L	<0.002					
Al mg/L	<0.10					

TDM XXVI	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L		1.17	1.66			2.15
Th-230 pCi/L			Comp. 2.46			<1.12 0.30
Uranium pCi/L		36	30			
pH		8.5	8.4			9.0
Conductivity $\mu mho/cm^2$		1384	1400			1312
TDS mg/L			1562			2160
$SO_4^=$ mg/L			850			941
Cl^- mg/L			100			85
NO_3 mg/L			8.9			0.5
As mg/L			<0.002			
Se mg/L			0.002			
Al mg/L						

TDM XXVII	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L		0.93	1.33		1.82	comp 1.23
Th-230 pCi/L			0.08 comp <1.83			<1.12 comp 0.23
Uranium pCi/L		12	60		5.5	
pH		11.8	11.7		pH probe out of order 11-12	11.6
Conductivity umho/cm²		3170	2870		2080	1519
TDS mg/L			1324			1370
$SO_4^=$ mg/L			200			242
Cl^- mg/L			248			93
NO_3 mg/L			2.9			1
As mg/L			<0.002			
Se mg/L			0.004			
Al mg/L						

TDM XXVIII	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L		0.86	1.42			0.77
Th-230 pCi/L			comp. < 1.83 ± 0.50			< 1.12 (0.63)
Uranium pCi/L		9.0	6.2			
pH		10.8	11.2			10.5
Conductivity umho/cm²		1073	1140			868
TDS mg/L			848			1306
$SO_4^=$ mg/L			440			456
Cl^- mg/L			52			45
NO_3 mg/L			0.84			2
As mg/L			< 0.002			
Se mg/L			< 0.002			
Al mg/L						

TDM XXIX	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L		0.67	1.80			
Th-230 pCi/L			Comp. <1.86 0.58			1.24
Uranium pCi/L		46	-2.7			
pH		11.9	11.8			12.2
Conductivity umho/cm²		—	7110			6030
TDS mg/L			3084			2904
$SO_4^=$ mg/L			45			35
Cl^- mg/L			510			337
NO_3 mg/L			0.25			2.5
As mg/L			<0.002			
Se mg/L			<0.002			
Al mg/L						

TDM XXX	October 1981	November 1981	December 1981	January 1982	February 1982	March 1982
Ra-226 pCi/L	1.24	0.74	1.35			
Th-230 pCi/L	1.44		Comp. 0.00 <1.86			<1.12 0.63
Uranium pCi/L	-18	II	1.4			
pH	10.8	9.2	9.3			8.0
Conductivity umho/cm²	441	507	398			519
TDS mg/L	284		150			908
$SO_4^=$ mg/L	106		140			172
Cl^- mg/L	21		12			5
NO_3 mg/L	0.15		0.17			1
As mg/L	<0.002		<0.002			
~~Se mg/L~~	~~<0.002~~		~~<0.002~~			
Al mg/L	0.18					

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