FINAL REPORT

VOLUME I

RESULTS AND DISCUSSION

CHARACTERIZATION OF DETRIMENTAL EFFECTS OF SALTS AND OTHER CHEMICAL CONSTITUENTS CARRIED IN SURFACE AND SUBSURFACE WATERS FROM BRINE AND DRILLING FLUID DISPOSAL PITS BURIED DURING OIL DEVELOPMENT

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EXECUTIVE SUMMARY

The purpose of this study was to develop techniques for locating and measuring the extent of brine contamination from buried brine evaporation pits, to identify pathways of salt movement from the pits and to suggest possible procedures for reclaiming or containing salt-affected areas to prevent further movement of the brine. The procedures developed in this study for the characterization of brine-affected areas are applicable to all areas where this problem occurs. However, the geologic materials and stratigraphy at the sites which were characterized in this investigation are peculiar to the study area, and the factors governing the movement of salts with surface and subsurface waters may vary at oil development sites located on different geologic strata in North Dakota.

The landscape at the sites that were studied in Tasks 2, 3 and 4-B is formed from till and glaciofluvial sediments. The topography is gently undulating with numerous small closed depressions which seasonally pond water. The soils at the study sites were developed over a uniform poorly-sorted till which is mantled by an ablation drift composed of a moderately-sorted somewhat stratified sediment. The till material is over 200 ft in depth. The mantle of ablation drift varies from about 2.5 to 8 feet in thickness, so that the surface of the underlying till does not conform to the landscape surface (surface of the ablation till). The underlying till is slowly permeable while the ablation drift is highly permeable and occasionally contains sand lens. Consequently, seasonal perched water tables can develop, and subsurface waters frequently move in different directions than surface waters. This is illustrated at the Fossum Site 1 by the southerly movement of subsurface waters as opposed to the easterly movement of surface waters. The water table is usually 10 ft or less in depth.

To determine the extent and future potential of contamination, the location and concentration of brine salts must be determined, and the direction of surface and subsurface water movement must be identified. In Task 2, studies were conducted to evaluate an above-ground inductive electromagnetic soil conductivity meter (EM38) for surveying brine-contaminated areas. Soil conductivity is related not only to the salt content of the soil but also to the moisture content, the amount and type of clay minerals, and the variations in these factors with depth. Correlations between EM38 readings and laboratory measurements of soil electrical conductivity (EC) using samples from the site of the EM38 readings showed that the use of the conductivity meter in the field gave a rapid and relatively accurate estimate of the salt content in the upper 1 to 2 meters of the soil.

Soils in the study area naturally contain various amounts of soluble salts in which sulfate is the predominate anion. Since chloride is the dominant anion in brine salts, it can be used as a tracer to identify the presence and movement of brine salts. However, conductivity meter measurements estimate only the total ionic concentration and do not differentiate between the various ionic species. Consequently, the chloride content of a representative number of soil samples must be determined by laboratory analyses to characterize the area of brine contamination. When the soil is in a saturated or near saturated condition, salts can move by diffusion. However, diffusion is extremely slow, and most of the salts move in dissolved form with the soil water. As mentioned above, the location of dissolved salts in the root zone can be monitored by use of the electromagnetic induction meter (EM38) and verification of their source can be obtained by laboratory analyses of selected soil samples. If salt movement is primarily due to overland (or surface) flow, potential movement of brine can be determined from the surface topography. But if the brine salts are being transported by underground flow in directions which are different from that reflected by surface topography, estimating the direction of potential further transport becomes more difficult.

If a less permeable layer below the surface is influencing subsurface movement as illustrated by the surface of the underlying till described in Task 2, salt movement can be affected in two ways. First, if the till layer is near the surface and a perched water table forms or if the soil immediately above the till becomes saturated, water containing dissolved salts can move upward by capillarity. Evaporation at the soil surface will deposit salts at the surface which can later be carried across the soil surface by overland flow with runoff waters. Second, if this water table is too deep for upward capillary water movement to the surface, hydrostatic pressure can result in lateral subsurface water movement. This lateral movement is occurring at both of the Fossum sites described in Task 2. If the dissolved salts move to a location where the mantle of ablation drift is thin enough to allow capillary movement to the surface, accumulation of salts could occur. At the present time, there is no indication that salts carried by underground lateral movement are being brought to the surface by evaporation at sites away from the initial zones of contamination at the Fossum sites.

By making some general assumptions about the average concentration of salts, the volumetric content of water at the saturation level for salt extraction, and that all chloride was present as sodium chloride, the total amount of salts at each site could be estimated. Calculations were made for the top 3 meters (approximately 10 feet) for each study area. Fossum Site 1, with a total area of 22.5 acres, contained approximately 500 tons of salt, while Fossum Site 2, with 19.0 acres, contained about 385 tons of salts. The average salt content of these sites was slightly more than 21 tons per acre.

It should be emphasized that these estimates are for only the top 3 meters; no estimate was made for total salt content below 3 meters. However, studies in Task 4-B indicated that brine salts had been moved to a depth of 70 feet in an area 500 x 500 feet around the brine pits. However, this brine is not as yet affecting a usable water supply. The results of this study are not adequate to determine if downward movement of brine salts is still occurring; given the arid climatic conditions, however, it appears likely that most of the downward salt movement was due to hydrostatic pressure at the time the pits were open and filled with brine.

Computer models have been developed which would allow an estimate of the total surface area that might ultimately be affected by salt movement from these buried pits, but insufficient data were obtained and the duration of the study was too short for this phase of the study to be completed. One preliminary estimate suggested that the contaminated area at the Fossum 1 site might ultimately double in size. After reaching this maximum area, the contaminated area might tend to decrease if salts tended to move to lower depths if precipitation runoff tended to accumulate in aquifer recharge sites. But if subsurface lateral movement was an important factor, further spread of contamination might occur.

Studies in Task 3 of this project indicated that high brine salt concentrations in the soil had a negligible effect upon the primary and secondary clay minerals in the soil. These studies also indicated that evaporite mineralogy could be used as in indicator of water movement in both brine-contaminated and non-contaminated soils. The minerals most useful as water movement indicators were gypsum and calcite in all soils, plus halite in brine-affected soils. Evaporite mineralogy characterization might be useful in identifying potential areas of contamination as brine salts move out of contaminated areas. It also offers interesting possibilities for studies of root zone hydrology. This is an area where additional research appears to be warranted.

The primary objective of Task 1 of this project was to evaluate the use of remote sensing techniques to identify areas of brine contamination. An area of 15 square miles (15 sections or 9,600 acres) lying within one oil field was selected for detailed studies. Aerial photographs taken during several years of active drilling were successfully used to locate brine pit sites. Aerial photographs were then taken from overflights in 1984 and 1985, using both vertical and oblique photographs; low-level oblique (200 ft) photographs were taken in black and white, color, and false color infrared, and high level vertical (20,000 ft) photographs were taken in black and white and false color infrared. Over 60 brine pits were located in the study area, and selected sites were verified by ground inspection using the EM38 meter. The soil areas affected by seepage from selected typical pits varied from no perceptible contamination outside the pit area to areas greater than 40 acres in extent. The average size of the contaminated area was 11.5 acres. The total contaminated acreage in the study area of 15 square miles was estimated to be about 1450 acres. If the average salt content of 21 tons per acre at the Fossum sites is assumed to be representative of that in the other study sites, over 30,000 tons of salts are present in the top 10 feet of the contaminated sites. The scope of this study was insufficient to estimate the longtime potential for further soil contamination or deleterious effects on groundwater aquifers.

The question now arises as to the practices required to either (1) reclaim the salt-affected areas or (2) stabilize the area to prevent further contamination. In order to do this, each site must be characterized with respect to topography, soil types and underlying stratigraphy, and total salt content.

Since salts move in dissolved form with water, the source and probable amount of incoming water must be identified. At some sites, interception and diversion of incoming waters may be sufficient to contain the salts and allow surface reclamation to proceed. At other sites, interception of incoming waters may be impractical, so that disposal of outcoming brine-contaminated waters becomes necessary. In either case, identification of the paths by which water moves into and out of the contaminated area is the first step in developing systems for the reclamation or containment of brine-contaminated areas. Reliable estimates of the total amount of brine salts in the contaminated areas are needed to predict the total area that may potentially be contaminated; this information will determine both the urgency and the scope of needed reclamation programs.

The simplest reclamation approach is to intercept and direct incoming water, either surface or subsurface, away from the contaminated site. At the two Fossum sites studied, movement of subsurface waters into the buried pit areas appeared to be minimal; most of the salt movement appeared to be due to collection and infiltration of runon waters into the depressed pit sites. Construction of a berm, or contour ditch, to intercept and divert incoming waters would confine infiltration to that amount of precipitation falling directly on the site and should retard the rate of outward salt movement. Construction of a mound over the site, using uncontaminated soil, so that surface runoff could occur would further reduce infiltration. The height of this mound should be such that the depth of the water table from the surface would preclude upward capillary movement of brine-contaminated water so that the mound could be vegetated.

Diversion of surface water is feasible only when minimal movement of subsurface waters is occurring. If appreciable quantities of subsurface waters are entering the site, they can be intercepted by means of a tile laid at the bottom of a gravel-filled trench; the tile can be drained into a suitable area at a lower elevation if it does not contain a prohibitive level of salts. Rather than using drainage tile, construction of an impermeable barrier to prevent water moving into or out of the site has been suggested. Bentonite, or smectite, clay is frequently used to seal ponds and irrigation ditches, but the use of clays to form an impermeable barrier is questionable at sites where high electrolyte (salt) concentrations may occur. These clays tend to flocculate and become permeable at high salt concentrations even when sodium is the dominant cation.

The above suggestions serve only to contain the brine-affected site without reclaiming the contaminated areas. Complete reclamation will require removal of excess salts and replacement of adsorbed sodium in the root zone with calcium, and prevention of future contamination by salts moving into the root zone from lower or adjacent areas. Standard reclamation procedures for replacement of adsorbed sodium can be used; the major problem is the removal of excess salts and disposal of the brine-contaminated water. Tile drains would need to be installed around and through the contaminated site at a specified depth below the root zone; these tile would drain into a sump and the brine-contaminated water disposed in an environmentally-acceptable manner, such as in an injection well. After excess salts are removed, the site could be reclaimed using standard agricultural procedures.

Injection wells, when improperly constructed or used, can also be a source of contamination, as is described in Task 4-A. The results suggest that the source of the outflowing brine is the nearby injection well. Further study is needed before this relationship can be definitely established, but this occurrence serves to emphasize the necessity for careful use and monitoring of injection wells.

INTRODUCTION

This study concerns two closely related problems resulting from North Dakota oil development. The first of these problems arises from the disposal of brine water brought to the surface with crude oil from producing wells. The crude oil may contain as much as 50 percent brine water which is nearly saturated with NaCl. The brine is separated from the crude oil near the well site. In the 1950′s and 60′s it was disposed of in evaporation pits. In 1972, the state rules and regulations governing oil and gas development were amended because most of the brine was moving downward and laterally from the pits and was not being left in the pits by evaporation of water from the brine. Therefore, brine is currently being pumped into deep injection wells. The brine disposal pits have been backfilled and leveled. However, the brine-saturated sediments beneath and adjacent to these reclaimed pits are a potential source of salt which may move either upward to the soil surface or downward to the groundwater aquifer. In the sites being studied in the current project, water apparently moves into the buried pits mostly by infiltration from the surface, and some possibly by underground lateral movement. Some of this water moves upward and laterally from the pits, carrying soluble salts which result in degradation of the surrounding surface soils. Another potential cause of land and water degradation is leakage from malfunctioning brine injection wells and the pipelines that connect them with producing wells. In some of these buried brine pits, subsidence of fill materials has created surface depressions in which precipitation ponds, thus creating groundwater recharge sites. This infiltrating water dissolves soluble salts as it comes in contact with the brine-rich sediments. The highly mineralized water which continues downward to the water table can cause degradation of the groundwater.

The land surface in the study area is nearly level with numerous small closed depressions. The soils are formed in till and glaciofluvial sediments. Many of the soils are poorly drained. The water table is high, and shallow groundwater aquifers serve as a source of water for farmsteads in the area. Movement of water carrying high concentrations of soluble salts from the buried brine disposal pits has potentially serious long-term detrimental implications with respect to both the quality of groundwater and soil degradation in the affected areas.

The second water-related problem occurs when waste drilling fluid from oil-and-gas wells is buried in shallow pits at the well site. Although the volume of drilling fluid disposed of at each site is usually small, the waste fluid contains a wide variety of hazardous chemical components. After disposal, waste components and leachates migrate through the unsaturated zones. Instrumentation of four reclaimed mud pits in western North Dakota indicated that most of the hazardous constituents are attenuated within the unsaturated zone while soluble salts such as NaCl may move through the unsaturated zone.

The subsurface migration of these water products is controlled by the lithologic and hydrologic properties of the materials beneath the pits. The western North Dakota sites are constructed in clayey "bedrock" materials and sediments derived from bedrock. Migration of oil-and-gas drilling fluids through the unsaturated zone and into the groundwater flow system may be greater than in other regions of North Dakota because of the (1) high water table (thin unsaturated zone); (2) presence of sandy, permeable sediment often containing shallow aquifers; and (3) higher annual precipitation. These conditions suggest the potential for considerable migration of waste constituents.

The purpose of the project reported herein was to measure the extent of degradation due to salts and other constituents moving from buried brine and drilling fluid pits and to develop the needed chemical, physical, mineralogical and groundwater criteria to characterize the potential amount and extent of water and land degradation from each pit. It is known that a potentially serious situation exists which may result in extensive environmental degradation, and the results of this project will provide a research approach to develop methods for preventing additional salt contamination and for improving the quality of groundwater and surface areas already affected.

EXPERIMENTAL METHODS AND RESULTS

Because of the complexity of the problem under study, work on this project was conducted under four separate, but coordinated, tasks with a principal investigator for each task, each of which was assisted by co-investigators for the same administrative unit. The methods and results for each task will be discussed separately, and the conclusions for the entire project were presented in the preceding Executive Summary.

The objective and principal investigators for each of the four tasks are listed below:

Task 1. Develop methodology to identify areas contaminated with salt brine and to estimate the extent and level of degradation of affected soils.

Principal Investigator:

Dr. John E. Foss
Soil Science Department
North Dakota State University

Task 2. Characterize chemical and physical properties of soils affected by salts from buried brine pits as related to salt movement in surface and subsurface water.

Principal Investigator:

Dr. Eugene C. Doll
Land Reclamation Research Center
North Dakota State University

Task 3. Identify the solid phases of the original salts and their mineralogy at various stages of salt migration as a function of the physical and chemical environment; study the effects of the dissolved salts on the mineralogy and physical properties of the soil.

Principal Investigator:

Dr. Gregory J. McCarthy
Chemistry and Geology Department
North Dakota State University

Task 4. Define the three-dimensional stratigraphy, geohydrology and hydrochemistry in the area of selected brine pits and oil-and-gas well drilling fluid pits.

Principal Investigator:

Mr. Edward C. Murphy
North Dakota Geological Survey
University of North Dakota

TASK 1

Identification of Salt-Seepage Areas from Oilfield Brine Pits

Principal Investigator:	J. E. Foss
Co-Investigators:	J. L. Richardson L. D. Prunty M. D. Sweeney D. K. Cudworth B. K. Hoag

SOIL SCIENCE DEPARTMENT
NORTH DAKOTA STATE UNIVERSITY

ABSTRACT

During initial development (1950-1970) of oil fields in Bottineau and Renville Counties, North Dakota, brine separated from crude oil was disposed of in evaporation pits or ponds. Subsequently, seepage from these pits has been noted at numerous locations. The objectives of this investigation were to (1) identify the location and areal extent of the brine pits and (2) determine the degree of contamination by seepage from the brine pits. Aerial photographs taken during the years of active drilling were used to identify the brine pits. Recent aerial photographs (both vertical and oblique) and field studies were used to evaluate seepage from the brine pits. Over 60 were located in the study area. The soil area affected by seepage from the pits ranged from no perceptible damage outside the immediate pit area to greater than 40 acres. The electromagnetic soil conductivity meter (EM 38) was useful in delineating seepage areas and the current extent of salinization. The meter aided in predicting future brine movement. Seepage was related to landscape position, geologic materials, and the total quantity of salts buried. The salts apparently move laterally through the soil toward the topographic low.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Robert L. Houghton, USGS, Department of Interior, for his invaluable help in taking the 35-mm oblique photographs. We would also like to thank Teresa Schneider for typing the manuscript and Marj Dobervich for assembling the final manuscript.

INTRODUCTION

During initial development (1950-1970) of oil fields in Bottineau and Renville counties, North Dakota (Fig. 1), brine separated from crude oil was disposed of in evaporation pits or ponds. Subsequently, seepage from brine disposal pits has been observed in numerous locations in these counties. The exact number and location of brine pits in Bottineau and Renville counties are unknown, because this information was not recorded during the early days of oil development. Thus, the potential areas for seepage from the brine pits are also unknown.

The general objective of this phase of the study was to determine the location and extent of the salt brine contamination in Bottineau and Renville counties. Because of the large area involved in the counties (2608 square miles or 1,668,991 acres), only those oil-field localities with obvious salt seepage problems were investigated. Figure 1 shows the location of the study area. Remote sensing techniques and field work to obtain ground truth were used to establish the magnitude of the salt seepage problem. This phase is just one of four phases dealing with the salt-seepage problem in Bottineau and Renville counties.

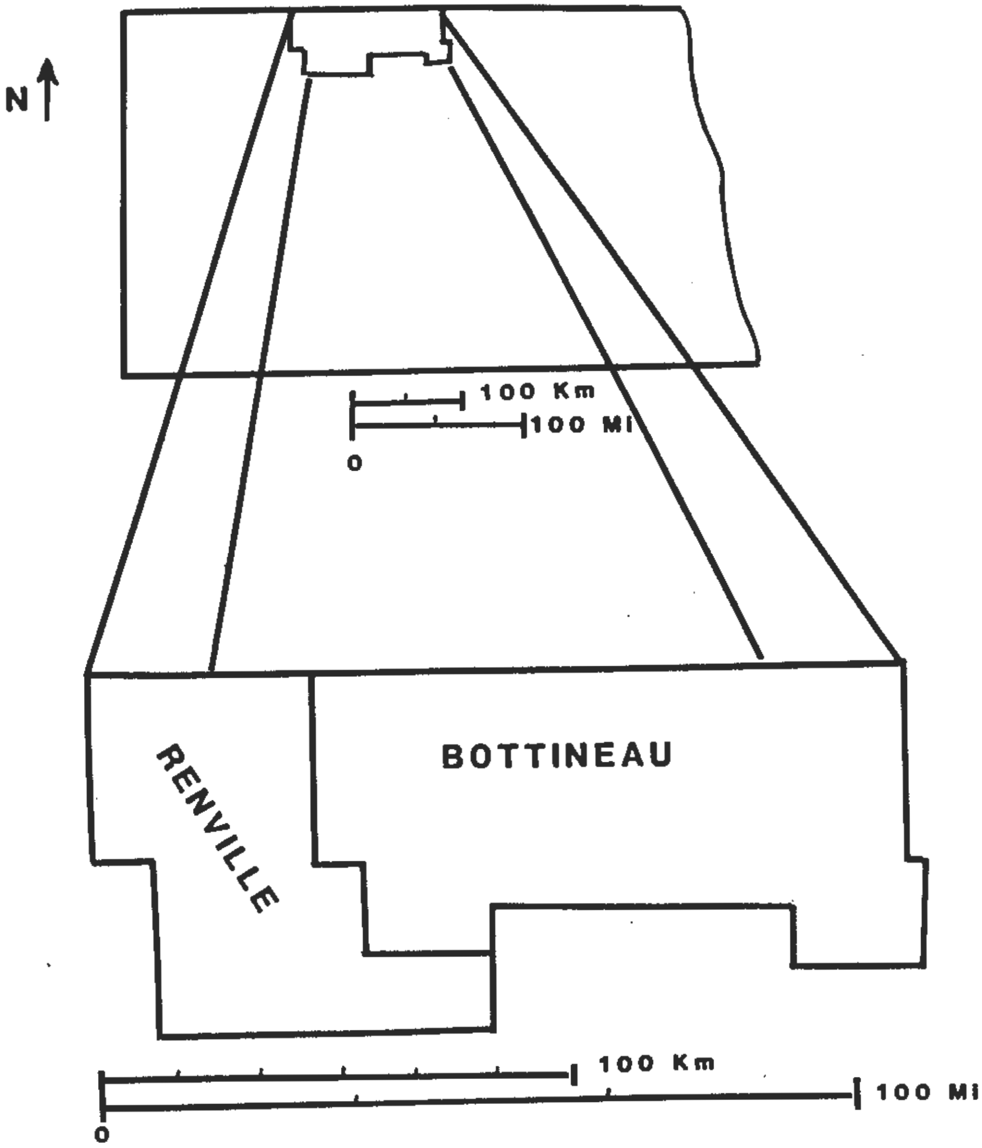


Figure 1 – The brine pit study area in North Dakota.

METHODS

Black and white aerial photographs from the Soil Conservation Service, USDA-ASCS and US Geological Survey were used to locate areas of brine pits in Bottineau and Renville counties. The photographs used in the identification process were from the following years: 1938, 1953, 1961, 1969, 1977, and 1979. The 1961 photographs were the most useful in locating the active brine pits because of distinct contrasting tones and timing regards the crop. Earlier growth stages of crops reflect saline damage better than photos taken at maturity.

Figure 2 shows a typical 1961 aerial photograph of the study area near Maxbass, North Dakota. Some caution is needed in the interpretation of pond sites. Point A shows a typical brine pit while point B shows an area of excavations associated with a gravel operation, and point C a watering pond used for cattle. The surface water of the brine pits did provide a good contrasting tone in comparison to the surrounding soil or vegetation. By knowing the exact location of the active brine pits from the aerial photography, it was quite easy to locate areas of potential contamination by salts moving from the pit area.

Overflights during this study were also used to evaluate contamination of salts originating from the pits. A 15-square mile area west of Maxbass was selected for the overflights. Figure 3 shows the location of the study area. Low-level oblique (approximately 200 feet) and high-level vertical (20,000 feet) photographs were taken in 1984 and 1985 to evaluate contaminated areas. Hand-held 35 mm cameras were used to take black and white, color, and false color infrared oblique photographs. The vertical black and white and false color infrared pho-

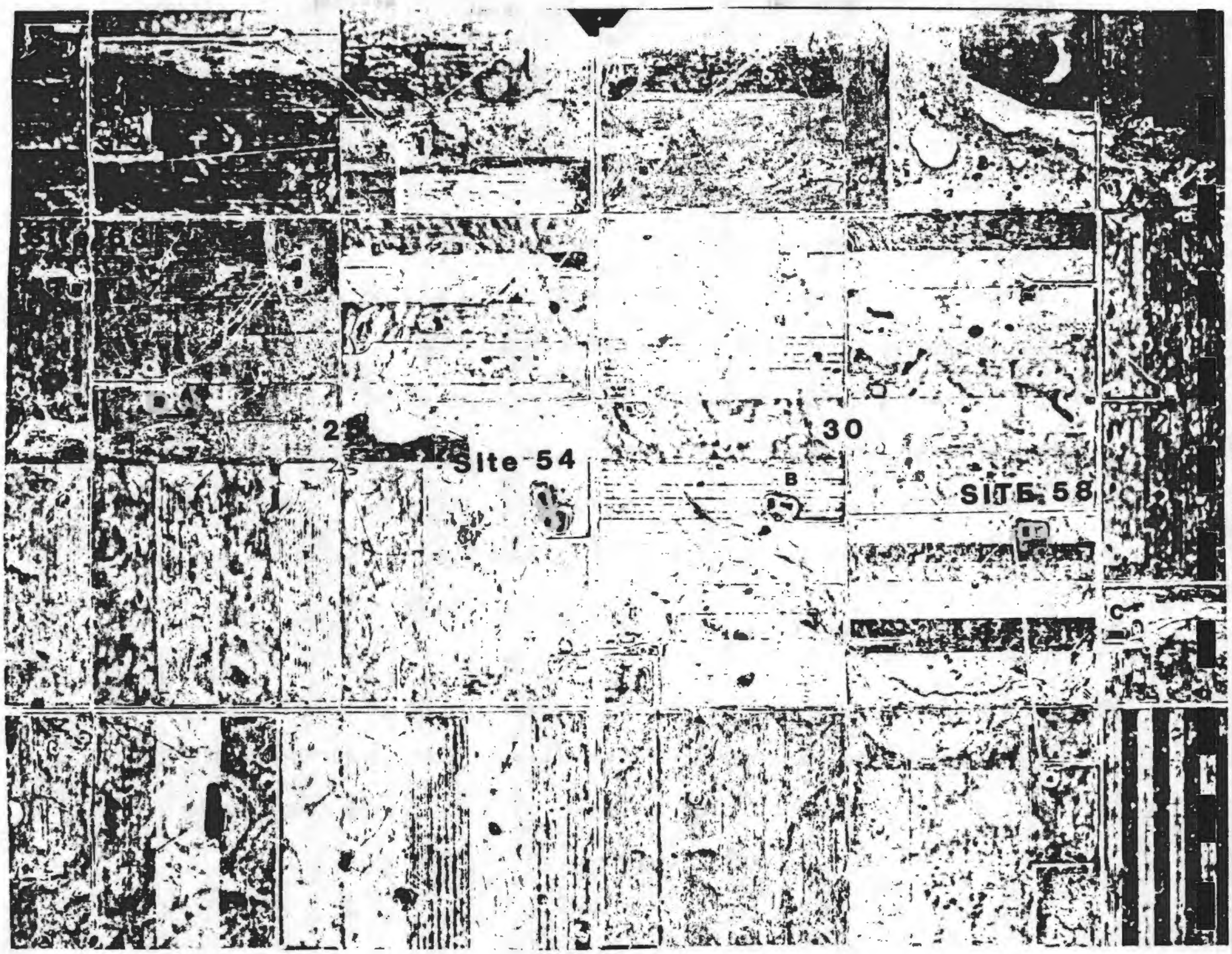


Figure 2--Aerial photograph of study area near Maxbass, N.D. showing brine pits. (Scale 1:20,000) Location: SW25, T161N, R82W, Sec. 30, T 161 N, R 81W. Photograph BA4 4 BB-200; 10-15-61. Point A shows a typical brine pit; point B shows a gravel pit operation, and point C is a dugout for watering cattle.

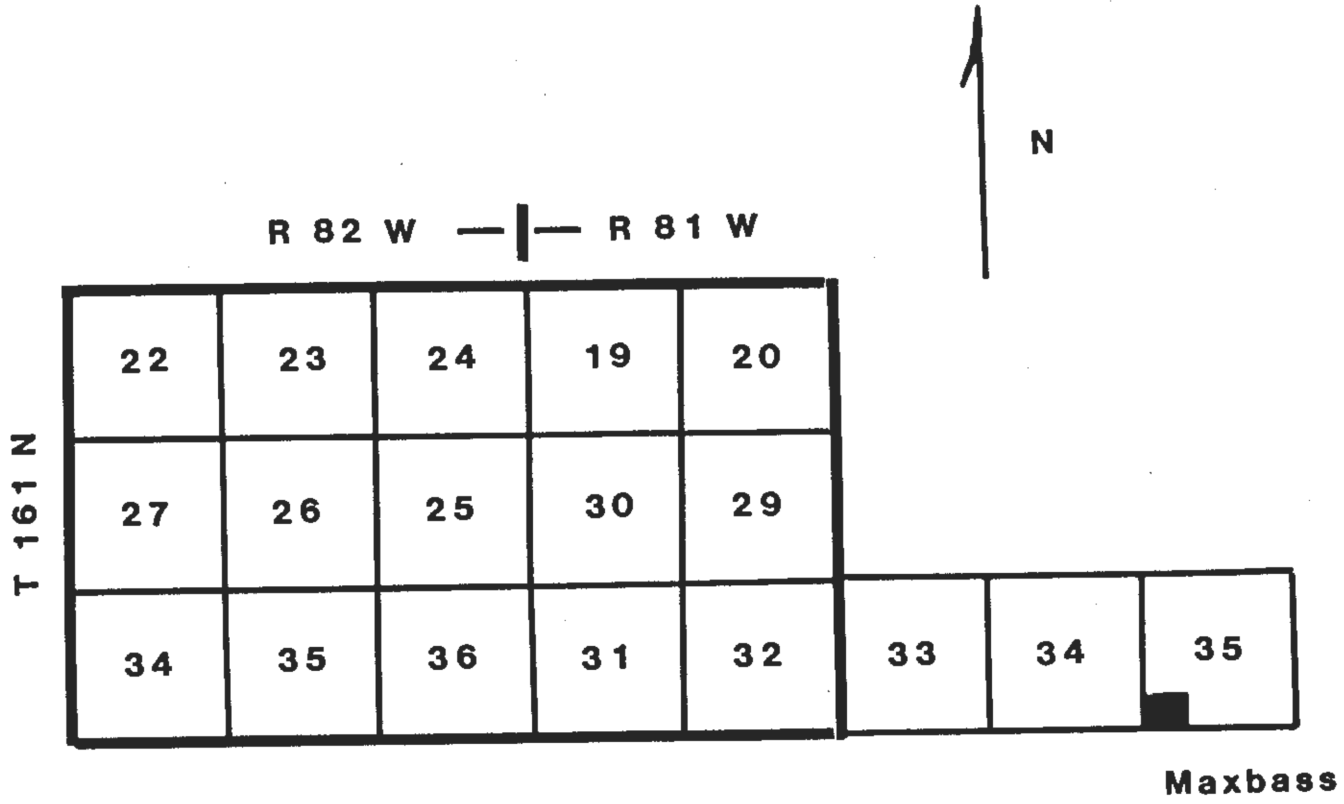


Figure 3—Location of a major study area west of Maxbass, North Dakota.

tographs were taken by KBM, Inc., Grand Forks, North Dakota using a Wild RC-8 aerial mapping camera with a Universal Aviogon 6 inch focal length lens (9 x 9 inch format).

Study areas for ground truth were obtained by (1) locating pit sites or contaminated areas on the 1961 to 1979 photographs and (2) reconnaissance surveys of the entire area to locate suspected areas of contamination. Levels of salt contamination in the soils were determined in the field by the use of an electromagnetic soil conductivity meter (EM-38) and the techniques of Wollenhaupt et al. (1986). Measurements were made at 50-foot intervals along several traverses at the various study sites. The information obtained on the traverses were transferred onto black and white aerial photographs (8 inches = 1 mile) to compare areal extent of the contaminated area in relation to the specific tones on the photographs. Figure 4 shows the location of the major brine problem areas in Bottineau and Renville counties.

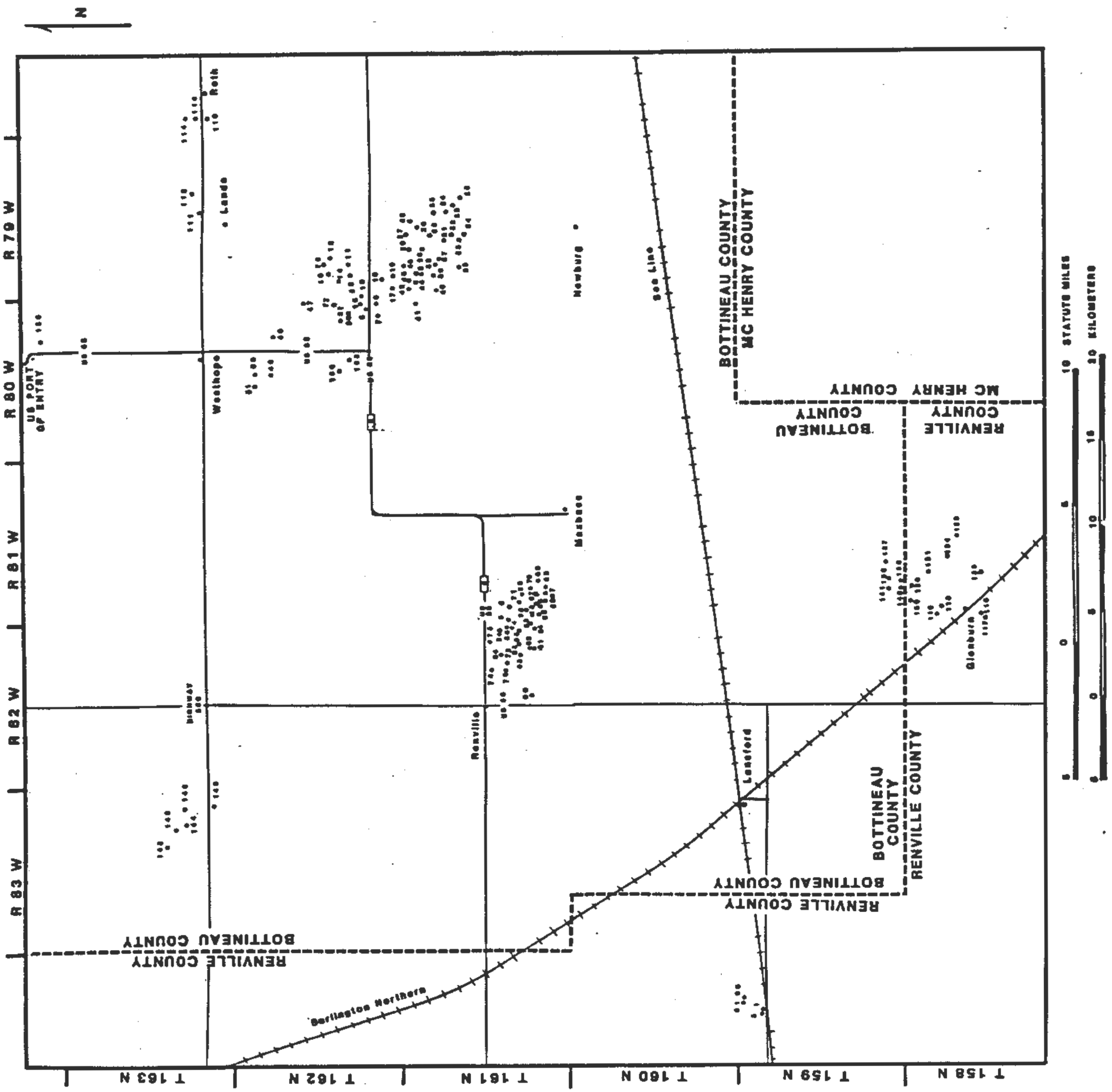


Figure 4. Major brine pit problem areas in eastern Renville and western Bottineau Counties, North Dakota.

RESULTS AND DISCUSSION

General Characteristics of Contaminated Areas

Figure 5 shows typical landscapes west of Maxbass, North Dakota in areas where salt has moved from the original brine pit. In Figure 5a the brine pit was located in the center (dark color) of the area which is devoid of vegetation. Salt has moved from the pit area into the surrounding landscape. Figure 5b shows the effect of typical overland flow of salt-charged water originating from the brine pit. Salts transferred in this manner was noted at numerous sites in Bottineau and Renville counties. Similar salt movement is seen in Figure 6, but the salt continues on the other side of the county road. The road ditch effectively blocks the overland flow spreading of salt. Seepage through the soil (throughflow) caused the downslope contamination on the other side of the road. Wheat is generally absent in low areas and grows better in higher areas in the field.

Identification of contaminated areas is quite easy in fields where crops are growing. It is more difficult to evaluate the level of contamination in fallow areas. Contamination of soils by throughflow is difficult to ascertain until the damage is severe (Griffin et al., 1984).

The distribution of contaminated areas correspond in most cases with the locations of the pits identified in the 1961 aerial photographs. The number and size of pits at a given site influence the level of contamination by the salt. Site 54 (Fig. 2 and 6), for example, had four pits and thus has resulted in 42.1 acres being severely contaminated with salt. Site 63, with one pit, had a total of 5.2 acres of salt contamination (Fig. 2). The length of time a salt brine pit was operating

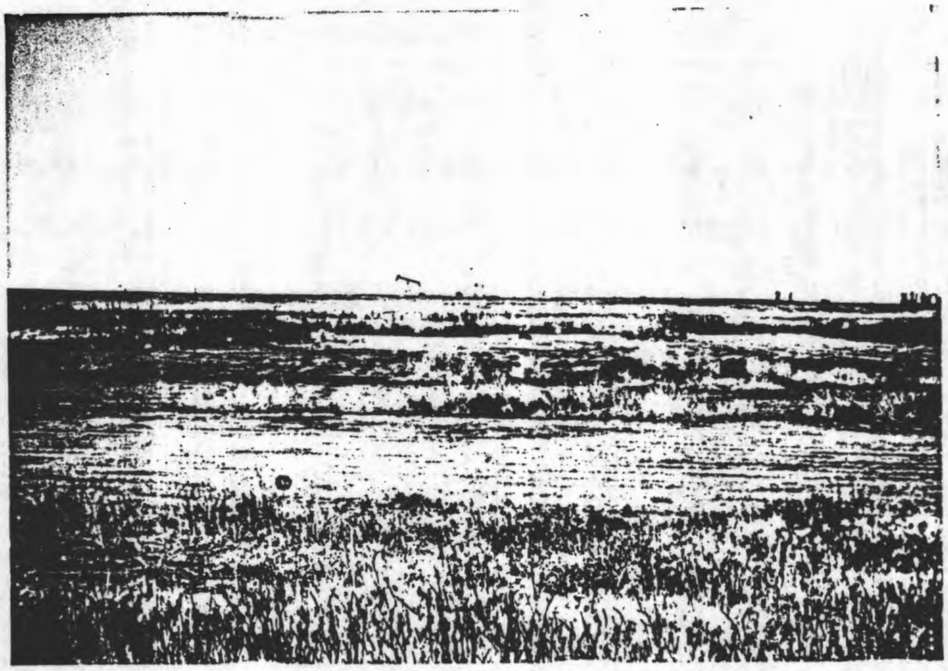


Figure 5a

Figure 5b

Figure 5--View of areas influenced by seepage from salt brine pits west of Maxbass, ND.

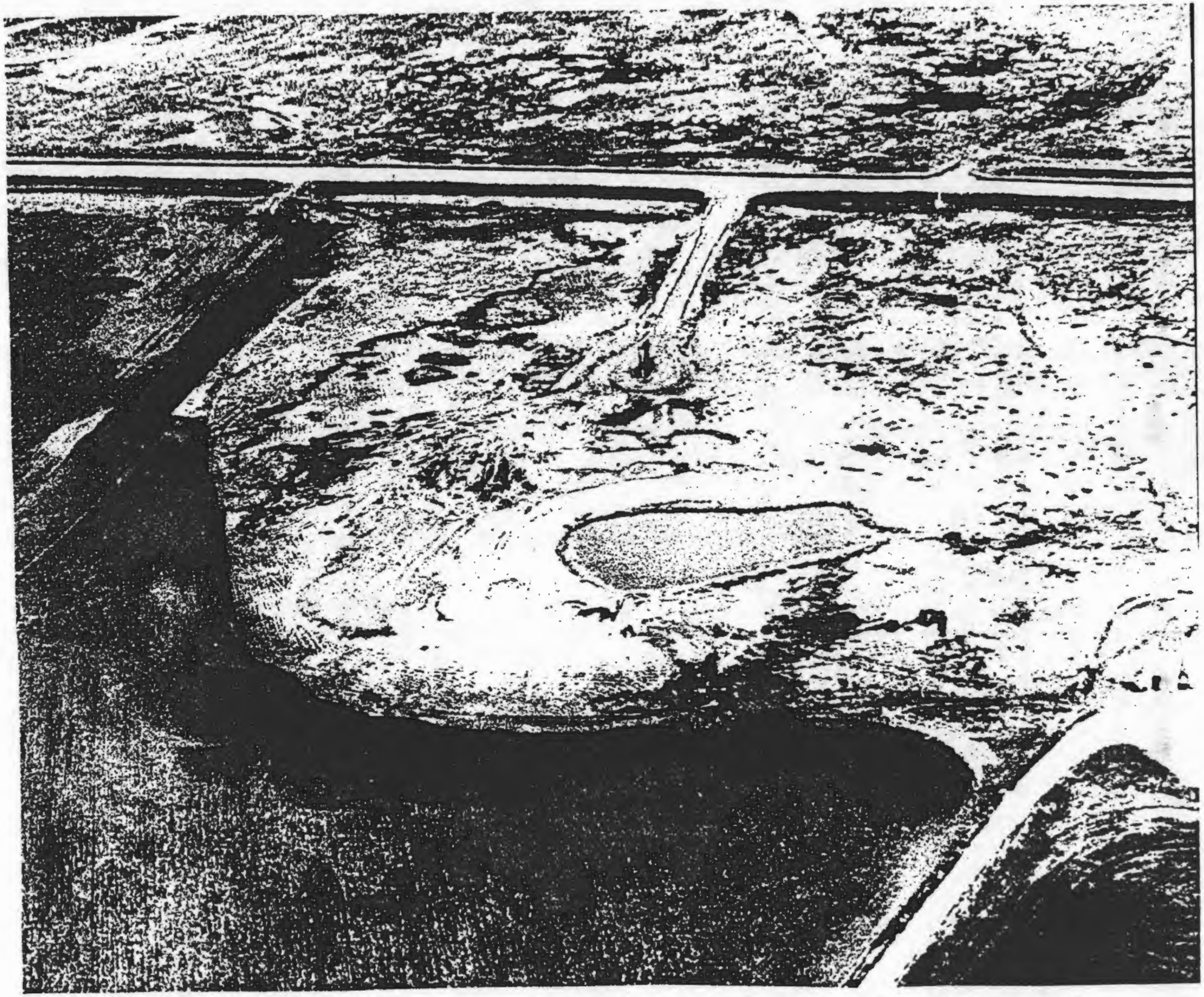


Figure 6--Oblique black and white serial photograph of study site S4, west of Maxbass, N.D.

undoubtedly played a role in the resulting contamination, but the air photo coverage was not frequent enough to determine the longevity of pits. Some pits noted in the 1961 photographs were still active in 1979.

Figure 4 shows the location of the areas where salt contamination was observed near brine pits. It is evident from the distribution of sites that contamination is widespread in the oil-drilling areas of Bottineau and Renville counties.

Remote Sensing Techniques

USDA Black and White Aerial Photographs. Black and white photographs obtained from the USDA were used for locating potential salt seepage sites and as base maps for field investigations. The scale of the photographs was 8 inches = 1 mile (1:9600). Figure 7 shows the 1979 USDA aerial photograph of a portion of the study area west of Maxbass, North Dakota. Areas of high salt contamination at sites 53, 54, and 65 are shown on the photograph. In poorly drained areas and wetlands, detection of high salt contamination was more difficult than in well drained areas because of the nature of reflectance from plant material not yet decayed from prior years. Site 65 is an active contamination site (Fig. 7). Complete coverage of the study area with these aerial photographs greatly facilitated the initial investigation of salt brine contamination.

Overflights. Oblique black and white, color, and false color infrared photographs were taken from approximately 200 feet above the land surface. Figures 6 and 8 illustrate the oblique black and white photographs of contaminated areas. The contaminated areas were quite

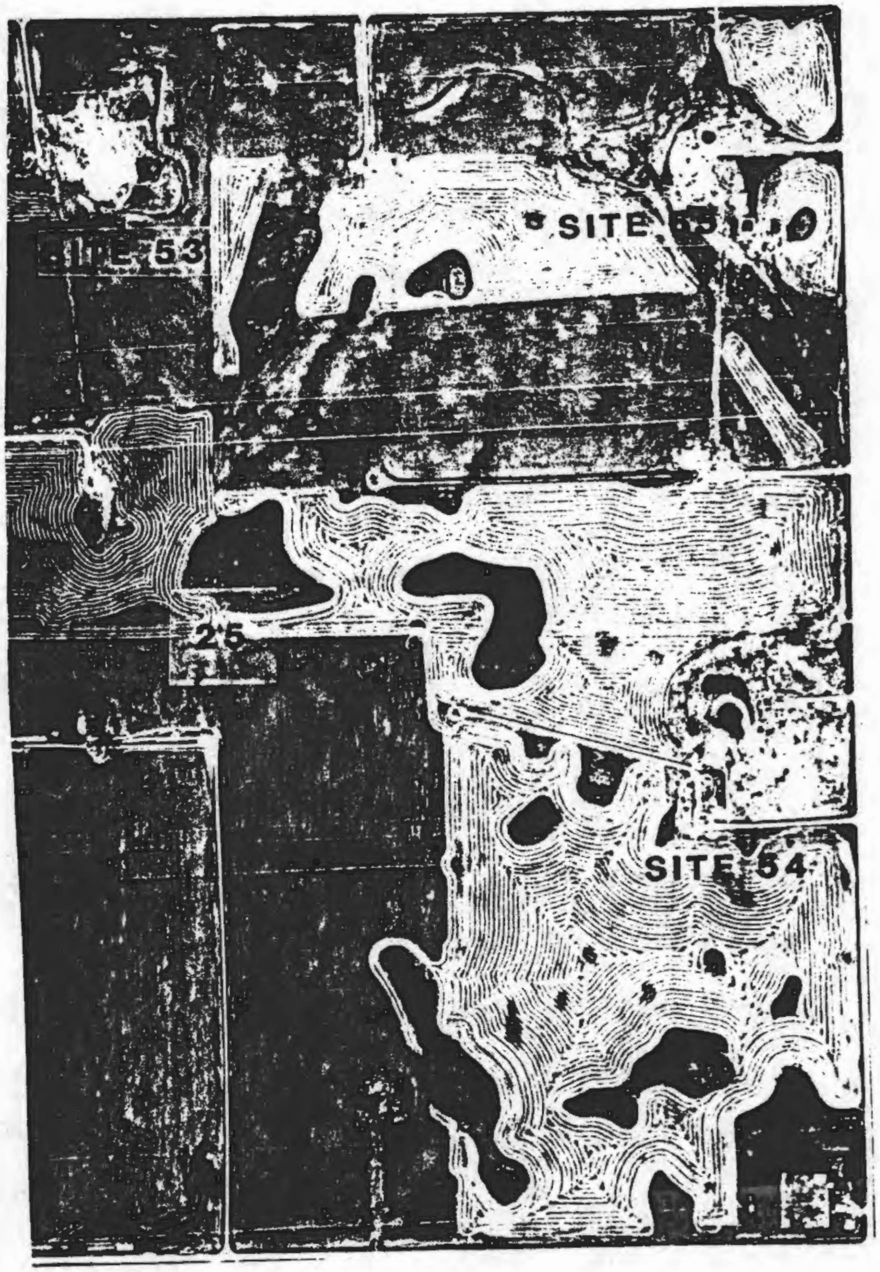


Figure 7-- USDA aerial photograph of study site west of Maxbass, ND. Location: E½ of Sec. 25, T161N, R82 W; Scale 1:9600 (8' = 1 mile)

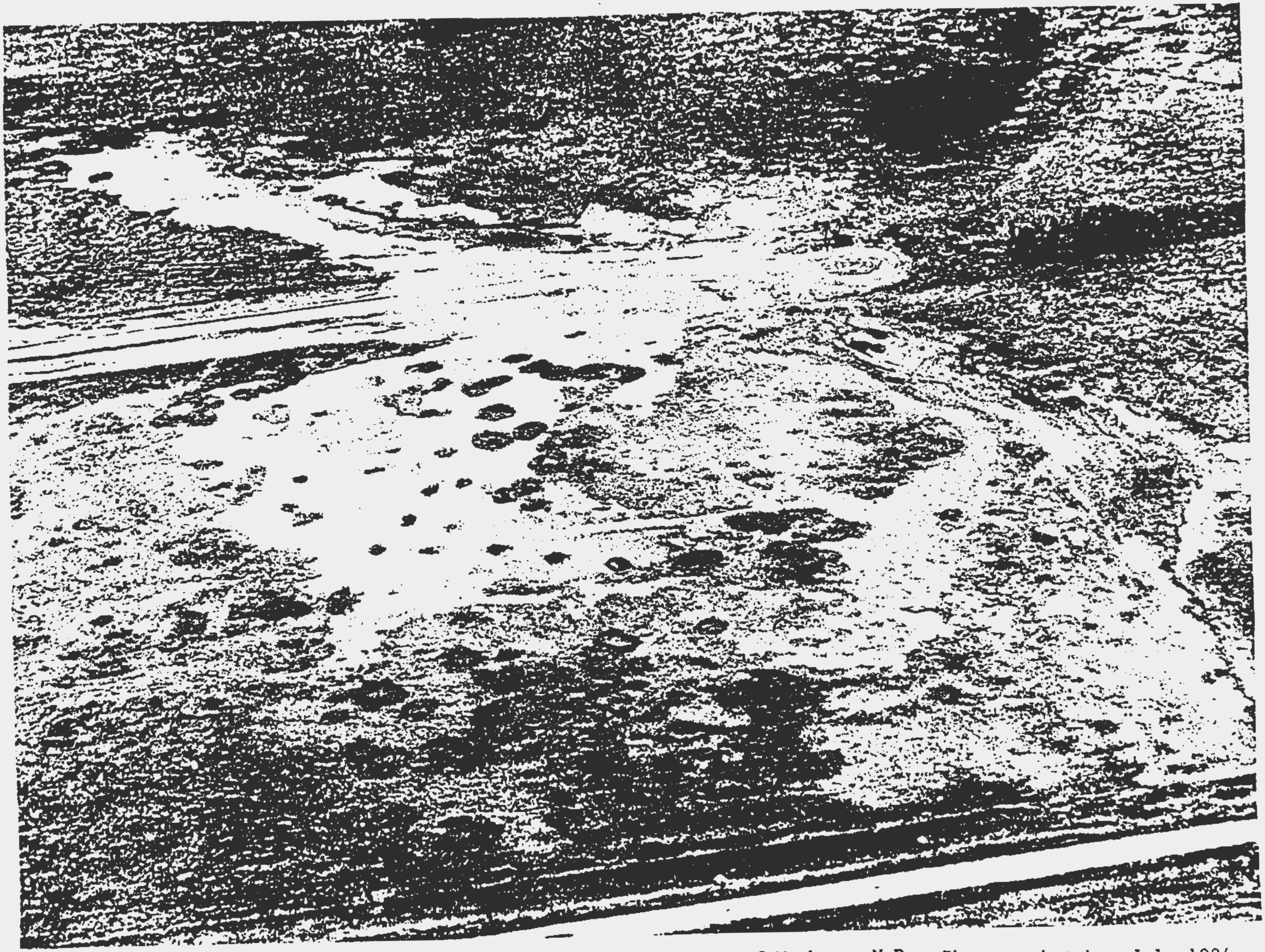


Figure 8--Black and white oblique aerial photograph of site 66, west of Maxbass, N.D. Photograph taken July 1984.

easy to detect because contrasting vegetation and soil tones are easily seen in the black and white photographs.

Figures 9a and 9b are color oblique photographs of site 54. Figure 9a shows the highly contaminated central area in nearly white tones, while the fringe areas show darker tones. The major direction of salt movement at Site 54 is to the northeast; thus, the flow is under the road and into the pasture. The numbers in Figure 9b refer to the measured meter readings of salt obtained from the salinity meter. Note the high values obtained in the central area (greater than 500 readings) and decreasing values in adjacent areas. Levels of 100 to 500 were noted in the pasture area and into the wheat field (lower edge of photograph).

Figure 10a shows a color and Figure 10b a false color infrared oblique photograph of Site 66 (41.5 acres) contaminated with salt. The color photograph shows the contrasting tones of the high salt area (base area) and the contrasting vegetation types in the salt-influenced area. The light green color is wild barley (Hordeum jubatum), a common indicator plant of salt in North Dakota. The origin of the salt is unknown, as the only pits noted on the aerial photographs in 1961 or 1979 were located approximately one-fourth mile west of the major area of salt concentration. A pipeline break could have resulted in the contamination.

Figure 11 shows the contrast between color (11a) and false color (11b) infrared aerial photographs in a pothole wetland being contaminated with salt from a brine pit. The salt brine pit was located to the south of the road just visible on the lower right hand corner of the photographs. The salt is moving laterally under the road and into the

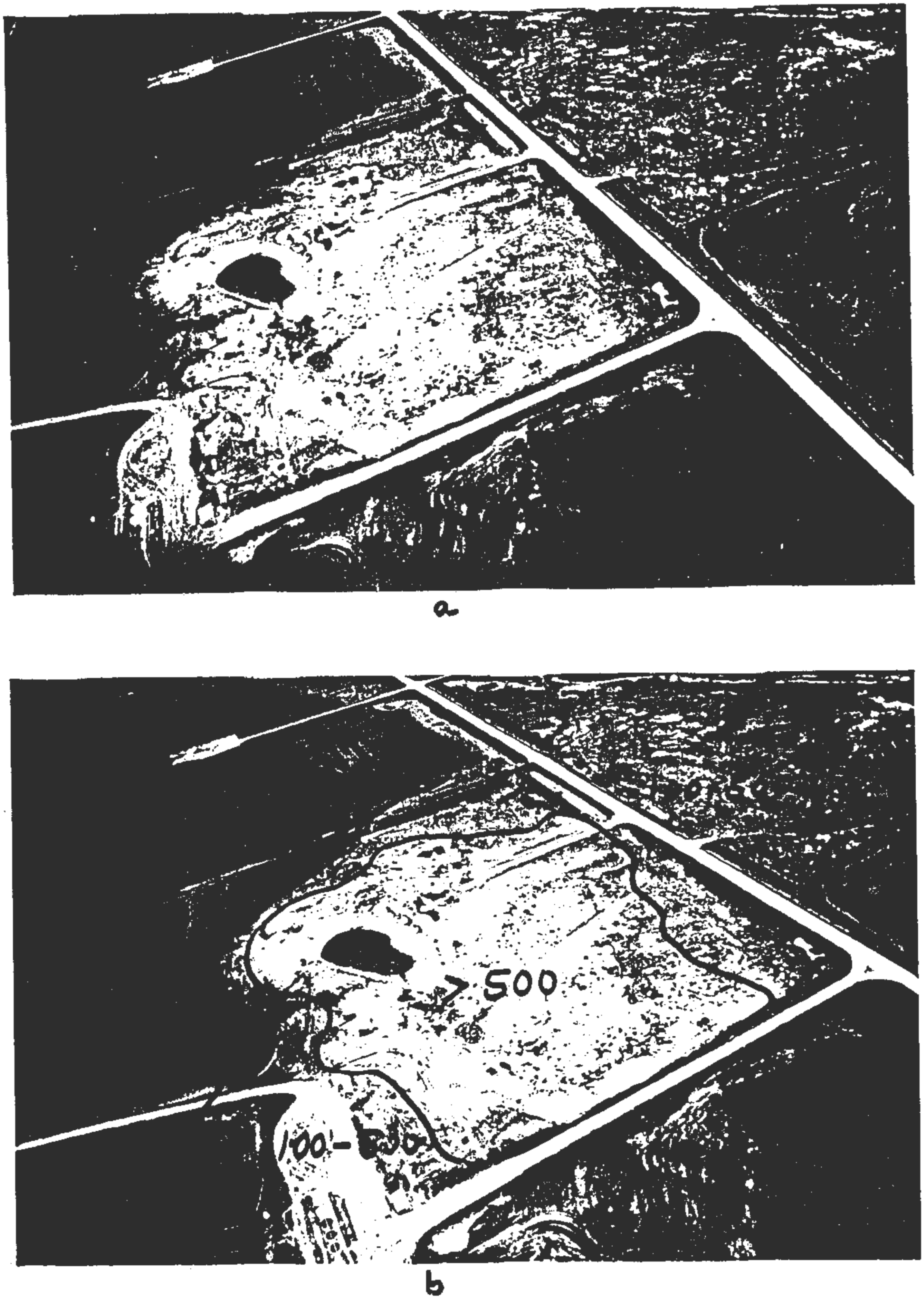


Figure 9. Oblique color aerial photographs of site S4, west of Maxbass, ND. Areas delineated in lower photograph show readings of salinity meter. Photographs taken July 1984; view is northeast.

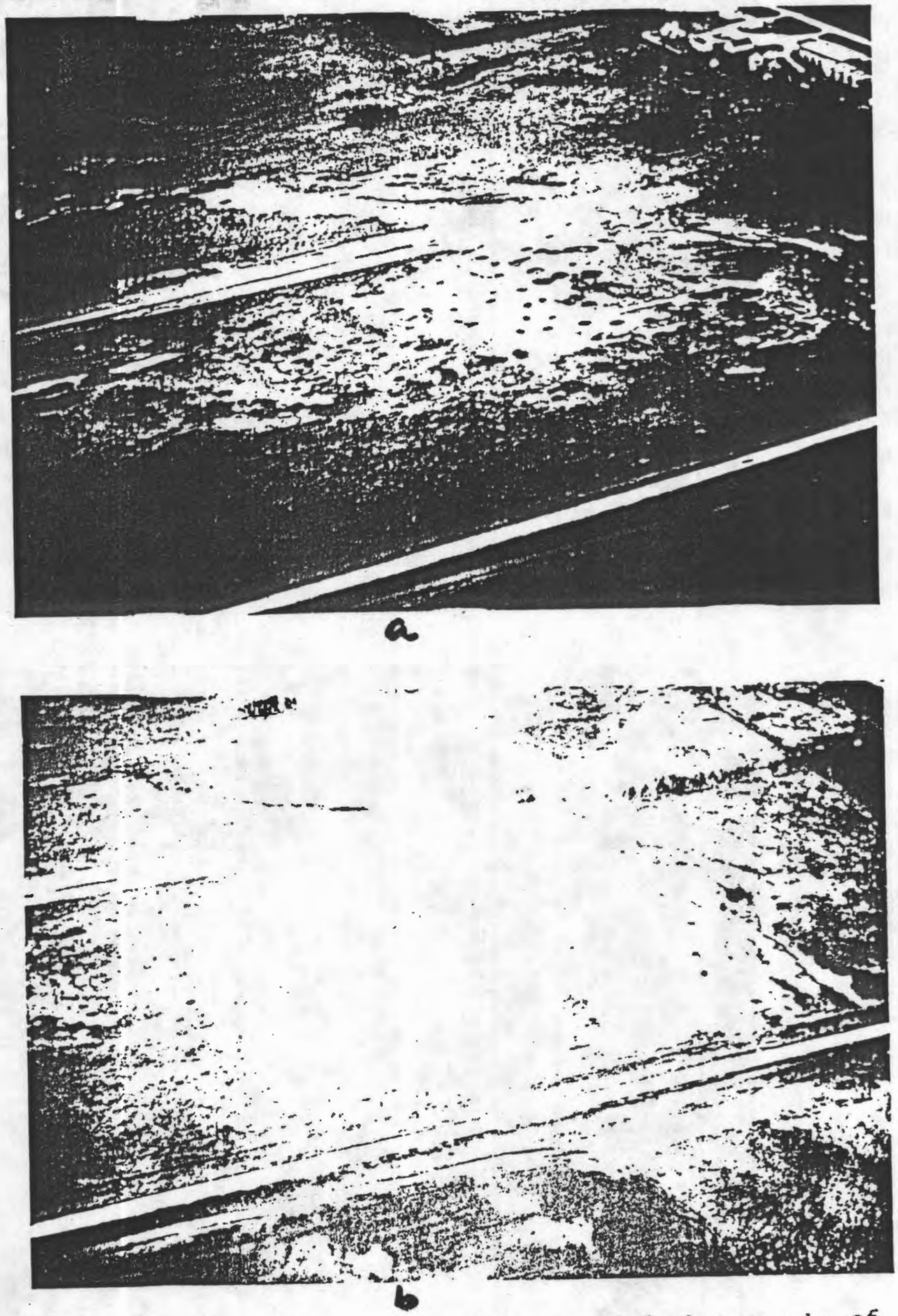


Figure 10--Color and false color oblique aerial photographs of site 66 showing salt contamination from brine. Photographs taken in July 1984.

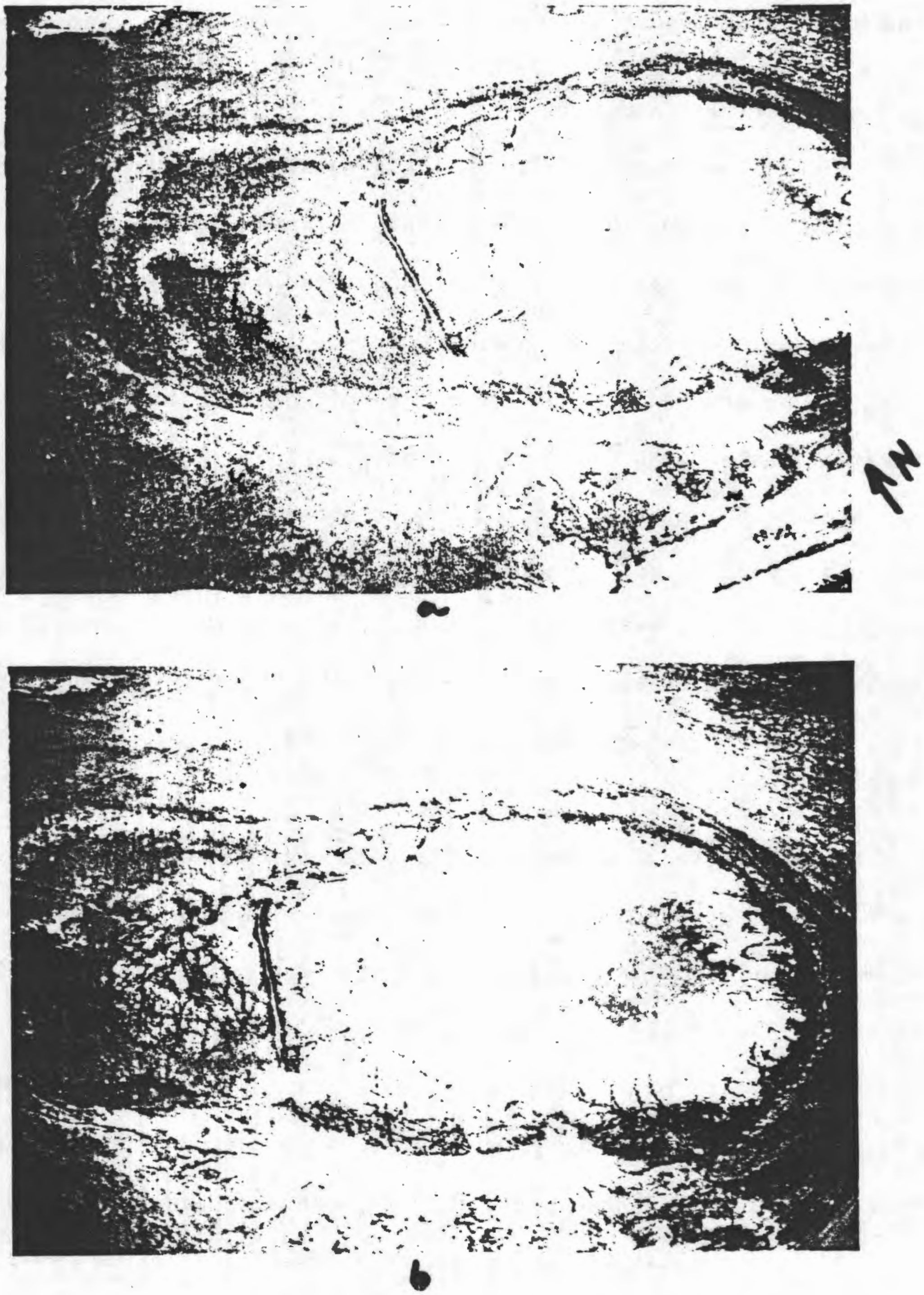


Figure 11--Color and false color infrared oblique aerial photographs of site No. 6 west of Maxbass, ND. View is north. Note salt movement into pothole. Photograph taken in July, 1984.

pothole. Observations subsequent to the photograph have determined that the throughflow under the road is causing further spreading.

Vertical Aerial Photographs

Figure 12 shows a 12-square mile area with salt contaminated soils generally showing lighter tones. Several areas were delineated on these photographs based primarily on field surveys using the salinity meter, with photo interpretation used to complete the delineations. Salinity could be separated into two categories of moderate (4-16 mmhos/cm) and severe (greater than 16 mmhos/cm) based on these interpretations.

Area A (Site 58) on Fig. 13a and b shows good contrasting tones between contaminated and uncontaminated areas. The infrared photograph readily shows the influence of high salt levels on the wheat field. Figure 14 demonstrates a similar comparison for Site 54. Note the salt influence on the wheat field to the south of the major zone of contamination.

Figures 15 to 18 illustrate (1) salt contamination growth during the period 1979 to 1985 and (2) the importance of high contrasting photographs for photo interpretation of salt contamination. In examining Sites 60 (Figure 15), 54, 58, and 93 (Fig. 16-18), it appears there has been some growth of the salt-affected areas during 1979 and 1985. Figure 19 illustrates the growth in areas of high salt contamination at Site 58 during the three years that the photographs were taken based on field data for 1984-1985 and photograph interpretation for 1979.

The importance of high contrast photographs for remote sensing is shown in Figure 15 to 18. Figure 15 demonstrates the variation of contrasting tones at Site 60, west of Maxbass. The photograph taken in July 1985 had strongly contrasting tones in the contaminated area; thus,

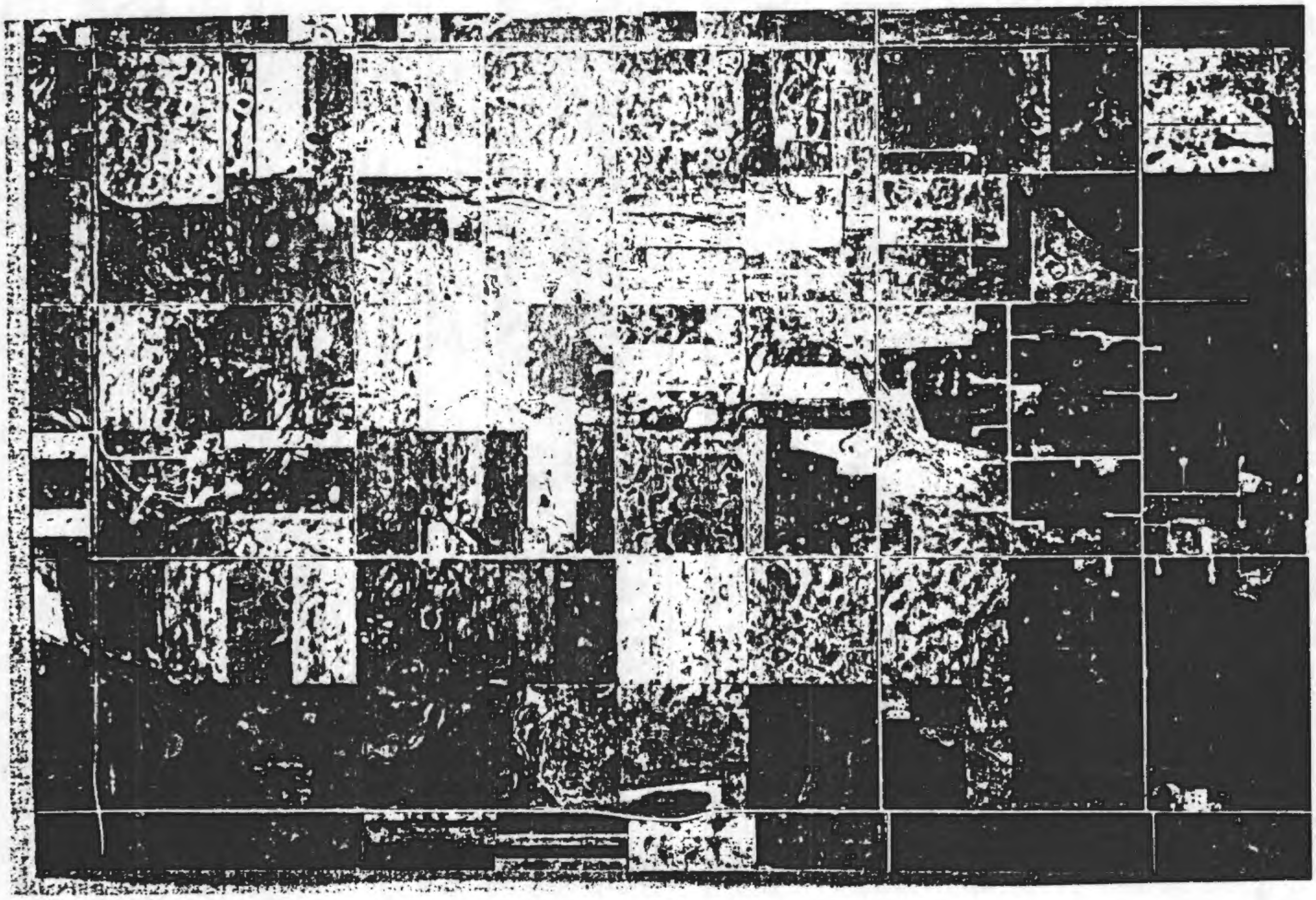


Figure 12--False color infrared aerial photograph of study area near Maxbass, ND. Photograph was taken July 19, 1984. Approximate scale is 1:45,257.

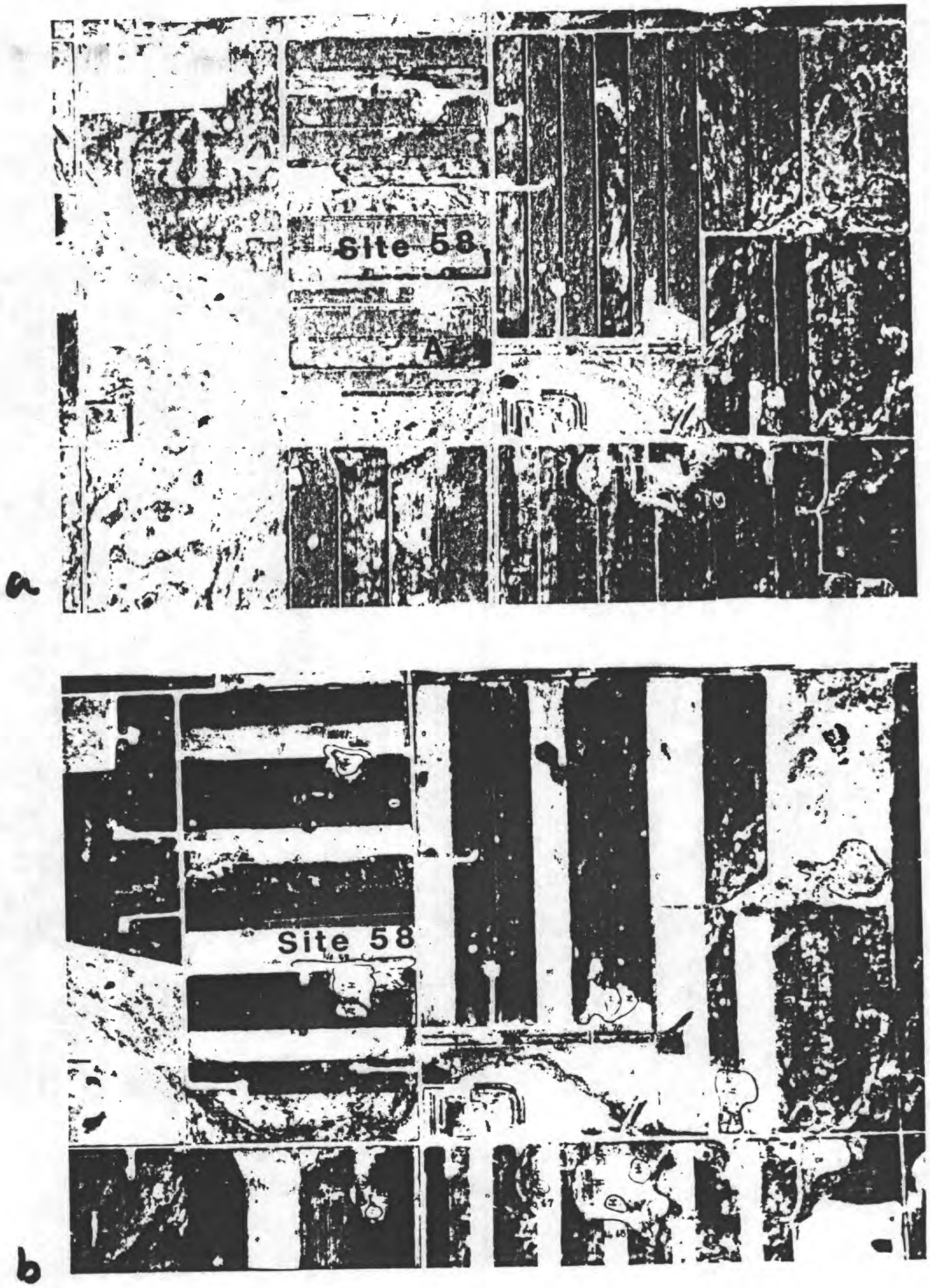


Figure 13a and b--False color infrared and black and white aerial photographs showing salt-influenced areas west of Maxbass, N.D. Note influence of salt on wheat growth at site 58.

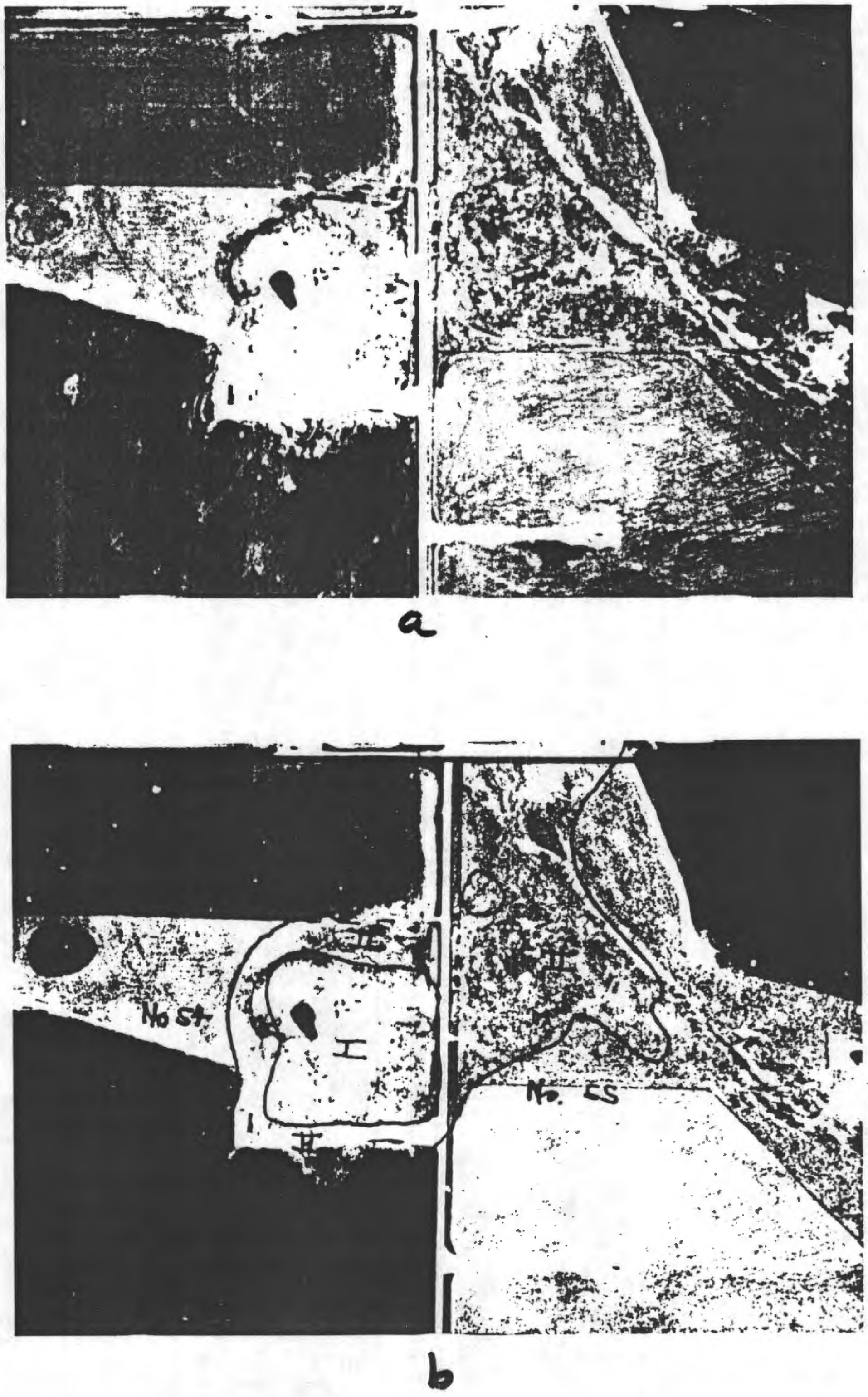
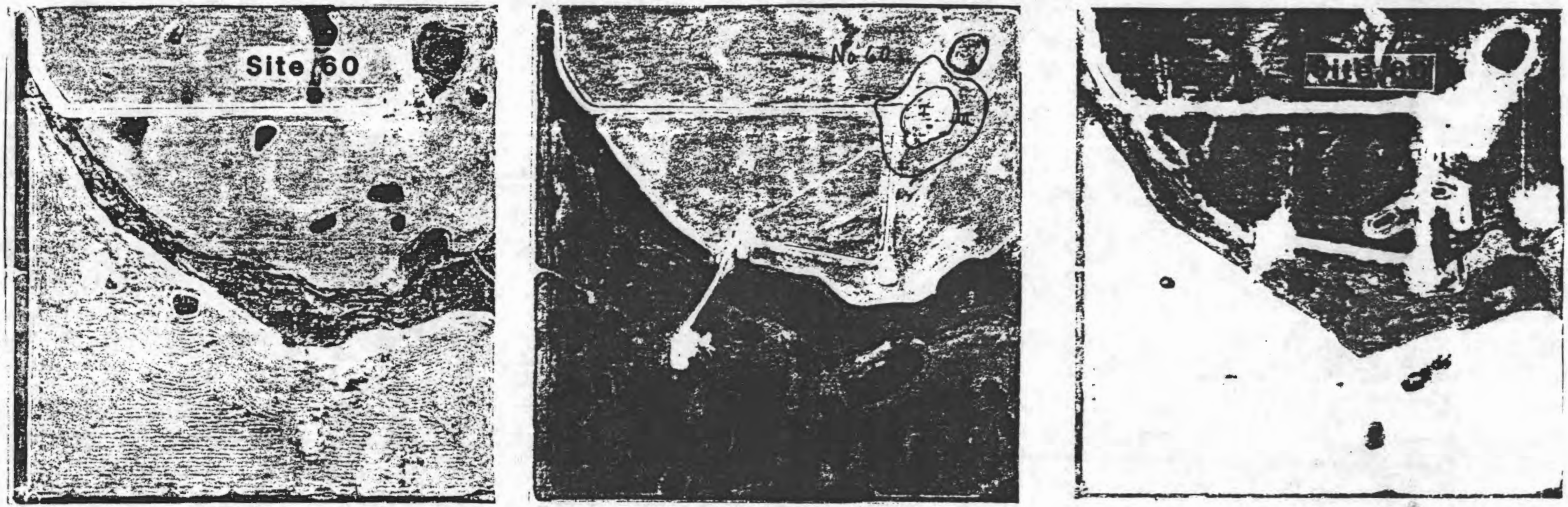


Figure 14--False color infrared and black and white aerial photographs of site 54 showing area of salt contamination from brine pits. Scale is approximately 1:11,652 (1" = 971').



a

1979

b

1984

c

1985

Figure 15 Black and white aerial photographs of Site 60 for 1979, 1984, and 1985. Scale is 1:9600.

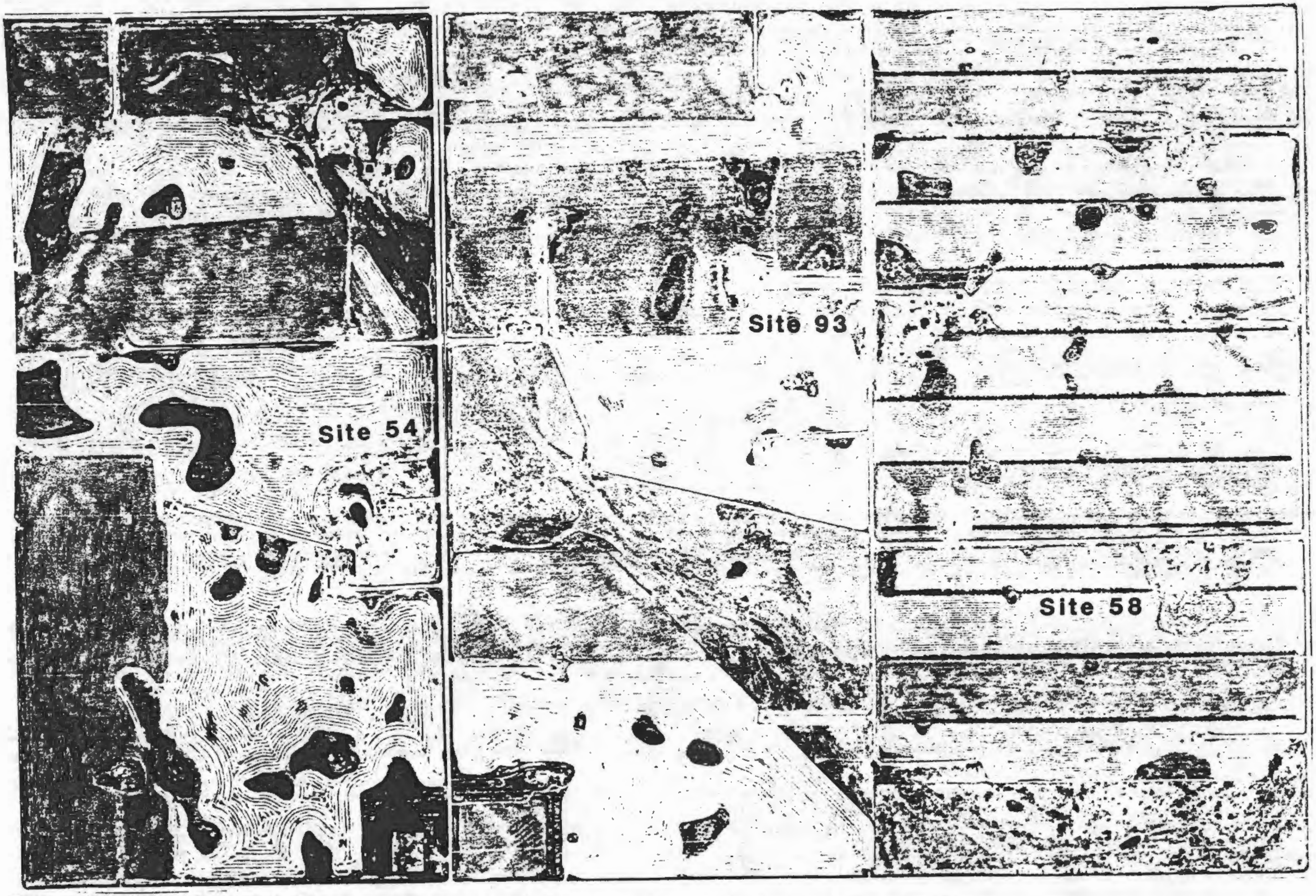


Figure 16--USDA black and white aerial photograph of a portion of study area west of Maxbass.

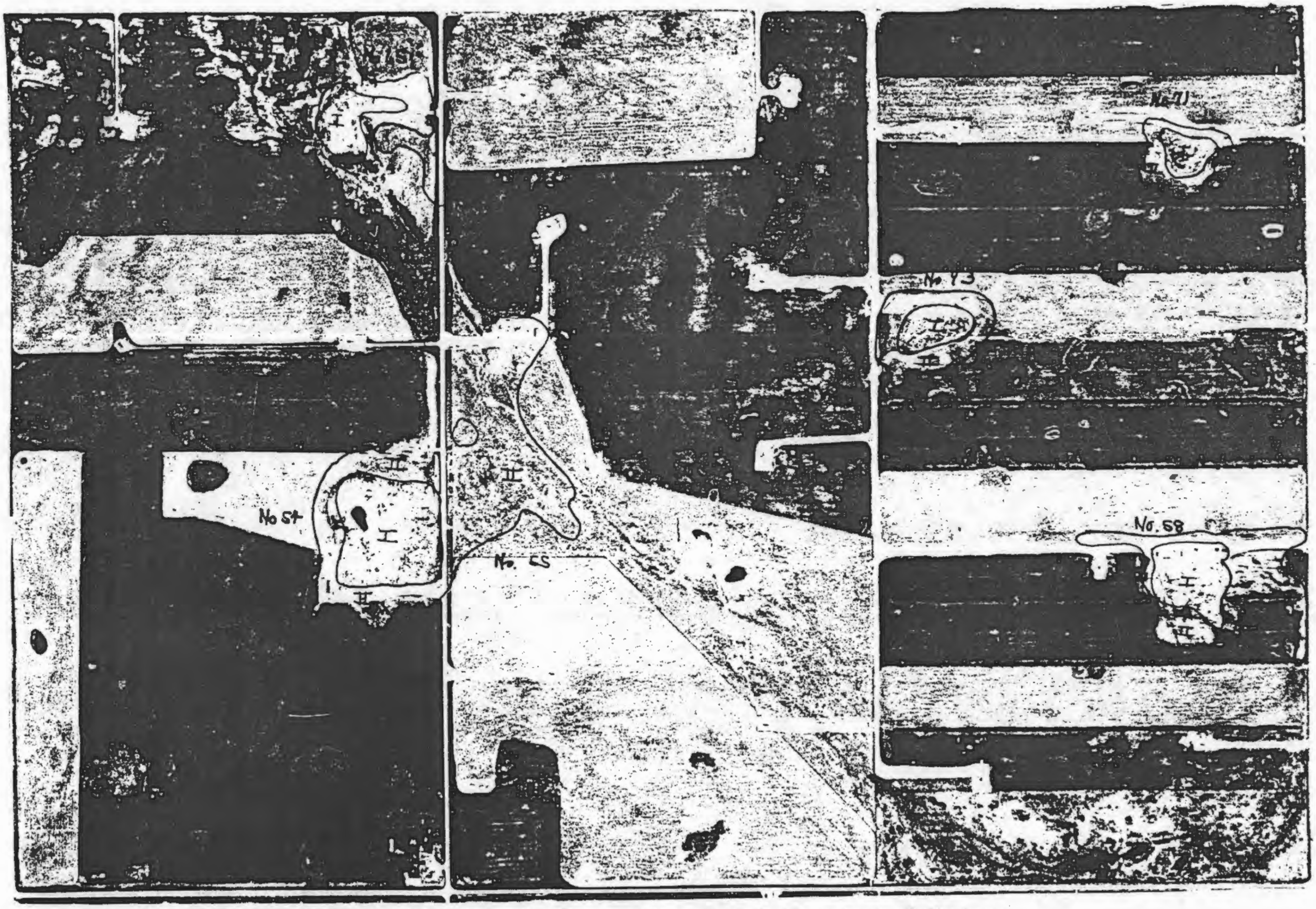


Figure 17--Black and white aerial photograph of a portion of study area west of Maxbass
Photograph taken July 12, 1984.

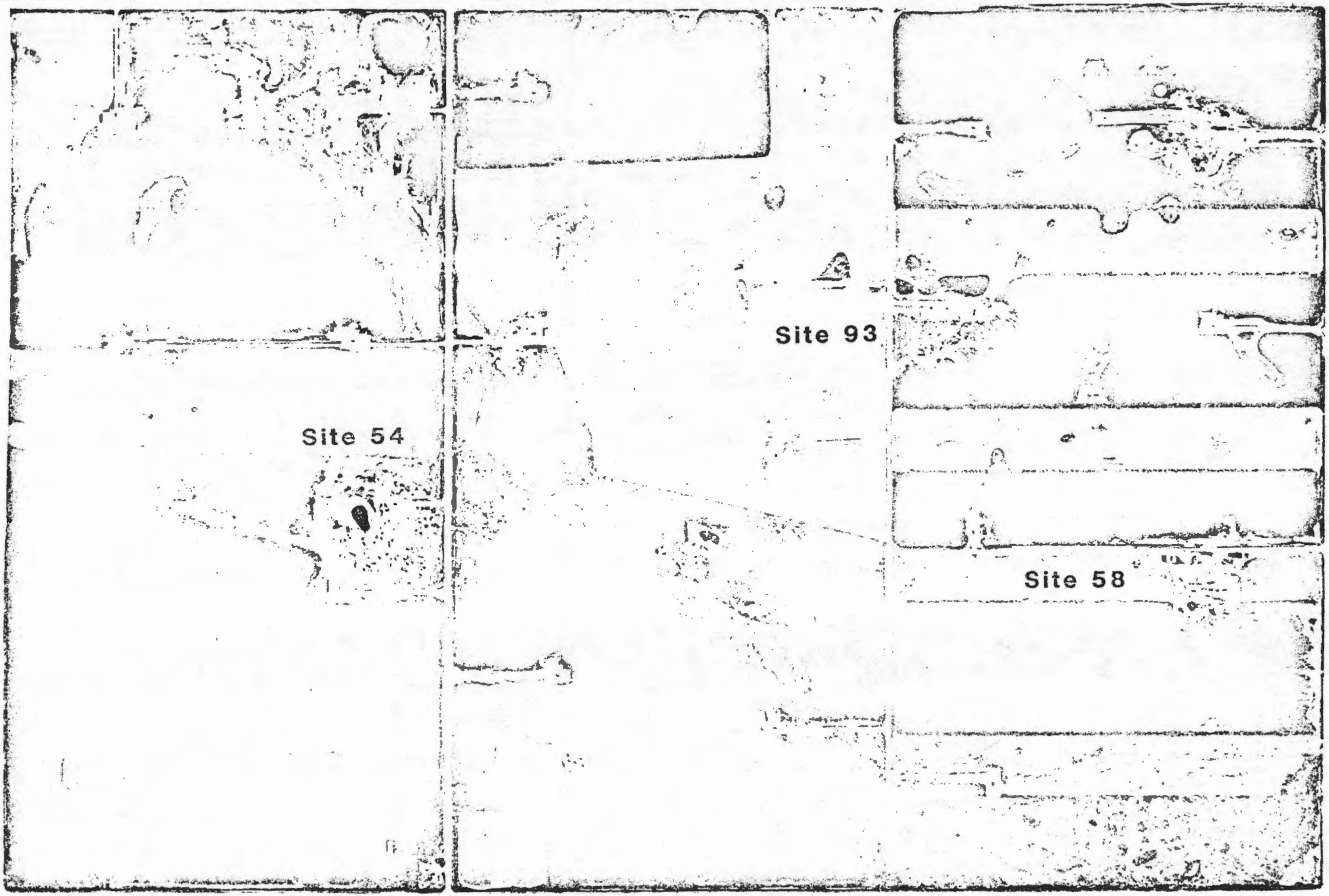


Figure 18--Black and white aerial photograph of a portion of study area west of Maxbass. Photograph taken July 19, 1984.

Brown Disposal

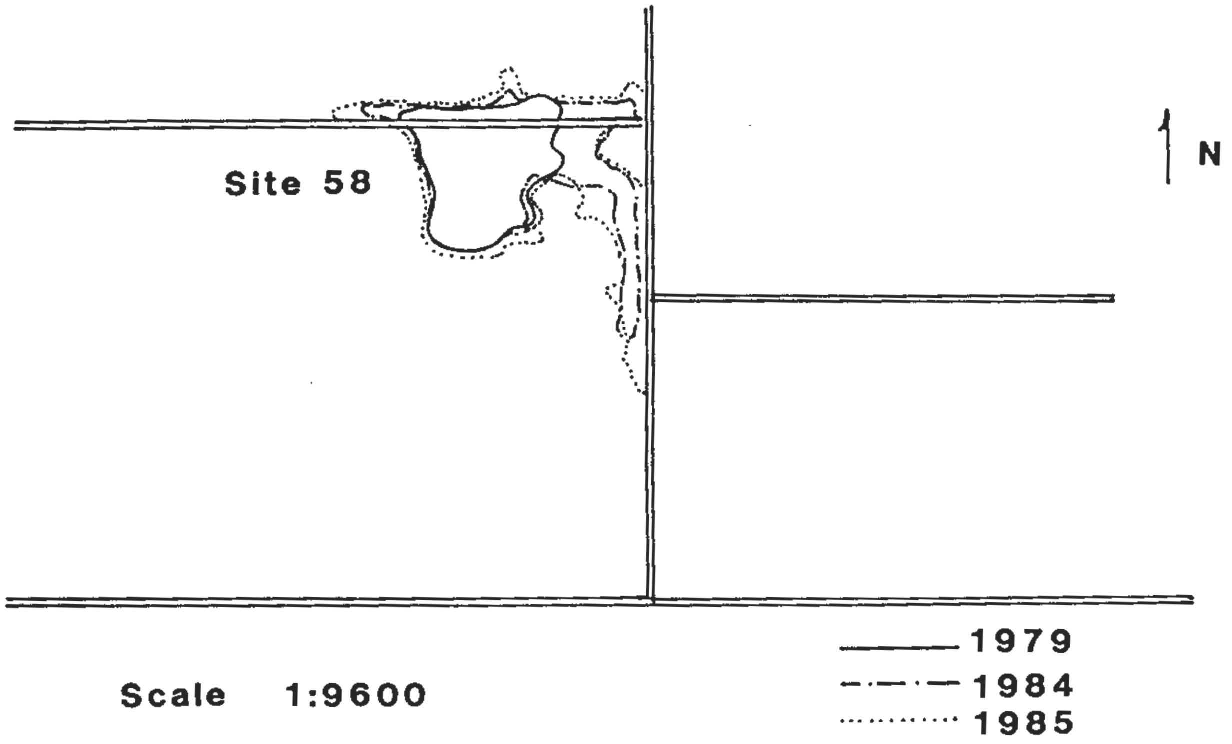


Figure 19 Sketch of site 58 showing salt contamination in 1979, 1984, and 1985

the mapping of these areas would be greatly facilitated by this new photography. A problem in 1985, however, was the abundant rainfall that occurred during the spring and summer. Many potholes were filled with water, as well as other poorly drained areas. Notice at Site 60, for example, that the pothole to the northeast of the sites was filled with water at the time the photograph was taken. The high water levels prevented investigation of some contaminated sites.

Areas of Brine Contamination

Table 1 shows the size of areas contaminated with salt brine in the major study area west of Maxbass, North Dakota. As noted on this table, 265.6 acres had meter readings greater than 100 (greater than 4 mmhos/cm) that would have a deleterious effect on the growth of wheat. Figure 20 shows the general relationship between the meter readings and a relative value for wheat growth. Meter readings greater than 400-500 generally showed little vegetative growth of wheat while values less than 100 showed little influence of wheat growth compared to surrounding uncontaminated areas. The average size of the 23 sites mapped in the 15 square-mile area was 11.5 acres but these had a large variability. The total acreage of contamination in the study sites in Bottineau and Renville counties is approximately 1450 acres.

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Wollenhaupt, N. C., J. L. Richardson, and E. C. Doll. 1986. A rapid method for estimating soil salinity from apparent soil electrical conductivity measured with an above-ground electromagnetic induction meter. Can. J. Soil Sci. Accepted for publication.

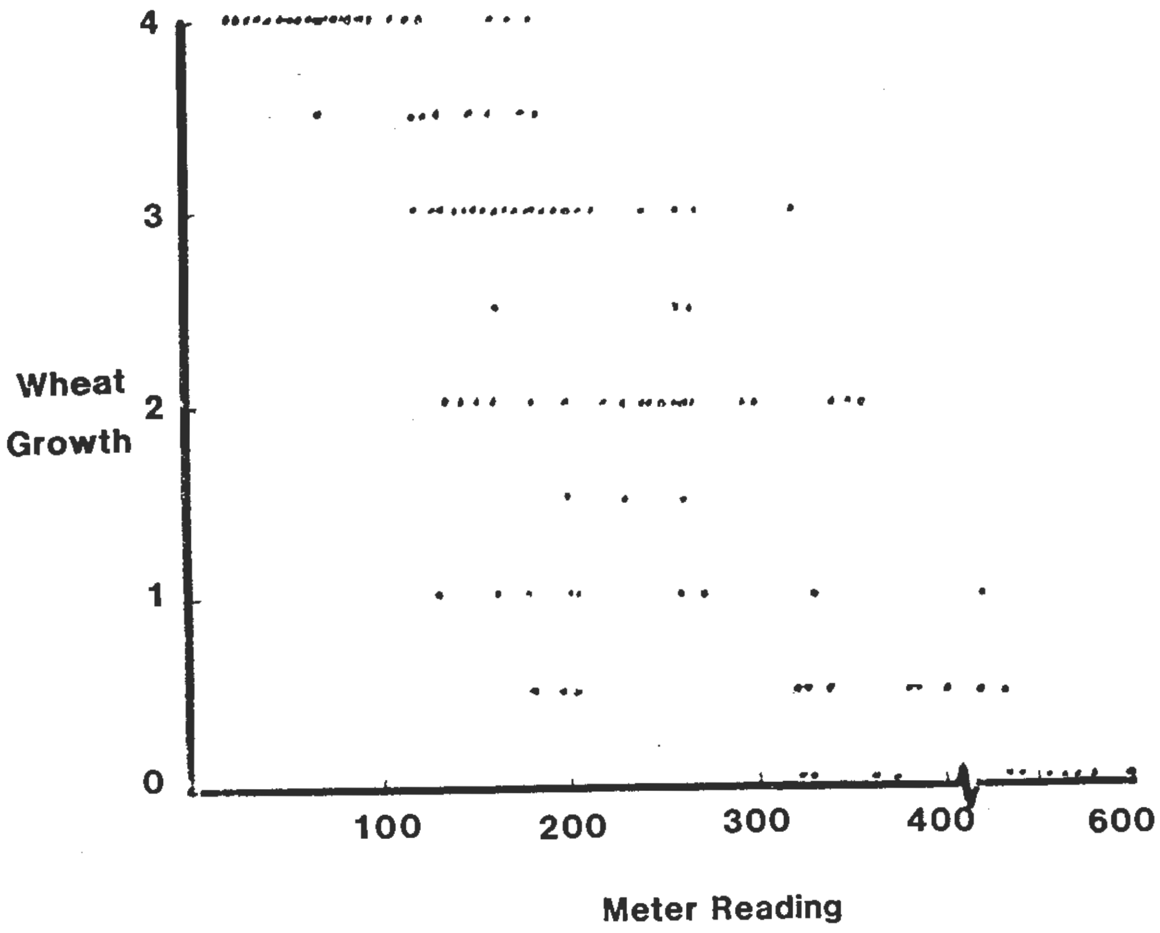

Figure 20--General relationship between meter readings and wheat growth for 5 representative sites in Bottineau County. Ratings are as follows: 0 = bare soil; 1 = sparse wheat plants, greatly stunted; 2 = stunted plants (50% of normal), sparse; 3 = stunted plants, 80% of normal height; 4 = normal plants.

Table 1. Size of salt contaminated areas in major study area west of Maxbass, North Dakota.

Site Number	Size of Area Acres	Site Number	Size of Area Acres
5	4.0	66	41.5
6	13.5	67	0.7
53	20.7	68	20.2
54,55	42.1	69	5.7
56	4.5	70	6.2
58	14.1	71	5.0
59	0.4	72	3.0
60	6.0	73	9.4
61	2.6	74	6.2
62	3.7	75	11.9
63	5.2	93	7.5
65	31.5		

Total Acreage = 265.6
Average Size = 11.5 Acres

TASK 2

Salt Movement in Buried Brine Disposal Pit Areas as related to Chemical and Physical Properties of the Soil and Geologic Materials and to the Surrounding Landscape

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INTRODUCTION

Brine saturated with NaCl from oil and gas production in North Dakota was disposed of by placement in evaporation pits in the 1950's and 1960's. After about 1972, regulations required that the brine be injected into deep disposal wells, and the pits were filled with the previously excavated soil materials. The soils surrounding the buried pits are now becoming contaminated with NaCl salts which are still moving from the pits. More land is becoming degraded each year.

The objective of this task of the study was to characterize the movement of salts and other chemical constituents in surface and subsurface waters from the buried brine pits. Samples were taken to a depth of 10 feet, although a few observations extended to 15 feet.

Detailed studies were made of two contaminated sites, and the data from each site will be discussed separately. A number of graphs and figures are used to illustrate salt movement at each site. Complete data for each site are given in Appendix 2.

The specific objectives of this phase of the project were to:

1. Develop a systematic approach to determine the amount of soluble salts in brine disposal pits and to evaluate the potential hazard for contamination due to movement of these salts in surface and subsurface water into the surrounding area as related to:
    a. topographic location
    b. surface and subsurface drainage
    c. soil type
2. Use information obtained in Objective 1 to prepare tentative methods to prevent and alleviate water and soil degradation by salts moving from brine disposal pits.

METHODS AND PROCEDURES

Site Selection:

At the two sites which were selected, preliminary survey data had previously been reported (Lang and Doll, 1983). The sites are located on the Fossum Farm, which is owned by North Dakota State University and managed by the NDSU Development Foundation.

Site 1 is located in the SW1/4, NE1/4, SE1/4 of Sec. 30, T. 161 N, R. 81 W, and site 2 is located in the SW1/4, NE1/4 of Sec. 30, T. 161 N., R. 81 W, both in Bottineau County, North Dakota. The general location is three miles west and one mile north of Maxbass or approximately 35 miles north of Minot.

The landscape at these sites is formed from till and glaciofluvial sediments. The topography is gently undulating with numerous small closed depressions which seasonally pond water.

The location and approximate size of the brine disposal pits were determined from 1959 black and white photographs. The initial assessment of the spread of brine from the buried disposal pits was made from color and false color infrared pictures taken with a hand-held 35 mm camera, supplemented by ground observations of the vigor of the vegetation at both sites. Dead and severely stressed vegetation, both shelterbelts and small grains, were good visual indicators of the extent of salt movement. Portions of both sites were fallow (bare ground). Because of the large size of the potentially contaminated areas, intensive systematic field sampling would have been impractical for establishing the boundaries of the spreading contamination. Therefore, a technique was developed to use an above-ground electromagnetic induction meter to survey the extent of brine contamination.

Electromagnetic Induction Meter (EM38):

Recently, instruments which apply electromagnetic techniques have been developed to measure soil electrical conductivity. The EM38 meter (manufactured by Geonics Limited) has an intersoil spacing and operating frequency which is effective for measuring conductivity to a depth of 2 meters. The apparent electrical conductivity (EC) of the soil as measured by the meter is related to several soil parameters including clay content, soil moisture, salinity, temperature and etc. However, at a given time and location most of these parameters are constant. As a result there is a high correlation between the meter reading in the field and conductivity measured in the laboratory using of a saturated paste extract (EC_e) of a soil sample. Wollenhaupt (1984) reviewed the literature on this technique and methods for correlating soil salinity to the meter conductivity measurements.

The EM38 meter was used to define the boundary of contamination movement, then a grid was laid out on a 100-foot cell spacing for each of the two research sites. The 100 foot coordinates were flagged. Meter readings (both horizontal and vertical position) were then recorded at 50 foot intervals. A salinity map of the area was constructed by transferring meter values to graph paper and drawing boundaries between the various levels.

The contoured EM data gave a precise approximation of the movement of salts from the brine pits and the concentration distribution over the entire degraded area to a depth of 2 meters.

Soil Sampling:

Core sample sites were based on the EM38 survey and were taken in a modified grid pattern. Initially, 24 and 20 undisturbed cores were collected at Fossum Sites 1 and 2, respectively, in October 1983. Eleven additional cores were collected at Site 1 and 4 at Site 2 in April 1984. The locations of the core samples for Site 1 are shown in Figure 3 and for Site 2 in Figure 23. The sample sites are identified by the distance from the 0,0 location on the diagram. For example, the core site at Fossum Site 1 which is 200 feet east and 300 feet south of the 0,0 corner would be identified as 2,3 where both distances are divided by 100.

The undisturbed cores were collected with a Giddings hydraulic coring machine. The sampling depth was 10 feet in most cases, with a few cores taken to 15 feet. Upon removal, the core segments were placed in metal trays to form one continuous core. The core was then described for color, texture, consistency, horizonation, weathering zones, parent materials, presence of secondary gypsum and carbonates, and other observable features. Standard soil survey terminology (USDA Handbook No. 18) was used except that weathering zone terminology was that defined by Hallberg et al. (1982). The cores were then separated into 1-foot increments and bagged for analysis of chemical and physical properties. A few surface (0-1 foot) samples were divided into 6-inch increments.

Two nearby noncontaminated (reference) toposequence transects were also sampled using the above procedure. Three cores were collected to a depth of 10 feet at transect FA and to a depth of 9 feet at transect FB (Figures 1a and 2a). These cores were also described and bagged for laboratory analysis. Additional cores were collected to 6 feet for description purposes only.

All core holes were left open and the depth to free water surface was measured at the end of each sampling tour.

Topography:

Using the same grid network as for the EM38 survey, relative elevations were determined at each sampling site at 50 feet spacing using a construction level. Elevations were recorded to the nearest 0.1 foot. Relative elevations were also recorded for the two reference transects.

Physical Analyses:

The soil samples were air dried and ground to pass through a 2 mm sieve. The amount of material greater than 2 mm was nominal for most samples and therefore discarded. Particle size analyses were conducted by the pipette method of Day (1965) with the following modifications. The samples were not pretreated for removal of soluble salts and organic matter. Also the dispersing solution was 35.7 g of $(NaPo_3)_6$ and 7.94g of $N_{02}CO_3$ dissolved in one liter of water (S.C.S., 1982).

Chemical Analyses:

Sodium, magnesium, calcium, chloride, carbonate, biocarbonate, pH, EC_e (saturation paste extract electrical conductivity), saturation percentage and SAR (sodium absorption ratio) were determined using procedures summarized by Sandoval and Power (1977). Mixing the saturated soil paste was accomplished with an electrical mixer. Sulfates were determined by difference (sum of cations - sum of anions) and by the turbidimetric method of Bardsley and Lancaster (1965) modified by using saturated paste extract solution and by not adding activated charcoal.

RESULTS AND DISCUSSION

A substantial amount of the data presented in the following sections are from analyses of saturated paste extracts. The determination of carbonates and bicarbonates in the saturation extract is somewhat suspect because of the rapidity with which CO_2 in the air equilibrates with CO_2 in the extract. The emphasis will be on ion distribution in the soil from a depth of 0 to 10 feet and the potential importance of saturated water flow in the soil on redistribution of these ions.

Comparison of Two Sulfate Determination Methods:

In soils of western North Dakota, sulfate is the dominate anion followed by bicarbonate and carbonate. Because of the difficulty of determination, sulfate is commonly estimated as the difference between the sum of the measured cations and the sum of the measured anions. This is referred to as the "difference" method. To test the validity of this assumption, a "wet density" turbidimetric method was used to determine sulfates on selected samples (Table 1). For 70% of the selected samples the difference between the two methods is ±10 meq/l, which we consider to be an acceptable error level for the turbidimetric method. Samples with variation greater than ± 10 meq/l occur in both contaminated and noncontaminated samples without a distinct pattern of occurrence. For the samples where the difference in sulfate values between the two methods is large, two likely explanations are: 1) all errors in determining the measured anions and cations are reflected in the estimated sulfate value in the by difference method, 2) the determination of carbonates and bicarbonates in extracts from saturated pastes is suspect as mentioned earlier. We therefore conclude the "difference" method for determining sulfates is sufficiently accurate for this study.

Table 1. Comparison of two methods for determining SO_4; sum of cations - sum of anions and wet chemistry (turbidimetric).

Site	Depth	SO_4		Difference	Site	Depth	SO_4		Difference
		Sum*	Turb**				Sum*	Turb**	
		---------meq/l----------					---------meq/l----------		
F1 6-5	0-1	50.5	60.4	- 9.9	FB6	0-1	2.2	1.3	0.9
	1-2	25.6	-----	-----		1-2	46.3	39.0	7.3
	2-3	8.8	45.9	-37.1		2-3	45.6	40.2	5.4
	3-4	2.4	22.9	-20.5		3-4	191.2	187.9	3.3
	4-5	135.7	50.0	85.7		4-5	241.1	236.8	4.3
	5-6	0.0	16.7	-16.7		5-6	330.2	335.4	- 5.2
	6-7	0.0	24.6	-24.6		6-7	347.4	362.9	-15.5
	7-8	----	-----	-----		7-8	368.1	390.7	-22.6
	8-9	22.5	23.2	- 0.8		8-9	294.3	355.2	-60.9
	9-10	84.5	16.1	68.4					
F1 6-3	0-1	11.3	16.1	- 4.8	F1 6-0.5	0-1	51.4	35.5	14.9
	1-2	43.7	34.3	9.4		1-2	28.6	29.5	- 0.9
	2-3	0.0	9.8	- 9.8		2-3	30.9	34.3	- 3.4
	3-4	0.0	8.1	- 8.1		3-4	29.7	32.7	- 3.0
	4-5	0.0	-----	-----		4-5	32.8	36.0	- 3.2
	5-6	0.0	8.8	- 8.8		5-6	36.2	37.7	- 1.5
	6-7	0.0	-----	-----		6-7	27.1	35.4	- 8.3
	7-8	71.4	-----	-----		7-8	15.5	21.7	- 6.2
	8-9	0.0	-----	-----		8-9	8.3	13.8	- 5.5
	9-10	0.0	8.2	- 8.2		9-10	12.8	13.9	- 1.1
	10-11	0.0	8.1	- 8.1		10-11	5.8	12.5	- 6.7
	11-12	0.0	5.2	- 5.2		11-12	6.0	9.0	- 3.0
	12-13	0.0	6.9	- 6.9		12-13	8.1	8.3	- 0.2
	13-14	0.0	7.7	- 7.7		13-14	6.3	7.9	- 1.6
	14-15	0.0	9.0	- 9.0		14-15	6.9	7.1	- 0.2
FA7	2-3	89.8	68.9	20.9	FA9	2-3	123.4	133.6	-10.2
	4-5	43.3	0	43.3		4-5	134.1	144.8	-10.7
	6-7	40.8	44.1	- 3.3		6-7	181.4	165.9	15.5

Table 1 continued.

Site	Depth	SO_4		Difference	Site	Depth	SO_4		Difference
		Sum*	Turb**				Sum*	Turb**	
		---------meq/l----------					---------meq/l----------		
FB6	5-6	330.2	299.9	30.3	F1	12-13	0	0	0
	6-7	347.4	347.2	0.2	4-0.5	13-14	0	0	0
F1	2-3	133.4	119.6	13.8	F1	4-5	0	9.0	- 9.0
0-3	3-4	102.4	110.6	- 8.2	6-3	6-7	0	12.2	-12.2
						7-8	71.5	14.6	56.9

* $SO_4 = (Ca + Mg + Na) - (HCO_3 + Cl)$

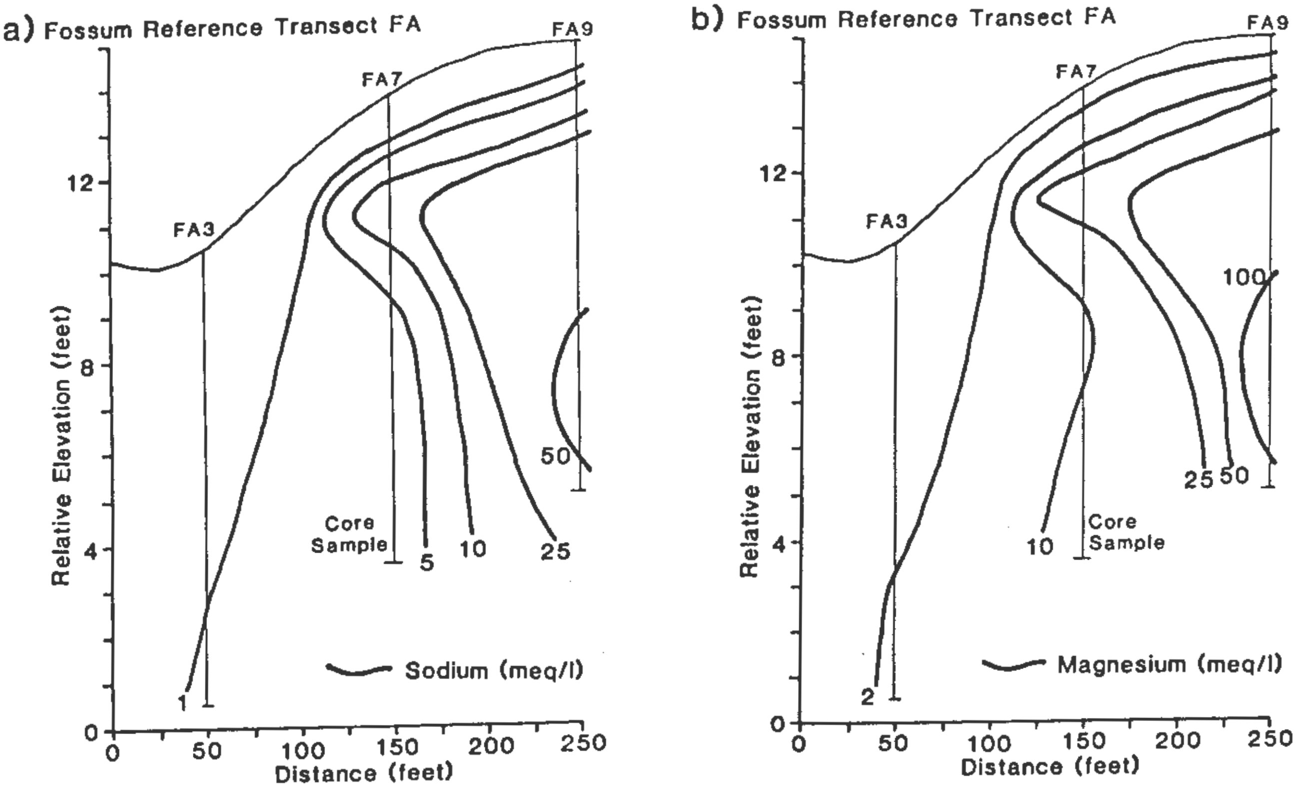
** Wet chemistry turbidimetric method

Undisturbed Transects FA and FB:

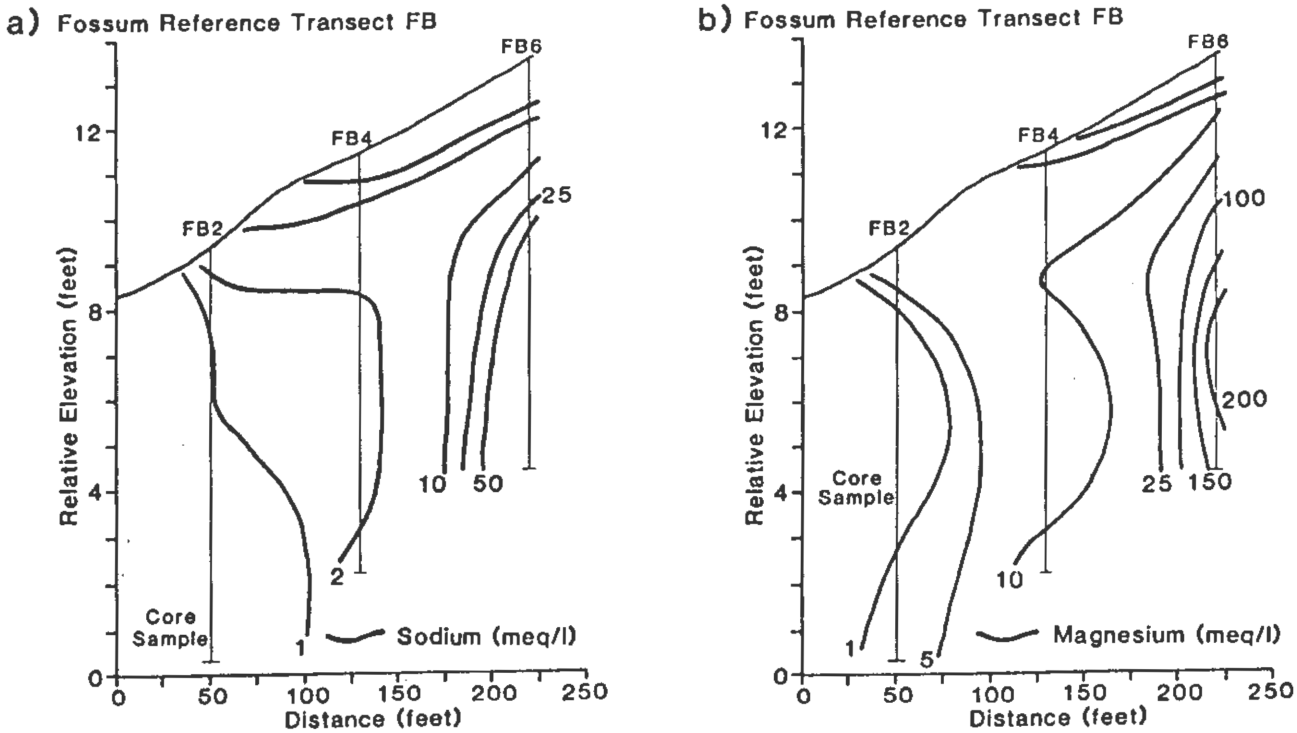
To evaluate the ion distribution in contaminated soils it is necessary to understand their distribution in noncontaminated soils. Assuming water to be the primary transport mechanism for ion movement in soils and that water movement is strongly influenced by topography, noncontaminated sampling transects were laid out to include the same major landforms as in the contaminated sites. Both noncontaminated sites contain at least one closed depression along with gently undulating low relief landforms. Transect FA was located 330 yards west and 110 yards north of Site 1 and transect FB was located adjacent to Site 2. Both transects begin in the center of a closed depression and extend outward in a straight line 230 and 250 feet respectively. The relative elevation difference from the lowest to highest transect point is approximately 5 feet for both transects.

The landscape components in the FA transect consist of a convex shoulder and backslope grading into a concave depression over a very short distance (Figure 1a). The FB transect consists of a linear backslope between sampling points FB6 and FB4 with a slight convex "high" occurring before the beginning of the concave depression (Figure 2a). The differences in topography between the two transects are very subtle in the field yet directly or indirectly affect cation and anion distribution in the soil.

The distribution of magnesium and sodium for transect FA is shown in Figures 1a and 1b. Note that even though the concentrations are different, the shape of the isoconcentration lines is similar. In both cases, the concentrations increase with distance from the center of the closed depression. In both figures the concentration lines bulge to the left at about midslope, indicating a zone of accumulation or slower removal. The concave portion of the transect



Figures 1a and 1 b: Vertical cross-section of the distribution of sodium and magnesium respectively for noncontaminated transect FA.



Figures 2a and 2b: Vertical cross-section of the distribution of sodium and magnesium respectively for noncontaminated transect FB.

is leached of both sodium and magnesium. Similar trends may be observed for the other cations and anions listed in Table 2.

As slope gradient increases, the depth to a given cation concentration decreases. Assuming that movement of water is the primary ion transport mechanism, it may be inferred that as the slope gradient increases, overland flow (runoff) and throughflow (movement of water parallel and very near to the land surface) increase, resulting in less downward water movement or leaching. Increased leaching occurs when slope gradients decrease because runoff and throughflow decrease and therefore increase the potential for water infiltration and leaching. Leaching is accentuated in the closed depression where water ponding occurs seasonally. The water and associated solutes continue to move in the soil from areas of high to low potential. If the closed depression is considered a point source of high potential water, the water and solutes should move downward and outward in a radial and somewhat spherical pattern. This may explain the low concentration of cations below higher concentrations adjacent to the closed depression. In the case where the matrix potential (capillarity) is less than the gravitational potential, water may move upward through the soil to the land surface (upslope), with salts being precipitated on the surface as the water evaporates. This condition occurs in transect FB.

In transect FB, the shapes of the isoconcentration lines are similar to those for transect FA for both sodium and magnesium (Figures 2a and 2b). Data for the other measured cations and anions are listed in Table 3. The cation distributions indicate that the convex shoulder on the edge of the closed depression is an area where soil water is moving upward by capillarity and salts are concentrating on the surface due to evaporation.

The amount of chloride in the noncontaminated sites ranges from 0.5 to 5 meq/l. The two higher values in transect FB may be due to contamination from

Table 2. Data from soil core samples of noncontaminated toposequence transect FA at the Fossum Farm.

Site	Depth (ft)	Ca	Mg	Na	HCO3	Cl	SO_4*	EC (mmhos/cm)	SAR	pH
		----------------	-------------meq/l	----------------						
FA3 (concave, depression)	0-1	2.5	1.5	0.3	2.7	0.8	0.9	0.6	0.2	6.2
	1-2	1.2	0.8	0.3	1.4	0.6	0.2	0.3	0.3	7.0
	2-3	2.3	1.3	0.4	3.6	0.6	0.0	0.4	0.3	7.3
	3-4	2.3	1.2	0.4	3.7	0.5	0.0	0.4	0.3	7.7
	4-5	2.7	1.6	0.6	3.7	0.5	0.7	0.5	0.4	7.6
	5-6	2.5	1.5	0.7	3.4	0.6	0.7	0.5	0.5	7.4
	6-7	2.7	1.7	0.8	3.3	0.7	1.3	0.6	0.5	7.7
	7-8	3.0	2.2	1.0	3.4	0.7	2.1	0.6	0.6	7.6
	8-9	3.1	2.4	1.2	3.5	0.7	2.5	0.7	0.7	7.7
	9-10	2.7	2.2	1.2	3.3	0.8	2.0	0.6	0.7	7.7
FA7 (convex backslope)	0-1	3.5	2.7	0.5	4.4	0.7	1.6	0.8	0.3	7.7
	1-2	6.0	15.1	5.7	3.1	0.7	22.9	2.5	1.7	7.9
	2-3	30.1	41.5	21.4	2.5	0.6	89.8	6.2	3.6	7.8
	3-4	30.1	13.2	8.2	2.3	0.5	48.7	3.9	1.8	7.6
	4-5	31.3	10.5	4.3	2.2	0.7	43.3	3.4	0.9	7.6
	5-6	15.4	6.3	2.5	2.6	0.5	21.1	2.1	0.8	7.6
	6-7	29.6	11.4	2.5	2.3	0.5	40.8	3.3	0.6	7.5
	7-8	31.1	13.9	2.7	2.2	0.7	44.9	3.5	0.6	7.6
	8-9	29.6	15.1	2.9	2.0	0.5	45.1	3.5	0.6	7.7
	9-10	27.1	17.5	3.4	2.3	0.5	45.2	3.7	0.7	7.9
FA9 (nearly level summit)	0-1	3.9	2.6	0.6	4.6	0.9	1.6	0.7	0.3	7.7
	1-2	12.9	23.6	7.7	3.0	0.5	40.7	3.4	1.8	7.9
	2-3	19.6	70.9	36.9	2.1	1.9	123.4	8.4	5.5	8.1
	3-4	17.1	70.0	40.0	2.0	0.9	123.9	8.5	6.0	7.9
	4-5	15.7	80.0	43.0	2.2	2.4	134.1	9.2	6.2	8.0
	5-6	24.0	102.8	47.9	1.6	2.4	170.7	10.6	6.0	7.9
	6-7	23.1	110.4	52.5	1.6	3.0	181.4	11.3	6.4	7.9
	7-8	21.4	113.6	52.7	1.6	3.8	182.5	11.7	6.4	7.9
	8-9	21.6	105.4	50.8	1.6	3.9	172.2	11.3	6.4	7.9
	9-10	22.4	97.8	48.7	1.8	4.4	162.6	10.7	6.3	7.9

* Determined by difference. Sum of cations -- sum of anions = SO_4.

Table 3. Data from soil core samples of noncontaminated toposequence transect FB at the Fossum Farm.

Site	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4*	EC (mmhos/cm)	SAR	pH
		meq/l								
FB2 (concave depression)	0-1	8.8	7.5	2.0	1.3	7.0	10.0	2.2	0.7	5.7
	1-2	1.5	1.1	1.1	1.0	1.4	1.2	0.5	0.9	6.9
	2-3	1.1	0.7	1.0	1.2	0.8	0.8	0.4	1.1	6.9
	3-4	2.6	1.4	1.1	3.0	1.0	1.1	0.6	0.8	7.5
	4-5	2.7	1.4	0.8	3.1	0.9	0.9	0.6	0.6	7.6
	5-6	2.9	1.6	0.6	3.1	1.4	0.6	0.6	0.4	7.7
	6-7	4.0	2.3	0.6	2.8	3.6	0.5	0.8	0.3	7.6
	7-8	6.5	3.9	0.6	2.5	8.7	0.0	1.4	0.3	7.6
	8-9	6.0	3.6	0.5	2.5	4.4	3.2	1.2	0.2	7.6
FB4 (rim of depression)	0-1	2.9	6.0	1.0	6.3	0.6	2.9	1.0	0.5	7.9
	1-2	1.0	8.8	2.7	4.3	1.3	6.8	1.2	1.2	8.3
	2-3	2.2	11.4	2.5	3.5	4.0	8.6	1.5	1.0	8.1
	3-4	1.9	6.5	1.8	4.5	2.8	3.0	1.2	0.9	8.2
	4-5	1.6	4.2	1.4	2.4	1.5	3.3	0.7	0.8	8.0
	5-6	2.3	3.9	1.3	3.6	1.9	2.0	0.8	0.7	8.0
	6-7	2.3	2.8	1.3	3.4	2.3	0.7	0.7	0.8	7.8
	7-8	3.5	3.5	1.5	3.2	1.0	4.2	0.8	0.8	7.9
	8-9	23.9	14.2	2.9	2.4	0.9	37.7	3.0	0.7	7.6
FB6 convex backslope)	0-1	5.4	1.9	0.5	5.1	0.4	2.2	0.8	0.3	7.8
	1-2	24.4	22.1	2.6	2.7	0.2	46.3	3.5	0.5	7.7
	2-3	3.2	26.6	19.7	3.2	0.7	45.6	3.9	5.1	8.2
	3-4	21.8	116.5	56.8	1.5	2.4	191.2	10.9	6.8	8.1
	4-5	21.7	153.1	72.0	2.1	3.5	241.1	13.1	7.7	8.0
	5-6	22.7	220.4	93.6	2.0	4.5	330.2	15.9	8.5	8.1
	6-7	21.8	240.4	91.8	1.9	4.8	347.4	16.5	8.0	8.2
	7-8	21.8	258.5	95.1	2.0	5.4	368.1	17.2	8.0	8.1
	8-9	17.2	185.9	100.0	1.8	7.0	294.3	16.7	9.9	8.1

* Determined by difference. Sum of cation - sum of anion = SO_4

an adjacent contaminated site. Since the soil contains only small amounts of chloride while the brine contamination is dominated by chloride, chloride concentrations can be used to trace the movement of brine. Since the chloride ion is negatively charged, it is not likely to be held by soil particles.

From the undisturbed transect data, the following criteria can be used to aid in evaluating the brine-contaminated sites.

1. The concentration of cations and anions varies dramatically over short distances.
2. The concentration of ions vary systematically and predictably according to landscape position.
3. The land surface shape governs water movement over and through the soil.
4. Assuming solute transport is accomplished primarily by water, the distribution of ions in the soil is a "map" of water movement.
5. The noncontaminated soils have chloride concentrations of 6 meq/l; levels above 6 meq/l are indicative of brine contamination.
6. The importance of capillary rise transporting water and salts to the land surface is illustrated in transect FB.

Contaminated Sites:

Our initial hypothesis was that the spread of NaCl was primarily due to the salt being transported to the land surface by capillary rise of water where it would precipitate and accumulate. When rainfall events occur, this salt dissolves and is subject to movement either across the surface by overland flow or by infiltration back into the soil. Our subsequent studies, however, indicate that this is only one of several mechanisms affecting the spread of salt from the buried brine disposal pits.

The factors and conditions which influence the movement of NaCl are presented in the following text as a series of figures with the distribution of

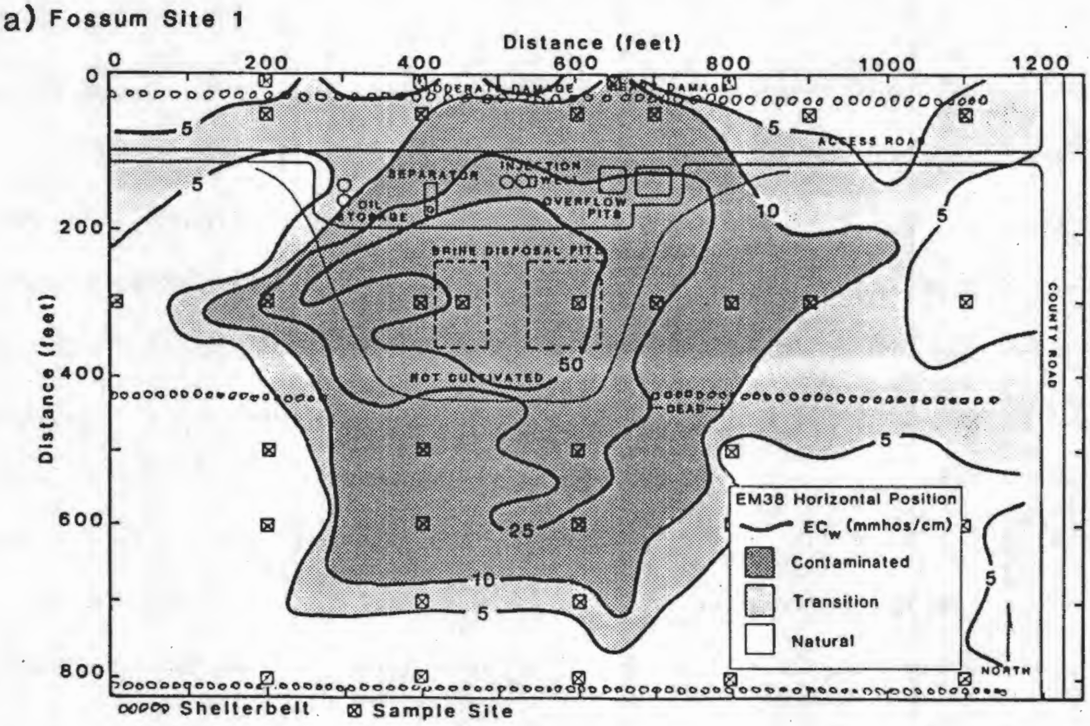


Figure 3: Location of cultural features and sampling sites for contaminated Fossum Site 1.

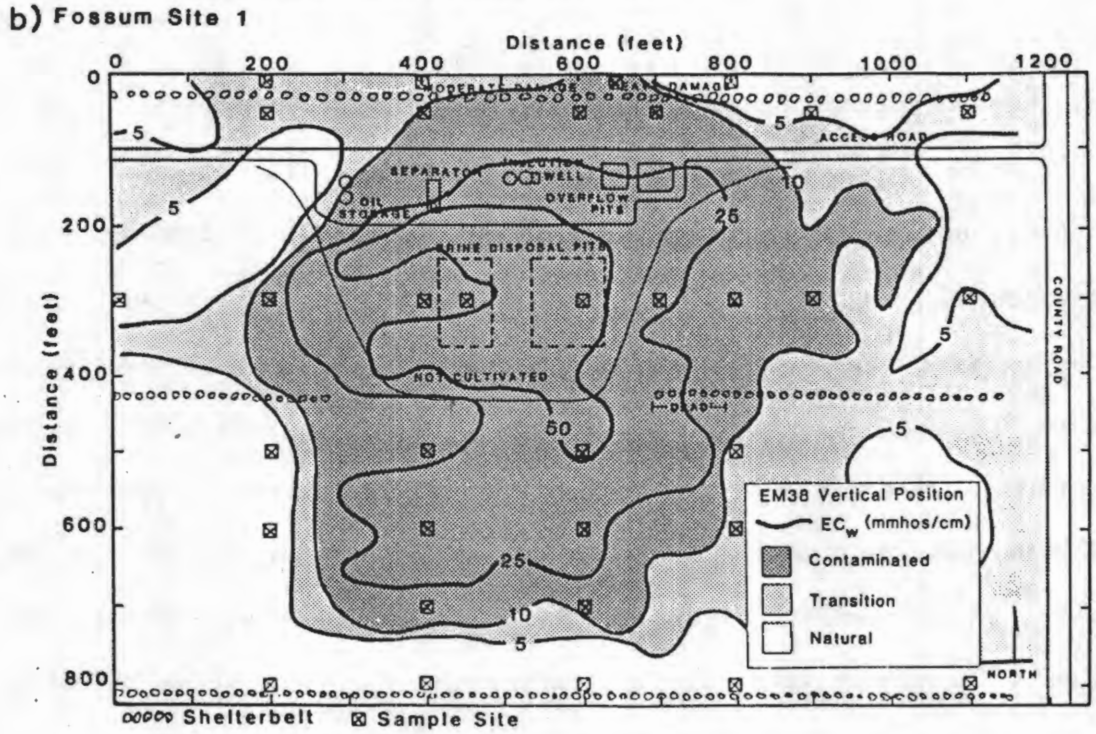


Figure 4: Topographic contour map of Fossum Site 1.

anions and cations shown in vertical crossections and in horizontal concentration contour maps for specific depth increments.

Fossum Site 1: The cultural features and approximate location of the buried brine disposal pit are shown in Figure 3. The study site was 22.5 acres in size. The extent of the spread of the brine contamination was identified with the EM38 meter; a grid pattern was then laid out to locate survey and sample points.

Relative elevations were recorded on a 50 foot spacing grid and 6-inch contour intervals were drawn by hand (Figure 4). The difference in elevation between the highest to lowest points on the site is 9 feet. The land surface generally slopes to the east and southeast. One closed depression occurs at location (4,5) immediately south of a buried brine disposal pit. The depression is distinct but very shallow (1.5 ft. depth). The two small rectangular areas with very close contour lines located at (5,1) are overflow pits used to collect overflow from brine storage tanks located at the injection well.

After core sampling, the core holes were left open and the depth to the free water surface was recorded at the termination of the field sampling tour. Contours drawn from these measurements show the relative water table surface (Figure 5). This diagram shows the gradient of the water table and possible direction of water movement (down gradient) and recharge. The depth of the free water surface from the land surface is shown in Figure 6; this information is needed to determine locations where capillary rise will bring salts to the surface. In soil science, the critical depth is the depth to the surface from free water below which salts will not be brought to the surface by capillarity. This depth varies with texture, climate and vegetation. For loam soils in this geographic region, the critical depth is approximately 5 feet. For sandy soils it would be about 3 feet, and about 8 feet for fine-textured soils. During

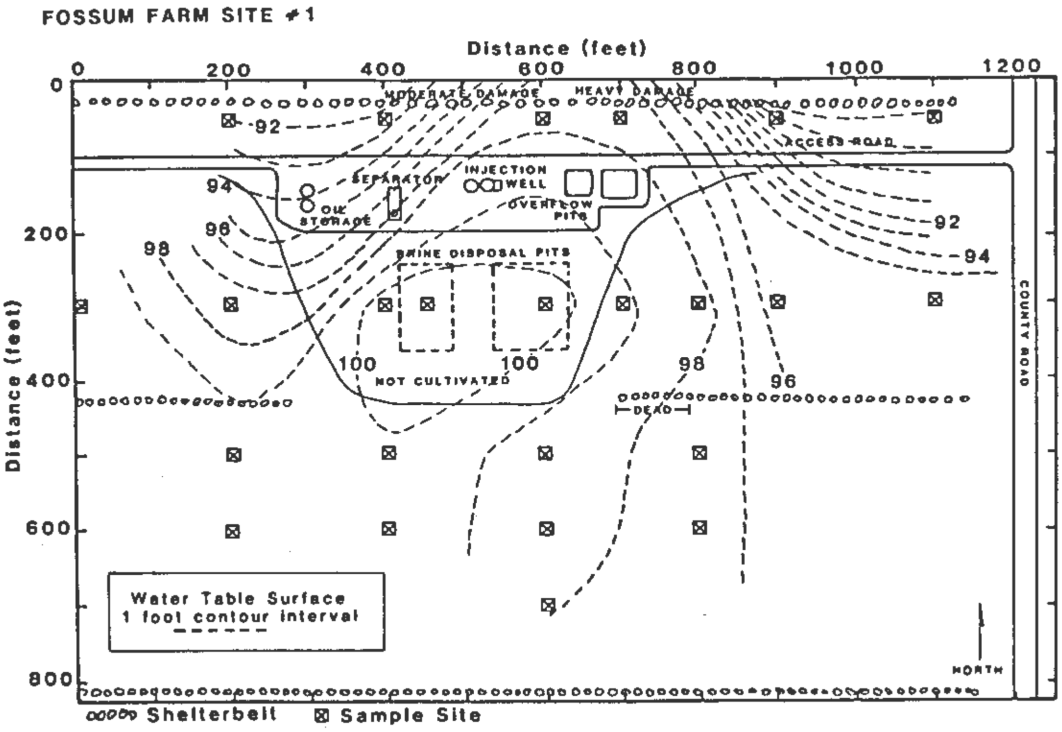


Figure 5: Relative water table surface contour map of Fossum Site 1.

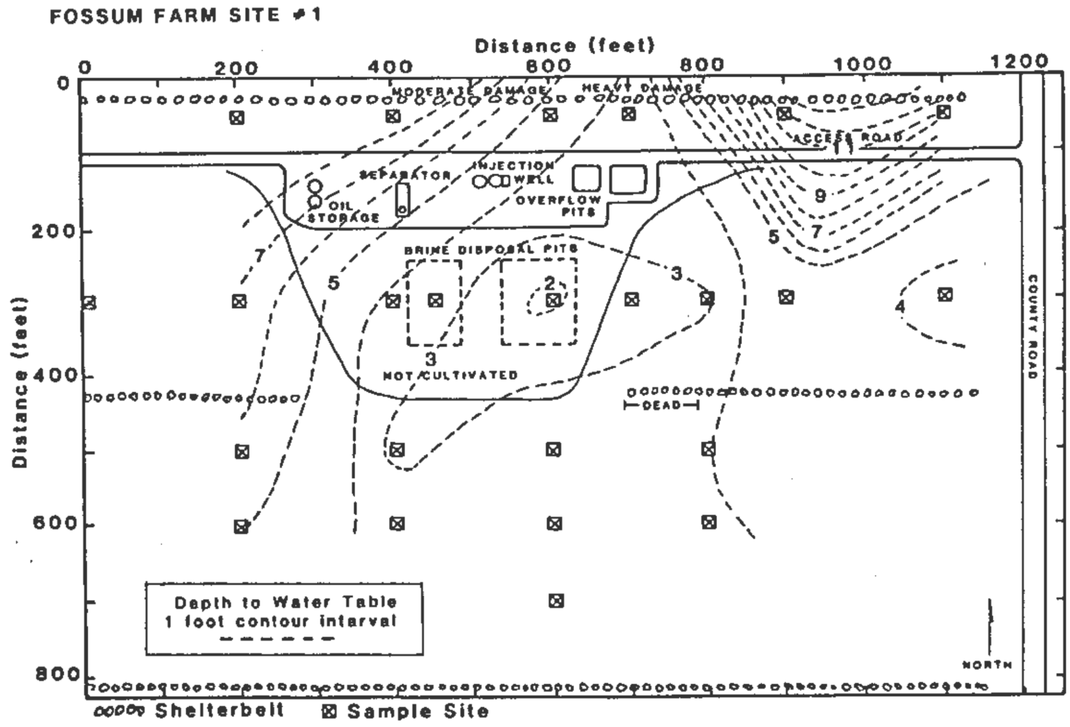


Figure 6: Map of the depth to the water table below the land surface for Fossum Site 1.

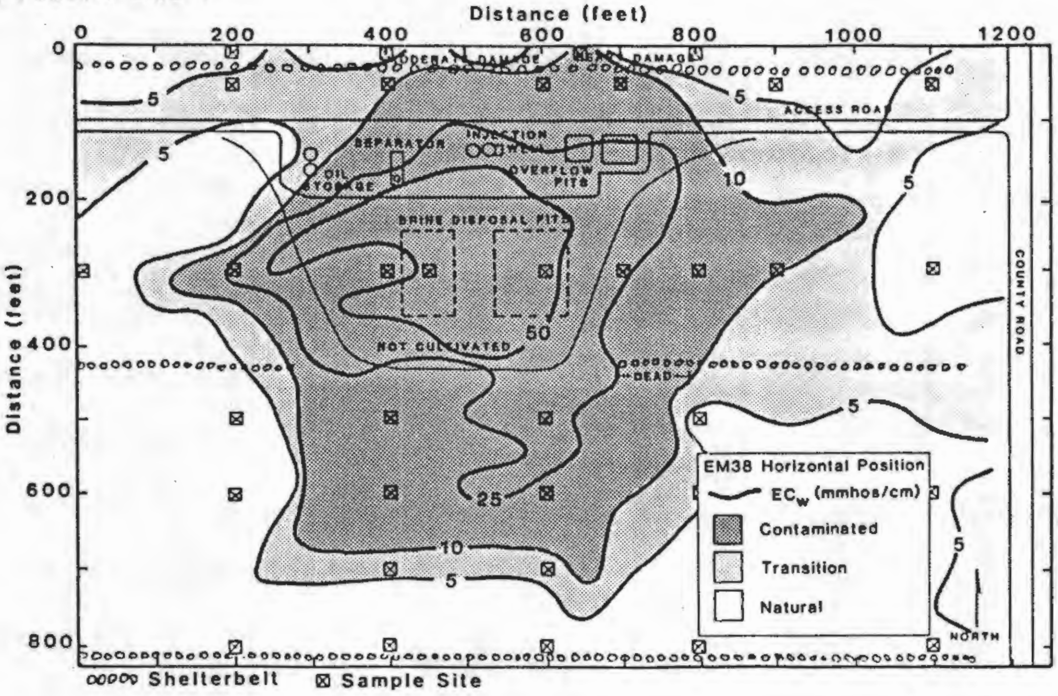
sampling, salts were observed on the soil surface when the water table was 2 to 3 feet below the surface (Figure 6). Sampling was in the fall after several substantial rains.

The EM38 meter readings were recorded at the same 50 ft grid points as elevations. Readings were taken in both the vertical and horizontal positions. In the horizontal position, 70% of the meter reading comes from a depth of 0 to 2 feet. In the vertical position, the same 70% comes from a depth of 0.5 to 4 feet. The meter readings were converted to weighted profile salinity values, using the calibrations shown in Appendix Figures 2-1 and 2-2, and salinity concentration contour diagrams were drawn (Figures 7a and 7b). A profile salinity of 10 mmhos/cm or greater always correlated with severe damage to vegetation. The area between 5 and 10 mmhos/cm is a transition zone, where the salinity may be due either to the brine or to naturally-occurring salts in the soil. Where the salinity is less than 5 mmhos/cm, the area is not affected by brine contamination. Note that the area contaminated is greater for the deeper reading (Figure 7b) than the shallow reading (Figure 7a).

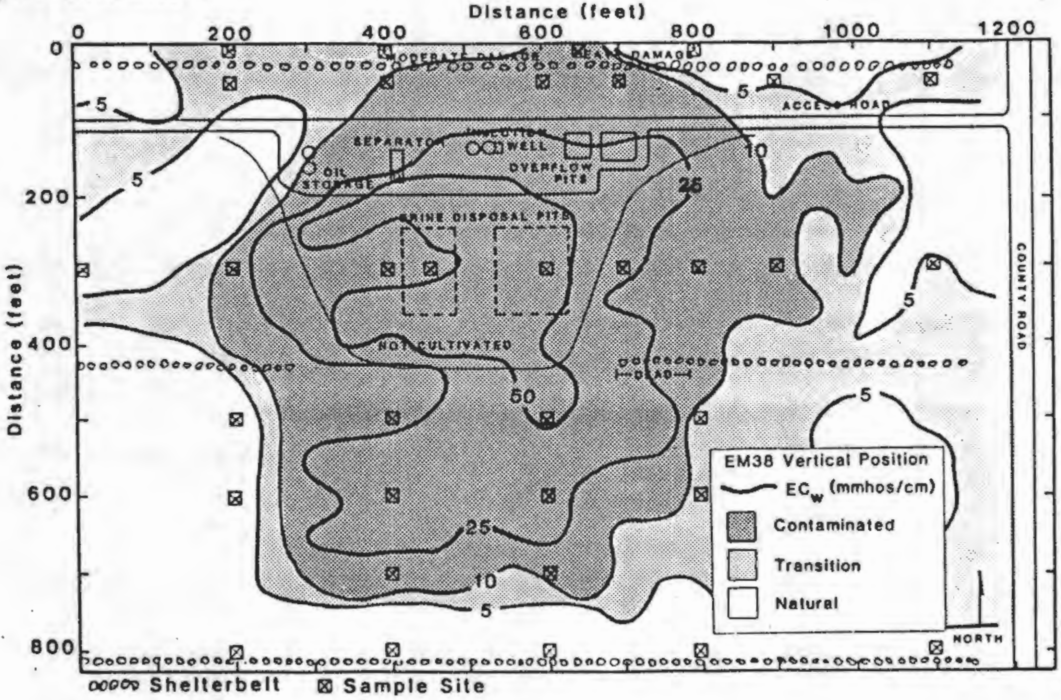
The meter readings give an excellent 2-dimensional picture of the area affected by the spreading brine contamination. However, they do not adequately explain why the brine is moving in a particular direction. Data from core samples give a more complete picture of brine movement and possible mechanisms controlling this movement.

<u>Transect A-A:</u> A-A′ is a vertical cross section of Fossum Site 1 (Figure 9). The different degrees of shading represent different soil materials. The soil materials are identified as ablation drift or till. The ablation drift is a moderately sorted, somewhat stratified sediment which mantles a uniform poorly sorted till. A pebble line or stone line is often present at the ablation drift-till contact. The ablation drift is friable and is moderate to

a) Fossum Site 1



b) Fossum Site 1



Figures 7a and 7b: Profile salinity contour map derived from the EM38 meter read in the horizontal and vertical position, respectively, for Fossum Site 1.

rapidly permeable. The till is firm and is moderate to slowly permeable. The particle size data support the separation of these two materials. Figure 8 shows that the till has a uniform texture whereas the texture of the sediment varies widely. The till surface is undulating and does not always reflect the land surface topography. The differential permeability of the two materials together with topographic variations create areas where a perched water table can develop. A series of small discontinuous perched water tables probably occur in the ablation drift above the till which may or may not be directly connected to a "permanent" water table at some greater depth. In Figure 9 the water table rises above the till surface between 400 and 850 feet on the horizontal axis.

Electrical conductivity (EC) values decrease with increasing distance away from the pits, maybe a little more rapidly in the upslope than in downslope direction (Figure 9). Also, the EC concentrations extend downward in a vertical manner.

The distribution of chlorides in cross section A-A′ (Figure 10) gives the best indication of the movement of the brine. The contamination extends substantially further in the downslope direction (to the right) than the upslope. The spacing between the concentration lines is much greater near the surface than at lower depths, suggesting more rapid movement near the surface. We would expect decreased permeability with increasing depth and less contamination movement. Also the high concentration of chlorides extend downward well beyond the pits. In fact, the permeability of the site was such that they probably never functioned as evaporation pits, but rather as leaching pits. The curves in the concentration line in the left of the diagram indicate that backflow of water is transporting salts upgradient from the pit area and that this backflow is being counteracted by leaching and throughflow in the soil

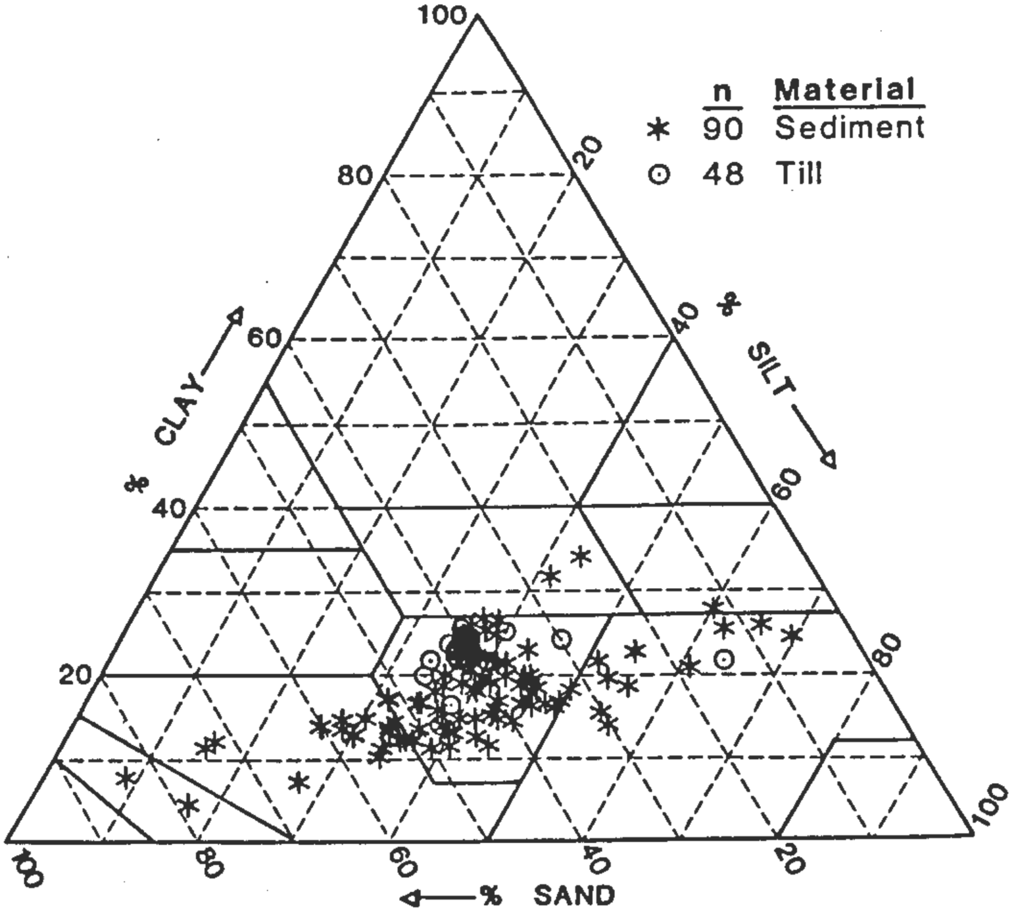


Figure 8: **Scatter diagram of particle size data for Fossum Site 1.**

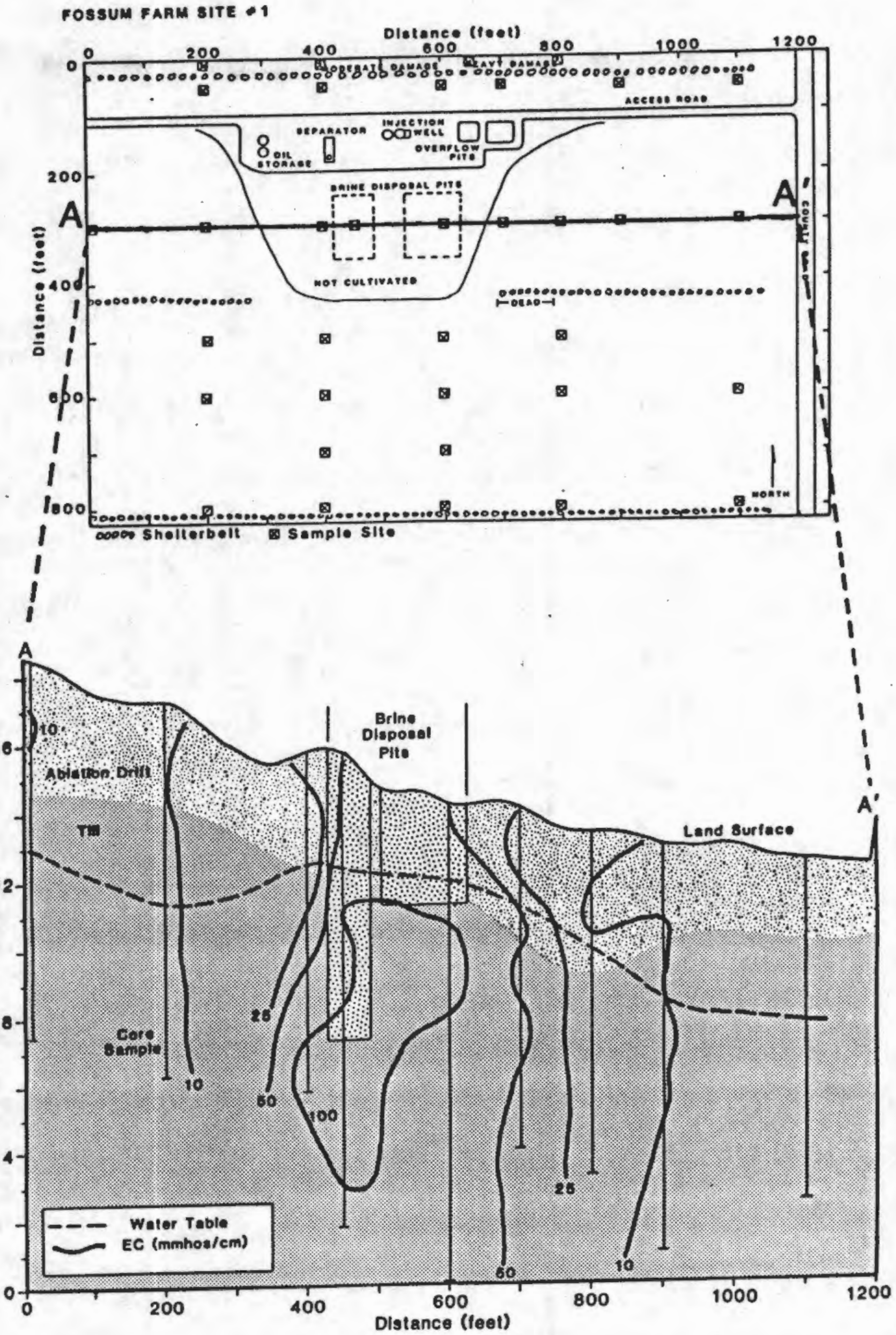


Figure 9: Vertical cross-section showing the electrical conductivity (EC) distribution for transect A-A' at Fossum Site 1.

surface. The concentration lines are perpendicular to the land surface on the right side of the disposal pits indicating that the contamination is being spread over as well as below the land surface.

The distribution of magnesium shown in Figure 11 is especially interesting. The two-tongued low concentration features are interpreted to be areas where substantial leaching has been occurring over a long period of time, probably thousands of years. It represents a map of the flow of water into and through the soil. The feature on the left of the deep pit is on the edge of the closed depression described earlier. The feature on the right does not presently correspond to the surface land feature, rather it may be related to the till surface shape. If a surface depression had occurred in the past, it may have been filled during the oil development activity.

We would expect that eventually the chloride distribution would show concentration relationships similar to those of magnesium due to water infiltration and leaching; however, the chloride concentrations are so high that diffusion is masked by leaching.

The sodium concentration is high in the soil near the disposal pits (Figure 12), and the shape of the concentration lines is similar to that of chloride (Figure 10). Interpretation of the sodium concentration becomes more difficult as distance from the pits increases because the soil may easily have 50 meq/l of sodium in a noncontaminated condition (as seen in reference transects FA and FB).

The distribution of calcium (Figure 13) is similar to that of magnesium with two tongue-shaped features, one on each side of the pits. The concentration of calcium measured in a saturated paste extract is limited by the solubility of carbonates and gypsum where there are excess sulfates. These soils are naturally high in sulfates. In the presence of excess sulfates

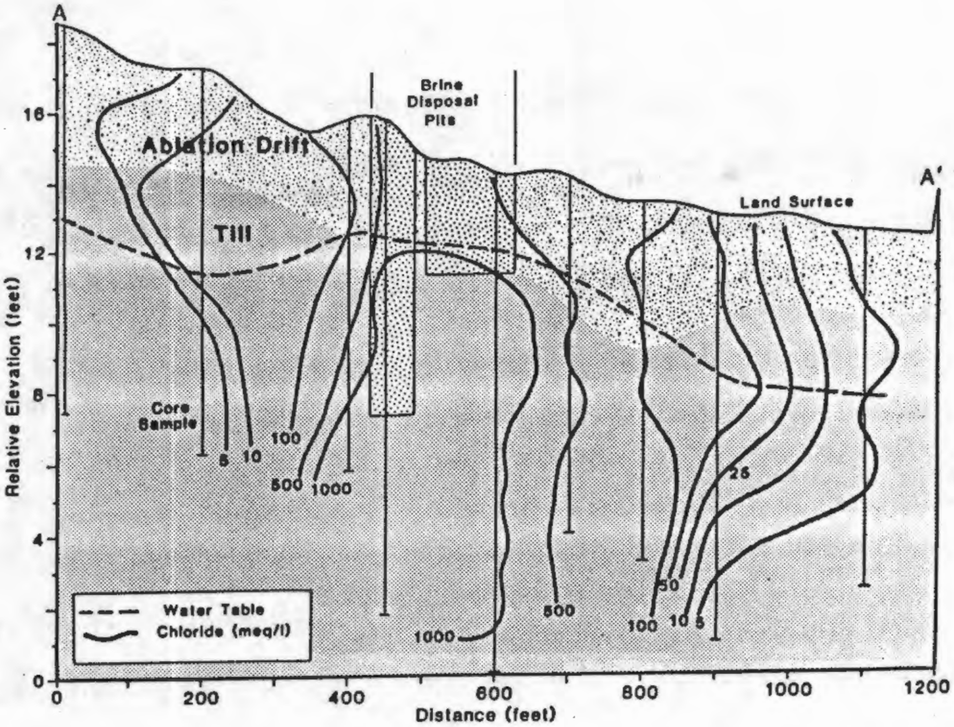


Figure 10: Vertical cross-section showing the distribution of chlorides for transect A-A' at Fossum Site 1.

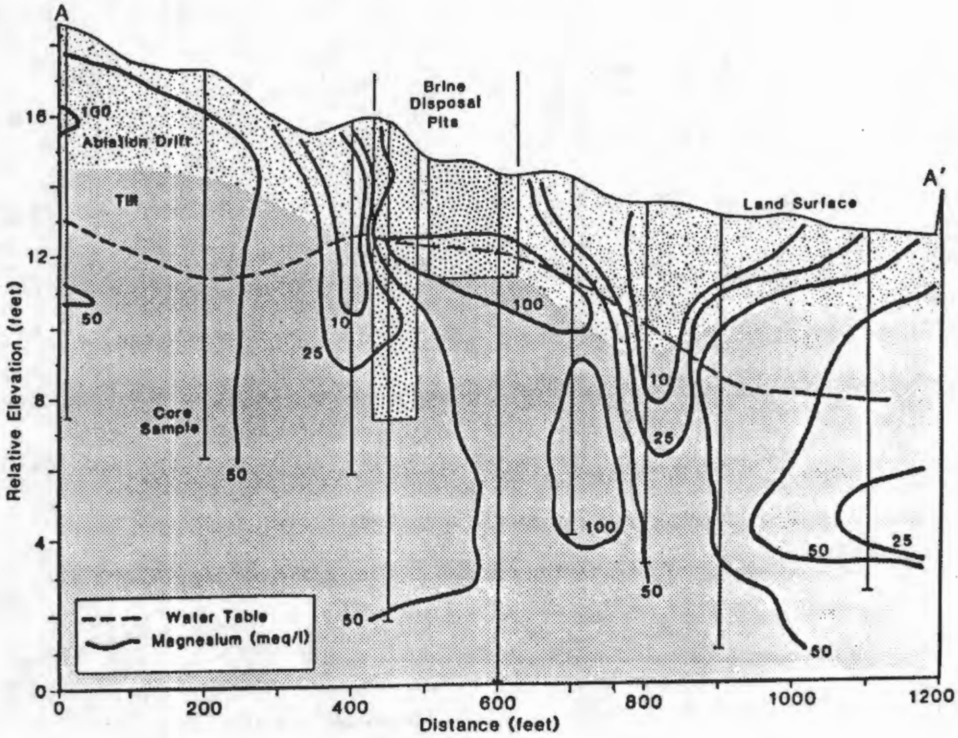


Figure 11: Vertical cross-section showing the distribution of magnesium for transect A-A' at Fossum Site 1.

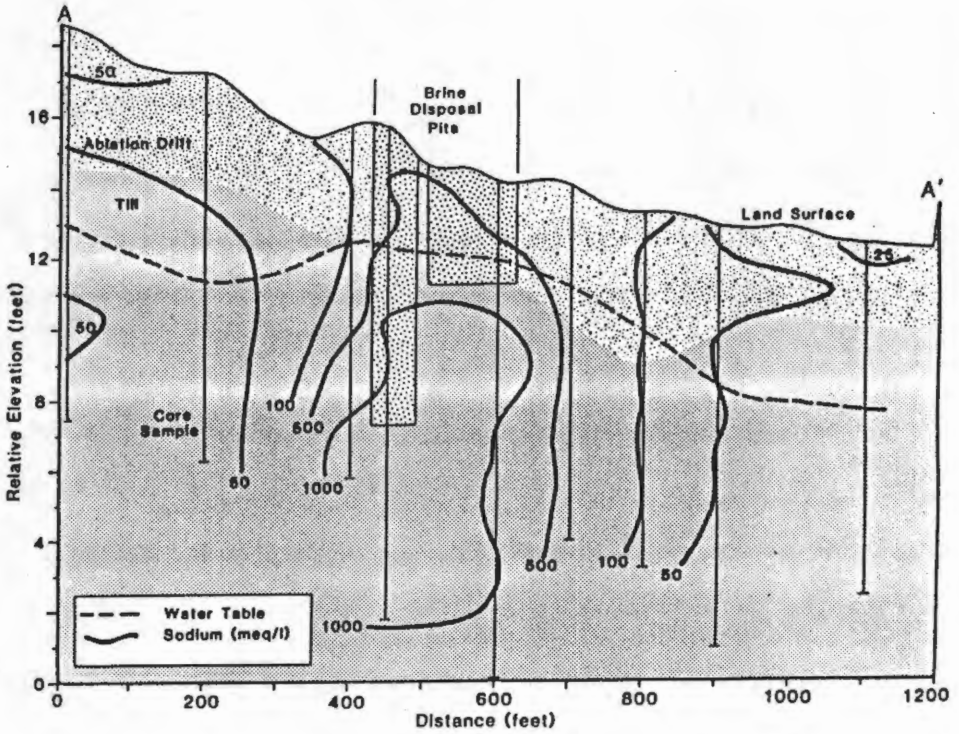


Figure 12: Vertical cross-section showing the distribution of sodium for transect A-A' at Fossum Site 1.

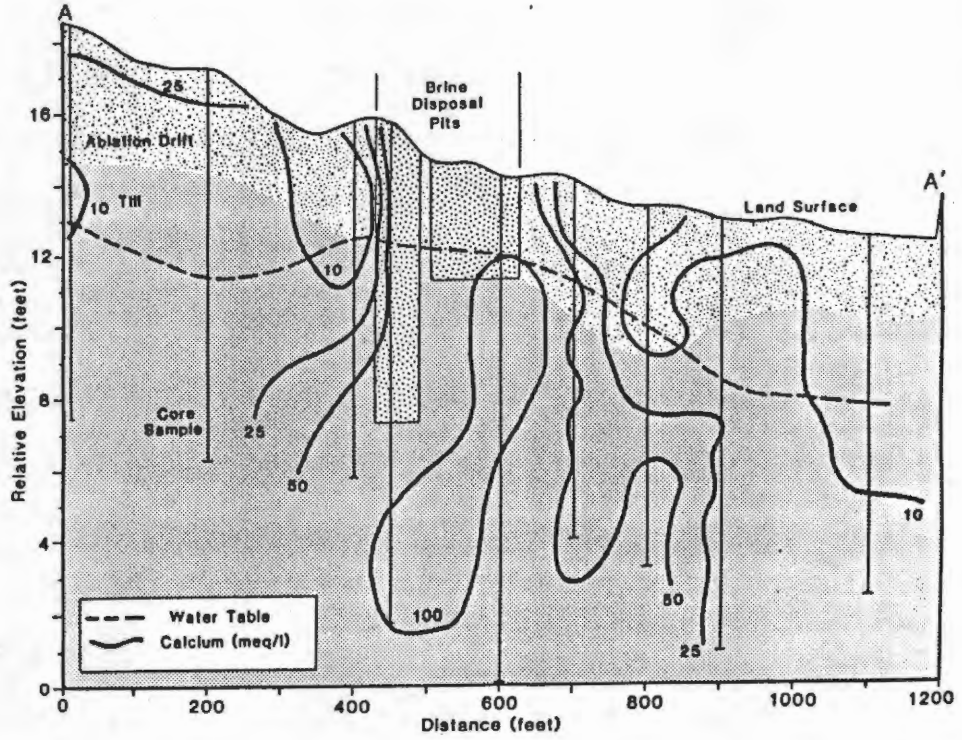


Figure 13: Vertical cross-section showing the distribution of calcium for transect A-A' at Fossum Site 1.

the calcium solubility in noncontaminated soils is limited to 24-26 meq/l. Higher concentrations of calcium in extracts from contaminated soils are probably due to the higher solubility of gypsum in high-salt solutions.

Transect B-B′: The location of transect B-B′ at Fossum Site 1 is shown in Figure 14. The importance of parent material stratigraphy is very evident in this diagram. The brine salts are moving strongly to the right (south) most likely in response to the dipping till surface and to the perched water table. Note also that as the till surface rises, the EC gradients diminish rapidly.

The chloride distribution is shown in Figure 15. Again, the brine salt movement as reflected in the concentration gradient appears to be highly correlated with the parent material stratigraphy. The chloride contamination extends to the right (south) until the till surface rises near the land surface, effectively decreasing the movement of brine salts. Identification of factors related to the movement of chlorides to the left (north) of the pit is masked by the open and actively-used overflow pits located adjacent to this transect Chloride distribution shows substantial downward movement of the contamination.

The distribution of magnesium is shown in Figure 16. Whether the increase in magnesium to the right of the pit is caused by the spread of the brine contamination or is naturally occurring is not known at this time. Note the near surface tongue feature which occurs at a horizontal distance of 600 feet. Whatever the case, the magnesium seems to be associated with the buried depressional till surface feature.

The sodium concentration lines in Figure 17 mimic those of EC shown in Figure 15. Sodium concentrations greater than 50 meq/l are probably related to the spread of the brine contamination. As before, the movement is dominantly downward and to the right (south) in this cross-section.

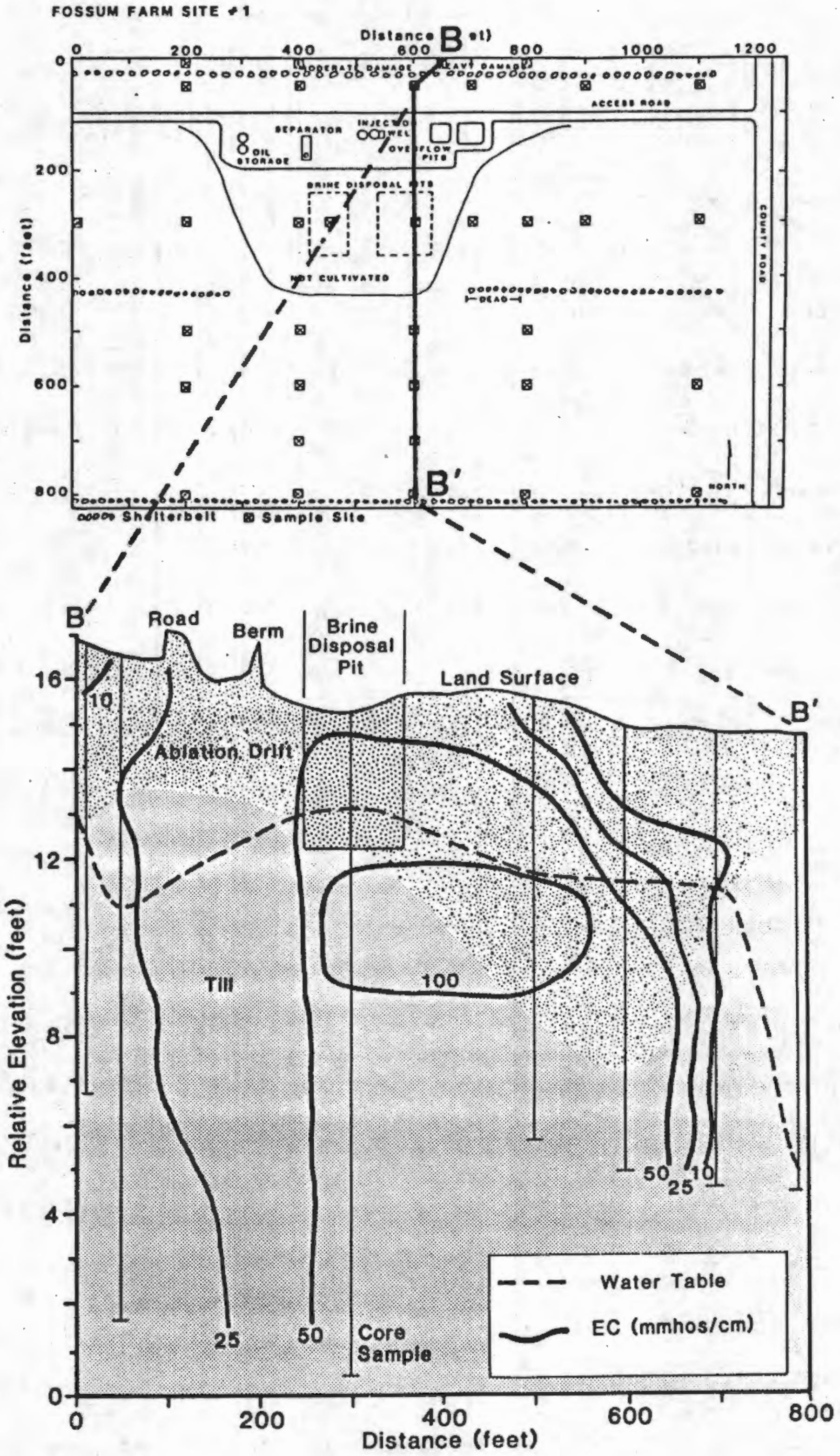


Figure 14: Vertical cross-section of the distribution of electrical conductivity (EC) for transect B-B' at Fossum Site 1.

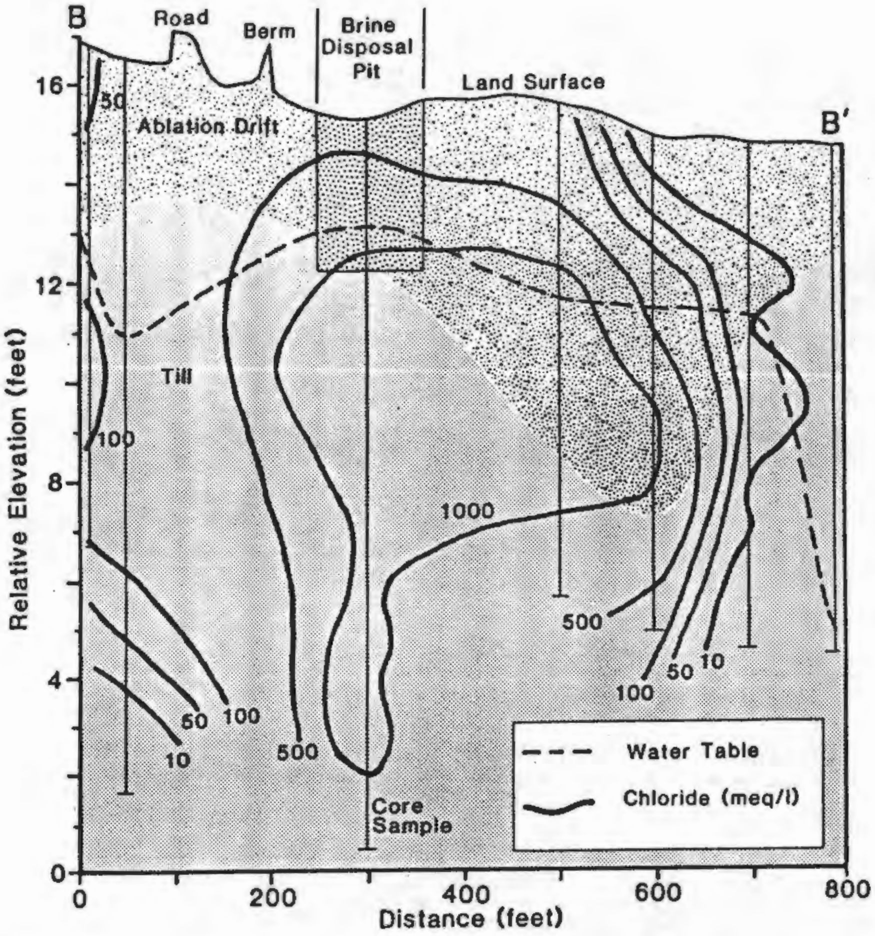


Figure 15: Vertical cross-section of the distribution of chlorides for transect B-B' at Fossum Site 1.

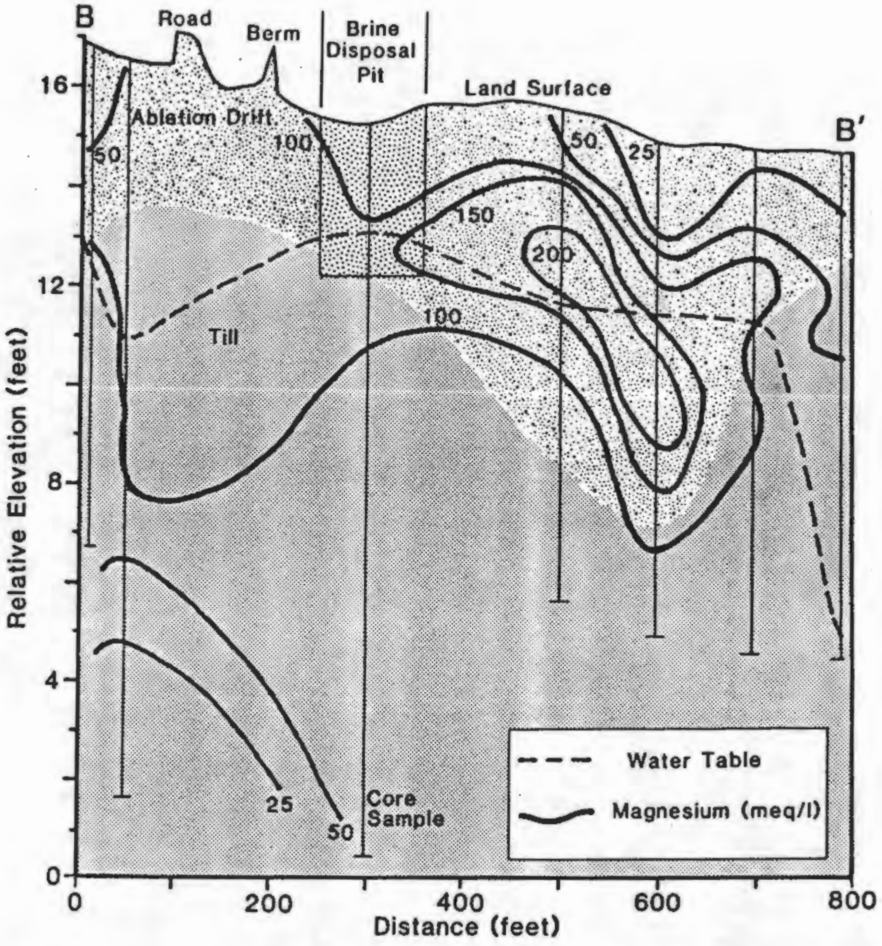


Figure 16: Vertical cross-section of the distribution of magnesium for transect B-B' at Fossum Site 1.

Calcium distribution (Figure 18) also seems to be affected by the parent material stratigraphy and water table. Note that the movement is occurring through the sediment below the land surface. The land surface rises immediately south of the buried brine pits, and then decreases, so that overland flow of brine salts cannot occur in this direction.

In this situation, where the contamination is concentrated below the land surface, the growth of vegetation does not always reflect high salt concentrations at deeper depths. This is especially true in growing seasons with average or higher precipitation. Use of the EM38 meter, however, was effective in detecting salt movement at these deeper depths.

Figures 19, 20, 21 and 22 are horizontal sections of Fossum Site 1 showing the distribution of EC at four different depths. The diagrams were created with the GCONTOUR procedure in the Statistical Analysis System (SAS) implemented on the NDSU IBM computer. Each figure consists of 35 real data points with the additional 322 points computed by a bivariate spline interpolation option. The diagrams aid in visualizing the area affected by brine at various depths. The EC diagram shows that the contamination covers an increasing large area with depth. Also the contamination spread is more pronounced towards the bottom (south) of the diagram.

Figures 20a, b, c and d show the distribution of chlorides for various depths. Note that both the area affected by contamination and the concentration increase with depth. Also the spread is most pronounced to the right (or east) in the surface (Figure 20a) but to the bottom (or south) in the other deeper sections (Figures 20b, c, and d).

The sodium distributions in Figures 21a, b, c and d show trends similar to that of the chlorides. Again the interpretation of the distribution is more

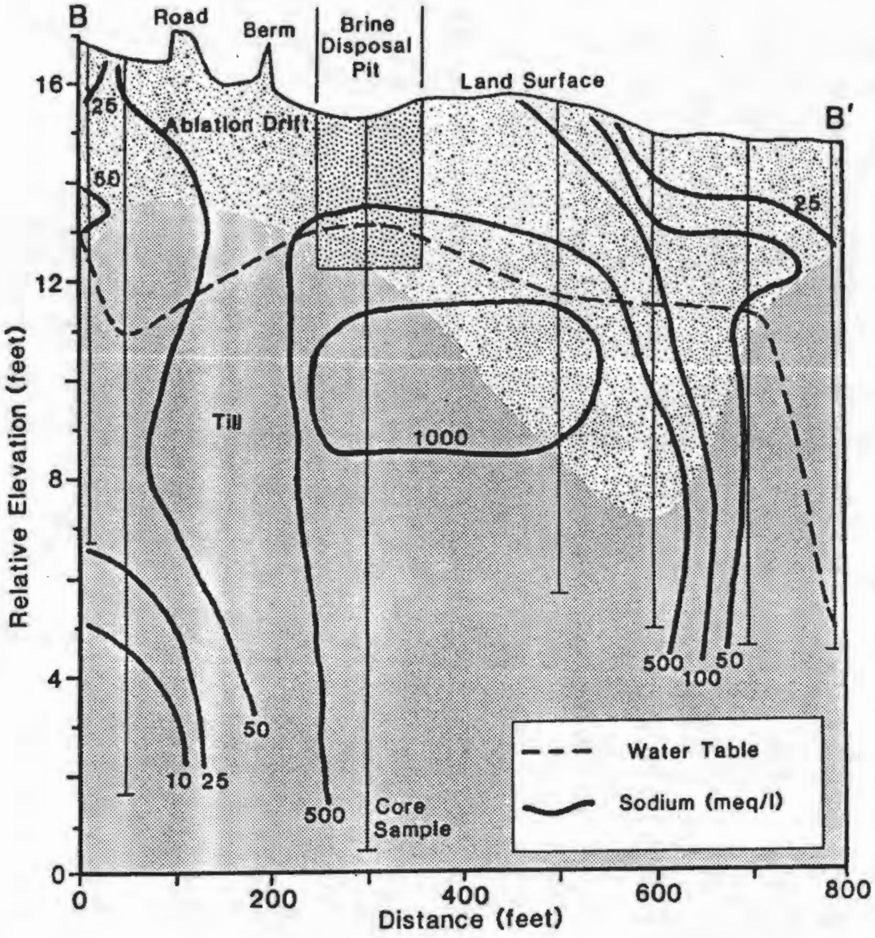


Figure 17: Vertical cross-section of the distribution of sodium for transect B-B' at Fossum Site 1.

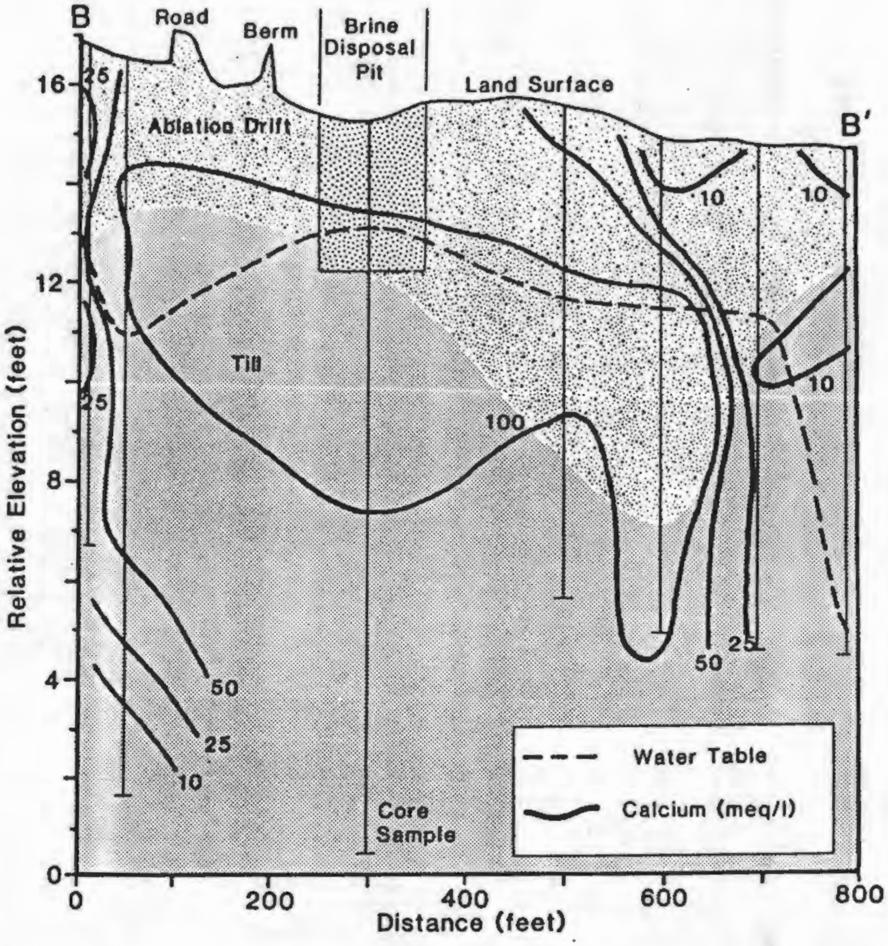


Figure 18: Vertical cross-section of the distribution of calcium for transect B-B' at Fossum Site 1.

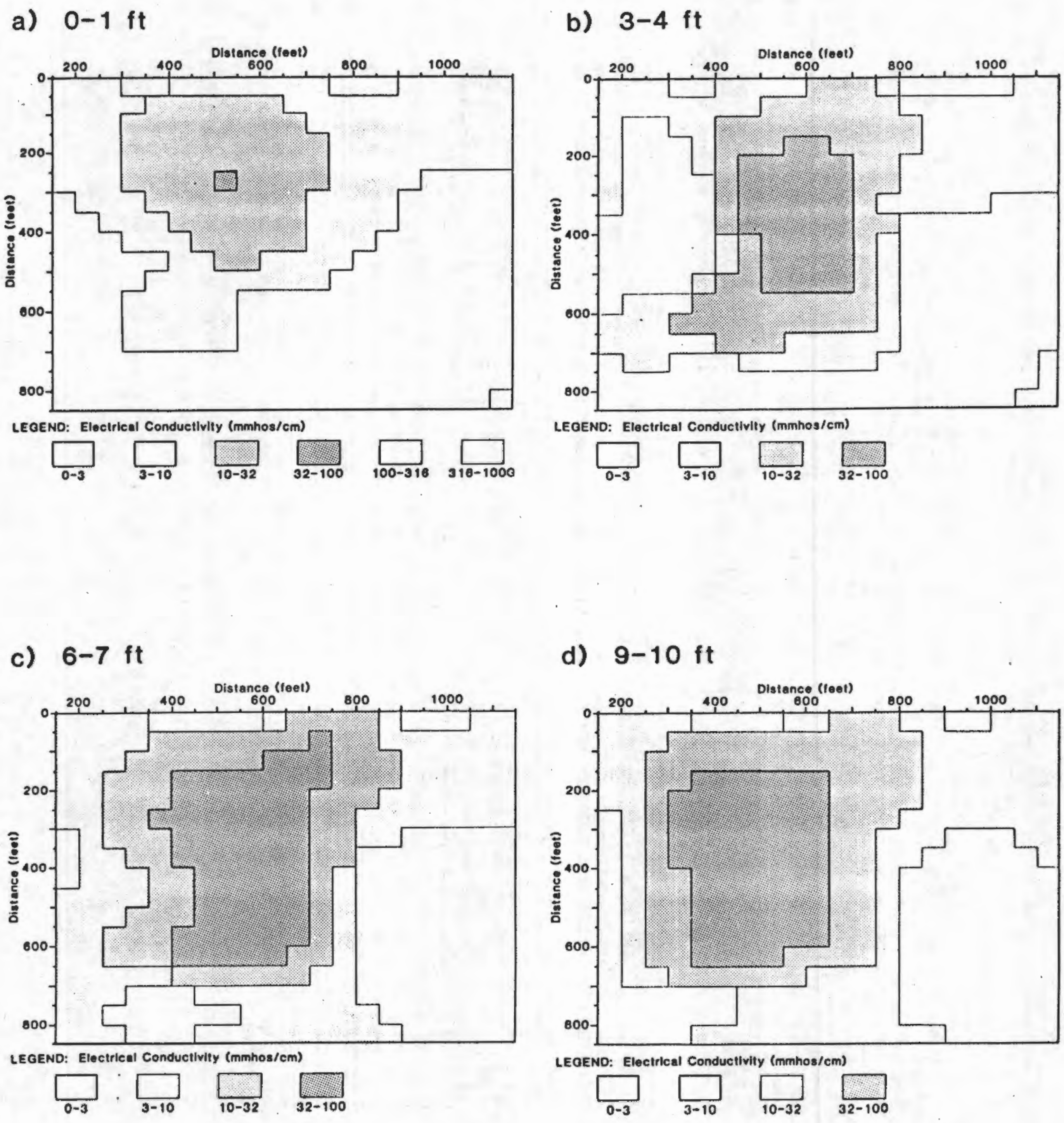
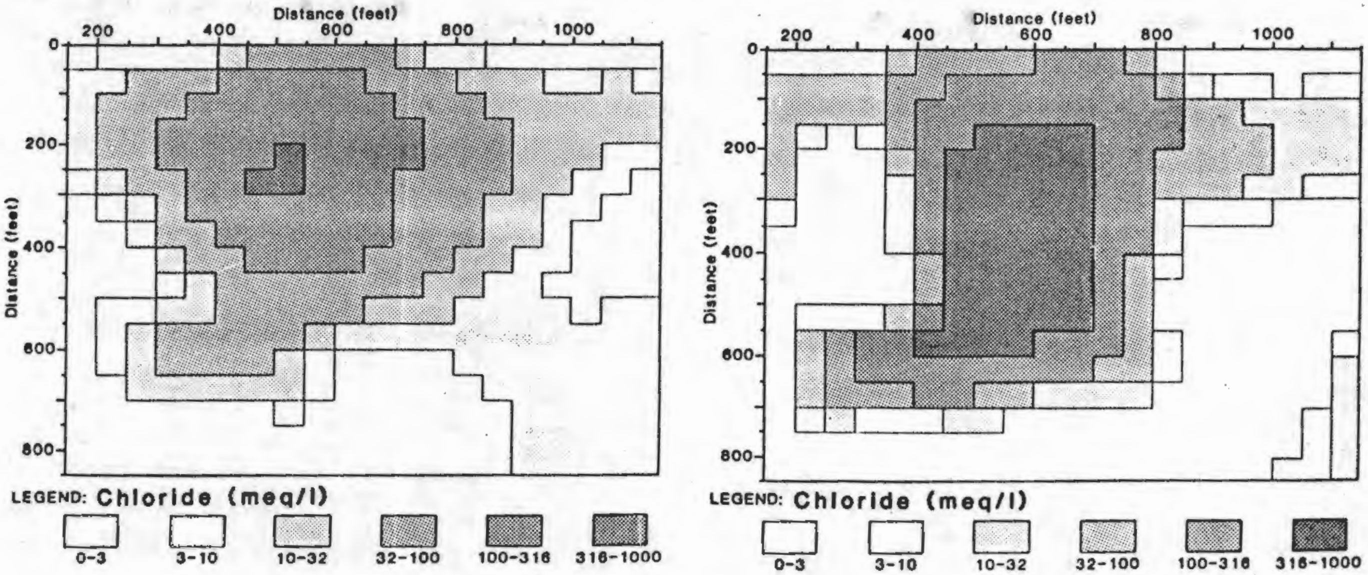


Figure 19 a, b, c, and d: Contour diagram of the electrical conductivity at various depths for Fossum Site 1.

a) 0-1 ft

b) 3-4 ft



c) 6-7 ft

d) 9-10 ft

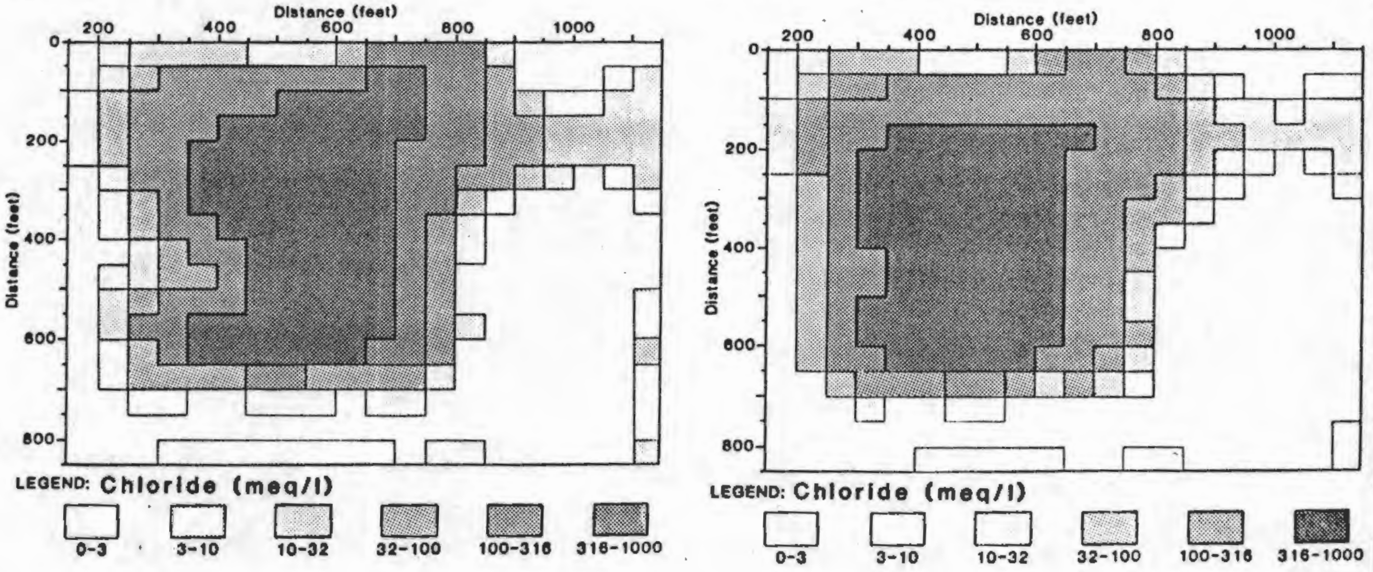


Figure 20 a, b, c, and d: Contour diagram of the distribution of chloride at various depths for Fossum Site 1.

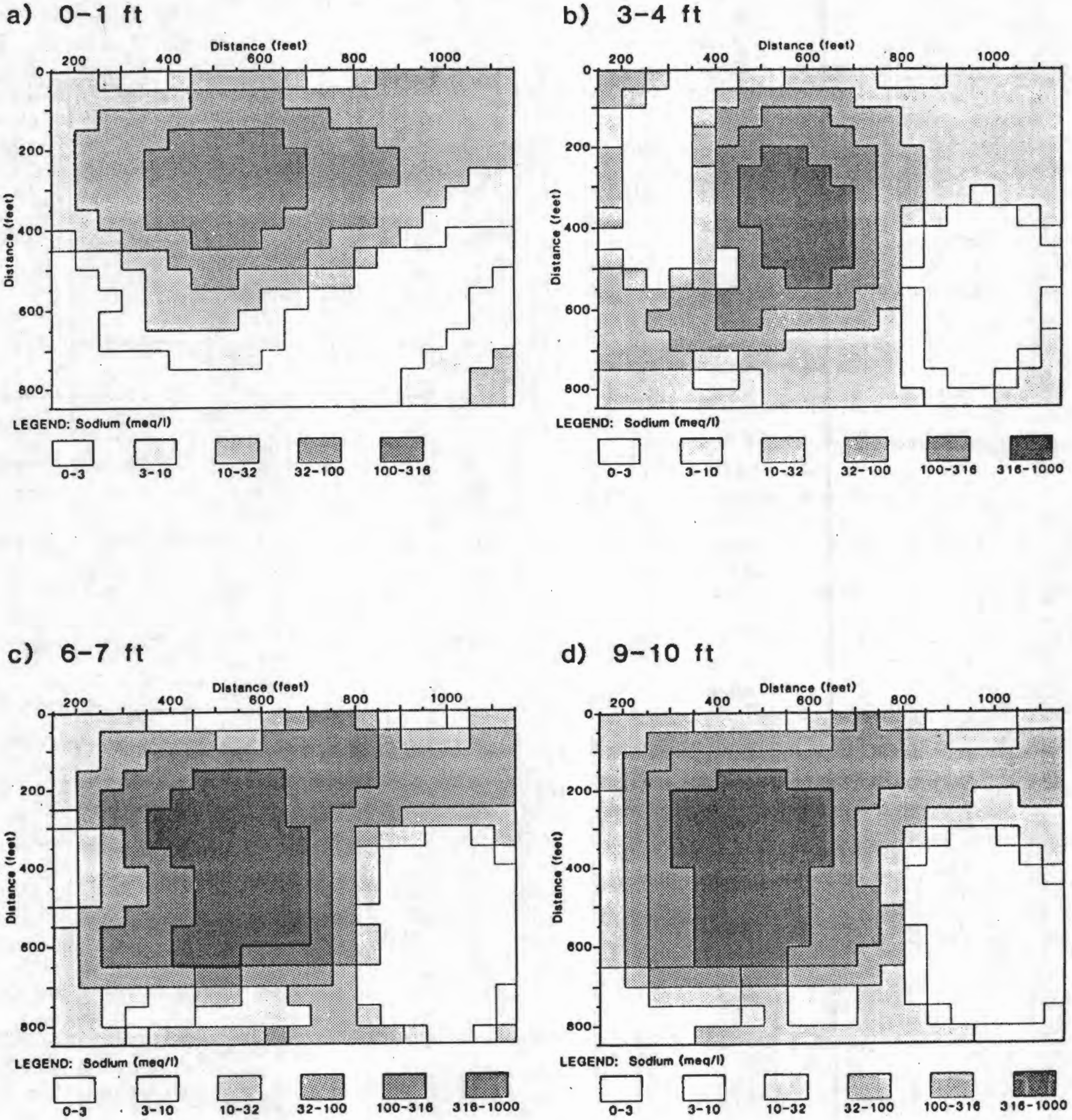


Figure 21 a, b, c, and d: Contour diagram of the distribution of sodium at various depths for Fossum Site 1.

difficult than with the chlorides because of the amount of sodium naturally occurring in the soil.

The distributions of magnesium at various depths is shown in Figures 22a, b, c and d. Note that an area of low concentration persists at all depths at location (400,400). This also is the location of a closed depression earlier identified on the topographic contour map (Figure 4). Apparently, leaching takes place to a depth of at least 10 feet in this depression.

The preceding diagrams have shown only part of the data collected at Site 1; complete data are listed in Task 2 Appendix Tables. Profile descriptions are also given in Task 2 Appendix Tables.

Fossum Site 2: The cultural features, sampling sites and approximate location of the buried brine disposal pit at Fossum Site 2 are shown in Figure 23. The study site is approximately 19 acres in size, and was laid out based on topography, vegetative damage and property boundaries. The site was flagged in a 100-foot grid spacing.

Relative elevations were recorded on a 50-foot grid spacing and six-inch elevation contour intervals were drawn (Figure 24). Closed depressions occur at locations (150,200), (650,350), (750,250), (700,600) and (0,600), and range from 1.5 to 5 feet in depth. The land surface generally slopes to the south-southwest.

The core holes were left open during sampling and the depth to free water was recorded at the end of the sampling tour (approximately four days). Figure 25 is a contour map of the relative water table elevation, and the depth of the free water surface from the land surface is shown in Figure 26. The critical depth is approximately 5 feet at this site, so that water may rise to the land surface by capillarity at this site.

Figure 22 a, b, c, and d: Contour diagram of the distribution of magnesium at various depths for Fossum Site 1.

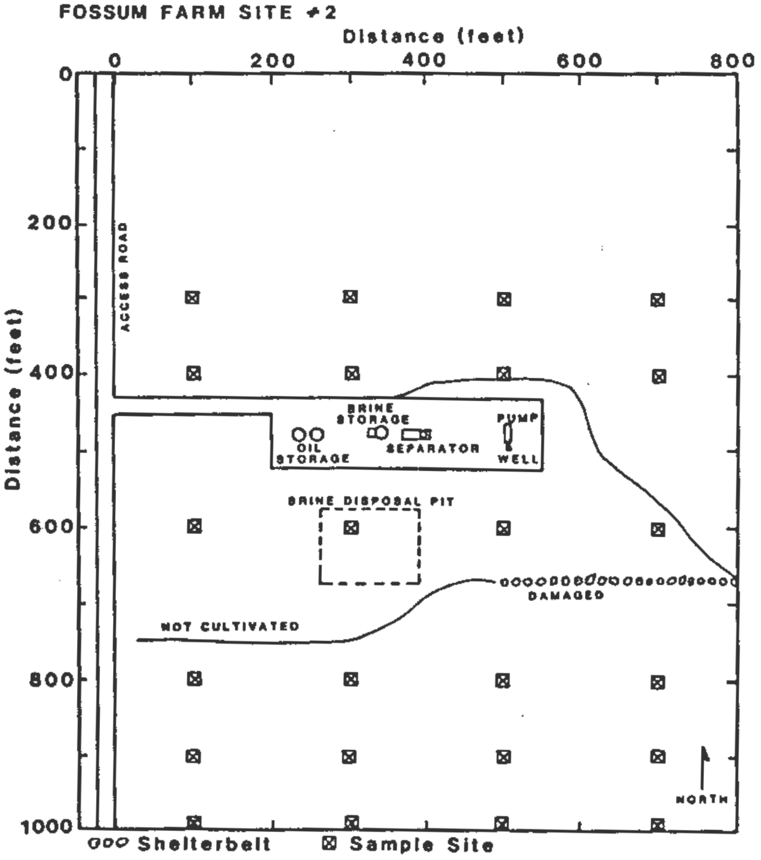


Figure 23: Location of cultural features and sampling sites for contaminated Fossum Site 2.

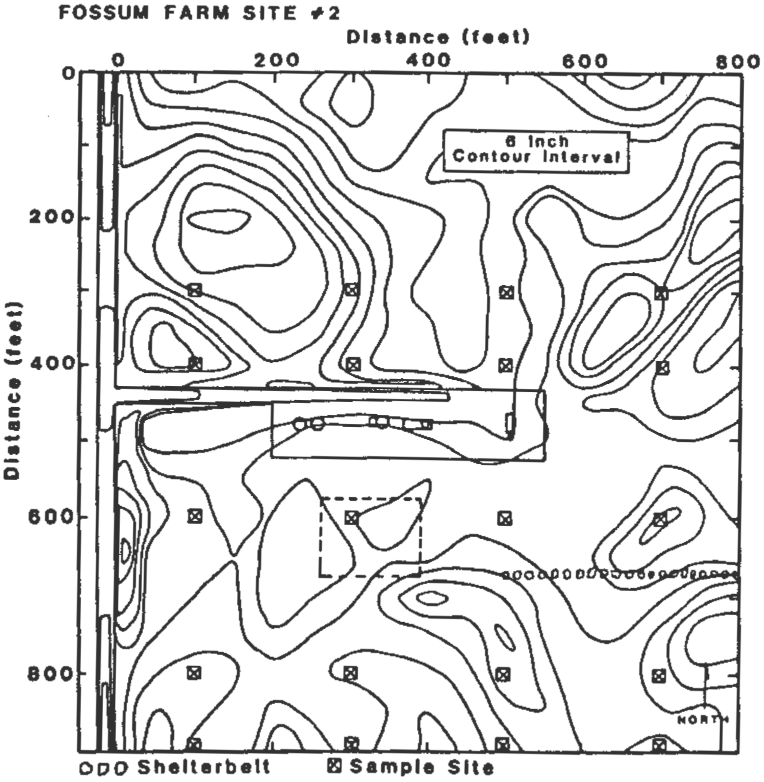


Figure 24: Topographic contour map of Fossum Site 2.

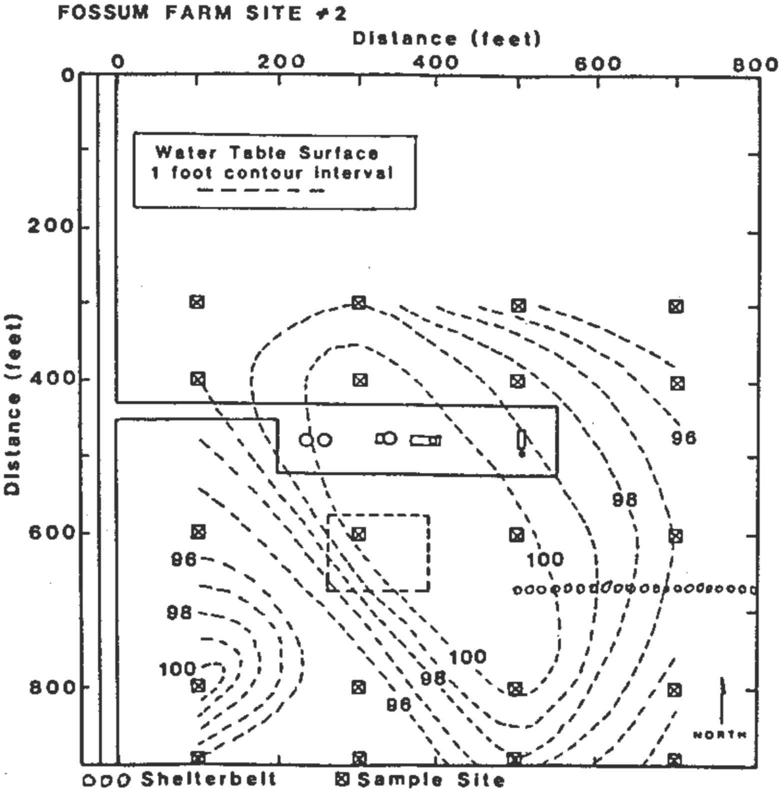


Figure 25: Contour map of relative water table elevation for Fossum Site 2.

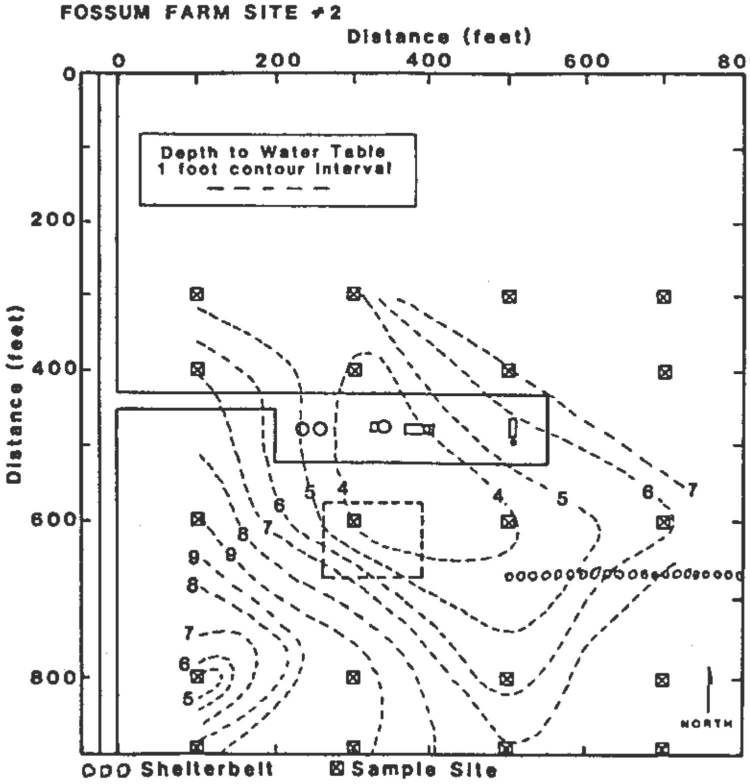


Figure 26: Contour map of the depth to the water table below the land surface at Fossum Site 2.

The EM38 meter readings were recorded on the same 50-foot grid spacing used for the topographic survey. The meter conductivity readings in both the horizontal and vertical positions were converted to weighted profile salinity (EC_e) using the relationships shown in Appendix Figures 2-1 and 2-2. Figures 27a and b are salinity contour maps for Site 2 as measured by the horizontal and vertical meter positions respectively. The transition zone between 5 and 10 mmhos/cm is very narrow at this site suggesting a fairly sharp front between contaminated and noncontaminated soils. Also the contaminated area increases with depth. The bulge in the concentration lines at location (200,300) indicates that the brine contamination is beginning to move into the closed depression near the same location. The separate areas of salinity greater than 50 mmhos/cm may indicate the pit is not the only source of contamination.

Core samples were laid out in a modified grid pattern based on the EM38 survey. The sample sites at y axis distance of 900 feet were on the edge of contamination movement. Sample sites at a y axis distance of 1000 feet were sampled in the spring to confirm the edge of contamination movement.

To better understand the movement of the brine contamination below the land surface a series of vertical cross-sections showing the distribution of certain ions have been constructed. The cross-sections are constructed for two transects C-C′ and D-D′ (Figure 28).

<u>Transect C-C′:</u> Two soil materials (ablation drift and till) are also identified at this site. The basis for making this separation comes from distinct differences in morphology and the degree of particle size sorting. The scatter diagram of the textural analysis (Figure 29) shows the difference in texture between the two materials. The range in sand content for the ablation drift is not as great as at Site 2 as at Site 1 (Figure 8). The till samples cluster very tightly as compared to the sediment. The ablation drift

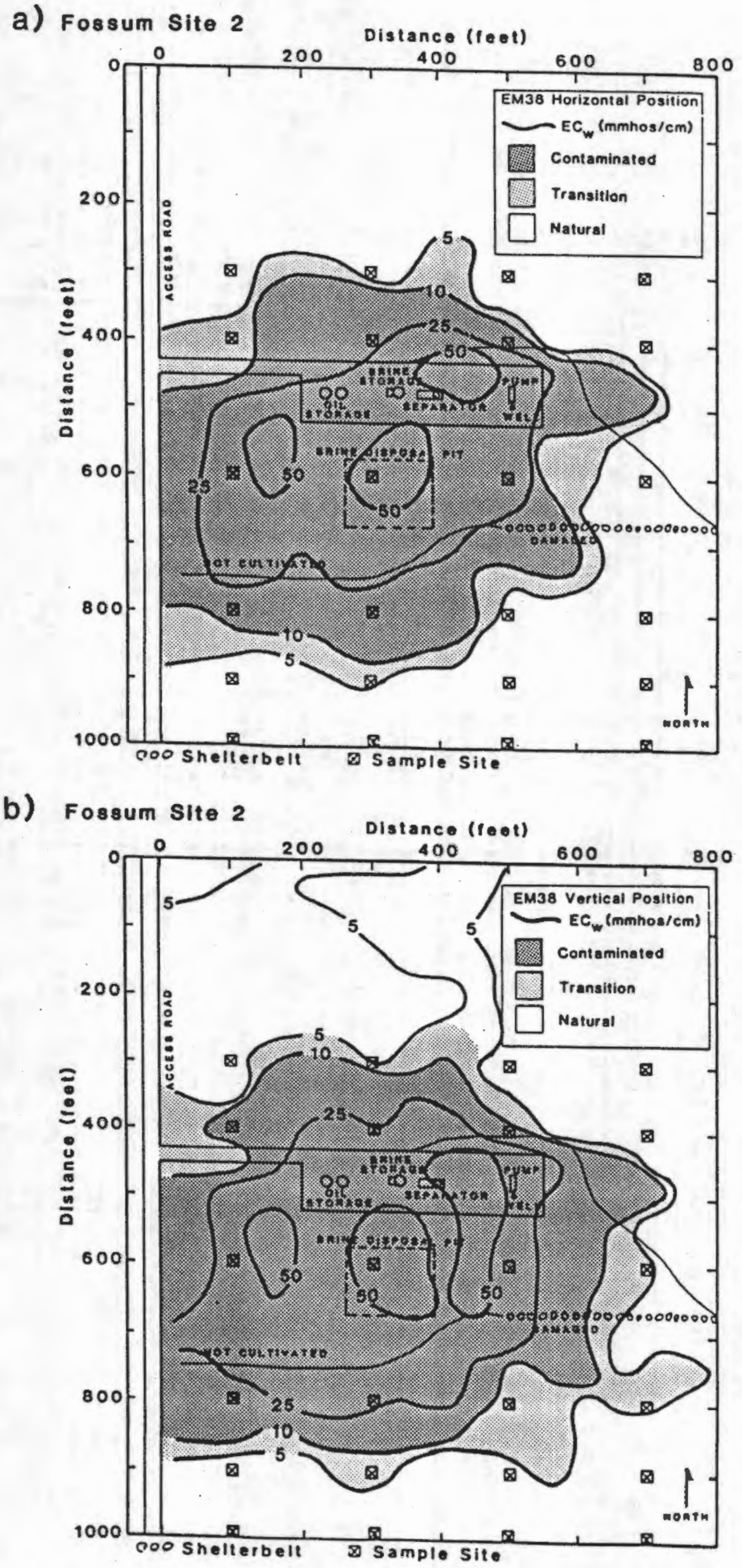


Figure 27 a and b: Contour maps of profile salinity as measured by the EM38 neter read in the horizontal and vertical position, respectively, for Fossum Site 2.

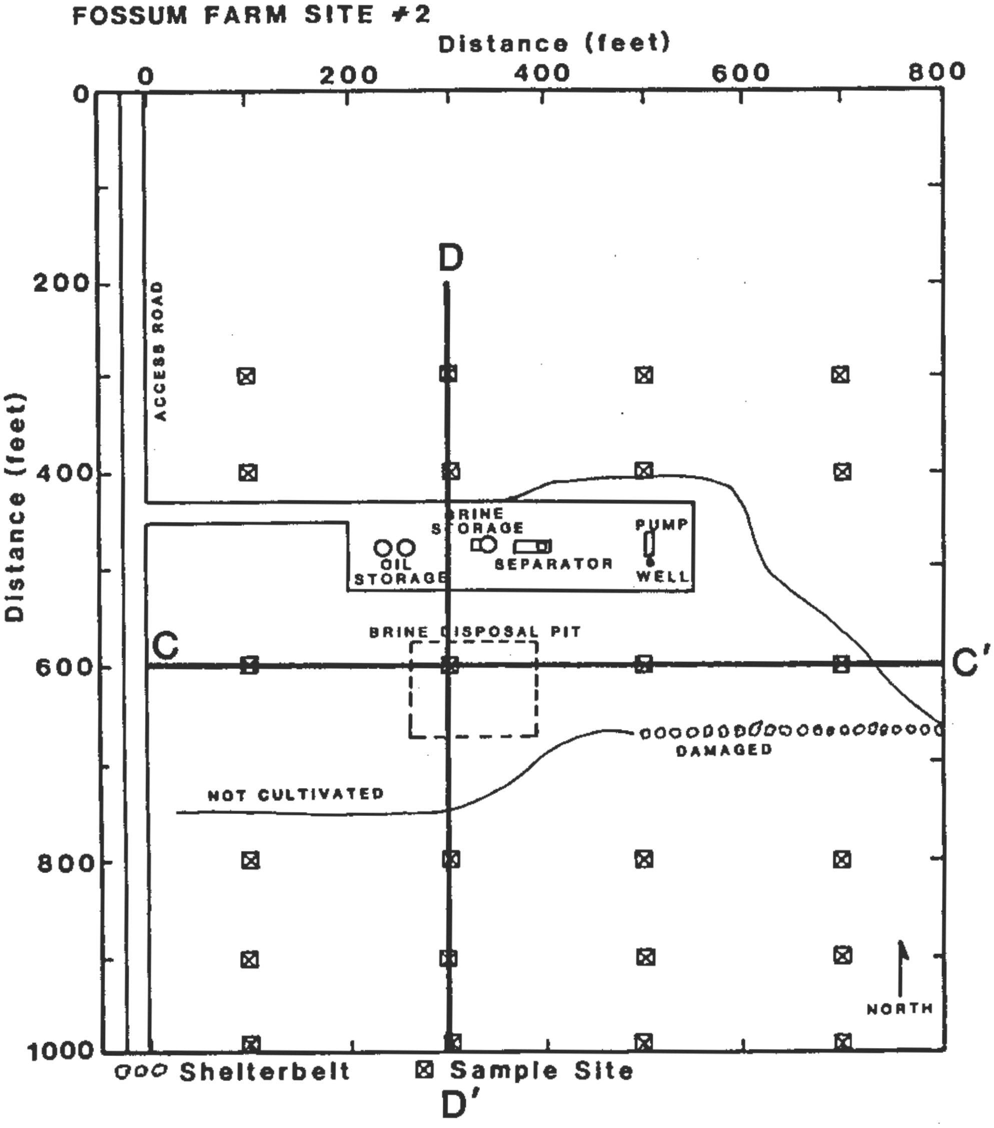


Figure 28: Location of cross-section transects C-C' and D-D' at Fossum Site 2.

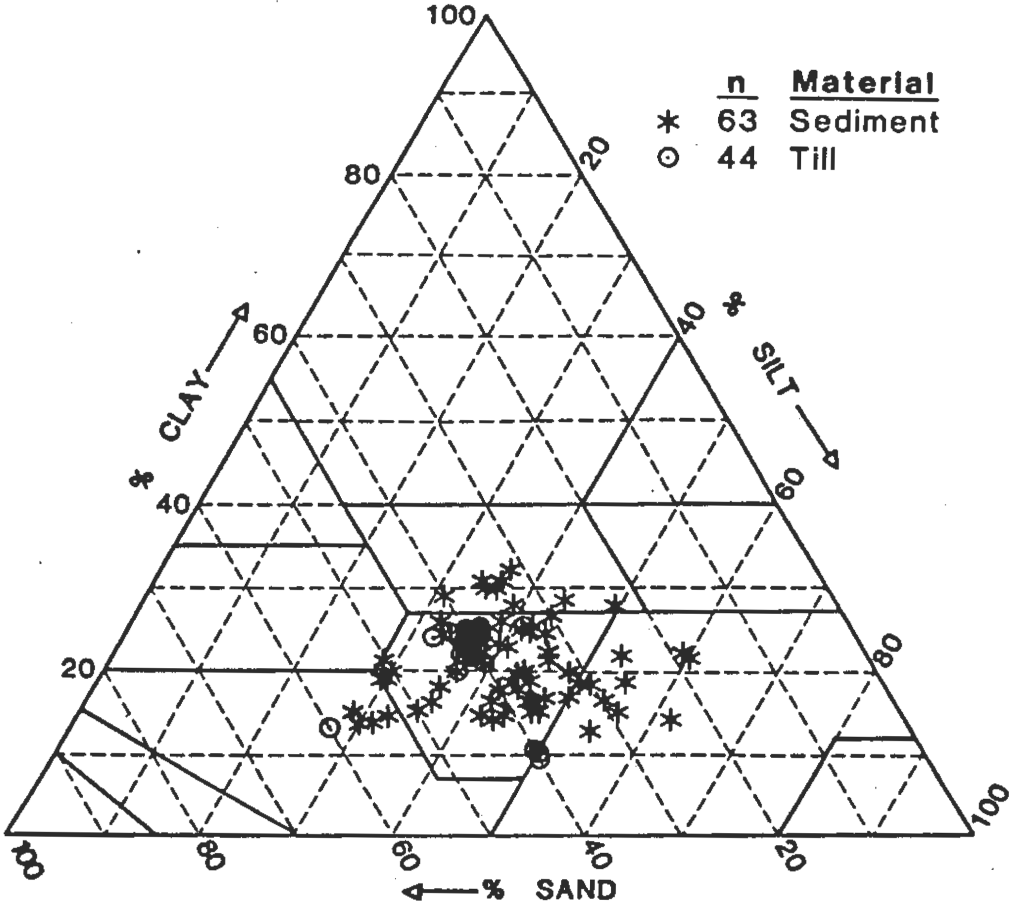


Figure 29: **Scatter diagram of particle size data for Fossum Site 2.**

sediment is moderately well sorted while the till sediments are poorly sorted. The sediment tends to be very friable while the till is firm and more dense. The hydraulic conductivity of the sediment is moderately rapid while that of the till is moderately slow.

The till is strongly fractured with oxidation of ion and secondary mineral formation occurring along the joint faces. The degree of jointing diminishes with depth and the affect of the joints on water movement into and through the till is not known. This jointing occurs at both Sites 1 and 2.

As at Site 1, the land surface does not mimic the buried till surface (Figure 30). There is no evidence of a perched water table. From the dashed line representing the free water surface, the water table tends to mound in the till and does not correlate with any particular land surface feature except for the backfilled disposal pit.

The distribution of magnesium (Figure 30) shows a tongue shape feature of low concentration at a horizontal distance of 700 feet associated with a surface depression. We interpret this to mean leaching and/or recharge is occurring at this location. There is a distinct increase (bulge) with depth at this same location which may be related to the sand lenses which occur between the disposal pits and the filled till depression. The highest concentration of chloride contamination (Figure 31) is outside of the pit, similar to Site 1. The bulge in the concentration lines to the right of the sand lenses may indicate more rapid movement of brine salts due to more rapid water movement through the sand lenses. The limit of the spread of the contamination to the left in the diagram under the road is not known; however the road crosses a closed depression at this point and EM38 readings indicate salinity has spread an additional 150 feet which corresponds to the far edge of the closed depression on the west side of the road.

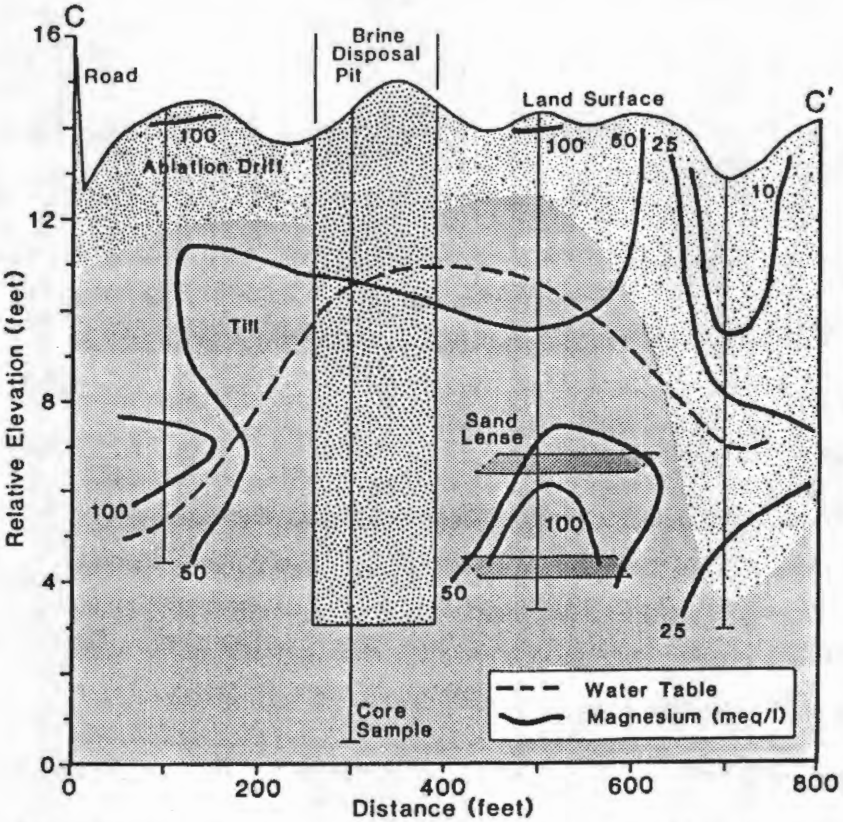


Figure 30: Vertical cross-section showing the distribution of magnesium for transect C-C' at Fossum Site 2.

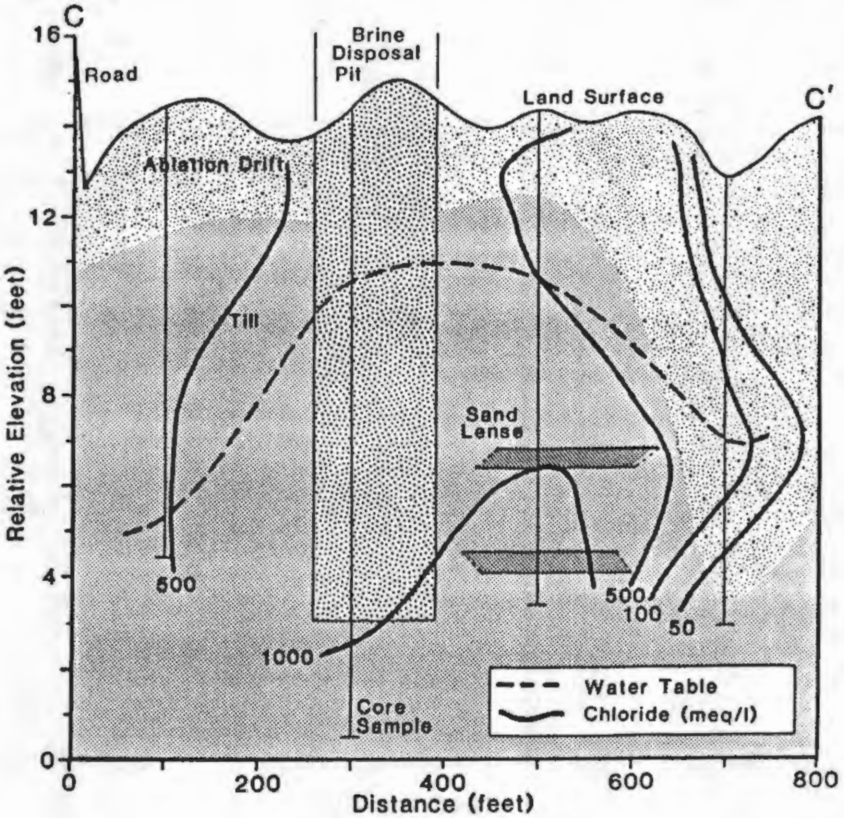


Figure 31: Vertical cross-section showing the distribution of chloride for transect C-C' at Fossum Site 2.

The distribution of sodium in the extract for transect C-C′ is shown in Figure 32. The pattern of concentration lines is similar to that of the chlorides. The highest concentration of sodium (greater that 1000 meq/l) occurs 100 feet away from the disposal pit between two sand lenses.

The highest concentration (>26meq/l) of calcium (Figure 33) is in the same area as that of chlorides and sodium. As with sodium, the highest concentrations are associated with the two sand lenses adjacent to the filled disposal pit.

<u>Transect D-D′:</u> Transect D-D′ runs from north to south respectively. The distribution of chlorides is shown in Figure 34. The closeness of the concentration lines on either side of the buried pit indicates a sharp boundary between contaminated and noncontaminated soil. A similar interpretation of a sharp boundary was concluded from the EM38 salinity survey data. To the right of the buried pit in the diagram the contamination front corresponds to a distinct rise in the till surface. To the left of the diagram the bulges in the concentration lines accelerated movement of chlorides along the sediment-till interface into an adjacent closed depression.

The magnesium distribution (Figure 35) is similar to the chloride distribution. To the right of the diagram the concentration lines are located a little farther to the right than the chloride lines. This may indicate that magnesium is affected by the brine contamination and is moving in response to the spread of the brine contamination. The highest concentration of magnesium is associated with a rise in the underlying till surface.

The distribution of sodium in transect D-D′ (Figure 36) shows a similar pattern to the chlorides except on the upper right hand area of the diagram. The sodium concentration lines do not bulge into the depression area. Perhaps magnesium and/or calcium are moving in response to the chlorides instead of

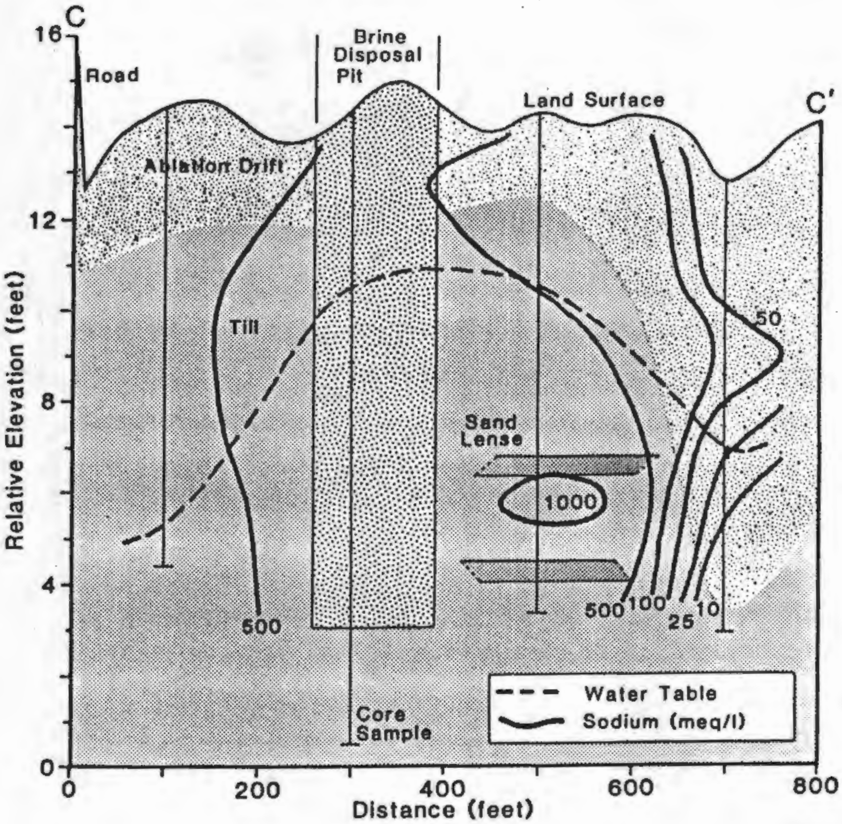


Figure 32: Vertical cross-section showing the distribution of sodium for transect C-C' at Fossum Site 2.

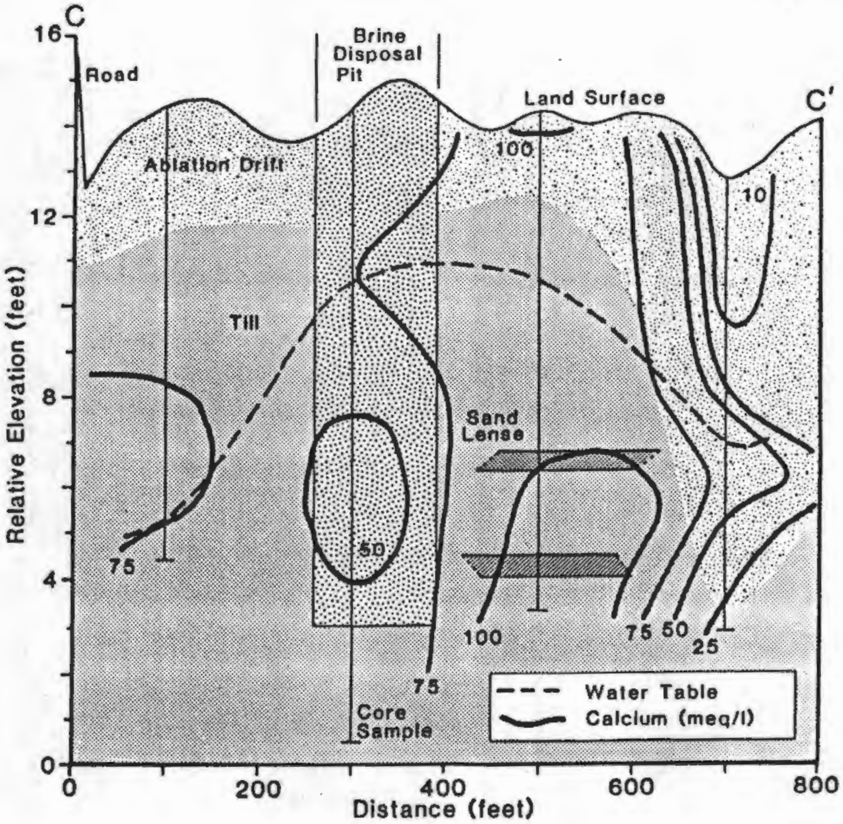


Figure 33: Vertical cross-section showing the distribution of calcium for transect C-C' at Fossum Site 2.

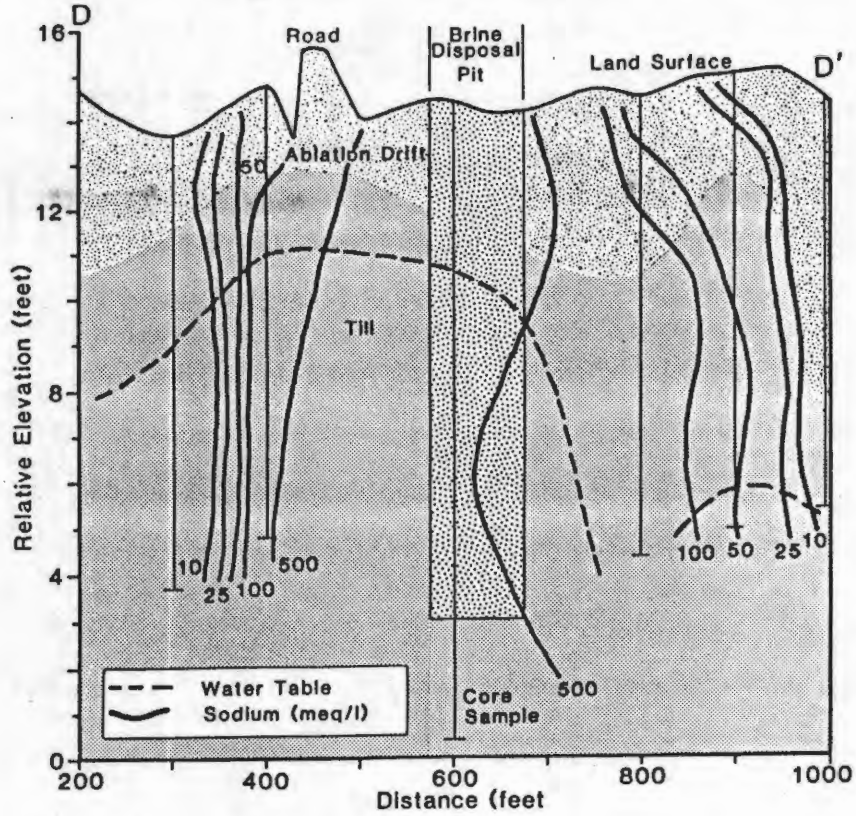


Figure 34: Vertical cross-section of the distribution of chloride for transect D-D' at Fossum Site 2.

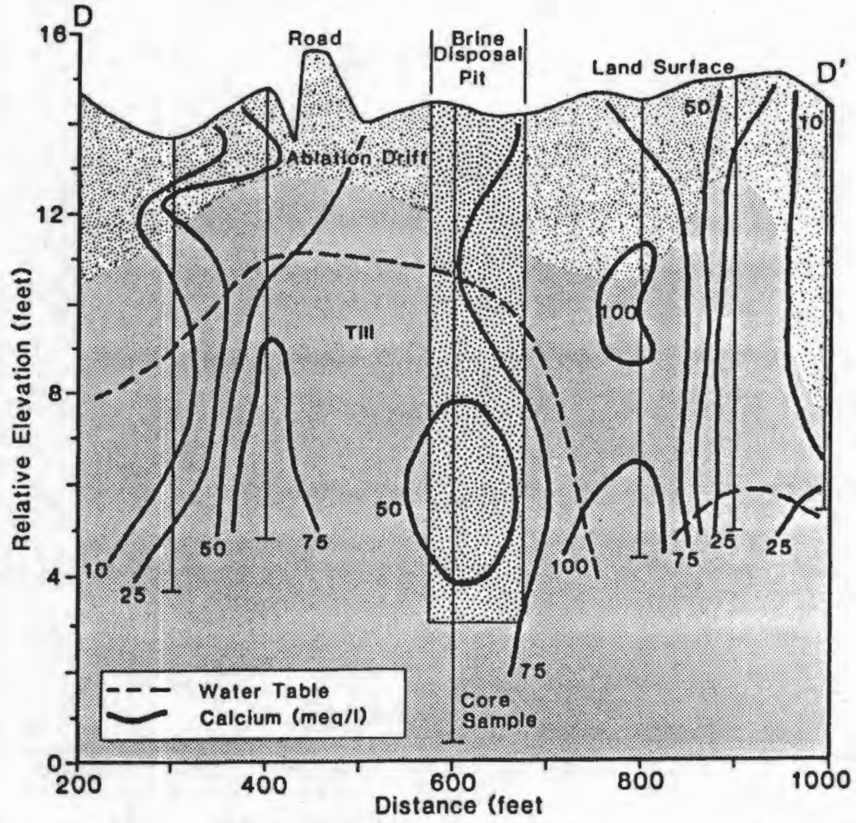


Figure 35: Vertical cross-section of the distribution of magnesium for transect D-D' at Fossum Site 2.

sodium. As in the other diagrams of transect D-D′ (Figures 34 and 35), the concentration lines are nearly vertical suggesting the contamination is also spreading along the land surface. The depth of the contamination movement is apparently below 15 feet which is the deepest core sample collected at this site.

The calcium distribution (Figure 37) seems to be affected by the brine contamination, where higher than expected amounts of calcium in the soil solution are measured.

Figures 38, 39, 40 and 41 are contour diagrams showing the concentration distribution of certain ions at various depths. Each figure contains 24 measured data points and 231 points computed by a bivariate spline interpolation technique in SAS.

Figures 38a, b, c and d show how electrical conductivity of the saturated paste extract varies with depth. Assuming the electrical conductivity values are directly related to the brine contamination, the smallest area affected is located at the land surface. Both the area affected and the degree of contamination increase with depth.

Figures 39a, b, c and d for chloride and Figure 40a, b, c and d for chlorides show the same pattern of distribution with depth as electrical conductivity. Note that the contaminated area forms a somewhat elongated pattern.

The last set of figures (Figure 41a, b, c and d) show the concentration distribution of magnesium at various depths. The pattern of magnesium distribution is somewhat different than for the other ions and the reason for the differences not apparent.

The distribution of ions in the soil as measured in saturated paste extracts is directly related to water movement both over and through the soil.

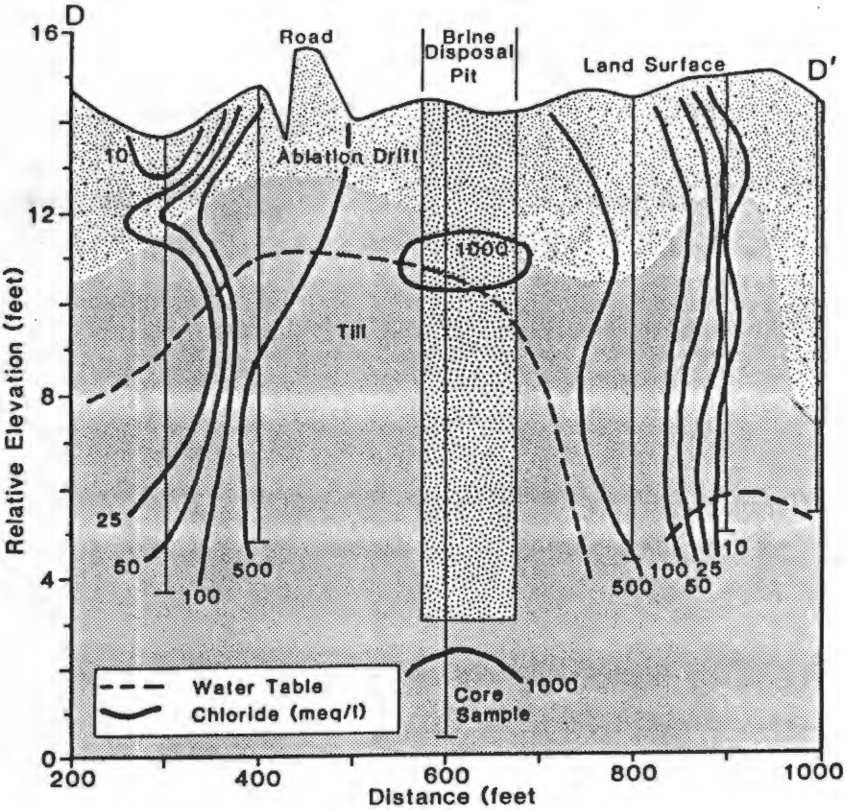


Figure 36: Vertical cross-section of the distribution of sodium for transect D-D' at Fossum Site 2.

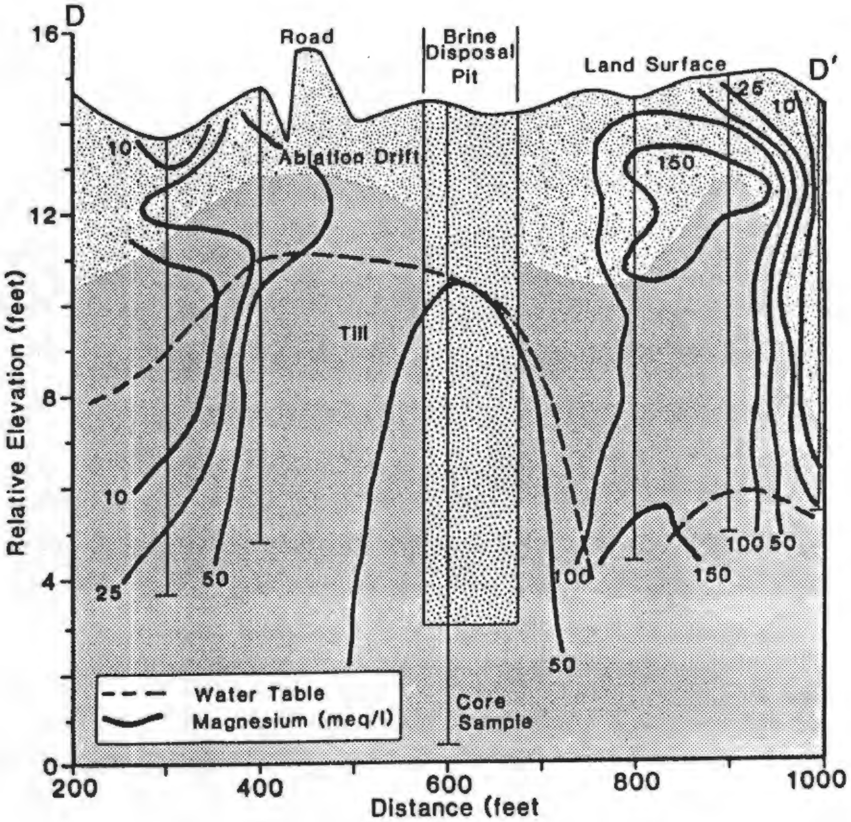


Figure 37: Vertical cross-section of the distribution of calcium for transect D-D' at Fossum Site 2.

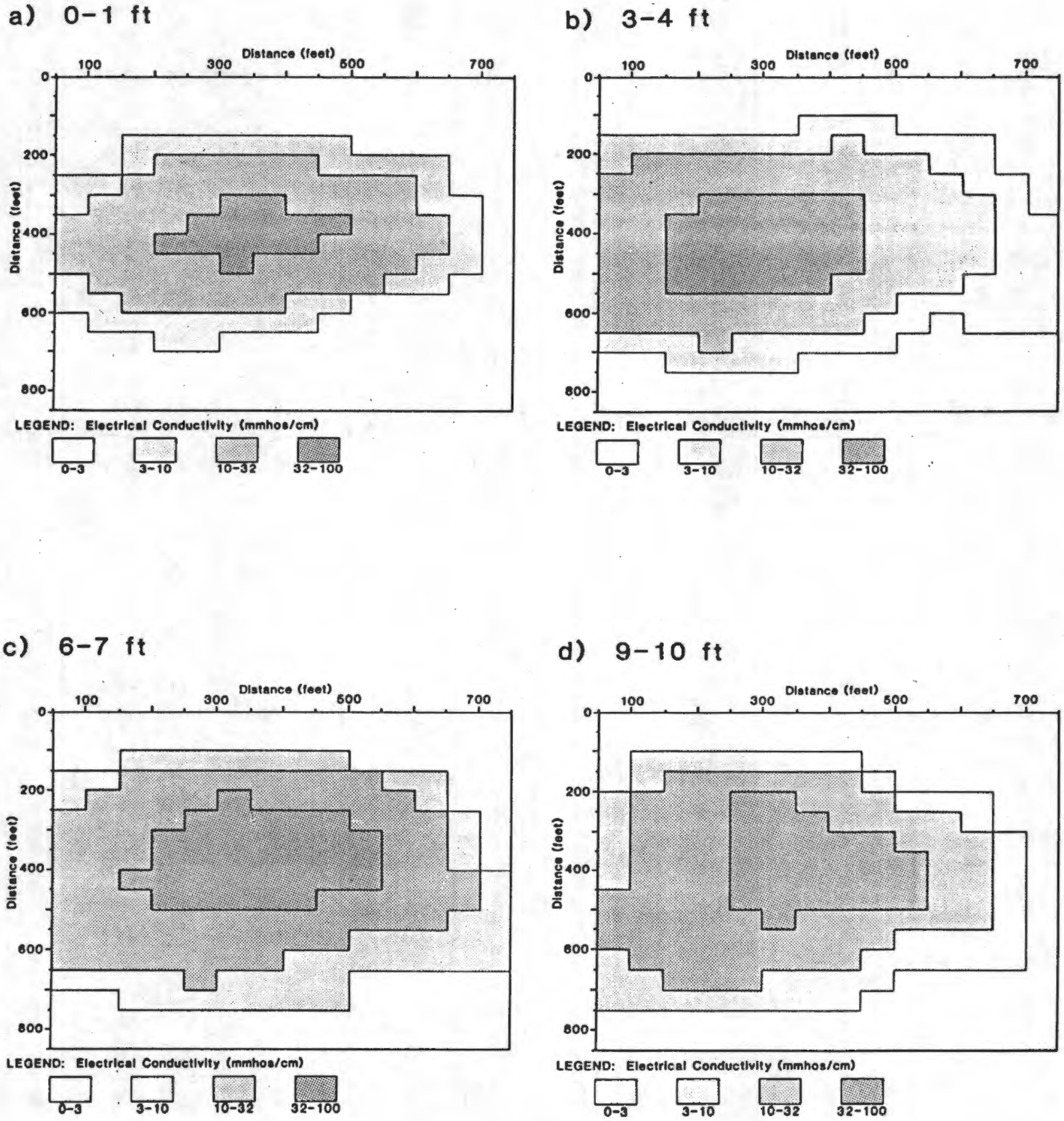


Figure 38 a, b, c and d: Contour diagram of the soil electrical conductivity at various depths for Fossum Site 2.

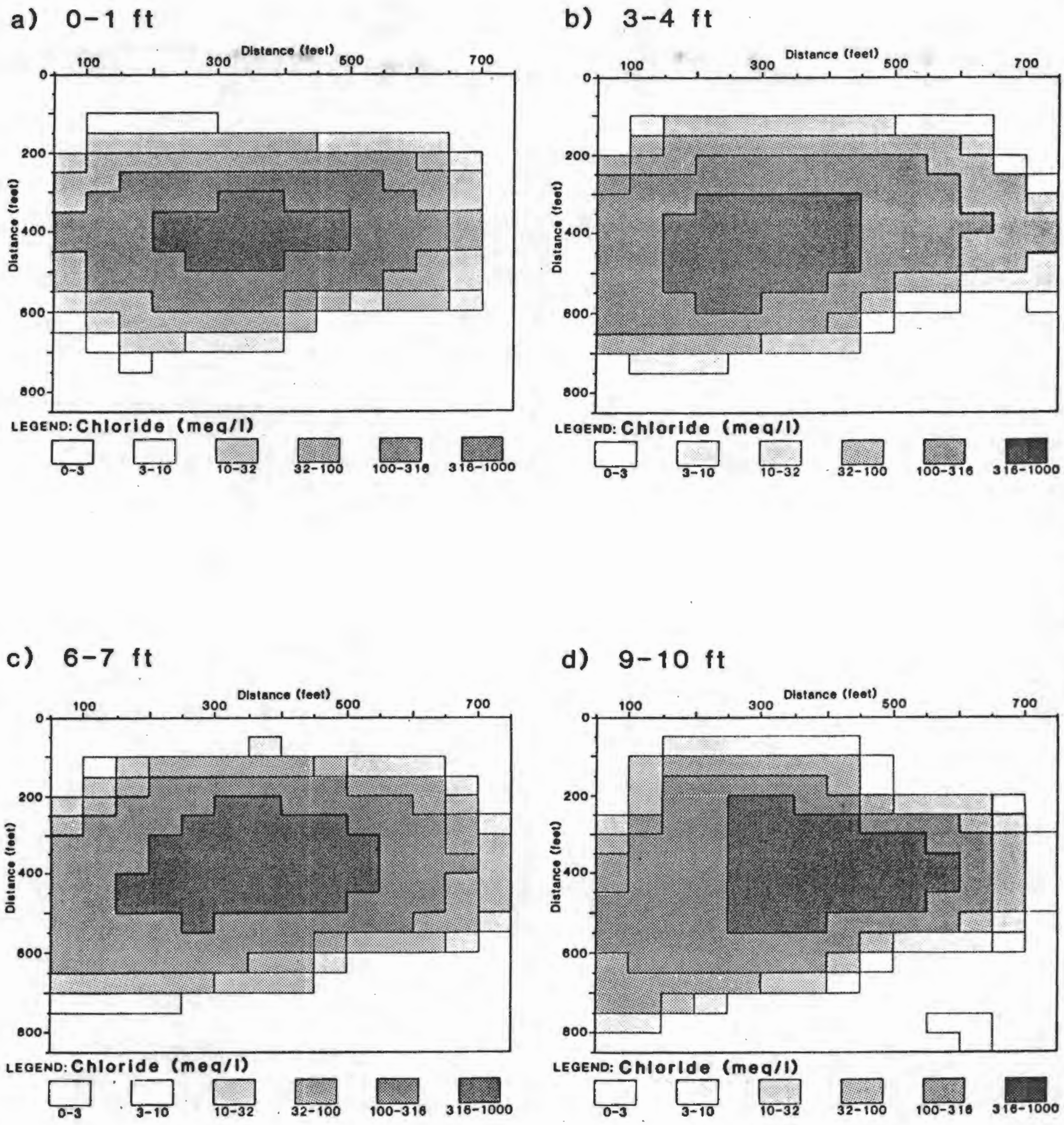


Figure 39 a, b, c and d: Contour diagram of the distribution of chloride at various depths for Fossum Site 2.

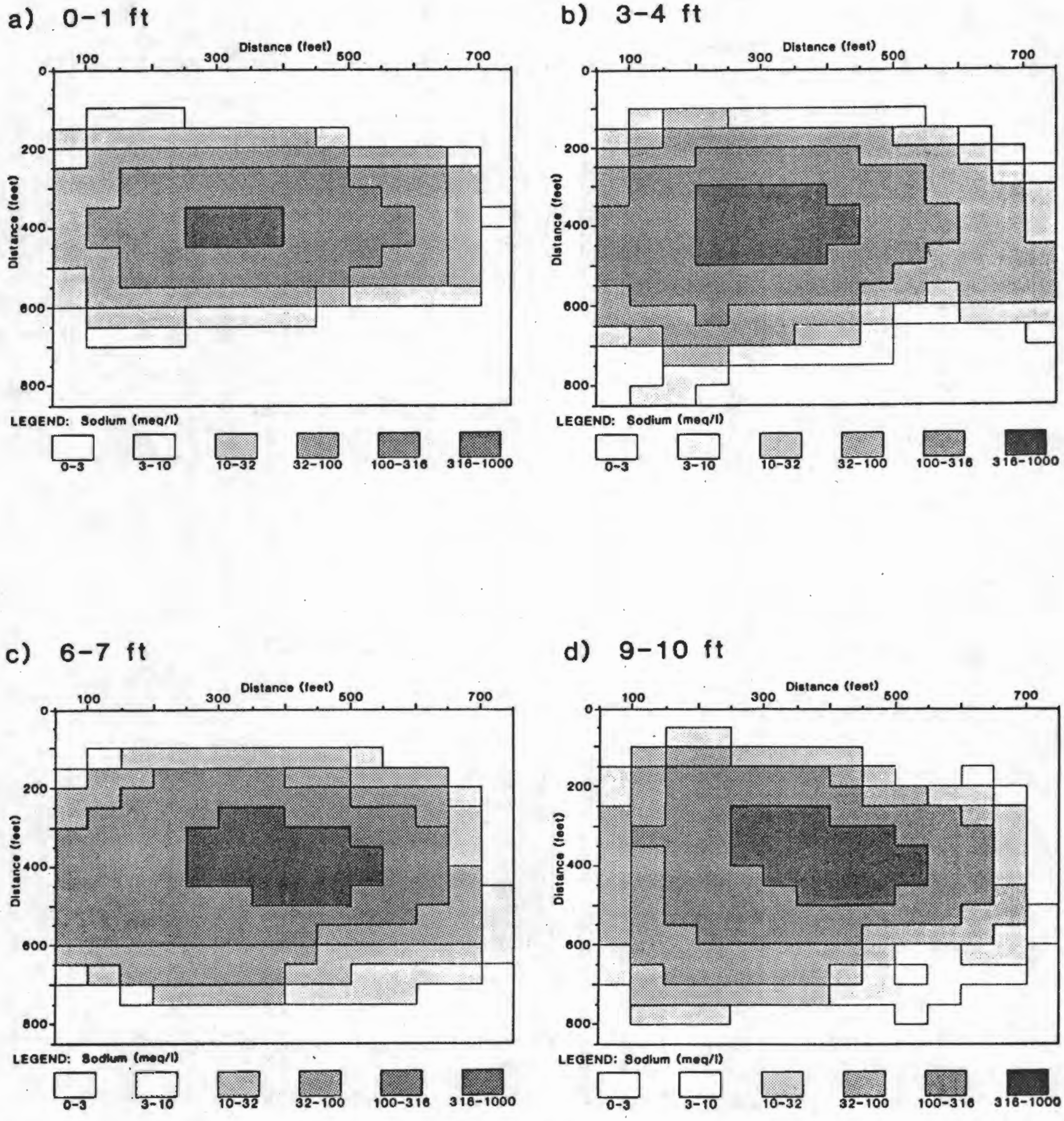
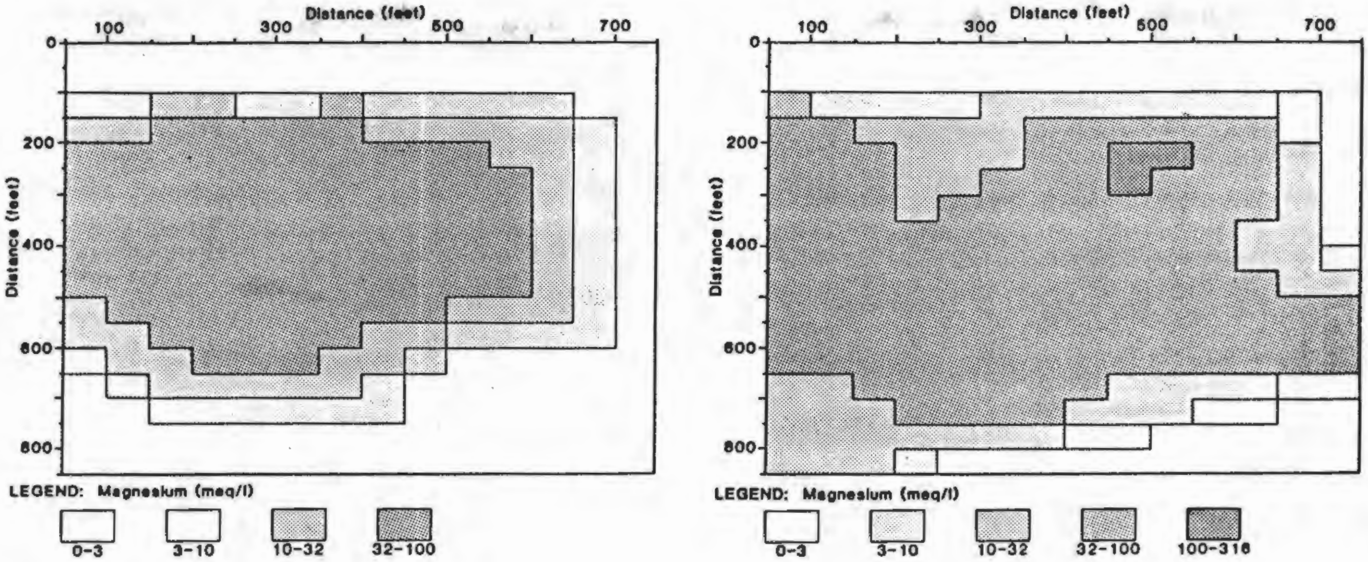


Figure 40 a, b, c and d: Contour diagram of the distribution of sodium at various depths for Fossum Site 2.

a) 0-1 ft b) 3-4 ft



c) 6-7 ft d) 9-10 ft

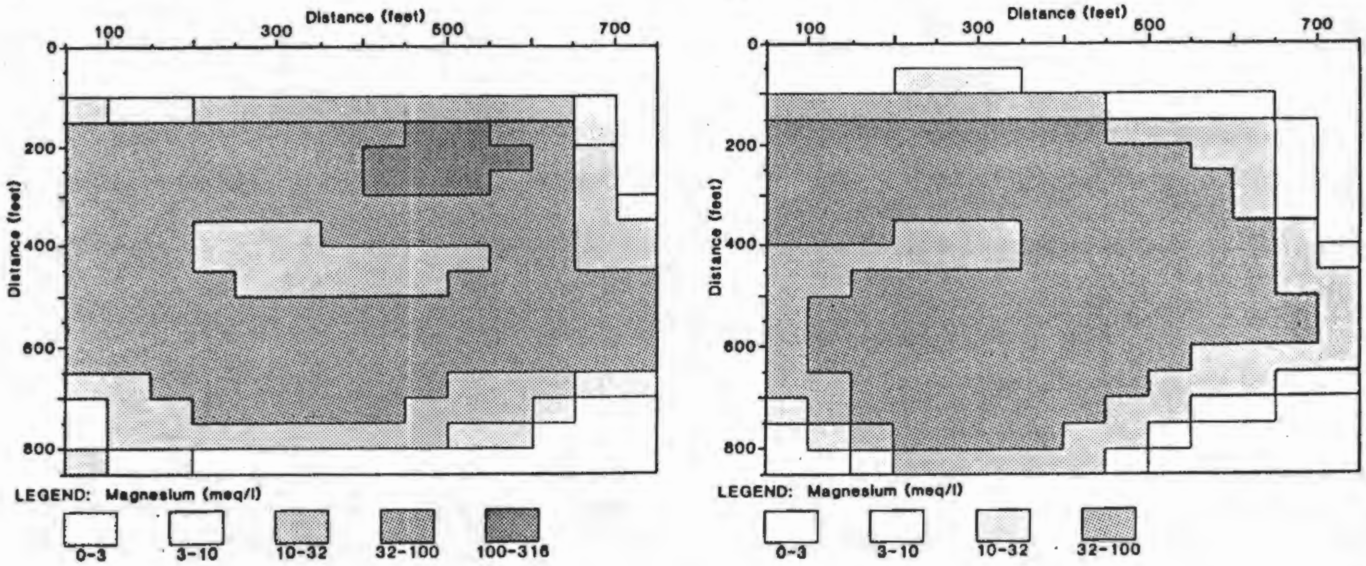


Figure 41 a, b, c and d: Contour diagram of the distribution of magnesium at various depths for Fossum Site 2.

The movement of water is controlled by surface topography and parent material stratigraphy. The high concentrations of sodium and chloride that result from brine contamination apparently affect the solubilities of primary and secondary minerals in the soil.

Capillary rise of water from a free water surface to the soil surface will result in surface accumulation of salts. Leaching will move these salts downward in the soil while overland flow will transport the salts to other land areas where they may either leach into the soil or concentrate on the surface.

In the soil, water moves from high to low potential, and the rate of movement depends upon the hydraulic conductivities of the various soil materials. At Fossum Site 1, a perched water table occurs as a result of the higher permeability of the sediment which overlies the less-permeable till. In addition, subsurface water moves in response to the gradient of the till surface as well as to that of the land surface. Since the noncontaminated soils are low in chlorides, the location and extent of brine contamination can be determined from the chloride concentration. The interpretation of calcium, sodium and magnesium concentrations is more difficult because they occur in relatively high amounts in noncontaminated soils and the calcium and magnesium concentrations are dependent upon the solubility of the primary and secondary minerals in the soil and upon the electrolyte concentration of the soil solution. The mineral solubilities are increased by the increased ionic strength of the soil solution when the soil is contaminated by brine.

Electrical conductivity (salinity) measured with the EM38 meter correlates closely with the concentration and spread of the brine contamination.

To reclaim these two study sites will require drainage as to lower the free water table and chemical amendments to prevent soil dispersion during reclamation. The drainage water will need to be disposed of by injection underground the same as the brine. Also overland water flow should be contained at each site and disposed of in the same manner.

ACKNOWLEDGMENTS

Appreciation is expressed to Mr. Roy Johnson of the NDSU Development Foundation and manager of the Fossum Farm, for his cooperation and support of this study. We also wish to express our appreciation to the following LRRC staff who assisted with the field and laboratory work on this project: Zann Nash, Linda Thomas, and LeRoy Zimmerman. Special appreciation is expressed to Karen Stastny for the many hours devoted to typing, retyping, duplicating and assembling this report.

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CHARACTERIZATION OF DETRIMENTAL EFFECTS OF SALTS AND OTHER CHEMICAL CONSTITUENTS CARRIED IN SURFACE AND SUBSURFACE WATER FROM MINE AND DRILLING FLUID DISPOSAL PITS BURIED DURING OIL DEVELOPMENT

Task 3

SOIL MATERIALS CHARACTERIZATION

FINAL REPORT

to the

North Dakota Water Resources Research Instutute

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September, 1985

INTRODUCTION AND SUMMARY

The objectives of Task 3 were (1) to provide soil materials characterization support, primarily in the area of soil mineralogy, for the other tasks of the contract and (2) to look for any chemical or physical interactions of the migrating salt and soil materials. These objectives were met early in the project. Mineralogy of bulk soils and of soil sand, silt and clay fractions was determined in detail at the principal study site of the project (the Fossum farm) and at selected additional sites. Surprisingly little interaction of the migrating salt with soil materials had occurred. Even the Na for Ca exchange in the Ca-smectite clays was only partial in highly contaminated areas.

Water movement was one of the key issues in this project. After the necessary materials characterization work was completed and the level of reaction in salt contaminated systems was found to be small, effort in Task 3 was focussed on the water movement issue. During the first year of the contract, a detailed study was made of a transect on the Fossum Farm site, located approximately 35 miles northeast of Minot, ND. Distribution of the evaporite minerals gypsum, calcite and (in contaminated areas) halite, was found to be an effective indicator of water movement. The minerals were routinely identified by x-ray diffraction. Chemical analysis of the solutions from saturation paste extractions and geochemical modeling of those solutions were consistent with the model developed from the mineralogical data.

In the second year, water movement was studied in three of the other sites in the contract to see if the water movement model developed during that first year could be applied to different classes of soil materials and surface topographies. Natural and contaminated toposequences formed from three different glacial parent materials were sampled during April 1985 to determine water movement. The soil materials of the toposequences were of till, outwash, and lacustrine origin and had similar slope and relief. Moisture content, electrical conductivity, and chlorine ion determinations were performed. These data, along with field observations, were used to determine how salt movement away from the brine pits occurs. The results confirmed the validity of the original model. A general model for water movement in the spring, when a frost layer at depth is an important factor, was also developed.

The results from Task 3 have been integrated into the descriptions of salt migration and suggestions for reclamation described throughout this report. The general models for water movement in these glacial and lacustrine materials should also be of interest to the agricultural, wildlife, and land and water managment sectors of the state.

SITE SELECTION AND FIELD DESCRIPTIONS

During the summer months of 1984, five cores of a non-saline toposequence (FA-2, FA-4, FA-6, FA-7A, and FA-8) and one saline core (F-1) were obtained at the Fossum Farm site in Bottineau County for mineralogical analyses. Four additional cores (FA-3, FA-5, FA-7, and FA-9) obtained by N.C. Wollenhaupt were also provided for this study. Specimens from these cores were selected in 6 inch depth intervals. Field descriptions of the materials from the FA transect are given in Table 1A.

In April 1985, specimens were collected at three different geological settings, all glacial in origin, also in Bottineau County. For each geological setting a natural and contaminated toposequence was chosen. All toposequences have similar relief and landscape position.

The till toposequences were designated FSA and PSC, natural and contaminated (C), respectively. The FSA toposequence is located along the same transect as the FA toposequence (Figure 1a). The location of the PSC toposequence is shown in Figure 1b. The outwash toposequences were designated BSN and BSC, natural (N) and contaminated respectively (Figure 1a). The lacustrine toposequences were designated SSN and SSC (Figure 1c). Field descriptions of all of the materials from these new sites are given in Tables 1B-1G.

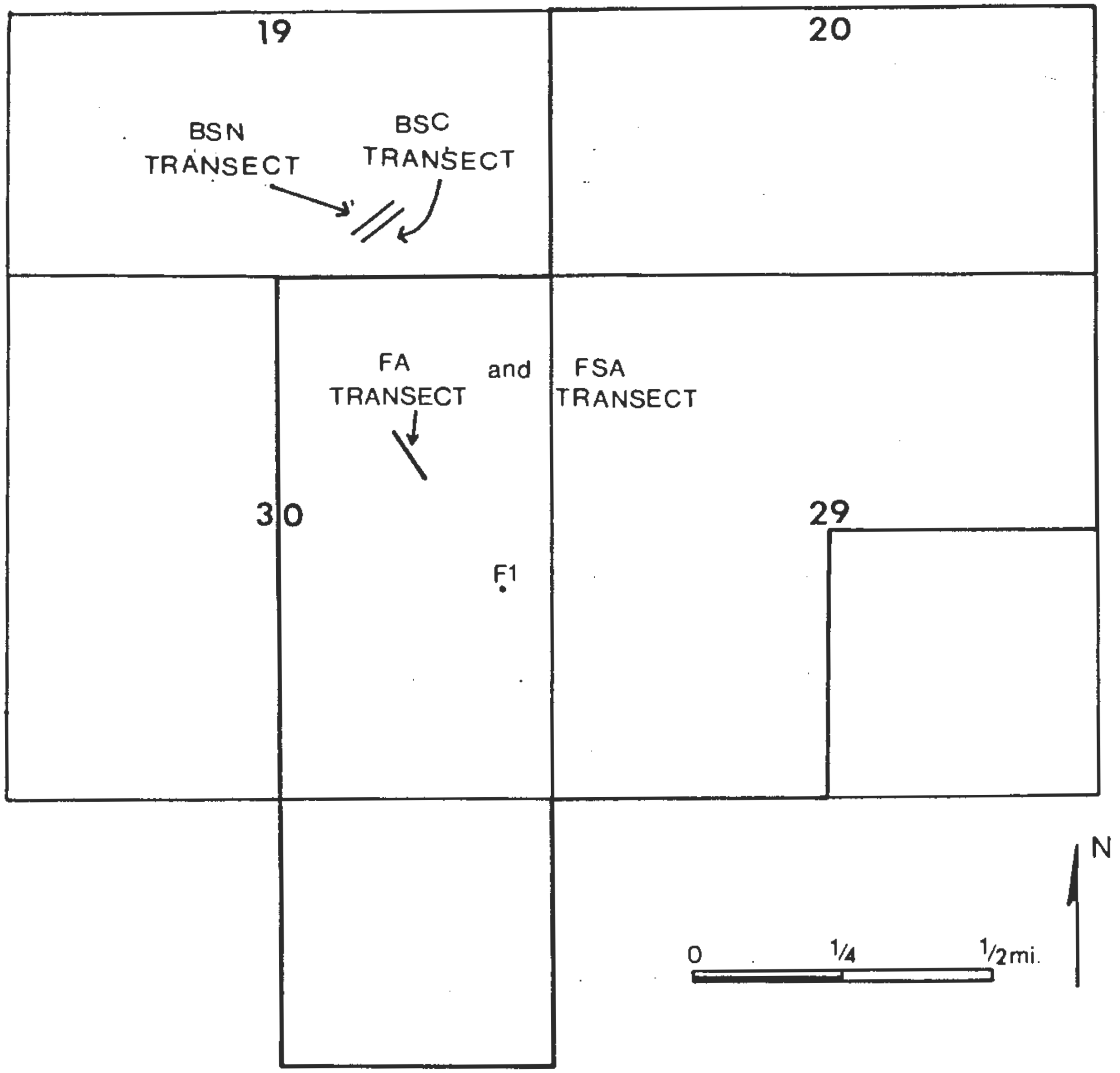


FIGURE 1a

LOCATION OF FA, FSA, BSN, AND BSC TRANSECTS AND F-1 SITE

T.161N., R.81W.

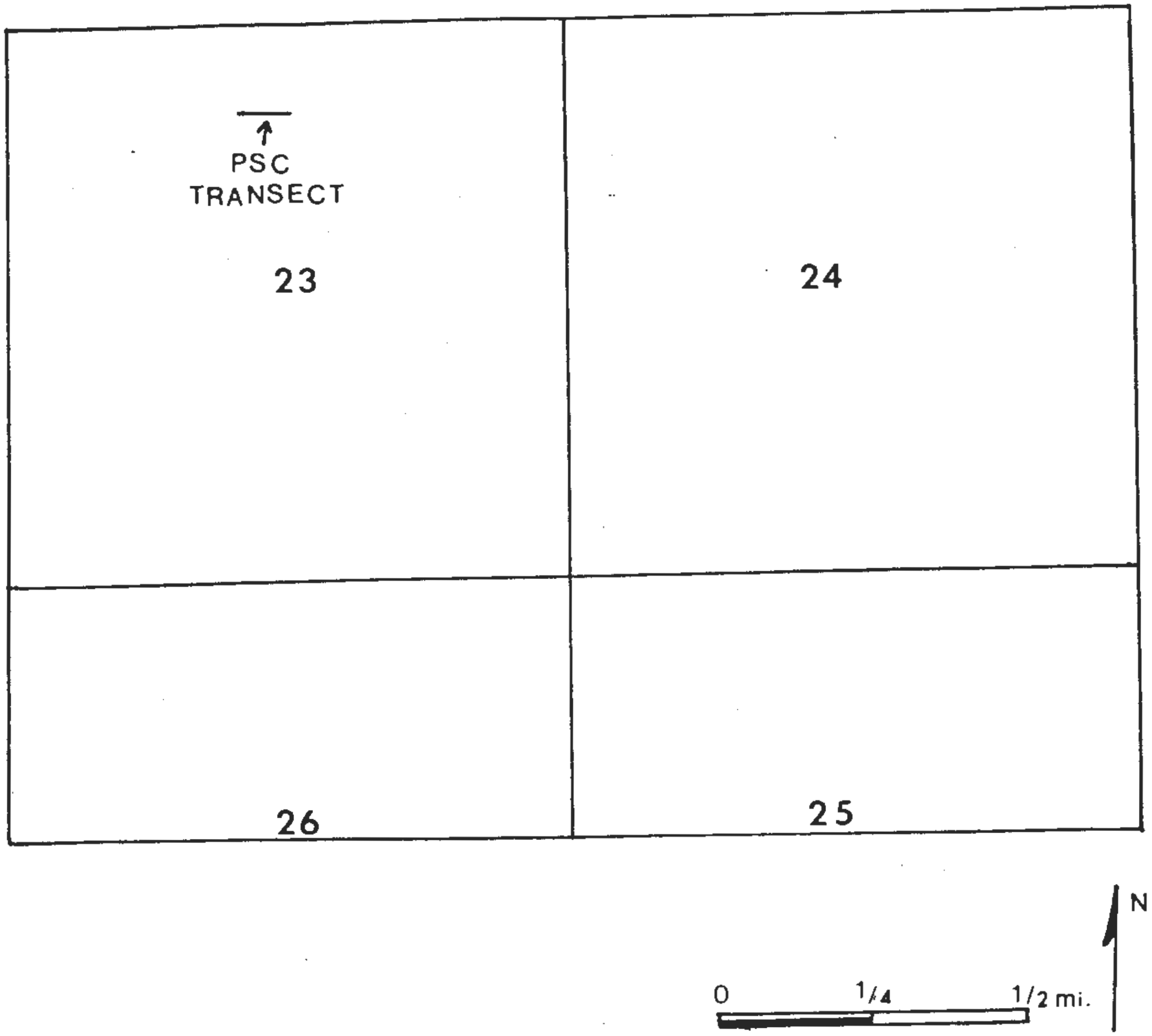


FIGURE 1b

LOCATION OF PSC TRANSECT

T.161N., R.82W.

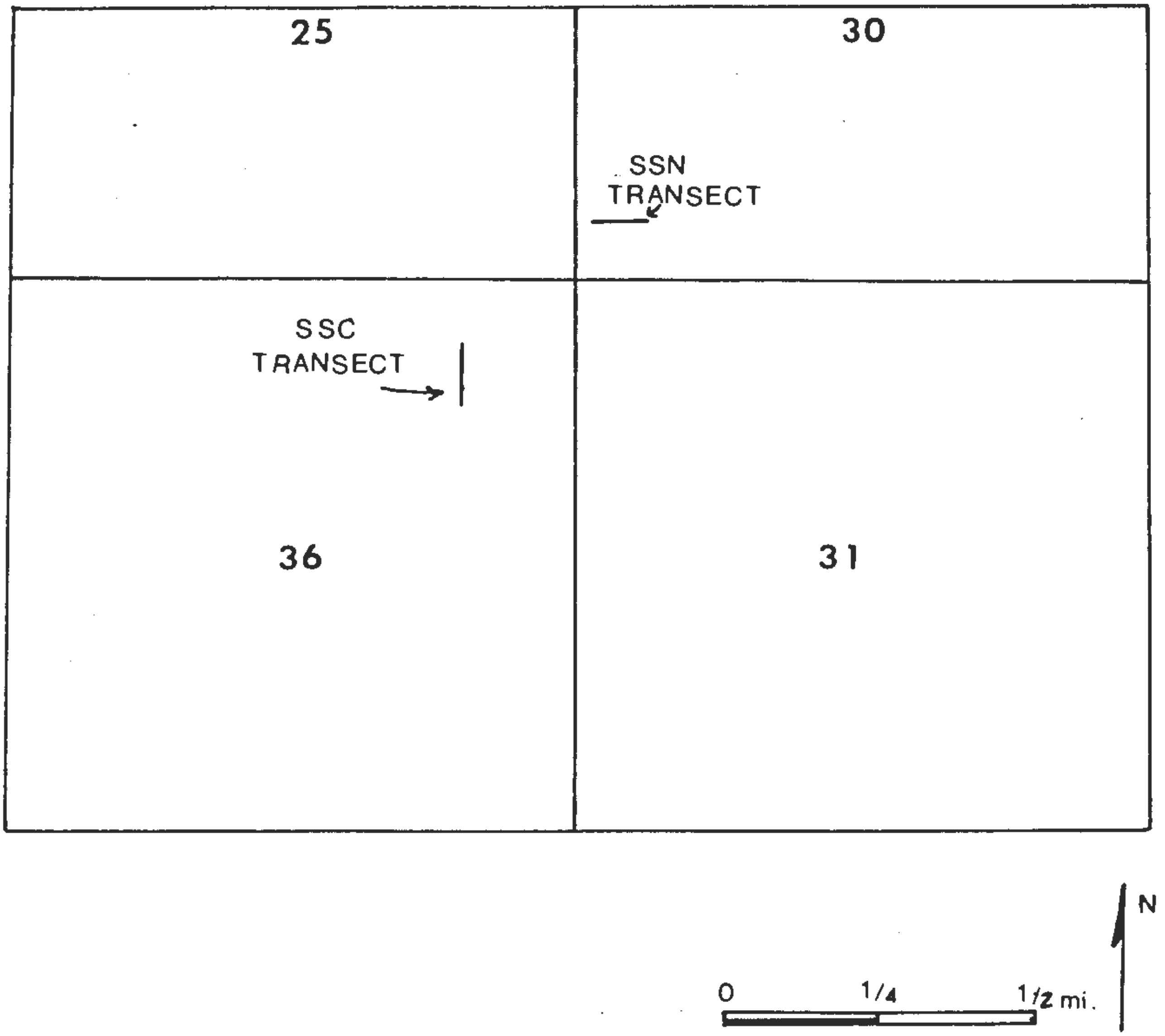


FIGURE 1c

LOCATION OF SSN AND SSC TRANSECTS

T162N., R.79W. AND R.80W.

TABLE 1A

FIELD DESCRIPTIONS OF SELECTED SPECIMENS FROM THE FA TRANSECT

CORE	DEPTH	COLOR		TEXTURE	REACTION	BOUNDARY	REMARKS
#		DRY	MOIST		WITH HCL		
FA-2	6	10YR 2/1					
	30	10YR 2/1	10YR 2/1	CLAY LOAM		GRADATIONAL	
	36	2.5Y 6/2	2.5Y 5/2	FINE SAND	NONE	DISTINCT	SAND LENSE
	48	2.5Y 5/4	2.5Y 4/4	SILT LOAM	SLIGHT	GRADATIONAL	IRON STAINING
	60	2.5Y 5/6	2.5Y 5/6	SILT	MODERATE		IRON STAINING, CO3 INCREASING WITH DEPTH
	60	5Y 5/1	5Y 5/1	LOAM			OXIDIZED TILL
FA-4	6	10YR 2/1			NONE		
	12	10YR 2/1	10YR 2/1	CLAY LOAM	NONE	DISTINCT	LEACHED
	24	5Y 3/1	5Y 2.5/2	SILT LOAM	NONE	INDISTINCT	LEACHED
	30	5Y 2.5/1	2.5Y 4/2	SILT LOAM	NONE	WAVY	LEACHED
	36	5Y 4/2	5Y 3/2	SILT LOAM	SLIGHT	WAVY	TRANSITION ZONE, OXIDIZED TILL
	60	5Y 5/2	5Y 5/2	F.SILT LOAM	MODERATE	WAVY	CO3 IN FILLINGS, IRON MOTTLES
	99	5Y 5/1	5Y 5/1	F.SILT LOAM	WEAK	WAVY	
FA-6	6	10YR 2/1					
	12	10YR 2/1	10YR 2/1	SILT LOAM	NONE	WAVY	LEACHED, IRON MOTTLING
	18	2.5Y 5/4	2.5Y 5/4	SILT LOAM	NONE	DISTINCT	LEACHED, IRON MOTTLING AT TOP
	24	5Y 4/2	5Y 2.5/2	SILT LOAM	NONE	DISTINCT	COBBLES PRESENT
	30	2.5Y 4/2	2.5Y 4/2	SILT LOAM	SLIGHT	WAVY	SMALL CO3 IN PORES
	48	2.5Y 6/2	2.5Y 6/2	SILT LOAM	MODERATE	INDISTINCT	IRON MOTTLING, OXIDIZED TILL, CO3 IN PORES
	64	2.5Y 5/2	2.5Y 5/2	SILT LOAM	STRONG	WAVY	MINOR IRON MOTTLING, ZONE OF CO3 ACCUM.
	99	2.5Y 4/4	2.5Y 4/4	SILT LOAM	MODERATE		OXIDIZED TILL
FA7A	6	10YR 2/1			WEAK	DISTINCT	PLOW LAYER
	12	2.5Y 6/2	2.5Y 5/2	CLAY LOAM	VIOLENT	DISTINCT	ZONE OF CO3 ACCUM.
	18	2.5Y 5/2	2.5Y 5/2	SILTY LOAM	STRONG	INDISTINCT	IRON MOTTLES, CO3 CONCEN., MOISTURE INCR.
	24	2.5Y 5/4	2.5Y 5/4	S.CLAY LOAM	STRONG	DISTINCT	MORE CLAY, BETTER STRUCT.
	30	2.5Y 5/4	2.5Y 5/4	SILT LOAM	STRONG	DISTINCT	SMALL CO3 CONCEN., IRON MOTTLES
	34	2.5Y 4/4	2.5Y 4/4	SILT LOAM	STRONG	DISTINCT	LARGE CO3 CONCEN.
	42	2.5Y 4/4	2.5Y 4/4	SILT LOAM	STRONG	DISTINCT	SMALLER CO3 CONCEN., MORE OXID., IRON MOTTLING
	48	2.5Y 5/4	2.5Y 4/4	SILT LOAM	STRONG	INDISTINCT	IRON MOTTLES, CO3 PORES, TRANS. ZONE
		2.5Y 4/4	2.5Y 4/4	SILT LOAM	STRONG	DISTINCT	OXIDIZED TILL
FA-8	5	10YR 3/2	10YR 2/1	SILTY LOAM	SLIGHT	VERY DISTINCT	UNLEACHED O.M.
	18	2.5Y 6/4	2.5Y 6/4	SILTY LOAM	STRONG	WAVY	UNLEACHED
	24	2.5Y 6/4	2.5Y 6/4	S.CLAY LOAM	STRONG		CO3 CONCEN. AND PORES
	36	2.5Y 5/4	2.5Y 4/4	SILT LOAM	STRONG	DISTINCT	IRON MOTTLING, CO3 CONCEN.
	42	2.5Y 5/4	2.5Y 4/4	SILT LOAM	STRONG	INDISTINCT	STONY, TRAN. ZONE
	48	2.5Y 5/4	2.5Y 4/4	LOAM	MED STRONG	WEAKLY DIST	IRON MOTTLES, POSS. BURIED "B"
	64	2.5Y 4/4	2.5Y 4/4	LOAM	WEAK	VERY DISTINCT	PEBBLY, CO3 CONCEN., OXID. TILL
	96	2.5Y 5/4	2.5Y 4/4	LOAM	STRONG	DISTINCT	VERY LARGE GYP. NESTS AND IN PORES FROM 80"

TABLE 1B

FIELD DESCRIPTION OF FSA TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
FSA-9						
	0-6	10YR 3/2	SILT LOAM	DRY	STRONG	TOP OF HILL
	6-10	2.5Y 5/4	SILT LOAM	MOIST	VIOLENT	
	10			FROZEN		
FSA-8	0-6	10YR 3/2	SILT LOAM	DRY	VIOLENT	SMALL DEPRESSION
	6-12	2.5Y 5/4	SILT LOAM	WET	VIOLENT	
	12			FROZEN		
FSA-7	0-6	10YR 3/2	SILT LOAM	DRY	STRONG	EDGE OF SMALL DEPRESSION
	6-12	2.5Y 5/4	SILT LOAM	WET	VIOLENT	
	12			FROZEN		
FSA-6	0-6	10YR 3/1	SILT LOAM	DRY	VIOLENT	INCREASING SLOPE
	6-12	2.4Y 6/4	SILT LOAM	WET	VIOLENT	
	12			FROZEN		
FSA-5	0-6	10YR 3/1	SILT LOAM	DRY	STRONG	ZONE OF RETURN FLOW
	6-9	5Y 8/1	SILT LOAM	MOIST	VIOLENT	
	9-13	2.5Y 6/2	SILT LOAM	WET	VIOLENT	
	13			FROZEN		
FSA-4	0-9	10YR 2/1	SILT LOAM	MOIST	WEAK	ZONE OF RETURN FLOW
	9-15	2.5Y 7/2	SILT LOAM	WET	STRONG	
	15			FROZEN		
FSA-3	0-6	10YR 2/1	SILT LOAM	WET	NONE	NEAR EDGE OF POND
	6-12	10YR 2/1	SILT LOAM	WET	NONE	
	12-18	10YR 3/3	SILT LOAM	WET	NONE	
	18			FROZEN		

TABLE 1C

FIELD DESCRIPTION OF PSC TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
PSC-1	0-6	10YR 3/1	SILT LOAM	DRY	MILD	SLIGHT SLOPE
	6-12	10YR 2/1	SILT LOAM	MOIST	NONE	
	12-18	2.5Y 5/4	SILT LOAM	WET	STRONG	
	18-24	2.5Y 5/4	SILT LOAM	WET	VIOLENT	
PSC-2	0-6	10YR 2/1	SILT LOAM	DRY	NONE	SLIGHT SLOPE
	6-12	10YR 2/1	SILT LOAM	MOIST	NONE	
	12-18	2.5Y 5/4	SILT LOAM	WET	MILD	
	18-24	2.5Y 5/4	SILT LOAM	WET	MILD	
PSC-3	0-6	10YR 3/1	SILT LOAM	MOIST	WEAK	SLIGHT SLOPE
	6-12	10YR 3/1	SILT LOAM	MOIST	NONE	
	12-18	2.5Y 4/2	SILT LOAM	MOIST	MILD	
	18-24	2.5Y 6/4	SILT LOAM	WET	STRONG	
PSC-4	0-6	10YR 3/1	SILT LOAM	DRY	NONE	SURFACE SALT CRUST
	6-12	10YR 3/1	SILT LOAM	MOIST	NONE	GULLY EROSION
	12-18	2.5Y 4/2	SILT LOAM	MOIST	WEAK	SLIGHT SLOPE INCREASE
	18-24	2.5Y 6/4	SILT LOAM	WET	STRONG	
PSC-5	0-6	10YR 2/1	SILT LOAM	MOIST	NONE	SIMILAR SLOPE TO PSC-4
	6-12	10YR 3/2	SILT LOAM	WET	NONE	ZONE OF RETURN FLOW
	12-18	10YR 3/2	SILT LOAM	WET	NONE	GULLY EROSION
	18-24	2.5Y 5/4	SILT LOAM	WET	MILD	SURFACE SALT CRUST
PSC-6	0-6	10YR 3/2	SILT LOAM	WET	WEAK	SHALLOWER SLOPE THAN PSC-5
	6-12	10YR 2/1	SILT LOAM	WET	NONE	SURFACE SALT CRUSTS IN HIGHS
	12-18	2.5Y 5/4	SILT LOAM	WET	STRONG	GULLY EROSION
	18-24			FROZEN		
PSC-7	0-6	10YR 2/1	SILT LOAM	WET	NONE	NEAR POND EDGE
	6-12	10YR 4/1	SILT LOAM	WET	NONE	
	12-18	10YR 5/1	SILT LOAM	WET	MILD	
	18-24			FROZEN	WEAK	

TABLE 1D

FIELD DESCRIPTION OF BSN TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
BSN-1	0-6	10YR 2/1	SILT LOAM	MOIST	NONE	TOP OF HILL
	6-12	2.5Y 4/2	SILT LOAM	MOIST	WEAK	
	12-18	10YR 6/2	SILT LOAM	WET	STRONG	
	18-24	2.5Y 5/2	F. SAND LOAM	WET	MILD	
	18			FROZEN		
BSN-2	0-6	10YR 2/1	SILT LOAM	MOIST	NONE	NO ELEVATION CHANGE
	6-12	2.5Y 4/2	SILT LOAM	WET	WEAK	
	12-18	10YR 5/3	SILT LOAM	WET	VIOLENT	
	18-20	2.5Y 5/4	F. SAND LOAM	WET	MILD	
	20		GRAVEL			
BSN-3	0-6	10YR 2/1	SILT LOAM	MOIST	NONE	SLIGHT SLOPE INCREASE
	6-12	10YR 2/1	SILT LOAM	WET	NONE	FROM BSN-2
	12-15	2.5Y 3/2	SILT LOAM	WET	WEAK	
	15-18	2.5Y 3/2	GRAVEL	FROZEN	MILD	
BSN-4	0-6	10YR 2/1	SILT LOAM	MOIST	MILD	SLOPE INCREASES FROM BSN-3
	6-12	10YR 2/1	SILT LOAM	WET	STRONG	
	12-14	5Y 5/1	GRAVEL	WET	VIOLENT	
	14			FROZEN		
BSN-5	0-3	10YR 2/1	SILT LOAM	WET	STRONG	RETURN FLOW REACHES
	3-6	10YR 2/1	SILT LOAM	WET	STRONG	SURFACE
	6-11	5Y 3/1	SILT LOAM	WET	VIOLENT	SLOPE INCREASES FROM BSN-4
	11			FROZEN		
BSN-6	0-2	10YR 10/1	SILT LOAM	WET	STRONG	GREATEST SLOPE ALONG
	2-4	10YR 10/1	SILT LOAM	WET	STRONG	TRANSECT
	4			FROZEN		
BSN-7	0-4	10YR 2/1	SILT LOAM	WET	MILD	NEAR POND EDGE
	4-8	10YR 2/1	SILT LOAM	WET	MILD	
	8			FROZEN		

TABLE 1E

FIELD DESCRIPTION OF BSC TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
BSC-1	0-6	5Y 2.5/1	SILT LOAM	DRY	WEAK	TOP OF HILL NO RELIEF
	6-12	5Y 2.5/1	SILT LOAM	MOIST	NONE	NO VEGETATION EFFECT
	12-17	5Y 2.5/1	SILT LOAM	WET	NONE	
	17-19	2.5Y 3/2	CLAY LOAM	FROZEN	WEAK	
BSC-2	0-4	5Y 2.5/1	CLAY LOAM	MOIST	WEAK	NO RELIEF
	4-8	10YR 2/1	CLAY LOAM	WET	NONE	NO VEGETATION EFFECTS
	8-16	10YR 2/1	CLAY LOAM	WET	NONE	
	16-22	10YR 2/1	CLAY LOAM	WET	NONE	
	22-24	5Y 4/3	GRAVEL	FROZEN	NONE	
BSC-3	0-4	10YR 2/1	LOAM	MOIST	NONE	SLIGHT SLOPE
	4-8	10YR 3/2	LOAM	WET	NONE	NO VEGETATION EFFECTS
	8-12	2.5Y 4/2	LOAM	WET	MILD	
	12-17	2.5Y 4/4	GRAVEL	WET	STRONG	
	17			FROZEN		
BSC-4	0-4	10YR 2/1	CLAY LOAM	WET	NONE	SLIGHT SLOPE
	4-8	10YR 5/3	SAND LOAM	WET	WEAK	NO VEGETATION EFFECTS
	8-12	2.5Y 4/2	GRAVEL	WET	WEAK	
	12-17	2.5Y 4/2	GRAVEL	WET	STRONG	
BSC-5	0-4	5YR 2.5/1	SAND LOAM	MOIST	STRONG	HIGHER RELIEF THAN BSC-4
	4-8	2.5Y 6/4	GRAVEL	WET	VIOLENT	VEGETATION AFFECTED
	10			FROZEN		
BSC-6	0-4	5YR 2.5/1	SAND LOAM	MOIST	MILD	VERY LITTLE VEGETATION
	4-8	2.5Y 6/4	GRAVEL	WET	STRONG	
	10			FROZEN		
BSC-7	0-4	10YR 2/1	SAND LOAM	MOIST	STRONG	ZONE OF RETURN FLOW
	4-8	2.5Y 5/2	GRAVEL	WET	VIOLENT	NO VEGETATION
	8-12	2.5Y 5/2	GRAVEL	WET	VIOLENT	GULLY EROSION
	12			FROZEN		
BSC-8	0-4	10YR 2/1	SAND LOAM	WET	STRONG	NO VEGETATION
	4-9	2.5Y 5/2	GRAVEL	WET	VIOLENT	NEAR POND EDGE
	9			FROZEN		

TABLE 1F

FIELD DESCRIPTION OF SSN TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
SSN-0	0-6	10YR 3/1	CLAY LOAM	DRY	NONE	NEAR TOP OF HILL
	6-10	2.5Y 4/2	CLAY LOAM	WET	NONE	LITTLE RELIEF
	10			FROZEN	NONE	
SSN-0.5	0-6	10YR 2/1	CLAY LOAM	DRY	STRONG	SLIGHTLY MORE RELIEF
	6-10	10YR 2/1	CLAY LOAM	WET	WEAK	
	10	2.5Y 6/4		FROZEN	MILD	
SSN-1	0-6	10YR 3/1	SILTY CLAY	WET	NONE	NO RELIEF
	6-12	10YR 3/1	SILTY CLAY	WET	NONE	
	12-14			FROZEN		
SSN-2	0-6	10YR 3/1	SILTY CLAY	WET	NONE	NO RELIEF
	6-10	2.5Y 5/4	SILTY CLAY	WET	MILD	
	10			FROZEN		
SSN-3	0-6	10YR 3/1	SILTY CLAY	WET	NONE	NO RELIEF
	6-10	2.5Y 5/4	SILTY CLAY	WET	NONE	
	10			FROZEN		
SSN-4	0-6	10YR 3/1	SILTY CLAY	WET	MILD	NO RELIEF
	6-10	2.5Y 5/4	SILTY CLAY	WET	NONE	
	10			FROZEN		
SSN-5	0-4	10YR 3/1	SILTY CLAY	DRY	WEAK	SLIGHT RISE
	4-12	2.5Y 5/4	SILTY CLAY	MOIST	NONE	
	12			FROZEN		
SSN-6	0-5	10YR 3/1	SILTY CLAY	WET	NONE	NO RELIEF
	5-10	2.5Y 5/4	SILTY CLAY	WET	NONE	NEAR POND
	10			FROZEN		

TABLE 1G

FIELD DESCRIPTION OF SSA TOPOSEQUENCE

CORE #	DEPTH	COLOR MOIST	TEXTURE	CONSISTENCE	REACTION WITH HCL	REMARKS
SSC-1	0-6	10YR 2/1	CLAY LOAM	DRY	NONE	NEAR SUMMIT
	6-12	2.5Y 3/2	CLAY LOAM	MOIST	NONE	VERY SLIGHT SLOPE
	12-18	2.5Y 4/4	CLAY LOAM	MOIST	NONE	
	18-24			FROZEN	NONE	
SSC-2	0-6	10YR 2/1	CLAY LOAM	DRY	NONE	VERY SLIGHT SLOPE
	6-12	2.5Y 3/2	CLAY LOAM	MOIST	NONE	
	12-18	2.5Y 4/4	CLAY LOAM	WET	STRONG	
	18			FROZEN		
SSC-3	0-6	10YR 2/1	CLAY LOAM	DRY	NONE	SURFACE SALT CRUST
	6-12	10YR 4/3	CLAY LOAM	WET	NONE	INCREASING SLOPE
	12-14	2.5Y 5/2		FROZEN	VIOLENT	
SSC-4	0-6	10YR 2/1	CLAY LOAM	MOIST	NONE	ZONE RETURN FLOW
	6-12	2.5Y 4/2	CLAY LOAM	WET	NONE	GULLY EROSION
	12	2.5Y 5/2		FROZEN	VIOLENT	VEGETATION AFFECTED
SSC-5	0-6	10YR 2/1	CLAY LOAM	DRY	MILD	LOCALIZED HIGH
	6-12	2.5Y 4/4	CLAY LOAM	WET	STRONG	VEGETATION AFFECTED
	12			FROZEN		
SSC-6	0-6	10YR 2/1	CLAY LOAM	WET	NONE	NEAR POND EDGE
	6-10	2.5Y 4/4	CLAY LOAM	WET	MILD	VEGETATION AFFECTED
	10			FROZEN		

EXPERIMENTAL METHODS

Moisture Content

Gravimetric moisture content samples collected in the field were immediately sealed to prevent moisture loss. The samples were then weighed in the lab at field moisture conditions, oven-dried at 106°C for three days, and reweighed. The moisture content was calculated using the following formula from Gardner (1965): Moisture Content = ((weight of wet soil/weight of dry soil) - 1)

Saturation Paste Extracts and Electrical Conductivity

Saturation paste extracts were prepared using the standard method employed by the North Dakota State University Soils Characterization Laboratory. Hand ground soil is mixed into 100 mL of distilled water until three conditions are met:

1. paste flows slowly
2. surface indentations close when sample container is tapped gently
3. a glossy sheen remains on the paste's surface

Saturated pastes were allowed to equilibrate for a minimum of eight hours. Soil solution was extracted under a vacuum and refrigerated until chemical analysis was performed.

Electrical conductivity was measured using a YSI 31 Conductivity Bridge with corrections made for temperature and dip cell. Chemical analysis methods are given in Table 2.

Mineralogy of the Bulk Specimens and Size Separates

Five grams of air-dried sample were ground and homogenized in a Spex Mixer Mill operated for twenty minutes. In the early stages of the study, the crushed sample was sieved by hand through a 325 mesh (45um) sieve before preparing a "smear mount" on a glass microscope slide for x-ray diffraction

TABLE 2

PROCEDURES FOR CHEMICAL ANALYSIS OF SATURATION PASTE EXTRACTS

Ca^{2+} + Mg^{2+} Determination

1. Draw 5 mL of sample and place in plastic cup.
2. Place 1 full dropper of NH_4Cl-NH_4OH and 2 drops of F-241 in the sample.
3. Place stir bar and analyzer in sample and turn on the stir plate.
4. Adjust column of EDTA.
5. Titrate with EDTA until color change is complete.
6. Record mL of EDTA used.
7. Multiply mL used by 4.07 to convert to meq/L.
8. Discard sample and wash analyzer and stir bar

Ca^{2+} Determination

1. Draw 5 mL of sample and place in plastic cup.
2. Place 1 even scoop of murexide and 1 dropper full of KOH in the sample.
3. Place stir bar and analyzer in sample and start the stir plate.
4. Adjust column of EDTA.
5. Titrate with EDTA until color change is complete.
6. Record mL of EDTA used.
7. Multiply mL used by 4.16 to convert to meq/L.
8. Discard sample and wash analzer and stir bar.

Cl^- Determination

1. Draw 5 mL of sample and place in plastic cup.
2. Place 1 squirt of HNO_3 to the sample.
3. Place stir bar and analyzer in sample and start the stir plate.
4. Adjust column of AgCl.
5. Titrate with AgCl until ~ 175 mv are read.
6. Record mL of AgCl used.
7. Multiply mL used by 1 to convert to meq/L.
8. Discard sample and wash analyzer and stir bar.

CO_3^{2-} and HCO_3^- Determination

1. Warmup the pH meter.
2. Hookup the correct wires to the back of the console.
3. Calibrate meter by placing the analyzer in the pH 4 and 7 solutions and receiving the same pH's on the meter.
4. After calibrating, draw off 5 ml of sample and place in a plastic cup.
5. Adjust column of H_2SO_4.
6. If pH is above 8.2, titrate until pH is 8.2 for the carbonate ion, record mL used, adjust column again, titrate to 4.5 for the bicarbonate ion, and record the mL used. Otherwise, just titrate to 4.5 for the bicarbonate ion.
7. Multiply mL used for the determination of the carbonate ion by 4 to convert to meq/L.
8. Subtract mL used for the determination of the carbonate ion from the mL used for the determination of the bicarbonate ion and multiply by 2 to convert to meq/L.
9. Discard sample with plastic cup and wash analyzer and stir bar.

studies. This step was later discontinued when it was determined that greater than 97% by weight of the crushed sample had been ground to -325 mesh and that there were no substantial differences in the x-ray patterns of the -325 and +325 fractions.

In addition to mineralogical analyses of the bulk specimen, selected specimens from each core were separated into sand, silt, and clay fractions prior to mineralogical analysis. Specimen preparation for the mineralogical analyses was based on a method developed by Kunze (1965) for cases where the samples were believed to contain soluble salts. The specimens were washed by placing 5 grams of air-dried bulk sample in a 500 mL bottle of distilled water. These bottles were agitated approximately every twenty minutes over a two hour period and then left to settle. A day later, the presence of soluble salts was tested by addition of acetone to the solution. If a white precipitate formed gypsum, was considered to be present. If any soluble salts were still present in the sample, the procedure was repeated. Otherwise, the sample was oven-dried at 65°C. For the samples which did not need washing, 5 grams of bulk sample were air-dried overnight.

The following morning, the samples were dispersed in distilled water following a modified procedure from Moen _et. al._ (1984). The 5 grams of dried sample were placed in a 50 mL beaker. Twenty-five mL of distilled water were added to the beaker. The sample was dispersed by use of ultrasound for 10 minutes using a Sonicator Cell Disruptor Model W-225R having a half-inch "disruptor horn" and using a tip depth of 0.75 cm. The sonicator was operated at 80 watts power.

Following dispersal, the sample was wet sieved by hand through a 230 mesh sieve in order to collect the sand fraction (Pettijohn _et al._, 1972) defined by the Udden-Wentworth size classification for sediment grains. The remaining suspension containing the silt and clay fractions was placed in a one liter bottle and left for about seven hours with adjustments for room temperature fluctuations to allow the silt size particles to settle (Day, 1965). A suspension containing the clay fraction was removed using a pipette inserted to a 5 cm or 10 cm depth, depending on elapsed time. The remaining suspension contained the silt fraction and some clay fraction still in suspension. Using Jackson's (1969) formulas, it was determined that the silt fraction could be separated by centrifugation at 500 rpm for 30 seconds using a Servall KSB-3(4) Continuous Flow Centrifuge.

Both the sand and the silt fractions were oven-dried at 65°C. The fractions were then crushed to a powder in a mortar and pestle. This powder was used to make "smear mount" x-ray diffraction specimens on glass slides.

The slide preparation of the clay fraction followed the filter-membrane peel technique by Drever (1973). The clay fraction suspension was poured into a funnel and filtered for 5 minutes using a vacuum pump to insure an even withdrawal pressure during filtration. Next, the filter paper containing the clay-sized fraction was placed face down onto a glass slide. Removal of the filter paper reveals an oriented clay fraction adhering to the slide. An alternate method of removing suspended solids that utilizes a porous ceramic tube or "candle" to make a slurry that is smeared onto a glass slide was employed for selected specimens as a comparison to Drever's method. The results indicated that the "candle method" involved more time for the separation of the suspension and the "smear mount" slide gave less reproducible x-ray diffractograms than did Drever's method.

A manual Philips x-ray powder diffractometer equipped with a copper target tube, diffracted beam graphite monochromator, theta compensating slit, proportional counter, and strip chart recorder was used for the x-ray diffraction analyses. The instrument was operated at 40 KV and 20 ma. The counting electronics were operated at a time constant of two seconds and a scale factor of 250 or 500 cts/sec full scale. Heights of characteristic peaks of each mineral of interest were measured. The peak heights for the 500 cts/sec scans were doubled so that all peak heights in this report are for a 250 cts/sec scale factor.

The sand and silt fractions were scanned from 35-5^{o} two-theta at 1^{o} two-theta per minute, the clay fraction was scanned from 35-2^{o} at 2^{o} per minute. Relative humidity (R.H.) was recorded during each group of measurements. R.H. ranged from 52-82% during the summer months in which the laboratory work was performed.

After the clay fraction diffractograms were obtained, two additional treatments were performed on the clay fraction slides. The first involved glycolating several slides in order to determine the possible presence of chlorite. In the untreated sample, the chlorite reflection overlaps with the broad smectite reflection. Glycolation causes the smectite structure to expand to its maximum interlayer spacing. This expansion causes the smectite reflection to shift to a lower angle and thus reveals the unshifted chlorite reflection. The results of this test in all cases indicated no detectable chlorite. Glycolation was also used to check for the type of smectite present. The expansion of the lattice is characteristic of the exchange cation. Ca-saturated smectites expand to 18.0 A whereas Na-saturated smectites expand to 17.0 A and keep expanding as R.H. is increased.

The second test involved heating selected slides at 550^{o}C for two hours in order to confirm the presence of kaolinite. Kaolinite becomes amorphous and its characteristic x-ray peaks disappear

Griffin's (1971) x-ray data analysis method was employed for comparisons of the mineralogies of the core specimens. This method involves measuring the height of a characteristic strong peak of each mineral of interest. The peak chosen for each mineral is listed in Table 3. Griffin's method can be used only semi-quantitatively because of particle statistics, peak overlap, and preferred orientation factors, but it was considered to be satisfactory to meet the objectives of this study.

TABLE 3

CHARACTERISTIC X-RAY DIFFRACTION PEAKS OF SOIL MINERALS

Mineral	Two-theta	d
Quartz	26.65	3.34
Alkali Feldspar	27.4-27.6	3.25-3.23
Plagioclase	27.9-28.1	3.20-3.18
Calcite	29.4	3.04
Dolomite	30.9	2.89
Illite	8.8	2.59
Gypsum	11.7	7.56
Smectite	4.8	18.00
Kaolinite	12.3-12.4	7.2-7.1

RESULTS AND DISCUSSION

Salt Movement

Because the background concentration of chloride is so low in the region of interest, salt migration from a brine pit can be traced by comparing electrical conductivity (EC) and chloride concentrations of contaminated and natural toposequences formed from similar parent materials. Results of EC and Cl measurements for all 1985 cores are given in Table 4.

The brine pit contaminating the BSC toposequence is located to the south of the transect and at the same elevation as BSC-1. Data for the BSC toposequence show a general trend of increasing Cl and EC with depth. EC and Cl have a similar trend moving from the summit of the toposequence downslope. These data would indicate that the salt from the brine is moving downslope by subsurface throughflow downslope. BSC-7 is the exception to the EC and Cl trends described previouly. The BSC-7 profile is the only one located in the zone of visible return flow. This zone is defined as the region where the soil profile becomes saturated with water from an impermeable layer (in this case the frost layer) to the air-soil interface. Water movement in this zone will occur as overland flow. The highest EC and Cl contents would be expected at the surface in this zone, as the data for BSC-7 indicate.

The BSN toposequence located 150 to 200 feet north of the BSC toposequence shows no effects of salt damage on vegetation effects but does have appreciable Cl concentrations at the lowest depth above the frost layer, indicating that salt movement is not just downslope. Subsurface lateral salt migration must also be occurring. The high Cl content of BSN-1 is a result of salt migration along an adjacent road ditch. Thus, although this site was originally thought to be natural, it was actually somewhat contaminated.

The PSC toposequence has the brine pit located above the PSC-1 site. The EC and Cl, while being much higher in this toposequence than in the BSC

TABLE 4

EC AND CL^-

SITE	DEPTH (in.)	EC (mmhos/cm)	Cl (meq/l)
BSN-1	0-6	1.5	6.5
	6-12	1.6	9.4
	12-18	3.3	53.0
BSN-3	0-6	1.1	0.9
	6-12	0.6	1.1
	12-15	0.6	1.9
BSN-5	0-3	0.9	0.8
	3-6	1.2	1.5
	6-12	2.4	15.2
BSN-6	0-2	1.8	4.2
	2-4	1.9	11.0
BSC-1	0-6	1.1	1.5
	6-12	0.7	2.2
	12-17	1.1	3.4
BSC-3	0-4	1.1	2.0
	4-8	1.1	2.6
	8-12	1.1	1.9
BSC-5	0-4	3.4	16.3
	4-8	6.0	41.5
	8-10	6.0	40.0
BSC-6	0-4	2.1	3.4
	4-8	6.4	47.5
	8-10	12.0	105.0
BSC-7	0-3	43.2	505.0
	3-8	38.3	415.0
	8-10	37.5	410.0
FSA-8	0-6	0.7	0.3
	6-10	0.4	0.3
FSA-5	0-6	1.1	0.2
	6-9	4.4	0.8
	9-12	0.7	0.4
FSA-4	0-9	1.2	0.2
	9-15	0.7	0.4

TABLE 4 (CONT.)

EC AND CL^-

SITE	DEPTH (in.)	EC (mmhos/cm)	Cl (meq/l)
FSA-3	0-6	0.7	0.5
	6-12	1.3	0.3
	12-18	0.8	0.4
PSC-1	0-6	17.8	205.0
	6-12	22.2	405.0
	12-18	32.0	335.0
	18-24	47.6	550.0
PSC-3	0-6	23.3	245.0
	6-12	26.5	285.0
	12-18	33.2	375.0
	18-24	44.3	475.0
PSC-5	0-6	16.6	105.0
	6-12	20.4	105.0
	12-18	36.6	639.0
	18-24	47.6	550.0
PSC-6	0-6	17.3	155.0
	6-12	33.2	340.0
	12-18	67.6	835.0
SSN-0	0-6	0.9	1.8
	6-10	0.6	0.9
SSN-4	0-6	0.4	1.0
	6-12	0.5	1.0
SSC-1	0-6	0.4	0.4
	6-12	0.3	1.0
	12-18	0.5	0.6
SSC-3	0-6	1.2	1.2
	6-12	4.4	3.1
SSC-5	0-6	2.6	16.0
	6-12	9.3	72.5
	12-14	9.5	71.5

toposequence, have a similar trend indicating subsurface flow downslope. The gravimetric moisture content data (APPENDIX A) for the PSC and FSA toposequences also confirm this model for water movement.

The SSC toposequence has the brine pit located in the depression at the bottom of the transect. The salt migration in this toposequence is a result of water movement upslope due to capillary rise as the soil profile dries. SSC-5, located 2-4 feet upslope of the brine pit, has the highest Cl^- content. SSC-3, located 100 feet upslope from SSC-5, has enough Cl^- in the 6-12 inch depth to suggest that the salt is moving at least that far upslope under drying conditions. This salt is then washed back down to the depression by water moving downslope during the spring. Water movement probably occurs as subsurface throughflow above the frost layer. This conclusion is substantiated by the gravimetric moisture data for the SSC toposequence (see APPENDIX A).

Bulk Mineralogy

Bulk mineralogy of the material of the FA cores was investigated in some detail. Table 5 lists the peak heights of the minerals found in the bulk specimens and in the macropore fillings of the FA cores. Typically, each bulk sample contained five minerals observable by XRD: quartz (Qz), potassic feldspars (K-spar, K-Sp), sodic plagioclase feldspar (Pg), calcite (Cc), and dolomite (Do). The technique was not sensitive to smectite, mica-illite, and kaolinite clay minerals in these randomly oriented bulk specimens. Some specimens contained several additional peaks due to the presence of an amphibole mineral.

The data in Table 5 clearly demonstrate the effect topography has on soils and their mineralogy. In the bulk mineralogy, calcite and dolomite occurred throughout the profile on the backslope and summit (FA-5 through FA-9). However, these minerals occurred only at depth near the closed depression (FA-

TABLE 5

BULK SOIL MINERALOGY OF FA CORE MATERIALS

CORE	DEPTH		MINERAL PEAK HEIGHTS*						MOL.%	VUG	
#	(in.)	(cm)	Qz	K-Sp	Pg	Cc	Do	Gp	$MgCO_3$	Cc	Gp
FA-2	30	76	1200	38	65	0	0	0	0.0		
FA-2	42	107								14	0
FA-2	48	122	800	30	56	50	92	0	0.9		
FA-2	60	152								180	0
FA-2	72	183								182	0
FA-2	84	213	840	30	54	43	82	0	1.5	280	0
FA-2	90	229								344	0
FA-3	17	43	1580	43	67	0	0	0	0.0	0	0
FA-3	24	61	1340	42	53	0	0	0	0.0	0	0
FA-3	30	76	1260	36	60	0	0	0	0.0	0	0
FA-3	38	97	1160	32	64	0	0	0	0.0	0	0
FA-3	42	107	1060	24	45	68	77	0	2.5	340	0
FA-3	48	122	1040	27	43	55	77	0	3.4	268	0
FA-3	60	152	1120	28	47	55	73	0	2.5	220	0
FA-3	72	183	1060	29	53	53	78	0	3.4	172	0
FA-3	76	193	1180	26	49	50	80	0	1.5	252	0
FA-4	30	76	1200	34	65	0	0	0	0.0		
FA-4	36	91								0	0
FA-4	42	107	1000	30	50	42	96	0	0.9	32	0
FA-4	48	122	960	33	57	45	116	0	2.8	192	0
FA-4	60	152	1160	34	54	48	90	0	0.0	330	0
FA-4	72	183								320	0
FA-4	84	213	960	28	58	50	66	0	2.5	395	0
FA-4	90	229								780	0
FA-5	20	51								480	0
FA-5	24	61								480	0
FA-5	30	76	740	29	47	83	114	0	3.8	500	0
FA-5	36	91								480	0
FA-5	42	107	840	28	52	62	116	0	2.5	288	0
FA-5	48	122	800	39	59	46	98	0	3.1	58	0
FA-5	60	152	1100	28	56	50	84	0	2.5	142	0
FA-5	72	183								280	0
FA-5	80	203	980	28	51	42	70	0	4.4	280	0
FA-6	24	61								0	0
FA-6	30	76	1080	34	54	11	77	0	2.8	0	0
FA-6	36	91								720	0
FA-6	42	107	960	32	66	60	96	0	2.8	780	0
FA-6	48	122	800	21	41	60	58	0	4.0	600	0
FA-6	60	152	900	34	56	56	88	0	3.4	580	0
FA-6	72	183								120	0

TABLE 5 (CONT.)

BULK SOIL MINERALOGY OF FA CORE MATERIALS

CORE	DEPTH		BULK MINERALS						MOL.%	VUG	
#	(in.)	(cm)	Qz	K-Sp	Pg	Cc	Do	Gp	$MgCO_3$	Cc	Gp
FA-6	84	213	880	22	50	46	71	0	4.4	360	0
FA-6	90	229								140	0
FA-7	18	46	980	27	63	78	65	0	5.8	188	0
FA-7	24	61	1120	27	49	56	67	0	4.8	328	8
FA-7	30	76	1280	28	61	51	70	0	4.0	80	8
FA-7	36	91	1480	34	59	52	62	8	2.8	44	750
FA-7	42	107	1540	23	43	45	73	7	2.1	750	1400
FA-7	48	122	1480	30	100	42	82	10	0.6	324	1200
FA-7	60	152	1460	32	65	40	70	0	4.0	44	1260
FA-7	72	183	1480	34	67	39	87	0	1.8	36	1400
FA-7	84	213	1620	37	67	40	71	0	3.4	36	1200
FA-7	90	229	1160	29	54	40	70	0	1.5	40	1360
FA7A	24	61								182	0
FA7A	30	76	740	24	95	55	123	0	3.4	235	0
FA7A	36	91								158	0
FA7A	42	107	1000	18	34	50	86	0	2.5	132	0
FA7A	48	122	960	26	55	47	77	0	3.8	235	0
FA7A	60	152	1100	26	54	48	94	0	2.5	86	0
FA7A	72	183								130	0
FA7A	84	213	940	34	56	52	88	0	2.5	332	0
FA7A	90	229								135	0
FA-8	24	61								72	0
FA-8	30	76	840	30	51	52	93	0	3.8	154	0
FA-8	36	91								156	0
FA-8	42	107	1020	26	50	52	82	0	2.5	45	0
FA-8	48	122	840	31	55	48	76	0	4.0	122	0
FA-8	60	152								61	0
FA-8	72	183								580	1080
FA-8	84	213	880	31	51	47	80	0	2.5	260	1780
FA-8	96	244	1100	26	46	36	80	0	2.5	440	500
FA-9	18	46	800	24	41	77	63	0	4.8	240	0
FA-9	24	61	700	26	47	55	80	0	5.8	160	0
FA-9	30	76	1000	22	50	47	71	0	8.0	140	0
FA-9	36	91	1440	48	70	30	83	0	0.9	252	0
FA-9	42	107	1400	23	48	32	65	0	5.0	580	0
FA-9	48	122	1460	25	48	34	55	0	6.7	460	92
FA-9	60	152	1500	29	44	34	65	0	4.0	276	132
FA-9	72	183	1360	30	56	33	64	0	1.3	44	1200
FA-9	84	213	1320	32	55	37	71	5	0.9	40	1100
FA-9	96	244	1600	40	66	35	68	5	1.3	224	308

2 and FA-3) due to the greater amount of water accumulation and leaching of near-surface carbonates. Gypsum was found only at depth in some backslope and summit cores again due to leaching by downward moving soil solutions. The absence of gypsum in FA-7A suggests that water entering the soil from a small swale located above FA-8 has prevented gypsum precipitation. The relative abundance of insoluble minerals (quartz, feldspars) increased where the more soluble minerals (calcite and gypsum) and clays were removed in part by water dissolution or transport.

A shift to higher two-theta values was observed for many of the calcite peaks in the diffractograms due to the limited, random substitution of Mg^{2+} for Ca^{2+} in the crystal structure of calcite. The mole percent of Mg^{2+} for Ca^{2+} substitution was determined from a graph of the d-spacing of the (104) reflection of calcite versus composition (Brown, 1980). The magnesium content of the calcite varied from 0-12 mole percent with most containing 3-5 mole percent. Mg-calcite was most abundant in zones where secondary calcite precipitation was occurring through evapotranspiration.

Mineralogy of the Particle Size Fractions

Table 6 lists the peak heights of the minerals found in the sand, silt, and clay fractions of the FA cores. The sand and silt fractions contained the same minerals found in the bulk. As was the case with the bulk specimens, an amphibole was occasionally detected.

The diffractograms of the clay size fraction were dominated by the clay minerals but also contained small amounts of quartz, feldspar, calcite, and dolomite. No chlorite was detected in the clay size fraction x-ray diffractograms. The glycolation test indicated that the smectite had Ca as the principal exchange site cation. The 550°C heating test confirmed the presence of kaolinite and the absence of dectectable chlorite.

A comparison of the mineralogy in the three size fractions can be

TABLE 6

MINERALOGY IN PARTICLE SIZE FRACTIONS OF FA CORE MATERIALS

CORE	DEPTH		SAND MINERALS					SILT MINERALS					CLAY-SIZED MINERALS								PARTICLE-SIZE%		
#	(in.)	(cm.)	Qz	K-Sp	Pg	Cc	Do	Qz	K-Sp	Pg	Cc	Do	Sm	Il	Kao	Qz	K-Sp	Pg	Cc	Do	SAND	SILT	CLAY
FA-2	30	76	2680	65	78	0	8	1720	66	120	0	32	88	47	22	95	27	20	0	0			
FA-2	48	122	1500	31	90	63	247	1140	38	100	154	340	120	30	28	70	15	20	28	16			
FA-2	84	213	1720	64	100	55	46	1160	42	88	118	368	85	28	34	85	21	25	35	18			
FA-3	30	76	2420	92	132	0	0	1800	108	142	0	20	232	138	100	180	56	34	0	0	29	38	33
FA-3	48	122	1520	168	186	124	148	1460	34	76	146	420	184	64	60	140	42	22	84	30	39	35	26
FA-3	76	193	1520	96	116	140	150	1580	64	110	92	320	140	64	44	74	30	30	72	36	33	47	20
FA-4	30	76	1780	58	134	12	0	2000	88	220	0	46	130	48	30	80	25	23	0	0			
FA-4	48	122	1800	172	210	140	118	1200	140	68	134	400	95	25	25	71	21	19	35	14			
FA-4	84	213	1800	600	142	138	156	1100	40	152	200	380	93	20	26	95	18	21	43	23			
FA-5	30	76	1900	56	120	96	122	1180	48	142	285	640	55	15	17	64	17	16	49	21			
FA-5	48	122	2160	80	304	84	126	1460	68	122	162	368	80	26	35	136	16	15	24	33			
FA-5	84	213	1700	36	154	88	100	1500	54	84	124	425	80	27	31	136	20	21	39	24			
FA-6	30	76	2300	138	314	48	74	1700	54	158	22	530	140	31	38	78	20	16	0	13			
FA-6	48	122	1800	195	600	126	122	1440	92	160	126	490	77	20	28	63	17	16	28	14			
FA-6	84	213	2100	74	176	114	164	1440	40	100	116	500	124	23	30	75	19	20	29	17			
FA-7	30	76	1700	60	194	114	118	1040	56	84	90	272	160	42	50	134	32	32	36	26	43	51	6
FA-7	48	122	1700	98	132	126	86	1380	60	124	100	380	176	74	72	170	36	44	60	38	46	50	4
FA-7	84	213	1200	58	134	168	116	1000	48	96	110	320	228	60	78	150	40	38	46	30	36	51	23
FA7A	30	76	1540	84	142	126	332	1300	42	86	110	540	65	13	22	63	17	18	35	18			
FA7A	48	122	1880	92	333	124	104	1480	40	88	104	430	118	22	27	80	17	20	29	14			
FA7A	84	213	1820	62	126	160	102	1400	34	74	90	470	110	17	29	71	18	18	24	12			
FA-8	30	76	1400	29	93	70	216	1560	60	120	144	388	68	20	23	90	20	20	33	36			
FA-8	48	122	1480	44	124	69	124	1180	48	156	128	404	80	21	24	134	16	22	33	28			
FA-8	84	213	2300	66	116	86	180	1300	38	78	195	415	114	20	27	140	21	22	27	18			
FA-9	30	76	1520	48	112	130	146	920	66	94	110	252	168	30	44	112	26	30	46	0			
FA-9	48	122	1580	68	176	88	84	1340	54	82	146	244	164	66	62	136	30	28	32	30	38	39	23
FA-9	84	213	1500	56	116	96	100	1100	38	82	94	320	120	58	68	252	60	84	48	80	36	52	12
F-1	30	76	1800	38	370	94	128	1440	50	118	90	480	75	22	24	116	23	24	34	17	42	38	20
F-1	48	122	2100	124	273	54	50	1720	122	146	82	430	114	32	48	150	33	32	32	18	43	38	19
F-1	84	213	2000	56	150	38	54	1740	52	128	52	550	77	23	19	122	24	28	21	10	45	36	19

developed from the data in Table 6. As expected, quartz was most abundant in the sand fraction, decreased in the silt fraction, and was least abundant in the clay fraction. Potassium feldspar showed little difference in abundance in the sand and silt fractions but showed a noticeable decrease in the clay fraction. Plagioclase feldspar abundance had a similar trend to that of quartz in the separate fractions. Calcite was least abundant in the clay fraction. Dolomite was more abundant in the silt fraction while least abundant in the clay fraction.

The sand fraction minerals, quartz and feldspars, showed no trends in relative abundance with depth in the cores. Calcite and dolomite quantities were affected by the location of the site in the toposequence and the ability of water to move down in the profile and leach the minerals. Calcite was not found in the 24-30 inch depth in either FA-2 or FA-3. A small amount of calcite was found in the sand fraction of FA-4, but none was observed in the silt and clay fractions. Apparently, the smaller calcite grains have been removed by leaching. Dolomite was present in a small amount in FA-2 and none was found in FA-3 or FA-4 above the 30 inch depth.

In the silt fraction, the abundances of quartz and feldspars showed no noticeable trend. Dolomite followed the same trend as in the sand fraction, with depth and location controlling the amount being present in FA-2, FA-3, and FA-4. Calcite was not present in FA-2, FA-3 or FA-4. Calcite abundance followed the trend found in the sand fraction, with the exception of FA-5 and FA-8. Both of these sites showed an increase in calcite near the surface, resulting from evapotranspiration. It is proposed that this calcite increase is due to an "edge" effect. Both of the sites are near the edge of a depression (FA-5) or swale (FA-8).

Illite and kaolinte showed no discernible trends in relative abundance with depth in the profile but differences in abundance among the core specimens were noted. The Ca-rich smectite provided insights into water movement. Cores FA-2, FA-3, and FA-4 showed greater smectite abundance in the B-horizon as a result of illuviation. FA-7 also showed this enrichment of smectite. The minerals in FA-9, located on the summit, have not been leached to the same extent as those in the lower cores. This is evidenced by the high crystallinity of the smectites in comparison to the other sites. The crystallinity of the smectite is reflected in the sharpness of its peaks in the x-ray diffractograms. Smectites from FA-7A and FA-8, the cores located just below the swale, also showed lower crystallinity due to leaching/ hydrolysis.

Mineralogy of the Macropore Fillings

Calcite and gypsum were the minerals present in macropore fillings. Calcite was found only at depth in FA-2, FA-3, and FA-4 but was present in all other sites at all depths were macropore fillings could be found. Gypsum was found at depth in FA-7, FA-8, and FA-9.

Saturated paste extract data on the FA cores are given in Table 7. It can be seen that the macropore filling mineralogy correlates very well with the abundance of dissolved salts in the saturated-paste extracts and thus that macropore fillings are a good source of data on water movement. As will be discussed below, the presence of macropore minerals is consistent with the geochemical modeling of the SP data.

Mineralogy of the Materials from the Buried Brine Evaporation Pit

The results of mineralogical characterization of the buried brine evaporation pit core (FA-1) are listed in Table 8. With the exception of halite (NaCl), the same minerals were found in these materials as were found in the nine cores from the undisturbed site. Halite was first detected in materials from a depth of 48 inches and its abundance increased with depth. This halite results from crystallization of the saline porewater while the

TABLE 7

SATURATION PASTE EXTRACT CHEMICAL DATA AND NDEGM SATURATION INDICIES

SAMPLE	DEPTH		Ca	Mg	K	Na	CO_3	HCO_3	Cl	SO_4	EC	Saturation Index	
	(in.)	(cm.)	meq/L								(mmhos/cm)	gypsum	calcite
FA-2	30	76	1.7	1.4	0.2	1.7	0.5	1.1	0.4	3.0	0.3	-1.72	0.35
FA-2	48	122	2.3	1.5	0.1	1.4		1.2	1.3	2.8	0.4	-1.63	-0.49
FA-2	84	213	2.0	1.5	0.2	2.2	0.7	0.5	0.7	4.0	0.4	-1.56	0.20
FA-3	12	30	2.5	1.5		0.3		2.7	0.8	0.9	0.6	-2.04	-0.06
FA-3	24	61	1.2	0.8		0.3		1.4	0.6	0.2	0.3	-2.89	-0.60
FA-3	36	91	2.3	1.3		0.4		3.6	0.6	0.0	0.4	------	0.05
FA-3	48	122	2.3	1.2		0.4		3.7	0.5	0.0	0.4	------	0.06
FA-3	60	152	2.7	1.6		0.6		3.7	0.5	0.7	0.5	-2.13	-0.10
FA-3	72	183	2.5	1.5		0.7		3.4	0.6	0.7	0.5	-2.15	0.03
FA-3	84	213	2.7	1.7		0.8		3.3	0.7	1.3	0.6	-1.88	0.03
FA-3	96	244	3.0	2.2		1.0		3.4	0.7	2.1	0.6	-1.67	0.07
FA-3	108	274	3.1	2.4		1.2		3.5	0.7	2.5	0.7	-1.59	0.08
FA-3	120	305	2.7	2.2		1.2		3.3	0.8	2.0	0.6	-1.72	0.01
FA-4	30	76	1.8	0.7	0.2	2.1	3.2	0.0	1.1	0.5	0.4	-2.39	0.50
FA-4	48	122	2.1	1.0	0.1	1.7	0.5	0.9	0.6	2.8	0.4	-1.65	0.38
FA-4	84	213	1.8	1.6	0.1	2.3	0.0	0.4	0.9	4.5	0.5	-1.56	-1.11
FA-5	30	76	2.3	1.8	0.2	2.1	2.2	3.7	0.6	0.0	0.5	------	1.03
FA-5	48	122	1.8	2.3	0.3	3.0	2.2	1.4	0.5	3.3	0.6	-1.71	0.59
FA-5	84	213	1.8	1.5	0.2	2.0	2.0	0.8	0.4	2.2	0.5	-1.82	0.49
FA-6	30	76	2.7	1.6	0.3	2.5		2.5	1.6	3.0	0.5	-1.57	-0.13
FA-6	48	122	1.9	1.8	0.3	1.9		2.2	0.6	3.0	0.4	-1.69	-0.33
FA-6	84	213	1.8	1.7	0.2	1.8	0.8	1.5	0.8	2.3	0.4	-1.81	0.51
FA-7	12	30	3.5	2.7		0.5		4.4	0.7	1.6	0.8	-1.74	0.24
FA-7	24	61	6.0	15		5.7		3.1	0.7	23	2.5	-0.76	0.03
FA-7	36	91	30	42		21		2.5	0.6	90	6.2	0.11	0.36
FA-7	48	122	30	13		8.2		2.3	0.5	49	3.9	0.04	0.46
FA-7	60	152	31	11		4.3		2.2	0.7	43	3.4	0.04	0.48
FA-7	72	183	15	6.3		2.5		2.6	0.5	21	2.1	-0.37	0.39
FA-7	84	213	30	11		2.5		2.3	0.5	41	3.3	.00	0.49
FA-7	96	244	31	14		2.7		2.2	0.7	44	3.5	0.03	0.48
FA-7	108	274	30	15		2.9		2.0	0.5	45	3.5	0.02	0.41
FA-7	120	305	27	18		3.4		2.3	0.5	45	3.7	-0.02	0.43
FA7A	30	76	1.3	11	0.2	4.0		2.2	2.1	13	1.4	-1.53	-0.68
FA7A	48	122	1.3	4.9	0.2	4.0		3.4	0.7	6.2	0.9	-1.67	-0.39
FA7A	84	213	1.8	5.3	0.2	3.7		1.2	0.6	9.2	0.7	-1.41	-0.74
FA-8	30	76	6.5	12	0.5	7.5		3.0	0.7	23	2.3	-0.72	0.05
FA-8	48	122	5.8	11	0.5	7.5		2.3	0.9	21	1.7	-0.77	-0.10
FA-8	84	213	26	9.9	0.6	7.0		1.9	0.7	41	2.6	-0.03	0.36

TABLE 7 (CONT.)

SATURATION PASTE EXTRACT CHEMICAL DATA AND NDEGM SATURATION INDICIES

SAMPLE	DEPTH (in.)	DEPTH (cm.)	Ca	Mg	K	Na	CO_3	HCO_3	Cl	SO_4	EC	Saturation Index gypsum	Saturation Index calcite
			meq/L								(mmhos/cm)		
FA-9	12	30	3.9	2.6		0.6		4.6	0.9	1.6	0.7	-1.70	0.30
FA-9	24	61	13	24		7.7		3.0	0.5	41	3.4	-0.35	0.24
FA-9	36	91	20	71		37		2.1	1.9	123	8.4	-0.04	0.02
FA-9	48	122	17	70		40		2.0	0.9	124	8.5	-0.10	-0.07
FA-9	60	152	16	80		43		2.2	2.4	134	9.2	-0.13	-0.08
FA-9	72	183	24	103		48		1.6	2.4	171	11	0.08	-0.09
FA-9	84	213	23	110		53		1.6	3.0	181	11	0.07	-0.12
FA-9	96	244	21	114		53		1.6	3.8	183	12	0.03	-0.15
FA-9	108	274	22	105		51		1.6	3.9	172	11	0.03	-0.14
FA-9	120	305	27	98		49		1.8	4.4	163	11	0.11	0.02
F-1	12	30	82	56		479		5.2	569	43	54	-0.09	0.98
F-1	24	61	65	49		525		6.3	586	47	55	-0.15	0.96
F-1	36	91	58	69		416		2.4	604	0.0	56	------	0.54
F-1	48	122	76	101		638		7.9	786	21	66	-0.49	1.12
F-1	60	152											
F-1	72	183	66	24		1142		2.6	1239	0.0	101	------	0.58
F-1	84	213	61	27		1016		7.9	1118	0.0	99	------	1.03
F-1	96	244	56	27		1017		3.0	1124	0.0	97	------	0.58

TABLE 8

MINERALOGY IN THE SALT PIT SPECIMENS

CORE #	DEPTH (in.)	DEPTH (cm.)	Qz	K-Sp	Pg	Cc	Do	Hl
F-1	24	61	1160	28	56	38	60	0
F-1	36	91	1000	22	46	38	62	0
F-1	48	122	820	24	48	36	76	18
F-1	60	152	920	26	178	32	48	16
F-1	72	183	900	26	44	20	20	28
F-1	84	213	940	30	56	42	44	30
F-1	96	244	960	28	56	50	70	40

samples were being oven-dried. The only other trend obvious from the data in Table 8 is an increase in smectite abundance at a depth of 48 inches. This site is located in an area of very little relief and illuviation of clay minerals should account for this observation. In spite of the high concentration of Na in these materials, x-ray results indicated that Ca is the dominant interlayer cation. The smectite peak in the x-ray diffractogram does show a small shoulder indicative of partial replacement of Ca by Na in the interlayer sites.

Saturation Paste Extracts

Chemical analyses and electrical conductivities of saturation paste extracts are shown in Table 7. Data for FA-3, FA-7, FA-9, and F-1 were provided by the Land Reclamtion Research Center in Mandan, N.D. Except for the determination of potassium concentration at NDSU, similar procedures were used for all the analyses. Sulfate originates from the oxidation of sulfide minerals. The acidity produced from this process was neutralized by the dissolution of calcite and dolomite present in the parent material. The calcium apparently reprecipitates with SO_4 as gypsum. Some of the calcium and small amounts of magnesium precipitate as secondary calcite. The resultant soil solution contains high concentrations of Mg, SO_4 and Na. The crystalline sulfate salts of Na and Mg are extremely soluble, and are strictly a surface phenomenon in soil profiles, and thus remain in solution. The concentration of calcium in the soil solution is controlled by the solubility of gypsum. Dissolution of dolomite accounts for the majority of the magnesium observed in the soluble species.

Plots of ionic concentration versus depth or electrical conductivity (EC) for five ions in FA-3, FA-7, and FA-9 are shown in Figures 2-8. The effect of topography on water movement is again evident from the ion concentration versus depth plots. In FA-3, the concentration of the soluble species

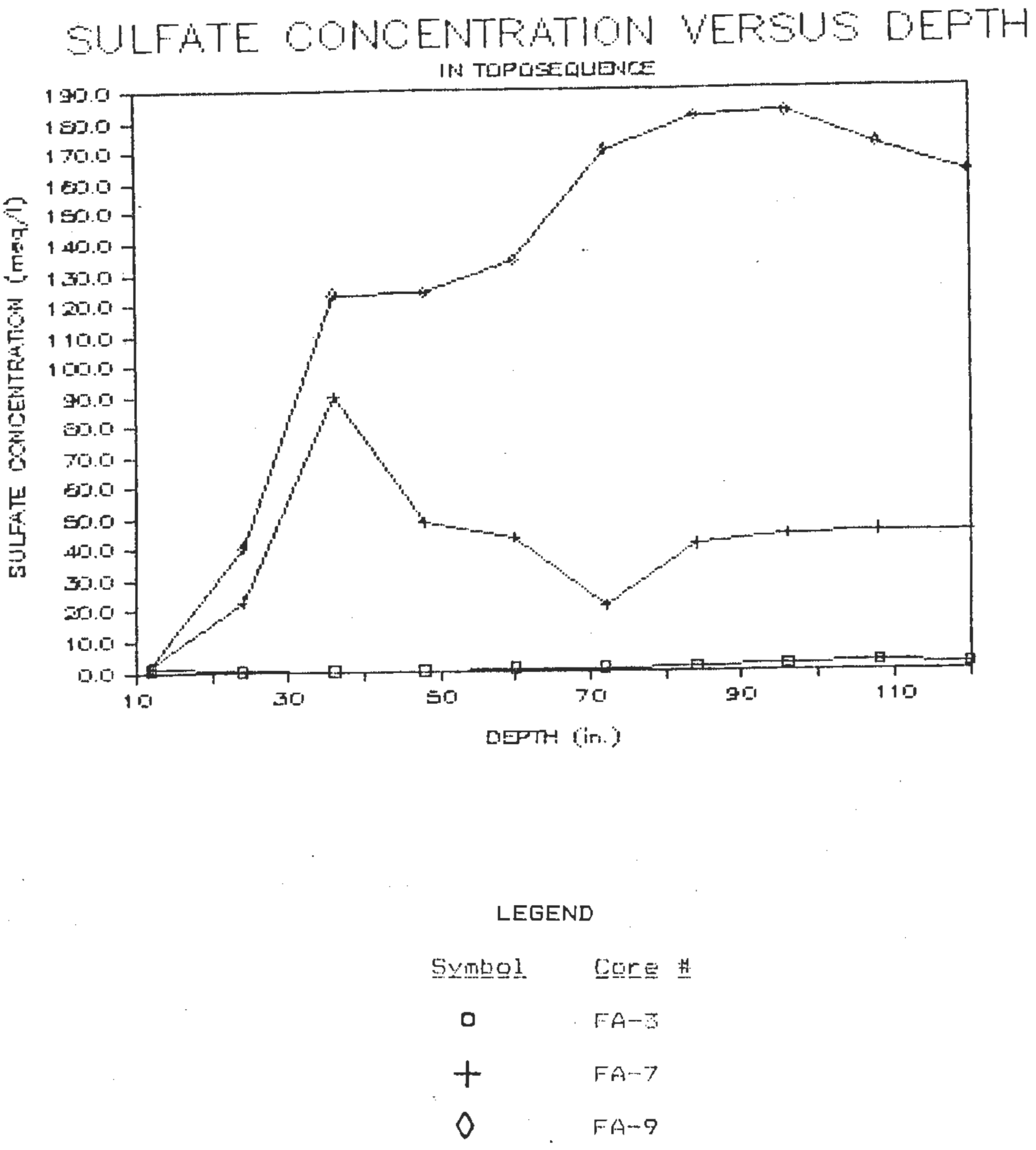
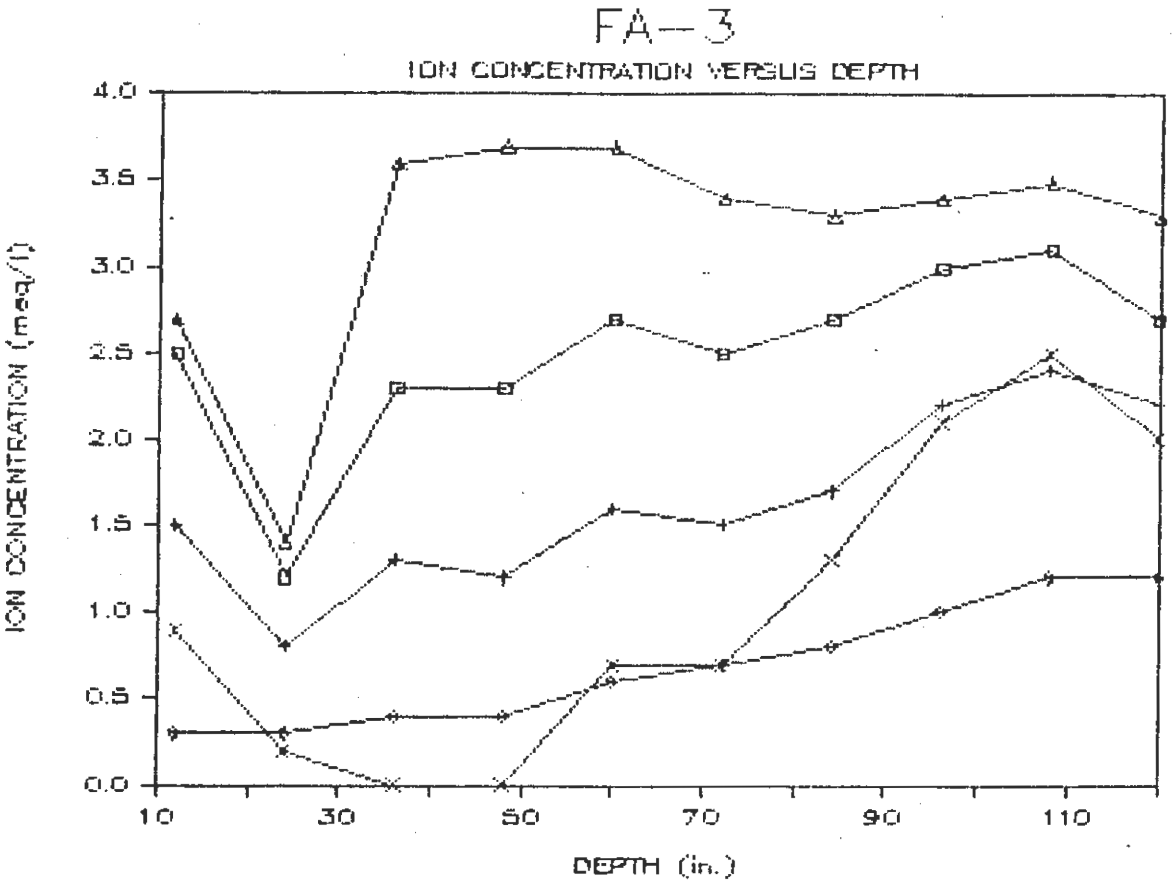

SULFATE CONCENTRATION VERSUS DEPTH
IN TOPOSEQUENCE
SULFATE CONCENTRATION (meq/l)
190.0
180.0
170.0
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
00.0
10
30
50
70
90
110
DEPTH (in.)
LEGEND
Symbol
Core #
□ FA-3
+ FA-7
◊ FA-9

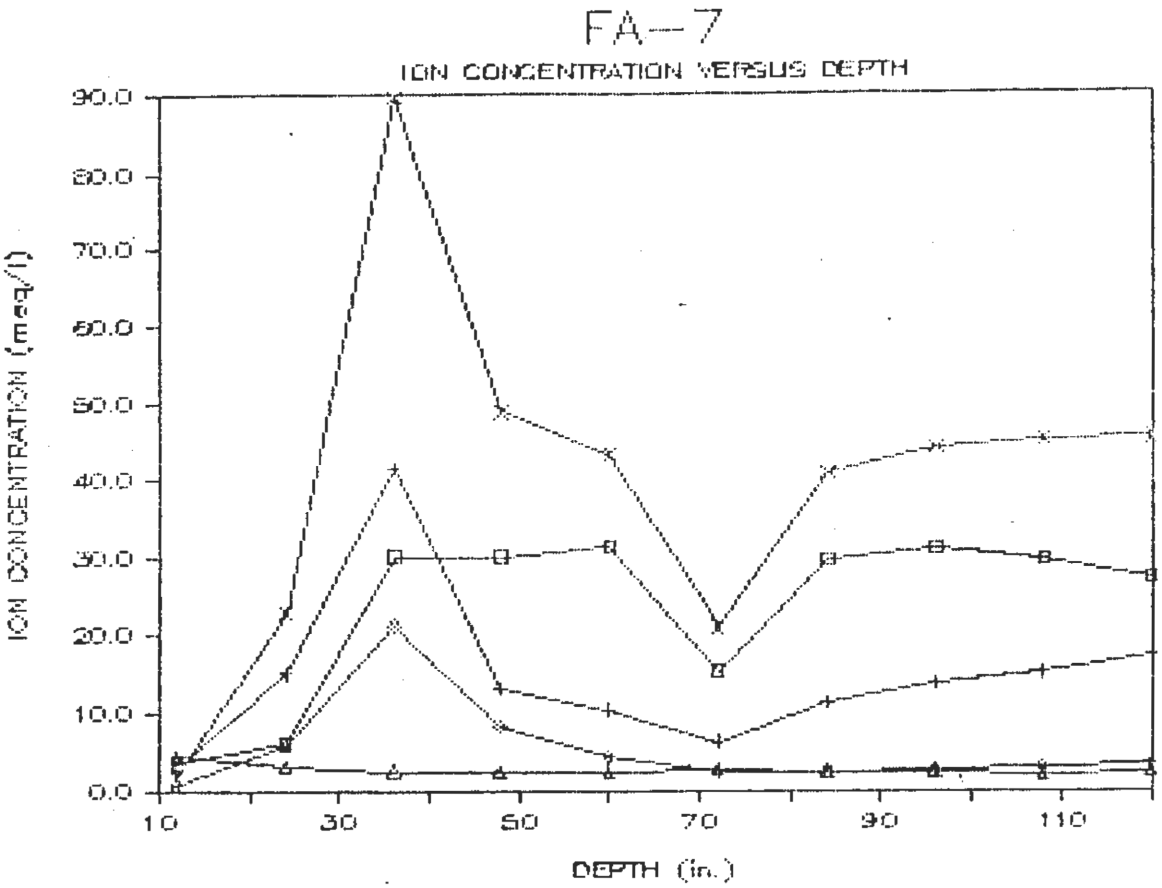
FIGURE 2



LEGEND

Symbol	Ion
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^{-}
X	SO_4^{2-}

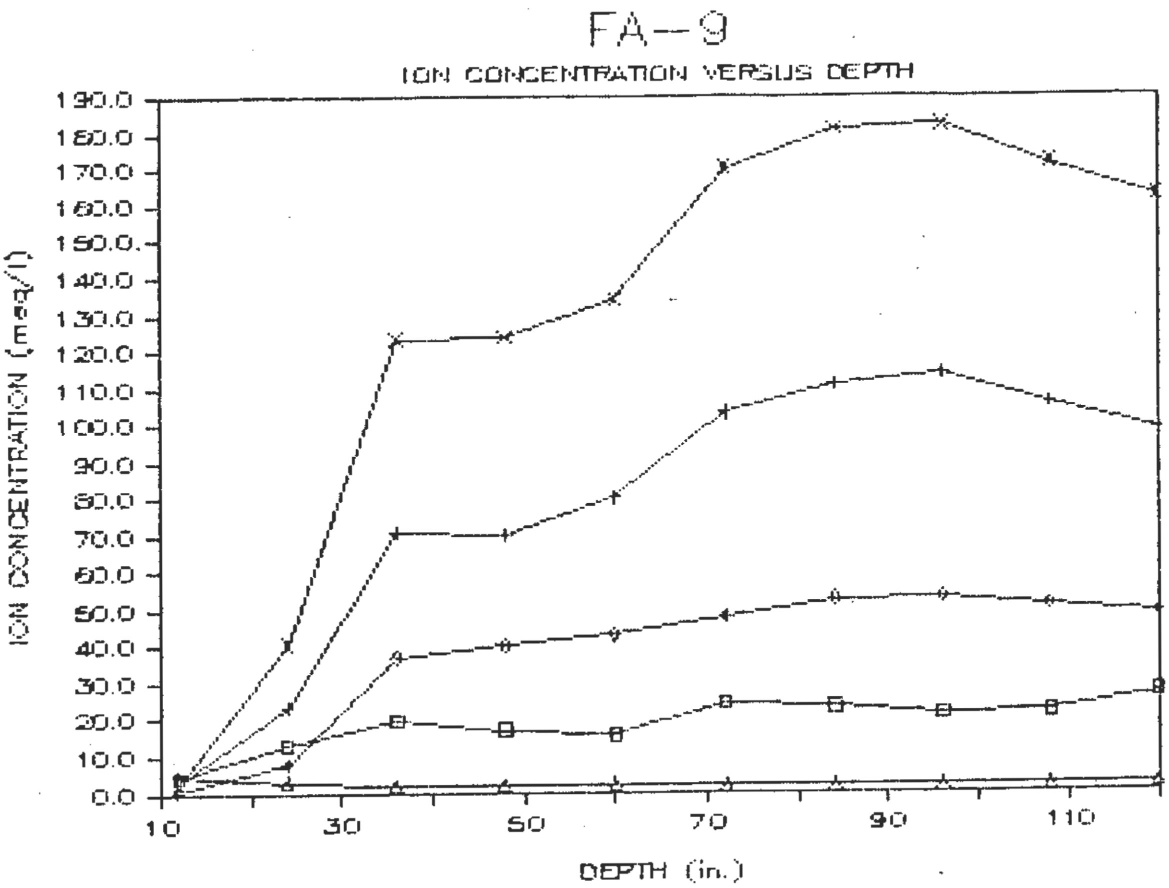
FIGURE 3



LEGEND

Symbol	Ion
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^{-}
X	SO_4^{2-}

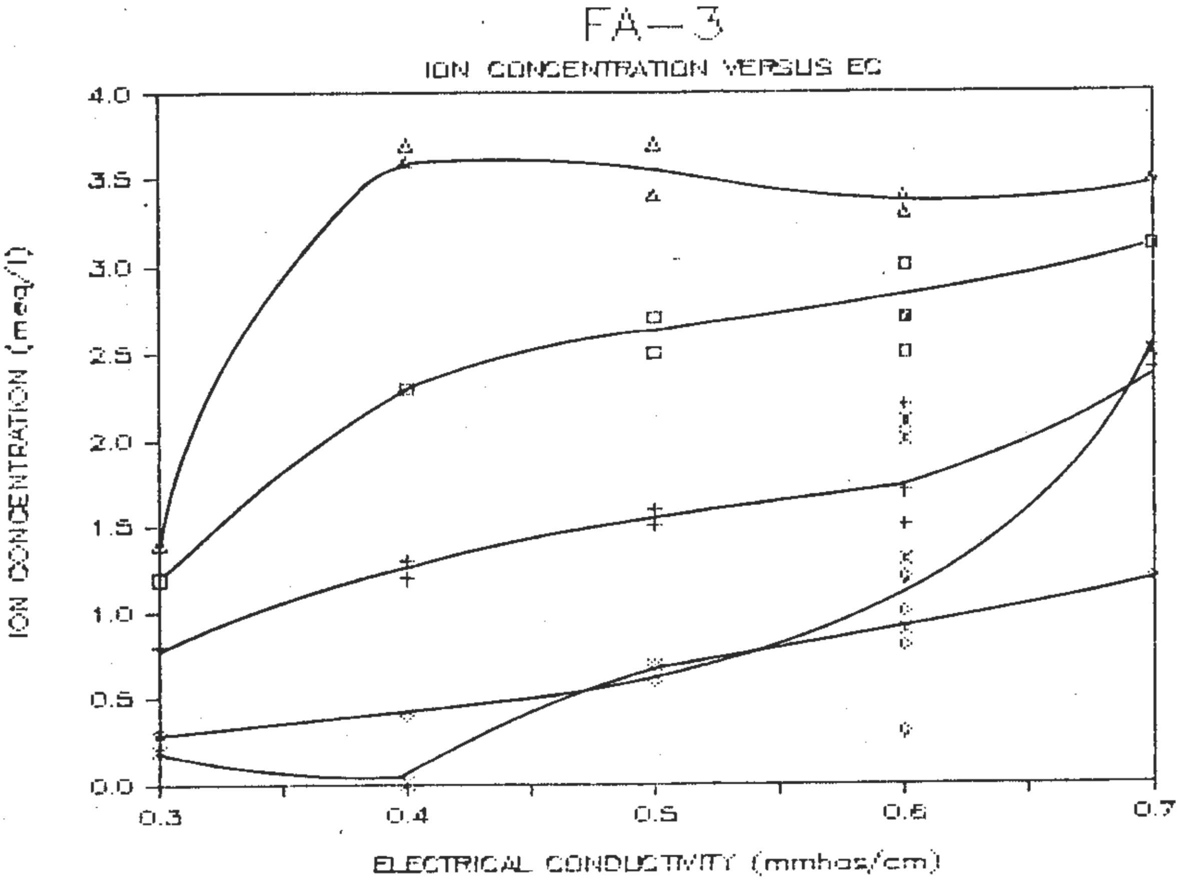
FIGURE 4



LEGEND

Symbol	Ion
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^{-}
X	SO_4^{2-}

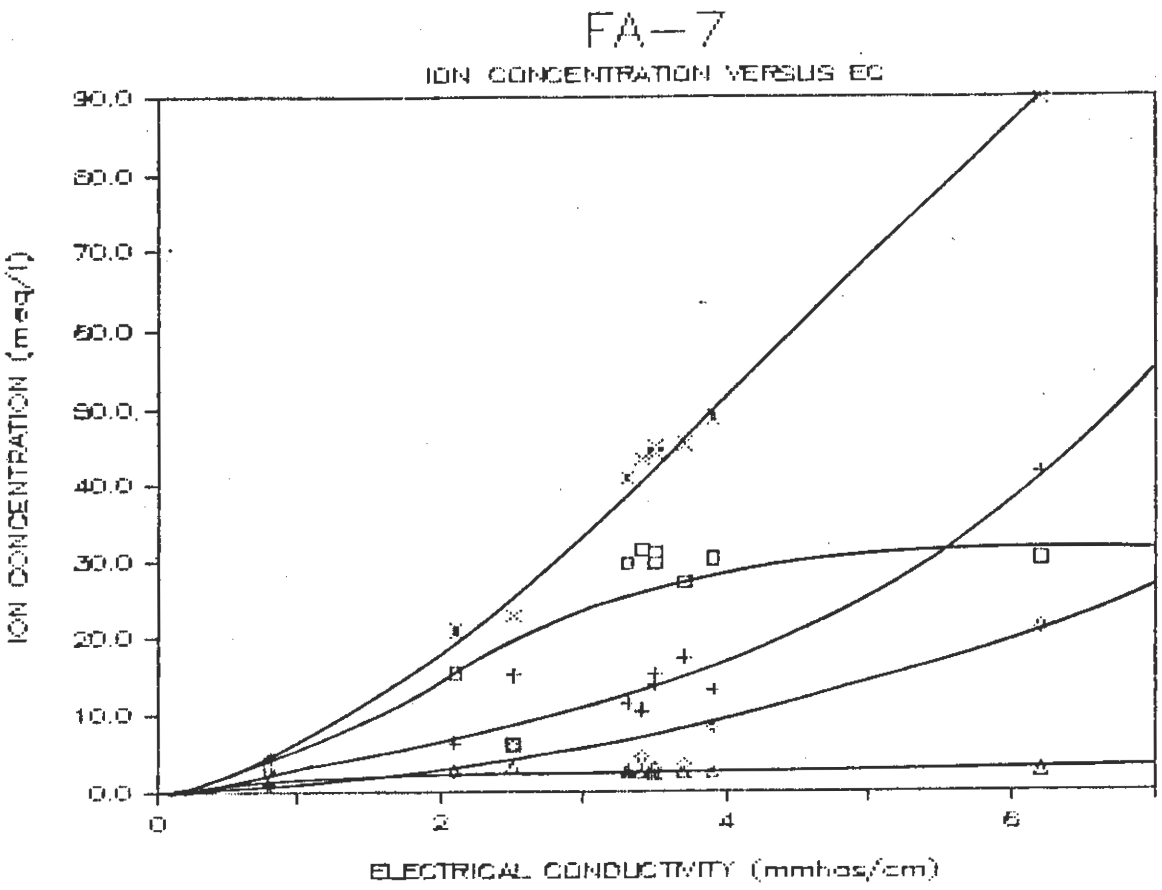
FIGURE 5



LEGEND

Symbol	Ion
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^{-}
X	SO_4^{2-}

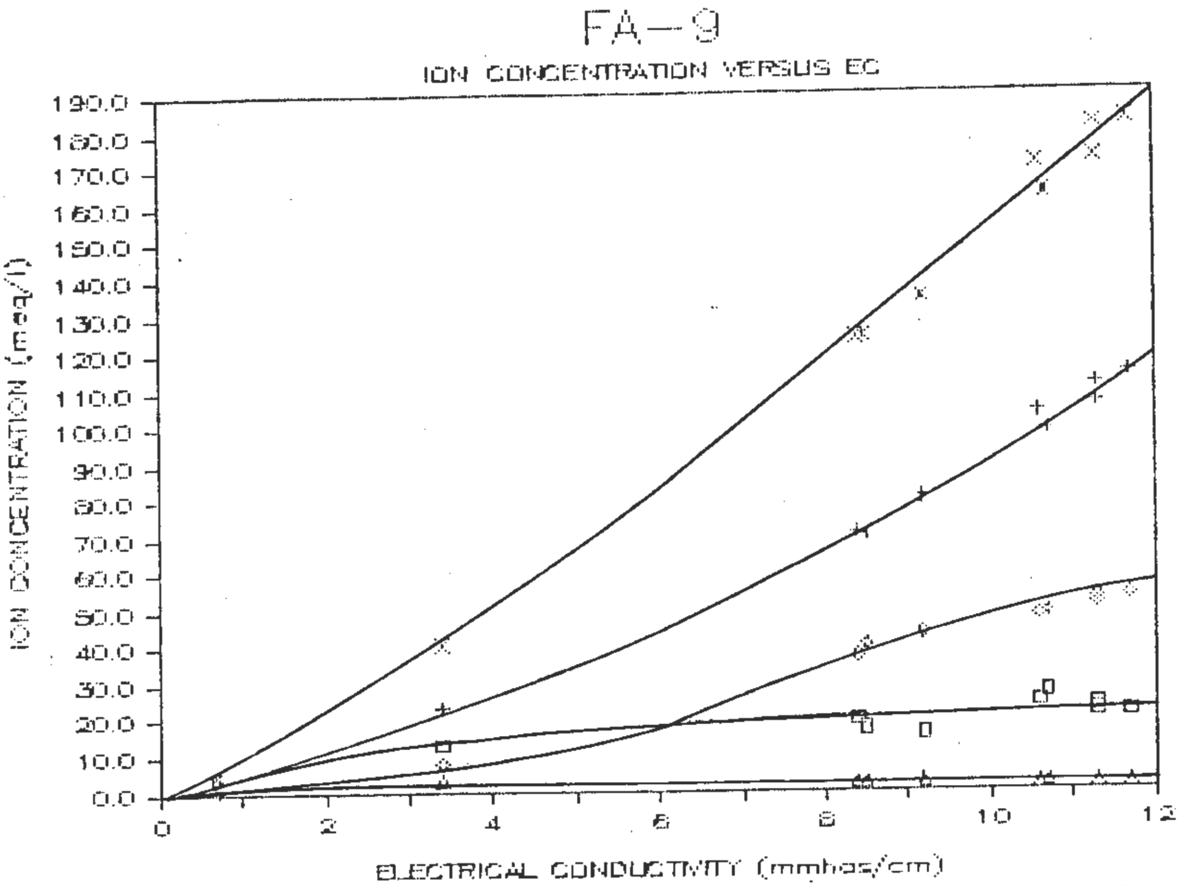
FIGURE 6



LEGEND

Symbol	Ion
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^-
X	SO_4^{2-}

FIGURE 7



LEGEND

<u>Symbol</u>	<u>Ion</u>
□	Ca^{2+}
+	Mg^{2+}
◇	Na^{+}
△	HCO_3^{-}
X	SO_4^{2-}

FIGURE 8

increases with depth due to leaching. Evapotranspiration from the "edge" effect causes moderately high concentrations at approximately one foot below the surface. FA-7 has more throughflow limiting the infiltration, which results in a concentration of soluble species at a depth of 34 inches. The concentration of soluble species increases with depth in FA-9 due to limited leaching.

In FA-7 the Ca and SO_4 concentrations level off at depth due to the presence of gypsum. The Ca concentration in FA-9 levels off at depth due to gypsum precipitation. The SO_4 concentration increases continually with depth due to the proximity of the sulfate-rich groundwater.

Model for Water Movement Based on Mineralogy

A model for water movement is illustrated in Figure 9. It is proposed that water movement on the summit and backslope is primarily by throughflow. Compacted till occurs at depths varying from 3-4 feet and acts as a natural boundary along which water moves. FA-4, located on the edge of the depression, begins to show leaching near the surface, as evidenced by lack of near-surface (less than 12 in.) calcite. Water movement in the closed depression is downward and results in the leaching of carbonates and soluble salts. The closed depression holds water in the spring and this water moves downward and laterally. Unsaturated flow then occurs and calcite precipitates at the capillary fringe.

Microrelief also influences water movement. Due to the swale above FA-8, enough water percolates down through the profile to remove the gypsum from FA-7A. The depth to gypsum in FA-8 is also affected by this swale. Maximum carbonate precipitation occurs at the surface of FA-6. This carbonate acculuation marks the boundary of maximum capillary movement near the surface from the closed depression. Sites FA-8 and FA-9 display a similar near surface "edge" effect resulting from the swale.

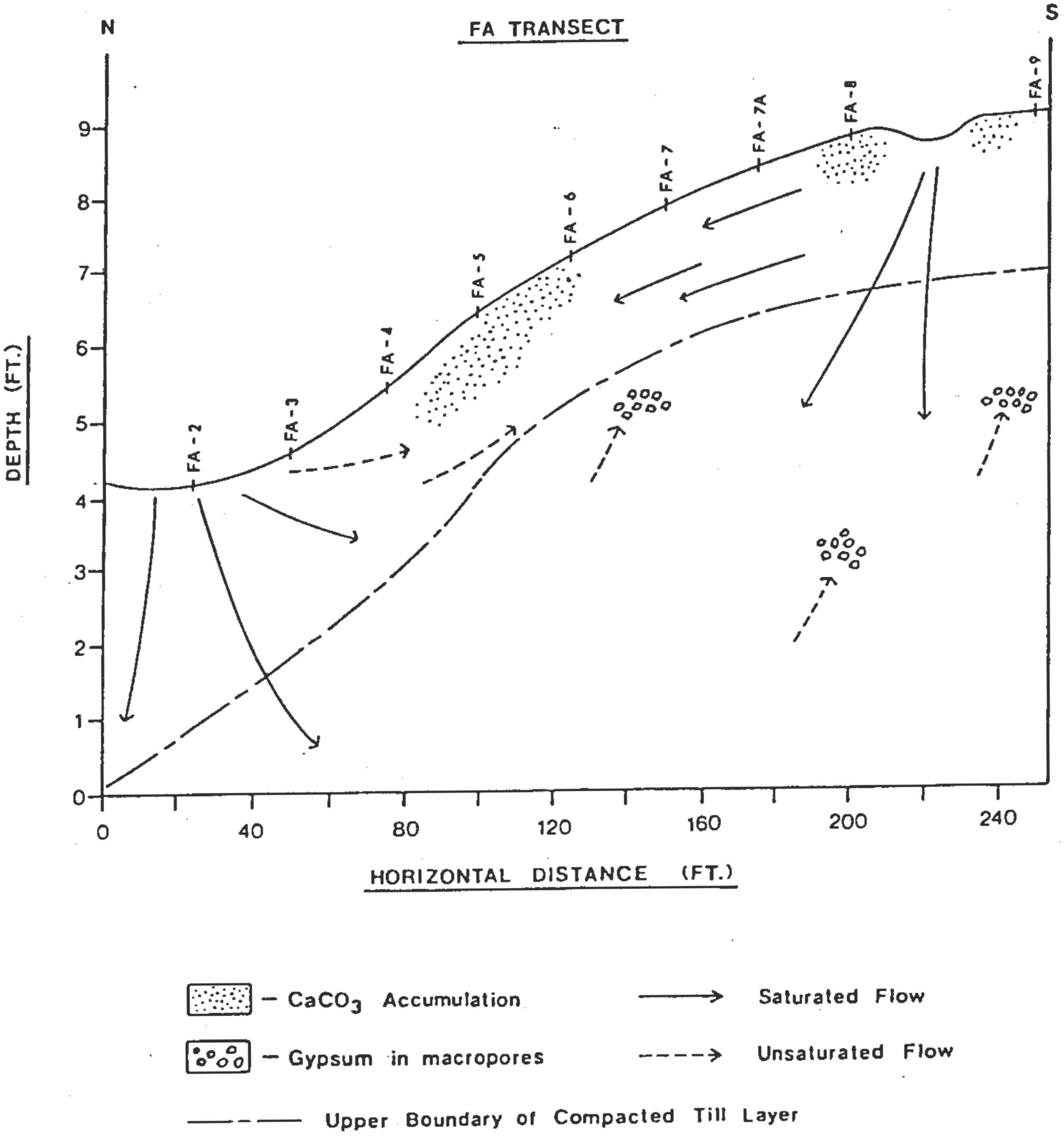


FIGURE 9

WATER MOVEMENT MODEL FOR FA TRANSECT

Based on the 1985 observations, a general water movement in the spring model for three parent materials has been developed. This model is summarized in Figure 10. Water moves over the frozen layer of soil as subsurface throughflow. Most water movement occurs at this time. Water movement in the summer is mainly due to capillarity. If enough precipitation occurs, water movement by saturated throughflow will occur on the till toposequence. The water will flow over the compacted till layer as previously described. This movement was observed in the field during late August, 1985. The outwash and lacustrine toposequences were sampled at this same time, but there were no indications of subsurface throughflow having occurred recently. The water movement in both toposequences is probably down into the profile as there is not an impermeable boundary to impede its flow.

Geochemical Modeling

Soil water chemistries derived from saturation paste extracts of FA toposequence soil cores were entered into the North Dakota Equilibrium Geochemical Model Personal Computer (NDEGMPC) program. NDEGMPC is a version of the WATEGM-SE program by Carl Palmer (1983) that has been adapted for use on a microcomputer by R. G. Garvey of the NDSU Chemistry Department. WATEGM-SE was developed with computational routines and a database tailored for groundwaters of the Upper Plains Region of the United States and Canada. The program derives saturated indices (SI), a measure of how saturated a sample is with respect to a group of specified minerals, for minerals consistent with the chemistry entered. These SI's can be used to model the minerals that control the chemistry of soluble species in the soil water of a given soil profile. Use of this geochemical modeling program was included in our studies in order to explore other evidence for the water movement model in Figure 9. The agreement between the observed chemistries, mineralogies and the model was very good.

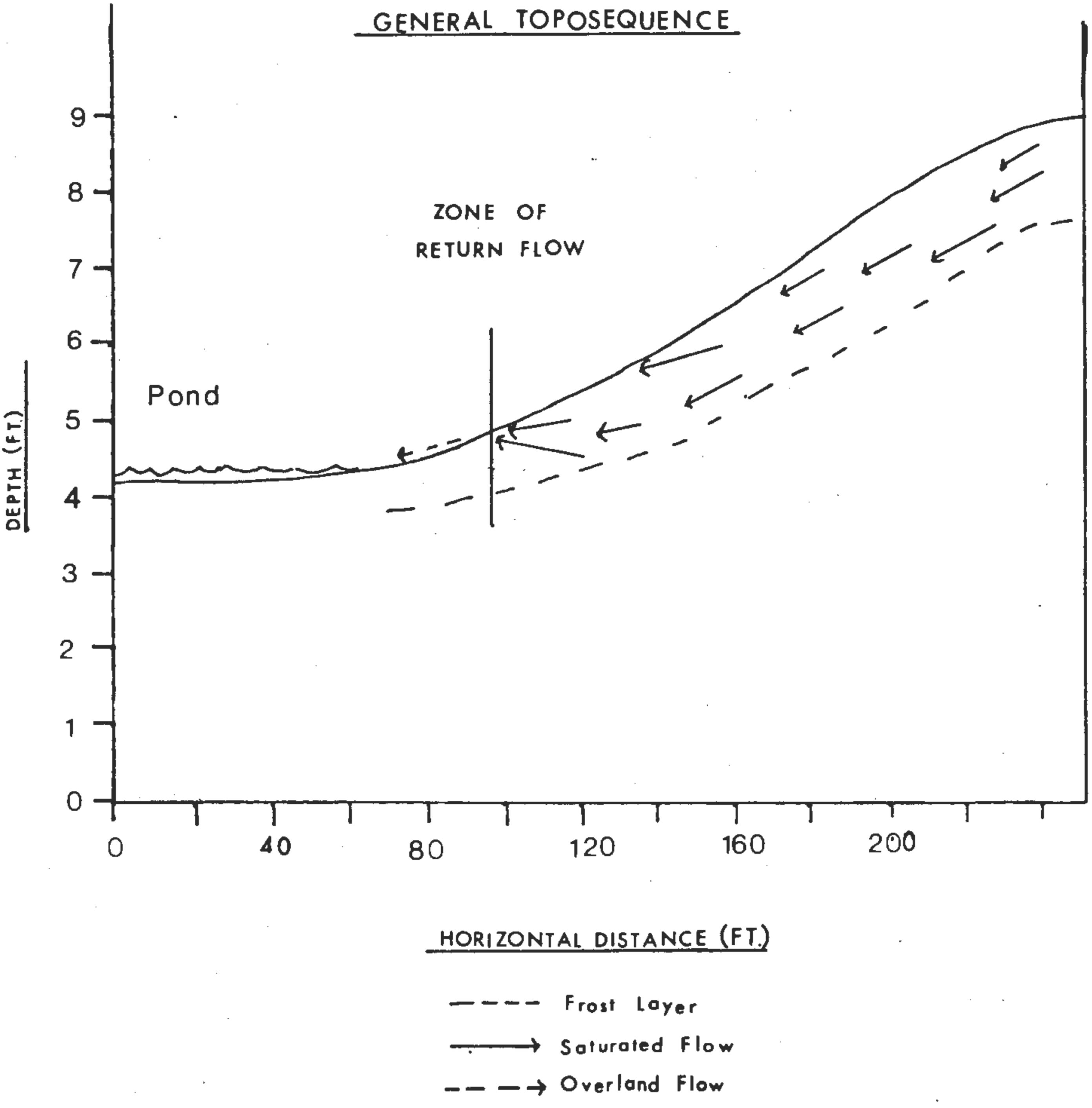


FIGURE 10

GENERAL WATER MOVEMENT MODEL FOR SPRING

NDEGMPC was run on an IBM-PC with the following standard parameters: temperature = 25°C, pressure = 1 atm, pO_2 = 0.21 atm and a solution density of 1 g/mL. Actual pH's of the saturation paste extracts were not available, so an assumed pH of 8.4 or 7.5 was used, depending on the presence or absence, respectively, of the carbonate anion. Alkalinity, derived from bicarbonate and carbonate data, was used as the entry for total inorganic carbon. A sample was considered saturated with respect to a given mineral if the mineral's SI = 0.0 ± 0.1, slightly saturated or slightly unsaturated if SI = 0.1 to 0.3 or -0.1 to -0.3, respectively. A sample was considered supersaturated if the SI > 0.3 and undersaturated if SI < -0.3. These somewhat broad ranges were used because of the usual uncertainties in the modeling process and the lack of individual pH and temperature data for each analysis. SI's derived from the chemical data in Table 7 are also included in the table.

From Figure 9, gypsum can be seen to occur in profiles FA-7 at approximately 36 inches, in FA-8 at approximately 60 inches, and in FA-9 at approximately 36 inches. The NDEGMPC results in Table 7 agree very well with the water movement model. The soil is saturated with respect to gypsum in only these 3 cores and at depths of 36+ inches, 84+ inches and 36+ inches, respectively. The results for calcite saturation also agree well with the proposed model. The profiles into the zones of calcite accumulation, i.e. FA-5, FA-8 and FA-9, are saturated or supersaturated with respect to calcite at nearly all depths. The saturation at depth is due to the carbonate rich till that underlies the soil. Profiles FA-2, FA-3, FA-4 and FA-6 are saturated or slightly undersaturated in the surface depth increment due to evapotranspiration, while calcite is being leached from other depths above the till layer. FA-7 is saturated with respect to calcite at all depths due to lack of leaching in this slope position. FA-7A does not exhibit the same effect due to the adjacent microrelief high at profile FA-8. The water is drawn upward toward the high by capillarity where calcite precipitates at the surface.

CONCLUSIONS

It has been shown that evaporite mineralogy and saturation paste extract data can be used a indicators of water movement. The minerals most useful as water movement indicators were gypsum, calcite and, in salt contaminated areas, halite. The low background of Cl in the natural materials made Cl a unique tracer of water movement in those cases where there were nearby sources of contamination. It was shown that salt migration from brine pits located on summits occurs mainly by subsurface throughflow. Water movement resulting from capillarity accounts for the major salt migration when the brine pit is located in a closed depression.

The results from Task 3 have been integrated into the descriptions of salt migration and suggestions for reclamation described throughout this report. The general models for water movement in these glacial and lacustrine materials should also be of interest to the agricultural, wildlife, and land and water managment sectors of the state.

ACKNOWLEDGEMENTS

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TASK 4-1

INVESTIGATION OF A SURFACE BRINE FLOW FROM AN ABANDONED SEISMIC SHOT HOLE IN THE BLACK SLOUGH OIL FIELD, BURKE COUNTY, NORTH DAKOTA

by:

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December, 1985

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We would like to thank Mr. Gary Amundsen for allowing us access to his land and the many kindnesses he extended to us.

We would like to also thank Mrs. Elizabeth McCarney for allowing us access to her land.

We wish to acknowledge the following employees of the North Dakota State Department of Health (Rick Nelson, Rod Reetz, Ken Kary, and Cindy Auen) and also Ken Kallestad, Bruce Hicks, Bob ~~Garvey~~ GARBE, and Jim Dufty of the Oil and Gas Division of the North Dakota State Industrial Commission for their help and cooperation in the project.

The U.S. Fish and Wildlife Service issued us a special use permit (DL-36-34) allowing us access to the Beaver Lake Waterfowl Production Area. We wish to thank Del Pierce and Thad Fuller for their help in issuing this permit.

The North Dakota Geological Survey provided vehicles support, including a truck mounted auger and a geophysical logging van. All of the diagrams were drafted by Mr. Kenneth L. Dorsher of the North Dakota Geological Survey.

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ABSTRACT

In January of 1983, salt water (119,00 mg/l NaCl) began flowing at the surface from a 200-foot (61-m) abandoned seismic hole in the Black Slough Oil Field in Burke County, North Dakota. The shot hole was located within 1/3 mile (1/2 km) of an active injection well and two abandoned oil wells. Salt-water flow from the shot hole covered an area of 40 acres (98.8 hectares). All attempts to cement the shot hole failed until the injection well was shut in. As a result of this apparent direct relationship, the injection well was plugged and abandoned.

Piezometers were nested at various depths in the four major permeable zones in the area to a depth of 200 feet (61 m) to determine the vertical and lateral extent of brine migration in the subsurface and, if possible, to pinpoint the source of the leak.

In all, seven nests (39 piezometers) were placed within a 1/2 mile (0.8 km) radius of the injection well. Shelby-tube cores were also taken in an attempt to locate the path of salt-water migration.

The surface of the one-mile-square study area is underlain by a thin layer of Holocene alluvium and 20 to 60 feet (6.1 - 18.3 m) of glacial drift. The uppermost unit of the drift consists of 2 to 14 feet (6.6 - 4.3 m) of glaciolacustrine clay. Beneath the lake sediment, the drift is predominantly pebbly clay till in the northeastern part of the study area and outwash to the southwest. These deposits are underlain by Paleocene sediments composed of alternating sands, silts, clays, and lignites.

Brine was not found in any of the four monitored horizons. Groundwater within the Pleistocene interval contained extremely high concentrations of

naturally occurring sodium sulfate. The other intervals contained major-ion concentrations within the range of background levels. Trace-metal concentrations were extremely high in all of the groundwater samples from the study site. The trace-metal analyses are being verified by selected analysis of samples in a second laboratory. If these concentrations are verified by subsequent analyses, a source will be determined.

INTRODUCTION

Saltwater Flow Incident

On January of 1983, an abandoned 200-foot (61-m) seismic shot hole began flowing salt water at the surface. A 45-foot (13.7-m) deep well approximately 1/4 mile (0.4 km) to the north on the Amundsen farm, flowed fresh water during this time. The shot hole was located 1/3 of a mile (1/2 km) from an active injection well and two abandoned oil wells within the Black Slough Oil Field in Burke County, North Dakota (Fig. 1). Salt water flowed over an area of 40 acres (98.8 hectares) and was determined by the North Dakota State Health Department to contain 119,000 mg/l of NaCl (Appendix 4-1A). All attempts to cement the shot hole failed until the injection well was shut in. As a result of this apparent direct relationship, the injection well was plugged and abandoned.

During early 1984, the North Dakota State Department of Health requested that our research group consider monitoring of this site as part of our ongoing WRRI research project. An Earth resistivity survey of the area was attempted during the summer of 1984 to determine the zone of brine migration. However, it was determined that too much of the area was covered by water and an appropriate grid system could not be established. We therefore decided to instrument the area with piezometers as a means of determining and characterizing the lateral and vertical components of the brine plume.

Subsurface Brine Injection in North Dakota

Brine is produced along with oil and gas at most oil wells in North Dakota. The problem of brine disposal has existed in North Dakota since oil

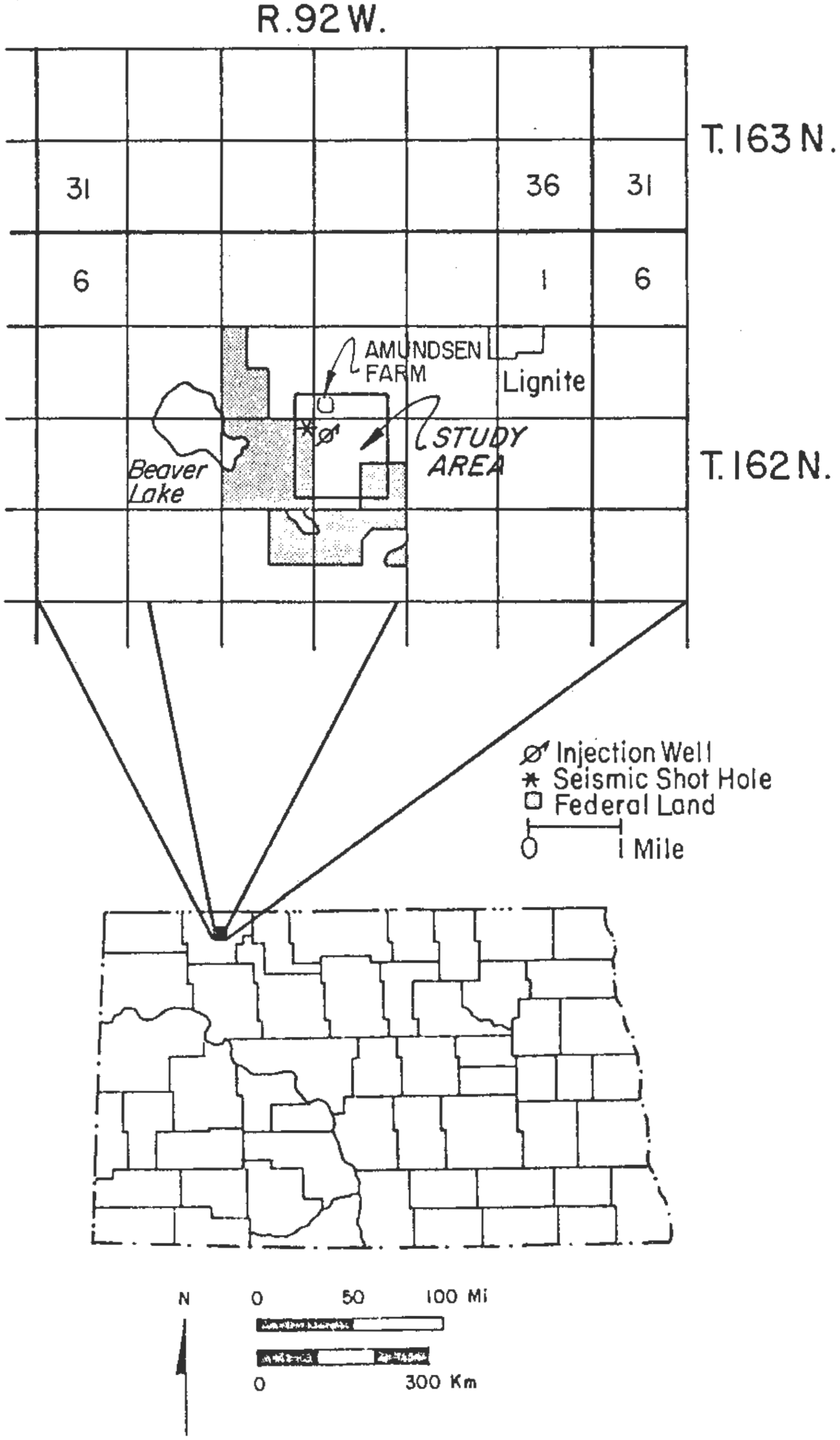


FIGURE 1 - THE LOCATION OF THE STUDY AREA

production first began in the Williston Basin in 1951. Initially, brine was disposed of at the surface in evaporation pits and in the subsurface by injection or disposal wells. Environmental problems associated with surface disposal have resulted in essentially all brine currently produced in North Dakota being disposed of by injection into the subsurface.

Brine injection wells are placed into two categories depending upon the injecting horizon. If the well is injecting the brine into an oil producing formation for pressure maintenance, it is termed an enhanced recovery injection well. If the well's sole purpose is to inject the brine into the subsurface for disposal purposes, it is termed a salt-water disposal well. The majority of salt-water disposal wells in North Dakota are injecting brine into the Lower Cretaceous Dakota Group at depths of approximately 3000-5000 feet (914 - 1524 m) throughout the basin.

As of January 1985, there were 221 disposal wells and 161 injection wells operating in North Dakota. These wells disposed of 68,200,000 barrels and injected 29,600,000 barrels of brine into the subsurface during 1984 (Hicks, 1985). The following is the status of brine injection and disposal wells in the state (as of January 1985):

Well Type	Active	Permitted	Inactive	Plugged
Disposal	221	35	32	32
Injection	161	5	161	94

This brings the total number of salt-water disposal and injection wells that are operating, have operated, or will soon be operating within the state to 730.

Wells that inject or dispose of oil-produced brines are classified as type II injection wells under the Federal Underground Injection Control Program (UIC). The Oil and Gas Division of the North Dakota State Industrial Commission is the state regulatory agency for type II injection wells.

This agency enforces the rules and regulations governing type II wells as stated in Rules 701-705 in the General Rules and Regulations for the Conservation of Crude Oil and Natural Gas. Rule 704 states that "The operator of an injection project shall keep accurate records and report monthly to the Enforcement Officer the amount of fluid produced, the volumes of fluid injected, and the injected pressures."

In addition, the Commission requires that the operator maintain a pressure gauge on the injection well annulus and the tubing. Any violations must be reported immediately to the Commission. The operator is required to perform a mechanical integrity test at least once every five years (Hicks, 1985).

Study Site

The study site is located 2 miles (3.2 km) southwest of the town of Lignite in Burke County (Fig. 1). The one-mile-square (1.6 km^2) study area contains the western 2/3 of section 15 and the eastern 1/4 of section 16 (T162N, R92W).

Six oil wells are located within the study area. All were drilled during the early 1960's (Fig. 2). The Einar A. Amundsen "B" #1 (ND#3216) produced oil from 1962-1968. In 1968, it was converted to an injection well and injected brine into the Madison Formation at a depth of 6395 feet (1949.2 m). During the period it was active (1968-1983) it injected 2,808,051 barrels of brine into the subsurface (Industrial Commission, 1984).

There are no naturally occurring brines within the Cenozoic sediments of the Williston Basin of North Dakota. Brines with the NaCl concentrations that were found in the water that flowed from the seismic hole are generally present within the Paleozoic section. Therefore, the surface leak was

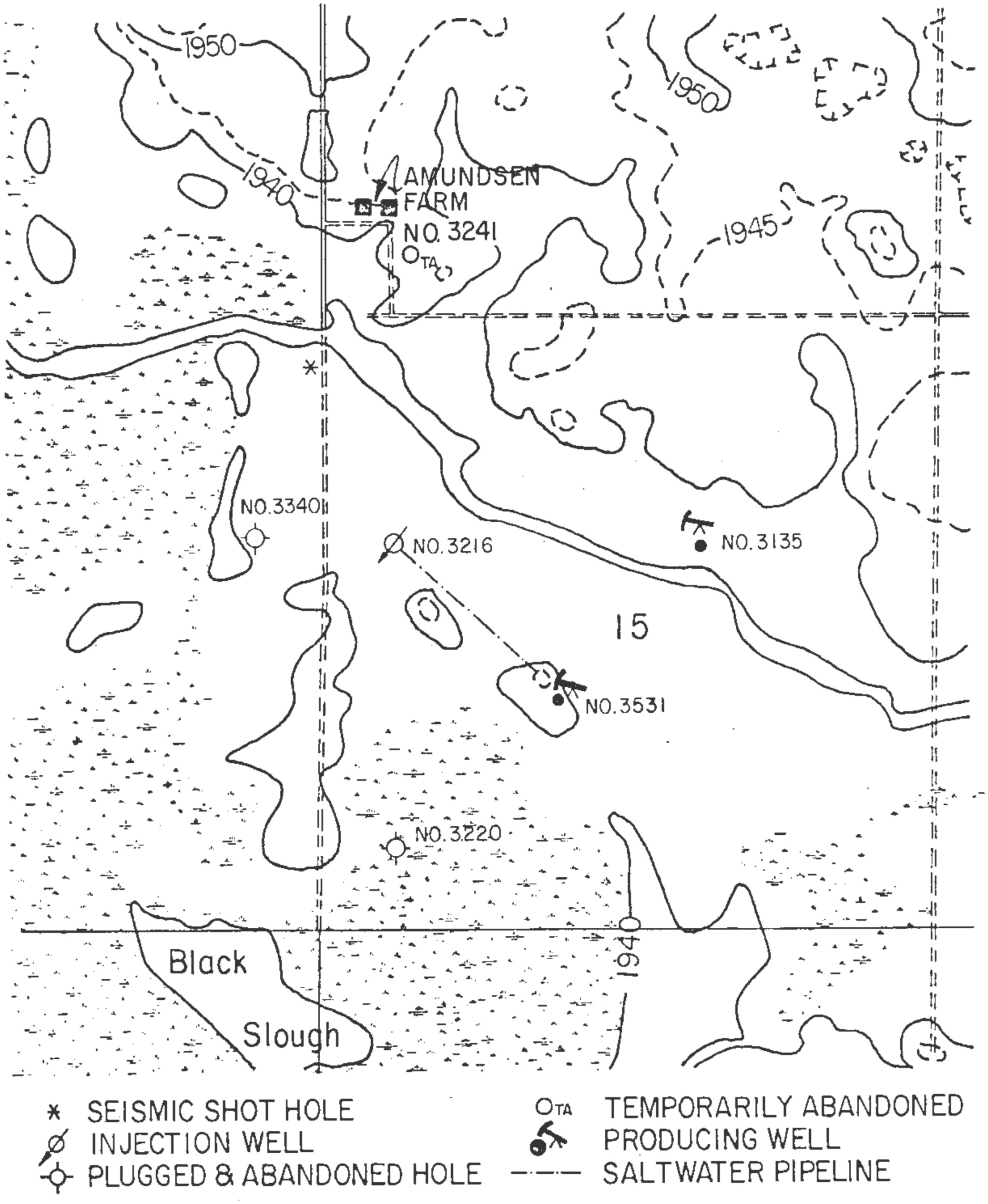


FIGURE 2 - OIL ACTIVITY WITHIN THE STUDY AREA

immediately recognized as being oil-field related. The injection system appeared to be the most likely source of the brine because the salt water flowed out of the abandoned shot hole under pressure and the pressure dissipated when the injection well was shut in. The brine could have been coming either directly or indirectly from the injection well.

If the brine came directly from the injection system, it could have been derived from two possible sources. One possible source was the shallow pipeline that brings salt water into the well for injection. The other possible source was the injection well itself. Salt water could have migrated up along the outside of the casing from a depth as great as 6400 feet (1951 m) and then migrated laterally in the shallow subsurface (Fig. 3). It is also possible that there was a parting in the surface casing above the injection horizon. Brine could also have migrated up the annulus of the abandoned oil wells located in the immediate vicinity of the study site (Fig. 3). This possibility was given serious consideration because the Einar A. Amundsen #B-2 (ND#3241) well was placed on temporarily abandoned status in 1963, and never plugged.

Eight injection or disposal wells are located within a two-mile (3.2-km) radius of the seismic shot hole.

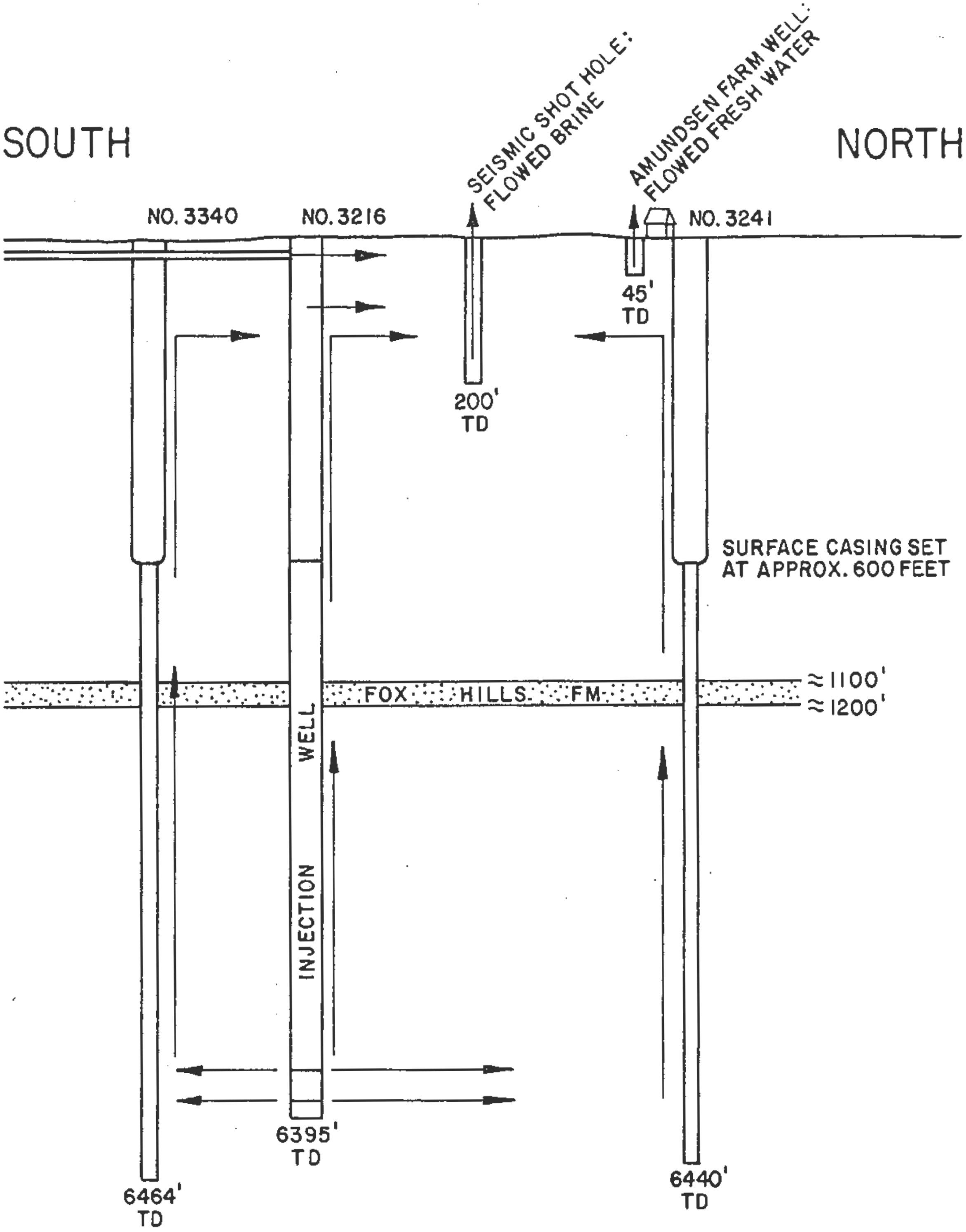


FIGURE 3 - CROSS SECTION OF STUDY SITE SHOWING POTENTIAL SOURCES AND AVENUES OF BRINE MIGRATION AT THE BLACK SLOUGH STUDY SITE. SEE FIGURE 2 FOR LOCATION OF CROSS SECTION.

GEOLOGY

The study site is located within the central lowlands physiographic province just north of the Missouri Coteau Escarpment. The lowlands province is a gently undulating glaciated plain of low relief (Fig. 4) (Armstrong, 1971).

The surface of the study area is underlain by Pleistocene sediments. These sediments thicken from 20 feet (6.1m) in the northeast corner of the study area to 70 feet (21.3 m) in the southwestern corner (Fig. 5). The uppermost Pleistocene sediments are comprised of from 2 to 10 feet (0.61 - 3.0 m) of lacusterine clay. In the western portion of the study area the Pleistocene sediments beneath the lacusterine clay are mostly sand and gravel outwash. To the north and east, these sediments become a pebbly till. The injection well site is located upon the northwest - southeast trending contact of the till and outwash and contains interfinering lenses of both (Fig. 5).

The Pleistocene deposits are underlain by Paleocene sediments of terrestrial origin. These sediments are comprised of alternating sands, silts, clays, and lignites. Five lignites occur within 200 feet (61 m) of the surface. For ease of discussion, they have been arbitrarily named A, B, C, D, and E in descending order from the surface. Only the D and E lignites are present throughout the study area. The top three lignites (A, B, and C) have been removed by glaciation in the southern and western portions of the study area (Fig. 5). The D and E lignites are separated by a medium - to fine grained 50-60 foot (15.2-18.3 m) sandstone.

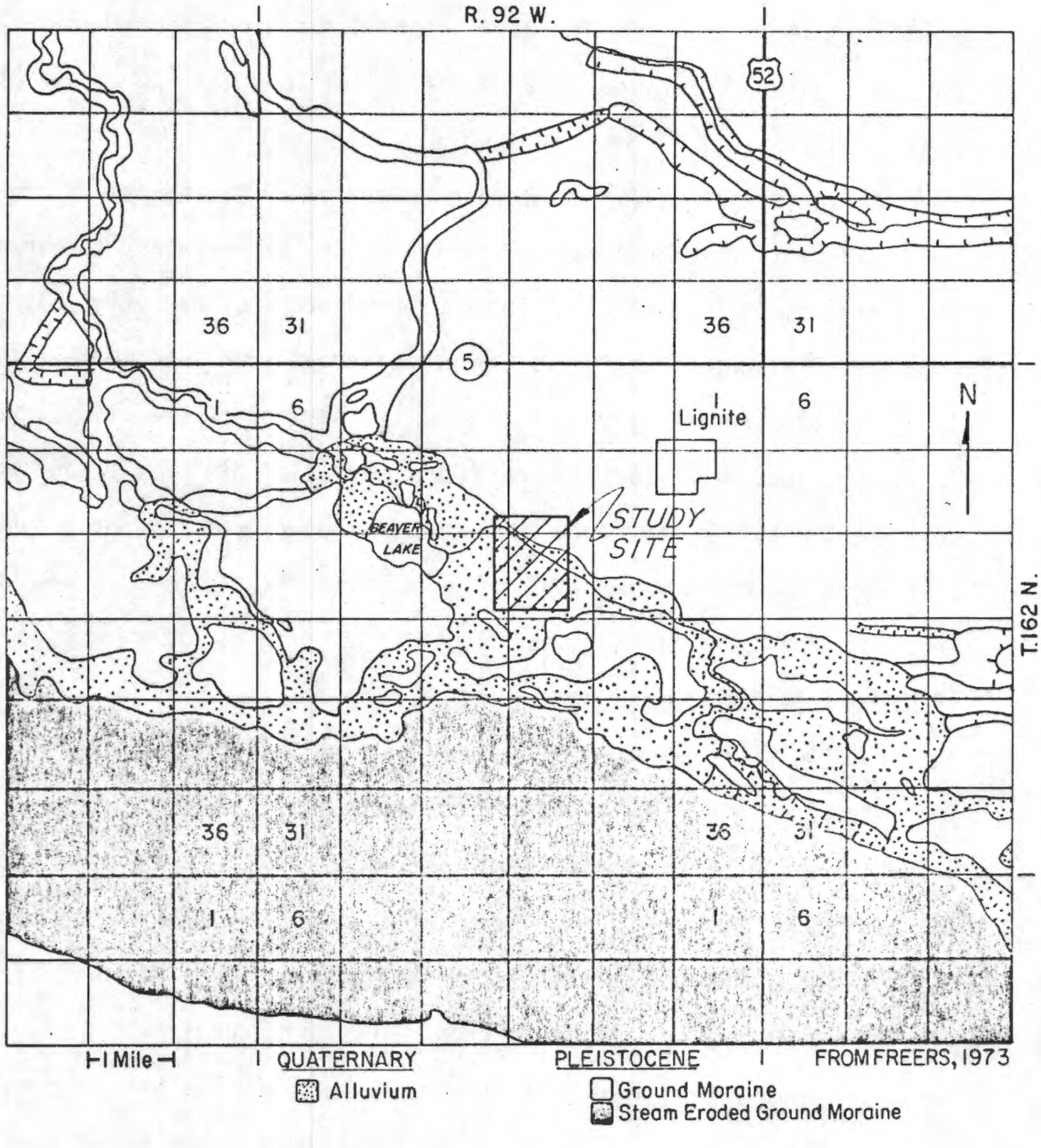


FIGURE 4 - THE SURFACE GEOLOGIC MAP OF CENTRAL BURKE COUNTY INCLUDING THE STUDY SITE.

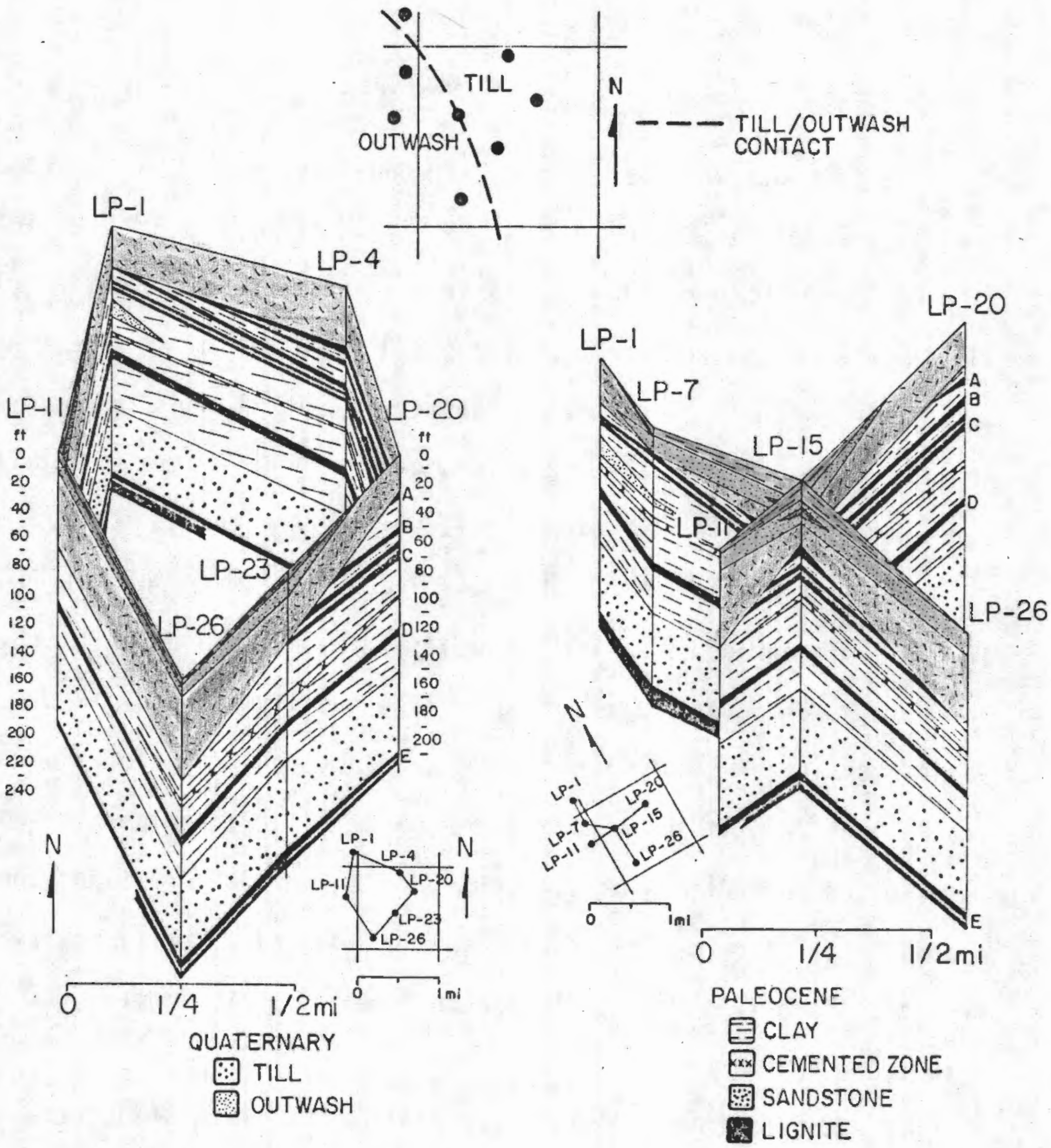


FIGURE 5 - GEOLOGIC FENCE DIAGRAMS OF THE STUDY SITE.

GEOHYDROLOGY

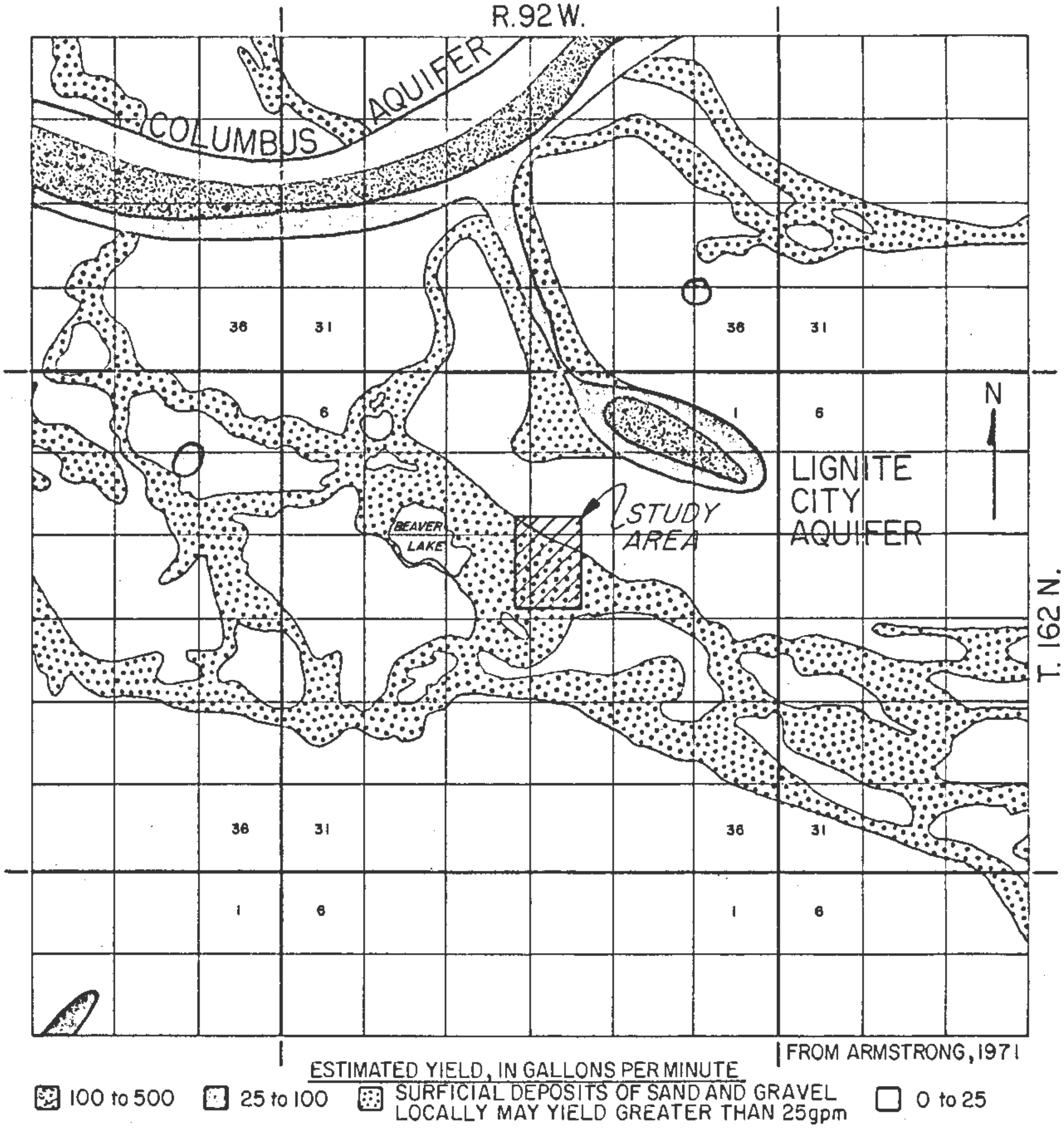
The Columbus and the Lignite City Aquifers, two of the three major shallow aquifers in Burke County, lie within five miles of the study site (Fig. 6). The Columbus Aquifer is an east-west trending, buried glaciofluvial channel which locally exceeds 400 feet (122 m) in thickness. The Lignite City Aquifer is a small tributary buried channel to the Columbus Aquifer. The water in these aquifers generally is a calcium-bicarbonate type and can contain high amounts of sulfate (Armstrong, 1971).

The surficial outwash and alluvial deposits cover much of Burke County (Fig. 6). These deposits are generally thin, but can be of local importance for both domestic and livestock use. The quality of water in these deposits varies considerably with topographic position and drainage. The topographically high deposits have good quality water (i.e., sodium-bicarbonate type with TDS concentrations of approximately 800 mg/L). The topographically low deposits have poor drainage and a poor quality of water (i.e., typically a sodium sulfate type with TDS concentrations of approximately 2000 mg/L) (Armstrong, 1971).

In addition to the Pleistocene aquifers, numerous Paleocene sand and lignite aquifers are also being used locally by farmsteads (Armstrong, 1969).

The Fox Hills Formation is one of the most extensive fresh water aquifers in western North Dakota. However, only one well was completed in the Fox Hills Formation in Burke County by 1971 (Armstrong, 1971).

Throughout most of the Black Slough study area the watertable is at or within five feet (1.5 m) of the surface. Groundwater flow is to the south-



FROM ARMSTRONG, 1971

FIGURE 6 - MAJOR PLEISTOCENE AQUIFERS IN CENTRAL BURKE COUNTY.

southwest with a water-table gradient of 2×10^{-3} ft/ft (6×10^{-4} m/m) (Fig. 7).

Water levels were taken during December 1984 and June 1985 (Appendix 4-1B). The results were generally inconclusive in regards to the vertical component of flow. The comparison of hydraulic head values in some piezometer nests indicated a downward gradient, an upward gradient, and in others, the head values were too variable to indicate either condition.

Previous work in west-central North Dakota has shown that these slough networks generally act as recharge areas (Rehm et al., 1982). Recent work by Williams (1984) demonstrated that these areas can act as recharge areas in the spring and discharge areas in the late summer and fall. The fluctuating head values may be a result of this transition from one flow condition to the other. These values may also be reflecting the influence from the Missouri Coteau to the south.

The local shallow (200 feet (61 m) or less) aquifers beneath the study site consist of Pleistocene outwash in the southwest portion of the area, the five lignites (A-E) and the thick bedrock sandstone between lignites D and E.

Hydraulic conductivity values have been established for the major sediments within the Bullion Creek and Sentinel Butte Formations in western North Dakota. Groenewold et al., (1979) determined the following ranges in hydraulic conductivity values for sand (2×10^{-5} to 2×10^{-7} m/s) and lignite (3×10^{-5} to 1×10^{-8} m/s). The porosity of lignite is due to fracturing and parting along bedding planes.

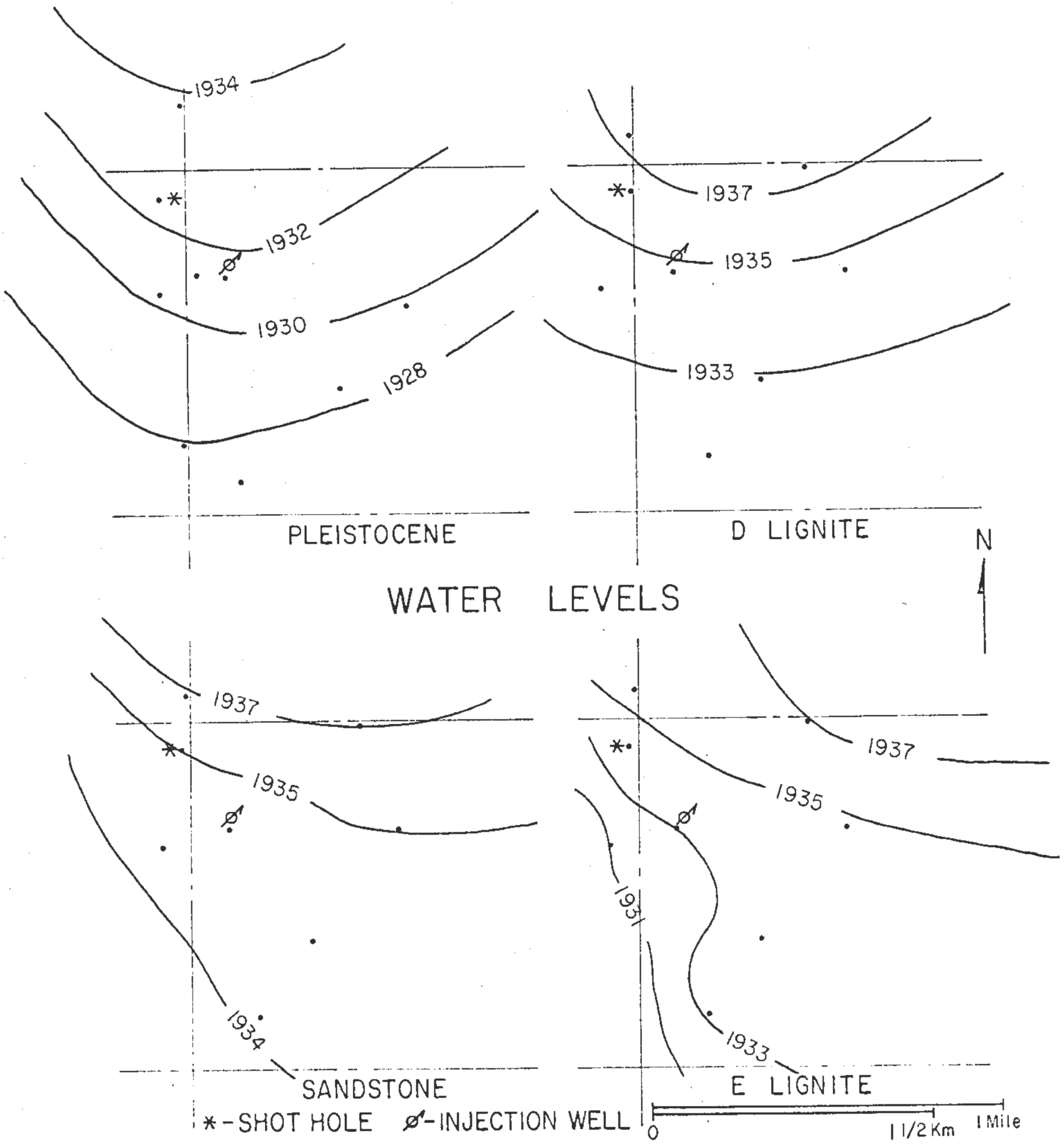


FIGURE 7 - GROUNDWATER TABLE MAP AND POTENTIOMETRIC SURFACE MAPS FOR THE FOUR INSTRUMENTED INTERVALS. READINGS WERE TAKEN IN JUNE, 1985. THESE MAPS INDICATE A LATERAL COMPONENT OF FLOW TO THE SOUTH SOUTHWEST IN ALL OF THE INTERVALS.

FIELD METHODS

The initial drilling program took place during July of 1984. The volume of salt water that flowed from the shot hole indicated that the zone or zones of brine migration were very permeable (20-40 acre/feet per day (162-324 hectare/metres per day)) (Dufty, 1984). The landowner and state officials concurred that the shot hole had been drilled to a depth of 200 feet (61 m). Therefore, the drilling program concentrated on the relatively permeable zones within this 200-foot (61 m) interval.

The initial hole (L-15) was drilled to a depth of 240 feet (73 m) on the injection-well pad. The major permeable zones included five lignites and the 50- to 60-foot-thick (15-18 m) sandstone between lignites D and E. The sandstone and two of the lignites (D and E) were screened at seven nests in a 1/4- to 1/2-mile (0.4 -0.8 km) radius around the injection well (Figs. 8 and 9). Screens were placed in both the top and base of the sandstone to enable determination of a fresh water/brine interface if one was present. Shallow water-table wells were also installed at four of the nests. The holes were drilled using either air, fresh water, or a fresh water/bentonite drilling mud system (Appendix 4-1C). To minimize the effects of a bore-hole mud filtrate, the piezometers were back-flushed for 1/2 hours prior to cementation.

The deepest hole at each of the 8 piezometers nests was geophysically logged by the North Dakota Geological Survey (Appendix 4-1D and 4-1E). The log suite was examined at each nest to determine lithologic boundaries for proper piezometer placement. The resistivity logs were carefully scrutinized for zones of extremely low resistivity that would indicate brine.

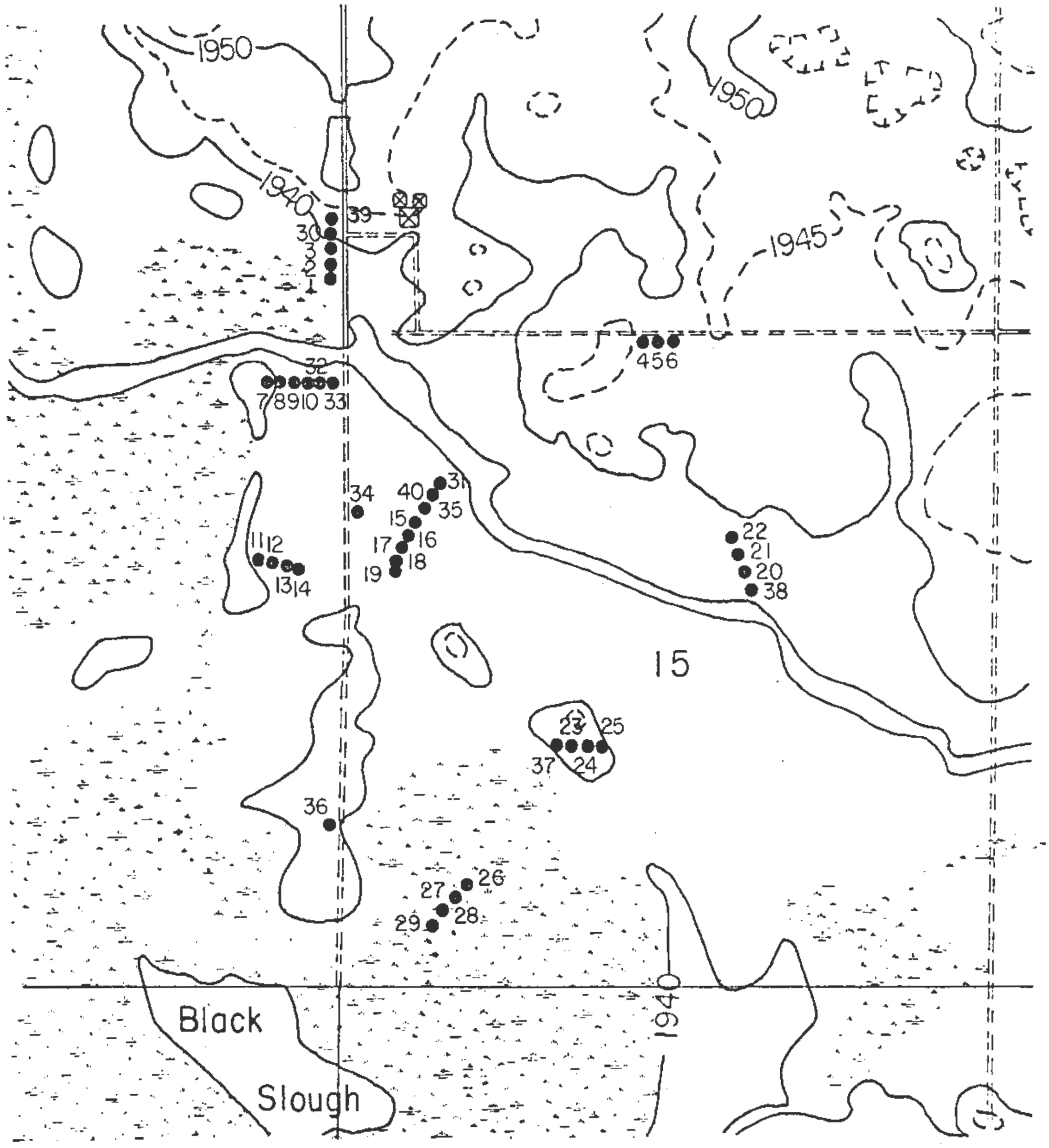


FIGURE 8 - THE LOCATION OF PIEZOMETERS WITHIN THE STUDY AREA.

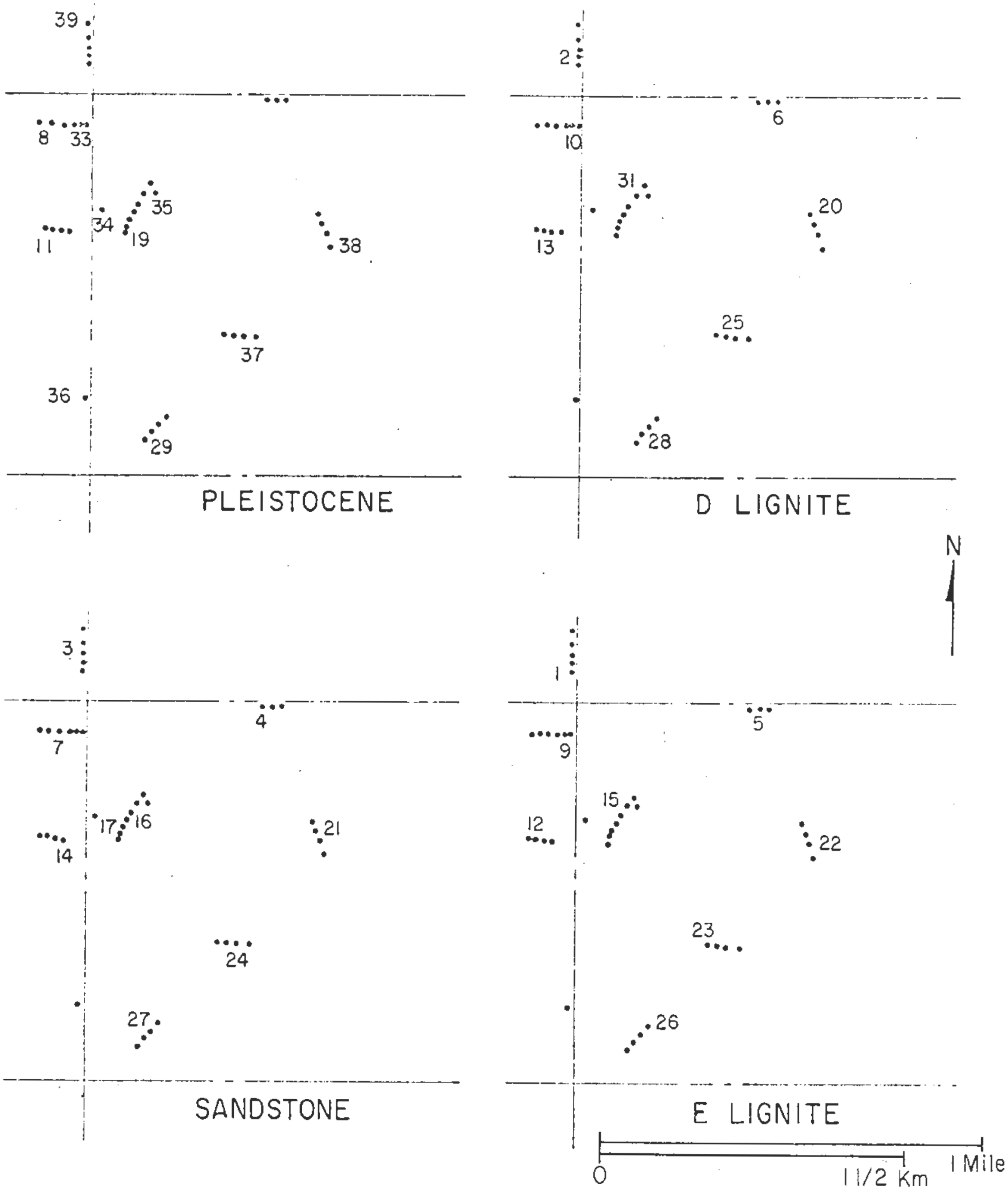


FIGURE 9 - PIEZOMETER NESTS AND IDENTIFICATION NUMBER OF PIEZOMETERS SCREEN IN EACH OF THE FOUR INTERVALS.

A thick, white precipitate developed on the cuttings as they came out of the drill holes at the injection-well site. Crude oil (in excess of 1 foot (0.3 m)) was found in the annulus of piezometers L-15, L-16, and L-17 as they stood open for a day prior to cementation (they are screened in the sandstone and the E lignite). No crude oil was found in L-18, which is screened in the A lignite, indicating that the oil was leaking from below this horizon. At the time, we speculated that it was coming from either the D lignite or the sandstone.

During the rotary drilling program, 4300 feet (1310 m) were drilled and 30 piezometers were installed. Throughout the study area, the water table was found to be at or near the surface. Because of this, access by vehicles was strictly limited to the section trails and the lease roads into existing or abandoned locations. Therefore, five of the eight piezometer nests were placed on oil pads.

Temperature, pH, and electrical conductivity of the water samples were determined in the field at the time of sample collection. Prior to sample collection, the piezometers were bailed dry two times. The water samples were filtered through a series of prefilters and ultimately through 0.45-micron filters, placed in plastic quart (0.946 litre) and pint (473 ml) bottles, and packed in ice during transport to the lab. The water samples in the pint (473 ml) bottles were analyzed for trace-metal content. Five milliliters of concentrated nitric acid were added to the trace-metal samples after filtering to prevent precipitation. All water samples were analyzed by the Chemistry Department Lab at North Dakota State University in Fargo.

Water samples were collected on December 4, 1984, and June 25, 1985. The first set of samples was analyzed only for majors and the second set was analyzed for both trace-metal and major-ion content.

The field conductivity values of the groundwater samples taken in December were low, suggesting that none of the piezometers were screened in the interval containing the brine. One possible explanation for the low conductivities was that the piezometers had not been properly developed and that the samples were actually pore water that had been injected during the rotary drilling program. Therefore, in January of 1985, 600 gallons (2271L) of water was pumped from two piezometers (L-16 and L-17). Continuous conductivity readings and additional chemical samples (16A and 17A) were taken at this time. The conductivity values remained stable during the 3-hour test period. This eliminated injection water as a factor and it was concluded that the December water-sample analyses were representative of the screened interval.

Additional water samples were taken from a dozen selected piezometers during January of 1985 and analyzed by the North Dakota State Department of Health for their oil and grease content.

In May of 1985, additional holes were augered with the North Dakota Geological Survey 8-inch (20.3 cm) Mobile B-50 Truck-mounted auger. The clay cuttings from a depth of 100-118 feet (33.5-36 m) contained varying amounts of crude oil at the injection well site. Oil appeared to be concentrated along fractures or lenses in the clay. However, there was no indication in the cuttings that the clay contained any sand or silt lenses. Shelby tubes could not be obtained from this interval. A piezometer (L-40) was placed at this horizon and two other piezometers were placed at this same stratigraphic horizon adjacent to the shot hole (L-32) and next to the Amundsen farm (L-30) (Fig. 8).

During the augering program, a strong salty taste was detected on both the Pleistocene outwash and till sediments. Seven additional piezometers were installed within this interval. This brought the total number of piezometers installed during this project to 40 (Figs. 8 and 9).

In addition, fifty feet (15.2 m) of shelby tube samples were taken through the Pleistocene and into the Paleocene sediments at the injection-well site.

RESULTS

A total of 68 individual water samples from the study site were analyzed by the Chemistry lab at North Dakota State University. Thirty-eight of these were analyzed for both trace-metal and major-ion content. The water sample analyses are listed in Appendix 4-1F.

Isoconcentration maps for 15 parameters are presented in Appendix 4-1G. The values plotted are the means of the major-ion concentrations for the two sampling periods and the values for the trace metals are from the summer sampling. Isoconcentration maps are presented for each of the four main monitoring horizons. These maps represent data from 36 of the 40 piezometers at this site.

Pleistocene Interval

The values for most of the parameters reached their highest concentrations in the Pleistocene interval. Within this interval, values were generally highest in the vicinity of the shot hole: TDS (66,000 mg/L), SO_4^{--} (40,000 mg/L), Na^+ (13,689 mg/L), Cr (4387 µg/L), and Pb (857 µg/L). Values were also high at the injection well and in piezometer L-29 near the southern border of the study area. The chloride-ion concentration in water from the Pleistocene sediments was above the normal background levels in most of the piezometers, but far below that of a brine.

D Lignite Interval

The quality of the water in the D Lignite zone was much better than in the Pleistocene interval. The highest concentrations in this zone were found beneath the injection well site: TDS (18,000 mg/L), SO_4^{--} (6390 mg/L), Na^+ (4936 mg/L) and Cr (353 µg/L). Values were also high in piezometer L-28 near the southern border of the study area. The chloride ion reached a concentration of 3600 mg/L at the injection well site but all the other readings at this horizon were only moderately elevated above the normal background levels.

Sandstone Interval

The isoconcentration maps for this horizon do not display any consistent observable pattern. The major-ion concentrations are normal or near normal in comparison to the average groundwater chemistry generally found in Paleocene bedrock: TDS (2700 mg/L), SO_4^{--} (740 mg/L) and Na^+ (1022 mg/L). The trace-metal content was lower in this unit than the Pleistocene or D Lignite, but was still above normal with highs of: Cr (48 μg/L), Pb (545 μg/L), and Cu (426 μg/L). The chloride ion reached a maximum concentration of 270 mg/L beneath the injection well at this horizon. The chloride levels in all of the other piezometers were above background and were slightly higher than those in the D Lignite.

E Lignite Interval

The isoconcentration maps for this horizon do not exhibit any consistent pattern. The major-ion concentrations are very similar to that of groundwater in the sandstone interval with highs of: TDS (3200 mg/L), SO_4^{--} (388 mg/L), and Na^+ (918 mg/L). This interval contains trace-metal concentrations that were the lowest of the four zones. These concentrations were normal for chromium (11 μg/L), but still high for lead (151 μg/L) and copper (504 μg/L). The chloride-ion levels were still higher than normal background levels but comparable to the other intervals. The highest chloride-ion concentration was 476 mg/L recorded near the Amundsen farm.

Additional Piezometers

All but 4 of the 40 piezometers installed at the study site were screened within one of the four major horizons. The four exceptions were piezometers L-18, L-30, L-32 and L-40. Piezometer L-18 was screened in the A lignite at the injection well site. The groundwater in this well contained high concentrations of TDS (7660 mg/L), SO_4^{--} (3878 mg/L), Na^+ (2320 mg/L), and Pb (400 μg/L). The chloride-ion concentration (443 mg/L) was high, but did not indicate the presence of brine.

The other three piezometers (L-30, L-32, and L-40) were all screened in a clay above the D lignite. Piezometer L-40 was installed at the injection well site, L-32 at the seismic shot hole site, and L-30 adjacent to the Amundsen farm. Piezometer L-40 contained crude oil and the poorest quality water sampled, with the following characteristics: TDS (19,970 mg/L), Cl^- (7334 mg/L), SO_4^- (4376 mg/L), Na^+ (6312 mg/L), Cr (314 μg/L), and Pb (826 μg/L). In comparison, water from piezometer L-32 was characterized as follows: TDS (43,900 mg/L), Cl^- (80 mg/L), SO_4^{--} (23,207 mg/L), Na^+ (9608 mg/L), Cr (1307 μg/L), and Pb (900 μg/L). Piezometer L-30 contained water of the following characteristics: TDS (11,830 mg/L), Cl^- (102 mg/L), SO_4^{--} (6700 mg/L), Na^+ (2903 mg/L), Cr (431 μg/L), and Pb (800 μg/L).

Oil and Grease

The following piezometers were analyzed by the North Dakota State Department of Health for their oil and grease content: L-7, L-8, L-9, L-10, L-11, L-14, L-15, L-16, L-17, L-19, L-25, and L-29. All of the samples contained less oil and grease than the 5 mg/L detectable limit.

DISCUSSION

Pleistocene Interval

The field conductivities from the Pleistocene interval indicated that this zone contained water with a very high TDS, initially suggesting the presence of brine. However, the chemical analyses revealed that the water within this zone was a sodium-sulfate and not the sodium-chloride type water that originally flowed from the seismic hole (Fig. 10). The groundwater within the Pleistocene sediments is of extremely poor quality due to the high Na^+ and SO_4^{--} content (Fig. 10).

Oil-produced brines in the Williston Basin contain high concentrations of many ions. The following table lists the high, low, and mean concentrations of selected ions in brine taken from oil wells in T162N, R92W:

	Cl^- (mg/L)	Na^+ (mg/L)	SO_4^{--} (mg/L)
High	200,940	123,539	3835
Low	49,320	28,693	470
Mean	150,716	82,877	1452

It is obvious from these data that the SO_4^{--} concentration is not sufficiently high in the brines to have been the source for the concentrations found within the Pleistocene interval at the study site. The absence of high chloride concentrations within this interval also strongly suggests no relationship to the injection well (Fig. 10). The chloride ion is very mobile in an aqueous system. It is typically not attenuated by clay or organic complexes because of its negative charge and large ionic radius. Therefore, it is highly unlikely that the chloride ion could have been removed from the brine if it had been injected into the Pleistocene interval.

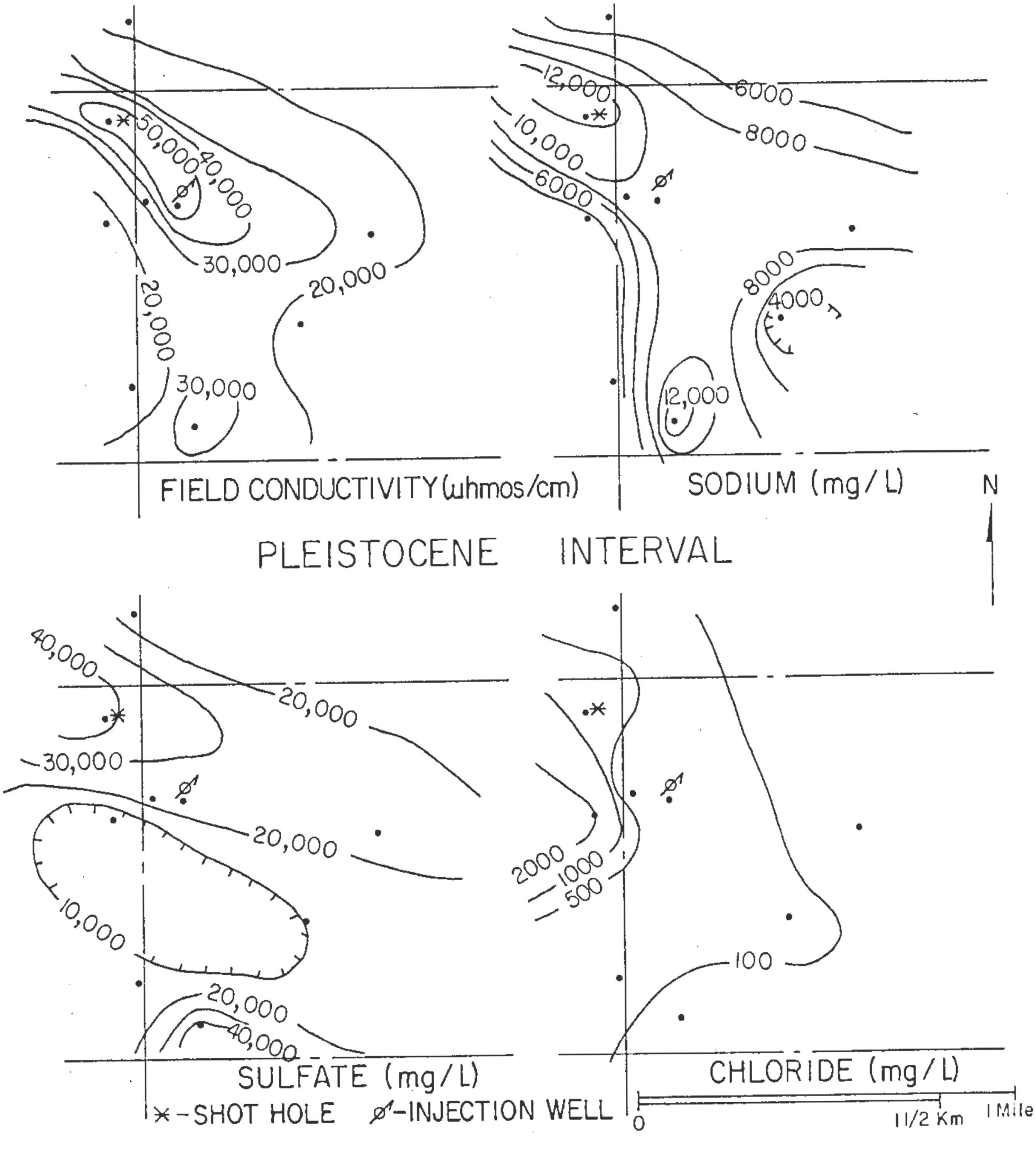


FIGURE 10 - ISOCONCENTRATION MAPS FOR FIELD CONDUCTIVITY, Na$^+$, SO$_4^{-2}$, and Cl$^-$ WITHIN THE PLEISTOCENE INTERVAL.

Grossman (1949) documented high concentrations of sodium-sulfate salts in closed basin lakes in northwestern North Dakota. He collected 14 water samples from selected lakes in this area with the following results:

	Cl^- (ppm)	Na^+ (ppm)	SO_4^{--} (ppm)
High	3905	49,931	124,309
Low	58	652	2,635
Mean	1177	25,303	48,202

Considering Grossman's data, the high sodium-sulfate concentrations within the Pleistocene interval at the study site appear to be natural. This chemistry results from the evaporation of surface water and shallow groundwater and the resulting concentration of these ions in the shallow groundwater beneath the sloughs. Grossman's data also may explain the elevated chloride concentrations that are found in this interval. A similar hypothesis was proposed by Wallick (1981) for a saline lake in Alberta located in a groundwater discharge area. Sodium-sulfate type water at the Alberta site has been attributed to evaporative concentration of groundwater discharging into the lake.

The trace-metal concentrations are exceedingly high within the Pleistocene interval. These concentrations exceed the maximum permissible drinking water standards set for lead (50 µg/L), copper (1000 µg/L), and chromium (50 µg/L) (Fig. 11). Four plausible explanations are possible for these high concentrations: 1) The trace metal concentrations may be natural and the result of leaching of till with a high trace-metal content; 2) As previously mentioned, vehicle access was severely limited within the field area. As a result, five of the nine piezometers screened within this interval are situated adjacent to oil wells. The trace metals may be leaching out of the buried drilling fluid at these sites. Previous work has demonstrated that this will occur (Murphy and Kehew, 1984). The trace-metal concentrations

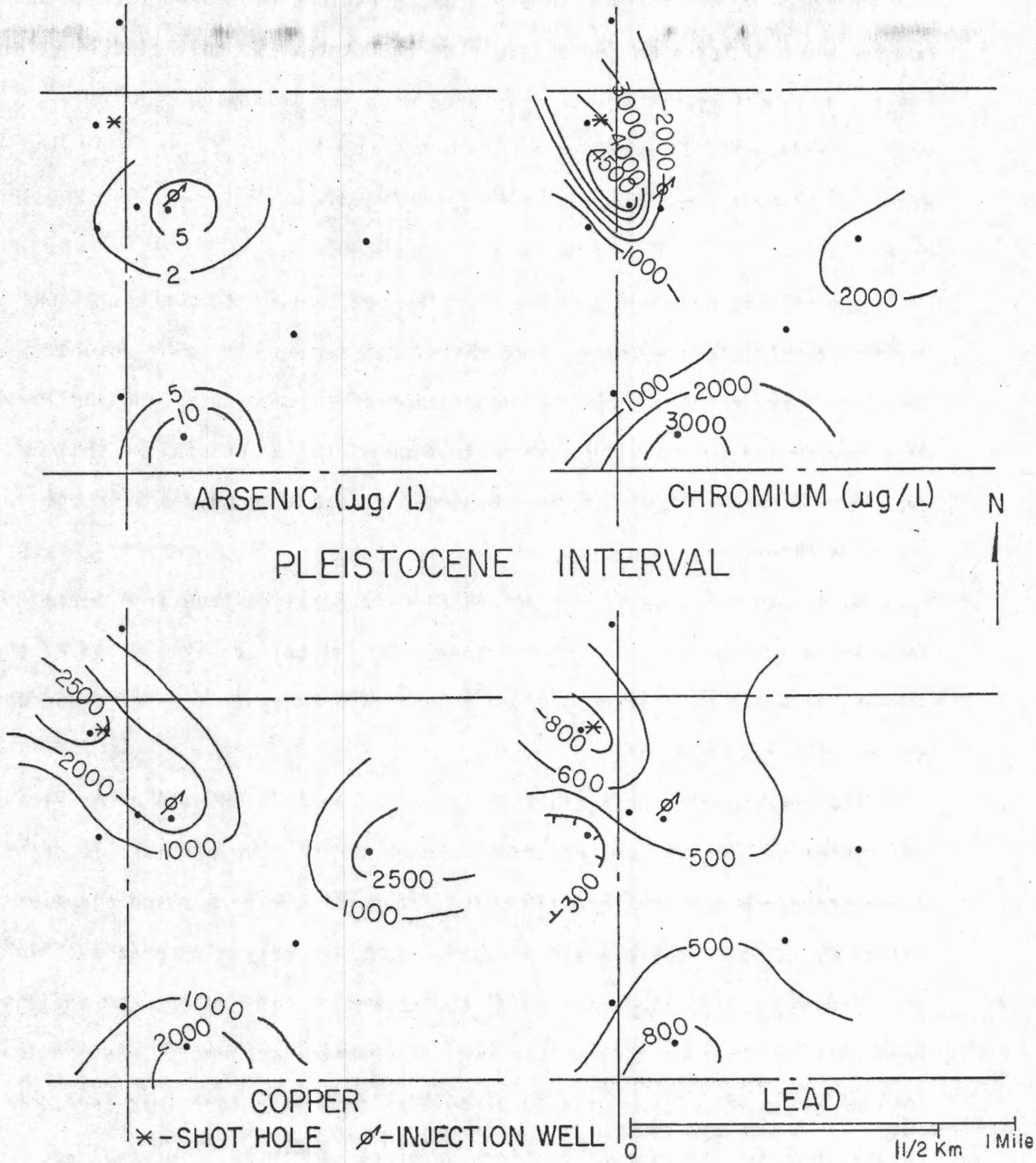


FIGURE 11 - ISOCONCENTRATION MAPS FOR As, Cr, Cu, AND Pb WITHIN THE PLEISTOCENE INTERVAL.

are generally highest in the vicinity of the existing or abandoned oil wells, the exception being the area beneath the seismic shot hole (Fig. 11). The drilling muds used in the Williston Basin are generally salt-water based; i.e., they contain approximately 300,000 mg/L of NaCl. High concentrations of chloride should also be found leaching from the drilling fluid at these sites. However, of the five piezometers adjacent to a well site, only L-11 had a high chloride ion content; 3) Trace metals could be concentrated by evaporation in a manner similar to major ions. In addition, adsorption of the metals would be decreased by complexation with sulfate or chloride at the high concentrations present. This effect has been described by Langmuir and Mahoney (1984); 4) The trace-metal analyses from the lab may be incorrect.

At first analysis, the Pleistocene outwash appeared to be the logical zone through which the brine had migrated to the seismic shot hole. The source was either the leaking injection well directly, or indirectly through one of the two abandoned wells nearby. The sand and gravel in this zone probably have a higher hydraulic conductivity than either the lignites or the bedrock sandstone, and the amount of brine that was reported to have flowed from the seismic hold would require a zone of high permeability. The overlying 2- to 10-foot- (0.1- to 3.05- m) thick lacustrine clay is assumed to act as an upper confining layer and thus would prevent the pressurized brine from entering the slough unless this confining unit was penetrated, such as would happen when a seismic hole was drilled. The till below the outwash would likely act as a lower confining layer.

This scenario would also explain why the Amundsen farm well, screened in the B or C lignite, flowed fresh water at the surface. In the vicinity of the seismic shot hole, the till below the outwash thins to the point that the outwash rests upon the B lignite and most likely penetrates it because of glacial erosion prior to deposition (Fig. 5). The interconnection of the outwash and the B lignite therefore would have made it possible for the pressurized brine to push fresh water through the B lignite; i.e., a brine/fresh water interface existed and, if the injection well had not been shut in, the interface would have eventually reached the Amundsen farm and the well would have been impacted by the salt water.

However, this scenario has merit only if the stratigraphy and the hydraulic conductivity of the sediments is considered. The screens of piezometer L-8 and L-33 covered the entire outwash interval at the seismic shot hole site. The screens of piezometers L-19 and L-35 also covered the entire outwash interval at the injection well site. None of these piezometers recovered any groundwater sufficiently high in Cl^- to indicate that large-scale brine movement had occurred within this horizon (Fig. 16). If the brine was confined to a 1 foot (.305 m) layer within this screen interval and if the hydraulic conductivity was equal throughout the 10-foot (3.05-m) interval, there would be a 1:9 dilution. However, the zone that contains the brine would have a much higher hydraulic conductivity than the surrounding sediment (to account for its being confined) and therefore more water from this horizon would flow into the piezometer screen, thereby substantially reducing the ratio of fresh water to brine in the screen. Therefore, even taking into consideration moderate dilution of the brine in the piezometer screen, we would expect the chloride concentrations to be higher than those levels found.

The D Lignite, Sandstone, and E Lignite Intervals

The major-ion chemistry is very similar for groundwater within the D lignite, the sandstone, and E-lignite intervals. These values are within the normal range of concentrations found in shallow Paleocene aquifers in this region. The only exceptions are piezometers L-31 (at the injection well) and L-28 (at the abandoned well pad along the southern border of the study area). Crude oil and salt water were present in a Paleocene clay immediately above the D lignite in piezometer L-31. It is possible that the top of the piezometer screen extended beyond the top of the D lignite and into this zone. This seems plausible because the groundwater in the D lignite at the shot-hole site contains normal concentration levels. The elevated concentration levels at the L-28 piezometer appear to be local and result from the activity associated with the drilling of the oil well.

The trace-metal concentrations are generally high in all three of these intervals. Lead exceeds the maximum permissible concentration (mpc) throughout all of these intervals (Fig. 12). The lead concentrations render this water unfit for human consumption. Chromium exceeds the mpc throughout the central portion of the study area in the D lignite. The chromium concentrations are high in the sandstone but reduced to background levels within the E lignite (Fig. 12). Arsenic concentrations are low in all of the intervals.

The three possible explanations that are given for the high trace-metal concentrations within the Pleistocene sediments are applicable to these intervals. The concentrations of these metals decrease with depth from the surface. Therefore, the source appears to be within the Pleistocene interval.

Alternative Zones of Brine Migration

The following discussion lists three possible alternatives to explain why the seismic hole flowed brine and the Amundsen farm well flowed fresh water.

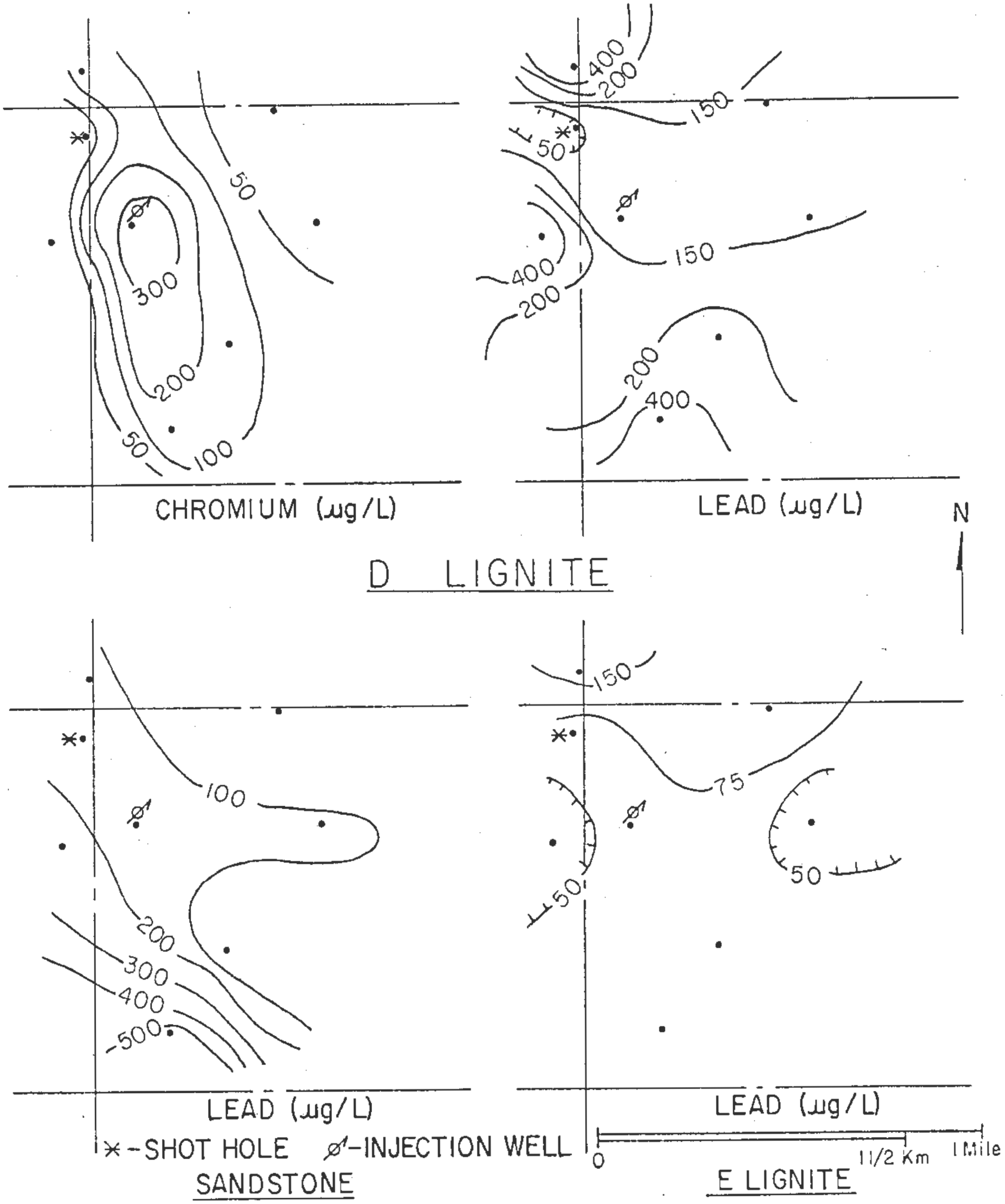


FIGURE 12 - ISOCONCENTRATION MAPS FOR Cr and Pb IN THE D LIGNITE INTERVAL AND Pb IN THE SANDSTONE AND E LIGNITE INTERVALS.

Alternative 1

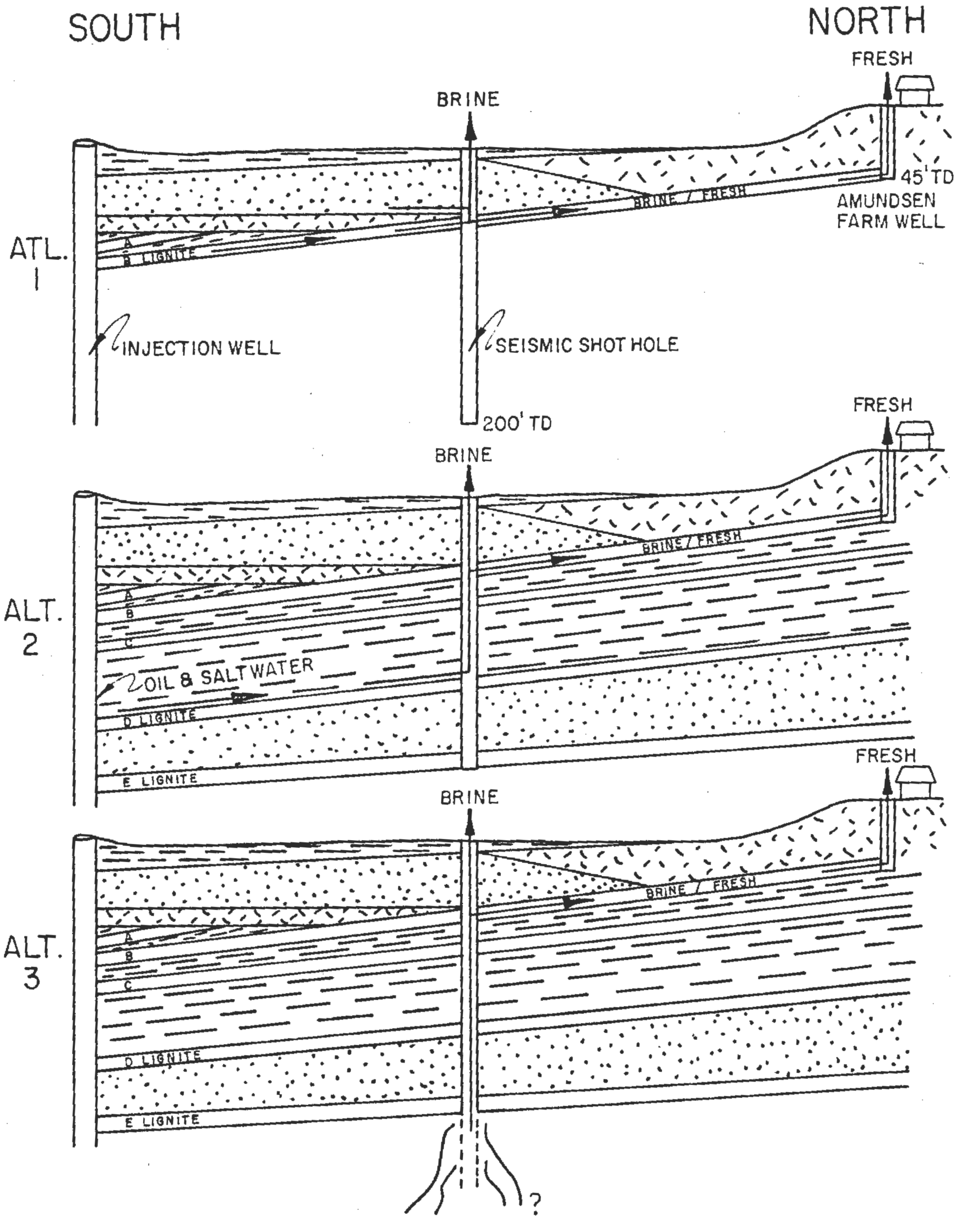
In this scenario, the brine flowed radially away from the injection well site through the B lignite. As it reached the seismic shot hole, a portion of it flowed vertically and the remainder created a brine-fresh water interface that flowed northward towards the Amundsen farm. The pressurized brine caused fresh water to flow at the Amundsen well, which is believed to be screened in this lignite. If the injection well had not been shut in, the interface would have eventually reached the Amundsen farm and the well would have flowed salt water (Fig. 13).

No piezometers were screened in the B lignite. The resistivity log from the injection well site showed a normal fresh-water kick for both the B and C lignites. A hole was augered to the base of the C lignite and the hole was left to stand open overnight. There was no indication of brine in the hole and so piezometers were not installed in either of these two lignites.

Alternative 2

In this alternative the oil and salt water that were found in piezometer L-40 are not an isolated incident, as suspected, but rather, are indicative of brine migration to the shot-hole site (Fig. 13). Brine could have migrated laterally along this horizon until it intercepted the poorly plugged seismic hole and then flowed vertically to the surface. A portion of the brine traveling through the shot hole could have traveled laterally through the B lignite thereby pressuring it and causing Amundsen's farm well to flow. Piezometer L-40 was flowing during October of this year, indicating that, for some reason, this zone is under pressure.

A piezometer with a 20-foot (6.1-m (L-32)) screen was placed at this same stratigraphic horizon at the seismic shot hole location. The screened



<u>FIGURE 13</u> - THREE POSSIBLE ALTERNATIVES TO EXPLAIN WHY THE SEISMIC HOLE FLOWED BRINE AND THE AMUNDSEN WELL FLOWED FRESH WATER.

interval coincided with a zone of low resistivity as indicated by the resistivity log (Fig. 16). The chloride concentration in groundwater from that piezometer was only 80 mg/L. Even taking into consideration that mixing of the brine with fresh water in such a thick screen may have occurred, the chloride concentration would not have been diluted to such a low level. Although it is possible that this screen was placed in an incorrect position at this site (relative to L-40), there are no other indications on the resistivity log of any other zones of low resistivity. In addition, sediment cuttings and the E logs from this horizon indicate it to be a Paleocene clay. Although this clay is possibly fractured, it does not appear to possess the hydraulic conductivity that would be required to transport the volume of brine that had flowed to the surface at this site. A very small amount of crude oil may remain in the brine after separation and during disposal. However, the large volume of crude found at this horizon seems to indicate that the leak may have occurred during the period that it was a producing oil well.

Alternative 3

The previous two alternatives each have some merit but are not favored because of contradictory evidence. However, they are the best alternatives within the 200-foot (61-m) thick zone of investigation. There is, however, one other alternative that deserves consideration. It is possible that the seismic hole may have been drilled deeper than the 200-foot (61-m) depth that was reported. If this is true, then the brine could have entered the seismic hole from a deeper horizon. Alternatively, the seismic charge may have created fractures that extend below the depth of the hole and into the zone that contains brine. Very little is known or understood about the effect of blasting and the extent of fracturing that may or may not develop in the surrounding sediment (Beaver, 1984). If fractures did develop beneath the base of the seismic hole, they would not be expected to extend vertically much more than 50 feet (15.2 m).

CONCLUSIONS

The following can be concluded from this study:

1. There are seven zones which may be sufficiently permeable to be aquifers within 200 feet (61 m) of the surface at this study site; Pleistocene outwash, five lignites, and a Paleocene sandstone.
2. The brine was not encountered in any of the four zones that were monitored; the Pleistocene outwash, the D and E lignites, and the bedrock sandstone.
3. Crude oil and brine were found in a Paleocene clay at a depth of 105-115 feet (32-35 m) at the injection well site. Crude oil and brine were not present at the seismic shot hole or at the Amundsen farm at this same stratigraphic horizon.
4. The Pleistocene outwash contains extremely high levels of sodium sulfate. These concentrations are assumed to be controlled by natural processes. These concentrations make the water unfit for humans, crop or livestock consumption.
5. Groundwater within the other three intervals (D lignite, sandstone, and E lignite) contain concentrations of major ions that are within the normal range for shallow Paleocene aquifers in this region.
6. The extremely high trace-metal (esp. Pb and Cr) concentrations occur in the groundwater in the Pleistocene, D lignite, sandstone, and E lignite zones. These concentrations make the water hazardous for human or livestock consumption (i.e., if the analyses are correct).
7. The source of the high trace-metal concentrations (if they are valid) is not readily apparent.

8. A strong possibility exists that the zone of brine migration is at a greater depth than the 200-foot (61-m) zone of investigation.

RECOMMENDATIONS

Although not identified in this study, the data suggest a zone of brine somewhere within the fresh water interval at the study site. The chemistry of this brine, which was determined by the North Dakota State Dept. of Health, indicates that its source was oil field related. Once the zone of brine migration is located, it could be instrumented in a radial pattern and the groundwater chemistry should enable determination of the ultimate source or sources of the brine contamination.

Any future studies that use rotary drilling to find zones of brine migration within a fresh water system should monitor the portable mud pit. Periodic samples of the mud should be taken and then subjected to either a field resistivity or chloride analyses.

The North Dakota Geological Survey is in the process of renovating an 8-inch (20.3cm) hollow stem truck-mounted to obtain auger Shelby-tube sediment cores down to a depth of 120 feet (36.5 m). Next spring we intend to return to the injection well site and take Shelby-tubes down to this maximum depth. The cores will be carefully scrutinized for any indications of the presence of brine. We will also install a piezometer in the B and C lignites at the injection well site.

If the augering project does not suggest any new hypotheses, we will solicit other state and federal agencies for funding to drill a 300- to 500-foot (91.4- to 152.3-m) deep hole at the seismic shot hole site. Once the zone of brine is identified, we will seek additional funding for a detailed monitoring project.

Half a dozen selected groundwater samples from this site will be collected and analyzed by the North Dakota State Dept. of Health to determine trace-metal concentrations. This will verify or disprove the values previously obtained. If the high trace-metal concentrations are verified, an attempt will be made to determine their source.

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TASK 4-2

MOVEMENT OF LEACHATE FROM A BURIED OIL AND GAS BRINE-DISPOSAL POND IN THE WYLIE FIELD, BOTTINEAU COUNTY, NORTH DAKOTA

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The North Dakota Geological Survey provided vehicle support, including a truck-mounted auger and a geophysical logging van. Mr. David O. Lechner determined textural analyses and Mr. Kenneth L. Dorsher drafted all of the diagrams; both are NDGS employees.

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ABSTRACT

The Edson Brown #1 was drilled by Cardinal Petroleum in 1959 and converted to a saltwater-disposal well in 1978. Two unlined ponds were used for holding and evaporation of brines produced with the oil and gas. These ponds measured approximately 100 x 90 feet (30.5 x 27.4 m) and 60 x 100 feet (18.3 x 30.5 m) with an average depth of 5 feet (1.5 m). The brine-evaporation ponds were in use from 1959 up to the late 1970's when they were filled and leveled. No records are available for the amount of saltwater that was disposed of in these ponds. However, disposal amounts ranged from one-half to 410 barrels per day in similar ponds. Brines in this field range in concentration from 19,000 to 250,000 mg/L of NaCl.

The pits are constructed upon 220 feet (67.1 m) of Pleistocene drift, which overlies the Cretaceous Fox Hills Formation. The drift consists of till with discontinuous sand lenses of varying thickness. The water table lies within 10 feet (3.05 m) of the land surface. Continued saltwater migration has decreased crop yields in surrounding fields and has killed trees in a shelterbelt within an area of approximately 10 acres.

Water quality instrumentation includes eight soil-water samplers in the unsaturated zone and 28 piezometers below the water table. Piezometers are nested with screened intervals at 30, 40, 80, and 160 feet (9.1, 12.2, 24.4, and 48.8 m). Nests extend up to 500 feet (152.4 m) from the evaporation ponds.

Earth resistivity surveys using the Wenner electrode configuration were conducted to delineate vertical and horizontal salt migration. Readings were taken at 14 successive electrode spacings ("a") of up to 100 feet (30.5

m). Sediment samples from 198 feet (60.4 m) of shelby-tube cores are being analyzed by x-ray fluorescence to obtain additional data on leachate migration.

The isoresistivity maps delineate a 360,000 ft^2 area of extremely low resistivity for all of the electrode spacings. The electrode spacing is generally believed to equal the depth of current penetration. However, at this site, the extremely low resistivity of the salt-saturated, near-surface sediments has probably resulted in the concentration of the current through this zone, thereby reducing the amount of current that penetrates below the pit bottoms.

Isoconcentration maps indicate that a highly saline leachate plume extends laterally in a 500-foot (15.24 m) radius around the pond and vertically to a depth of 70 feet (21.3 m) below the surface. This leachate is confined to the till aquitard and is not presently endangering a domestic water supply.

The low groundwater recharge rate at this site is due to the semi-arid climate and the low hydraulic conductivity of the near-surface sediments. Very little flushing of the brine at the study site has resulted in the porewater within the reclaimed ponds containing essentially the same ionic concentrations as that of brine disposal in these ponds 10 to 25 years ago.

This site will continue to generate brine leachate at slow rates for tens and possibly hundreds of years if no action is taken.

Three remedial actions have been suggested to decrease the amount of leachate that is spreading laterally at the surface and in the vadose zone at this site.

INTRODUCTION

Brines typically are produced along with crude oil at oil-well sites. These produced brines are recognized as the major source of potential environmental contamination associated with production (Knox and Canter, 1980). The issue of how to properly dispose of oil-field brines has been considered in the state of North Dakota since oil production first began in 1951. Fortunately, the state of North Dakota has benefited from the experience of earlier oil-producing states and avoided problems such as the direct dumping of brines into streams as occurred in Illinois in the 1930's (Reed et al., 1981).

Initially, saltwater at North Dakota drilling sites was primarily disposed of in evaporation ponds and injection wells. In 1963, the Interstate Oil Compact Commission determined that nationwide, 88 percent of the brine was being disposed of in the subsurface by injection wells and 12 percent was disposed of in surface evaporation ponds. These ponds were so named because it was believed that all of the saltwater in these brine-holding ponds evaporated. Evaporation ponds in North Dakota generally were unlined, although a small number did have either a soil or synthetic liner. The pits were variable in size and ranged from dimensions of 45 x 60 feet (13.7 x 18.3 m) up to 90 x 180 feet (27.4 x 54.9 m) with depths of 4 to 9 feet (1.2 to 2.7 m). They received anywhere from ½ to 420 barrels of saltwater a day.

The cumulative production of oil in North Dakota, during the period from 1951-1982, was 640,416,179 barrels. Saltwater production during this same period was 570,601,613 barrels. The ratio of crude oil-to-brine production varies significantly from well to well and will generally increase over the life of a given well. The overall cumulative production ratio of oil-to-brine in North Dakota is approximately 1:0.9.

In 1969, the North Dakota Geological Survey, then the regulatory agency responsible for oil and gas exploration, became concerned with brine-holding ponds and evaluated several of these facilities by obtaining groundwater samples adjacent to the ponds. As a direct result of this work, the North Dakota Geological Survey began, in 1969, to require a permit for all saltwater-handling facilities. During the period from 1969 to 1982, 707 permits were issued. The majority of these permits were for metal-settling tanks, while 206 were for evaporation ponds.

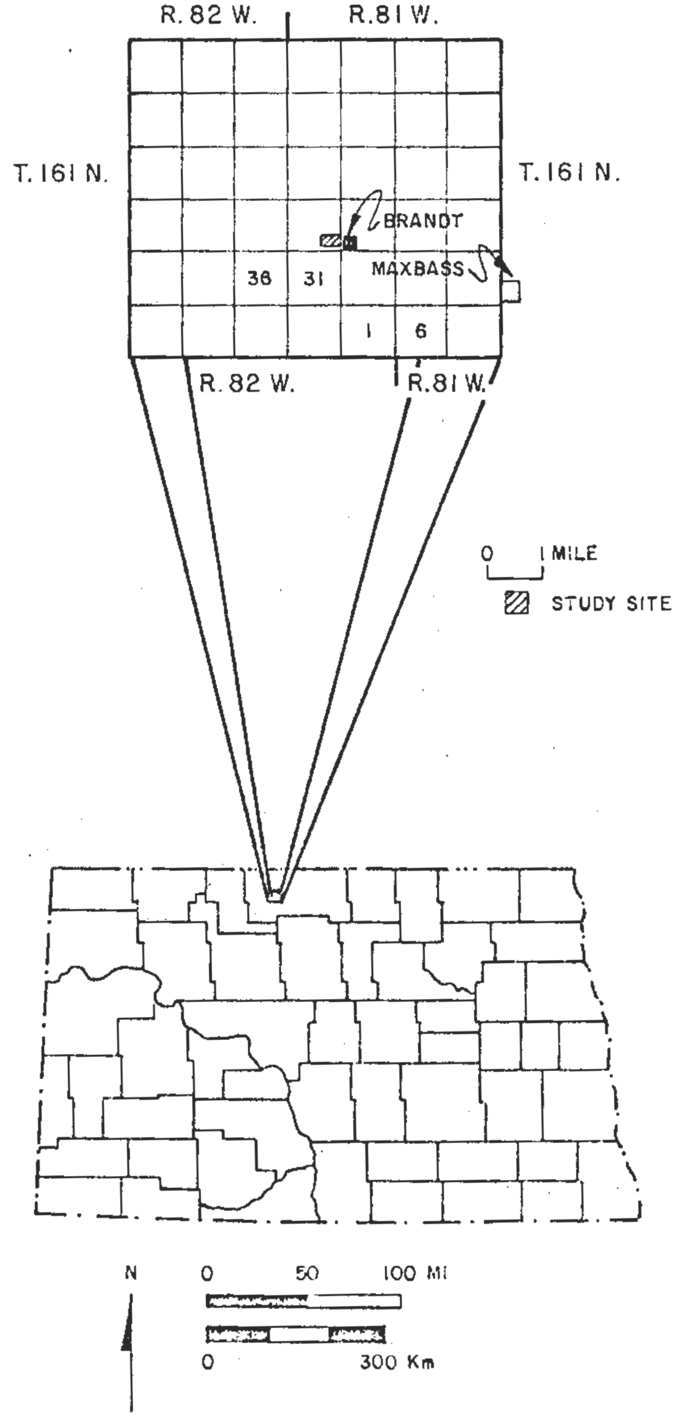
At this time, there are only two active brine-holding ponds in the state. Therefore, current environmental concern is no longer focused on active ponds, but rather, is now focused on abandoned brine-holding ponds. These abandoned ponds have been recognized as potential sources of soil and surface and subsurface water contamination. The salt that remains in the pond sites after evaporation of fluids can generate leachates at a rate dependent upon the local precipitation and the hydraulic conductivity of the near-surface sediments.

This study utilized a multidisciplinary research team from the North Dakota Geological Survey, the Department of Geology and Geological Engineering at the University of North Dakota, the North Dakota Mining and Mineral Resources Research Institute, the Land Reclamation Research Center at the North Dakota State University and the departments of Soils and Chemistry at North Dakota State University.

STUDY SITE

A reclaimed brine-holding pond site was chosen for study within the Wylie Field near the village of Maxbass in Bottineau County (Fig. 1). This site was chosen because of obvious salt damage to crops and a shelterbelt adjacent to the pond site. The site is located on land owned by North Dakota State University, which cooperated with this study and allowed access to the land.

The producing well at the site, the Edson Brown #1, was drilled by Cardinal Petroleum Co. in T161N R81W Sec 30 in 1959. It was plugged and abandoned in 1970 and converted to a saltwater disposal well (Stratton SWD #1) by Phillips Petroleum in 1978. Two brine-holding ponds were located at this site from 1959 through at least 1976 (Kallestad, pers. comm., 1985). The amount of brine that was disposed in these ponds during that 17-year period is not known.



#2318

FIGURE 1 - LOCATION OF STUDY SITE IN BOTTINEAU COUNTY.

PREVIOUS WORK

As one would expect, the earliest articles on oil-produced brine contamination come from the states with an early history of oil production. These states include Kansas, Kentucky, Ohio, and Alabama.

As early as 1932, it was recognized in Kansas that brine-holding facilities were causing serious environmental problems. During that year, the Kansas state legislature passed a law allowing the return of brines to the subsurface by injection to decrease the amount of brine disposed of at the surface (Grandone and Schmidt, 1943).

However, it is in the literature from the 1960's that the problems associated with surface brine-disposal became well documented. Many of these 1960 studies document the decline in water quality around producing oil fields (Shaw, 1963; Krieger and Hendrickson, 1960). A study of groundwater and surface waters in four Alabama oil fields during 1963 documented widespread brine pollution (Powell et al., 1973). As a direct result of this study, the Alabama Oil and Gas Board requested that the use of brine pits be discontinued (Powell et al., 1973).

A number of studies over the last twenty years have focused upon the rate of movement of the brine plumes, the length of time needed for the natural restoration of water quality to a degraded aquifer, and the cost effectiveness of different methods of disposal-site and aquifer reclamation (Boster, 1967; Pettyjohn, 1973; Fryloger, 1972; Baker and Brendecke, 1983).

In 1972, the North Dakota Geological Survey studied the hydrogeology of eight brine holding ponds in north-central North Dakota (Moran, 1972). This study reported the presence of brine in groundwater within permeable zones up to 75 feet (22.9 m) away from the brine pits. At most of the sites, chloride concentrations decreased by a factor of 10 after vertical migration through 5 to 10 feet (1.5 to 3.05 m) of silty clay sediments.

FIELD METHODS

An electrical earth resistivity survey, using the Wenner electrode configuration, was conducted at the Stratton SWD #1 site during June of 1984. The Wenner method utilizes four electrodes which are equally spaced along a line. The distance between adjacent electrodes, the electrode spacing, is designated as "a." The center of the electrode array is the point for which the data is obtained and has been designated in this report as the resistivity station. The Vertical Electrical Sounding method (VES) was used at this site. The VES method involves a fixed center of the electrode array (resistivity station) and expansion of the electrodes about this point. Thirty-six resistivity stations were surveyed in and adjacent to the brine pits (Fig. 2). Readings were taken at successive electrode spacings ("a") of 3, 5, 8, 10, 12, 16, 20, 24, 30, 40, 50, 60, 80, and 100 feet (0.9, 1.5, 2.4, 3.1, 3.7, 4.9, 6.1, 7.3, 9.1, 12.2, 15.2, 18.3, 24.4, and 30.5 m). The results of the earth resistivity survey were used to determine the optimum placement of piezometers and lysimeters.

During July of 1984, a Gardner Denver rotary rig was used to drill holes to provide geologic and geohydrologic data as well as to enable installation of piezometers at the study site. A total of 2100 feet (640 m) was drilled at this site.

Shelby-tube sediment samples were taken using the North Dakota Geological Survey's truck-mounted, hollow-stem 8-inch auger. These 2.5-foot (0.762 m) by 3-inch (7.62 cm) sediment cores provided detailed lithologic information and relatively undisturbed samples for textural analysis and laboratory chemical analyses. A total of 198 feet (60.4 m) of Shelby-tube

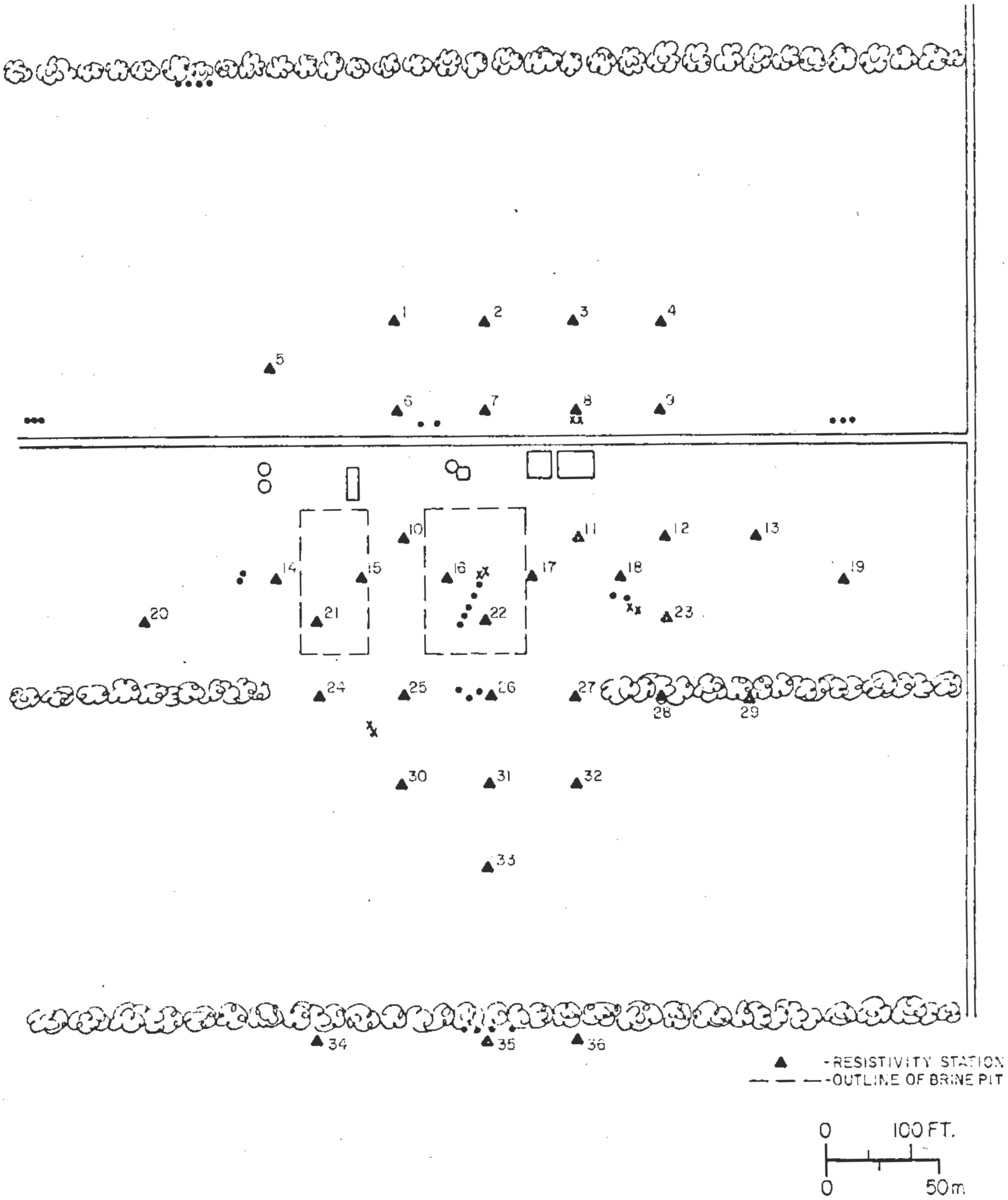


FIGURE 2 - LOCATION OF EARTH RESISTIVITY SURVEY STATIONS.

sediment cores was retrieved from 10 holes drilled within and adjacent to the brine ponds (Fig. 3). The maximum coring depth reached was 32.5 feet (9.9 m). Cores were sealed and frozen in the tubes. They were extruded during late 1984 and stored in waxed boxes (Appendix 4-2A).

Pressure-vacuum lysimeters (soil water samplers) (Soil Moisture Equipment Corp. Model 1920) were used to obtain water samples from the unsaturated zone. The soil-water samplers were 3 inches (7.6 cm) in diameter and 25 inches (0.64 m) in length. A 2-inch (5.08 cm) ceramic cup, attached to the bottom of the PVC body, forms the membrane through which vadose-zone water is drawn into the device.

The annulus between the ceramic cup and the edge of the bore hole was filled with silica flour to prevent the clogging of the 1.0-micron-diameter ceramic pores. A 1-foot (30.5 cm) bentonite plug was placed above this interval to prevent percolation of water down through the backfilled bore hole. Tubes were run to the surface to enable the application of a vacuum and collection of the water sample at the surface. Eight soil-water samplers were placed within and adjacent to the brine pits. These were installed in four pairs positioned at depths of 4 and 9 feet (1.2 and 2.7 m) (Fig. 3).

Piezometers were installed to provide water samples from within the zone of saturation. The piezometers were also used to determine the elevation and gradient of the water table, and to enable slug tests to be performed for estimation of the hydraulic conductivity of the sediment adjacent to the screened interval. The piezometers consisted of 2-inch (5.08 cm) diameter, schedule 40 PVC bottomed with 5-foot (1.52 m) preslotted 0.02-inch (5.1 mm) PVC screens. A washed gravel pack was placed around each screen and the holes were sealed with cement. A total of 28 piezometers

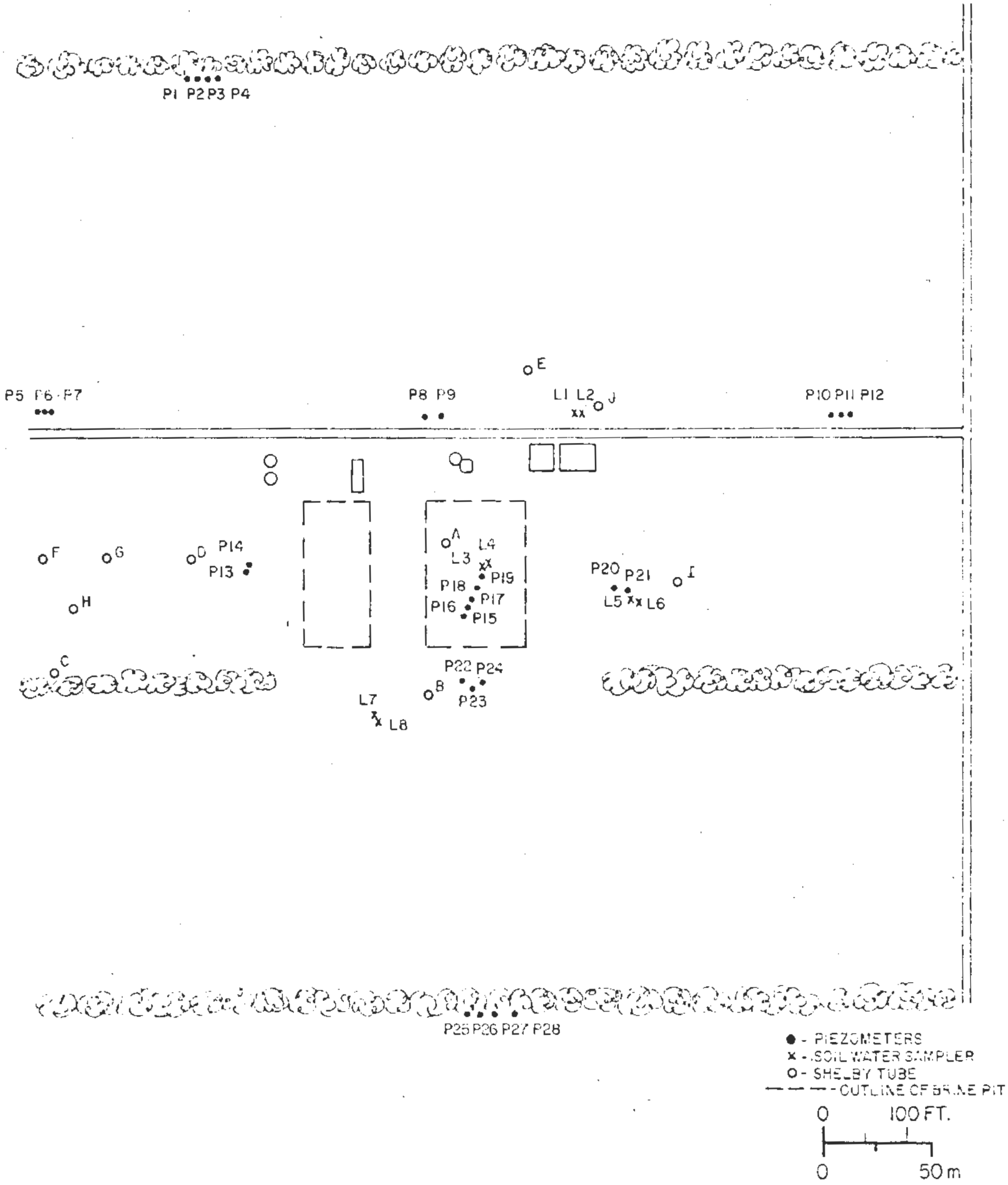


FIGURE 3 - LOCATIONS OF POREWATER AND GROUNDWATER SAMPLING EQUIPMENT AND SHELBY-TUBE HOLES AT THE STUDY SITE.

were placed within and adjacent to the brine ponds (Fig. 3). These piezometers were screened within four general zones: immediately below the water table at depths less than 40 feet (12.2 m), between 40-55 feet (12.2-16.8 m), between 70-80 feet (21.3-24.4 m), and at 160 feet (48.8 m) (Appendix 4-2B). Only one hole (P19) was drilled through the Pleistocene drift and into the underlying Fox Hills Formation. This piezometer was screened at 220 feet (67.1 m).

The deeper holes were geophysically logged by the North Dakota Geological Survey. These logs enabled the detection of lithologic boundaries and the proper placement of piezometer screens (Appendix 4-2C).

Because the brine pits are surrounded by cropland, piezometers were placed as to not inconvenience the farmer anymore than was absolutely necessary (Fig. 3). Where possible, rotary-rig test holes were drilled with air. When this proved difficult, fresh water was used and, where necessary, a bentonite mud system was used (Appendix 4-2D). All piezometers were backwashed with fresh water, injected by the drill rig pumps, until they flowed relatively clear water to minimize the effects of the drilling mud (approximately 20 minutes) .

Water samples were collected on December 9, 1984, and June 12, 1985. The first set of samples was analyzed for both trace-metal and major-ion content and the second set was analyzed only for majors.

Temperature, pH, and electrical conductivity of the water samples were determined in the field at the time of sample collection. The water samples were filtered through a series of prefilters and ultimately through 0.45-micron filters, placed in plastic quart (0.946 litre) and pint (473 ml) bottles, and were packed in ice during transport to the lab. The water samples in the pint (473 ml) bottles were analyzed for trace-metal content.

Five millilitres of concentrated nitric acid were added to these samples after filtering to prevent the trace metals from precipitating out of the solution. All water samples were analyzed by a chemistry lab at North Dakota State University in Fargo.

The site was surveyed with plane table and alidade to construct a base map and to obtain accurate elevation control for the monitoring equipment.

Hydraulic conductivity for sediment in the zone of saturation was determined directly by field tests. Single-well response tests (Hvorslev, 1951) were used to determine the hydraulic conductivity of the sediment adjacent to the screened interval. This test is conducted by displacing the hydraulic head (water level) and measuring the time required for it to return to equilibrium. In this study, a slug is used to raise the water level in a 2-inch (5 cm) PVC pipe 3.3 feet (1.0 m). Upon insertion of the slug, the time was recorded for the water level to return to its original equilibrium level (falling head test). The time was also recorded for the water level to return to equilibrium when the slug was withdrawn (rising head test). Hydraulic conductivities were determined for the tested intervals by analysis of these data using techniques developed by Hvorslev (1951). A step-by-step discussion of single-well response test methods and procedures is provided in Groenewold et al., (1979).

LABORATORY METHODS

The groundwater and pore-water chemistry were determined by the Chemistry Department Laboratory at North Dakota State University. Trace metals were analyzed using a graphite furnace on a Perkin-Elmer 603 atomic absorption unit. The method of standard addition was used on these metals with the exception of arsenic, which was analyzed by generating the hydride and trapping it in a Kl_3 solution prior to injection into the graphite furnace. Because of the uniformity of the matrix a standard curve was used for arsenic.

Alkalinity and hardness were analyzed by standard titrimetric methods using standard HCl and EDTA respectively. Na, K, and Ca were analyzed using a flame atomic absorption unit, Mg was determined by difference. NO_3^- was analyzed using the brucine colorimetric method. SO_4^{2-} was analyzed by ion chromatography. Cl^- was determined coulometrically and pH and conductance were found using a pH meter and conductance cell and meter, respectively.

Megascopic mineral evaluation was performed on the Shelby-tube cores. Sand, silt, and clay percentages were determined for selected samples. This procedure for determining grain size of the sample, involved air drying and disaggregating the fragments to less than 15 mm in diameter. Approximately 45 grams of the sample were weighed and soaked in 125 ml of 4 percent Calgon solution overnight. A test solution of 125 ml of 4 percent Calgon with deionized water was prepared in a 1000 ml graduated cylinder and also allowed to stand overnight. After soaking, the sample was stirred and agitated until all the clumps had been broken up. The sample and solution were placed in a 1000 ml graduated cylinder with deionized water and shaken until all the sediment was in suspension. After the sample settled for 2 hours and 30 minutes, a hydrometer reading was taken and the hydrometer reading of the test solution subtracted from it to determine the clay weight. The sample was wet-sieved to remove the silt and clay, and the remaining sand and gravel was oven-dried overnight. The sand and gravel fractions were separated with a Ro-Tap mechanical shaker and No. 10 (2 mm), No. 18 (1 mm), and No. 230 (0.063 mm) sieves. The sand and gravel percentages were calculated, and all the sediment not accounted for by clay, sand, or gravel was reported as silt.

Some of these same Shelby-tube sediment samples were also analyzed for major-ion content by the Northern Great Plains Research Center (U.S.D.A.) in Mandan, North Dakota. Deionized water was added to 200 to 1000 gms of air-dried samples with known weight and water content until the saturation point was reached. At the saturation point, the soil paste glistens as it reflects light, and the soil flows slightly as the container is tipped. The saturation percentage was calculated from the weight of the air-dried sample, and sum of the weights of the water originally present in the sample plus the water that was added to reach the saturation point. After the sample was allowed to stand at least four hours, the pH was determined. The paste then was transferred to a funnel equipped with filter paper, and the extract was removed with a vacuum. To prevent precipitation of $CaCO_3$, 1 ml of $(NaPO_3)_6$ was added per 25 ml of extract. The electrical conductivity (EC) and sodium adsorption ratio (SAR) of the extract were determined in addition to concentrations of potassium, sodium, bicarbonate, sulfate, and chloride (Sandoval and Power, 1977).

The same samples that were sent to the North Dakota State University Land Reclamation Research Center Laboratory are presently being analyzed by x-ray fluorescence for both major ion- and trace-metal concentrations in the Mining and Mineral Resources Research Institute Natural Materials Analytical Lab (NMAL) at the University of North Dakota. Each sample was oven-dried overnight at 25°C. The samples taken from the disposal pit and those that smelled of hydrocarbons were oven-dried an additional five days at 75°C to "burn off" any hydrocarbons that could volatilize in the XRF sample chamber. Ten grams of the sample were ground up with a porcelain mortar and pestal until six grams would pass through a number 200 (.074 mm) sieve. Three drops of deionized water were thoroughly mixed with the sample to act as a binder. The pressed pellets were made by placing the sample in a 1.25-inch diameter spec aluminum cap and applying five tons per square inch of weight for three minutes.

CLIMATE AT THE STUDY SITE

The climate in this area is semi-arid with a mean annual precipitation rate of 15-19 inches (38.1-48.3 cm). The majority of the precipitation falls during the five month growing season between April and September. The mean annual temperature is approximately 37°F (2.3°C) and the mean annual evaporation from lake surfaces in the area is approximately 33 in. (83.8 cm) (Randich and Kuzniar, 1984).

GEOLOGY OF THE STUDY SITE

The Stratton SWD #1 is situated upon approximately 220 feet (67.1 m) of Pleistocene till which overlies the Cretaceous Fox Hills Formation. The surface deposits in the area around the study site consist of Pleistocene sediments of Late Wisconsinian Age (Fig. 4). These deposits consist of till, glaciofluvial, and gluciolacustrine sediments of the Coleharbor Group. The study site is located upon low-relief, collapsed glacial topography.

The till at this site is a mixture of clay, silt, sand, pebbles, cobbles, and boulders. The depth of oxidation of this till ranges from 12 to 25 feet (3.7 to 7.6 m). The oxidized till is generally pale to medium-yellowish brown with numerous iron-oxide stains along the fractures. The unoxidized till is generally medium- to dark-gray-blue.

Numerous sand and gravel zones, with thicknesses of 5-15 feet (1.5-4.6 m), were encountered within the till. These zones could not be traced between bore holes and therefore appear to be thin-discontinuous lenses (Fig. 5).

During the drilling program, glauconitic sand was recovered from a depth of 200-240 feet (61-73.2 m). The mineral glauconite is an indicator of marine deposition and its presence is useful in recognizing the Fox Hills Formation in well cuttings. A 5-foot (1.5 m) gravel zone at a depth of 212 ft. (64.6 m) suggests that the 12-foot-thick (3.7 m) sand above is probably a glacial thrust block. The top of the Fox Hills Formation in this area of Bottineau County is between 1300 and 1350 feet (396 and 411.5 m) above sea level (Bluemle, 1985). This agrees with the 1310 feet (399.3 m) above sea level that was determined for the top of the Fox Hills Formation at the study site.

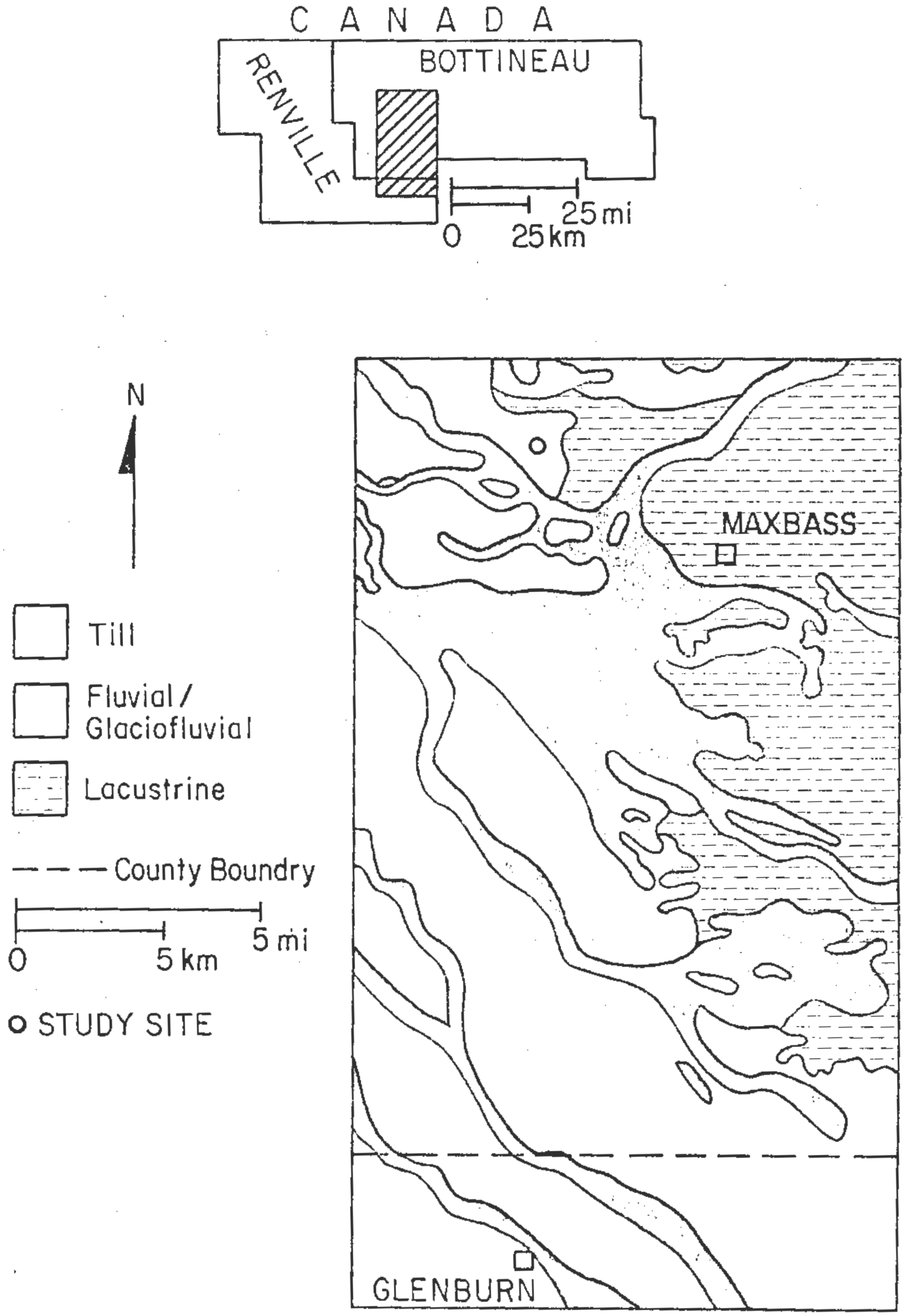


FIGURE 4 - SURFACE GEOLOGIC MAP OF A PORTION OF BOTTINEAU AND RENVILLE COUNTIES. TAKEN FROM BLUEMLE (1985).

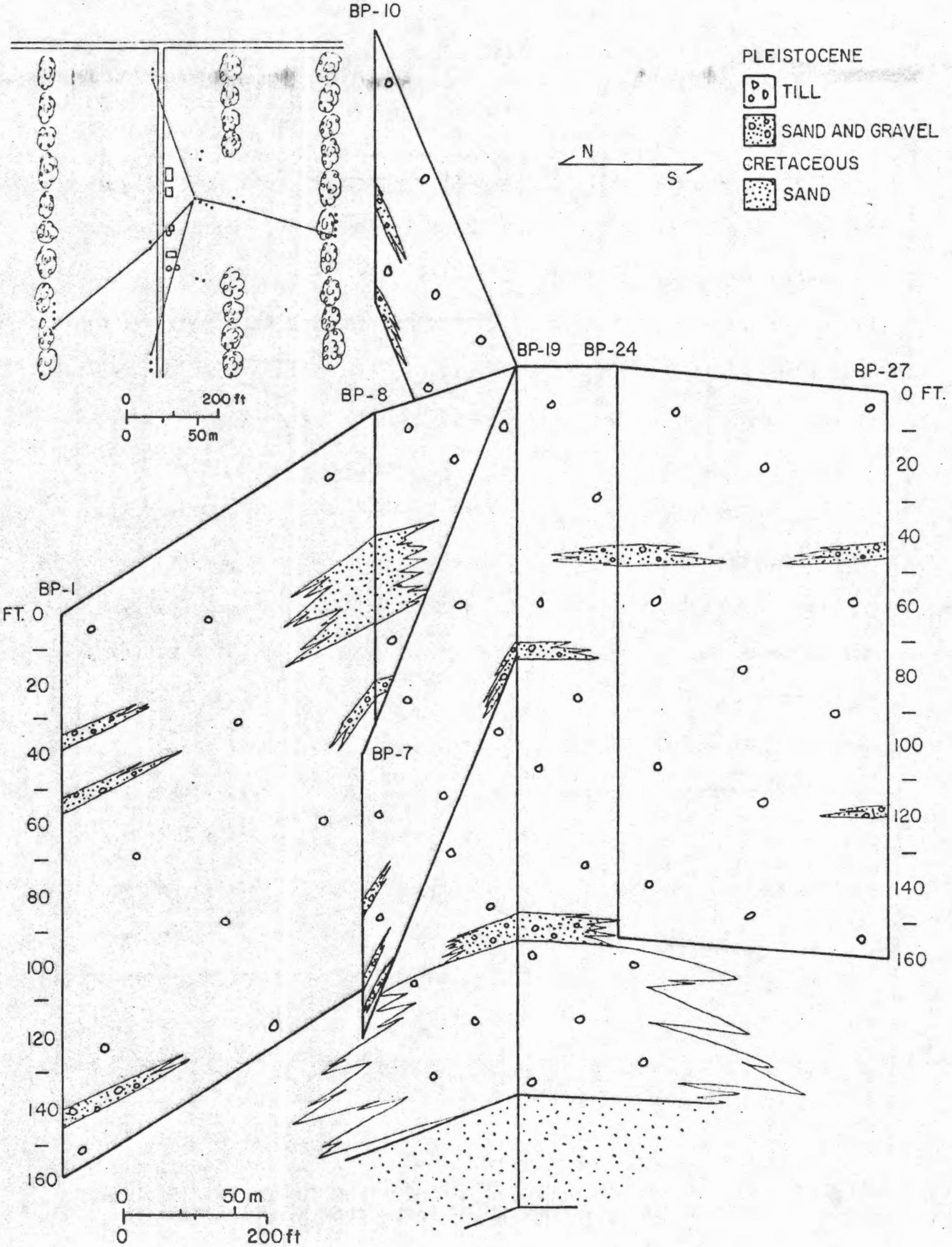


FIGURE 5 - GEOLOGIC FENCE DIAGRAM OF THE STUDY SITE.

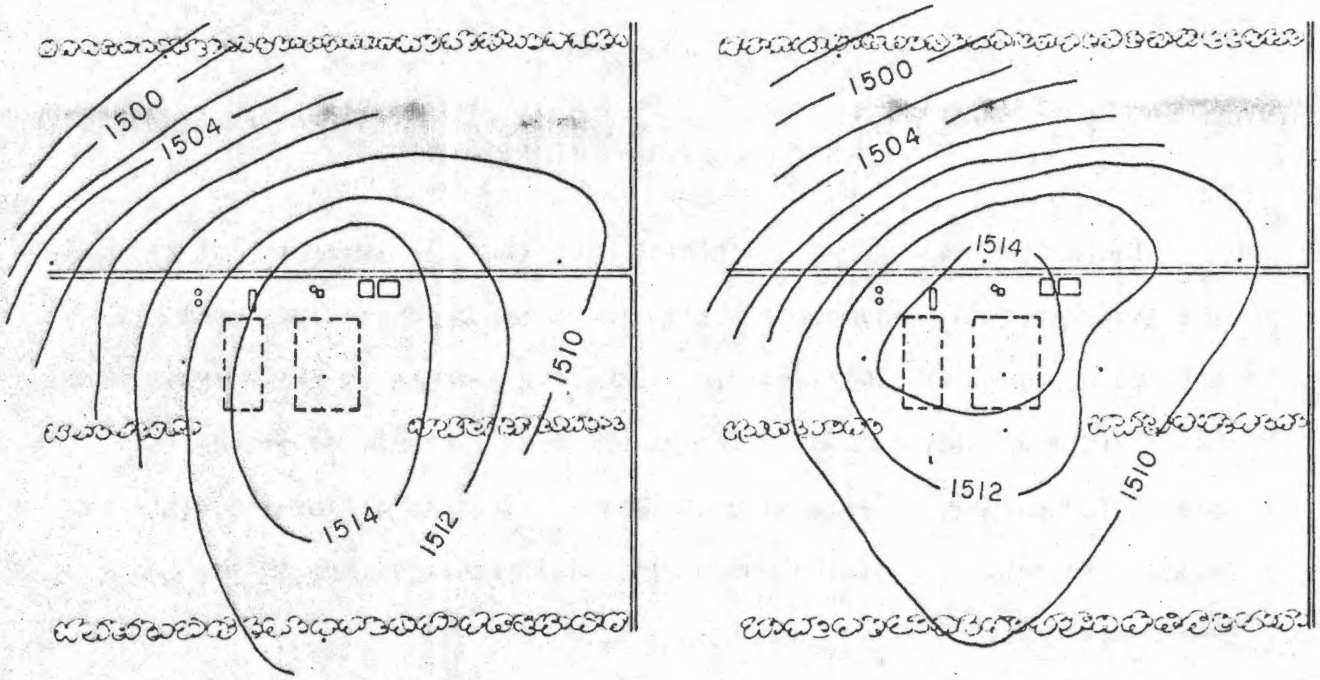
GEOHYDROLOGY OF THE STUDY SITE

The water table is at a depth of approximately 10 feet (3.1 m) around the study area. It is mounded below the brine ponds and the zone of saturation is within 10 feet (3.05 m) of the surface in those areas (Fig. 6). This mound may extend as far as 500 feet (152 m) beyond the pond boundaries and may be affecting the water levels in all of the water-table wells. There could also be some artificial recharge through the two emergency pits.

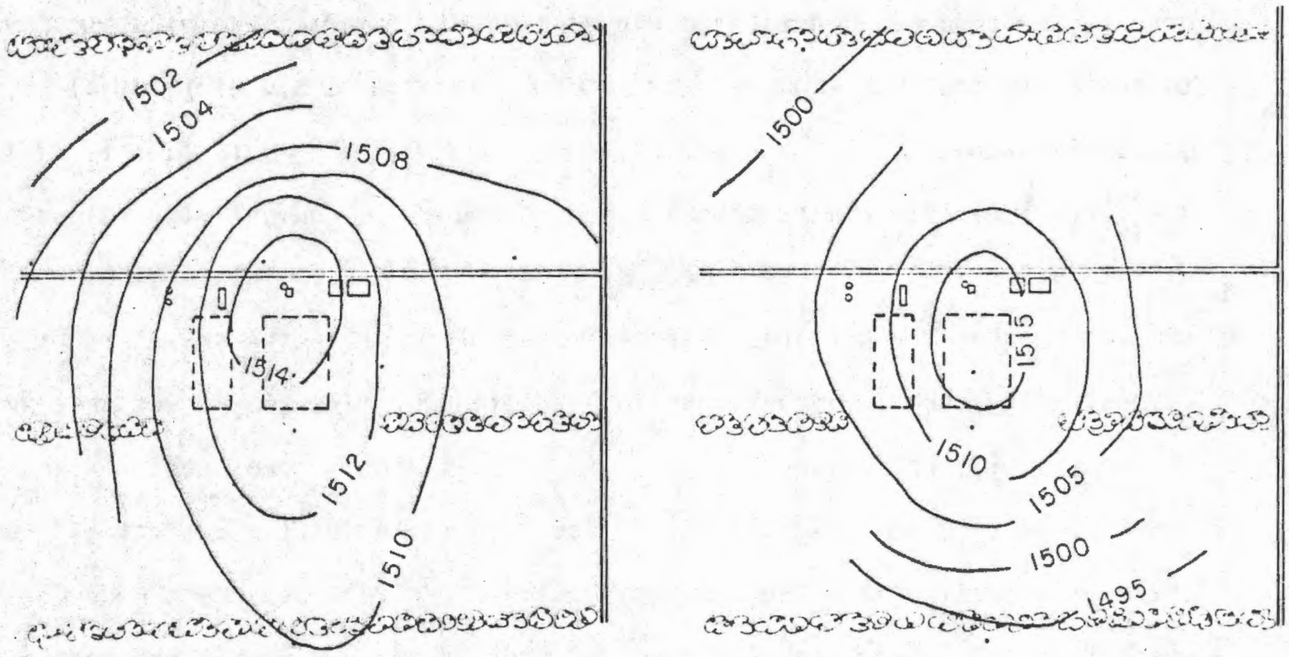
It is difficult to determine the direction of groundwater flow in the study area due to the large-scale effects of the groundwater mound. In general, head values decrease to the northeast. However, the head decreases to the south in the piezometers screened at 160 feet (48.8 m) (Fig. 6) (Appendix 4-2E).

The slug-test results gave a range of hydraulic-conductivity values of 4.79 to 9.9 x 10^{-5} cm/s and a mean of 7.28 x 10^{-5} cm/s. These values were similar whether the screened interval was in till or in the gravel zones, demonstrating that the gravel was in discontinuous lenses. As was observed in the shelby tube sediment cores, this till is highly fractured. These fractures will have a significant effect upon the hydraulic conductivity of the overall till unit. The slug-test results are very dependent upon whether or not a major set of fractures was intercepted within the screen zones.

The till unit in this area is a widespread aquitard and, therefore, there are no farm wells completed within either the silty-clay till or the discontinuous sand and gravel lenses. However, this unit does contain a



SCREENED FROM 25-40 FEET SCREENED FROM 45-60 FEET



SCREENED FROM 70-80 FEET SCREENED AT 160 FEET

FIGURE 6 - POTENTIOMETRIC MAPS AT THE FOUR SCREEN INTERVALS AT THE STUDY SITE (1 foot = .3048m).

number of unconfined and confined aquifers in buried glaciofluvial deposits. The five major Pleistocene aquifers in Bottineau County are named but the numerous smaller ones are not (Randich and Kuzniar, 1984).

The Stratton well (SWD #1) is situated near the northern extent of the east arm of the Glenburn Aquifer System (Randich and Kuzniar, 1984) (Fig. 7). This portion of the buried glaciofluvial aquifer is approximately ½-mile (0.8k m) in width and is quite variable in both thickness (up to 150 feet) (45.7 m) and in depth from the surface (Fig. 7). Parts of this aquifer yield up to 1000 gal/min (3785 L/min) (Randich and Kuzniar, 1984).

A deposit of Holocene alluvium is located approximately 1/3 mile (0.5k m) south of the Stratton Lease. This shallow unconfined aquifer was a source of water for the Brandt farmstead (Brandt, pers. comm., 1984).

The Fox Hills Formation is the most extensive bedrock aquifer system in Bottineau County. In some portions of the county it is the only aquifer system that can produce sufficient quantities of water for domestic or stock use (Randich and Kuzniar, 1984).

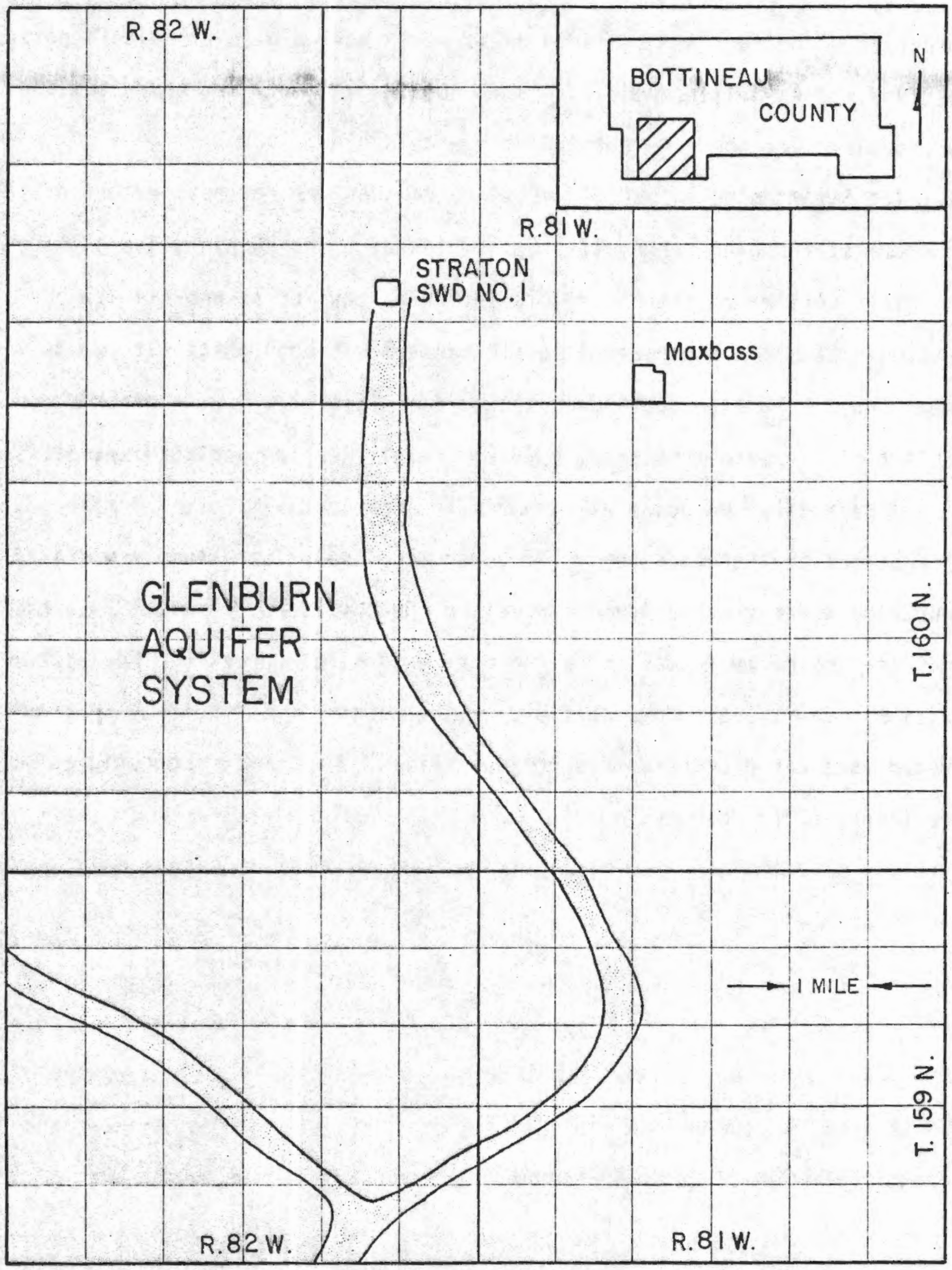


FIGURE 7 - GLENBURN AQUIFER SYSTEM IN SOUTHWESTERN BOTTINEAU COUNTY (FROM RANDICH AND KUZNIAR, 1984).

RESULTS

Apparent Resistivity

Apparent resistivity values for the study site are presented in Appendix 4-2F. These same apparent resistivity values are plotted on isoresistivity maps for the fourteen electrode spacings (Figs. 8-10). The maps all depict a zone of extremely low resistivity immediately beneath the brine ponds that is somewhat elongated to the southeast. Resistivity values increase in all directions outward from the pits.

In the presentation of the apparent resistivity profiles, the electrode spacing and depth of current penetration are depicted as equal. This has generally been found to be true for electrode spacings of less than 100 feet (30.5 m) (Soiltest, 1968). This 1:1 ratio of depth-to-electrode spacing has been demonstrated by a number of VES projects in Illinois (Cartwright and Sherman, 1972). However, the presence of sedimentary layers with greatly differing resistivities and/or saline pore water has been shown to distort the electrical field and reduce the depth of current penetration (Reed et al., 1981).

Water Analyses--A total of 59 water samples were analyzed by a chemistry lab at North Dakota State University. Nine of these were pore-water samples and fifty were groundwater samples. All of the samples were analyzed for major-ion concentrations and 22 were analyzed for As, Cu, Cr, and Pb (Appendix 4-2G).

As expected, the highest TDS concentrations occur in pore water at a depth of 4 feet (1.2 m) within the largest brine pit (BL-3). This sample was characterized as follows: 214,000 mg/L of TDS, 120,000 mg/L of Cl^-,

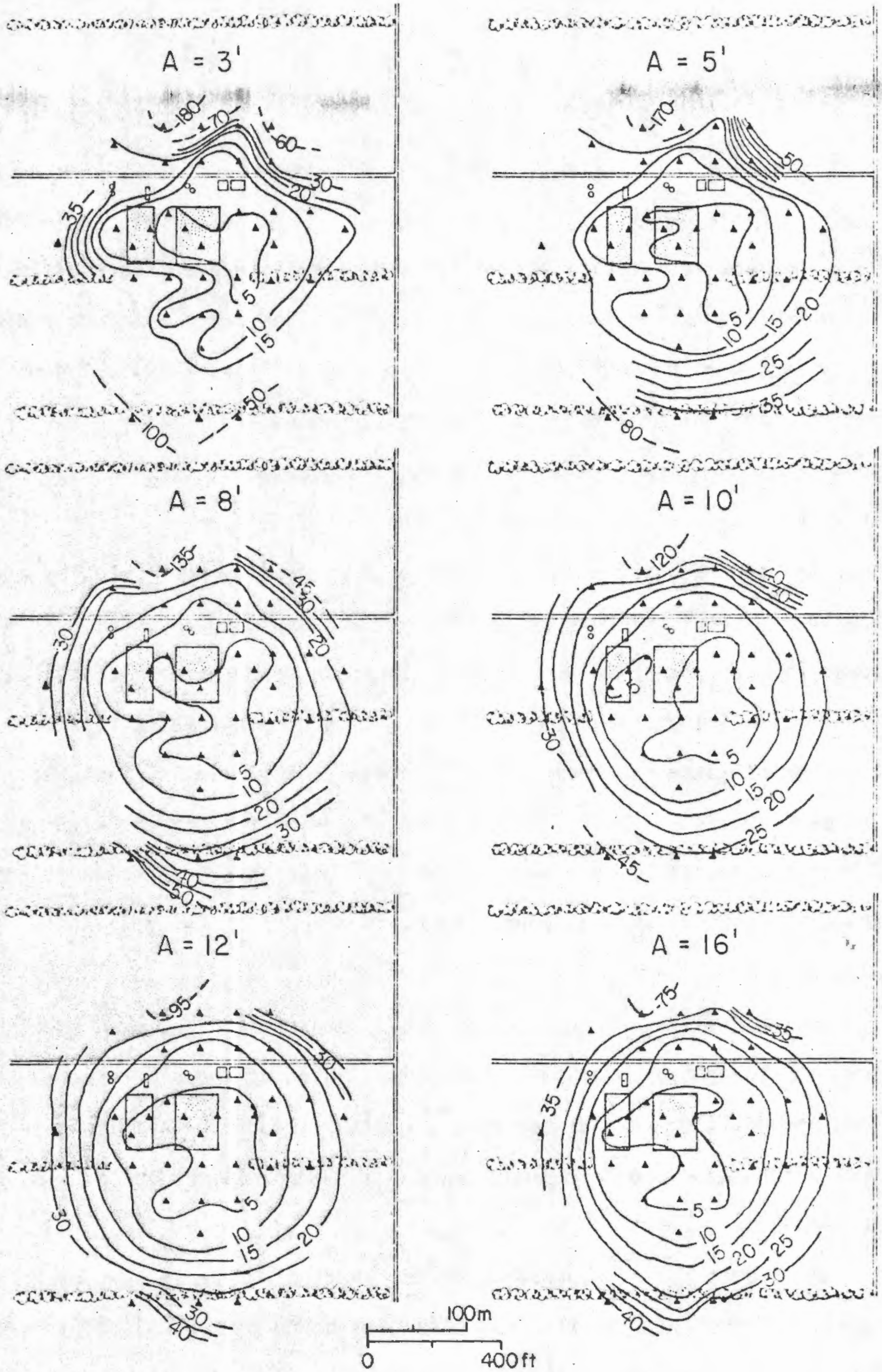


FIGURE 8 - APPARENT ISORESISTIVITY MAPS FOR ELECTRODE SPACINGS OF 3, 5, 8, 10, 12, and 16 feet (0.9, 1.5, 2.4, 3.1, 3.7, and 4.9 m).

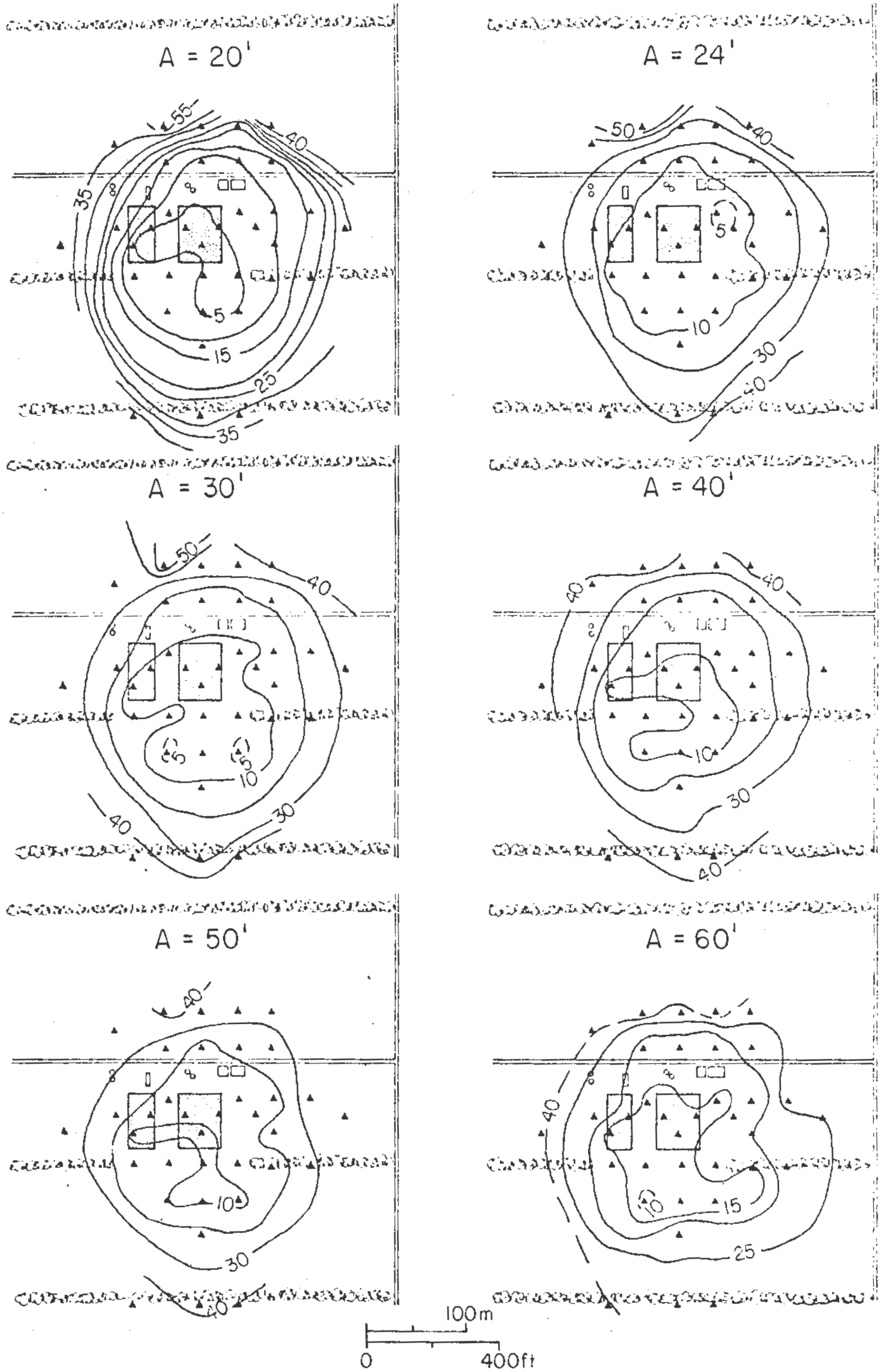


FIGURE 9 - ISORESISTIVITY MAPS FOR ELECTRODE SPACINGS OF 20, 24, 30, 40, 50, AND 60 FEET (6.1, 7.3, 9.1, 12.2, 15.2, and 18.3 m).

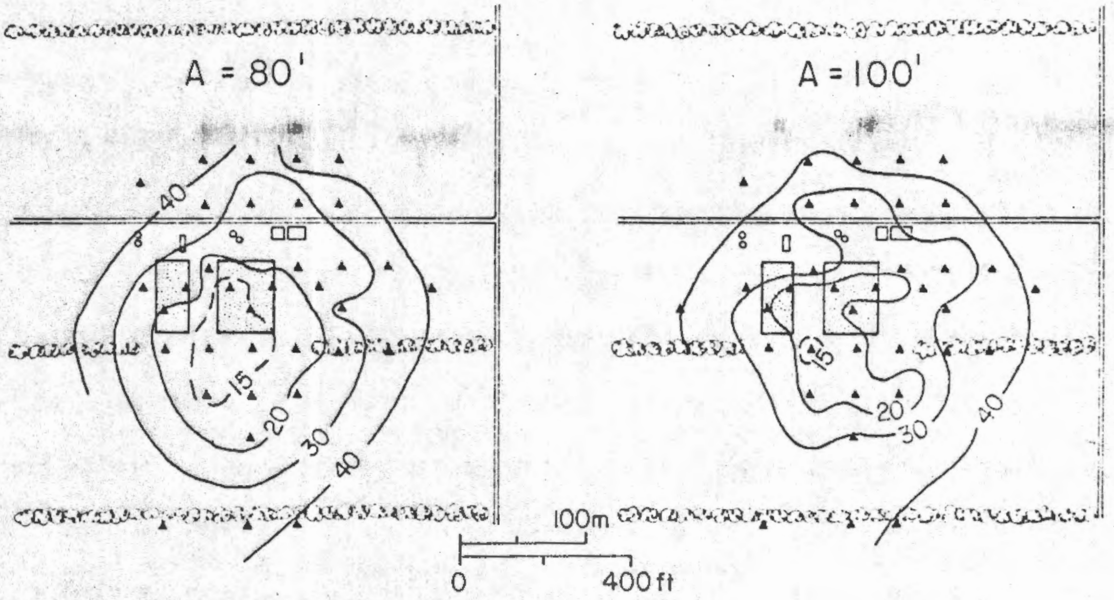


FIGURE 10 - ISORESISTIVITY MAPS FOR ELECTRODE SPACINGS OF 80 AND 100 FEET (24.4 AND 30.5 m).

61,000 mg/L of Na^+, and 800 mg/L of SO_4^{-2} (Figs. 18 and 19). These concentrations had been reduced to: 101,000 mg/L of TDS, 68,000 mg/L of Cl^-, 32,000 mg/L of Na^+, and 1300 mg/L of SO_4^{-2} in pore water at a depth of 9 feet (2.7 m) below this pit (Appendix 4-2H) (Figs. 18 and 19).

Isoconcentration maps were constructed for 15 parameters at the four screened horizons at the study site (Appendix 4-2I). These maps were constructed to determine total migration of the leachate. The values plotted are the mean of the December, 1984 and June, 1985 samples.

The highest concentrations were found within the 25- to 40-foot (7.6- to 12.2 m) depth interval in groundwater beneath the brine pits (120,000 mg/L of TDS, 75,000 mg/L of Cl^-, 30,000 mg/L of Na^+, and 2000 mg/L of SO_4^{-2}) (Figs. 23-26). These concentrations were essentially the same as those in pore water beneath the pits at a depth of 9 feet (2.7 m) from the surface.

The chemical characteristics of groundwater within the depth interval from 45 to 60 feet (13.7 to 18.3 m) were: 50,000 mg/L of TDS, 20,000 mg/L of Cl^-, 10,000 mg/L of Na^+, and 1000 mg/L of Na^{+2}. The maximum concentrations of TDS and Cl^- within this zone were approximately 60 percent that of groundwater within the 25 to 40 foot (7.6 to 12.2 m) zone.

The chemical characteristics of groundwater in the depth interval from 70 to 80 feet (21.3 to 24.4 m) showed significant reductions in the concentrations of specific ions relative to the 40 to 60 foot interval. Maximum concentrations in the 70 to 80 foot interval were as follows: 2800 mg/L TDS, 600 mg/L Cl^-, 500 mg/L Na^+, and 1000 mg/L SO_4^{-2} (Figs. 23-26). The highest concentrations in this interval occurred in a piezometer immediately to the south of the pit boundary. The range in concentrations of specific ions in water samples from piezometers screened in this horizon was generally very small.

The quality of groundwater at a depth of 160 feet (48.8 m) beneath the study site was similar to that found at a depth of 70 to 80 feet (21.3 to 24.4 m). Maximum concentrations at the 160 foot (48.8 m) depth, which were measured in the piezometer nest just south of the brine pond, were: 2500 mg/L of TDS, 500 mg/L of Cl^-, 500 mg/L of Na^+, and 1000 mg/L of SO_4^{-2}.

One piezometer was screened in the Fox Hills Formation at a depth of 220 feet (67.1 m) beneath the major brine pond (BP-19 (Appendix 4-2G)). Groundwater from this piezometer contained 3300 mg/L of TDS, 1500 mg/L of Cl^-, 1100 mg/L of Na^+, and 6 mg/L of SO_4^{-2}.

Elutriation Experiment

The North Dakota State University Land Reclamation Research Center Laboratory (LRRC) elutriated 43 sediment samples from the unsaturated and saturated zones at the study site. The concentrations of eleven parameters in fluids separated by elutriation of sediment samples are presented in Appendix 4-2J. The sediment samples were obtained from seven Shelby-tube holes placed in and around the brine pits (Fig. 3). As expected, the highest Na^+ and Cl^- concentrations were found in sediments from within and beneath the brine pits. These concentrations generally decreased in concentration with depth and distance from the brine pit boundaries, although concentrations varied significantly with depth in hole number A beneath the brine pit (Appendix 4-2J).

XRF Experiment

Splits of sediment samples sent to the LRRC were prepared for XRF major ion and trace-metal analysis in the NMAL at the University of North Dakota. The purpose for doing this was to enable comparison of the data from both analytical methods and to expand our knowledge and understanding of the data generated by the XRF. Unfortunately, reliable standards have not been developed for the XRF and the standard error is too large; therefore, the data are not reproducible. The XRF data will be incorporated into subsequent reports on this study when this situation is remedied.

Textural Analysis

A total of 66 sediment samples were texturally analyzed (Appendix 4-2K). The mean values for till at the study site were: sand (35.6%), silt (37.9%), and clay (26.5%).

DISCUSSION

Depth of Resistivity Current Penetration

An area of extremely low resistivity measuring approximately 360,000 ft^2 (33,379 m^2) was delineated in all of the "a" spacings down to 100 feet (30.5 m) around and beneath the brine ponds. We have assumed in this project that the electrode spacing is equal to the depth of current penetration. However, previous studies have shown that the current will generally be concentrated in the zone of lowest resistivity. At the study site, this zone is the highly-concentrated brine in the near surface. This assumption was supported by the failure of 2/3 of the apparent resistivity soundings, to run through an interpreted resistivity program developed by Zohdy and Bisdorf (1975). This program calculates layer thicknesses and resistivities but cannot interpret VES curves that exceed a slope of 45°. It was only able to interpret data from 11 of the 36 resistivity stations. These stations (1, 4, 5, 6, 12, 14, 19, 20, 29, 34, and 35) are all located along the edges of the grid and indicate that the current at the interior stations was greatly affected by the near-surface brine (Fig. 2).

Although evidence suggests that at least a portion of the current is not reaching a depth equal to the electrode spacing, we are still assuming that these two values are equal because of the lack of a method to determine quantitatively the depth to which the current is actually penetrating. Reed et al., (1981) working around brine ponds in Illinois, speculated that because of the highly saline pore water, the current at electrode spacings of 80 feet (24.4 m) was only penetrating to a depth of 5 to 20 feet (1.5 to 6.1 m).

The electrical surface resistivity survey provided valuable information that aided in the placement and depth of our pore water and groundwater instrumentation. Surface resistivity is a valuable tool for such projects notwithstanding some of the inherent problems associated with surveying over highly conductive zones.

Depth of Weathering

The oxidation-reduction contact, i.e., the contact between mottled and unmottled till, was observed in six of the seven Shelby-tube holes augered in and around the brine ponds. The contact ranged from 10 to 27 feet (3.04 to 8.2 m) beneath the surface with a mean of 20 feet (6.1 m). A 4-inch (9.4 cm) thick layer of salt crystals was found at a depth of 17.5 feet (5.3 m) in hole number A beneath the brine pit (Appendix 4-2J). This layer corresponded with the oxidation-reduction contact in this hole. The water table generally was 10 feet (3.04 m) or more above the oxidation-reduction contact.

The Chemistry of Williston Basin Brines

The chemistry of subsurface brines may vary significantly between and within geologic formations in the Williston Basin of North Dakota. The chemical analyses of 1656 oil-field drill stem tests demonstrated that the majority of brines within the basin contain a concentration of greater than 250,000 mg/L of TDS (Fig. 11). However, 12 percent of the brines contain less than 50,000 mg/L of TDS (Fig. 11).

The major-ion chemistry of brines in the vicinity of the study site was obtained from analyses of eighteen Mississippian brines produced in the Wylie Field (Fig. 12). This chemistry should be representative of the brines that were disposed of in the brine pits at the study site. These brines contain mean concentrations of 180,000 mg/L of TDS, 110,000 mg/L of

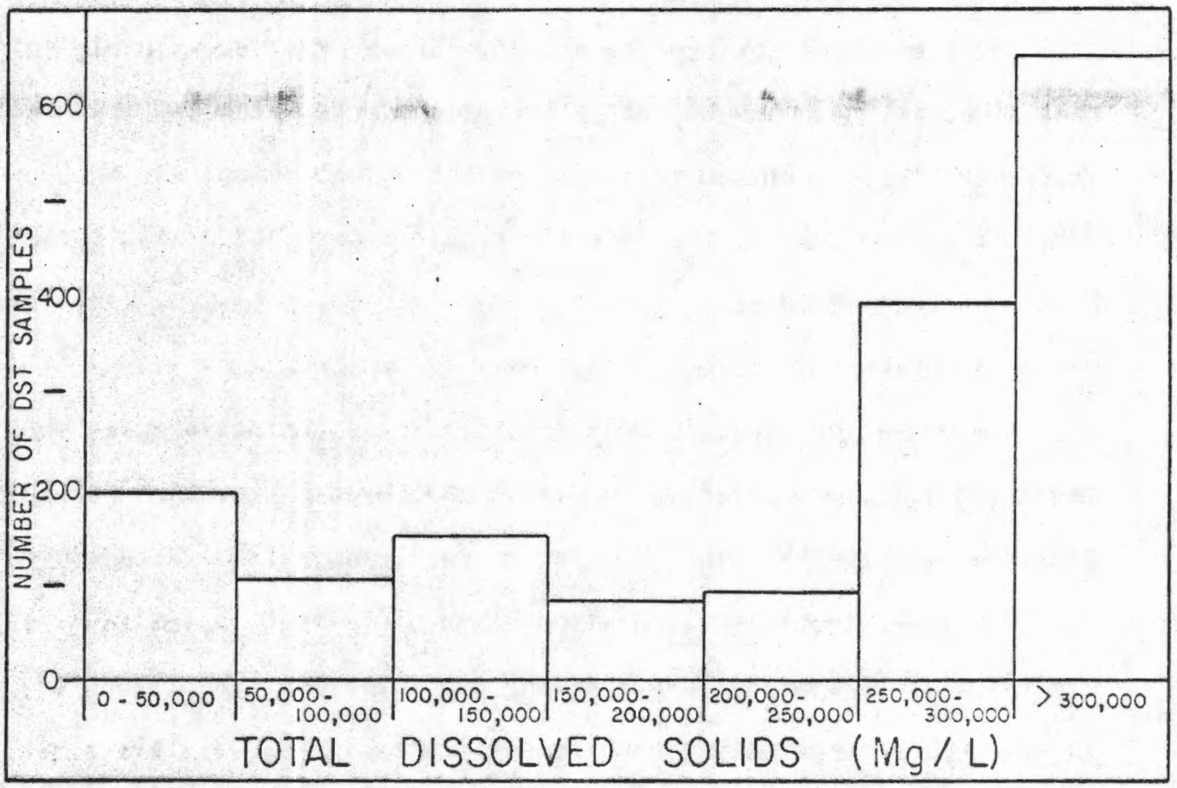


FIGURE 11 - TOTAL-DISSOLVED-SOLIDS CONCENTRATION FOR1656 BRINE SAMPLES WITHIN THE WILLISTON BASIN.

	TEMP	RES	PH	TDS	CA	MG	NA	FE	CL	CO3	HCO3	SO4
HIGH	68	650	7.1	268,036	5510	2310	96,823	0	163,000	0	440	3634
LOW	68	49	5.3	21,287	1348	302	6,141	0	10,250	0	82	1102
MEAN	68	93	6.3	182,414	4338	1298	64,535	0	109,686	0	227	2132

FIGURE 12 - HIGH, LOW, AND MEAN CONCENTRATIONS OF BRINE SAMPLES WITHIN THE WYLIE FIELD, BOTTINEAU COUNTY, NORTH DAKOTA.

Cl^-, 65,000 mg/L of Na^+, 4300 mg/L of Ca^{++}, and 2100 mg/L of SO_4^{-2} (Fig. 12).

Impacts on Major Aquifers

The Fox Hills Formation

The Fox Hills piezometer at the study site contained groundwater with a concentration of 1500 mg/L of chloride. The Fox Hills Formation normally contains chloride concentrations of 50- to 200 mg/L in west-central North Dakota. These concentrations generally increase to 1000-1500 mg/L in the northern counties (Wanek, per. comm.). Kuznair and Randich (1982) reported chloride concentrations as high as 4000 mg/L within the Fox Hills Formation in Bottineau County. An isoconcentration map for this interval was constructed from NDSWC data to enable comparison of chloride concentrations with oil field activity (Fig. 13). Although there appear to be two point sources, T161N, R83W and T160N, R74W, they are not situated within oil fields or near abandoned wildcat wells. This map supports Kuznair and Randich's (1984) statement that the Souris valley is the approximate location for an interface between fresh to slightly saline Fox Hills waters moving west from the Turtle Mountains and saline water moving east. The chloride concentrations in the Fox Hills Formation beneath the study are similar to surrounding wells. The high chloride concentrations within this formation appear to be natural.

Glenburn Aquifer

Twenty groundwater samples were obtained from various depths in the Glenburn Aquifer and analyzed by the NDSWC (Kuznair and Randich, 1982). These samples had a maximum chloride concentration of 680 mg/L and a mean of 300 mg/L. These values are extremely high in comparison to the normal concentrations of the chloride ion (20-40 mg/L) generally found in glacial

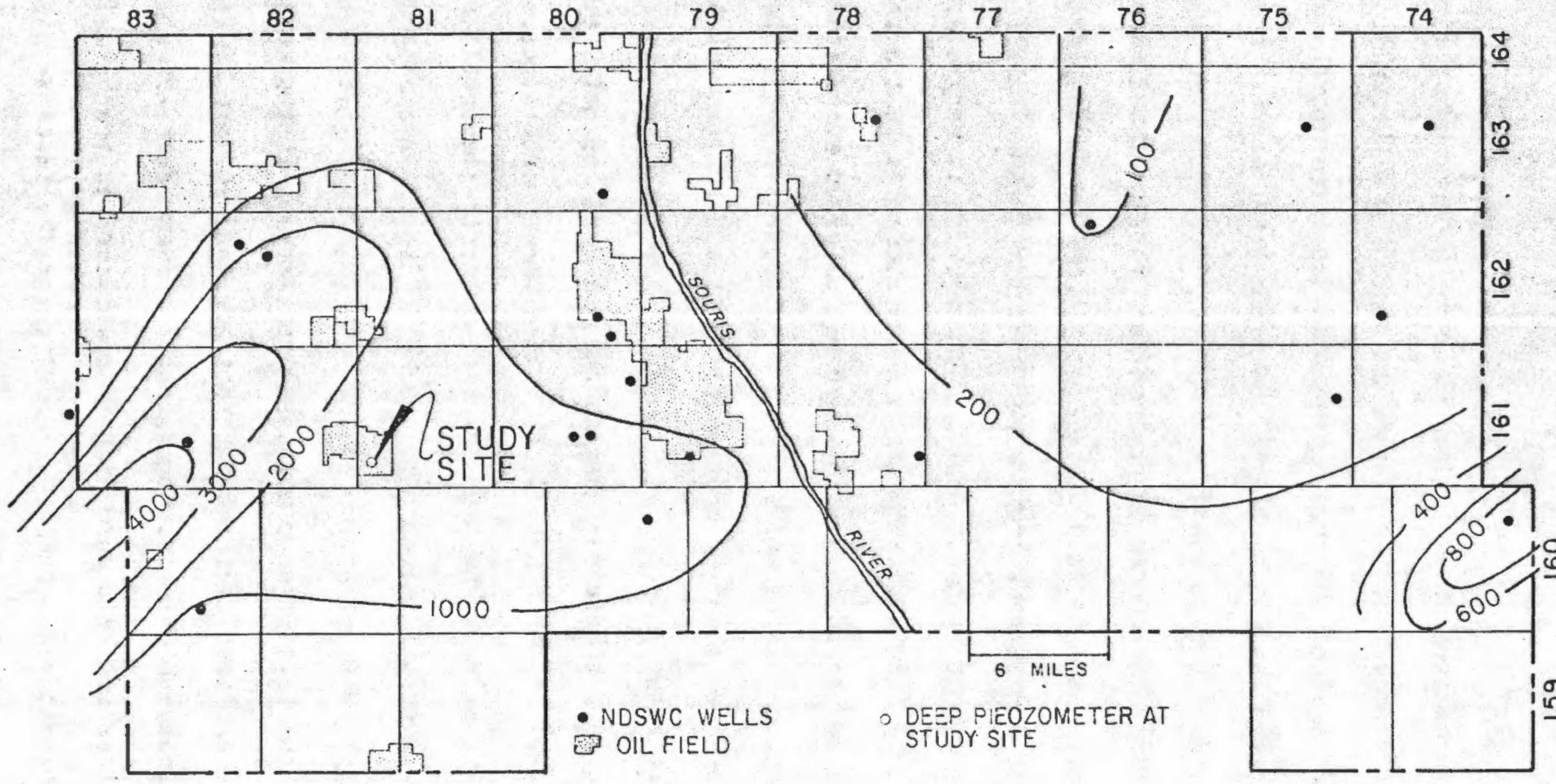


FIGURE 13 - ISOCONCENTRATION MAP OF THE CHLORIDE IÒN (IN mg/L) IN THE FOX HILLS FORMATION IN BOTTINEAU COUNTY. DATA OBTAINED FROM KUZNAIR AND RANDICH (1982).

sediments. A large part of this aquifer rests directly upon or very close to the upper contact of the Fox Hills Formation. The source of the high chloride concentration appears to be leakage from the underlying Fox Hills Formation. This does not mean to suggest that brine ponds are not a possible source of chloride for portions of this aquifer. This theory is supported by chemical analyses of groundwater from two piezometers in sec 14, T160N, R82W (Kuznair and Randich, 1982). The shallow well (75 feet (22.9 m)) contained 36 mg/L of chloride and the deep well (193 feet (58.8 m)) contained 350 mg/L. Another set of piezometers in T159N, R82W had higher concentrations of chloride in the deeper piezometer and further indicated that the source was not surface related.

The head of the northern arm of the Glenburn Aquifer is very close to the study site (Fig. 7). There is no evidence that suggests that brine from the Edson Brown #1 site has reached this major aquifer. However, it is readily apparent that, had these brine pits been situated over the Glenburn aquifer, it would have experienced brine contamination.

Impacts on Near-Surface Intervals

The chemistry of the pore water at a depth of 4 feet (1.2 m) within the Edson Brown brine pond (214,000 mg/L of TDS, 120,000 mg/L of Cl^-, 61,000 mg/L of Na^+, 5600 mg/L of Ca^{++}, and 800 mg/L of SO_4^{-2}) is almost identical to the mean concentrations of brines from the Wylie Field. The exception to this is the generally lower sulfate concentrations in the pore water in comparison to the brine. This reduction may be the result of the removal of sulfate from the aqueous system by the precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) in the unsaturated zone. Large concentrations of gypsum crystals were observed in Shelby-tube sediment cores from the unsaturated zone (Appendix 4-2A). However, there is not a parallel reduction in the calcium concentrations within this same interval. This is probably due to the release of Ca^{++} by cation exchange as Na^{+} is adsorbed onto the clays. This mechanism usually involves the release of Na^{+} but is reversed in this situation because of the extremely high concentrations of sodium relative to calcium within the brines.

Pore water at a depth of 4 feet (1.2 m) in the reclaimed pond has essentially the same chemistry as that of the brines disposed of in the pond 10 to 25 years ago. Apparently, minimal flushing has occurred in the shallow subsurface at the site. Because of the semi-arid climate in this region, there are generally only a few major recharge events per year. In addition, this water is restricted from moving through the site by the reduction of sediment porosity as a result of the exchange of sodium from the brine to the clays.

The high ion concentrations in the pore water may also result from the original evaporative concentration of salts at the base of the pond. Although salt was observed macroscopically throughout the sediment cores, it did not occur in a concentrated layer in the unsaturated zone. These sediments may have become supersaturated with salts because of the evaporation of the brine and now constitute a source of leachate when fresh water comes in contact with the site.

Chemical analyses of groundwater samples from the study site define a brine-generated leachate plume that extends laterally beneath an area of 250,000 ft^2 (5806 m^2) around the brine ponds. This plume extends down to a depth of 70 feet (21.3 m) (Fig. 14). An area of high chloride that occurs at a depth of 160 feet (48.8 m) beneath the pond appears to be the result of upward leakage from the Fox Hills Formation.

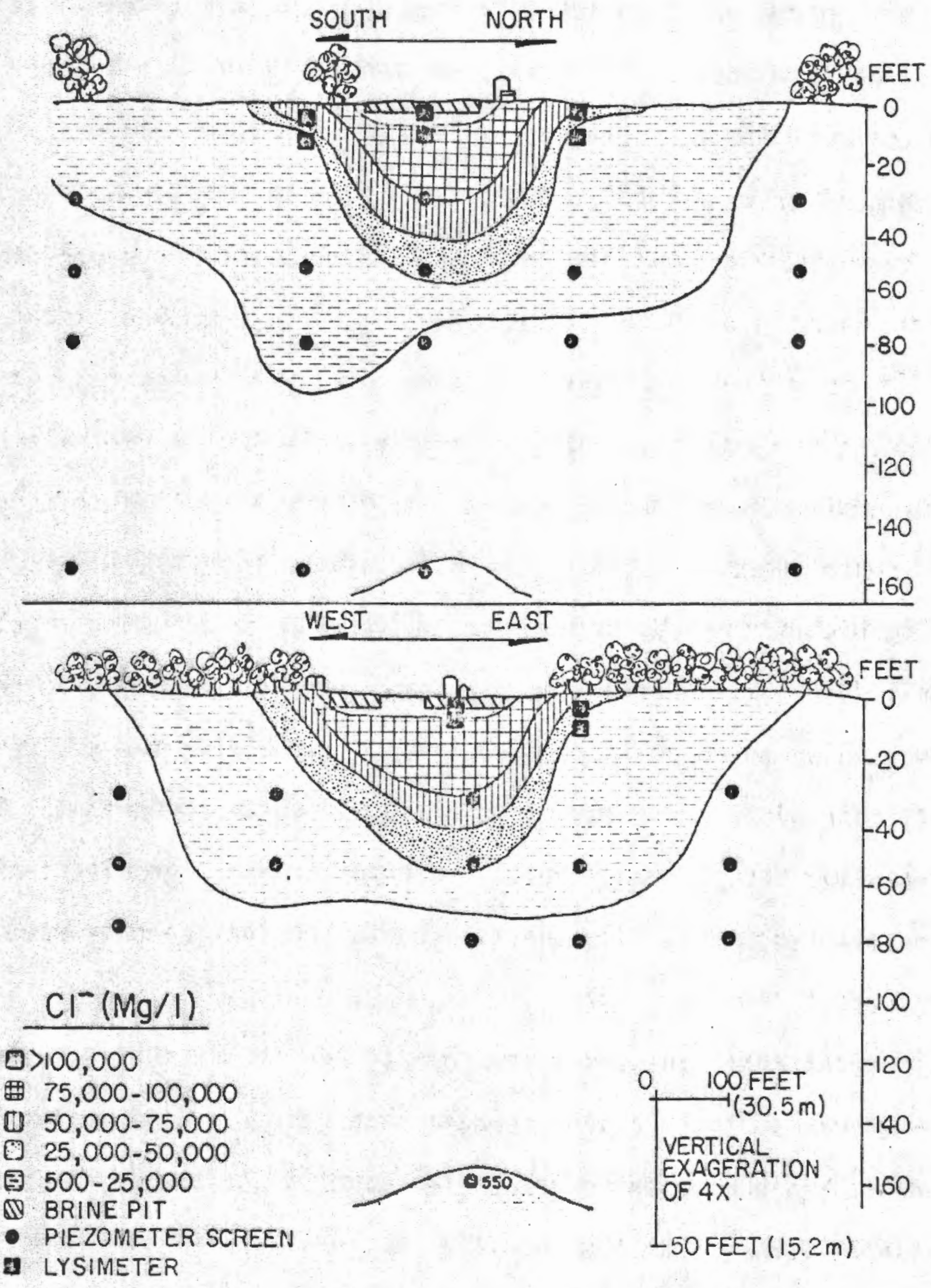


FIGURE 14 - NORTH-SOUTH AND EAST-WEST PROFILES OF BRINE MIGRATION AT THE EDSON BROWN #1 SITE.

The results of the apparent resistivity surveys and groundwater chemistry indicate that the brine contamination is restricted to the till aquitard and has not affected any usable groundwater supply. However, the Brandt farmstead had a well completed in shallow alluvial sediments (approximately 15 feet (4.6 m) deep) with very poor quality water (Brandt, per. comm.). The source of the poor quality water may be natural, farm, or oil-field related. A chemical analyses was not obtained from this well, so no conclusions can be drawn. The farmstead is now on a rural water line system and the well is no longer in use.

The Future of the Study Site

A major remaining question involves determining how long, and to what depth, the reclaimed brine pond at the Edson Brown #1 site will impact subsurface water. Powell et al. (1963) documented widespread contamination of shallow aquifers by brine-evaporation pits in Alabama. A study of these same areas 10 years after the pits had been shut down documented the rapid cleansing of these aquifers (Powell et al., 1973). The same environmental conditions which had created rapid and widespread contamination by brines at these sites, i.e., high yearly precipitation, shallow water table, and permeable sediments, also contributed to the rapid improvement of the aquifers.

In contrast, the semi-arid climate and low hydraulic conductivity of the sediments at the Edson Brown #1 site have resulted in only small- to moderate-scale movement of brine leachate in the shallow subsurface. The minimal flushing that has occurred at this site indicate, that the amount of salt remaining at the site today is not significantly different from the amount at the time of pond abandonment.

The horizontal component of leachate migration is seven times that of the vertical component (500 vs. 70 feet (152 vs. 21 m)) at the study site. It is this lateral surface and near-surface component of brine migration which is of most concern at this site. Salt migration is causing soil sterility, decreasing crop yields, and killing trees in a shelterbelt within a 250,000 ft^2 (23,226 m^2) area around the ponds. Interpretation of aerial photographs of this and other brine ponds taken over the last twenty-five years has documented the gradual lateral spread of brine from these sites over time (Foss, pers. comm.).

The heavily-concentrated brine in the shallow subsurface within the reclaimed brine ponds at the study site is evidence that little dilution has occurred over the last ten years. If no remedial action is taken, this site will continue to generate highly saline leachate for tens and possibly hundreds of years. The area of brine contamination will continue to grow as snowmelt and heavy precipitation events cause runoff. Infiltrating water can be expected to become saline as it comes in contact with the brine-saturated sediments at the surface of the ponds and surrounding areas. At present, the brine runoff is allowed to flow freely from the site, and spread to the surrounding area.

CONCLUSIONS

1. The study site is underlain by 220 feet (67 m) of Pleistocene till. The till was observed to be highly fractured in both the oxidized and reduced zones. It is characterized by a mean hydraulic conductivity of 7.3×10^{-5} cm/s.
2. The water table is mounded to within 10 feet (3.05 m) of the surface in the area around the brine ponds.
3. Apparent resistivity values delineated an area of extremely low resistivity measuring approximately 360,000 ft^2 (33,379 m^2) at all of the electrode spacings down to 100 feet (30.5 m) at the study site.
4. Groundwater with a high chloride concentration was delineated in an area 500 x 500 feet (152.4 x 152.4 m) around the brine ponds and to a depth of 70 feet (21.3 m).
5. Pore water at a depth of 4 feet (1.2 m) within the brine pit contained the same chemical concentration as the brines that were disposed at this site 10 to 25 years ago.
6. The brine leachate is contained within the till aquitard and is not presently affecting a usable water supply.
7. The horizontal component of leachate migration is seven times that of the vertical component.
8. This site will continue to generate leachate for tens and possibly hundreds of years.

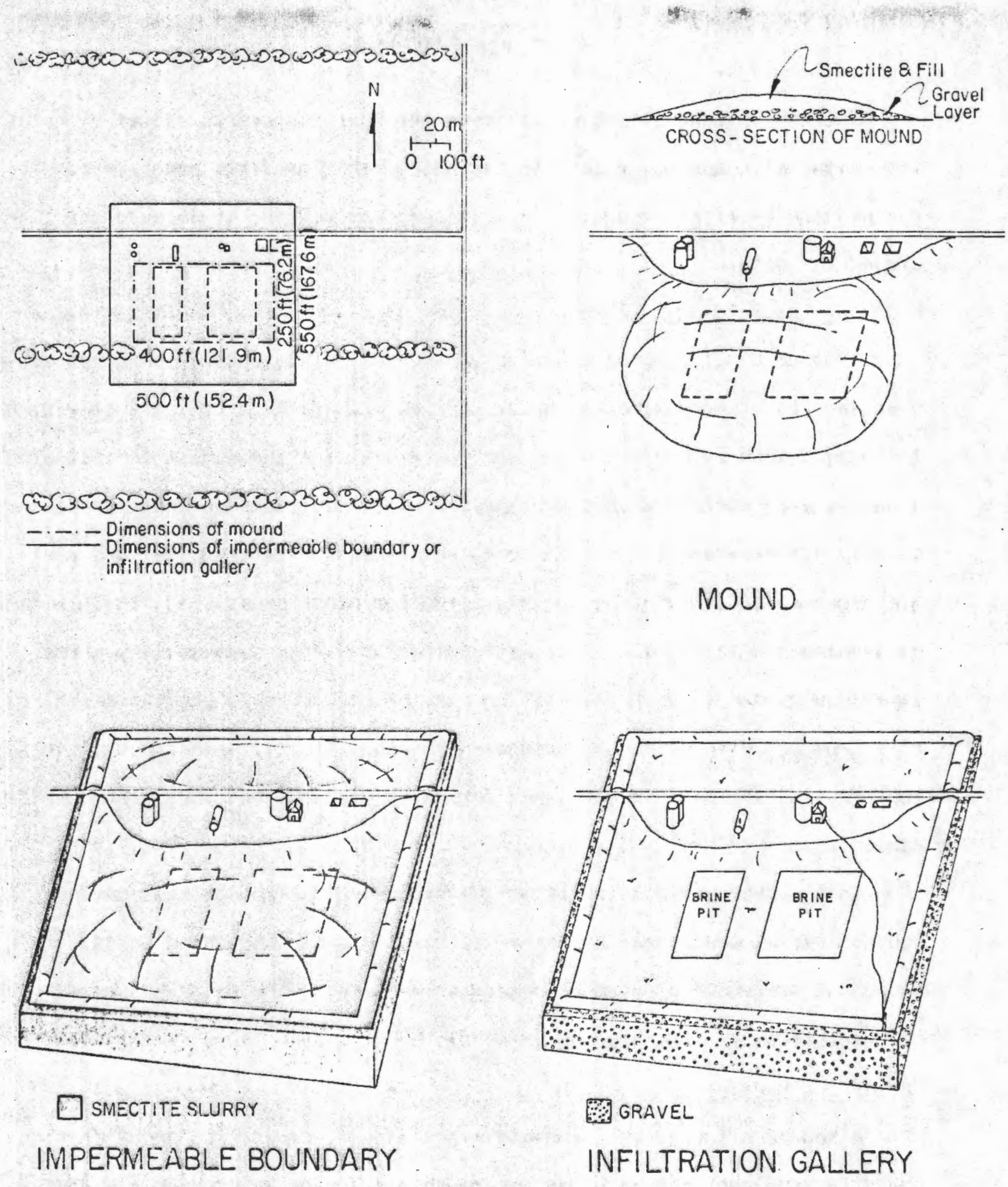


FIGURE 15 - PLAN AND OBLIQUE VIEWS OF THREE POSSIBLE REMEDIAL METHODS FOR THE EDSON BROWN #1 SITE.

RECOMMENDATIONS

The key to controlling or limiting the near-surface spread of brine at this site is to control runoff in and out of the immediate pond areas. This can be done by either mounding the site or constructing an impoundment around the site.

Mounding the Site

A mound consisting of a bentonite and soil mixture could be constructed over an area of approximately 500 x 250 feet (152.4 x 76.2 m). A clay-rich till could also be used. This mound would minimize the direct contact of snowmelt and rainfall with the brine-saturated sediments, direct runoff quickly off of the site, prevent ponding of water over the site, and minimize the amount of runoff into this site from other areas (Fig. 15). Either an impermeable layer, i.e., a plastic liner or a high permeability gravel layer would have to be placed at the base of the mound to prevent capillary rise from bringing salts up through the mound. If this is not done, the mound would eventually become salt saturated and would no longer be beneficial.

This method would be relatively inexpensive. Although this method would minimize the spread of brine leachate from the abandoned ponds, it would not solve the problem of removing or flushing the brine-saturated sediments from the near surface.

Subsurface Barrier

A second alternative for minimizing leachate generation and migration would involve emplacement of an impermeable membrane by digging a 9-foot (2.7 m) deep trench with dimensions of approximately 500 x 550 feet (152.4 x

Artificial recharge could be induced at this site on a large scale by irrigating within the rectangular area with periodic volumes of $CaCl_2$ and fresh water. The flushing of the site with a $CaCl_2$ mixture would enable calcium to exchange with the adsorbed sodium on the clays. This would increase the permeability of the soil and increase the flushing of the leachate.

This would be the most expensive method of remedial action and would have an initial cost of \$20,000.00 - \$30,000.00 (Appendix 4-2N). There would also be subsequent costs associated with maintaining the sump pump and injecting the leachates.

This method has the same advantages as the other methods with respect to minimizing the spread of brine in the near surface from the site. It has the added advantage, however, of making it possible to flush the brine from the shallow subsurface beneath and adjacent to the abandoned brine ponds. The infiltration gallery makes it possible to return this land to production in the foreseeable future. A portion of the induced leachate will not flow to the pump but will travel to the saturated zone. This does not pose a problem at this site because this area is an aquitard and therefore the groundwater is not usable for stock or domestic purposes. The head values are higher in the Fox Hills Formation than in the till. Therefore leachate will not enter the Fox Hills Formation beneath this site as long as that condition prevails.

167.6 m) around the site (Fig. 15). This trench would be filled with a relatively impermeable material such as smectitic clay. This barrier would prevent pore water in the unsaturated zone from either entering or leaving the site. It would also be necessary to cap the site with till or a smectite-soil mixture and to mound the barrier to prevent surface runoff from either entering or leaving the site and to prevent infiltration within the site.

Trench construction would cost approximately $4,000.00 and the bentonite fill would cost approximately $5,000.00 (EPA, 1978). This method would not only prevent surface runoff and infiltration from entering or leaving the site, but would also minimize the amount of heavily saline pore water that could migrate from the site through the unsaturated zone and later be brought to the surface by evapotranspiration. The construction of the surface barrier would cause water to pond within the site and therefore increase the likelihood of recharge through the site. However, this would be minimized by the cap.

Infiltration Gallery

An infiltration gallery (ditch) could be constructed at this site with the same dimensions as the impermeable membrane (Fig. 15). The rectangular ditch would be graded so that natural drainage was into the southeast corner. A drain tile system would be placed at the base and the trench would be backfilled with gravel. A sump pump would be placed in the southeast corner and would pump any collected water into a holding tank adjacent to the injection well. This water would then be periodically pumped down the injection well. A surface barrier, consisting of till excavated from the trenches, would be constructed on the inside of the trench.

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DISSEMINATION OF RESULTS

A number of state and federal agencies and individuals have been contacted for advice and help in this project. Their contributions have been acknowledged in the discussions of each of the individual tasks.

On April 10, 1985, a conference entitled "Identifying and Remedying Effects of Oilfield Brine and Drilling Fluids on Soils and Groundwater" was held in Dickinson, North Dakota. All of the cooperators in this project participated. About 75 people attended the conference, including landowners, oil company personnel, representatives of state and federal agencies, and lawyers. The meeting was widely covered in the media of western North Dakota and eastern Montana by radio, television, and newspapers.

The results of the project have been presented at several technical meetings, at least one journal article is in the process of publication, and several proposed journal articles are being prepared. A partial list of presentations and publications is given below:

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CHARACTERIZATION OF DETRIMENTAL EFFECTS OF SALTS AND OTHER CHEMICAL CONSTITUENTS CARRIED IN SURFACE AND SUBSURFACE WATERS FROM BRINE AND DRILLING FLUID DISPOSAL PITS BURIED DURING OIL DEVELOPMENT

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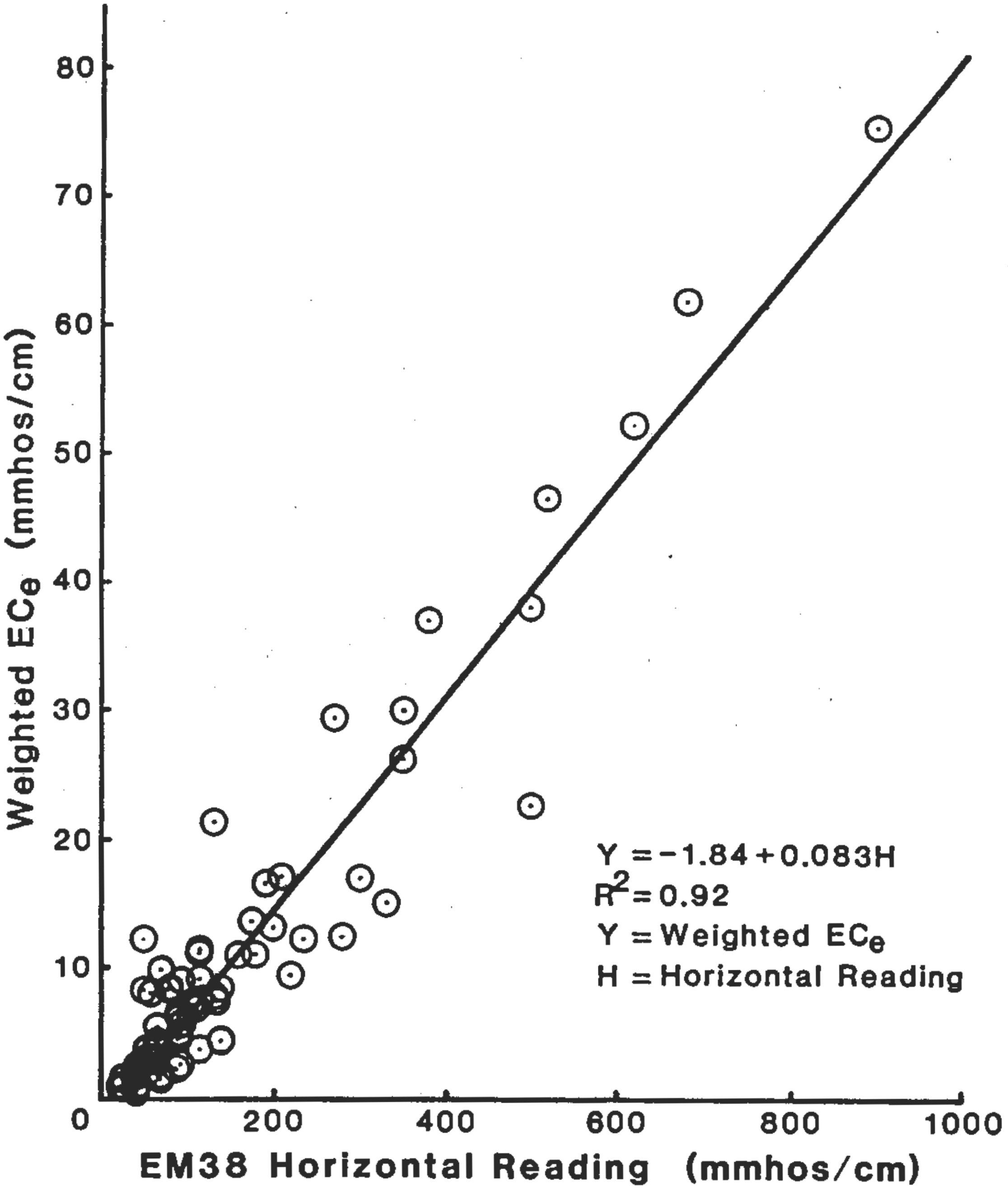

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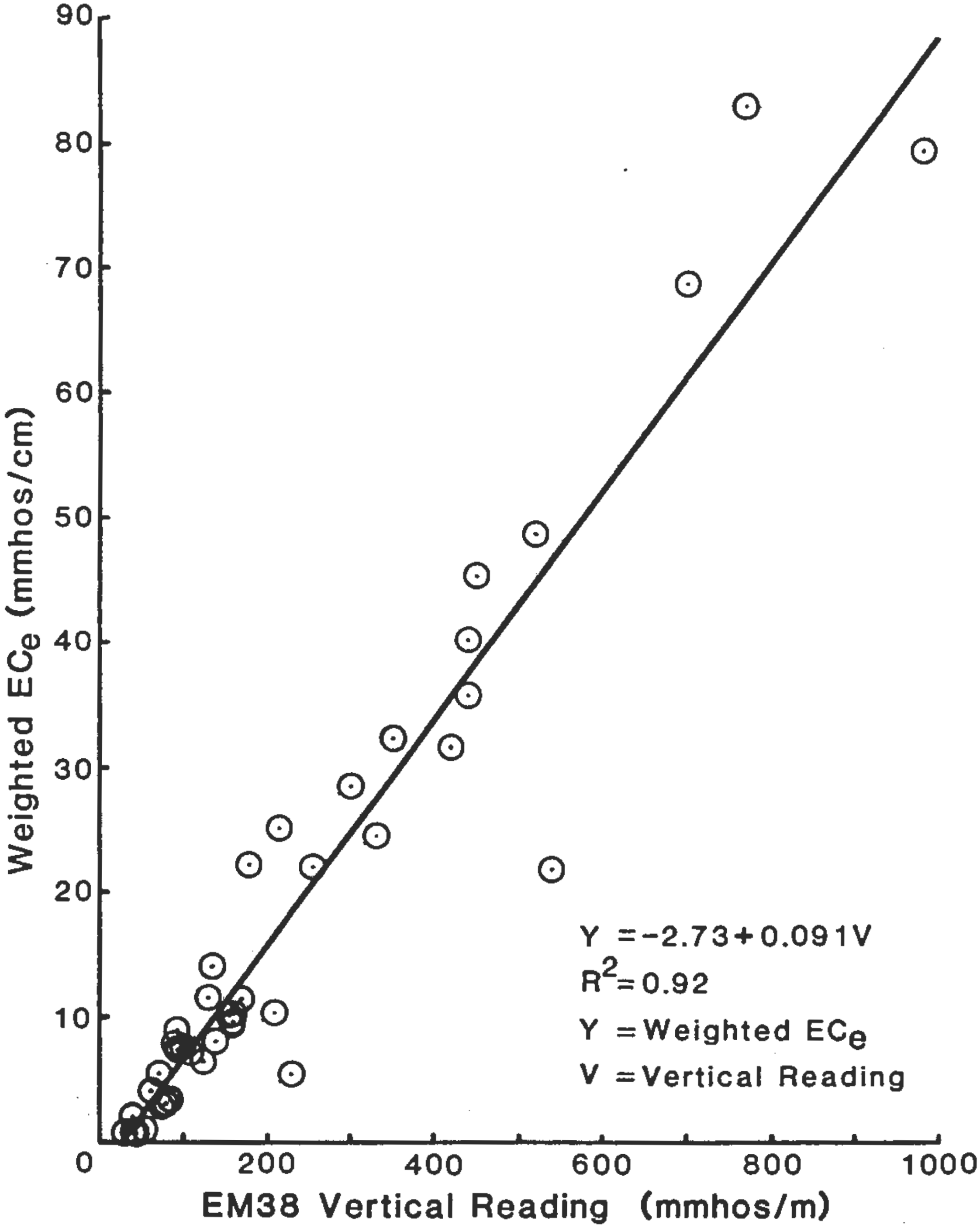


Figure A 2-2. Relation of EM38 vertical reading to weighted soil electrical conductivity (WEC_e) to a depth of 7 feet.

$$WEC_e = 0.1\ EC_{0-1} + 0.2\ EC_{1-2} + 0.2\ EC_{2-3} + 0.2\ EC_{3-4} + 0.1\ EC_{4-5} + 0.07\ EC_{5-6} + -.03\ EC_{6-7}$$

Appendix Table 2-1: Fossum Site 1: Chemical and Particle Size Data.

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
0-3	0-1	25.7	42.5	28.8	2.8	1.4	229.6	6.8	7.8	46	4.9	41.3	42.6	16.1
	1-1.3	22.0	81.3	51.7	2.7	2.9	149.5	9.6	7.9	46	7.2	40.3	44.7	15.0
	1.3-2	21.3	104.0	59.9	2.3	4.0	178.8	10.5	8.2	42	7.6	31.9	50.4	17.6
	2-3	10.5	78.6	50.0	2.6	3.2	133.4	9.2	8.3	35	7.5	51.2	32.1	16.7
	3-4	6.3	57.8	42.8	2.7	1.9	102.3	5.4	8.3	43	7.6	40.8	44.0	15.2
	4-5	5.0	48.7	36.4	2.7	1.4	86.0	6.6	8.2	50	7.0			
	5-6	20.9	80.0	43.0	1.8	1.8	140.3	8.8	7.7	53	6.1	39.2	36.4	24.4
	6-7	5.0	44.4	49.2	3.0	1.9	93.8	6.1	7.9	51	9.9			
	7-8	22.1	79.1	58.2	1.8	2.9	154.8	9.0	7.7	51	8.2			
	8-9	21.7	72.8	49.8	1.8	3.9	138.6	8.9	7.6	46	7.3			
	9-10	22.3	71.8	28.3	1.5	2.4	118.6	8.6	7.7	49	4.1	40.8	35.4	23.8
2-0.5	0-1	26.9	78.6	35.5	2.0	35.6	103.4	9.5	7.9	49	4.9	36.7	37.0	26.3
	1-2	15.5	67.4	35.8	1.9	31.7	85.1	8.4	8.0	51	5.6	37.5	34.5	28.0
	2-3	7.5	47.2	30.3	2.0	31.9	51.1	6.7	8.0	48	5.8			
	3-4	25.9	52.6	27.3	2.3	27.0	76.4	7.5	7.2	48	4.4	41.6	35.5	22.9
	4-5	27.1	43.7	19.8	4.9	18.2	67.4	6.4	7.4	48	3.3			
	5-6	24.7	52.8	21.7	3.2	10.7	85.3	6.5	7.6	50	3.5			
	6-7	22.6	65.7	26.3	1.9	6.8	105.9	7.3	7.6	53	4.0	40.1	35.8	24.1
	7-8	24.1	69.1	28.5	1.9	4.3	115.5	7.6	7.7	50	4.2			
	8-9	23.5	65.3	28.8	2.9	4.1	110.6	7.5	7.6	48	4.3			
	9-10	22.2	65.2	31.1	1.9	2.8	113.8	7.5	7.6	47	4.7			
	10-11	23.1	61.7	30.8	1.1	4.1	110.4	7.5	7.8	53	4.7	40.1	36.0	23.9
	11-12	23.0	58.2	30.8	2.0	4.3	105.6	7.5	7.7	54	4.8			

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
2-3	0-1	28.0	39.3	52.8	3.5	5.5	111.1	5.9	7.5	52	9.1	34.8	45.8	19.4
	1-1.5	22.6	70.9	53.5	2.0	7.4	137.7	8.5	7.7	52	7.8	27.4	41.2	31.4
	1.5-2	20.9	80.0	61.7	2.1	11.4	149.1	8.8	7.8	57	8.7	21.9	43.4	34.7
	2-3	20.3	80.2	63.4	1.5	15.9	146.5	8.5	7.9	50	9.0	33.7	42.1	24.2
	3-4	23.9	67.8	29.0	2.0	14.9	103.8	8.3	7.5	52	4.3			
	4-5	23.7	70.9	30.9	0.7	16.3	108.5	8.4	7.6	48	4.5	40.4	34.8	24.8
	5-6	22.6	67.3	30.0	2.8	8.4	108.8	7.8	7.6	50	4.5			
	6-7	22.4	64.6	31.7	1.8	3.1	113.8	7.6	7.6	50	4.8			
	7-8	21.9	67.2	31.9	1.8	1.6	117.6	7.7	7.7	50	4.8			
	8-9	22.2	66.3	31.4	1.8	1.6	116.6	7.6	7.7	50	4.7			
	9-10	22.0	62.0	32.5	2.1	2.4	112.1	7.6	7.7	49	5.0	40.0	36.2	23.8
2-5	0-1	4.6	2.5	1.0	4.9	2.4	0.9	1.1	7.7	46	0.6	47.1	37.6	15.3
	1-2	3.7	3.2	1.6	4.2	2.2	2.2	0.9	7.9	42	0.9	51.6	35.5	12.9
	2-3	2.8	21.9	11.8	3.5	3.7	29.3	2.9	8.2	50	3.4	43.0	37.3	19.7
	3-4	2.2	26.2	15.5	3.1	4.3	36.4	3.5	8.1	57	4.1			
	4-5	2.2	21.9	15.5	4.1	3.3	32.1	3.3	8.1	50	4.5	40.0	35.8	24.2
	5-6	3.6	33.2	19.5	2.6	3.6	50.1	4.3	8.1	49	4.6			
	6-7	22.0	74.0	29.1	2.2	4.4	118.5	8.3	7.8	48	4.2			
	7-8	22.4	104.4	37.5	2.2	4.6	157.5	10.1	7.9	48	4.7			
	8-9	22.3	105.5	37.8	2.7	4.8	158.1	10.2	7.9	50	4.7			
	9-10	22.1	99.7	37.9	1.9	4.6	153.1	9.8	7.8	48	4.9	40.2	35.6	24.2
2-6	0-1	5.2	2.2	1.1	3.6	2.9	2.0	1.1	7.8	30	0.6			
	1-2	21.2	10.2	1.8	3.2	1.3	28.8	2.5	7.6	31	0.5	57.1	29.5	13.4
	2-3	9.9	28.0	12.6	3.6	3.1	43.9	3.8	8.0	31	2.9	48.4	40.3	11.3
	3-4	5.8	41.3	37.4	2.7	5.9	75.9	6.4	8.2	36	7.7			
	4-5	10.1	86.7	46.9	2.8	4.5	136.4	9.3	8.1	31	6.8	53.3	34.4	12.3
	5-6	14.8	139.4	69.9	3.2	5.1	215.9	13.0	8.1	28	8.0			
	6-7	20.4	115.6	63.0	2.2	4.0	192.9	12.2	8.0	31	7.6			
	7-8	15.8	84.3	50.5	2.8	3.2	144.5	9.8	8.0	35	7.1			
	8-9	13.2	86.1	51.5	3.2	3.0	93.0	10.4	8.0	33	7.3			
	9-10	21.6	107.1	55.8	2.3	3.8	178.4	11.5	8.1	33	7.0	46.7	38.2	15.1

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
4-0.5	0-1	89.7	61.8	5.1	1.6	146.3	8.6	15.4	6.7	39	0.6	53.4	33.3	13.3
	1-2	42.8	44.7	2.0	3.6	57.8	28.2	9.0	6.4	32	0.3	72.7	16.7	10.6
	2-3	43.0	37.4	1.6	3.2	80.0	0.0	8.5	7.1	47	0.3			
	3-4	46.6	35.5	1.5	1.8	77.5	4.3	8.5	7.3	48	0.2			
	4-5	52.2	41.2	2.2	2.3	87.3	0.0	9.4	7.4	49	0.3	40.9	36.0	23.1
	5-6	71.6	66.5	4.7	2.0	110.0	30.8	11.7	7.4	49	0.6			
	6-7	62.9	79.8	32.0	2.1	179.2	0.0	14.2	7.2	48	3.8			
	7-8	56.1	81.1	31.7	2.5	157.3	9.1	16.2	7.2	47	3.8			
	8-9	56.9	75.6	38.3	4.6	159.7	6.4	16.5	7.3	46	4.7			
	9-10	56.4	61.8	35.4	1.6	134.1	17.9	16.0	7.3	48	4.6			
	10-11	46.5	40.0	24.0	0.3	157.5	0.0	13.7	7.2	50	3.7	40.6	36.6	22.8
	11-12	45.1	40.0	10.8	1.3	89.7	4.9	9.7	7.3	48	1.7			
	12-13	27.5	19.0	2.2	1.9	48.3	0.0	5.3	7.4	47	0.5			
	13-14	20.5	14.2	1.9	2.7	36.1	0.0	4.2	7.4	49	0.5			
	14-15	23.9	16.5	2.5	6.1	40.9	0.0	4.6	7.3	46	0.6			
4-3	0-1	17.2	13.8	316.4	5.2	321.7	20.5	33.6	7.5	53	80.0	36.4	44.6	19.0
	1-2	4.0	2.6	149.9	6.1	153.1	0.0	16.8	8.1	69	82.0	29.7	46.6	23.7
	2-3	2.3	1.2	105.8	4.1	97.0	8.1	14.3	8.3	85	79.0	30.0	43.7	26.3
	3-4	2.8	1.6	124.8	4.3	112.2	12.7	13.0	8.2	97	84.0			
	4-5	9.7	5.9	258.9	2.4	280.8	0.0	26.2	7.8	58	93.0	40.0	35.4	24.6
	5-6	18.7	10.2	433.4	8.6	455.4	0.0	42.6	7.6	55	114.0			
	6-7	45.0	23.5	755.8	2.0	854.7	0.0	69.3	7.8	51	129.0			
	7-8	52.9	29.1	861.4	2.6	961.5	0.0	82.1	7.3	46	134.0			
	8-9	91.6	48.1	1299.4	2.0	1525.5	0.0	123.2	7.2	39	155.0			
	9-10	83.2	41.4	1140.3	1.7	1280.1	0.0	105.2	7.2	43	144.0	41.7	35.1	23.2
4-5	0-1	4.6	3.5	33.7	5.3	24.5	12.0	4.8	7.7	52	17.0	41.8	40.3	17.9
	1-2	1.2	0.9	27.0	4.5	20.1	4.6	3.4	7.3	46	26.0	40.2	40.6	19.2
	2-3	1.1	0.8	29.0	4.4	22.9	3.5	3.4	7.7	51	30.0	47.6	38.5	13.9
	3-4	1.2	0.7	36.4	4.1	32.2	1.9	4.1	8.1	55	37.0	52.1	33.1	14.8

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		----------------	----------------	meq/l	----------------	----------------	----------------	(mmhos/cm)		%		-------	%	-------
4-5	4-5	2.0	1.1	60.9	3.4	55.3	5.2	7.1	8.1	59	49.0	39.6	43.2	17.2
	5-6	2.4	1.0	100.4	3.5	89.6	10.7	11.2	8.2	58	77.0	44.6	36.8	18.6
	6-7	6.7	2.8	240.9	2.9	231.6	15.8	24.3	8.0	59	110.0	44.9	33.9	21.2
	7-8	8.3	4.3	208.5	3.0	203.9	14.2	21.9	8.0	41	83.0	62.8	26.7	10.5
	8-9	15.0	6.3	374.0	2.7	414.5	0.0	38.4	7.9	47	114.0			
	9-10	30.8	13.3	587.9	4.7	674.6	0.0	60.0	7.5	47	125.0	40.3	36.0	23.7
4-6	0-1	50.4	83.2	39.4	2.8	161.5	8.8	15.5	7.5	46	4.8	38.6	45.2	16.2
	1-2	77.5	166.8	87.4	1.4	316.4	14.0	29.9	7.8	42	7.9	37.2	41.0	21.8
	2-3	83.2	148.2	126.3	1.4	294.8	61.5	32.5	7.6	42	12.0	37.2	36.5	26.2
	3-4	104.4	132.8	270.1	1.5	702.4	0.0	45.7	7.4	41	25.0			
	4-5	112.3	102.5	424.9	1.2	739.7	0.0	57.2	7.6	37	41.0	27.1	53.2	19.8
	5-6	135.1	99.5	628.7	3.6	897.2	0.0	70.1	7.5	34	58.0			
	6-7	111.6	63.7	795.5	2.6	991.2	0.0	77.7	7.4	38	85.0			
	7-8	107.1	57.0	1065.4	1.6	1200.6	27.4	97.6	7.0	49	118.0			
	8-9	129.9	70.3	1249.4	2.0	1459.9	0.0	108.4	7.3	31	125.0			
	9-10	97.8	48.4	957.7	2.4	1267.9	0.0	90.4	7.3	44	112.0	31.9	47.6	20.5
4.6-3	0-1	82.4	55.7	479.3	5.2	569.0	43.2	53.9	7.2	49	58.0	40.0	40.7	19.3
	1-2	65.1	48.7	525.1	6.3	585.5	47.0	55.0	7.2	51	70.0	38.4	40.8	20.7
	2-3	57.9	69.4	416.4	2.4	604.3	0.0	55.5	7.5	53	52.0	41.5	38.4	20.1
	3-4	76.4	100.7	638.0	7.9	786.2	21.0	66.2	7.5	51	68.0	42.5	38.3	19.2
	4-5	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	5-6	66.2	24.1	1141.8	2.6	1238.6	0.0	101.3	7.3	43	170.0			
	6-7	60.5	27.3	1015.5	7.9	1118.0	0.0	98.9	7.4	43	153.0	44.9	35.9	19.2
	7-8	55.7	27.2	1017.0	3.0	1123.8	0.0	96.7	7.5	48	158.0			
	8-9	49.9	26.2	1173.0	3.4	1349.6	0.0	102.4	7.6	48	190.0	35.8	39.9	24.3
	9-10	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	10-11	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	11-12	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	12-13	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	13-14	111.3	49.6	1527.1	1.8	1759.4	0.0	122.0	7.2	41	17.0			
	14-15	102.6	48.2	896.9	2.6	1017.2	27.7	87.4	7.2	49	103.0	39.5	35.0	25.5

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
6-0.5	0-1	68.3	127.2	54.9	4.0	195.1	51.4	21.1	7.5	39	5.6	54.7	28.9	16.4
	1-2	59.7	115.3	38.0	2.5	181.9	28.6	19.1	7.6	35	4.1	58.2	25.8	16.0
	2-3	122.0	122.5	37.5	2.3	248.8	30.9	24.7	7.4	34	3.4	60.7	25.8	13.5
	3-4	104.9	98.6	34.0	3.9	203.9	29.7	21.0	7.3	51	3.4			
	4-5	101.4	112.5	38.7	2.6	217.0	32.8	22.3	7.3	48	3.7			
	5-6	97.7	115.2	41.6	1.0	217.3	36.2	22.6	7.3	49	4.0	39.0	35.8	25.2
	6-7	88.1	104.2	40.0	1.4	203.9	27.1	20.6	6.9	53	4.1			
	7-8	81.7	100.1	40.9	1.5	205.6	15.5	20.4	7.1	46	4.3			
	8-9	81.2	102.8	46.4	1.3	220.7	8.3	21.3	7.1	50	4.8			
	9-10	74.2	86.1	38.8	1.5	184.9	12.8	18.9	7.2	48	4.3			
	10-11	38.3	35.0	15.0	2.0	80.3	5.8	8.9	7.4	49	2.5	40.3	35.3	24.4
	11-12	27.7	25.6	11.1	3.4	55.1	6.0	6.5	7.4	51	2.2			
	12-13	10.8	8.7	5.3	2.0	14.6	8.1	2.6	7.6	49	1.7			
	13-14	6.5	5.2	4.2	3.0	6.8	6.3	1.6	7.5	48	1.8			
	14-15	5.4	4.3	4.1	2.5	4.3	6.9	1.4	7.6	47	1.9			
6-3	0-1	71.6	79.6	357.9	2.0	495.8	11.3	49.5	7.4	49	41.0	38.9	39.2	21.9
	1-2	90.6	92.0	475.3	2.6	611.6	43.7	55.2	7.2	49	50.0	36.7	44.4	18.9
	2-3	139.6	125.6	674.9	1.4	939.6	0.0	76.9	7.3	43	59.0	25.8	55.5	18.7
	3-4	154.2	116.7	942.1	1.8	1290.0	0.0	99.6	7.2	44	81.0			
	4-5	149.0	94.2	1297.4	1.4	1583.3	0.0	117.2	7.2	45	118.0	15.3	62.5	22.2
	5-6	144.7	86.3	1436.6	1.4	1725.4	0.0	118.3	7.2	50	134.0			
	6-7	104.5	66.3	1014.4	1.4	1202.9	0.0	94.0	7.3	47	110.0			
	7-8	102.1	66.5	923.4	1.5	1019.1	71.4	91.1	7.4	48	101.0			
	8-9	90.7	58.8	896.9	1.4	1082.7	0.0	86.4	7.4	48	104.0			
	9-10	85.2	53.5	847.0	1.6	1028.7	0.0	83.6	7.4	50	102.0	39.6	35.7	24.7
	10-11	93.6	56.0	905.2	1.6	1126.3	0.0	86.0	7.4	48	105.0			
	11-12	89.1	52.4	915.6	1.4	1065.5	0.0	84.9	7.4	49	109.0			
	12-13	90.2	56.8	846.3	1.4	1032.5	0.0	84.1	7.4	48	99.0			
	13-14	90.4	57.8	773.1	2.2	960.8	0.0	79.2	7.3	48	90.0			
	14-15	98.3	68.3	755.8	1.6	946.9	0.0	78.2	7.3	49	83.0	39.8	35.4	24.8

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
6-5	0-1	45.9	49.4	72.2	3.2	113.8	50.5	15.0	7.6	49	10.0	46.8	40.4	12.8
	1-2	68.2	181.3	219.1	3.8	439.2	25.6	39.2	7.6	43	20.0	37.5	42.2	20.3
	2-3	57.6	218.6	368.4	1.8	633.9	8.8	53.6	7.6	48	31.0	23.2	53.6	23.2
	3-4	109.8	238.0	881.2	1.8	1224.9	2.4	94.0	7.4	36	67.0	47.9	39.8	12.3
	4-5	158.0	133.2	1430.1	1.6	1584.0	135.7	122.0	7.3	38	119.0			
	5-6	116.8	94.8	1333.7	3.2	1607.2	0.0	114.8	7.3	50	130.0	11.5	60.0	28.5
	6-7	94.1	82.3	1109.0	1.4	1396.7	0.0	102.1	7.1	32	118.0			
	7-8	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	8-9	71.4	76.7	843.9	2.4	967.1	22.5	85.1	7.4	39	98.0			
	9-10	86.3	97.4	608.9	2.0	706.3	84.5	67.1	7.4	40	64.0	39.6	36.3	24.1
6-6	0-1	5.3	3.8	10.8	3.9	6.3	9.8	2.2	7.5	48	5.1	45.2	24.2	12.4
	1-2	15.3	12.6	40.5	2.7	46.0	19.7	7.0	7.6	38	11.0	50.9	36.8	12.3
	2-3	82.3	83.5	98.6	1.4	225.8	37.2	23.9	7.5	37	11.0	41.3	42.5	16.1
	3-4	143.0	156.5	156.4	1.1	390.5	64.3	41.7	7.6	39	13.0	37.6	46.2	16.2
	4-5	199.5	215.3	278.0	1.1	700.8	0.0	54.2	7.3	36	19.0			
	5-6	304.2	257.1	590.8	0.7	1061.3	90.1	82.5	7.1	37	35.0			
	6-7	233.0	155.3	764.3	1.0	1088.8	62.8	84.8	7.1	34	55.0	48.7	34.4	16.9
	7-8	-----	-----	------	----	------	-----	-----	---	---	-----	----	----	----
	8-9	156.9	94.4	745.9	4.2	994.3	0.0	74.3	7.3	42	67.0			
	9-10	118.2	72.4	638.6	2.0	779.9	47.4	67.4	7.3	46	65.0	41.0	35.7	23.3
6-7	0-1	11.2	32.0	9.3	3.6	5.7	43.1	5.2	7.7	39	2.0	54.0	34.3	11.7
	1-2	11.5	50.3	47.9	6.7	7.1	95.8	7.3	8.2	34	8.6	53.6	31.4	15.0
	2-3	13.1	121.0	61.8	1.6	17.2	177.1	11.7	8.1	44	7.5	32.9	49.8	17.3
	3-4	11.2	90.5	39.3	0.6	9.5	130.8	8.9	8.1	51	5.5			
	4-5	8.0	97.9	39.9	2.8	18.1	124.8	9.0	8.0	43	5.5	46.7	32.9	20.4
	5-6	22.3	101.5	40.8	2.2	18.1	144.3	10.0	8.0	48	5.2	40.3	35.7	24.0
	6-7	21.9	82.0	40.8	2.0	10.0	132.6	9.2	7.9	33	5.7			
	7-8	22.2	70.9	37.5	2.0	9.5	119.1	8.7	7.9	45	5.5			
	8-9	21.5	64.6	36.9	2.6	6.2	114.1	8.2	7.9	47	5.6			
	9-10	21.6	57.9	35.8	2.4	2.8	110.1	7.7	7.4	49	5.7	40.2	36.3	23.5

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
7-0.5	0-1	60.6	55.9	14.6	4.1	114.1	12.9	12.3	7.2	41	1.9	48.9	34.4	16.7
	1-2	23.8	25.7	6.9	2.4	48.3	5.8	5.7	7.2	34	1.4	51.3	30.5	18.2
	2-3	47.9	90.1	10.5	1.8	133.6	13.0	14.0	7.2	30	1.3	82.7	9.0	8.3
	3-4	162.6	224.4	46.6	1.6	419.0	13.0	40.3	7.0	34	3.4	67.9	24.2	7.9
	4-5	178.5	199.9	164.2	1.8	468.3	72.5	45.8	6.9	54	12.0	30.5	46.0	23.5
	5-6	179.6	199.1	354.1	1.9	549.4	181.3	51.5	7.2	48	26.0			
	6-7	119.0	115.5	460.8	1.2	706.7	0.0	60.9	7.2	45	43.0			
	7-8	111.7	109.4	499.5	2.7	724.9	0.0	62.6	7.2	45	48.0			
	8-9	118.2	114.5	352.3	1.8	544.5	38.7	47.1	7.3	43	33.0			
	9-10	83.7	88.8	312.7	4.2	482.4	0.0	42.3	7.3	47	34.0			
	10-11	81.4	85.9	211.1	1.4	428.7	0.0	36.7	7.3	48	23.0	41.2	35.3	23.5
	11-12	101.8	101.0	107.5	1.3	282.3	26.8	25.7	7.4	49	11.0			
	12-13	91.8	79.6	48.0	1.7	155.6	62.2	14.9	7.4	48	5.2			
	13-14	61.3	47.3	23.8	2.6	67.8	61.9	10.4	7.5	46	3.2			
	14-15	43.9	31.7	26.2	2.9	87.3	11.6	9.7	7.6	50	4.3	40.4	37.2	22.4
7-3.0	0-1	19.4	14.1	153.1	3.4	180.8	2.4	20.0	7.7	49	37.0	41.2	40.1	18.7
	1-2	19.7	16.5	146.4	2.0	177.0	3.6	17.8	7.9	38	34.0	35.7	44.4	19.9
	2-3	50.3	61.6	299.4	1.8	389.2	20.3	40.3	7.7	34	40.0	50.3	38.3	11.4
	3-4	57.5	120.2	409.0	1.2	578.4	7.1	51.9	7.7	42	43.0	36.5	46.5	17.0
	4-5	32.5	97.5	329.5	1.8	462.7	0.0	42.5	7.7	47	41.0			
	5-6	63.8	133.4	399.4	1.4	533.9	61.3	49.8	7.7	48	40.0	40.2	36.2	23.6
	6-7	57.5	141.7	413.0	1.6	525.3	85.3	53.4	7.7	44	41.0			
	7-8	49.6	150.1	339.1	1.4	453.1	84.3	44.7	7.5	45	34.0			
	8-9	45.1	181.3	269.8	1.4	384.7	110.2	40.4	7.7	45	25.0			
	9-10	40.3	170.8	176.7	1.6	278.0	108.2	30.1	7.8	44	17.0	39.6	38.7	21.7
8-3	0-1	12.1	8.9	108.3	3.7	111.1	14.6	13.2	7.5	56	33.0	35.2	45.1	19.7
	1-2	7.8	6.0	74.7	2.0	89.0	0.0	9.8	7.2	46	28.0	36.8	46.3	16.9
	2-3	6.2	4.6	73.5	2.2	77.5	4.7	8.8	7.4	44	31.0	57.7	27.2	15.1
	3-4	6.8	4.6	91.3	2.0	102.4	0.0	10.4	7.5	44	38.0	72.0	16.1	11.9

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO3	Cl	SO4	EC	pH	SATN %	SAR	SAND	SILT	CLAY
		----------------	meq/l	----------------				(mmhos/cm)				--------	%	--------
8-3	4-5	12.1	7.8	86.3	2.0	104.3	0.0	10.8	7.6	46	27.0			
	5-6	17.5	9.5	66.2	1.8	91.3	0.1	9.9	8.1	48	18.0	38.8	39.8	21.4
	6-7	41.8	22.4	78.0	1.4	143.0	0.0	14.3	7.7	40	14.0			
	7-8	56.8	34.6	83.0	1.4	170.4	2.7	16.7	7.5	41	12.0			
	8-9	62.9	43.1	89.9	1.1	174.8	19.8	17.5	7.5	39	12.0			
	9-10	54.5	39.7	67.1	1.6	153.9	5.8	15.6	7.5	42	9.8	47.8	34.7	17.5
8-5	0-1	30.5	26.4	7.0	4.0	22.4	37.4	5.5	7.4	34	1.3	52.6	35.6	11.8
	1-2	23.8	50.4	23.5	3.6	9.5	84.5	6.6	7.7	32	3.9	57.4	29.9	12.7
	2-3	22.5	74.3	26.1	2.6	12.4	107.9	8.6	7.9	42	3.8	39.4	35.8	24.8
	3-4	8.9	40.1	19.8	3.0	11.0	54.7	5.3	7.9	43	4.0			
	4-5	8.8	36.0	20.5	3.0	6.2	56.1	5.2	7.9	40	4.3	40.4	35.8	23.8
	5-6	23.8	59.8	23.7	2.0	22.9	82.3	7.4	7.8	40	3.7			
	6-7	15.2	56.7	23.5	2.6	18.1	74.6	7.3	7.7	40	3.9			
	7-8	24.6	56.1	22.1	2.4	18.1	82.3	7.1	7.7	38	3.5			
	8-9	23.8	56.0	21.9	2.6	13.4	85.8	6.8	7.7	39	3.5			
	9-10	23.6	54.4	20.9	2.6	8.6	87.8	6.6	7.7	39	3.4	41.2	36.6	22.2
8-6	0-1	12.5	6.3	3.0	3.6	12.4	5.7	2.4	7.7	44	1.0			
	1-2	24.2	25.7	29.0	3.0	13.4	62.5	5.6	7.8	40	5.8	52.8	33.9	13.4
	2-3	12.9	53.1	50.0	4.2	49.2	62.5	8.9	8.2	32	8.7	60.0	26.1	14.0
	3-4	9.2	65.9	41.3	2.4	55.5	58.5	8.9	8.1	44	6.8	36.4	48.6	15.0
	4-5	13.5	86.7	46.6	3.2	50.2	93.4	10.3	8.1	33	6.6			
	5-6	9.9	84.7	41.3	2.6	33.0	100.3	9.7	8.3	28	6.0			
	6-7	11.4	95.9	47.7	4.2	41.6	109.1	10.3	8.1	27	6.5			
	7-8	11.3	93.6	42.6	3.6	32.5	111.5	9.9	8.2	29	5.9			
	8-9	5.7	112.9	51.1	2.6	55.9	111.2	11.6	8.1	29	6.6	78.8	17.1	4.1
9-0.5	0-1	23.0	67.8	31.5	4.1	16.5	101.7	8.2	7.6	64	4.7	27.8	39.8	32.4
	1-2	20.5	72.7	38.1	2.0	10.0	119.4	8.2	7.9	60	5.6	28.3	34.7	37.0
	2-3	18.2	64.9	34.9	5.2	8.5	104.3	7.7	7.9	50	5.4	38.5	35.1	26.4
	3-4	22.2	57.5	27.6	1.8	6.8	98.7	7.4	7.8	50	4.4			
	4-5	22.2	54.9	25.5	1.8	4.3	96.4	6.9	7.7	48	4.1	38.5	36.7	24.8

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%	%			
9-0.5	5-6	21.2	63.1	32.3	2.0	4.3	110.2	7.6	7.8	49	5.0			
	6-7	13.5	74.2	37.0	1.8	4.1	118.7	8.9	7.6	51	5.6			
	7-8	21.0	81.5	46.0	2.9	3.9	141.7	9.4	7.8	53	6.4			
	8-9	20.6	75.7	46.0	2.3	5.1	134.9	9.4	7.9	52	6.6	40.4	36.2	23.4
	9-10	18.6	65.8	42.9	3.2	5.1	119.0	8.6	7.8	52	6.6			
	10-11	21.5	57.6	39.8	2.2	4.1	112.6	8.2	7.8	52	6.3			
	11-12	20.9	53.4	38.0	2.5	4.3	105.4	7.7	7.8	49	6.2			
	12-13	21.9	51.2	36.0	2.4	4.3	102.3	7.5	7.7	50	6.0			
	13-14	21.3	44.4	35.0	3.3	3.9	93.6	7.0	7.7	48	6.1			
	14-15	21.1	40.2	32.3	3.4	4.8	85.4	6.6	7.7	51	5.8	39.5	36.0	24.5
9-3	0-1	6.0	3.9	46.3	3.4	44.0	8.7	6.3	7.6	52	21.0	37.2	45.7	17.1
	1-2	10.7	6.9	58.6	3.1	53.4	19.6	7.5	7.8	40	20.0	50.0	35.8	14.2
	2-3	28.9	38.4	62.9	2.2	51.6	76.4	10.9	7.8	40	11.0	47.0	34.4	18.6
	3-4	14.8	58.8	46.9	2.2	61.0	57.4	10.4	8.0	49	7.7			
	4-5	11.3	60.6	49.4	2.4	69.0	49.8	10.4	8.0	46	8.2	38.9	40.0	21.1
	5-6	25.9	77.7	50.8	1.8	57.2	95.3	11.7	7.9	45	7.1			
	6-7	16.5	69.1	46.9	2.4	41.2	88.8	10.1	7.9	46	7.2			
	7-8	23.0	92.1	46.5	1.8	25.9	133.8	10.4	7.9	47	6.1			
	8-9	12.5	51.0	31.2	2.8	8.6	83.4	6.8	8.1	50	5.5	39.9	36.4	23.7
	9-10	22.1	52.5	28.6	2.5	5.5	95.2	6.7	7.9	49	4.7			
	10-11	21.4	34.7	22.8	2.3	3.9	72.8	5.5	7.7	51	4.3			
	11-12	21.2	28.1	20.1	2.2	2.4	64.8	5.0	7.7	49	4.1			
	12-13	21.7	24.9	18.9	2.5	3.2	59.8	4.8	7.8	48	3.9	39.6	36.5	23.9
11-0.5	0-1	24.1	57.3	41.4	4.9	16.5	101.3	8.1	7.7	48	6.5	27.7	51.1	21.2
	1-2	15.6	77.9	57.3	2.6	11.4	136.9	9.9	8.1	44	8.4	18.0	60.9	21.1
	2-3	17.6	78.5	60.2	2.1	8.9	145.3	10.3	8.0	58	8.7	5.7	69.1	25.3
	3-4	21.4	64.5	47.8	1.8	7.3	124.6	9.2	7.9	55	7.3	11.6	62.2	26.2
	4-5	20.3	88.5	61.6	1.8	6.9	161.7	10.8	7.8	63	8.4			
	5-6	21.2	123.7	73.4	1.8	6.8	209.7	12.6	7.9	57	8.6	8.1	66.2	25.7

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
11-0.5	6-7	21.6	115.3	70.7	3.6	11.5	192.5	12.9	8.0	48	8.6			
	7-8	21.7	119.3	70.3	1.7	5.8	203.8	11.6	8.1	50	8.4			
	8-9	20.5	118.2	69.1	1.7	5.3	200.8	12.0	8.0	48	8.3	34.8	39.9	25.3
	9-10	20.7	115.6	64.9	1.7	4.6	195.0	12.2	8.0	52	7.9			
	10-11	20.9	114.2	64.8	2.0	4.5	193.4	11.8	8.0	52	7.9			
	11-12	21.2	121.5	65.5	1.7	4.7	201.7	11.8	8.1	50	7.8			
	12-13	21.3	127.7	62.7	2.0	4.8	204.9	11.7	8.1	50	7.3			
	13-14	18.1	105.9	55.8	1.8	4.0	174.0	10.9	8.0	53	7.1			
	14-15	22.0	109.0	53.9	1.8	3.9	179.2	10.9	8.0	49	6.7	40.0	35.5	24.5
11-3	0-1	23.4	27.1	12.2	3.2	2.7	56.8	4.4	7.9	46	2.4	43.7	39.6	16.7
	1-2	8.6	88.4	47.1	3.2	4.6	136.4	9.0	8.3	48	6.8	35.6	37.9	26.5
	2-3	4.5	47.7	34.2	2.3	4.5	79.7	6.2	8.2	56	6.7	48.0	31.5	20.5
	3-4	4.9	43.0	34.9	4.8	6.9	71.1	6.1	8.1	54	7.1			
	4-5	4.7	36.1	33.6	1.0	5.5	68.0	5.6	8.1	46	7.4	38.8	37.5	23.7
	5-6	4.8	32.5	32.1	3.5	3.1	62.9	5.2	8.1	47	7.4			
	6-7	5.5	31.3	29.9	2.8	6.5	57.3	5.2	7.8	52	7.0			
	7-8	19.4	14.1	36.7	3.0	4.6	62.6	7.8	7.7	51	9.0			
	8-9	19.7	16.3	38.4	1.9	3.2	69.3	8.0	7.7	51	9.1			
	9-10	22.1	59.5	38.6	2.2	3.2	114.8	8.3	7.7	48	6.1	30.3	40.9	23.8

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO3	Cl	SO4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
2-0	0-1	24.8	39.7	15.8	2.3	0.8	77.3	5.5	7.1	55	2.8			
	1-2	13.8	81.5	49.8	1.9	3.3	139.9	9.6	7.8	47	7.2			
	2-3	9.8	103.8	55.1	2.1	5.3	161.1	10.7	8.0	42	7.3			
	3-4	10.4	106.6	52.3	1.7	5.1	162.4	10.9	7.9	53	6.8			
	4-5	21.2	136.9	59.3	1.3	6.7	209.4	13.1	7.9	50	6.7			
	5-6	21.7	125.2	58.2	1.1	6.8	197.2	12.5	7.9	56	6.8			
	6-7	21.7	128.7	57.5	1.2	7.6	199.1	12.6	7.9	52	6.6			
	7-8	21.1	122.6	54.4	1.4	5.5	191.1	12.0	7.9	54	6.4			
	8-9	22.4	112.8	50.9	1.3	4.6	180.2	11.5	7.9	53	6.2			
	9-10	21.9	97.6	47.1	1.3	3.8	161.6	10.6	7.9	54	6.1			
2-8	0-1	3.7	1.9	0.3	4.9	0.3	0.7	0.6	6.9	48	0.2			
	1-2	2.3	1.4	0.4	2.2	0.4	1.4	0.4	7.4	48	0.3			
	2-3	4.2	5.6	2.2	1.8	0.8	9.2	1.1	7.6	50	1.0			
	3-4	17.1	35.1	12.8	1.5	1.4	62.0	4.5	7.5	50	2.5			
	4-5	23.4	54.9	19.3	1.4	1.3	94.9	6.3	7.6	48	3.1			
	5-6	21.5	63.5	23.6	1.3	1.3	106.0	6.8	7.6	49	3.6			
	6-7	22.2	71.7	24.8	1.3	0.8	116.4	7.4	7.6	51	3.6			
	7-8	21.6	67.1	24.1	1.4	1.3	110.0	7.2	7.7	49	3.6			
	8-10	22.4	44.8	19.3	1.6	1.3	83.5	5.6	7.7	51	3.3			
4-0	0-1	2.5	1.5	0.4	3.4	0.4	0.5	0.4	7.8	39	0.3			
	1-2	6.3	3.5	0.9	2.1	4.7	4.0	1.1	8.0	34	0.4			
	2-3	10.3	25.3	1.0	1.9	30.6	4.0	3.9	7.8	38	0.2			
	3-4	8.6	25.7	1.1	1.6	30.3	3.5	3.8	7.9	57	0.3			
	4-5	4.7	6.0	0.8	1.8	9.1	0.6	1.3	7.9	46	0.4			
	5-6	2.7	2.9	0.6	2.2	3.1	0.9	0.7	7.8	51	0.4			
	6-7	2.8	2.8	0.6	2.1	4.5	0.0	0.7	7.9	50	0.4			
	7-8	3.2	3.0	0.6	1.7	4.8	0.2	0.8	7.8	52	0.4			
	8-9	3.2	2.8	0.6	1.7	4.3	0.6	0.8	7.8	51	0.4			
	9-10	3.2	2.5	0.6	1.9	4.4	0.1	0.7	7.8	51	0.4			

Continued
Appendix Table 2-1

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
4-7	0-1	28.4	28.8	9.3	2.2	6.3	58.0	4.9	7.6	40	1.7			
	1-2	25.5	47.1	22.9	1.5	16.9	77.2	6.8	7.8	32	3.8			
	2-3	6.3	31.5	23.8	2.0	29.8	29.6	5.4	8.0	47	5.5			
	3-4	9.3	48.5	31.2	1.0	59.6	28.4	8.1	8.0	48	5.8			
	4-5	20.9	86.7	39.6	1.1	113.0	33.0	13.1	7.8	47	5.4			
	5-6	27.9	19.7	4.7	1.1	7.5	43.7	3.8	7.7	47	1.0			
	6-7	26.7	20.6	5.5	1.2	2.3	49.3	3.7	7.7	47	1.1			
	7-8	24.9	26.4	9.4	1.2	1.2	58.3	4.3	7.6	46	1.9			
	8-9	23.5	31.6	13.1	1.1	0.8	66.3	4.8	7.7	48	2.5			
	9-10	23.1	34.4	17.1	1.1	0.8	72.6	5.2	7.7	47	3.2			
4-8	0-1	2.4	1.3	0.3	3.1	0.3	0.6	0.2	7.6	45	0.2			
	1-2	1.7	2.2	1.1	3.3	0.0	1.7	0.2	7.7	47	0.8			
	2-3	0.4	1.8	5.7	3.3	0.8	3.0	0.2	8.3	48	5.4			
	3-4	0.4	2.4	8.9	4.0	0.5	6.7	1.2	8.4	50	7.4			
	4-5	0.4	3.0	10.5	3.8	0.6	8.8	1.9	8.4	50	8.0			
	5-6	0.7	3.9	11.5	3.1	0.8	11.5	1.6	8.2	49	7.6			
	6-7	9.4	19.4	18.0	1.8	0.8	44.1	3.9	7.9	51	4.7			
	7-8	22.8	39.6	22.8	2.2	1.8	81.2	5.7	7.7	47	4.1			
	8-9	22.9	55.0	29.4	1.7	1.9	103.6	7.0	7.7	49	4.7			
	9-10	21.4	63.2	35.0	1.4	2.4	115.9	7.8	7.8	48	5.4			
6-8	0-1	4.3	3.1	0.8	2.5	0.3	5.4	0.7	7.5	43	0.4			
	1-2	16.8	30.6	11.7	1.9	1.8	55.4	4.3	7.7	50	2.4			
	2-3	7.2	39.9	28.3	1.9	2.9	70.6	5.6	8.0	54	5.8			
	3-4	8.9	37.4	27.3	1.7	2.3	69.5	5.5	7.9	53	5.7			
	4-5	21.7	61.0	33.9	1.4	3.2	112.0	7.5	7.8	48	5.3			
	5-6	21.3	75.2	41.6	1.2	3.4	133.5	8.9	7.9	48	6.0			
	6-7	21.4	88.3	46.7	1.3	4.2	150.9	9.7	7.9	47	6.3			
	7-8	21.2	87.4	46.5	1.4	4.3	149.4	9.6	7.9	47	6.3			
	8-9	20.7	81.2	44.7	1.3	4.0	141.2	9.6	7.9	50	6.3			
	9-10	21.6	81.3	42.9	1.2	3.5	141.1	9.3	7.9	54	6.0			

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
6.5-0	0-1	37.0	58.0	15.5	2.7	54.4	53.4	8.9	7.6	44	2.2			
	1-2	14.5	82.4	26.6	1.4	87.7	34.4	11.0	7.8	42	3.8			
	2-3	23.1	103.3	38.6	1.3	123.5	40.2	14.5	7.8	38	4.9			
	3-4	46.8	137.3	56.0	1.3	200.3	38.6	21.0	7.7	36	5.8			
	4-5	31.5	79.2	42.6	1.4	125.8	26.1	14.0	7.7	47	5.7			
	5-6	20.4	52.7	31.1	0.1	84.1	19.9	9.9	7.8	48	5.1			
	6-7	23.3	49.8	28.3	2.1	80.2	19.2	9.6	7.7	51	4.7			
	7-8	27.9	51.9	27.0	1.1	84.2	21.5	10.1	7.6	50	4.3			
	8-9	33.8	75.7	34.9	1.0	105.1	38.3	13.5	7.7	53	4.7			
	9-10	35.2	79.1	35.7	0.9	120.9	28.1	13.9	7.6	51	4.7			
8-0	0-1	2.1	1.5	0.5	2.2	0.7	1.2	0.2	7.8	47	0.4			
	1-2	2.3	3.5	1.0	1.9	1.8	3.1	0.2	7.9	51	0.6			
	2-3	4.4	16.6	4.2	1.7	2.3	21.2	2.1	8.1	50	1.3			
	3-4	5.6	12.6	4.8	1.9	2.1	19.1	1.9	8.0	50	1.6			
	4-5	25.1	25.0	4.9	1.4	3.7	50.0	4.0	7.7	49	1.0			
	5-6	32.0	116.1	42.4	0.9	163.6	26.0	17.7	7.6	50	4.9			
	6-7	57.9	149.1	68.0	0.7	241.5	32.8	24.1	7.6	47	6.7			
	7-8	59.7	140.0	64.7	0.8	222.6	41.0	23.0	7.5	48	6.5			
	8-9	32.7	115.6	49.2	1.0	142.1	54.4	16.7	7.7	47	5.7			
	9-10	27.1	78.2	34.5	1.0	48.2	90.6	10.3	7.8	49	4.8			
8-8	0-1	2.6	1.6	0.5	4.2	0.0	0.6	0.5	7.2	48	0.3			
	1-2	1.9	3.5	2.8	3.0	0.7	4.4	0.8	7.7	48	1.7			
	2-3	1.4	9.8	12.5	2.6	2.3	18.8	2.2	8.2	56	5.3			
	3-4	3.0	16.6	18.3	2.2	2.7	33.1	3.1	8.1	52	5.9			
	4-5	22.6	52.0	29.2	1.5	2.8	99.5	6.9	7.7	52	4.8			
	5-6	22.6	56.7	32.0	1.4	2.6	107.3	7.2	7.8	52	5.1			
	6-7	22.5	63.0	34.7	1.2	2.7	116.2	7.7	7.8	50	5.3			
	7-8	22.2	59.3	35.9	1.2	3.7	112.5	7.7	7.8	50	5.6			
	8-9	22.7	54.3	35.0	1.3	3.6	107.0	7.3	7.8	50	5.6			
	9-10	22.6	47.0	33.4	1.2	4.0	97.7	7.0	7.8	49	5.7			

Continued
Appendix Table 2-1

Site	Depth	Ca	Mg	Na	HCO3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
11-6	0-1	3.5	9.3	9.5	2.9	12.6	6.8	2.3	7.5	55	3.8			
	1-2	1.5	12.9	10.7	2.1	16.5	6.4	2.6	8.0	53	4.0			
	2-3	2.2	12.2	10.2	1.9	18.1	4.6	2.6	8.0	49	3.8			
	3-4	4.1	11.7	5.9	1.4	17.3	2.9	2.3	7.8	47	2.1			
	4-5	8.6	15.1	2.6	1.5	20.5	4.3	2.8	7.7	38	0.8			
	5-6	6.9	6.8	0.6	1.2	11.6	1.4	1.6	7.6	46	0.2			
	6-7	8.1	6.7	0.5	1.3	12.6	1.4	1.7	7.6	45	0.2			
	7-8	10.1	7.7	0.6	1.2	15.5	1.8	2.1	7.6	45	0.2			
	8-9	9.4	6.8	0.5	1.1	14.6	1.0	1.9	7.6	46	0.2			
	9-10	8.4	5.7	0.4	2.7	0.6	11.2	1.7	7.6	46	0.2			
11-8	0-1	27.8	17.0	22.0	2.2	15.0	49.6	5.3	7.5	47	4.7			
	1-2	29.9	34.0	36.8	2.0	32.7	66.0	7.9	7.7	49	6.5			
	2-3	23.7	44.5	33.8	1.4	29.8	70.8	7.6	7.8	51	5.8			
	3-4	27.0	47.3	25.6	1.4	19.6	78.9	7.0	7.8	51	4.2			
	4-5	25.8	38.2	17.8	1.6	8.6	71.7	5.7	7.7	52	3.2			
	5-6	26.4	32.4	14.6	1.5	5.7	66.1	5.0	7.7	51	2.7			
	6-7	4.9	12.0	9.2	1.9	5.2	19.0	2.4	7.9	51	3.2			
	7-8	3.5	8.5	7.5	2.0	5.1	12.4	1.8	8.0	54	3.1			
	8-9	2.8	6.6	7.2	2.5	4.9	9.1	1.6	7.9	52	3.3			
	9-10	2.7	6.5	8.3	2.0	4.2	11.3	1.7	8.0	52	3.9			

Appendix Table 2-2: Fossum Site 2: Chemical and Particle Size Data

Site (x,y)	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
1-3	0-1	5.2	3.8	1.9	2.2	4.4	4.3	1.3	6.9	48	0.9	32.9	53.6	13.5
	1-2	1.6	1.1	1.4	1.9	1.5	0.7	0.5	6.9	63	1.2	31.2	36.7	32.1
	2-3	4.2	2.5	1.3	3.5	3.3	1.2	0.9	7.6	48	0.8	42.7	32.4	24.9
	3-4	4.5	2.8	1.0	3.2	2.7	2.4	0.8	7.7	49	0.5	37.8	38.2	24.0
	4-5	5.8	4.6	0.8	3.0	7.1	1.1	1.3	7.7	50	0.4			
	5-6	3.6	3.2	0.7	2.2	15.7	0.0	1.5	7.7	50	0.4			
	6-7	5.7	4.4	0.6	3.0	7.3	0.4	1.2	7.7	47	0.3			
	7-8	5.3	3.8	0.6	3.2	6.3	0.1	1.2	7.7	48	0.3			
	8-9	5.9	4.2	0.6	3.1	7.9	0.0	1.3	7.6	47	0.3			
	9-10	8.0	5.7	0.8	2.7	11.4	0.4	1.7	7.7	46	0.3	40.7	36.9	22.3
1-4	0-1	27.1	72.6	42.3	2.7	29.1	110.1	1.0	7.8	54	6.0	40.4	38.4	21.2
	1-2	24.6	96.8	52.9	1.0	33.6	139.7	12.2	8.1	50	6.8	34.7	34.1	31.2
	2-3	24.6	104.9	56.0	2.0	40.3	143.2	12.6	8.1	52	7.0	37.8	47.2	14.9
	3-4	24.4	109.5	50.4	1.9	44.2	138.1	12.9	8.2	47	6.2			
	4-5	24.1	93.8	46.0	1.6	28.6	133.8	11.4	8.0	49	6.0	40.0	50.3	9.7
	5-6	23.3	88.6	50.2	1.3	24.7	136.2	11.3	7.9	49	6.7			
	6-7	22.0	105.5	61.0	1.7	13.8	172.9	12.2	8.0	47	7.6	40.2	49.5	10.3
	7-8	17.2	126.7	64.6	1.9	5.8	200.9	13.1	8.1	50	7.6			
	8-9	21.5	145.5	70.1	1.8	5.2	230.1	13.5	8.2	48	7.7			
	9-10	21.3	142.1	67.1	2.0	4.4	224.2	14.4	7.9	49	7.4			
	10-11	20.9	148.3	60.8	1.8	3.8	224.4	13.6	8.2	49	6.6			
	11-12	21.1	151.0	60.1	2.1	4.0	226.0	13.8	8.1	48	6.5			
	12-13	20.5	148.5	61.0	2.1	5.2	222.7	13.1	7.9	49	6.6	40.1	35.3	24.6
1-6	0-0.5	69.0	105.1	148.0	2.4	259.8	59.9	28.2	7.2	59	16.0	38.4	42.3	19.3
	0.5-1	45.1	67.4	114.0	2.0	197.3	27.2	21.4	7.4	55	15.0	27.4	44.0	28.6
	1-2	59.1	82.8	140.1	3.4	253.6	24.9	26.3	7.4	44	17.0	34.4	40.9	24.7
	2-3	74.1	76.3	228.3	1.0	333.9	43.7	34.6	7.4	36	26.0	50.5	29.5	20.0
	3-4	64.5	52.6	295.7	1.6	372.2	39.0	38.2	7.3	48	39.0			
	4-5	55.0	51.6	358.8	1.2	439.2	25.0	43.6	7.3	47	49.0	39.4	36.2	24.4
	5-6	61.1	60.6	385.8	1.4	463.1	42.9	46.6	7.3	46	49.0			
	6-7	84.3	88.1	389.8	1.4	488.5	72.3	49.5	7.3	48	42.0			

Continued
Appendix Table 2-2

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
1-6	7-8	88.5	114.7	367.1	1.4	498.1	70.7	49.7	7.3	47	36.0			
	8-9	86.5	97.3	304.6	1.4	428.7	58.4	43.8	7.3	46	32.0			
	9-10	67.5	58.5	109.2	2.0	196.1	37.0	21.9	7.3	49	14.0	40.3	36.1	23.6
1-8	0-1	23.9	25.0	32.8	3.2	47.8	30.7	7.7	7.6	44	6.6	55.0	31.7	13.3
	1-2	39.6	80.6	74.2	1.6	161.2	31.6	17.7	7.7	39	9.6	50.5	30.6	19.0
	2-3	55.1	121.6	116.7	1.8	266.5	25.1	25.9	7.5	34	12.0	57.1	29.6	13.3
	3-4	84.6	123.7	156.1	1.6	348.3	14.5	33.8	7.4	45	15.0			
	4-5	127.5	146.1	247.1	2.2	496.6	21.9	46.6	7.3	35	21.0	53.5	32.5	14.0
	5-6	138.7	148.4	288.1	1.2	534.9	39.0	49.9	7.3	32	24.0			
	6-7	72.9	129.8	165.0	1.2	300.4	66.0	32.1	7.4	43	16.0			
	7-8	25.8	117.7	104.8	1.0	161.7	85.7	20.5	7.8	49	12.0			
	8-10	24.3	111.4	66.4	1.4	49.2	151.4	13.7	7.8	50	8.1	40.4	34.8	24.7
1-9	0-1	10.4	5.0	0.8	4.5	3.8	7.9	1.8	7.5	43	0.3	49.9	35.3	14.8
	1-2	9.7	4.7	0.9	2.7	7.8	4.8	1.6	7.5	45	0.4	45.7	35.8	18.5
	2-3	16.7	10.6	0.8	1.6	22.2	4.3	3.1	7.1	48	0.2	43.7	36.6	19.7
	3-4	20.7	12.0	0.9	2.5	28.1	3.0	3.7	7.2	38	0.2			
	4-5	17.2	9.7	0.8	2.6	21.6	3.5	3.0	7.4	47	0.2	40.0	36.2	23.8
	5-6	19.1	10.3	0.8	1.8	23.9	4.5	3.3	7.4	46	0.2			
	6-7	23.8	12.8	1.4	1.4	31.7	4.9	4.1	7.4	46	0.3			
	7-8	46.5	24.6	7.1	1.2	73.0	4.0	8.0	7.2	45	1.2			
	8-9	63.9	36.8	24.9	1.1	111.4	13.1	12.9	7.2	47	3.5			
	9-10	61.9	36.5	26.8	1.2	107.1	16.8	12.6	7.3	46	3.8	42.0	34.4	23.6
3-3	0-0.5	7.4	5.3	1.0	3.9	6.6	3.4	1.6	6.9	56	0.4			
	0.5-1	6.3	4.7	1.7	3.0	7.7	2.0	1.4	7.1	45	0.8	32.7	46.4	20.9
	1-2	36.3	31.0	4.6	1.7	51.0	19.2	6.6	7.3	47	0.8	30.7	50.8	18.5
	2-3	12.8	16.2	1.8	2.7	23.2	5.0	3.1	7.6	46	0.5	38.3	42.2	19.5
	3-4	5.6	12.1	1.2	3.1	14.5	1.3	2.0	7.9	49	0.4			
	4-5	4.5	11.1	1.2	3.2	12.0	1.6	1.9	7.9	48	0.5	39.8	36.1	24.1
	5-6	6.1	12.4	1.5	3.4	12.8	3.9	2.0	7.9	47	0.5			

Continued
Appendix Table 2-2

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
(x,y)	(ft)	meq/l						(mmhos/cm)		%		%		
3-3	6-7	8.2	14.6	1.3	2.7	16.3	5.0	2.5	7.8	50	0.4			
	7-8	14.8	21.5	1.6	2.4	29.4	6.1	3.9	7.6	47	0.4			
	8-9	25.7	32.2	2.1	2.3	48.1	9.7	5.8	7.5	48	0.4			
	9-10	33.2	36.8	2.9	4.5	68.4	0.0	7.0	7.6	46	0.5	40.0	37.2	22.8
3-4	0-0.5	43.5	85.5	71.8	3.2	63.3	134.2	16.0	7.7	57	8.9	36.2	43.5	20.3
	0.5-1	29.1	76.7	80.2	1.7	147.2	37.1	17.1	7.8	53	11.0	32.9	36.5	30.6
	1-2	19.4	42.4	94.5	3.2	137.8	15.3	15.5	7.4	44	17.0	42.2	31.9	25.9
	2-3	40.2	35.5	115.1	1.5	131.2	58.0	18.0	7.4	52	19.0	37.7	36.9	25.4
	3-4	38.3	28.2	154.9	1.5	155.1	64.8	21.0	7.5	52	27.0			
	4-5	63.9	60.6	317.3	1.4	390.5	50.0	40.9	7.3	44	40.0	41.7	32.4	25.9
	5-6	75.9	75.3	391.5	1.3	497.3	44.1	53.7	7.3	47	45.0			
	6-7	73.7	94.8	423.8	1.1	539.5	51.6	53.8	7.3	46	46.0			
	7-8	84.0	94.9	457.1	1.4	543.7	90.9	57.3	7.4	46	48.0			
	8-9	89.7	90.0	475.3	1.1	580.7	73.2	60.5	7.3	46	50.0			
	9-10	89.4	97.6	488.2	1.2	573.3	100.6	57.1	7.4	44	50.0	40.9	34.6	24.5
3-6	0-1	66.8	84.3	699.7	1.4	812.4	37.0	75.2	7.5	52	80.0	33.7	36.2	30.0
	1-2	62.7	78.9	655.6	1.4	778.9	16.8	70.4	7.6	48	78.0	40.3	30.5	29.1
	2-3	72.2	86.4	663.9	1.4	791.4	29.7	73.1	7.4	51	75.0	39.2	34.0	26.8
	3-4	74.7	71.2	935.9	2.0	1057.4	22.4	93.0	7.5	47	110.0			
	4-5	65.9	36.5	889.1	1.2	975.1	15.2	86.0	7.5	51	124.0			
	5-6	60.5	30.1	828.3	3.8	886.9	28.2	81.7	7.5	51	123.0	32.3	41.6	26.1
	6-7	50.8	27.8	648.5	1.4	711.5	14.2	66.2	7.5	51	103.0			
	7-8	47.5	27.9	565.2	1.8	626.0	12.8	61.0	7.5	50	92.0			
	8-9	45.4	28.7	544.6	1.8	611.5	5.4	58.1	7.6	50	89.0			
	9-10	46.9	30.2	628.7	2.0	692.8	11.1	64.3	7.3	54	101.0	35.7	41.0	23.3
	10-11	50.3	31.5	738.5	3.0	822.0	0.0	74.5	7.5	49	115.0			
	11-12	55.4	28.3	914.1	1.6	970.8	25.4	87.3	7.3	46	141.0			
	12-13	63.5	31.6	979.6	1.6	1066.0	7.1	93.5	7.2	47	142.0	39.5	34.6	25.9

Continued
Appendix Table 2-2

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
	(ft)	meq/l						(mmhos/cm)		%		%		
3-8	0-1	69.4	103.9	40.5	2.2	154.5	57.1	18.0	7.2	48	4.4	40.7	43.3	16.0
	1-2	88.2	168.4	84.6	1.2	301.4	38.6	29.9	7.5	48	7.5	22.3	49.4	28.3
	2-3	86.9	128.1	100.6	1.4	261.2	53.0	26.6	7.5	42	9.7	35.6	46.3	18.0
	3-4	132.6	160.8	250.9	2.0	487.1	55.3	45.7	7.3	29	21.0			
	4-5	94.9	100.1	192.6	1.6	338.7	47.4	33.4	7.4	50	20.0	40.9	34.2	24.9
	5-6	102.5	116.7	188.8	1.2	372.2	34.6	38.0	7.1	44	18.0			
	6-7	95.8	112.0	214.7	1.0	386.6	35.0	38.1	7.2	44	21.0			
	7-8	91.7	123.8	195.5	1.0	386.6	23.5	37.3	7.3	47	19.0			
	8-9	120.6	145.1	190.9	1.2	434.4	20.9	41.3	7.3	46	17.0			
	9-10	140.5	156.4	219.4	1.2	490.9	24.3	44.6	7.3	46	18.0	40.0	36.7	23.3
3-9	0-0.5	31.7	16.8	3.7	3.3	1.8	47.1	4.1	7.5	50	0.8	43.0	40.6	16.4
	0.5-1	29.4	34.2	13.3	1.9	5.0	70.0	5.4	7.6	49	2.4	36.6	38.4	25.0
	1-2	25.6	122.4	43.2	2.0	17.3	171.8	12.6	7.9	44	5.0	31.5	44.4	24.1
	2-3	23.8	159.1	40.6	2.1	16.0	205.5	12.9	7.9	46	4.3			
	3-4	21.8	118.6	35.2	1.6	6.4	167.6	10.6	7.7	53	4.2			
	4-5	22.0	129.0	45.2	1.6	11.2	183.4	11.7	7.7	48	5.2	37.2	35.9	26.9
	5-6	22.1	131.7	50.8	1.8	16.5	186.4	12.9	7.8	50	5.8			
	6-7	21.7	137.1	55.0	1.7	7.8	204.2	12.9	7.8	46	6.2			
	7-8	21.7	131.3	53.4	1.8	3.5	200.9	12.4	7.8	46	6.1			
	8-9	21.3	122.9	51.3	1.7	2.9	190.8	11.7	7.8	47	6.0			
	9-10	21.9	120.2	50.4	1.7	3.3	187.5	11.5	7.8	49	6.0	38.7	36.2	25.1
5-3	0-1	4.7	3.8	0.3	4.2	0.8	3.8	1.0	7.3	54	0.2	29.5	53.5	17.0
	1-2	4.9	9.0	0.9	5.0	4.1	5.7	1.4	7.8	54	0.3	19.1	58.7	22.2
	2-3	6.5	12.4	2.2	4.0	2.1	15.1	1.7	7.9	40	0.7	42.5	42.7	14.8
	3-4	13.6	11.1	7.2	3.1	2.3	26.5	2.6	7.8	42	2.1			
	4-5	18.5	15.2	9.1	2.8	1.4	38.6	3.3	7.8	47	2.2	42.4	36.1	21.5
	5-6	11.8	8.7	4.9	2.4	1.8	21.2	2.2	7.1	47	1.5			
	6-7	11.5	4.8	3.9	2.3	1.3	16.6	2.1	7.4	45	1.4			
	7-8	13.2	5.2	3.2	2.2	1.4	18.0	2.1	7.5	42	1.1			
	8-9	11.1	4.2	2.6	2.2	1.2	14.5	1.8	7.5	47	0.9			
	9-10	9.8	3.7	2.3	2.4	0.9	12.5	1.6	7.6	47	0.9	39.5	37.9	22.6

Continued
Appendix Table 2-2

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
	(ft)	meq/l						(mmhos/cm)		%		%		
5-4	0-0.5	26.1	59.0	23.3	6.9	36.8	64.8	8.2	7.6	56	3.6	39.8	42.3	17.9
	0.5-1	23.1	123.0	48.0	6.3	76.0	111.8	12.5	7.6	49	5.6	37.2	45.9	16.9
	1-2	21.0	187.8	76.0	3.0	137.8	144.0	18.4	8.2	46	7.4	30.3	51.0	18.7
	2-3	24.5	224.0	88.5	2.0	142.5	192.4	22.7	8.2	36	7.9	52.3	28.3	19.4
	3-4	33.1	214.4	79.7	1.0	176.0	150.2	22.7	8.1	48	7.2			
	4-5	39.6	228.4	91.4	1.4	223.9	134.2	26.0	7.9	49	7.9	39.7	49.8	10.5
	5-6	43.9	265.8	102.7	4.2	271.7	136.3	29.1	7.8	46	8.3			
	6-7	43.6	278.6	107.2	2.0	290.4	137.0	30.8	7.8	45	8.4			
	7-8	24.0	122.2	59.5	1.6	51.9	152.3	13.6	7.9	48	7.0			
	8-9	21.5	76.5	34.5	1.8	9.8	120.9	9.2	7.9	48	4.9			
	9-10	22.2	55.9	29.3	1.8	4.8	100.8	7.1	7.8	46	4.7	40.5	35.2	24.3
5-6	0-0.5	109.1	149.9	405.1	2.2	578.0	83.9	56.0	7.2	50	36.0	37.2	42.6	20.2
	0.5-1	87.5	86.2	248.8	1.6	367.4	43.4	38.2	7.4	33	27.0	33.0	39.0	28.0
	1-2	81.9	86.2	229.6	1.4	333.9	62.3	36.0	7.4	47	25.0	35.0	35.0	30.0
	2-3	87.4	97.3	277.5	1.8	420.1	40.3	41.7	7.4	43	29.0	40.3	36.1	23.6
	3-4	88.1	86.2	391.1	1.6	497.1	66.7	50.1	7.4	45	42.0			
	4-5	85.5	53.2	555.3	2.0	599.0	92.9	58.8	7.2	49	67.0	37.8	36.0	26.2
	5-6	87.3	46.3	651.0	2.0	685.6	97.0	66.5	7.3	47	80.0			
	6-7	94.7	53.4	803.7	1.6	821.0	129.1	74.9	7.2	45	93.0			
	7-8	98.2	61.6	815.2	2.4	882.8	89.8	79.6	7.3	48	91.0			
	8-9	124.5	101.8	1071.6	1.4	1190.9	105.6	99.6	7.1	45	101.0			
	9-10	115.4	138.5	829.8	1.6	1013.9	68.3	87.1	7.2	47	74.0	32.8	40.8	26.4
5-8	0-0.5	7.9	3.5	0.9	3.1	0.8	8.5	1.3	7.6	47	0.4	47.6	36.3	16.1
	0.5-1	9.6	4.6	1.0	2.8	1.3	11.0	1.5	7.6	38	0.4	56.6	28.6	14.8
	1-2	7.4	5.3	2.0	3.1	0.8	10.9	1.3	7.9	40	0.8	49.8	33.2	17.0
	2-3	21.1	81.1	44.8	2.1	2.6	142.3	9.4	7.9	49	6.3	37.5	35.6	26.9
	3-4	18.3	84.3	46.9	2.3	3.1	144.1	9.6	7.8	53	6.6			
	4-5	21.3	90.8	50.2	2.2	3.1	157.0	10.1	7.9	48	6.7	38.3	36.7	25.0
	5-6	21.4	90.0	49.5	2.1	2.8	155.9	10.3	7.9	46	6.6			
	6-7	21.4	94.2	50.3	2.0	2.7	161.3	10.5	7.3	47	6.6			
	7-8	21.2	85.1	41.3	4.5	2.8	140.3	9.7	7.8	45	5.7			
	8-9	21.7	81.2	38.6	2.6	2.8	136.0	9.2	7.8	44	5.4			
	9-10	19.2	78.9	41.0	4.1	3.0	132.0	9.4	7.8	45	5.9	38.3	39.7	22.0

Continued
Appendix Table 2-2

Site	Depth (ft)	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		meq/l						(mmhos/cm)		%		%		
5-9	0-1	7.8	4.0	0.8	3.6	2.9	6.1	1.4	7.4	53	0.4	30.7	49.5	19.8
	1-2	3.9	4.9	1.4	2.8	3.3	4.1	1.0	7.8	47	0.7	24.9	52.9	22.2
	2-3	25.7	39.5	6.2	2.3	2.8	66.3	5.0	7.8	46	1.1	40.4	33.0	26.6
	3-4	25.2	34.6	8.9	2.2	1.7	64.8	4.9	7.6	47	1.6			
	4-5	24.7	34.1	10.7	2.3	1.0	66.1	4.9	7.8	33	2.2	59.6	27.1	13.3
	5-6	24.1	35.2	12.1	1.8	0.9	68.7	5.1	7.6	44	2.2			
	6-7	22.7	48.3	18.1	2.4	1.7	85.0	6.3	7.7	38	3.0			
	7-8	22.5	52.6	21.4	2.0	1.3	93.1	6.6	7.6	45	3.5			
	8-9	23.0	44.5	19.8	2.1	1.3	83.9	6.0	7.6	49	3.4			
	9-10	22.8	37.7	18.6	2.2	1.2	75.8	5.6	7.6	47	3.4	39.6	36.5	23.9
7-3	0-1	5.6	2.3	0.5	6.1	3.8	0.0	1.2	7.5	59	0.3	35.5	45.1	19.4
	1-2	3.1	2.2	0.5	3.5	1.8	0.4	0.6	7.7	49	0.3	40.0	38.9	21.1
	2-3	3.5	2.5	0.6	3.7	1.4	1.5	0.7	7.7	45	0.4	43.1	37.0	19.9
	3-4	2.7	1.6	0.5	3.1	0.8	0.9	0.5	7.6	43	0.3			
	4-5	3.8	2.5	0.6	4.2	1.3	0.7	8.2	8.2	31	0.4			
	5-6	5.6	4.3	0.8	6.6	0.8	3.3	1.0	7.8	47	0.4	41.0	35.9	23.1
	6-7	2.4	1.6	0.6	3.4	0.5	0.7	0.5	7.7	46	0.5			
	7-8	2.4	1.6	0.6	3.2	0.8	0.6	0.5	7.7	47	0.4			
	8-9	2.4	1.6	0.7	3.0	0.6	1.0	0.4	7.8	43	0.5			
	9-10	2.6	1.7	0.7	3.0	0.6	1.3	0.5	7.7	46	0.5	40.9	37.1	22.0
7-4	0-0.5	2.7	4.9	0.6	5.6	1.2	1.3	0.8	8.1	53	0.3	36.1	38.3	25.6
	0.5-1	1.6	8.9	0.8	5.3	1.1	4.9	1.1	8.3	44	0.4	49.9	28.5	21.6
	1-2	0.6	6.5	0.7	4.0	0.8	3.0	0.8	8.3	49	0.4	42.1	32.8	25.1
	2-3	0.9	4.7	0.8	3.9	0.2	2.3	0.6	8.2	51	0.5	37.8	36.1	26.1
	3-4	1.2	3.9	1.0	3.5	0.6	2.0	0.6	8.0	45	0.6			
	4-5	1.4	3.1	0.7	3.4	0.6	1.2	0.5	7.9	46	0.5	40.1	36.2	23.6
	5-6	1.6	2.9	0.7	3.1	0.6	1.5	0.5	7.9	45	0.5			
	6-7	1.7	2.6	0.7	3.2	0.5	1.3	0.5	7.9	46	0.5			
	7-8	2.0	2.7	0.7	3.4	0.5	1.4	0.5	7.9	47	0.5			
	8-9	2.0	2.5	0.6	3.0	0.5	1.6	0.5	7.9	46	0.4			
	9-10	2.3	2.2	0.7	2.9	1.2	1.1	0.6	7.3	47	0.5	40.7	36.4	22.9

Continued
Appendix Table 2-2

Site	Depth	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
	(ft)	meq/l						(mmhos/cm)		%		%		
7-6	0-1	2.0	1.0	32.0	3.2	28.7	3.1	4.2	6.7	58	26.0	29.4	55.8	14.8
	1-2	1.3	0.5	35.4	3.8	31.5	1.8	4.1	7.1	27	37.0	23.7	62.2	14.1
	2-3	2.5	1.5	37.7	1.8	42.1	0.0	4.6	7.1	64	27.0	30.3	42.6	27.1
	3-4	15.9	10.4	65.8	1.0	91.3	0.0	10.6	6.8	57	18.0	32.9	41.5	25.6
	4-5	20.0	12.2	61.5	3.2	89.9	0.6	10.4	7.1	43	15.0			
	5-6	59.9	34.2	30.5	1.8	126.8	0.0	13.1	7.1	51	4.5	19.3	59.7	20.9
	6-7	73.0	40.0	12.1	1.6	127.2	0.0	12.8	7.1	39	1.6			
	7-8	48.0	26.5	5.7	1.0	80.8	0.0	8.6	7.2	53	0.9			
	8-9	29.0	16.0	2.6	1.6	47.3	0.0	5.4	7.4	52	0.6			
	9-10	22.7	12.2	2.1	3.0	37.3	0.0	4.3	7.4	44	0.5	26.3	54.7	19.1
7-8	0-1	10.1	4.9	1.2	2.0	4.1	10.2	1.8	7.7	46	0.5	37.9	45.7	16.4
	1-2	17.5	23.5	11.6	2.9	2.4	47.3	4.1	7.7	43	2.6	33.2	49.5	17.2
	2-3	20.5	95.9	60.6	2.2	1.8	172.9	11.4	7.9	50	8.0	37.5	36.3	26.2
	3-4	16.7	93.0	57.3	2.1	1.7	163.2	10.6	7.9	46	7.7			
	4-5	20.8	96.7	58.4	2.4	1.9	171.5	11.2	7.8	45	7.6	39.6	35.6	24.8
	5-6	21.2	100.1	60.8	2.1	2.2	177.8	11.6	7.8	47	7.8			
	6-7	20.7	90.3	56.0	2.0	2.3	162.7	10.6	7.8	47	7.5			
	7-8	21.5	80.3	50.6	2.3	2.3	147.7	9.8	7.8	43	7.1			
	8-9	20.9	70.7	44.8	2.5	2.1	131.9	9.0	7.7	44	6.6			
	9-10	21.8	52.4	34.6	2.1	2.1	104.5	7.4	7.7	46	5.7	38.7	36.1	25.2
7-9	0-1	5.8	2.7	0.4	3.9	1.2	3.8	1.0	7.4	48	0.2	37.0	44.9	18.1
	1-2	3.8	2.1	0.4	2.0	3.5	0.8	0.8	6.9	46	0.3	32.5	45.4	22.1
	2-3	5.3	2.5	0.5	0.1	3.6	4.7	0.9	7.5	43	0.3	41.3	43.9	14.8
	3-4	2.8	1.3	0.5	2.7	0.6	1.3	0.4	7.6	45	0.4			
	4-5	2.4	1.3	0.5	2.7	0.4	1.1	0.4	7.6	46	0.4	39.6	38.2	22.2
	5-6	2.7	1.4	0.5	2.6	1.0	0.9	0.5	7.6	47	0.4			
	6-7	2.6	1.3	0.5	2.5	0.7	1.2	0.4	7.6	44	0.4			
	7-8	2.9	1.6	0.5	3.5	0.8	0.7	0.5	7.6	44	0.4			
	8-9	2.8	1.4	0.5	3.6	0.6	0.5	0.5	7.5	43	0.4			
	9-10	2.8	1.4	0.5	3.6	0.6	0.6	0.5	7.7	45	0.4	39.7	38.4	21.9

Continued
Appendix Table 2-2

Site	Depth (ft).	Ca	Mg	Na	HCO_3	Cl	SO_4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		----------------meq/l					----------------(mmhos/cm)			%		-------%-------		
1-10	0-1	5.8	2.2	0.6	2.6	0.4	5.7	0.9	7.7	41	0.3			
	1-2	27.6	15.7	1.4	1.8	0.4	42.4	3.1	7.7	40	0.3			
	2-3	25.5	47.4	6.0	1.4	0.9	76.6	4.9	7.9	41	1.0			
	3-4	25.1	50.1	9.1	1.6	0.7	82.0	5.2	7.8	52	1.5			
	4-5	25.4	39.8	7.2	1.4	0.8	70.2	4.7	7.7	51	1.3			
	5-6	25.8	32.9	5.9	1.2	0.8	62.6	4.2	7.8	52	1.1			
	6-7	24.7	23.6	4.3	1.2	0.3	51.0	3.7	7.7	49	0.9			
	7-8	6.1	5.6	2.5	1.7	0.3	12.2	1.2	7.8	49	1.0			
	8-9	2.9	2.5	1.6	2.1	0.3	4.5	0.7	7.9	49	1.0			
	9-10	3.2	2.5	1.3	2.0	0.3	4.6	0.7	7.8	48	0.8			
3-10	0-1	2.0	3.5	0.7	3.5	0.1	2.6	0.5	7.8	58	0.4			
	1-2	1.2	8.6	1.0	2.8	1.1	6.9	0.9	8.1	56	0.5			
	2-3	2.0	6.9	0.8	3.9	1.2	4.6	0.8	8.0	48	0.4			
	3-4	2.7	4.8	0.8	1.9	1.3	5.1	0.7	8.0	48	0.4			
	4-5	2.2	2.7	0.7	2.1	0.4	3.1	0.5	7.9	49	0.5			
	5-6	2.4	2.3	0.7	1.8	0.6	3.1	0.5	7.8	49	0.5			
	6-7	3.9	3.3	1.2	2.0	0.6	5.9	0.8	7.8	43	0.6			
	7-8	6.3	4.8	1.9	0.4	0.4	12.1	1.2	7.7	48	0.8			
	8-9	27.0	16.7	3.3	1.4	0.1	45.4	3.2	7.6	50	0.7			
5-10	0-1	5.0	2.0	0.5	2.4	0.6	4.6	0.8	7.6	57	0.3			
	1-2	5.2	2.8	0.6	1.6	0.9	6.1	0.9	7.7	51	0.3			
	2-3	2.8	3.6	0.6	1.9	1.2	3.9	0.6	7.9	46	0.4			
	3-4	2.2	4.6	1.0	2.0	1.8	4.0	0.7	7.9	43	0.6			
	4-5	1.7	2.5	1.0	2.1	0.9	2.2	0.5	7.8	43	0.7			
	5-6	5.0	3.3	1.1	1.7	0.8	6.8	0.8	7.7	50	0.6			
	6-7	28.2	11.1	1.9	1.4	0.3	39.4	3.0	7.8	43	0.4			
	7-8	27.5	12.6	2.1	1.2	0.4	40.6	3.1	7.5	48	0.5			
	8-9	27.5	13.8	2.5	1.0	0.3	42.5	3.0	7.5	48	0.6			
	9-10	26.5	14.9	2.9	1.3	0.4	42.6	3.1	7.5	49	0.6			

Continued
Appendix Table 2-2

Site	Depth (in)	Ca	Mg	Na	HCO3	Cl	SO4	EC	pH	SATN	SAR	SAND	SILT	CLAY
		----------------	----------------	meq/l	----------------	----------------	----------------	(mmhos/cm)		%		--------	%	--------
7-10	0-1	4.8	2.3	0.3	2.7	0.4	4.3	0.8	7.2	51	0.2			
	1-2	1.9	1.5	0.3	0.7	0.4	2.6	0.4	6.6	48	0.3			
	2-3	1.7	1.5	0.3	0.7	0.5	2.4	0.4	6.6	43	0.3			
	3-4	2.3	2.5	0.5	2.2	0.5	2.5	0.5	7.1	35	0.3			
	4-5	1.6	2.0	0.5	2.1	0.4	1.6	0.4	7.7	38	0.4			
	5-6	1.2	1.8	0.7	2.1	0.2	1.3	0.3	7.8	45	0.6			
	6-7	1.2	1.8	0.8	2.2	0.0	1.6	0.3	7.8	46	0.6			
	7-8	1.3	1.9	0.7	2.3	0.8	0.8	0.3	7.9	46	0.6			
	8-9	1.4	1.8	0.7	2.2	0.3	1.4	0.4	7.9	46	0.6			
	9-10	1.5	1.8	0.7	2.4	0.3	1.2	0.3	7.8	45	0.5			

Table A 2-3: Fossum Site 1: Log of Subsurface Data

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 20-300 Sampled by: NDW
Sample Location:
Surface Elevation 8.6'

WATER LEVEL OBSERVATIONS
W.L. 7' @ 4days
W.L. 5'6" @ 8days

NOTES Should be noncontaminated sites
Possible reference site
3" samples - 2 bags

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-8"	AP O + L Sed.	V. DK Gray	Loam	friable		0-12"	(v. fine sandy Loam texture?)
8-17"	B	V. DK Grayish Brown				12-16"	
17-23"	Bca						
2	C O + UL Sediment	Pale Brown				16-24"	
		2.5Y Pale Brown		Soft friable			Pebble band
4	O + UL Till	DK Olive Brown	Clay Loam	Mod firm friable			
6				Firm			few gray color along joints
8							gypsum coated joints Plate to coarse ABK structure strong Fe coated joints
10	Bottom						
12							

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-28-83
Proj. No.: Fossum I Tech:
Boring No. 200,50 Sampled by: NW
Sample Location:
Surface Elevation 7.6'

WATER LEVEL OBSERVATIONS
W.L. NO WATER @ 4 days
W.L. 10' 3" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-4"	AP O+L	Black	LOAM	Friable			
	B + C O+UL	Brown	clay LOAM				
2	O+UL TILL	DK. Brown		Mod. Firm Friable			
4							
6							
8	MO+UL TILL			Firm			Fe Coatings on Joints
10							
12	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 200-300 Sampled by: NW
Sample Location:
Surface Elevation 7.3'

WATER LEVEL OBSERVATIONS
W.L. 7'9" @ 4days
W.L. 5'11" @ 8days

NOTES 3" Core Sample
Sampled for McCarthy

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Ap + A	V. DK Gray	Loam	Friable		0-12"	
	O+L						
	Bca O+UL Sediment	Lt. Yellowish Brown		Soft friable		12-12"	
						18-24"	
2	C	Lt. Olive Brown				24-[illegible]	
	O+UL Till	2.5Y Grayish Brown	Clay Loam	Mod. Soft + Friable			[illegible] abundant masses of gypsum [illegible] with [illegible]
4							
6							
8				V. Firm			Strongly Jointed Till
10	Bottom						
12							

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 200-500 Sampled by: NW
Sample Location:
Surface Elevation 8.5'

WATER LEVEL OBSERVATIONS
W.L. 6'9" @ 36 hr
W.L. @

NOTES nearly level slightly convex high

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7"	A O+L Sed.	Black	Loam	Friable			
7-13"	B	DK. Brown					Combic B
	O+UL Sediment	10yr-2.5y Lt. Yellowish Brown					
2	C						Secondary carbonates 2½-3½'
	O+UL till	Lt. Olive Brown	Clay loam	Slightly Firm Friable			} gradual transition
4							
				mod. firm Slightly Plastic			
6		to Olive Brown					
							Few gypsum masses
8							
	mo+UL till			Firm			
10	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 200,600 Sampled by: NW
Sample Location:
Surface Elevation 77'

WATER LEVEL OBSERVATIONS
W.L. 6'0" @ 36 hr.
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-6"	A O+L Sed.	Black	Loam	Friable			
6-13"	B	Brown					
13-20"	Bca Mo+ULL Sediment	LT. Brownish Gray					
2	C	LT. Olive Brown					
	Mo+ULL till with sand lenses		Clay Loam				
4							
6							
	O+UL TILL			Firm [illegible] Hard			
8							
10	Bottom						
12							

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-28-83
Proj. No.: Fossum I Tech: ____
Boring No. 400,50 Sampled by: NW
Sample Location: ____
Surface Elevation 6.4'

WATER LEVEL OBSERVATIONS
W.L. 13' @ 4 days
W.L. 12' @ 8 days

NOTES ____

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	AP O+L	V. DK. Grayish Brown	Loam to Sandy Loam	Friable			
	A+B	DK. Brown	Loamy Sand				
2							
	2"	V. DK. Brown	Silty Clay	Mod. Firm			Strong mfABK structure (inclusion of B horizon)
	O+UL TILL	Brown	Clay Loam	Friable			
4							
		Brown with few Gray Mottles					
6							
8							
		DK. Yellowish Brown with few Fe Mottles		Firm			
10							
12							
		DK. Brown					
14							
	Bottom						

BORING STARTED ____

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 400,300 Sampled by: NW
Sample Location:
Surface Elevation 5.8'

WATER LEVEL OBSERVATIONS
W.L. 3'4" @ 4 days
W.L. 3'4" @ 8 days

NOTES Next to west side of Pit. Good sample for Comparison with Pit materials.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	FI+L L UL	V. DK Gray to V. DK. Grayish Brown	Loam	Slightly friable Plastic			Oil Contaminated
2	Sediment B+C ? OtUL	LT. Olive Brown					
	O+UL Till		Clay Loam	Slightly Plastic			
4							
6	thin sand lense						
8							Soft zone at 8'
10	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 400-500 Sampled by: NW
Sample Location:
Surface Elevation 4.8'

WATER LEVEL OBSERVATIONS
W.L. 2'11" @ 36 hr
W.L. @

NOTES Near lower edge of natural depression South of pit area, very chunky soil on surface, Surface dispersed and slippery.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-10"	O+L sed. A	Black	Loam	Friable			
		5Y V. DK. Gray		Soft+ Plastic			
2	B C	10YR-2.5Y Brown	Sandy loam				▽
4	O+UL Sediment	Lt. Olive Brown					
							} gradual transition
6	O+UL till		Clay loam	Firm slightly plastic			
	gravelly sand		Gravelly sandy loam	mushy			
8	O+UL till		Clay loam	V. Firm			
	Bottom						
10							

BORING STARTED

1

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 400-600 Sampled by: NW
Sample Location:
Surface Elevation 5.2'

WATER LEVEL OBSERVATIONS
W.L. 3'5" @ 36 hr
W.L. @

NOTES Very wet Coring, Stratified Sand & Silt to 10' wide, water in core hole tastes Salty

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7"	A OtL	Black	Loam	Friable			
7-19"	B OtUL Sediment	V. DK Grayish Brown					
	C						
2	Mo + UL Stratified silts and sands	2.5Y-10YR Brown		Soft plastic			few secondary carbonates
4		2.5Y Brown	Sandy loam w/silt loam strata				
6							Very wet
8	Coarse Sand lense		Sand – Loam				
10	Mo+UL till? Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 460-300 Sampled by: NW
Sample Location:
Surface Elevation 5.8'

WATER LEVEL OBSERVATIONS
W.L. 3'5" @ 4 days
W.L. 3'5" @ 8 days

NOTES Should be in pit
water table ≈ 9' while drilling

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Fill material	mixed Black & Yellowish Brown	Clay loam	Firm			
2							
	Oil Contaminated	Black to Bluish Black		Soft Plastic			
4							
		Yellowish Brown with Black Inclusions					
6							
8							
		greenish Yellowish Brown					pit Bottom ▽
	O + UL Sand + Gravel	Yellowish Brown	Gravelly sand	loose			free water
10							
	O + UL Till		Clay loam	V. Firm			No Sample
12							
14							
		V. Dk. Brown					
	Bottom						almost U + UL till

BORING STARTED

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-28-83
Proj. No.: Fossum I Tech:
Boring No. 600,50 Sampled by: NW
Sample Location:
Surface Elevation 5.5'

WATER LEVEL OBSERVATIONS
W.L. 5'10" @ 4 days
W.L. 5'8" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7"	Ap O+L	Black	Loam	Friable			
	O+UL Sand	Brown	Sand to Loamy Sand				
2							
	MO+UL TILL	Dk Grayish Brown	Clay Loam	Slightly Firm Friable			Carbonates & gypsum
4							
6		Olive Brown		Firm Friable			Gypsum & Fe on vertical faces Gypsum slope at 7'
8				Firm			
10							
12							Strong Fe Coating on vertical Joint faces
14		10 YR Brown					
	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 600-300 Sampled by: NW
Sample Location:
Surface Elevation 4.2'

WATER LEVEL OBSERVATIONS
W.L. 1'9" @ 4 days
W.L. 2'2" @ 8 days

NOTES Shallow Brine Disposal pit East of Main Pit ?
Sampled for McCarthy

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Fill material	mixed Yellowish Brown + Black	Clay loam	Mod. firm slightly Plastic			
	oil Contaminated	Black					
2		Yellowish Brown					
	mo + ul Till	Lt. Olive Brown with gray mottles		Soft plastic			
4							
	o + ul till	LT. Olive Brown					
6							
8				Firm slightly Plastic			No paper bag Samples beyond 9'
10				V. Firm			
12							
14		DK. Grayish Brown					
	Bottom						Possible gravel at 15'

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Folsom I Tech:
Boring No. 600-500 Sampled by: NW
Sample Location:
Surface Elevation 4.5'

WATER LEVEL OBSERVATIONS
W.L. 4'1" @ 4 days
W.L. 3'10" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	O+L Sed.	Black	Loam	Friable			
0-14'	A						
	B	Lt. Brownish Gray					
	+						
2	C						✓
	Sloppy Sed.	Lt. Olive Brown	Loamy Sand	mushy			Sand Liquified
4							
	O+UL Sediment		Loam	V. Soft			
6				Soft			thin pinkish sand lenses
	O+ILL till	Yellowish Brown	Clay loam	Firm V. Dense			} gradual transition no sample 7-8'
8							V. Dense till
10	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 600-600 Sampled by: NW
Sample Location:
Surface Elevation 3.8'

WATER LEVEL OBSERVATIONS
W.L. 3'4" @ 36 hr
W.L. @

NOTES High water table located in a small swale

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
		V. DK. Gray	Loam	Soft friable			
0-14"	A						
14-20"	B	V. DK. Grayish Brown					
2	Bca	pale Brown	Sandy loam	Soft Plastic			Very Wet
	C						
	mottl stratified Sands and silts	Lt. Olive Brown					
4							
6							
							No Sample 7-8'
8	ottl till		Clay loam	firm Slightly Plastic			
	Bottom						
10							

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 600-700 Sampled by: VW
Sample Location:
Surface Elevation 3.7'

WATER LEVEL OBSERVATIONS
W.L. 3'7" @ 36 hr
W.L. @

NOTES lost core hole

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-7"	A OtL	V. Dk Gray	Loam	Friable			
7-17"	B	Brown		Soft Plastic			Very Wet
	OtUL Sediment	Lt. Brownish Gray					
2	Bca C	Yellowish Brown					
		Lt. Olive Brown					
4	OtUL till	Olive Brown	Clay loam	Firm Slightly Plastic			Fe Mottles
	Sand lense OtUL till						
6							
8							
10	Bottom						Some traces of gypsum and Fe staining in till Joints

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-28-83
Proj. No.: Fossam I Tech:
Boring No. 700,50 Sampled by: NW
Sample Location:
Surface Elevation 3,3'

WATER LEVEL OBSERVATIONS
W.L. 3'9" @ 10 MIN.
W.L. 4'5" @ 4 days 4'4" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-5"	Ap MO + L Sediment	Black	Loam	Friable			
	A	V. DK. Grayish Brown					
5-17"	B	Black					
2	2A	Brown with Lighter & darker mottles	Sand				
			Loamy Sand				Saturated at 3'9"
4				Plastic			
	PaLcosoL	Grayish Brown to Brown	Clay Loam	Friable			first 6" has strong F. ARK Structure and is leached. Looks Like B horizon of a Paleosol.
	MO + UL TILL	Brown to DK. Yellowish Brown		Slightly Firm			Root channels filled with Carbonates at 5'.
6		with Gray & Fe Mottles		Friable Firm Friable			
				Firm			
8							thin diagonal Joint filled with fine sand.
10							
12							
	LL + UL TILL	V. DK. Grayish Brown V. DK. Gray		V. Firm			
14							
	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Forman I Tech:
Boring No. [illegible] Sampled by: [illegible]
Sample Location:
Surface Elevation 4.0'

WATER LEVEL OBSERVATIONS
W.L. 2'10" @ 4 days
W.L. 2'10" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-10"	A O + L Sed. Bca O + UL Sediment ↓	Black Pale Brown ↓ Lt. Olive	Clay loam ↓ Sandy loam ↓	V. firm ↓ Slightly firm Friable ↓			reworked A horizon?
2	↓	Brown ↓	Silt loam or loam ↓	Soft plastic ↓			¥ Saturated at 2½' } gradual transition
4	O + UL till ↓	↓	Clay loam ↓	↓ V. Firm ↓			
6	↓	↓	↓	↓			no paper bag samples below 6'
8	↓ Bottom	↓	↓	↓			
10							

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 9-29-83
Proj. No.: Fossum I
Tech:
Boring No. 800-300
Sampled by: NW
Sample Location:
Surface Elevation 3.3'

WATER LEVEL OBSERVATIONS
W.L. 2'11" @ 4 days
W.L. 3'5" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	A + Other O+L Sediment	Black	Silt Loam	Friable			
	A+B						
2		pale brown		Soft Slightly Plastic			
		Lt. Olive Brown	Sandy Loam				▽
4		Reddish Brown	Loamy Sand	Friable			
	O+UL till Few gray mottles	Yellowish Brown	Clay loam	Soft Slightly Plastic			
6				Firm			
8				V. Firm			Fe Coated Joints
10	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 9-29-83
Proj. No.: Fossum II
Tech:
Boring No. 800,500
Sampled by: DW
Sample Location:
Surface Elevation 3.4'

WATER LEVEL OBSERVATIONS
W.L. 4' @ 36 hr.
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	A — O+L Sediment	Black Brown	Loam	Friable			
	B	Dk. Brown					
	Bca — O+FL Sediment	[illegible] Brown					
2	C						
	Cca	Pale Brown					
	O+UL till	Lt. Olive Brown	Clay Loam	Md. Firm			
4				Firm			
6							
8							
10	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: Fossum I Tech:
Boring No. 800-600 Sampled by: NW
Sample Location:
Surface Elevation 3.1'

WATER LEVEL OBSERVATIONS
W.L. 3'9" @ 36 hr
W.L. @

NOTES Very Wet but Cannot taste Salt Yet. Salts may have not moved here yet.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
		Black ↓	Loam ↓	Friable ↓			very wet Core hole
0-13"	A						
13-20"	B	V. DK Grayish Brown					20-36" very Calcareous
20-28"	O+L Sed. ↓						▽
2	Bcg C U + UL Sloppy Sediment ↓	grayish Brown ↓ Pale Brown ↓	↓	Soft Plastic ↓			
4			Sandy loam ↓	Slop ↓			
6		Lt Olive Brown ↓	Sand ↓				
8	Bottom						
10							

BORING STARTED

Table 2-3 (con't)

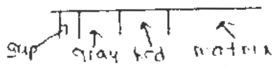
NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-28-83
Proj. No.: Fossum I Tech:
Boring No. 900-50 Sampled by: DW
Sample Location:
Surface Elevation 3.7'

WATER LEVEL OBSERVATIONS
W.L. 14'3" @ 4 days
W.L. 12'8" @ 8days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Ap B + C	V. DK Gray Lt. Olive Brown a Little	Loam	Friable			
2	O + UL Till	Darker 2.5Y DK. Grayish	Clay Loam	Slightly Firm Friable			gypsum few Fe Mottles
4		Brown		Firm			
6							gypsum cracks, veins, & root channels Expanded Cross-Section 
8		10YR-2.5Y DK. Grayish Brown					Fe Joint Coatings
10							
12	MO + UL Till	Brown		V. firm			Transition to R+UL Till Strongly Coated Joints.
14	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 900-300 Sampled by: NW
Sample Location:
Surface Elevation 2.9'

WATER LEVEL OBSERVATIONS
W.L. 5'6" @ 4days
W.L. 4'8" @ 2days

NOTES "good" till at 6' and deeper

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
A	O+L Sed.	Black	Loam	Friable			
B		Yellowish Brown					
C	O+UL Sediment						
2			Gravelly Sandy loam	Loose			
	O+UL+till few gray mottles		Clay loam	Firm Friable			
4							gray mottles on till Joints few Fe concretions
6				V. Firm			
8							No paper bag samples below 8'
10							
12							
	Bottom						
14							

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 9-28-83
Proj. No.: Fossum I
Tech:
Boring No. 11M-50
Sampled by: DW
Sample Location:
Surface Elevation 3.5'

WATER LEVEL OBSERVATIONS
W.L. 13'10" @ 4 days
W.L. 11'3" @ 8 days

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Ap B + C O + UL Sediment or Till?	V. DK Gray Yellowish Brown	Loam Loamy Sand	Friable			Friable blocky till or Sediment?
2		Yellowish Brown with Brown Coating	Silt Loam				few gypsum masses
4		Platy Structure					
6	O + UL till	Lt. Olive Brown	Clay loam	Firm Slightly Plastic			
8	mo + UL till						gypsum associated with gray zones in Joints Abundant Fe mottles & Concretions
10							
12	mo + UL till	Transition Zone To Mo + UL till Grayish Brown					Strong Fe Coatings on Vertical Joints
14	Bottom						

BORING STARTED

Table 2-3 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 9-29-83
Proj. No.: Fossum I Tech:
Boring No. 1100-300 Sampled by: NW
Sample Location:
Surface Elevation 2.4'

WATER LEVEL OBSERVATIONS
W.L. 4'8" @ 4 days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
	Ap B + C O+L O+UL Sediment Sand + gravel	Black Yellowish Brown	Loam TO Silt loam gravelly	Friable			
2			Sand	loose			
	O+UL+till	2.5Y DK Grayish Brown	Clay loam	Soft friable Mod. Firm friable			till darker color than at previous sites
4				Firm			
6							
8							gypsum on joint faces
10	Bottom	Lt. Olive Brown					

BORING STARTED

Table A 2-4: Fossum Site 2: Log of Subsurface Data

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech: ______
Boring No. 100-300 Sampled by: NW
Sample Location: ______
Surface Elevation 5.8'

WATER LEVEL OBSERVATIONS
W.L. 4'10" @ 3 days
W.L. ______ @ ______

NOTES Just into west edge of a depression

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-8"	A	Black	Loam	Friable			
8-13"	E	Grayish Brown		↓			
	B-C 2B	V. Dk. Gray	Clay loam	Firm Plastic			graduated transition to till
2	C motul till	Lt Gray with Yellowish Brown mottles		Mod Firm Slightly Plastic			
	Cca						abundant carbonate core and coatings decreasing with depth
4							↓
	↓	↓		↓			few Fe core few gray mottles
6	otul till	Yellowish Brown		Firm Slightly Plastic			
8							
	↓ Bottom	↓	↓	↓			
10							

BORING STARTED ______

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 100-400 Sampled by: NW
Sample Location:
Surface Elevation 8.0'

WATER LEVEL OBSERVATIONS
W.L. 7'0'' @ 3days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-9''	Ap Sediment	V. DK. Gray w/Pale Brown mixed in	friable				
	≃2'' Bca	LT. Olive Brown					
9-22''	B+C	Yellowish Brown					
2							Gypsum masses beginning at 22''
	O + UL till	DK Olive Brown	clay loam				
4							
6							
8	mo + UL till	w/Gray mottles					
							Fe Joint Coatings
10							
12							
	Bottom						
14							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 100-600 Sampled by: NW
Sample Location:
Surface Elevation 7.41'

WATER LEVEL OBSERVATIONS
W.L. 9'4" @ 2 days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	A Sediment	V. DK Gray ↓	Loam ↓	Friable ↓			
	Cca ↓	LT. Brownish Gray ↓	↓	↓			
2	C ↓	Lt. Olive Brown ↓	↓	↓			Brown and gray mottles
	OtuL till ↓	2.5Y Brown ↓	Clay loam ↓	Slightly Firm Plastic ↓			
4	↓	↓	↓	↓			
6	↓	↓	↓	↓			
8	↓	↓	↓	↓			
	Bottom						Fe joint coatings
10							
12							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 10-4-83
Proj. No.: Fossum II
Tech:
Boring No. 100-800
Sampled by: NW
Sample Location:
Surface Elevation 8.4'

WATER LEVEL OBSERVATIONS
W.L. 4'7" @ 2 days
W.L. @

NOTES Wet core hole. a lot of sand 4-6'.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
		V. DK. Gray	Loam	friable			
	Ap+A O+L	↓	↓	↓			
	Aca						
	Bca O+UL Sediment	Lt. Brownish Gray					
2	↓	Lt. Olive Brown					
	gleyed Sediment	2.5Y Grayish Brown w/ Brown Mottles	↓				
			Sand ↓	↓			▽
4		Yellowish Brown w/ gray mottles	Loamy Sand	Sloppy			
	↓ w/oxidized zones						
6	↓	↓	↓	↓			
	O+UL till	2.5Y Brown	Clay loam	Firm Slightly Plastic			
8		↓					
	↓	Olive Brown					
10	Bottom	↓	↓	↓			

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 100-900 Sampled by: NW
Sample Location:
Surface Elevation 7.8'

WATER LEVEL OBSERVATIONS
W.L. 9'10" @ 2 days
W.L. @

NOTES South of contaminated area, inside of a Small swale.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-9''	Disturbed material O + L	V. DK. Gray w/ Yellowish Brown mixed in at 6-9''	Loam	Friable			Yellowish material is calcareous
9-14''	A						
14-24'' 2	B	V. DK Grayish Brown					
24-30''	2A	V. DK. Gray					
30-40''	2B	2.5Y Brown					
							Sandy Zone (45 48'') above till contact
4	MO + UL Till	DK. Brown to olive Brown w/ gray mottles	Clay loam	Slightly firm Friable to			Strong carbonate coatings, bay tills and some concretions decreasing with depth
6	O + UL Till	LT. Olive Brown		Slightly plastic Firm Slightly plastic			
8							
10	Bottom						

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 300-300 Sampled by: NW
Sample Location:
Surface Elevation 67'

WATER LEVEL OBSERVATIONS
W.L. 4'9" @ 3days
W.L. @

NOTES Lower edge of closed basin

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-6"	A O+L Sed.	Black	Loam	Friable			
6-16"	B	V. Dk. Grayish Brown	Sandy Loam				
2	C	2.5Y Grayish Brown					Pebble band
	MO + UL Till	2.5Y Brown	Clay loam	Firm Friable			Abundant carbonate coatings and channel fills (3-6')
4							
6							
	O + UL Till	2.5Y Dk. Brown		Firm Slightly Plastic			
8							
10	Bottom						
12							

BORING STARTED

1

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRR I Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 300-400 Sampled by: NW
Sample Location:
Surface Elevation 7.8'

WATER LEVEL OBSERVATIONS
W.L. 3'8" @ 3days
W.L. @

NOTES Soil and till very moist - Some difficulty Coring.
Paper and plastic bag samples.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis- tence	Sample Type	Sample No.	
0-6"	Ap O+L	Black	Loam	Friable		0-6	very fine white root channel fillings (not carbonates)
6-10"	Bca O+ul sediment	LT. Brownish Gray				6-12	
	B + C	Pale Brown + 2.5Y LT Yellowish Brown				12-24	10-18" very soft
2	Mo+ul+ill	2.5Y Brown	Clay loam	V. friable			Gypsum masses beginning at 3', decreasing with depth
4				Parts to ABK structure			
6	O+ul+ill	Yellowish Brown w/gray Joints		mod firm slightly plastic			
8				Parts to coarse ABK			Mn Splotches on some joint faces Fe coated joints
10	Bottom						

ORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-5-83
Proj. No.: fossum II Tech:
Boring No. 300-600 Sampled by: NW
Sample Location:
Surface Elevation 7.4'

WATER LEVEL OBSERVATIONS
W.L. Plugged at 4' @ 2 days
W.L. @

NOTES Leveled disposal Pit.
Paper and plastic bag samples

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	Pit fill material ULL	mixed Black & Yellowish Brown	Clay loam	mod. firm Plastic			
2							
4	Some oil Contamination	gleyed colors		Soft plastic			
		mixed Black & Yellowish Brown					
6							
	4" topsoil	V. DK. Gray					
8		mixed Black & Yellowish Brown					
	Oil Contaminated	Bluish Gray and Black					
10							
12	O + ULL + till	Lt. Olive Brown		V. firm			Fe joint coatings
14	Bottom						

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 300-800 Sampled by: NJW
Sample Location:
Surface Elevation 7.4'

WATER LEVEL OBSERVATIONS
W.L. Dry @ 2days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-7"	Ap O+L Sed.	Black	Loam	Friable			
	B	V. DK Grayish Brown					
	Bca O+UL Sediment	2.5Y Lt Brownish Gray					
2	C	2.5Y Brown	Loamy Sand				
4	O+UL till	2.5Y-10YR Brown	Clay loam	Slightly firm Friable			
6							
8				Firm Slightly Plastic			alot of water in the core hole, probably from sand at 4' No paper bag sample 8-10'
	Bottom						
10							
12							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 10-4-83
Proj. No.: Fossum II
Tech:
Boring No. 300-900
Sampled by: NW
Sample Location:
Surface Elevation 7.9'

WATER LEVEL OBSERVATIONS
W.L. 9'3" @ 2 days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-6"	Ap O+UL Sediment	V.DK.Gray	Loam	Friable		0-6	
6-13"	Bca	DK. Grayish Brown				6-12	
	C ↓	LT Olive Brown	↓			12-18	
2	O+UL till	2.5Y DK. Grayish Brown	Clay loam	↓ Mod. Firm Friable			pebble band sand (23-26") gypsum masses with horizontal and vertical orientation
4							↓
6				↓ Firm Slightly plastic			Fe joint coatings
8							
	↓	↓	↓	↓			↓
10	Bottom						
12							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 500-300 Sampled by: NW
Sample Location:
Surface Elevation 8.1'

WATER LEVEL OBSERVATIONS
W.L. Dry @ 3 days
W.L. @

NOTES On ridge between depressions

Log Depth (feet)	Weather. Zone	Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
	A	O+L Sed.	Black ↓	Loam	Friable			
	B	↓	V. DK. Grayish Brown ↓	↓				
2	Bca	O+uL Sediment	2.5Y Pale Brown	Sandy Loam				
	C	↓	↓	↓	↓			Fine Sand medium Sand
		O+uL till	10YR-2.5Y Brown	Clay loam	Slightly Firm Friable			Abundant Carbonate Coatings 3.5-6'
4		↓	↓	↓	↓			
6					Firm friable ↓			
8					Firm Slightly Plastic ↓			
10		Bottom						

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 500-400 Sampled by: NW
Sample Location:
Surface Elevation 8.21

WATER LEVEL OBSERVATIONS
W.L. 6'9" @ 3days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
0-9''	A O+L Sed.	V. DK. Gray	Loam	Friable		0-6	
	B	V. DK Grayish Brown				6-12	
9-15''		LT. Grayish Brown	Clay loam	Plastic		12-24	
15-21''	Bc g O+UL sediment						
2	C	Olive Brown	Loamy Sand				
	motill + till	2.5y Grayish Brown and	Clay loam	Slightly firm			
4		DK. Grayish Brown		Friable			Common gypsum masses 4½-7', decreasing with depth.
6				Firm Friable			
8				V. Firm			Fe joint coatings
	Bottom						
10							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 500-600 Sampled by: NW
Sample Location:
Surface Elevation 7.3'

WATER LEVEL OBSERVATIONS
W.L. 3'10" @ 2days
W.L. @

NOTES 100' South of well head, Sparse Vegetation

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-4"	Ap O+L	V. DK. Gray	Loam	Friable			
4-8"	Bca O+UL Sediment	Lt. Brownish Gray Lt. Olive Brown					
2	O+UL till	2.5Y Brown	Clay loam	Slightly Firm friable			Abundant gypsum masses decreasing with depth
4							
6		Olive Brown		Firm Slightly plastic			▽
8	Sand lense O+UL till		Sandy loam Clay loam	Soft Plastic			Fe joint coatings
10	Sand lense Bottom		Loam				

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 500-800 Sampled by: NW
Sample Location:
Surface Elevation 8.9'

WATER LEVEL OBSERVATIONS
W.L. 5'9" @ 2days
W.L. @

NOTES Rocky surface, convex swell. Very thin A+B.. Dark colored till.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7"	Ap O+L	V. DK. Gray	Loam	Friable		0-6	till color not directly related To surface damage
7-14"	B	DK. Yellowish Brown				6-12	
14-21"	Bca mo+uL +till	Pale Brown	↓	↓		12-24	
2	C ↓	2.5Y V. DK. Grayish Brown ↓	Clay loam	Mod. Firm Friable			
4	O+uL +till	2.5Y DK Grayish Brown					few gypsum masses 4-6'
6							Fe mottles and core
8	↓	LT. Olive Brown ↓	↓	↓			↓
10	Bottom						Fe joint coatings

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI
Date: 10-4-84
Proj. No.: Fossum II
Tech:
Boring No. 500-900
Sampled by: NW
Sample Location:
Surface Elevation 7.8'

WATER LEVEL OBSERVATIONS
W.L. 7'2" @ 2 days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7"	A Sediment	V. DK. Gray	Loam	Friable			
7-12"	B	V. DK. Grayish Brown					
12-20"	Bca	Pale Brown					
	C	Lt. Olive Brown					Sand and pebble bond
2	O + UL till	2.5 Y. Brown					abundant gypsum masses 34-52"
			Clay loam	Firm			
4				Slightly Plastic			
							gypsum masses
6		Lt. Olive Brown		Friable			water in sand lense
	Sand lense						
	O + UL till			Firm Slightly Plastic			
8							
							Fe joint coatings
10	Bottom						
12							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 700-300 Sampled by: NW
Sample Location:
Surface Elevation 6.5'

WATER LEVEL OBSERVATIONS
W.L. 9'0" @ 3 days
W.L. @

NOTES In the bottom of a depression oxidized below a reduced gleyed zone

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-10"	A + B O+L	Black	Loam	Friable			
	O+uL	V. DK. Brown	↓	↓			
	MO+L till?	LT. Olive Brown and Brown ↓	Clay loam				
2	R+uL till ↓	Mixed Gray, Greenish Gray, Bluish Gray ↓	↓	Slightly firm friable ↓			gleyed
4							
	MO+uL till ↓	2.5Y Brown w/Gray mottles ↓		Firm Plastic ↓			Some dark ox inclusions
6							
8							
	O+uL till ↓	Yellowish Brown ↓					
10	Bottom						

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-3-83
Proj. No.: Fossum II Tech:
Boring No. 700-400 Sampled by: NW
Sample Location:
Surface Elevation 8.21

WATER LEVEL OBSERVATIONS
W.L. Dry @ 3 days
W.L. @

NOTES

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-7	Ap Bca	Black ↓ Lt. Yellowish Brown ↓	Loam ↓	Friable ↓		0-6" 6-12" 12-24"	Somewhat dry from this years' crop
2	B + C	Yellowish Brown ↓	↓	mod. firm Friable ↓			
	O+UL Till ↓		clay loam ↓	V. Firm ↓			
4							
	mo+UL till ↓	Olive Yellowish Brown w/ gray mottles ↓					
6							Strong bright Fe core distinct absence of gypsum as compared to 4-1, 4-3, 4-5 ↓
	O+UL till ↓						
8							Fe Joint Coatings ↓
10	Bottom						

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 700-600 Sampled by: NW
Sample Location:
Surface Elevation 5.8'

WATER LEVEL OBSERVATIONS
W.L. 5'11" @ 2 days
W.L. @

NOTES Located in a depression, Strongly developed Soil. Very thick Sediment.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-10"	A O+L Sediment	V.DK.Gray	Loam	Friable			
		LT. Brownish Gray					
10-20"	E						
		Black		Firm			
2		DK. Yellowish Brown w/ Black coatings		Friable			B horizon has very strong structure and thick coats of omk clay
	B+						
	C						
4		Gray w/brown mottles					▽ Stratified sand silts
	O+ULL Sediment	Yellowish Brown w/Gray mottles		Soft Plastic			
6							
8							
	MO+L till		clay loam	firm Plastic			
10	Bottom						
12							

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 700-800 Sampled by: NW
Sample Location:
Surface Elevation 8.3'

WATER LEVEL OBSERVATIONS
W.L. Dry @ 2 days
W.L. @

NOTES Adjacent to lighter colored surface area.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consistence	Sample Type	Sample No.	
0-6"	Ap O+L	V, DK. Gray	Loam	Friable			
6-9"	A	V. DK. Grayish Brown					
	B						
12-16"	Bca O+UL	Pale Brown					
	C	LT. Olive Brown					
2	MO+UL						Secondary carbonates 24-32"
	O+UL till						
4		2.5Y Brown	Clay loam	mod. firm slightly Friable			Abundant gypsum masses decreasing with depth
6							Few fe core
8				mod. firm slightly Plastic			Fe coated joints
10	Bottom						9-10' gypsum in vertical joint (picture)

BORING STARTED

Table 2-4 (con't)

NORTH DAKOTA STATE UNIVERSITY
Land Reclamation Research Center
P. O. BOX 459
MANDAN, NORTH DAKOTA 58554

LOG OF SUBSURFACE DATA

Client: NDWRRI Date: 10-4-83
Proj. No.: Fossum II Tech:
Boring No. 700-900 Sampled by: NW
Sample Location:
Surface Elevation 7.1'

WATER LEVEL OBSERVATIONS
W.L. 9'11" @ 2days
W.L. @

NOTES Located in swale.

Log Depth (feet)	Weather. Zone Geol. Material	Color	Texture	Consis-tence	Sample Type	Sample No.	
	Ap O+L Sediment	V. DK. Gray	Loam	Friable			
	A	V. DK Grayish Brown					
	B						
2	C O+UL Sediment	LT. Olive Brown					Reddish brown sand lense (31-33")
	mo+UL till	2.5Y, Brown					Abundant Secondary carbonates 46-62"
4			Clay loam	mod. Firm Friable			
	O+UL till	LT. Olive Brown					
6				Firm Slightly Plastic			few Fe mottles and core
8							Fe joint coatings
10	Bottom						

BORING STARTED

APPENDIX

TASK 3

Table 3-1 Gravimetric moisture contents of spring 1985 samples A-72

Table A 3-1

GRAVIMETRIC MOISTURE CONTENTS OF SPRING 1985 SAMPLES

SITE	DEPTH	CAN #	CAN WT.	WET	DRY	WETNESS
SSC-1	0-3	355	34.301	81.992	74.210	0.19
	3-6	358	34.332	75.084	67.285	0.24
	6-9	356	34.406	93.741	83.442	0.21
	9-12	359	34.483	92.993	82.030	0.23
	12-15	349	34.441	86.915	76.913	0.24
	15-18	357	34.295	78.682	69.733	0.25
SSC-2	0-3	351	34.155	101.785	92.114	0.17
	3-6	350	34.550	110.442	94.765	0.26
	6-9	354	34.269	113.759	97.659	0.25
	9-12	348	34.149	110.172	92.762	0.30
	12-15	347	34.168	114.324	95.008	0.32
	15-16	346	34.293	94.055	77.863	0.37
SSC-3	0-3	352	34.498	95.691	83.623	0.25
	3-6	353	34.184	94.313	81.387	0.27
	6-9	321	34.664	98.349	85.518	0.25
	9-12	341	34.207	81.948	72.832	0.24
	12-14	342	33.914	125.668	108.910	0.22
SSC-4	0-3	344	34.075	103.501	90.099	0.24
	3-6	360	34.473	100.900	86.870	0.27
	6-9	345	34.217	102.324	88.189	0.26
	9-12	343	34.209	85.160	74.011	0.28
SSC-5	0-3	330	34.442	82.712	73.638	0.23
	3-6	331	34.534	121.863	101.673	0.30
	6-9	323	34.560	112.981	95.362	0.29
	9-12	326	34.384	96.669	83.873	0.26
	12-14	322	34.322	83.301	72.462	0.28
SSC-6	0-3	327	34.057	143.791	110.167	0.44
	3-6	335	34.426	96.709	80.642	0.35
	6-9	334	34.426	87.803	73.745	0.36
SSN-0	0-3	266	34.136	79.540	71.180	0.23
	3-6	242	34.310	80.760	70.640	0.28
	6-10	246	34.409	90.180	79.275	0.24
SSN-0.5	0-6	274	34.214	80.936	70.463	0.29
	6-10	267	34.264	86.075	74.480	0.29
	10-12	273	34.198	84.285	74.433	0.24
SSN-1	0-6	293	34.376	98.769	83.176	0.32
	6-12	292	34.243	126.467	92.787	0.58

Table 3-1 (con't)

GRAVIMETRIC MOISTURE CONTENTS OF SPRING 1985 SAMPLES

SITE	DEPTH	CAN #	CAN WT.	WET	DRY	WETNESS
SSN-2	0-6	277	34.254	159.273	123.360	0.40
	6-12	294	34.249	115.226	96.675	0.30
SSN-3	0-6	290	34.649	86.329	70.552	0.44
	6-12	297	34.194	84.747	71.204	0.37
SSN-4	0-6	264	34.517	112.122	91.878	0.35
	6-12	262	34.460	66.610	59.936	0.26
SSN-5	0-6	275	34.356	134.421	108.705	0.35
	6-12	248	34.434	84.967	74.028	0.28
SSN-6	0-5	281	34.330	147.088	109.491	0.50
	5-10	265	34.440	90.463	77.374	0.30
PSC-1	0-6	211	34.386	85.522	76.385	0.22
	6-12	191	34.614	97.766	86.683	0.21
	12-18	224	34.081	95.756	84.411	0.23
	18-24	207	34.486	115.382	101.203	0.21
PSC-2	0-6	220	34.785	95.131	82.288	0.27
	6-12	205	34.412	98.748	85.813	0.25
	12-18	218	34.249	95.660	84.372	0.23
	18-24	182	34.436	133.868	113.363	0.26
PSC-3	0-6	185	34.261	120.818	94.112	0.45
	6-12	221	34.333	111.300	97.291	0.22
	12-18	201	34.091	82.796	74.149	0.22
	18-24	186	34.004	140.541	120.717	0.23
PSC-4	0-6	202	34.309	94.423	82.506	0.25
	6-12	206	34.104	158.624	138.829	0.19
	12-18	190	34.073	121.076	108.212	0.17
	18-24	181	34.180	150.080	132.757	0.18
	24-28	195	34.245	142.624	123.692	0.21
PSC-5	0-6	291	34.503	74.258	64.700	0.32
	6-12	299	34.227	110.140	96.692	0.22
	12-18	127	34.243	88.669	78.077	0.24
	18-24	130	34.325	121.271	104.154	0.25
PSC-6	0-6	210	34.574	91.346	74.189	0.43
	6-12	198	34.547	98.076	84.750	0.27
	12-18	136	34.419	125.934	112.404	0.17

Table 3-1 (con't)

GRAVIMETRIC MOISTURE CONTENTS OF SPRING 1985 SAMPLES

SITE	DEPTH	CAN #	CAN WT.	WET	DRY	WETNESS
PSC-7	0-6	215	34.124	122.109	98.511	0.37
	6-12	192	34.368	134.749	111.982	0.29
	12-18	298	34.354	143.053	115.662	0.34
	18-24	237	34.196	87.701	75.085	0.31
FSA-9	0-3	239	34.237	127.536	111.082	0.21
	3-6	234	34.272	75.302	67.787	0.22
	6-10	229	34.422	122.111	105.487	0.23
FSA-8	0-3	236	34.076	94.472	86.279	0.16
	3-6	235	34.357	125.979	110.239	0.21
	6-9	233	34.621	113.284	98.920	0.22
	9-12	240	34.288	79.935	72.788	0.19
FSA-7	0-3	232	34.104	114.223	100.813	0.20
	3-6	231	34.119	112.802	97.243	0.25
	6-9	230	34.487	98.839	83.646	0.31
	9-12	238	34.252	78.525	67.788	0.32
FSA-6	0-3	189	34.141	98.379	86.835	0.22
	3-6	208	34.448	90.393	78.803	0.26
	6-9	228	34.374	92.438	80.197	0.27
	9-12	184	34.422	89.421	78.091	0.26
FSA-5	0-3	183	34.263	107.142	104.152	0.04
	3-6	209	34.365	92.420	81.143	0.24
	6-9	226	34.391	92.141	81.064	0.24
	9-12	187	34.402	95.566	83.988	0.23
FSA-4	0-3	217	34.168	104.465	88.945	0.28
	3-6	194	34.048	103.041	88.352	0.27
	6-9	203	34.366	87.028	75.787	0.27
	9-12	200	34.438	91.023	80.140	0.24
	12-15	213	34.131	109.309	92.152	0.30
FSA-3	0-3	212	34.542	97.765	76.627	0.50
	3-6	204	34.273	130.225	100.532	0.45
	6-9	219	34.505	106.951	86.434	0.40
	9-12	223	34.126	79.237	70.115	0.25
	12-15	216	34.217	81.507	71.269	0.28
BSC-1	0-4	161	34.182	83.190	73.368	0.25
	4-8	162	34.237	86.240	76.048	0.24
	8-12	163	34.334	85.179	75.886	0.22
	12-17	164	34.010	116.254	98.289	0.28

Table 3-1 (con't)

GRAVIMETRIC MOISTURE CONTENTS OF SPRING 1985 SAMPLES

SITE	DEPTH	CAN #	CAN WT.	WET	DRY	WETNESS
BSC-2	0-4	168	34.343	98.461	85.911	0.24
	4-8	167	34.383	112.821	95.059	0.29
	16-22	166	34.354	116.744	99.547	0.26
	22-24	165	34.359	87.903	80.714	0.16
BSC-3	0-4	169	34.390	98.923	83.989	0.30
	4-8	170	34.225	107.350	94.974	0.20
	8-12	173	34.467	84.350	74.928	0.23
	12-16	174	34.293	78.778	70.157	0.24
BSC-4	0-4	179	34.371	94.491	80.963	0.29
	4-8	176	34.305	134.291	119.757	0.17
	8-12	171	34.579	97.884	89.001	0.16
	12-16	172	34.176	104.510	96.224	0.13
BSC-5	0-4	175	34.212	115.925	104.752	0.16
	4-8	178	34.432	117.990	110.187	0.10
	8-10	177	34.445	98.532	90.778	0.14
BSC-6	0-4	148	34.150	104.010	92.478	0.20
	4-8	146	34.105	93.878	88.453	0.10
	8-10	147	34.353	103.253	97.306	0.09
BSC-7	0-3	143	34.345	103.081	89.376	0.25
	3-8	144	34.159	125.974	116.030	0.12
	8-10	180	34.526	97.879	97.515	0.01
BSC-8	0-4	153	34.289	90.774	76.529	0.34
	4-8	149	34.528	102.769	92.976	0.17
	9	150	34.284	123.425	111.622	0.15
BSN-1	0-6	126	34.279	102.413	88.814	0.25
	6-12	139	34.002	118.962	102.524	0.24
	12-18	145	34.286	104.240	91.247	0.23
	18-24	156	34.134	119.168	102.359	0.25
BSN-2	0-6	142	34.168	84.748	74.614	0.25
	6-12	158	34.210	125.536	110.617	0.20
	12-18	123	34.459	159.711	137.362	0.22
	18-24	134	34.492	115.557	104.936	0.15
BSN-3	0-6	128	34.117	86.953	74.749	0.30
	6-12	135	34.442	114.711	101.728	0.19
	12-15	160	34.032	142.462	128.934	0.14
	15-17	129	34.304	101.908	95.028	0.11

Table 3-1 (con't)

GRAVIMETRIC MOISTURE CONTENTS OF SPRING 1985 SAMPLES

SITE	DEPTH	CAN #	CAN WT.	WET	DRY	WETNESS
BSN-4	0-6	133	34.296	107.571	89.881	0.32
	6-12	159	34.479	138.641	115.369	0.29
	12-14	157	33.792	77.519	69.293	0.23
BSN-5	0-3	138	34.181	72.557	61.803	0.39
	3-6	140	34.122	75.235	62.543	0.45
	6-11	121	34.261	110.581	91.307	0.34
BSN-6	0-2	151	34.486	63.652	53.212	0.56
	2-4	122	34.334	81.715	63.785	0.61
	4	137	34.305	82.370	61.041	0.80
BSN-7	0-4	131	34.165	97.785	66.930	0.94
	4-8	125	34.076	78.330	65.948	0.39
	8	132	34.231	110.220	93.239	0.29

APPENDIX

Task 4-1

Table 4-1A Chemical Analysis of Water that Flowed from the Seismic Shot Hole and the Amundsen Farm Well................ A -78

Table 4-1B Water Levels.. A -80

Table 4-1C Piezometer Screen Interval and Drilling Method.............. A -83

Table 4-1D Lithologic Descriptions of Shelby Tube Sediment and Rotary and Auger Hole Cuttings.............................. A -85

Table 4-1E Lithologic Column, E Log Profiles, and Piezometer Placement at Piezometer Nests.............................. A -94

Table 4-1F Groundwater Chemical Analyses............................... A-103

Table 4-1G Isoconcentration Maps of Selected Parameters from the Four Monitored Intervals.............................. A-128

APPENDIX 4-1A

CHEMICAL ANALYSES OF THE WATER THAT FLOWED FROM THE SEISMIC SHOT HOLE AND THE AMUNDSEN FARM WELL

CHEMICAL ANALYSIS OF WATER THAT FLOWED FROM SEISMIC SHOT HOLE

Collected: 1-27-83

Total Alkalinity ($CaCO_3$)	321	mg/L
Bicarbonate (HCO_3)	392	mg/L
Calcium	3,980	mg/L
Carbonate (CO_3)	0	mg/L
Chloride	78,800	mg/L
Fluoride	0.0	mg/L
Total Hardness (as $CaCO_3$)	15,000	mg/L
Iron	9.10	mg/L
Magnesium	1,220	mg/L
Manganese	1.71	mg/L
pH	6.8	
Potassium	712	mg/L
Sodium	40,200	mg/L
Percent Sodium	85.3	%
Sulfate as (SO_4)	1,290	mg/L
Total Dissolved Solids (C)	126,000	mg/L
Turbidity	65.0	NTU
Oil and Grease	<5.	mg/L
Sodium Adsorption Ratio	143	
Conductivity	135,500	umhos/cm
Nitrate as (N)	<2	mg/L

CHEMICAL ANALYSIS OF WATER THAT FLOWED FROM AMUNDSEN FARM WELL

Collected: 1-31-83

pH	8.0	
Conductivity	3,910	umhos/cm
Total Dissolved Solids (C)	2,890	mg/L
Iron	0.76	mg/L
Manganese	0.070	mg/L
Calcium	18.5	mg/L
Magnesium	6.50	mg/L
Total Hardness (as $CaCO_3$)	73	mg/L
Potassium	6.30	mg/L
Sodium	958	mg/L
Chloride	26.0	mg/L
Sulfate as (SO_4)	1,260	mg/L
Total Alkalinity ($CaCO_3$)	1,030	mg/L
Bicarbonate (HCO_3)	1,260	mg/L
Carbonate (CO_3)	0	mg/L
Fluoride	0.8	mg/L
Percent Sodium	96.6	%
Turbidity	29.0	NTU
Sodium Adsorption Ratio	48.8	
Nitrate as (N)	2.00	mg/L
Total Hardness (as $CaCO_3$)	4.26	Grains/gal

APPENDIX 4-1B

WATER LEVELS

WATER LEVELS FROM JUNE 25, 1985

Pleistocene Piezometer No.	Elev. (Ft.)	Collar	Wt. Level (Ft.)	Head (Ft.)
39	1940		-5.61	1934.39
8	1936	2"	-3.97	1932.03
33	1936		--	
34	1936		--	
11	1936	2"	-6.33	1929.67
35	1936.4		-4.07	1932.33
19	1936.4	2"	-4.72	1931.68
38	1936		-5.61	1930.39
37	1935		-6.56	1928.44
36	1936		-8.46	1927.54
29	1936	2"	-4.66	1931.3
"D" Lignite				
			Ft.	Head
2	1940	2"	-3.51	1936.5
10	1936	2"	--	
6	1945	2"	7.84	1937.2
31	1936.4	?	8.53	?
13	1936	2"	2.13	1933.9
20	1936	2"	0.82	1935.2
25	1935	2"	1.97	1933
28	1936	2"	1.71	1934.3
40	1936.4	10"	1937.2 (Flowing oil)	>1937.2

Piezometer No.	Elev. (Ft.)	Wt. Level (Ft.)	Head (Ft.)
Sand			
3	1940	-2.89	1937.1
4	1945	-7.84	1937.2
7	1936	-1.2	1934.8
14	1936	--	--
17	1936.4	-2.88	1933.5
16	1936.4	-2.76	1933.6
21	1936	-1.05	1934.9
24	1935	-1.44	1933.6
27	1936	-1.84	1934.2
E - Lignite			
1	1940	4.76	1935.2
5	1945	-7.97	1937
9	1936	-0.98	1935
15	1936.4	-3.48	1932.9
12	1936	-5.05	1931
22	1936	-1.15	1934.9
23	1935	-1.51	1933.5
26	1936	-3.41	1932.6

APPENDIX 4-1C

PIEZOMETER SCREEN INTERVAL AND DRILLING METHOD

Piezometer No.	Piezometer Depth (Ft.)	Screen Thickness (Ft.)	Drilling System
1	189	5	
2	92.5	5	
3	146.5	10	
4	187	10	
5	225	5	
6	134	5	
7	169	10	AIR
8	11	10	AIR
9	196	5	AIR
10	104.5	5	AIR
11	17.25	10	AIR
12	200.4	5	WATER
13	110	5	WATER
14	172	10	WATER
15	241	Screen Interval is 215-225	
16	206	10	AIR
17	161.5	10	AIR
18	53	5	AIR
19	14	10	AIR
20	126	5	
21	177	10	
22	225	5	
23	215	10	
24	176.5	10	
25	112	5	
26	219	5	AIR
27	182	10	AIR
28	122	5	AIR
29	14	10	AIR
30	83.2	10	AUGERED
31	121	7	AUGERED
32	72	10	AUGERED
33	20	10	AUGERED
34	15	8	AUGERED
35	30	10	AUGERED
36	18	10	AUGERED
37	20	7	AUGERED
38	20	10	AUGERED
39	18	10	AUGERED
40			AUGERED

APPENDIX 4-1D

LITHOLOGIC DESCRIPTIONS OF SHELBY TUBE SEDIMENT AND ROTARY AND AUGER HOLE CUTTINGS

DESCRIPTION OF SHELBY TUBE SEDIMENTS

Feet	
0-1	soil, yellow/brown-orange/gray, plant roots, silty
1-5.5	clay, orange/brown, very silty; some very organic rich, black clay layers
5.5-8	clay, fatigue green, very calc., some small calcite grains, lacusterine
8-9.5	clay, light-green, very calc., some calc. crystals, lacusterine
9.5-12	clay, light-green, very calc., some calc. crystals, FeO staining, lacusterine silt in last two feet
12.-12.2	silt, gray, clay, lignite fragments, FeO stained
12.2-13	clay, light gray-green; alternate silty layers, gray-green, calc. crystals
13-14	sand, light green-light brown, medium green silt
14-18	silt, green-gray, clay, some FeO staining
18-19.2	till, clay, dark green-dark gray, pebbly (dolomite & lignite fragments), calc.
19.2-20.5	till, silty, light gray-green, pebbly (dolomite & lignite fragments), calc.
20.5-24	sand, medium green-gray, medium green subrounded
24-24.2	sand, medium green-gray, coarse green-pebbles, subrounded, gravely
24.2-29.9	sand, medium green-gray, medium green, subrounded
29.9-43	till, clay, dark gray-green, pebbly, calc., some calc. crystals
43-45.5	sand, green-gray, medium green, laminated with dark gray clay, lignite fragments, carbonate
45.5-49	clay, dark gray, carbonate, contains twin lignite stringers
49-	lignite

L-4

Feet	
0-37	till
37-40	clay, gray-blue
40-41	lignite
41-52	clay, dark gray
52-54	lignite
54-68	clay, dark gray
68-70	lignite
70-72	clay
72-76	lignite
76-94	clay, gray-brown
94-95	claystone, dark gray, very well indurated
95-127	clay, dark gray-gray, slightly silty
127-131	lignite
131-174.5	clay, dark green-gray, very silty
174.5-177	sandstone, green, moderately indurated, very fine grain
177-214	sand, gray-green, poorly indurated fine-very fine grain
214.5-222	lignite
222	TD

L-9

Feet	
0-2	clay and peat
2-3	peat
3-9	clay, clean
9-20	till, gray-blue, pebbly
20-20.5	coal
20.5-24	silt, gray-blue, clayey
24-25	coal, carbonaceous clay
25-62	clay, dark gray, clean
62-64	sandstone, yellow-brown, medium grained, moderately-well cemented
64-74	clay, dark gray-gray, clean
74-76	claystone, very dark-gray, very well-indurated
76-84	clay, gray-dark gray, clean
84-84.5	concretion, yellow-brown
84.5-97	clay, gray-dark gray
97-99.75	lignite
99.75-104	clay, green-gray, silty
104-112	clay, gray-brown
112-112.5	concretion
112.5-135	clay, gray-dark gray, very silty
135-185	sand, gray, silt, medium grained
185-196	lignite
196	TD

L-15

Feet	
0-15	We have shelby tubes for this interval
50-51	clay
51-53	lignite
53-59	clay, gray, very silty, carb
59-63	lignite
63-70	clay, silty, carb, gray
70-72	lignite
72-85	clay, silty, gray
85-95	silty, gray, clay
95-117	clay, gray
117-120.5	lignite
120.5-125	clay, gray, carb
125-135	clay, very silty, carb
135-160	clay, gray, silty
160-213	sand, medium grain, gray, well sorted, quartz
213-224	lignite
224-230	clay
230-235	sand
235-240	concentrations of cemented sandstone no returns
240	TD

Note: from 50' on down I detected the odor of brine & crude esp. strong at 160' with brine forming on top of mud.

L-22

Feet	
0-25	till
25-26	clay, gray-blue
26-27	lignite
27-39	clay, light gray, silty
37-38.5	claystone, moderately well incurated
38.5-49.5	clay, gray-moderately clean
49.5-54.5	lignite
54.5-62.5	clay, gray-green, moderately clean
62.5-67	lignite
67-69	clay parting
69-73	lignite
73-94	clay, gray-dark gray
94-97	siltstone, well indurated, gray-green
97-122	clay, gray, slightly silty
122-125.5	lignite
125.5-152	clay, silty, gray
152-159	siltstone, gray-green
159-164	sand, very fine grain, green-gray
164-166	sandstone concretions
166-214	sand, very fine grained, green-gray
214-220	lignite
220	TD

L-23

Feet	
0-7	till
7-9	till, sandy
9-10	till
10-23	till, sandy, yellow-brown, very fine grained
23-49	till
49-49.5	lignite
49.5-79	clay, gray-blue, silty
79-82	concretion
82-106	silt, gray-blue, clayey
106-109	lignite
109-150	clay, gray-blue, silty
150-151	concretion
151-153	siltstone, white, clayey
153-155	clay, gray-blue, silty
155-178	clay, dark gray, clean
178-179	lignite
179-180	clay, gray-blue, silty
180-198	sand, gray, medium grained
198-212	lignite
212-220	clay
220	TD

L-26

Feet	
0-4	clay, lacusterine
4-73	till
73-87	clay, silty, gray, carb
87-88	claystone, dark gray, very well indurated
88-115	clay, gray-dark gray
115.5-119.5	lignite
120-145	clay, gray, silty
145-150	silty, clay to clay silty, gray-dark gray
150-154	siltstone, moderately well indurated
154-170	silty, clay some very fine sand
170-203	sand, very fine grain, silty clay, gray
203-208	lignite
	6" split
208-215	lignite
215	TD

Bottom well at 180' & 120'

L-31 Screen from 121-114 in lignite oil found in clay from - 105-115- (sample appeared to be some very fine sand lenses within the clay (sample) no sign of oil within the lignite

L-32 (at seismic hole)

Feet	
0-2	organic clay
2-4	clay, gray-green, silty
4-17	sand, very fine silty, yellow-brown
17-19	(boulder)
19-	very fine sand, silty, clay, fatigue green, saturated
19-23	bedrock
25-	sand, medium-fine, gray-green
34-36	harder drilling clay, gray-blue, silty
36-	sand, medium-fine, gray-green
39-42	lignite?
42-	clay, gray-blue, clean to silty
49-52	very hard drilling
52-62	very easy drilling
62-64	very hard drilling
64-67	moderate
67-	very hard (extremely hard) put well in around 72' 20' screen

L-33 Drilled to 20' with 10' screen
bedrock contact at between 17-19'

L-34

Feet	
0-2'	dark organic clay
2-4	clay, gray-blue, clean
4-12	sand, light yellow-yellow, clay
12-15	sand, medium fine, gray-blue
15-	hit boulder, couldn't get through; screen is 8'

L-35 At injection well between 85-29 & 85-31

Feet	
0-2	clay, dark, organic
2-4	clay, gray to gray-brown, clean
4-8	tilly(?), yellow-brown, FeO stained, mottled
8-19	till, gray-blue, silty
19-21	boulder pavement?
21-24	sand, fatigue green, (scupy)
24-30	TD at 30' 10' screen

L-36

Feet	
0-4	light sand, silty, chocolate brown
4-18	sand light brown, saturated
18-20	till gray-blue, pebbly
	10' screen well bottomed at 18'

L-37

Feet	
0-3	dark brown till topsoil
3-13	sand dark brown very wet silty
13-15	sand medium gray silty
15-20	till, dark gray silty, sandy
	7' screen

L-38

Feet	
0-2	dark brown till sandy, silty (TS)
2-20	medium brown till silty, clayey
	10' screen

L-39

Feet	
0-14	till, light brown, FeO stained
14-17	till,, dark brown
17-17.5	sand; gravel?
18	boulder
	TD at 18'
	10' screen

APPENDIX 4-1E

LITHOLOGIC COLUMNS, E LOG PROFILES, AND PIEZOMETER PLACEMENT AT PIEZOMETER NESTS

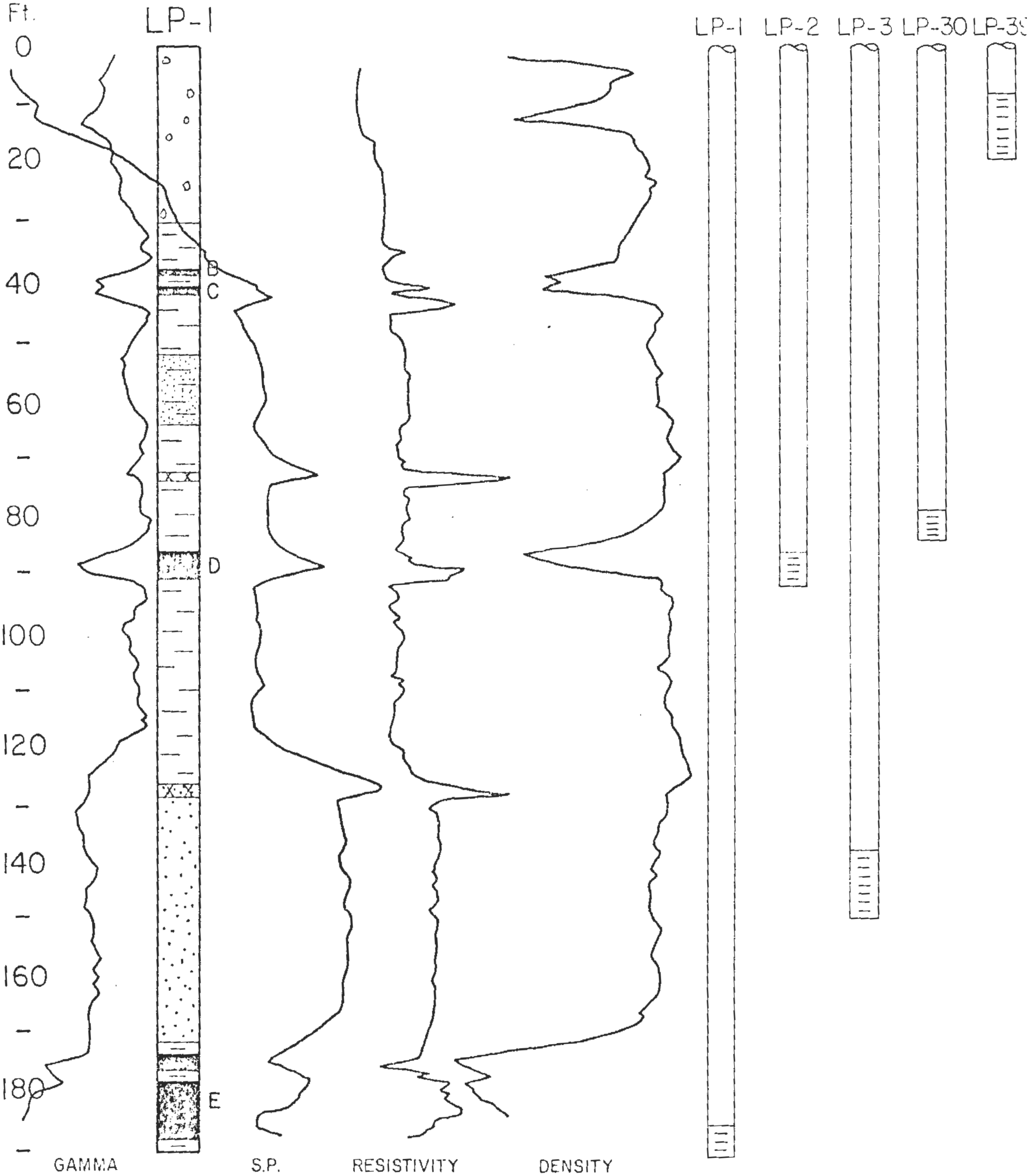


FIGURE 14 - LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NEST ADJACENT TO THE AMUNDSEN FARM.

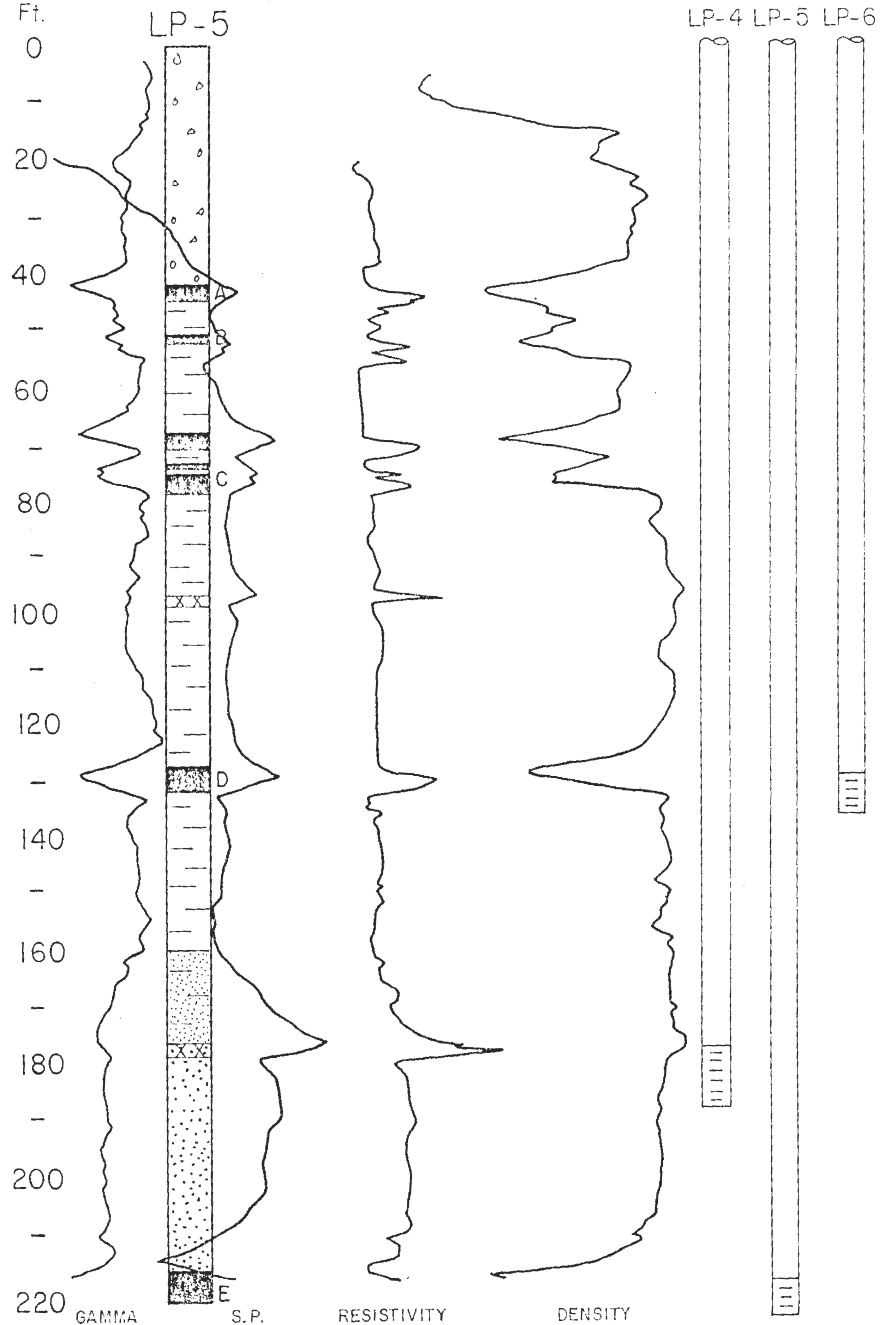


FIGURE 15 - LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NESTS SOUTHEAST OF THE AMUNDSEN FARM WELL.

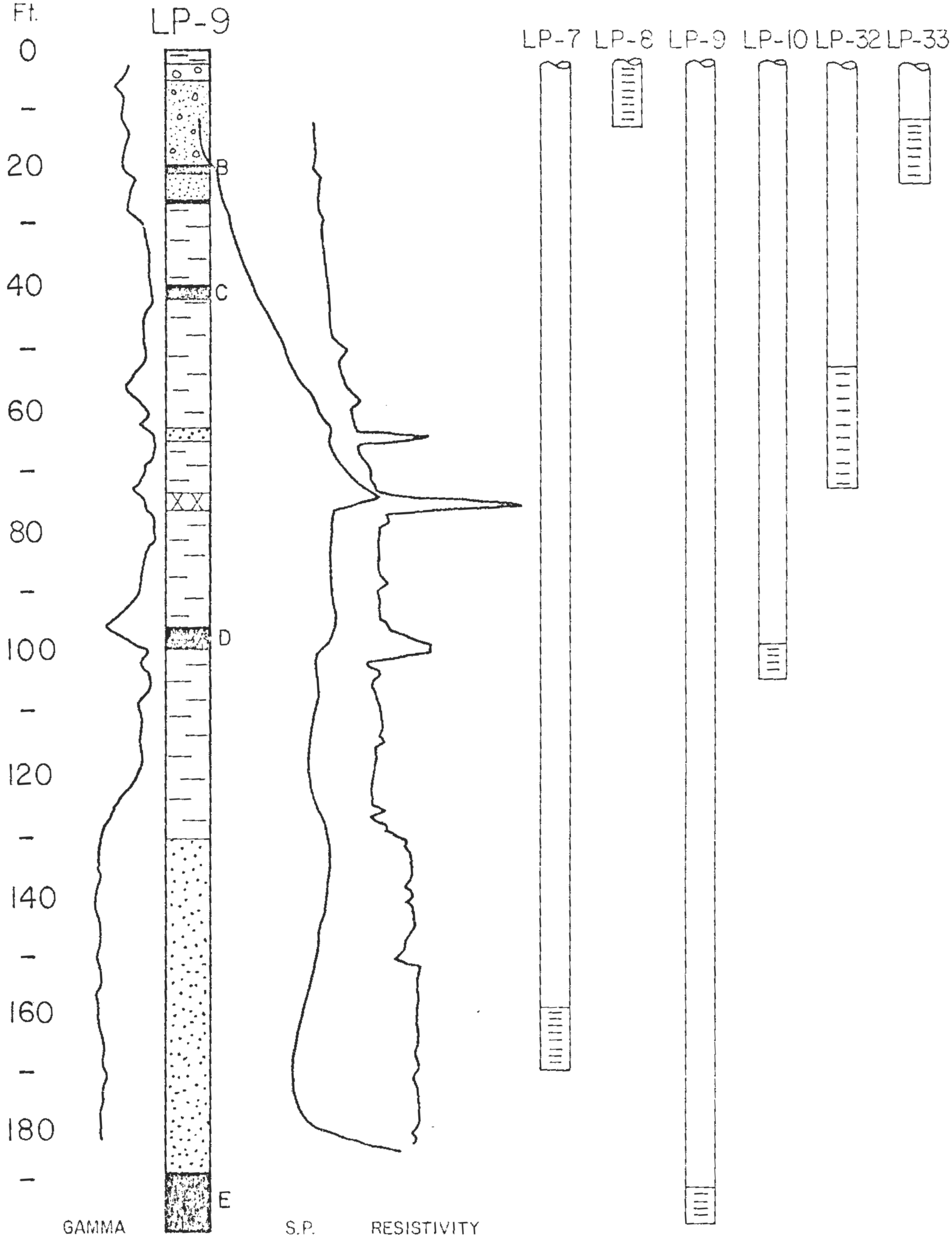


FIGURE 16 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NEST AT THE SEISMIC SHOT HOLE.

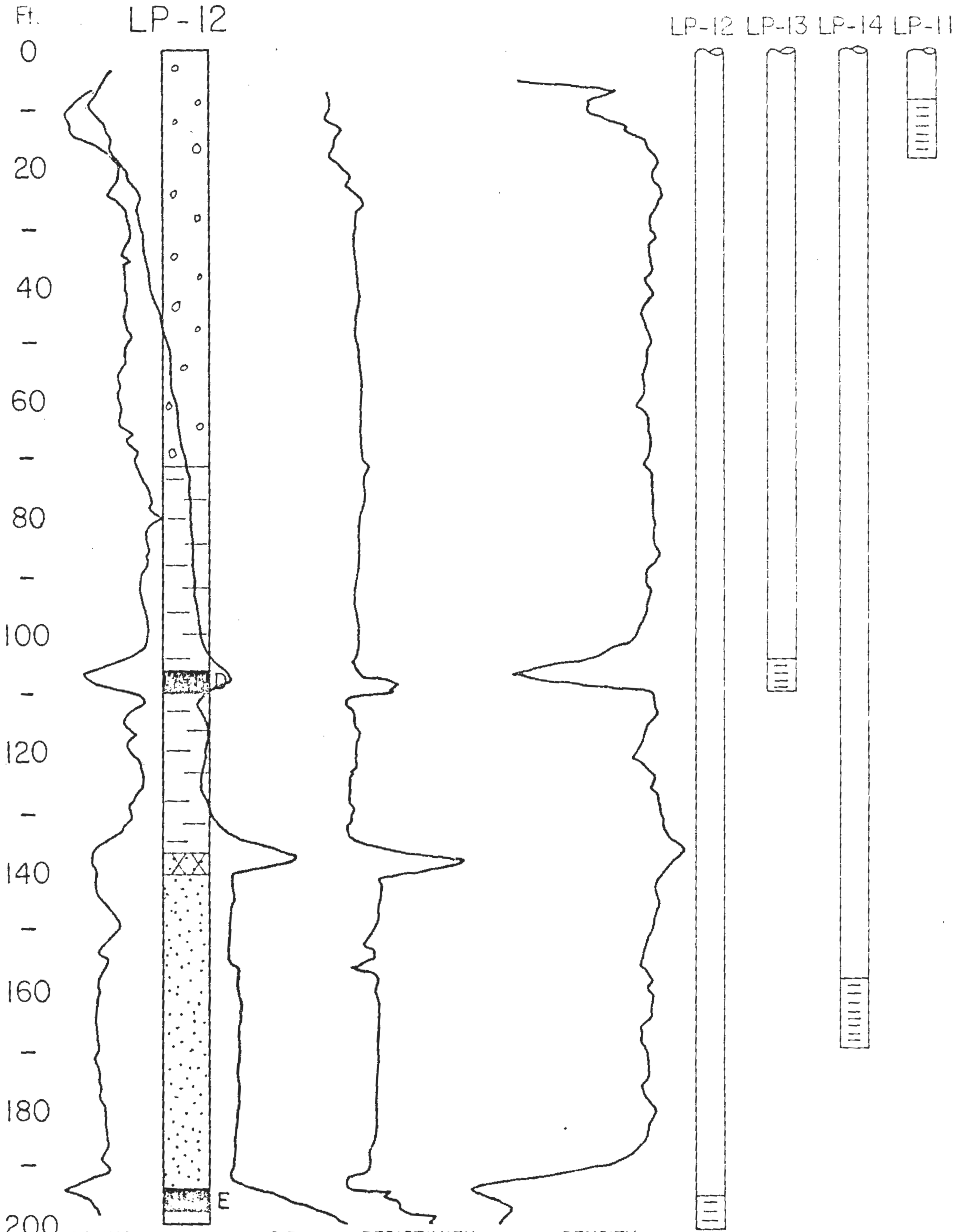


FIGURE 17 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NEST AT THE ND # 3340 WELL SITE.

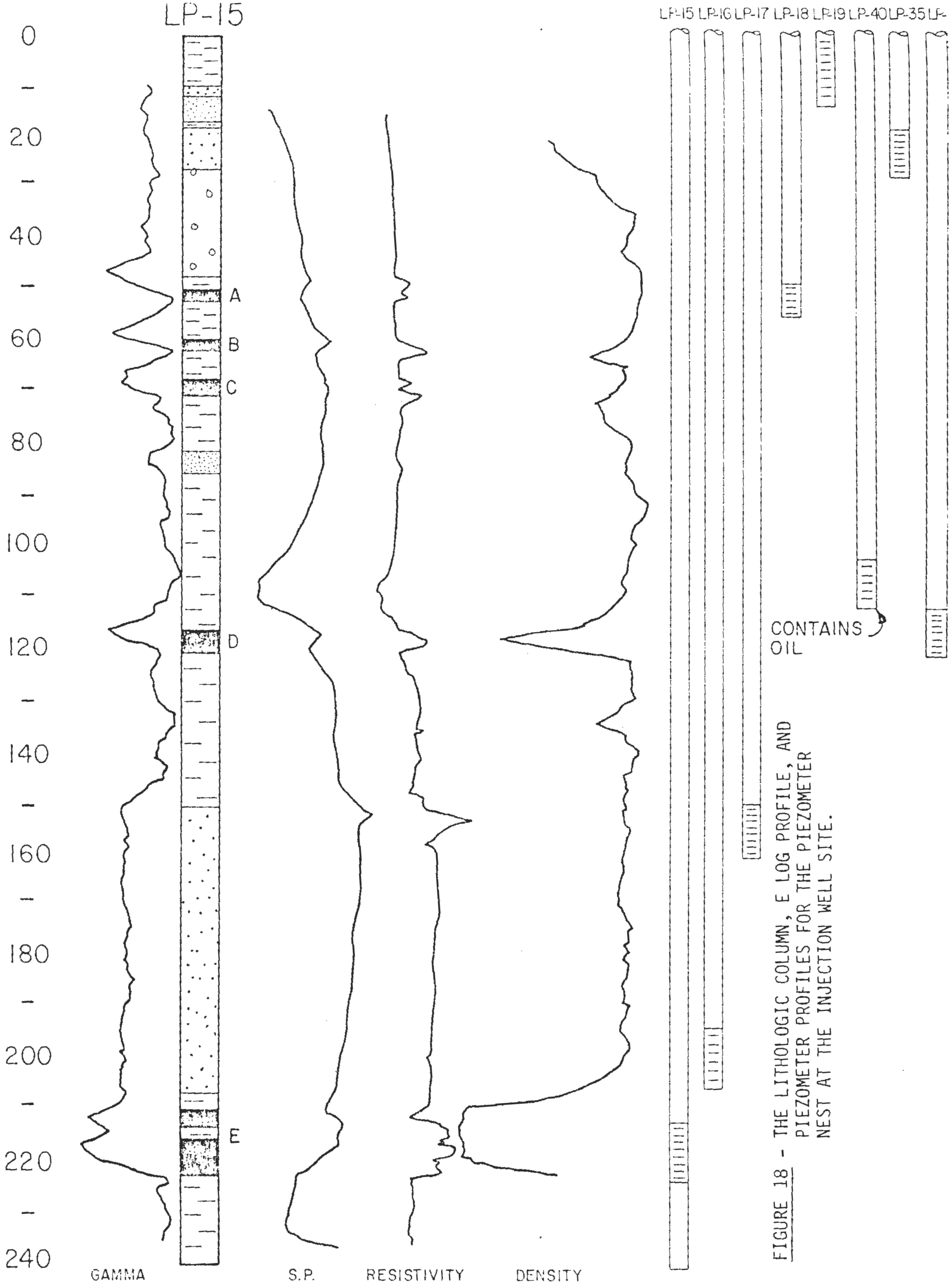


FIGURE 18 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NEST AT THE INJECTION WELL SITE.

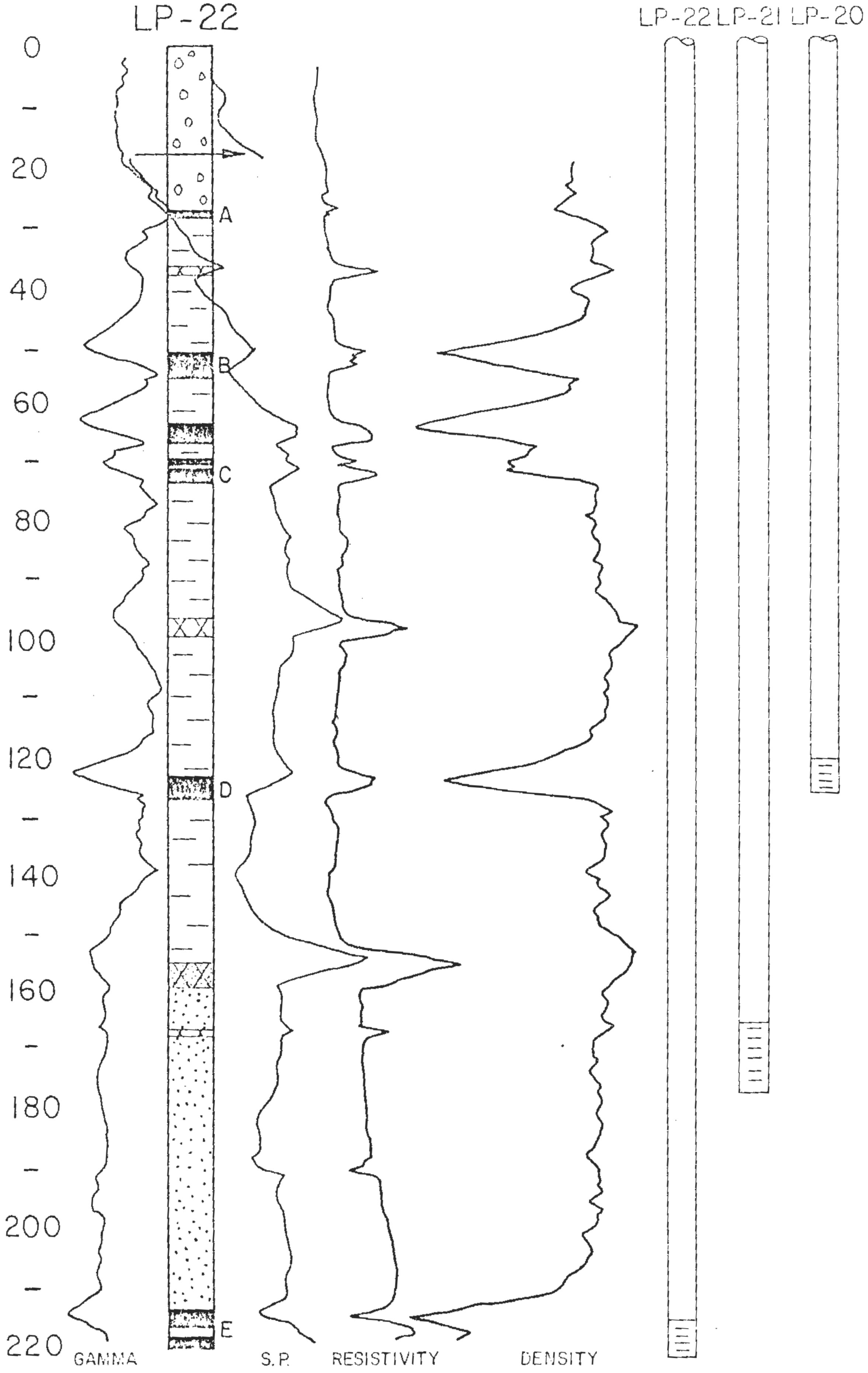


FIGURE 19 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES FOR THE PIEZOMETER NEST AT THE ND # 3135 WELL SITE.

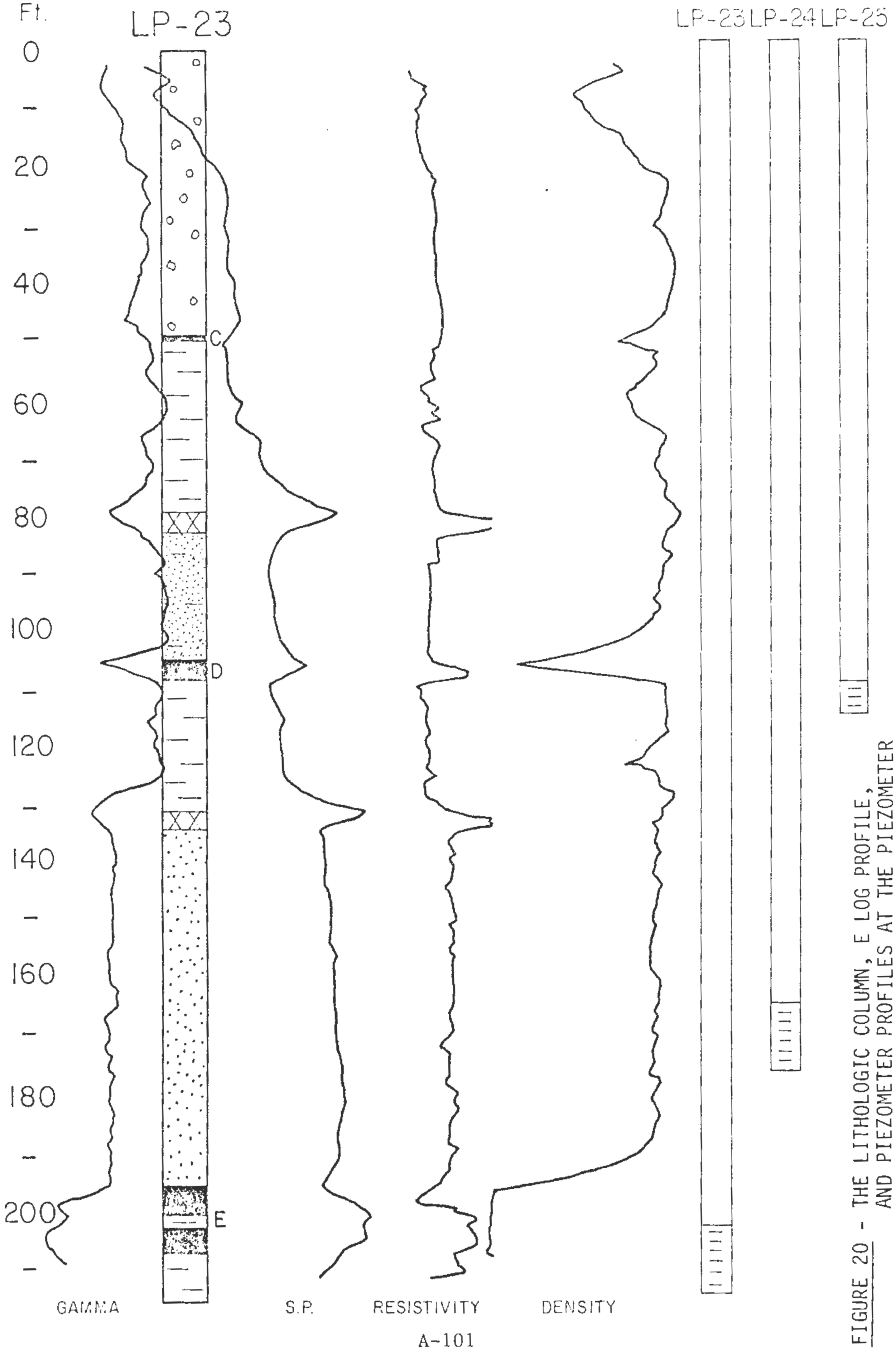


FIGURE 20 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES AT THE PIEZOMETER NEST AT THE ND # 3531 WELL SITE.

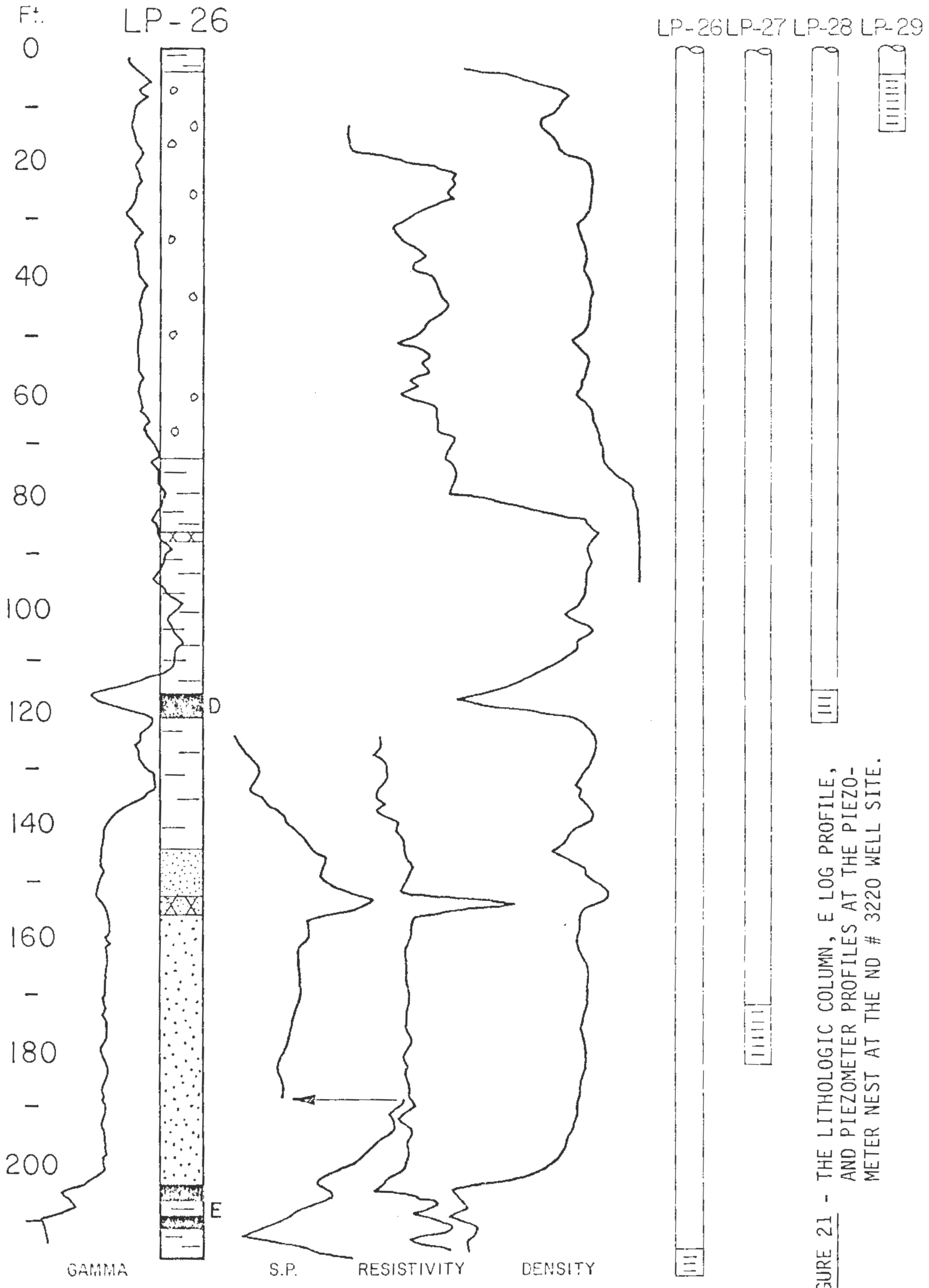


FIGURE 21 - THE LITHOLOGIC COLUMN, E LOG PROFILE, AND PIEZOMETER PROFILES AT THE PIEZOMETER NEST AT THE ND # 3220 WELL SITE.

APPENDIX 4-1F

GROUNDWATER CHEMICAL ANALYSES

Well No.	L-1	L-1	L-1	L-2
Sampling Date or Mean	12-4-84	6-25-85	$\bar{X}$	12-4-84
Field Temperature	5.0	6.0	5.5	5.5
Field pH	8.2	8.1	8.2	8.8
Field Conductivity	3,800	3,300	3,550	4,600
Lab pH	7.93	7.69	7.81	8.2
Lab Conductivity	2,593	5,015	3,804	3,096
TDS (mg/L)	1,826	3,180	2,503	2,360
Hardness (mg/L)	57	88	73	62
Alkalinity (mg/L)	1,430	1,376	1,403	1,279
Ca (mg/L)	4	4	4	5
Mg (mg/L)	12	19	16	12
Na (mg/L)	653	1,182	918	783
K (mg/L)	11	20	16	14
SO_4 (mg/L)	7	41	24	442
Cl (mg/L)	117	834	476	76
NO_3 (mg/L)	0.1	0.13	0.12	0.2
Fe (mg/L)		0.65	0.65	
Mn (mg/L)		0.1	0.1	
Cu (μg/L)		504	504	
As (μg/L)		<1	<1	
Pb (μg/L)		151	151	
Cr (μg/L)		7	7	

Well No.	L-2	L-2	L-3	L-3
Sampling Date or Mean	6-25-85	$\bar{X}$	12-4-84	6-25-85
Field Temperature	6.0	5.8	5.0	8.0
Field pH	8.5	8.7	8.4	8.2
Field Conductivity	4,000	4,300	3,000	3,200
Lab pH	7.9	8.1	7.8	8.1
Lab Conductivity	3,558	3,327	2,458	2,632
TDS (mg/L)	2,670	2,515	1,694	1,930
Hardness (mg/L)	42	52	31	28
Alkalinity (mg/L)	1,585	1,432	1,351	1,479
Ca (mg/L)	2	4	13	2
Mg (mg/L)	9	11	7	6
Na (mg/L)	911	847	650	693
K (mg/L)	4	9	9	2
SO_4 (mg/L)	450	446	--	28
Cl (mg/L)	118	97	128	133
NO_3 (mg/L)	<0.1	0.1	0.1	0.1
Fe (mg/L)	0.91	0.91		1.76
Mn (mg/L)	0.14	0.14		0.16
Cu (µg/L)	122	122		426
As (µg/L)	1.4	1.4		<1
Pb (µg/L)	414	414		95
Cr (µg/L)	110	110		5

Well No.	L-3	L-4	L-5	L-5
Sampling Date or Mean	$\bar{X}$	6-25-85	12-4-84	6-25-85
Field Temperature	6.5	5.0	4.5	6.0
Field pH	8.3	8.3	8.4	8.4
Field Conductivity	3,100	3,700	3,900	3,300
Lab pH	8.0	7.9	7.9	7.9
Lab Conductivity	2,545	4,021	2,652	1,931
TDS (mg/L)	1,812	2,710	1,855	1,340
Hardness (mg/L)	30	330	49	53
Alkalinity (mg/L)	1,415	1,496	1,431	1,113
Ca (mg/L)	8	8	1.4	3
Mg (mg/L)	7	75	11	11
Na (mg/L)	672	982	700	492
K (mg/L)	6	5	11	2
SO_4 (mg/L)	28	740	42	22
Cl (mg/L)	131	154	146	102
NO_3 (mg/L)	0.1	<0.1	<0.1	<0.1
Fe (mg/L)	1.76	0.86		0.57
Mn (mg/L)	0.16	0.27		0.15
Cu (μg/L)	426	317		14
As (μg/L)	<1	2.7		1.3
Pb (μg/L)	95	41		80
Cr (μg/L)	5	34		5

Well No.	L-5	L-6	L-6	L-6
Sampling Date or Mean	$\bar{X}$	12-4-84	6-25-85	$\bar{X}$
Field Temperature	5.3	5.0	5.0	5.0
Field pH	8.4	8.4	8.3	8.4
Field Conductivity	3,600	3,900	3,400	3,650
Lab pH	7.9	7.9	8.03	7.97
Lab Conductivity	2,292	2,490	2,575	2,533
TDS (mg/L)	1,598	2,087	1,750	1,919
Hardness (mg/L)	51	51	30	41
Alkalinity (mg/L)	1,272	1,467	1,536	1,502
Ca (mg/L)	2.2	1.4	2	1.7
Mg (mg/L)	11	12	6	9
Na (mg/L)	596	660	693	676
K (mg/L)	7	20	3	12
SO_4 (mg/L)	32	25	23	24
Cl (mg/L)	124	87	89	88
NO_3 (mg/L)	<0.1	--	--	--
Fe (mg/L)	0.57		1.41	1.41
Mn (mg/L)	0.15		0.14	0.14
Cu (µg/L)	14		287	287
As (µg/L)	1.3			
Pb (µg/L)	80		128	128
Cr (µg/L)	5		4	4

Well No.	L-7	L-7	L-7	L-8
Sampling Date or Mean	12-4-84	6-25-85	$\bar{X}$	12-4-84
Field Temperature	4.5	9.0	6.7	--
Field pH	8.3	8.3	8.3	--
Field Conductivity	3,900	4,500	4,200	--
Lab pH	7.8	8.0	7.9	8.7
Lab Conductivity	2,680	3,569	3,125	55,986
TDS (mg/L)	1,902	2,600	2,251	58,841
Hardness (mg/L)	46	180	113	12,697
Alkalinity (mg/L)	1,368	1,482	1,425	562
Ca (mg/L)	4	4	4	908
Mg (mg/L)	9	41	25	2,532
Na (mg/L)	681	866	774	14,797
K (mg/L)	11	3	7	108
SO_4 (mg/L)	66	458	262	33,469
Cl (mg/L)	173	190	182	3,497
NO_3 (mg/L)	<0.1	<0.1	<0.1	11.5
Fe (mg/L)		0.28	0.28	
Mn (mg/L)		0.1	0.1	
Cu (μg/L)		28	28	
As (μg/L)		1.3	1.3	
Pb (μg/L)		166	166	
Cr (μg/L)		48	48	

Well No.	L-8		L-8	L-9	L-9
Sampling Date or Mean	6-25-85	10-5-85	$\bar{X}$	12-4-84	6-25-85
Field Temperature	9.0		--	4.5	9.0
Field pH	8.4	7.7	8.4	8.3	8.3
Field Conductivity	46,500	46,030	46,500	3,900	3,600
Lab pH	8.0		8.4	7.8	8.15
Lab Conductivity	60,651		58,319	2,523	2,880
TDS (mg/L)	63,790	56,300	61,316	1,754	2,130
Hardness (mg/L)	13,043		12,870	36	68
Alkalinity (mg/L)	895		729	1,311	1,394
Ca (mg/L)	194	308	551	4	2
Mg (mg/L)	3,050	2180	2,791	6	15
Na (mg/L)	11,273	14,900	13,035	662	704
K (mg/L)	32		70	10	3
SO_4 (mg/L)	39,087	38,100	36,278	--	100
Cl (mg/L)	434	346	1,966	180	183
NO_3 (mg/L)	0.93		6.0	0.1	0.13
Fe (mg/L)	10.8	.032	10.8		2.6
Mn (mg/L)	3.3		3.3		0.03
Cu (μg/L)	900		900		18
As (μg/L)	2.65		2.65		
Pb (μg/L)	228	17	228		74
Cr (μg/L)	278	7	278		9

Well No.	L-9	L-10	L-10	L-10
Sampling Date or Mean	$\bar{X}$	12-4-84	6-25-85	$\bar{X}$
Field Temperature	7.0	5.0	10.0	7.5
Field pH	8.3	8.4	8.3	8.4
Field Conductivity	3,750	3,700	4,000	3,850
Lab pH	7.95	7.8	7.9	7.9
Lab Conductivity	2,702	2,501	3,083	2,792
TDS (mg/L)	1,942	1,804	2,220	2,012
Hardness (mg/L)	52	37	159	98
Alkalinity (mg/L)	1,353	1,419	1,152	1,286
Ca (mg/L)	3	7	5	6
Mg (mg/L)	11	4	36	20
Na (mg/L)	683	649	739	694
K (mg/L)	7	10	3	7
SO_4 (mg/L)	100	15	655	335
Cl (mg/L)	182	123	72	98
NO_3 (mg/L)	0.12	0.2	--	0.2
Fe (mg/L)	2.6		4.1	4.1
Mn (mg/L)	0.03		0.05	0.05
Cu (µg/L)	18		40	40
As (µg/L)				
Pb (µg/L)	74		37	37
Cr (µg/L)	9		40	40

Well No.	L-11	L-11	L-11	L-12
Sampling Date or Mean	12-4-84	6-25-85	$\bar{X}$	12-4-84
Field Temperature	--	8.0	--	4.5
Field pH	--	8.1	8.1	7.1
Field Conductivity	--	14,000	14,000	3,600
Lab pH	7.8	7.3	7.6	7.9
Lab Conductivity	13,188	14,841	14,015	2,523
TDS (mg/L)	10,534	11,610	11,072	1,849
Hardness (mg/L)	1,636	2,177	1,907	47
Alkalinity (mg/L)	191	395	293	1,343
Ca (mg/L)	230	94	162	9
Mg (mg/L)	258	472	365	6
Na (mg/L)	2,782	2,852	2,817	638
K (mg/L)	388	47	218	13
SO_4 (mg/L)	4,691	4,586	4,639	18
Cl (mg/L)	1,895	1,976	1,936	155
NO_3 (mg/L)	2.3	<0.1	1.2	0.1
Fe (mg/L)		0.91	0.91	
Mn (mg/L)		0.25	0.25	
Cu (µg/L)		293	293	
As (µg/L)		1.6	1.6	
Pb (µg/L)		299	299	
Cr (µg/L)		56	56	

Well No.	L-12	L-12	L-13	L-13
Sampling Date or Mean	6-25-85	$\bar{X}$	12-4-84	6-25-85
Field Temperature	7.0	6.0	5.0	8.0
Field pH	8.4	7.8	7.4	8.4
Field Conductivity	3,700	3,650	3,400	3,500
Lab pH	7.9	7.9	8.0	7.95
Lab Conductivity	3,061	2,792	2,534	2,665
TDS (mg/L)	2,000	1,925	1,740	1,990
Hardness (mg/L)	69	58	35	76
Alkalinity (mg/L)	1,309	1,326	1,349	1,352
Ca (mg/L)	3	6	3	4
Mg (mg/L)	15	11	7	16
Na (mg/L)	747	693	598	629
K (mg/L)	4	9	10	3
SO_4 (mg/L)	90	54	13	88
Cl (mg/L)	210	183	103	44
NO_3 (mg/L)	<0.1	0.1	--	<0.1
Fe (mg/L)	0.2	0.2		1.02
Mn (mg/L)	0.06	0.06		0.1
Cu (µg/L)	12	12		34
As (µg/L)	2.65	2.65		<1
Pb (µg/L)	17	17		476
Cr (µg/L)	2	2		13

Well No.	L-13	L-14	L-15	L-15
Sampling Date or Mean	$\bar{X}$	12-4-84	12-4-84	6-25-85
Field Temperature	7.0	4.5	5.0	8.0
Field pH	7.9	7.5	7.4	8.2
Field Conductivity	3,450	3,600	4,200	4,300
Lab pH	8.0	8.0	7.9	8.0
Lab Conductivity	2,600	2,544	3,259	3,208
TDS (mg/L)	1,865	1,776	2,302	2,380
Hardness (mg/L)	56	46	112	40
Alkalinity (mg/L)	1,351	1,280	1,592	1,570
Ca (mg/L)	4	5	9	2
Mg (mg/L)	12	8	22	9
Na (mg/L)	614	650	848	818
K (mg/L)	7	22	17	5
SO_4 (mg/L)	51	55	38	26
Cl (mg/L)	1,423	151	264	214
NO_3 (mg/L)	<0.1	<0.1	0.1	0.45
Fe (mg/L)	1.02			4.2
Mn (mg/L)	0.1			0.09
Cu (μg/L)	34			457
As (μg/L)	<1			2.45
Pb (μg/L)	476			73
Cr (μg/L)	13			11

Well No.	L-15	L-16	L-16A	L-16
Sampling Date or Mean	$\bar{X}$	12-4-84	1- -85	6-25-85
Field Temperature	7.0	4.0	--	8.0
Field pH	7.8	7.4	--	8.4
Field Conductivity	4,250	3,900	--	3,700
Lab pH	8.0	7.7	8.2	8.3
Lab Conductivity	3,234	2,663	2,512	2,654
TDS (mg/L)	2,339	1,897	1,763	1,740
Hardness (mg/L)	76	46	27	40
Alkalinity (mg/L)	1,581	1,294	1,331	1,347
Ca (mg/L)	6	7	5	2
Mg (mg/L)	16	7	3	9
Na (mg/L)	833	660	677	749
K (mg/L)	11	11	8	2
SO_4 (mg/L)	32	41	14	20
Cl (mg/L)	239	197	158	265
NO_3 (mg/L)	0.23	<0.1	2.9	<0.1
Fe (mg/L)	4.2			
Mn (mg/L)	0.09			
Cu (µg/L)	457			
As (µg/L)	2.45			
Pb (µg/L)	73			
Cr (µg/L)	11			

Well No.	L-16	L-17	L-17A	L-17
Sampling Date or Mean	$\bar{X}$	12-4-84	1- -85	6-25-85
Field Temperature	6.0	5.0	--	8.0
Field pH	7.9	7.4	--	8.3
Field Conductivity	3,800	3,900	--	3,600
Lab pH	8.1	7.7	8.26	8.1
Lab Conductivity	2,610	2,696	2,447	2,891
TDS (mg/L)	1,800	1,852	1,719	2,020
Hardness (mg/L)	57	43	34	40
Alkalinity (mg/L)	1,324	1,241	1,276	1,282
Ca (mg/L)	5	9	5	2
Mg (mg/L)	6	5	5	8
Na (mg/L)	695	657	633	719
K (mg/L)	7	9	8	3
SO_4 (mg/L)	25	20	4	134
Cl (mg/L)	207	258	158	196
NO_3 (mg/L)	1.0	<0.1	4.5	<0.1
Fe (mg/L)	0.7			0.3
Mn (mg/L)	0.07			0.02
Cu (µg/L)	219			346
As (µg/L)	--			<1
Pb (µg/L)	156			48
Cr (µg/L)	5			8

Well No.	L-17	L-18	L-19	L-19
Sampling Date or Mean	$\bar{X}$	6-25-85	12-4-84	6-25-85
Field Temperature	--	9.0	--	10.0
Field pH	7.9	7.6	--	7.3
Field Conductivity	3,750	9,400	--	50,000
Lab pH	8.0	7.9	7.9	7.8
Lab Conductivity	2,678	9,815	47,969	57,036
TDS (mg/L)	1,864	7,660	33,817	48,320
Hardness (mg/L)	39	631	5,253	8,078
Alkalinity (mg/L)	1,266	1,081	864	1,755
Ca (mg/L)	5	17	481	159
Mg (mg/L)	6	143	984	1,865
Na (mg/L)	670	2,320	6,639	9,388
K (mg/L)	7	14	74	36
SO_4 (mg/L)	53	3,878	21,415	27,516
Cl (mg/L)	204	443	158	70
NO_3 (mg/L)	1.0	<0.1	7.5	0.98
Fe (mg/L)	0.3	1.9		3.7
Mn (mg/L)	0.02	0.26		0.45
Cu (µg/L)	346	77		677
As (µg/L)	<1	--		9.0
Pb (µg/L)	48	400		535
Cr (µg/L)	8	77		379

Well No.	L-19	L-20	L-20	L-20
Sampling Date or Mean	$\bar{X}$	12-4-84	6-25-85	$\bar{X}$
Field Temperature	--	4.5	7.0	5.25
Field pH	7.3	7.4	8.2	7.8
Field Conductivity	50,000	3,950	4,400	4,175
Lab pH	7.9	7.94	8.0	8.0
Lab Conductivity	52,503	2,598	3,377	2,988
TDS (mg/L)	41,069	2,008	2,630	2,319
Hardness (mg/L)	6,666	48	226	137
Alkalinity (mg/L)	1,310	1,446	1,451	1,449
Ca (mg/L)	320	5	5	5
Mg (mg/L)	1,425	8	52	30
Na (mg/L)	8,014	678	786	732
K (mg/L)	55	15	3	9
SO_4 (mg/L)	24,466	35	443	239
Cl (mg/L)	114	102	109	106
NO_3 (mg/L)	4.25	<0.1	--	<0.1
Fe (mg/L)	3.7		1.06	1.06
Mn (mg/L)	0.45		0.13	0.13
Cu (μg/L)	677		255	255
As (μg/L)	9.0			--
Pb (μg/L)	535		143	143
Cr (μg/L)	379		39	39

Well No.	L-21	L-21	L-21	L-22
Sampling Date or Mean	12-4-84	6-25-85	$\bar{X}$	12-4-84
Field Temperature	4.5	9.0	7.0	5.0
Field pH	7.2	8.3	7.8	7.1
Field Conductivity	3,700	3,700	3,700	4,400
Lab pH	7.9	8.1	8.0	8.0
Lab Conductivity	2,620	2,756	2,688	3,421
TDS (mg/L)	1,839	1,920	1,880	2,520
Hardness (mg/L)	32	67	50	65
Alkalinity (mg/L)	1,329	1,312	1,321	1,443
Ca (mg/L)	3	3	3	13
Mg (mg/L)	6	14	10	8
Na (mg/L)	681	681	681	900
K (mg/L)	8	3	6	12
SO$_4$ (mg/L)	56	110	83	41
Cl (mg/L)	146	159	153	140
NO$_3$ (mg/L)	<0.1	<0.1	<0.1	<0.1
Fe (mg/L)		1.8	1.8	
Mn (mg/L)		0.06	0.06	
Cu (µg/L)		25	25	
As (µg/L)		11	11	
Pb (µg/L)		108	108	
Cr (µg/L)		8	8	

Well No.	L-22	L-22	L-23	L-23
Sampling Date or Mean	6-25-85	$\bar{X}$	12-4-84	6-25-85
Field Temperature	8.0	6.5	5.0	6.0
Field pH	8.3	7.7	8.3	8.4
Field Conductivity	4,000	4,200	3,800	3,700
Lab pH	8.6	8.3	7.9	8.0
Lab Conductivity	2,586	3,004	2,523	3,309
TDS (mg/L)	1,930	2,225	1,863	2,270
Hardness (mg/L)	60	63	46	168
Alkalinity (mg/L)	1,389	1,416	1,312	1,291
Ca (mg/L)	2	8	9	6
Mg (mg/L)	13	11	6	37
Na (mg/L)	685	793	653	828
K (mg/L)	3	8	11	4
SO_4 (mg/L)	158	100	52	388
Cl (mg/L)	133	137	152	131
NO_3 (mg/L)	<0.1	<0.1	<0.1	<0.1
Fe (mg/L)	1.3	1.3		0.3
Mn (mg/L)	0.72	0.72		0.01
Cu (µg/L)	23	23		42
As (µg/L)	4.4	4.4		--
Pb (µg/L)	35	35		62
Cr (µg/L)	6	6		6

Well No.	L-23	L-24	L-24	L-24
Sampling Date or Mean	$\bar{X}$	12-4-84	6-25-85	$\bar{X}$
Field Temperature	5.5	5.0	8.0	6.5
Field pH	8.4	8.4	8.4	8.4
Field Conductivity	3,750	4,200	4,000	4,100
Lab pH	8.0	8.5	8.2	8.4
Lab Conductivity	2,916	2,858	2,948	2,903
TDS (mg/L)	2,067	1,998	2,060	2,029
Hardness (mg/L)	107	60	77	69
Alkalinity (mg/L)	1,302	1,193	1,224	1,209
Ca (mg/L)	8	9	2	6
Mg (mg/L)	22	9	17	13
Na (mg/L)	741	708	813	761
K (mg/L)	8	12	5	9
SO_4 (mg/L)	220	223	233	228
Cl (mg/L)	142	196	191	194
NO_3 (mg/L)	<0.1	<0.1	--	<0.1
Fe (mg/L)	0.3		1.76	1.76
Mn (mg/L)	0.01		0.14	0.14
Cu (μg/L)	42		37	37
As (μg/L)	--		1.7	1.7
Pb (μg/L)	62		43	43
Cr (μg/L)	6		45	45

Well No.	L-25	L-26	L-26	L-26
Sampling Date or Mean	12-4-84	12-4-84	6-25-85	$\bar{X}$
Field Temperature	5.5	6.5	8.0	7.3
Field pH	8.4	5.8	8.4	7.1
Field Conductivity	4,500	3,400	3,500	3,450
Lab pH	7.86	7.87	8.14	8.0
Lab Conductivity	3,226	2,501	2,677	2,589
TDS (mg/L)	2,352	1,825	1,890	1,858
Hardness (mg/L)	115	37	39	38
Alkalinity (mg/L)	1,209	1,348	1,449	1,399
Ca (mg/L)	17	7	3	5
Mg (mg/L)	17	4	8	6
Na (mg/L)	787	645	768	707
K (mg/L)	23	11	3	7
SO_4 (mg/L)	381	9	26	18
Cl (mg/L)	182	154	214	184
NO_3 (mg/L)	<0.1	<0.1	<0.1	<0.1
Fe (mg/L)			0.4	0.4
Mn (mg/L)			0.07	0.07
Cu (μg/L)			260	260
As (μg/L)			1.65	1.65
Pb (μg/L)			74	74
Cr (μg/L)			4	4

Well No.	L-27	L-27	L-27	L-28
Sampling Date or Mean	12-4-84	6-25-85	$\bar{X}$	12-4-84
Field Temperature	--	10.0	10.0	4.5
Field pH	8.3	8.4	8.4	6.0
Field Conductivity	1,950	3,500	2,725	3,700
Lab pH	8.1	8.2	8.2	7.8
Lab Conductivity	5,186	2,564	3,875	2,663
TDS (mg/L)	4,686	1,720	3,203	2,891
Hardness (mg/L)	570	44	307	109
Alkalinity (mg/L)	1,259	1,312	1,286	1,403
Ca (mg/L)	27	2	15	9
Mg (mg/L)	122	9	66	21
Na (mg/L)	1,378	666	1,022	678
K (mg/L)	28	3	16	45
SO_4 (mg/L)	1,664	60	862	135
Cl (mg/L)	186	154	170	135
NO_3 (mg/L)	0.1	<0.1	<0.1	<0.1
Fe (mg/L)		0.26	0.26	
Mn (mg/L)		0.07	0.07	
Cu (µg/L)		38	38	
As (µg/L)		3.6	3.6	
Pb (µg/L)		545	545	
Cr (µg/L)		6	6	

Well No.	L-28	L-28	L-29	L-29
Sampling Date or Mean	6-25-85	$\bar{X}$	12-4-84	6-25-85
Field Temperature	7.0	5.5	4.0	7.0
Field pH	8.2	7.1	8.0	7.7
Field Conductivity	4,900	4,300	<20,000	38,000
Lab pH	8.0	7.9	7.8	8.2
Lab Conductivity	5,839	4,251	56,951	58,618
TDS (mg/L)	4,630	3,761	67,036	56,620
Hardness (mg/L)	643	376	15,886	11,241
Alkalinity (mg/L)	1,408	1,406	988	1,528
Ca (mg/L)	10	10	1,220	167
Mg (mg/L)	150	86	3,118	2,628
Na (mg/L)	1,325	1,002	14,285	12,432
K (mg/L)	8	27	467	76
SO$_4$ (mg/L)	1,958	1,047	42,125	37,894
Cl (mg/L)	98	117	26	86
NO$_3$ (mg/L)	0.25	0.25	6.9	0.74
Fe (mg/L)	0.35	0.35		0.17
Mn (mg/L)	0.11	0.11		0.69
Cu (µg/L)	319	319		2,286
As (µg/L)	--	--		11.45
Pb (µg/L)	465	465		842
Cr (µg/L)	170	170		3,109

Well No.	L-29	L-29	L-30		L-31
Sampling Date or Mean	--	$\bar{X}$	6-25-85	1-2-86	6-25-85
Field Temperature	--	5.5	6.0		9.0
Field pH	--	7.9	7.8		7.8
Field Conductivity	--	38,000	8,700		18,000
Lab pH	7.9	8.0	7.7		7.5
Lab Conductivity	58,575	58,048	12,333		19,381
TDS (mg/L)	72,464	65,373	11,830		17,940
Hardness (mg/L)	16,686	14,671	2,157		2,357
Alkalinity (mg/L)	1,061	1,192	1,256		1,310
Ca (mg/L)	575	654	79		98
Mg (mg/L)	3,704	3,150	476		513
Na (mg/L)	15,604	14,107	2,903		4,936
K (mg/L)	245	263	21		24
SO_4 (mg/L)	40,519	40,179	6,700		6,390
Cl (mg/L)	12	41	102		3,615
NO_3 (mg/L)	0.1	2.1	<0.1		<0.1
Fe (mg/L)		0.17	2.7		0.5
Mn (mg/L)		0.69	1.3		0.5
Cu (µg/L)		2,286	471		206
As (µg/L)		11.45	<1		
Pb (µg/L)		842	800	74	119
Cr (µg/L)		3,109	431	12	353

Well No.	L-32	L-33		L-34		L-35
Sampling Date or Mean	6-25-85	6-25-85	10-5-85	6-25-85	10-5-85	6-25-85
Field Temperature	7.0	10.0		7.5		7.0
Field pH	7.8	7.9		7.9		10.0
Field Conductivity	43,500	52,500		42,000		37,500
Lab pH	7.9	7.7		7.7		9.1
Lab Conductivity	53,874	60,763	43,900	54,664		54,439
TDS (mg/L)	43,900	67,430	53,700	42,480	35,500	40,690
Hardness (mg/L)	6,056	12,416	8750	7,140		4,641
Alkalinity (mg/L)	1,250	1,270		1,135		339
Ca (mg/L)	126	186	321	119	345	108
Mg (mg/L)	1,394	2,902		1,662	1220	1,061
Na (mg/L)	9,608	14,339	14,000	9,618	10,500	9,359
K (mg/L)	41	51		56	51	75
SO_4 (mg/L)	23,207	41,559	36,800	23,426	22,700	25,540
Cl (mg/L)	80	874	122	259	216	265
NO_3 (mg/L)	0.3	0.54		0.12		0.29
Fe (mg/L)	3.9	0.45	0.364	3.8	5.95	4.2
Mn (mg/L)	3.7	1.1	1.26	9.9		0.7
Cu (µg/L)	2,044	2,597		2,000		2,439
As (µg/L)						
Pb (µg/L)	900	857	54	571	26	130
Cr (µg/L)	1,307	4,387	3	4,625	23	1,960

Well No.	L-36	L-37	L-38	L-39	
Sampling Date or Mean	6-25-85	6-25-85	6-25-85	6-25-85	1-2-86
Field Temperature	5.0	7.0	6.0	7.5	
Field pH	7.8	8.0	7.3	7.5	
Field Conductivity	14,000	12,500	28,000	17,000	
Lab pH	7.9	7.9	7.8	7.9	
Lab Conductivity	16,072	15,417	51,841	44,274	
TDS (mg/L)	17,650	15,870	50,830	34,050	
Hardness (mg/L)	4,217	3,977	8,358	7,882	
Alkalinity (mg/L)	713	717	1,538	1,488	
Ca (mg/L)	117	108	144	154	
Mg (mg/L)	953	900	1,942	1,821	
Na (mg/L)	3,600	3,163	8,304	5,333	
K (mg/L)	37	23	42	42	
SO_4 (mg/L)	10,679	10,240	25,182	19,377	
Cl (mg/L)	140	11	38	222	
NO_3 (mg/L)	0.24	<0.1	0.88	0.16	
Fe (mg/L)	1.8	2.8	5.05	8.7	
Mn (mg/L)	0.3	3.8	9.7	6.9	
Cu (µg/L)	893	96	2,636	662	
As (µg/L)					
Pb (µg/L)	480	460	462	562	13
Cr (µg/L)	513	1,054	2,474	2,354	13

Well No.	L-40
Sampling Date or Mean	6-25-85
Field Temperature	8.0
Field pH	7.6
Field Conductivity	100,000
Lab pH	7.2
Lab Conductivity	45,064
TDS (mg/L)	19,970
Hardness (mg/L)	2,501
Alkalinity (mg/L)	971
Ca (mg/L)	117
Mg (mg/L)	536
Na (mg/L)	6,312
K (mg/L)	54
SO_4 (mg/L)	4,376
Cl (mg/L)	7,334
NO_3 (mg/L)	<0.1
Fe (mg/L)	1.9
Mn (mg/L)	1.5
Cu (µg/L)	280
As (µg/L)	
Pb (µg/L)	826
Cr (µg/L)	314

APPENDIX 4-1G

ISOCONCENTRATON MAPS OF SELECTED PARAMETERS FROM THE FOUR MONITORED INTERVALS

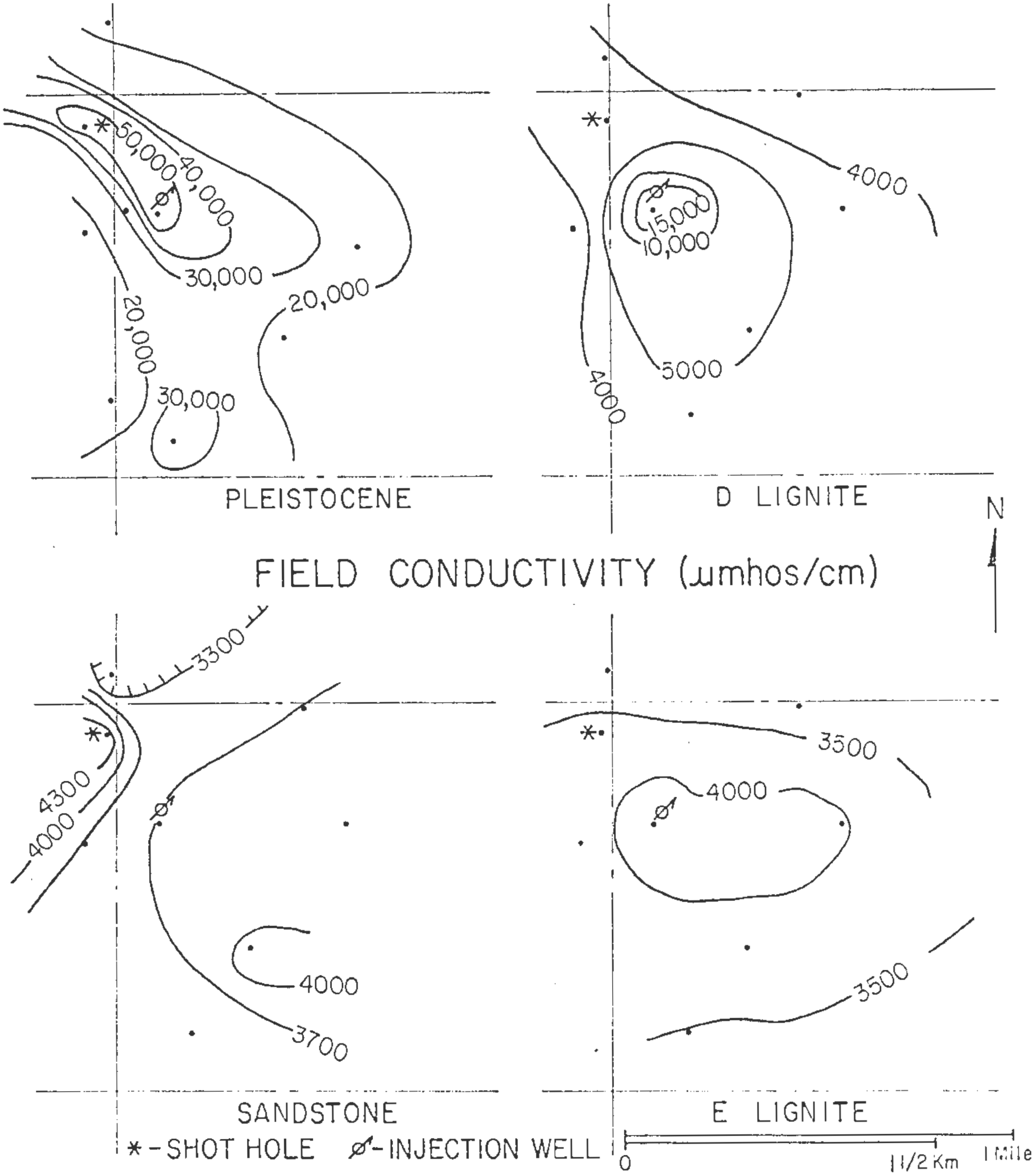


FIGURE 22 - THE ISOCONCENTRATION MAPS FOR FIELD CONDUCTIVITY IN THE FOUR INTERVALS.

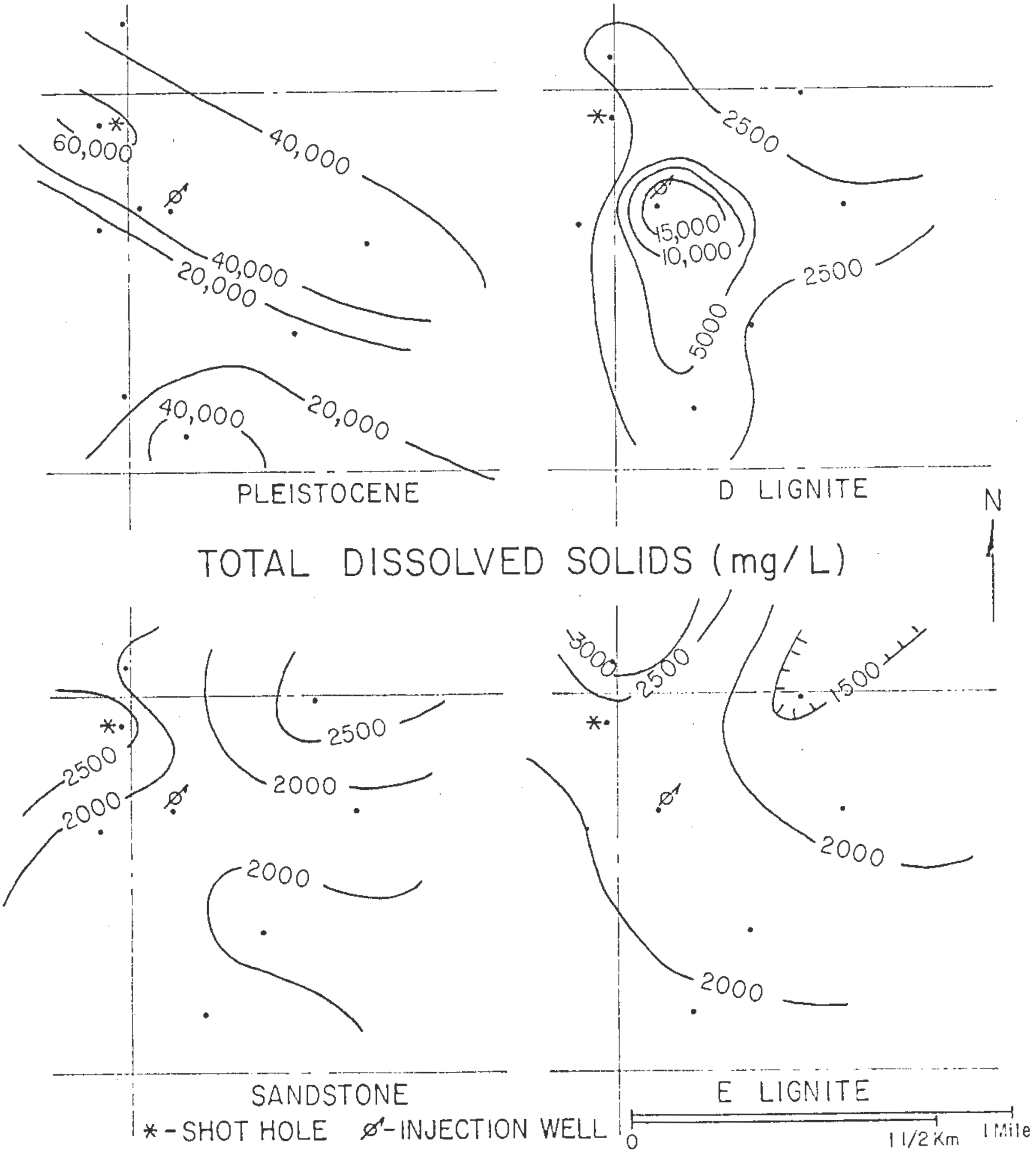


FIGURE 23 - THE ISOCONCENTRATION MAPS FOR TOTAL DISSOLVED SOLIDS IN THE FOUR INTERVALS.

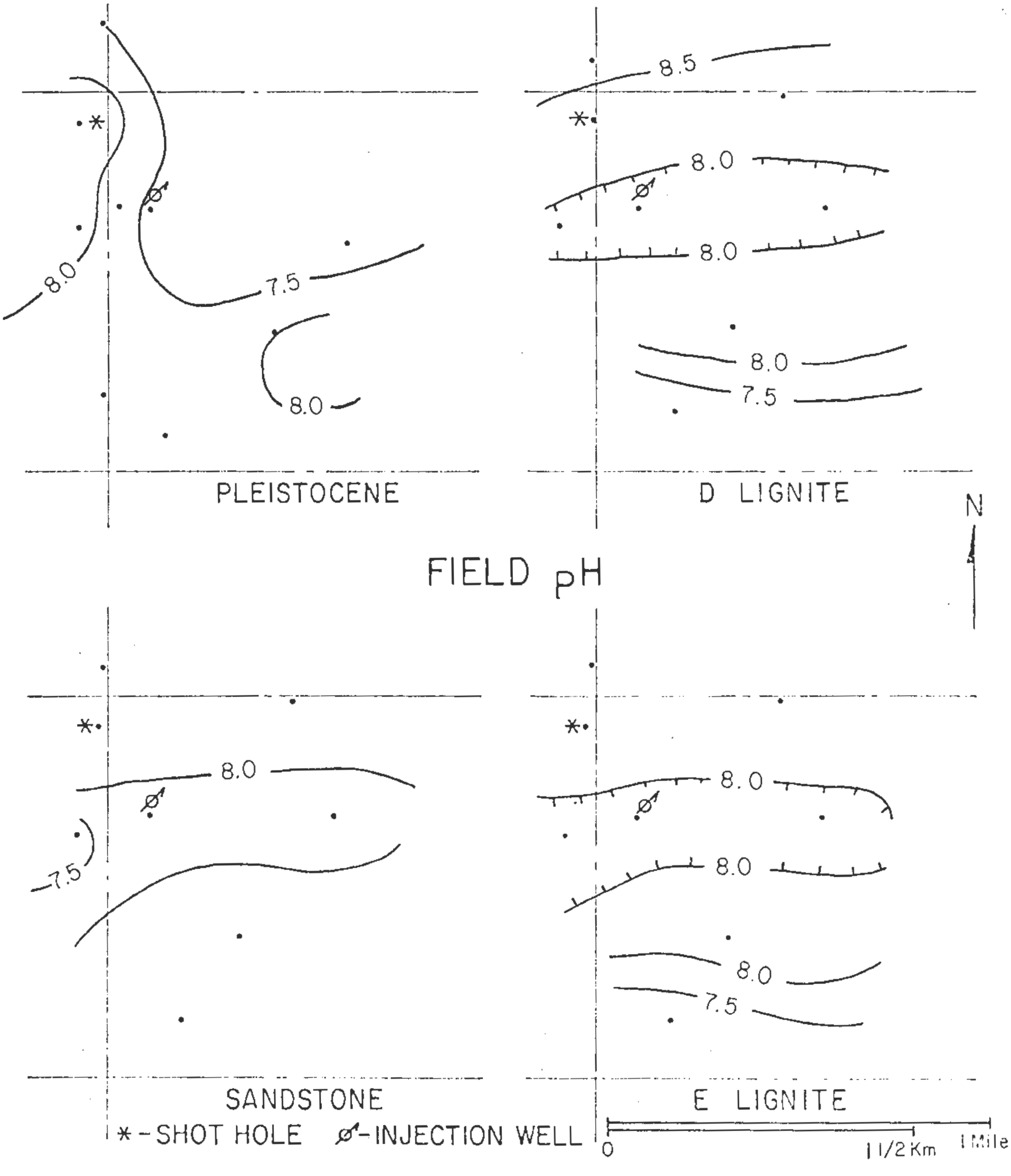


FIGURE 24 - THE ISOCONCENTRATION MAPS FOR FIELD pH IN THE FOUR INTERVALS.

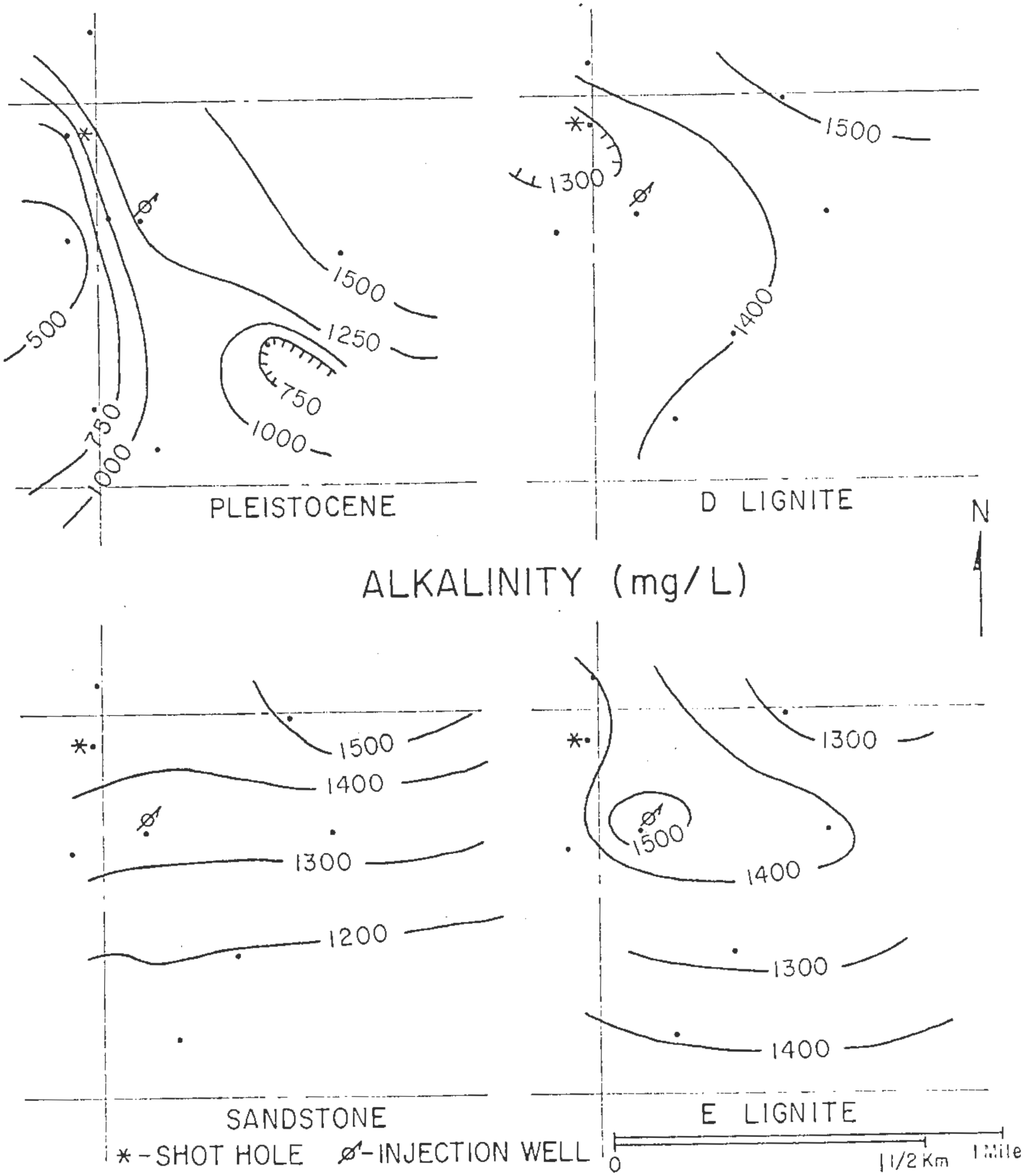


FIGURE 25 - THE ISOCONCENTRATION MAPS FOR ALKALINITY IN THE FOUR INTERVALS.

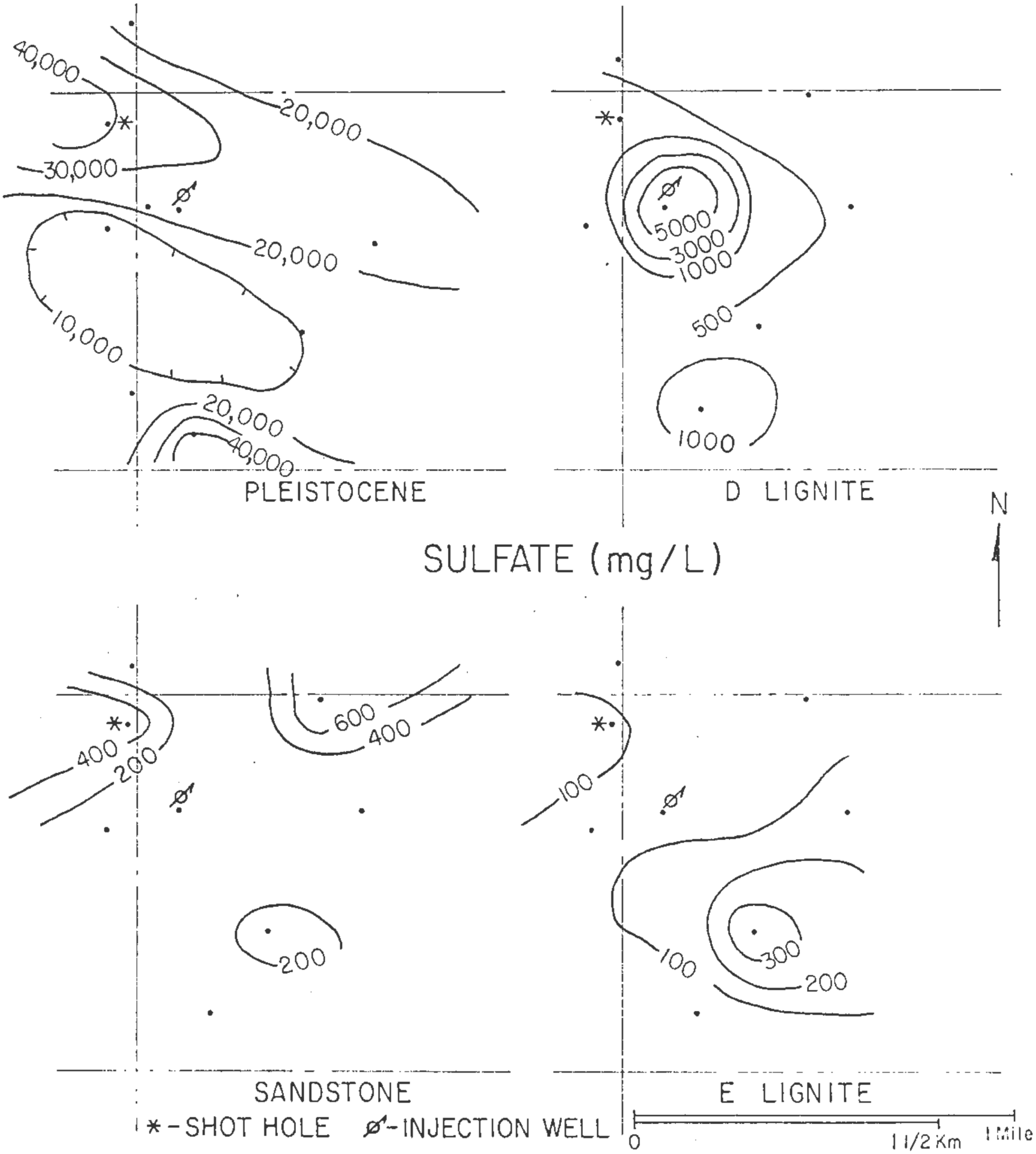


FIGURE 26 - THE ISOCONCENTRATION MAPS FOR SULFATE IN THE FOUR INTERVALS.

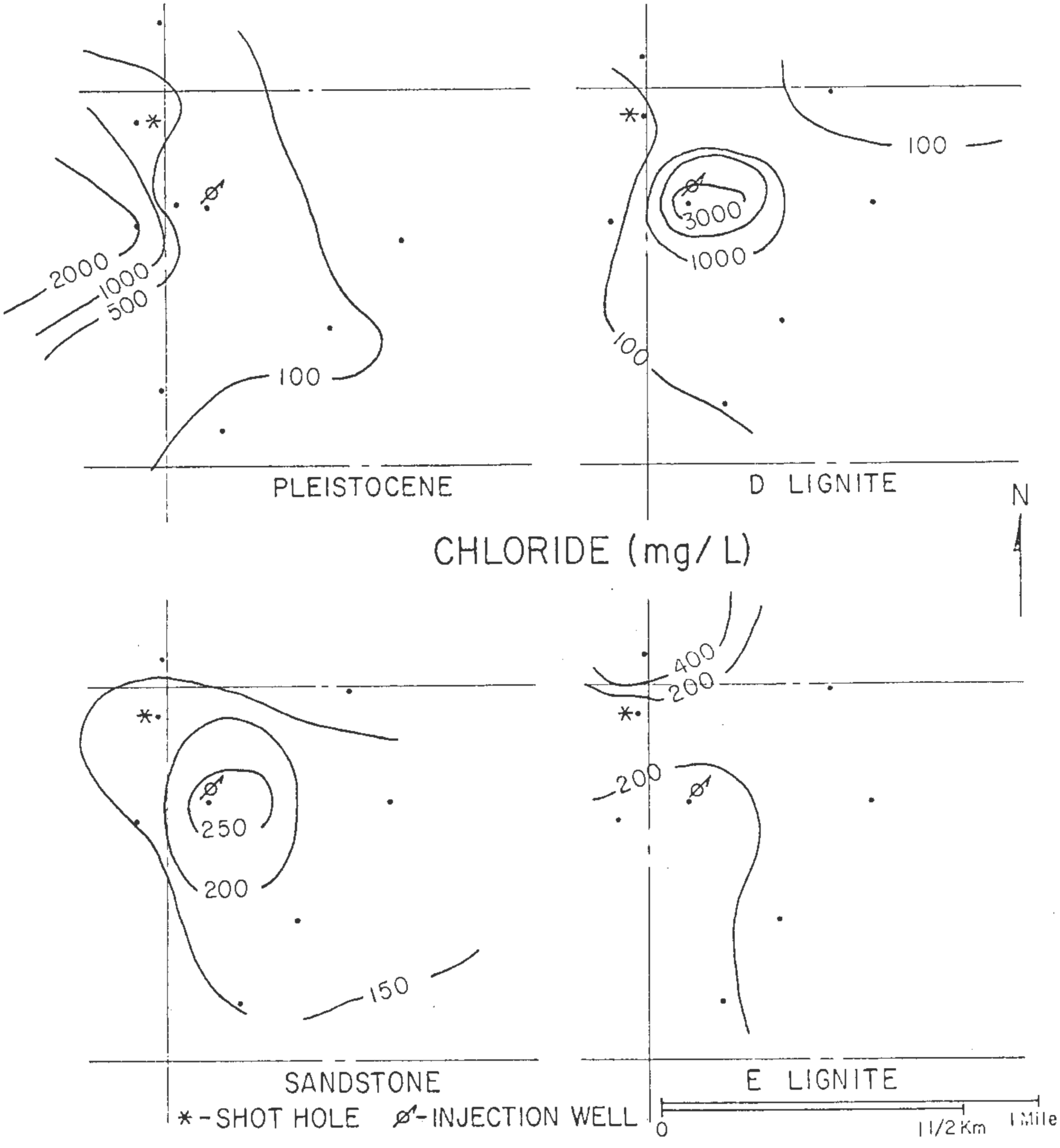


FIGURE 27 - THE ISOCONCENTRATION MAPS FOR CHLORIDE IN THE FOUR INTERVALS.

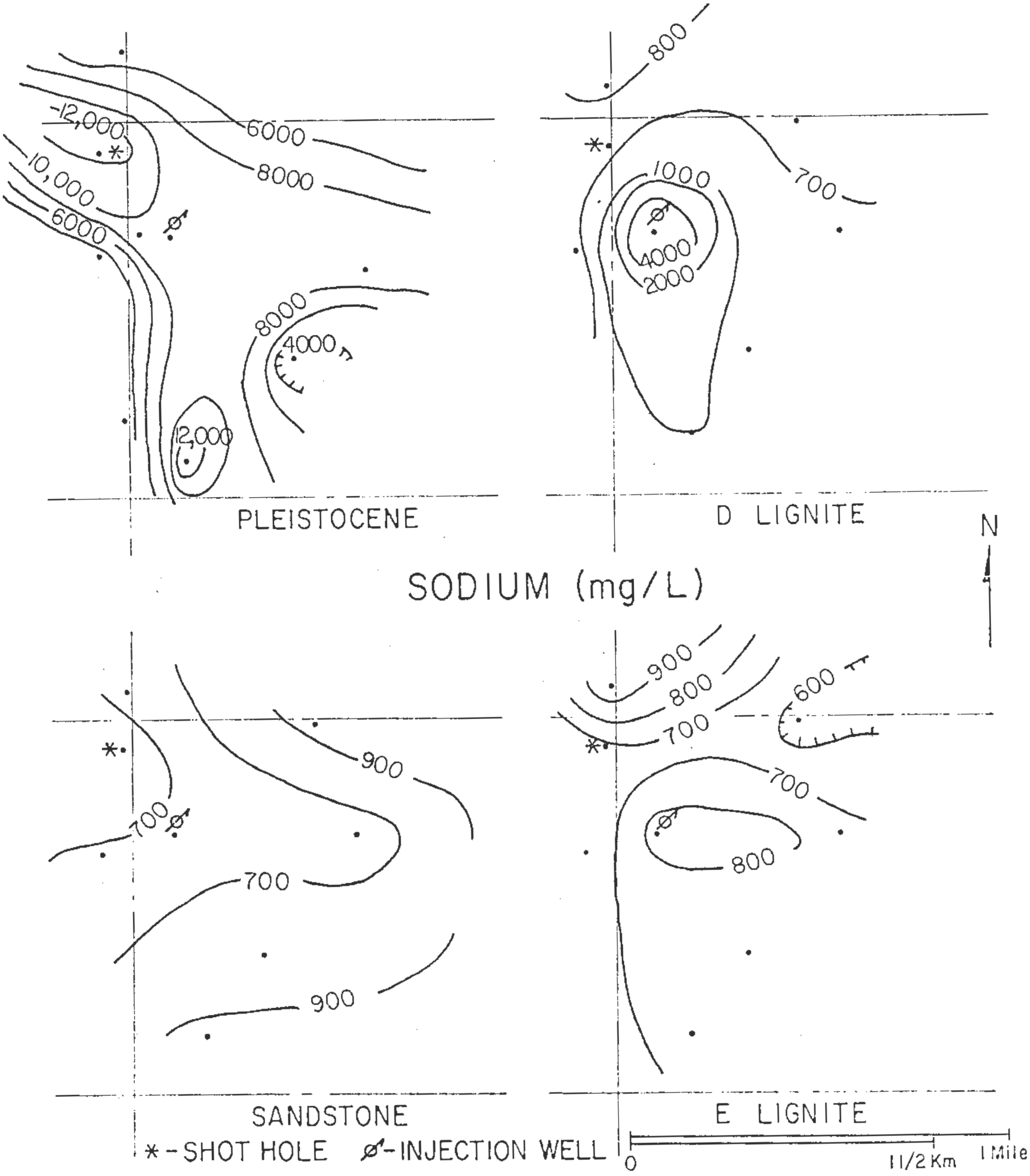


FIGURE 28 - THE ISOCONCENTRATION MAPS FOR SODIUM IN THE FOUR INTERVALS.

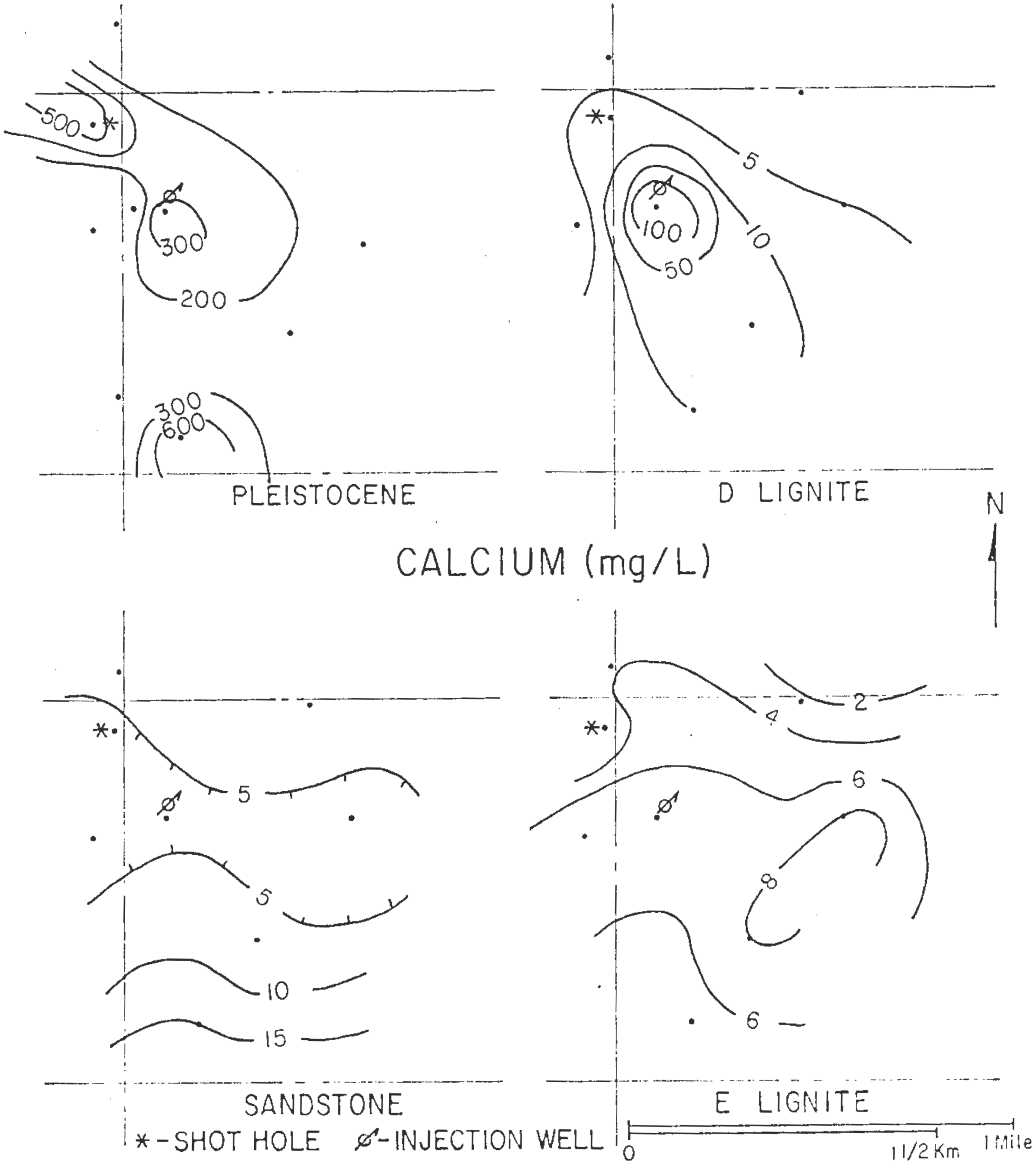


FIGURE 29 - THE ISOCONCENTRATION MAPS FOR CALCIUM IN THE FOUR INTERVALS.

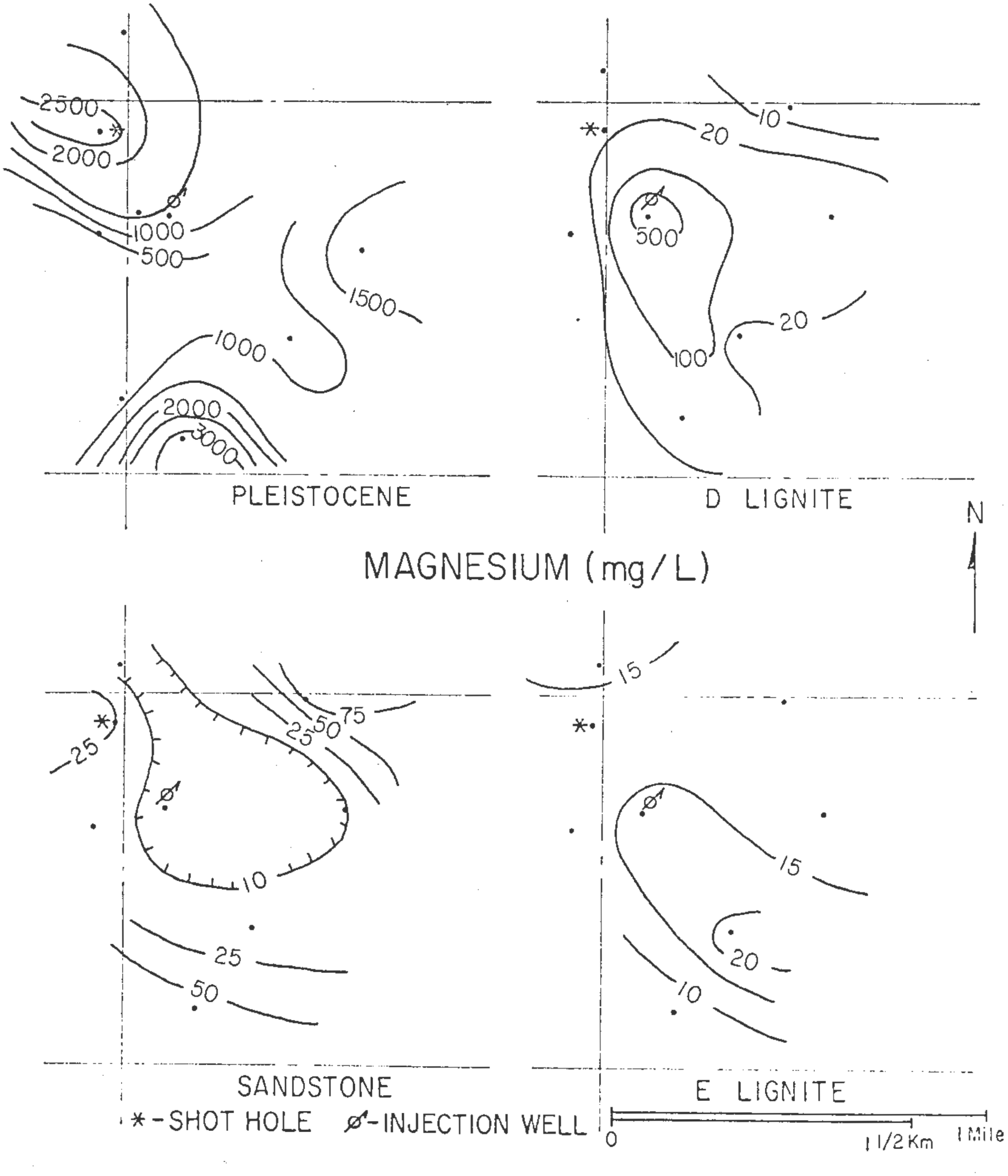


FIGURE 30 - THE ISOCONCENTRATION MAPS FOR MAGNESIUM IN THE FOUR INTERVALS.

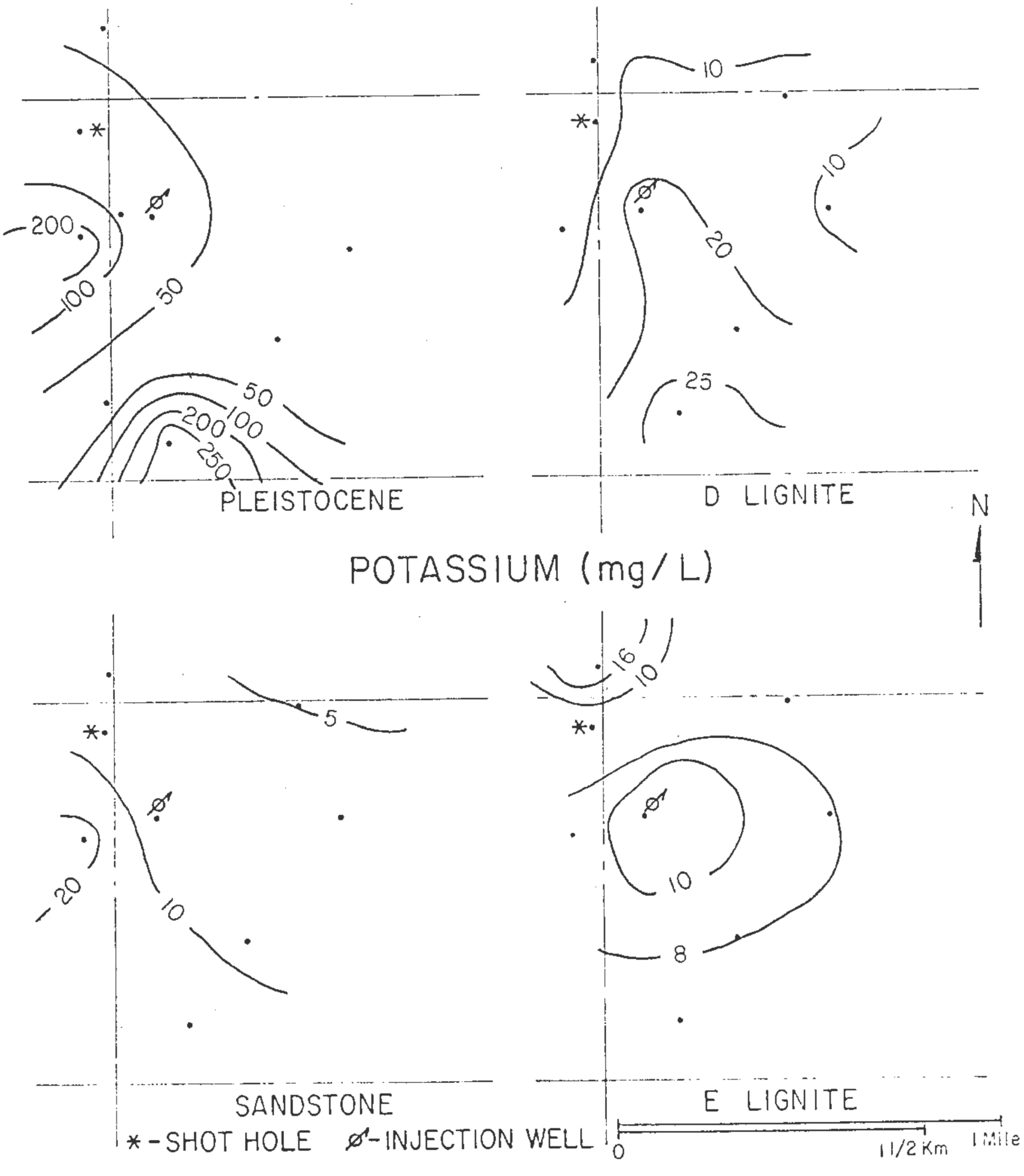


FIGURE 31 - THE ISOCONCENTRATION MAPS FOR POTASSIUM IN THE FOUR INTERVALS.

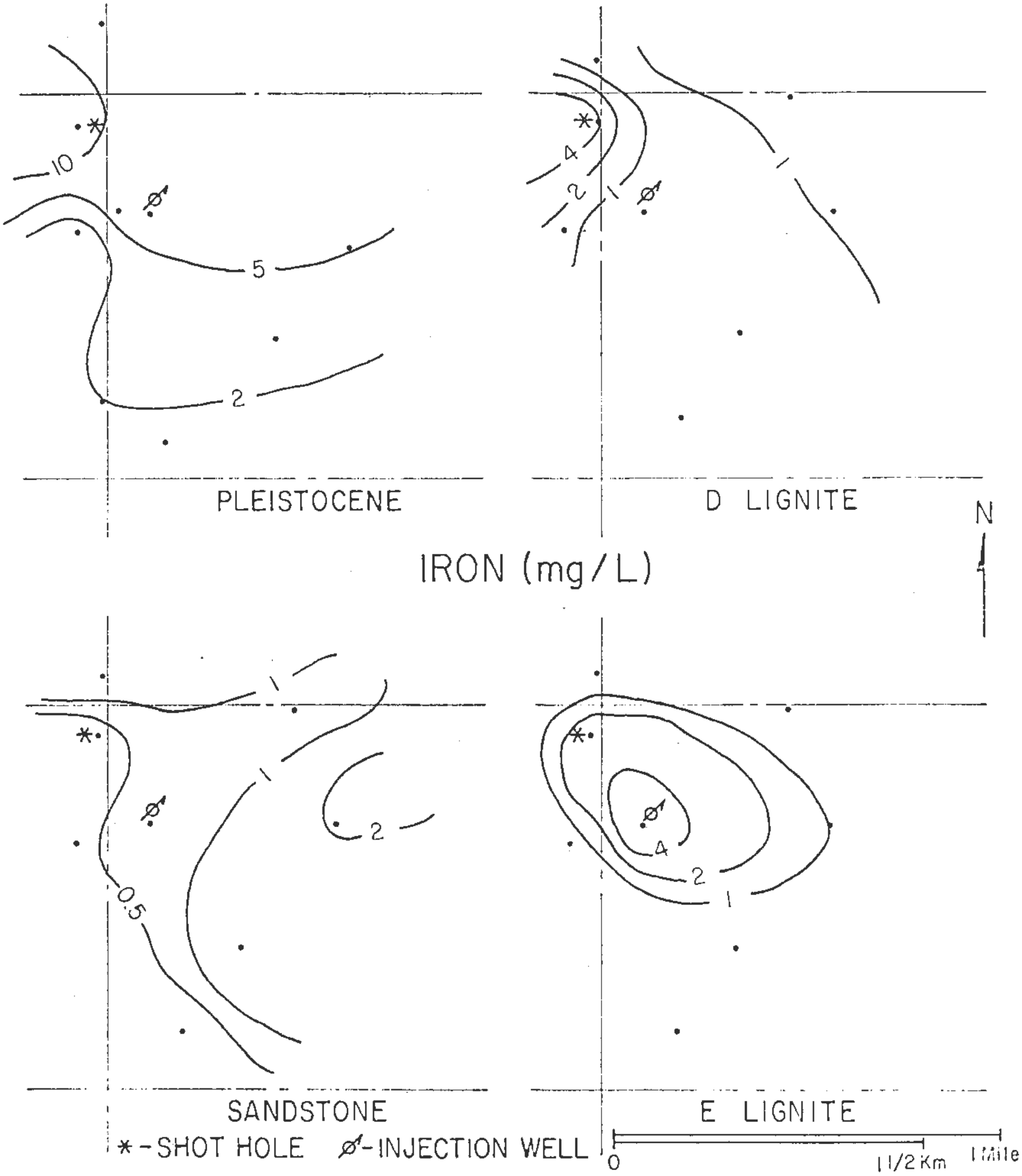


FIGURE 32 - THE ISOCONCENTRATION MAPS FOR IRON IN THE FOUR INTERVALS.

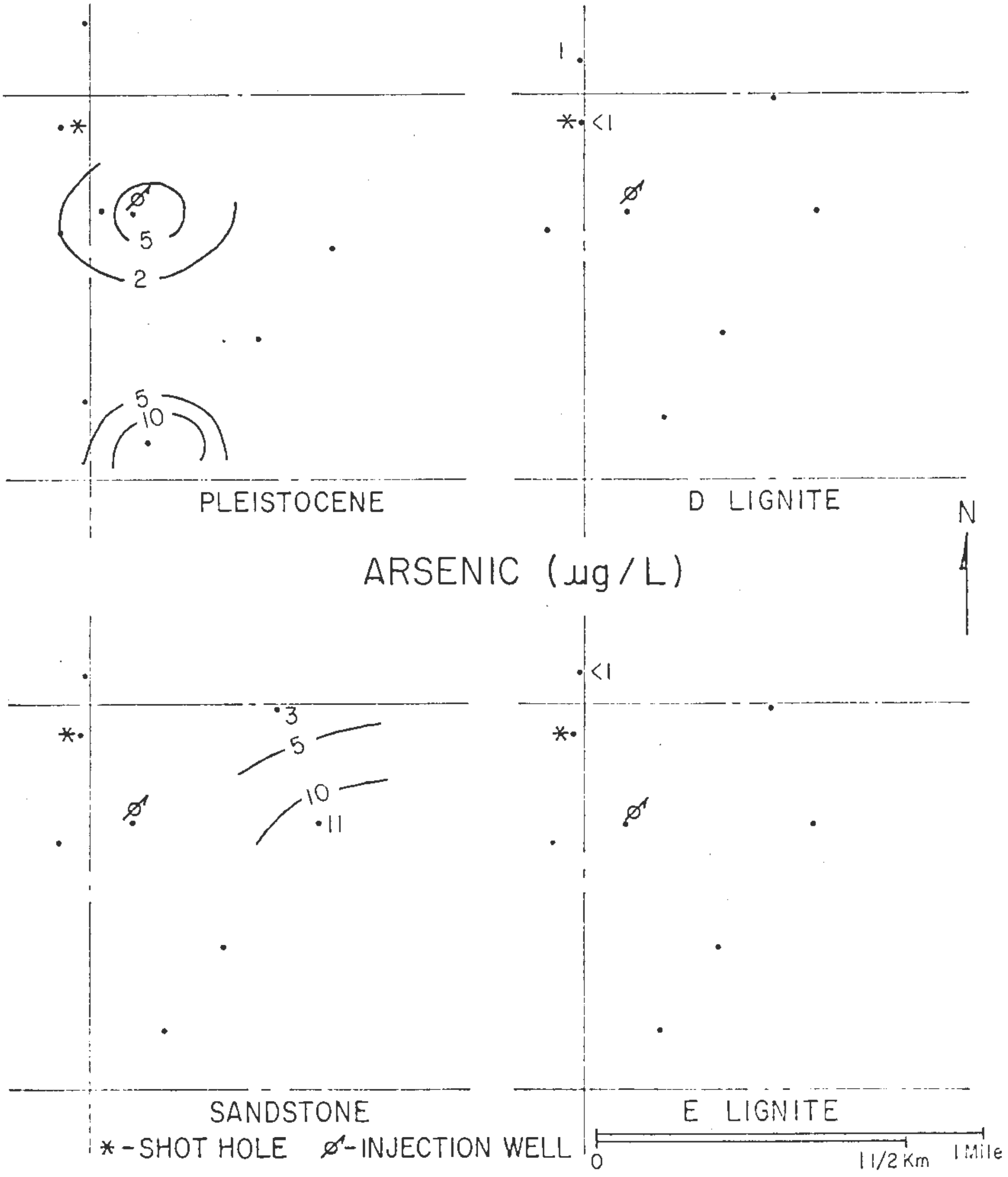


FIGURE 33 - THE ISOCONCENTRATION MAPS FOR ARSENIC IN THE FOUR INTERVALS.

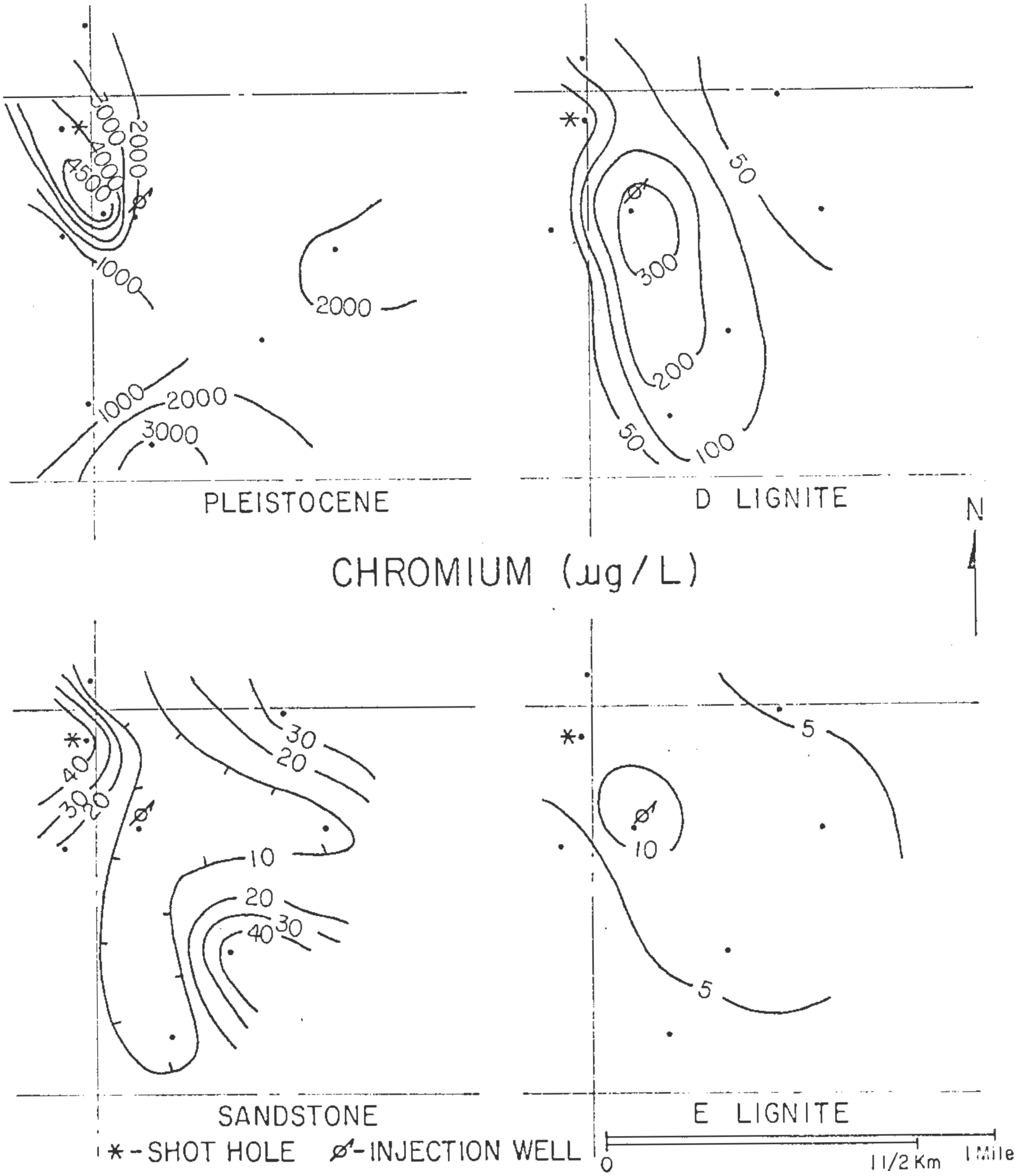


FIGURE 34 - THE ISOCONCENTRATION MAPS FOR CHROMIUM IN THE FOUR INTERVALS.

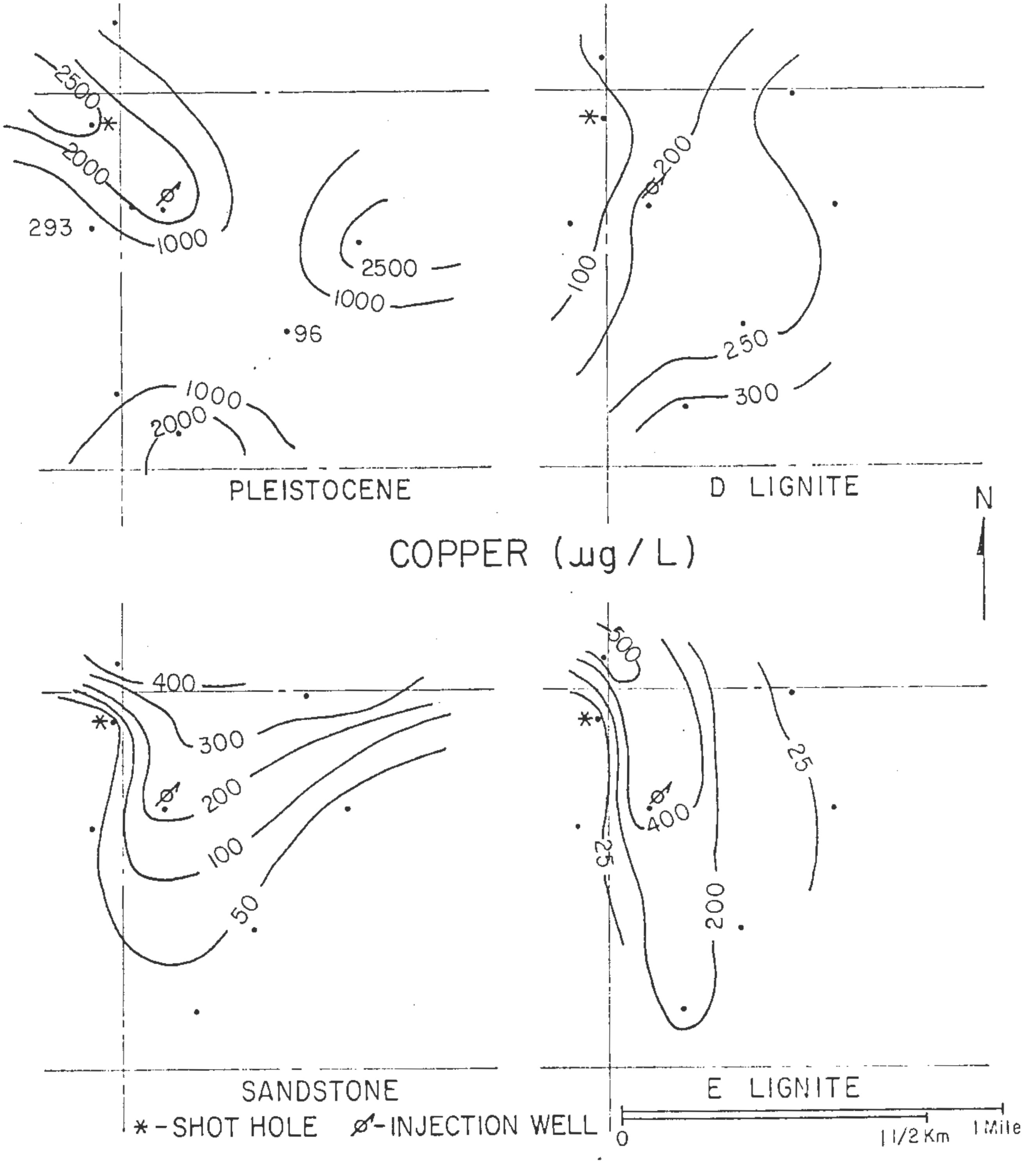


FIGURE 35 - THE ISOCONCENTRATION MAPS FOR COPPER IN THE FOUR INTERVALS.

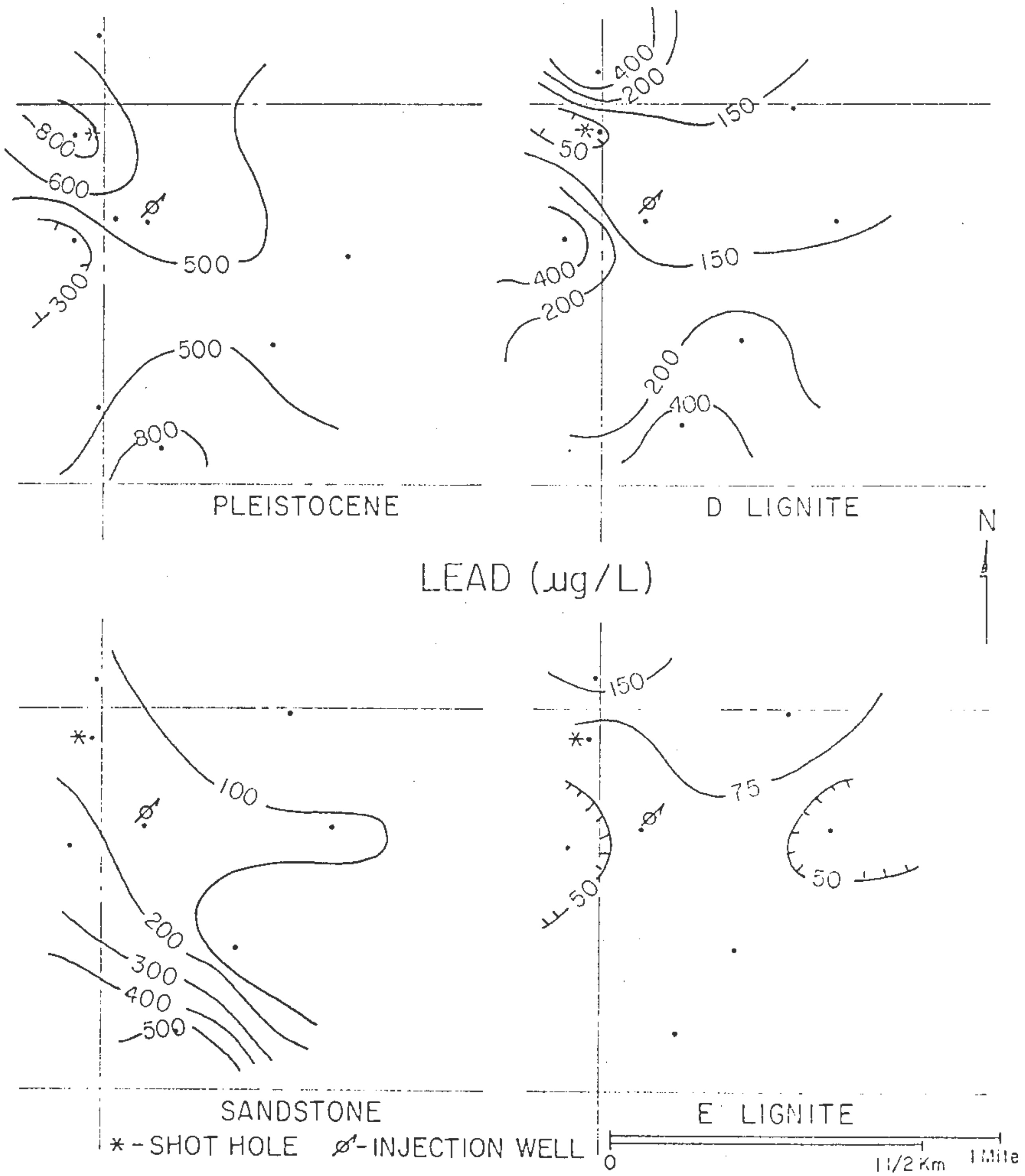


FIGURE 36 - THE ISOCONCENTRATION MAPS FOR LEAD IN THE FOUR INTERVALS.

APPENDIX

Task 4-2

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APPENDIX 4-2A

LITHOLOGIC DESCRIPTION OF SHELBY-TUBE SEDIMENTS

LITHOLOGIC DESCRIPTIONS FROM SHELBY TUBE SEDIMENTS

EDSON BROWN #1

[A]

0-5	Fill
5-17.5	Till, lt yel-brn, mottled, pebbly, FeO staining, scattered lignite fragments, FeO Stained Fractures
Note:	Concentration of salt x'lls at 12.5'
Note:	FeO stained fractures common above 17' mark

[wt-17.5]

17.5'-18'	Till, med-dk brn, pebbly, contains large salt crystals [corresponds to the watertable]
18'-32.5	Till, gry to md gry-bl, pbly

[B]

2.5-13.5'	Till/fill(?), sndy, poorly consolidated, pbly, lt gry brn, FeO stains
13.5'-22.5	Till, dk-mdgry to brn, mottled, cly, pbly, FeO stained, well indurated, many fractures filled with dk gry-br mineral
22.5-25	Till, md-dk gry, somewhat less mottled, very fractured, many at right angles, filled with FeO

[WT ARS]

25-32.5	Till, md-dk gry, <u>not</u> mottled, very few FeO stained fractures

[C]

0-4"	Soil
4"-7"	CMT? or just V. indurated pbly till
2.5'-5	Till, lt yel brn-gry, sndy, FeO cryst.
5-32.5	Till, lt yel brn-gry, cly, FeO cryst (small) mottled, from 7.5 ft. FeO stained fractures from 17.5 fractures filled with dk blue mineral also contains FeO stained fractures
Note:	Mottled but decrease with depth, but is still present at 32' - along with FeO stained fractures - there doesn't seem to be a strong break between the oxidized and reduced till [quite a lot of gypsum at 1.25']

[D]

0-10'	Till, md brn and gry, contains <u>abundant</u> gypsum x'lls and med fine very sandy till sand lenses, feO staining, mottled 6-7'

10'-22.5	Till, md brn and gry, mottled, FeO staining, contains some gypsum x'lls
22.5-27.5'	Till, dk gry and yel orng, mottled or just FeO stained along numerous fractures, clyey, well indurated
27.5-32.5	Till, dk gry, clyey

[E]

0-15	Till, lt yel-brn, pebbly, FeO stained
15-20	Till, lt gry-brn, pebbly, FeO stained, mottled
20-22	Till, dk gry, pebbly, FeO stained
22-27.5	Till, dk gry, pebbly

[I]

0-2.5	Silt, yel brn, lt yel-brn
2.5-6	v.f. sand and silt, buff to lt gry/brn, laminated
6-20	Till, lt gry brn, pebbly, FeO stained, mottled
20-22.5	Till, gry-dk gry, pebbly, FeO stained

[J]

0-1	Soil, blk, sandy
1-5	v.f. sand, silt, lt gry-brn, cly, FeO stained
5-10	Till, lt yel-brn, FeO stained, mottled
10-12.5	Till, md-dk gry, FeO stained

APPENDIX 4-2B

LITHOLOGIC DESCRIPTION OF DRILLING SAMPLES

B-1

Feet	
0-35	till
35-36	sand and gravel
36-52	till
52-56	gravel
56-140	till
140-145	sand
145-160	till
160	TD

B-2

Feet	
0-64	till
64-58	sand
68-78	till
78	TD

B-7

Feet	
0-42	till
42-43	sand and gravel
43-63	till
63-64.5	sand and gravel
64.5-72	till
72-74	sand and gravel
80	TD

B-8

Feet	
0-33	till
33-38	sand and gravel
38-58	till
58-65	gravel
65-77	till
77-80	gravel
80	TD

B-9

Feet	
0-35	till
35-60	sand and gravel
60	TD

B-13

Feet	
0-42	till
42-44	gravel
44-57	till
57-59	gravel
59-60	till
60	TD

B-15

Feet	
0-78.5	till, light brown, sandy, 5-15% pebbles.
78.5-82.5	sand and gravel
82.5-155	till, gray, sandy, increased pebble content
155-163	gravel and sand
163-207	till, gray
207-220	sand, light brown, looks like bedrock
220-230	sand; contains some gravel zones
230-240	sand, light brown, some glaconite grains, medium grained

B-22

Feet	
0-50	till
43-47	sand
47-80	till
80	TD

B-27

Feet	
0-42	till
42-46	sand
46-117	till
117-119	gravel
119-160	till
160	TD

APPENDIX 4-2C

LITHOLOGIC COLUMNS, GEOPHYSICAL LOG PROFILES, AND PIEZOMETER PROFILES

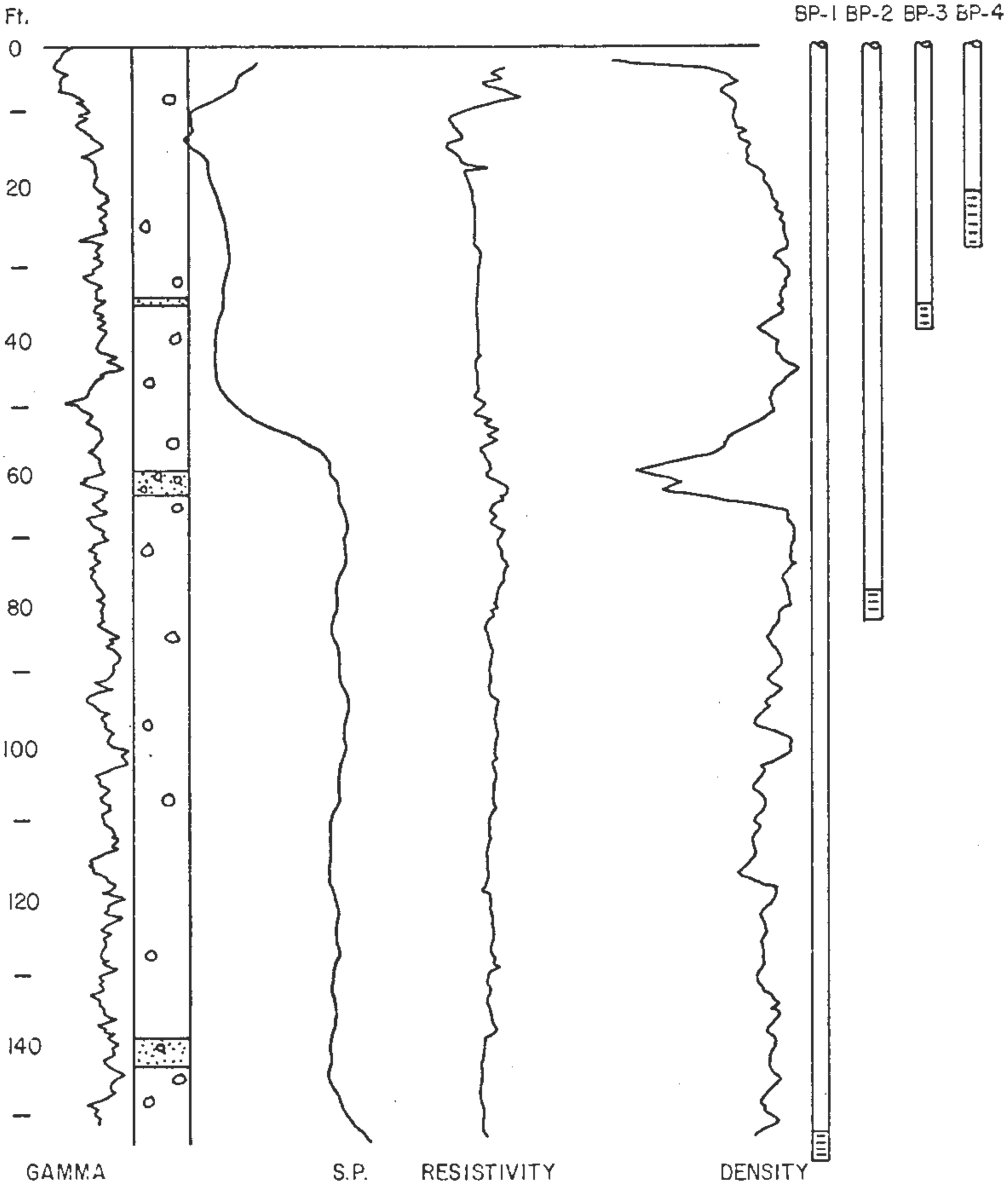


FIGURE 16 - PIEZOMETER NEST ALONG THE NORTH EDGE OF THE STUDY AREA.

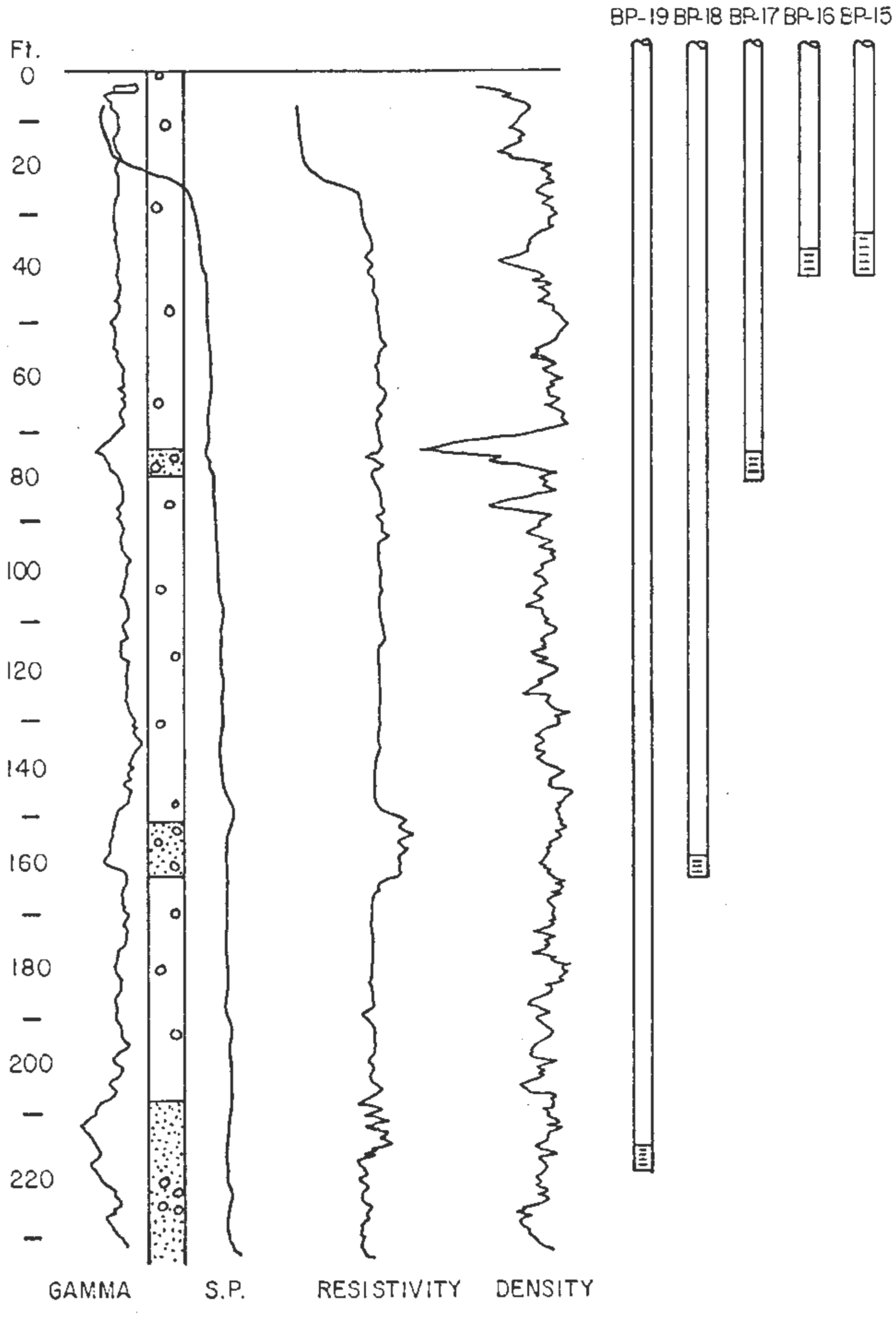


FIGURE 17 - PIEZOMETER NEST WITHIN ONE OF THE BRINE PONDS.

APPENDIX 4-2D

PIEZOMETER SCREEN INTERVAL AND DRILLING MUD SYSTEM

* Watertable Piezometer	Depth (in. ft.)	Zone	Screen Interval (in. ft.)	Drill Method
P1	156.5	Till	151.5-156.5	Mud
P2	78	Till	73-78	Mud
P3	40	Till	40-35	Air
P4*	31	Till	21-31	Air
P5*	35	Till	25-35	Air
P6	46	Sand & gravel	46-41	Air
P7	80.5	Till	75.5-80.5	Water
P8	75.75	Gravel	70.75-75.75	Mud
P9	53	Sand	48-53	Mud
P10	77	Sand & gravel	72-77	Mud
P11	50	Sand & gravel	45-50	Mud
P12	35	Till	25-35	Water
P13	53	Till	48-53	Air
P14	40	Till	35-40	Air
P15*	35	Till	25-35	Air
P16	40	Till	35-40	Water
P17	81	Sand & gravel	76-81	Mud
P18	161	Sand & gravel	156-161	Mud
P19	220	Sand & gravel	215-220	Mud
P20	71.75	Till	67-72	Mud
P21	45	Till	40-45	Water
P22	160	Till	155-160	Mud
P23	40	Till	35-40	Air
P24	71' 8"	Till	66.8-71.8	Water
P25*	34.8	Till	24.8-34.8	Air
P26	78.5	Till	73.5-78.5	Mud
P27	160	Till	155-160	Mud
P28	45.25	Till	40.25-45.25	Mud

APPENDIX 4-2E

PIEZOMETER WATER LEVELS

Piezometer	Reading in feet	Elevation in m.	12-9-84 (m)	2-17-85 (m)	5-21-85 (m)	(in ft)
1	1513.63	461.35	--	450.67	456.16	1496.59
2	1513.16	461.21	--	457.53	457.57	1501.21
3	1513.24	461.24	--	457.72	456.59	1498.0
4*	1513.24	461.24	--	456.07 (1496.29)	456.34	1497.18
5*	1511.51	460.71	--	458.02 1502.70	458.86	1505.45
6	1511.58	460.73	--	458.22	458.39	1503.90
7	1511.74	460.78	--	458.50	458.37	1503.84
8	1518.42	462.81	--	460.89	461.44	1513.91
9	1518.28	462.77	461.39	460.51	461.81	1515.12
10	1515.98	462.07	--	459.86	460.0	1509.19
11	1516.00	462.08	--	459.34	460.48	1510.76
12*	1516.02	462.08	--	459.21 1506.60	460.52	1510.89
13	1519.58	463.17	460.98	461.08	461.49	1514.01
14	1519.98	463.29	462.46	460.29	461.42	1513.85
15*	1518.50	462.84	461.23	460.45 1510.70	461.47	1514.01
16	1518.44	462.82	461.10	460.62	461.55	1514.27
17	1518.33	462.79	460.59	--	461.40	1513.78
18	1518.16	462.74	--	--	461.88	1515.35
19	1518.27	462.77	--	--	Flowing	Flowing
20	1517.30	462.47	460.60	--	460.52	1510.89
21	1517.21	462.45	460.41	--	460.50	1510.83
22	1518.92	462.97	461.38	--	461.17	1513.02
23	1518.67	462.89	461.51	--	461.10	1512.80
24	1518.61	462.87	460.82	--	461.08	1512.73
25	1519.83	463.24	459.99	460.27 1510.07	461.01	1512.50
26	1520.12	463.33	459.65	460.58	460.39	1510.47
27	1519.51	463.05	448.37 Not recovered	444.89	464.62	1491.54
28	1519.83	463.24	459.69	460.61	460.25	1510.01

APPENDIX 4-2F

APPARENT RESISTIVITY VALUES

"A" SPACING

Station Number	3	5	8	10	12	16	20	24	30	40	50	60	80	100	Comments
1	179.07	172.78	135.71	123.15	95.0	7.54	56.54	57.3	52.78	47.5	40.52	41.09	43.22	38.96	
2	68.05	34.24	22.62	21.99	24.35	28.85	26.89	28.35	32.99	35.69	38.64	38.83	31.16	44.61	
3	20.26	19.16	16.08	19.16	20.73	20.6	21.36	29.4	32.99	31.16	37.07	40.71	42.73	42.73	
4	58.43	49.63	45.74	39.58	40.71	42.22	41.46	40.71	46.56	42.73	32.36	37.32	42.22	43.35	
5	18.85	19.0	19.85	20.73	22.62	28.65	34.56	35.44	36.76	38.96	34.87	39.58	48.76	43.98	
6	18.28	17.59	14.57	12.31	12.29	18.97	14.33	15.23	18.85	21.87	26.7	23.75	32.17	28.27	
7	9.24	8.48	8.55	6.79	6.26	6.23	7.16	7.99	11.31	15.83	16.34	19.23	24.13	24.5	
8	9.8	11.94	11.06	7.79	9.27	10.15	9.8	13.27	16.02	18.34	21.68	21.87	26.64	32.67	
9	31.29	26.07	16.59	12.31	13.72	15.98	11.62	16.59	21.11	22.87	--	28.27	34.68	37.7	
10	3.58	5.43	4.78	5.34	4.0	4.62	6.28	5.73	7.92	13.57	11.94	12.44	19.10	33.3	
11	5.28	3.52	4.02	3.27	3.84	4.32	6.6	5.13	8.67	11.56	11.0	12.81	21.11	22.61	
12	7.73	4.55	5.08	6.09	7.09	6.84	8.55	9.8	10.74	13.82	16.96	18.10	24.13	22.62	
13	10.93	13.19	16.08	11.94	14.48	14.78	14.70	19.15	26.2	24.63	32.64	38.08	31.67	32.67	
14	6.6	7.85	7.54	10.05	9.65	13.67	16.96	18.25	21.11	22.87	25.13	32.04	28.15	32.67	Compacted area
15	5.47	5.97	4.93	4.15	3.85	5.33	5.4	7.23	9.05	10.81	13.19	15.46	22.12	18.85	
16	4.33	6.47	8.34	7.04	4.9	4.42	4.27	5.88	7.35	7.54	11.0	11.69	11.06	17.59	
17	4.9	4.08	4.67	3.52	4.45	6.13	5.15	6.94	7.35	9.05	12.25	15.08	18.6	18.22	
18	4.33	3.17	3.52	4.52	4.6	6.03	6.66	7.69	10.93	11.69	17.28	19.6	21.61	21.36	
19	13.76	16.65	21.11	20.11	22.54	26.04	27.65	26.7	32.23	34.18	34.87	35.44	41.22	43.98	Oil spill area
20	36.0	32.04	29.66	32.04	31.67	39.21	37.70	34.38	33.17	41.72	36.13	41.47	40.21	39.58	
21	7.35	6.91	6.58	4.27	3.77	4.02	4.78	6.33	6.79	9.05	8.17	13.19	19.1	20.1	No grain growing at surface
22	3.02	3.27	3.37	3.83	3.92	3.22	4.65	7.54	7.73	7.54	9.11	11.3	14.58	21.94	
23	6.22	6.53	6.89	7.22	6.93	7.94	9.68	10.55	12.94	19.35	23.24	25.25	31.16	32.67	
24	22.8	10.68	9.55	8.8	9.88	8.55	7.67	8.14	9.61	13.82	15.08	17.34	19.1	27.02	
25	16.21	12.88	10.05	8.86	6.64	6.64	7.04	7.24	11.12	13.07	12.25	14.32	10.56	14.45	
26	14.04	7.54	5.68	5.34	4.37	4.52	4.90	6.33	8.1	10.81	9.74	13.95	14.07	19.48	vegetated
27	3.02	3.58	2.87	2.83	3.02	4.72	4.65	6.64	6.22	8.04	15.08	16.59	18.1	23.24	non-vegetated
28	6.6	6.09	6.58	4.46	5.81	6.94	7.92	7.84	9.8	11.56	16.34	15.46	22.11	30.16	
29	12.63	12.1	12.06	13.32	14.25	15.68	19.1	19.6	23.18	25.38	27.96	30.54	34.18	33.3	vegetated
30	6.97	6.91	4.92	5.15	4.3	4.83	5.78	6.64	4.52	7.29	10.37	7.16	13.07	16.96	vegetated over pipeline
31	10.74	9.02	5.03	4.78	4.9	4.83	4.77	7.09	7.54	10.05	10.05	13.95	17.59	18.85	
32	5.65	2.83	3.02	3.71	3.62	4.22	4.65	7.39	4.15	10.05	7.54	13.19	20.61	13.19	
33	7.92	9.74	7.04	8.11	8.14	9.14	12.32	13.27	13.38	23.62	21.99	33.93	19.6	32.67	
34	107.07	82.31	58.31	48.38	40.72	43.23	41.47	37.7	43.35	44.74	43.67	39.96	37.7	35.18	
35	39.4	32.99	27.18	25.76	26.39	20.11	25.76	28.5	28.27	31.42	38.33	36.95	37.7	31.42	
36	52.97	37.07	31.67	28.28	28.65	31.16	30.54	45.24	41.85	38.45	39.9	36.95	40.72	43.35	

APPENDIX 4-2G

GROUNDWATER AND PORE WATER CHEMISTRY

Well No.	BL-1	BL-2	BL-3	BL-4	BL-4	BL-4	BL-5
Sampling Date or Mean ($\bar{x}$)	6-12-85	6-12-85	6-12-85	12-9-84	6-12-85	$\bar{x}$	6-12-85
Field Temp.	15°	14°	12°		15°		14°
Field pH	6.92	6.67	6.46		6.59		6.78
Field Cond.	2,200	>20,000	>20,000		>20,000		>20,000
Lab pH	7.34	7.18	6.81	6.87	7.1		6.95
Lab Cond.	17,879	90,242	106,618	101,018	89,790		66,636
TDS mg/L	16,580	84,340	214,470	117,751	100,590		59,410
Hardness	7,132	20,590	21,895	21,682	14,922		26,766
Alkalinity	317	335	212	182	412		333
Ca mg/L	1,219	3,989	5,597	6,873	2,542		1,800
Mg mg/L	993	2,581	1,923	1,098	2,082		5,408
Na mg/L	1,806	21,162	60,766	73,030	32,143		7,729
K mg/L	2	49	1,652	3,643	403		48
SO_4 mg/L	489	1,255	759	758	1,263		2,979
Cl mg/L	6,433	40,920	119,920	119,430	67,760		28,243
NO_3 mg/L	21.60	0.20		0.4	21.60		18.20
Depth	9'	4'	4'	9'			4'

Well No.	BL-6	BL-7	BL-8
Sampling Date or Mean ($\bar{x}$)	6-12-85	6-12-85	6-12-85
Field Temp.	14°	11°	13°
Field pH	7.10	6.75	7.32
Field Cond.	>20,000	>20,000	11,600
Lab pH	7.5	6.88	7.64
Lab Cond.	49,808	96,341	31,172
TDS mg/L	--	112,970	9,490
Hardness	9,408	7,891	1,223
Alkalinity	328	528	752
Ca mg/L	1,006	1,458	79
Mg mg/L	1,674	1,032	249
Na mg/L	5,411	40,215	2,795
K mg/L	8	1,208	2
SO_4 mg/L	1,056	619	565
Cl mg/L	12,053	60,850	3,975
NO_3 mg/L	115	--	7.2
Depth	9'	4'	9'

Well No.	BP-1	BP-1	BP-1
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$
Field Temp.	4.5	--	--
Field pH	7.54	7.49	7.52
Field Cond.	5,000	2,400	
Lab pH	7.83	7.56	7.70
Lab Cond.	2,317	3,082	2,700
TDS mg/L	1,668	2,020	1,844
Hardness mg/L	560	626	593
Alkalinity mg/L	432	435	434
Ca mg/L	114	93	104
Mg mg/L	67	95	81
Na mg/L	363	445	404
K mg/L	22	12	17
SO_4 mg/L	618	727	673
Cl mg/L	231	266	249
NO_3 mg/L	--	0.16	0.16
As µg/L		5.0	5.0
Fe µg/L		116	
Mn µg/L		2,703	
Pb µg/L		1.8	
Cr µg/L		24	

Well No.	BP-2	BP-2	BP-2	BP-3	BP-3	BP-3	BP-4
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$	6-12-85
Field Temp.	4.5	--	--	4.0	--	4.0	--
Field pH	7.46	7.44	7.45	7.61	7.39	7.50	7.22
Field Cond.	5,500	2,400		7,400	3,300		4,200
Lab pH	7.70	7.79	7.75	8.04	7.58	7.81	7.43
Lab Cond	2,447	2,894	2,671	4,336	4,011	4,174	6,142
TDS	1,952	2,320	2,136	3,879	3,280	3,580	6,190
Hardness	686	762	724	1,376	1,333	1,355	2,608
Alkalinity	356	433	395	127	220	174	494
Ca	138	98	118	334	144	239	162
Mg	83	126	105	132	236	184	537
Na	379	397	388	588	566	577	705
K	21	11	16	41	19	30	22
SO_4	1,048	998	1,023	2,082	2,010	2,046	3,319
Cl	60	63	62	300	119	210	172
NO_3	0.5	0.42	0.46	0.3	0.19	0.25	0.59
As µg/L		4.6	4.6		<1	<1	<1
Fe µg/L		587			299		
Mn µg/L		1,042			1,542		
Pb µg/L		3.7			15.8		
Cr µg/L		22			17.4		

Well No.	BP-5	BP-6	BP-6	BP-6	BP-7	BP-7	BP-7
Sampling Date or Mean ($\bar{x}$)	6-12-85	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$
Field Temp.	--	4.5	--	--	4.0	--	--
Field pH	7.15	7.33	7.33	7.33	7.66	7.42	7.54
Field Cond.	3,200	6,800	2,700		5,000	2,400	
Lab pH	7.68	7.59	7.6	7.6	7.73	7.89	7.81
Lab Cond	4,299	3,172	3,476	3,324	2,663	2,601	2,632
TDS	4,100	2,773	3,190	2,982	1,760	2,320	2,040
Hardness	2,117	1,438	1,383	1,411	594	721	658
Alkalinity	433	332	480	406	334	440	387
Ca	152	241	126	184	119	91	105
Mg	423	203	260	232	72	119	96
Na	467	400	402	401	383	417	400
K	18	29	15	22	21	11	16
SO_4	2,110	1,451	1,451	1,451	932	954	943
Cl	264	180	129	155	59	64	62
NO_3	<0.1	1.7	0.1	0.9	--	0.19	0.19
As µg/L	<1		2.6			4.2	
Fe µg/L			223			141	
Mn µg/L			1,607			600	
Pb µg/L			7.6			2.4	
Cr µg/L			26			24	

Well No.	BP-8	BP-8	BP-8	BP-9	BP-9	BP-9
Sampling Date or Mean $(\bar{x})$	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$
Field Temp.	5.0	--	--	5.5	--	
Field pH	7.56	7.38	7.47	7.32	7.20	7.26
Field Cond.	5,600	2,700		11,300	6,600	
Lab pH	7.79	7.66	7.73	7.23	7.46	7.35
Lab Cond	2,328	2,653	2,491	6,886	8,911	7,899
TDS	1,786	2,140	1,963	4,956	6,690	5,823
Hardness	642	774	708	1,837	2,078	1,958
Alkalinity	364	486	425	292	467	380
Ca	117	96	107	379	165	272
Mg	85	129	107	216	406	311
Na	403	463	433	857	1,212	1,035
K	20	10	15	41	23	32
SO_4	956	1,008	982	799	861	830
Cl	77	55	66	1,803	2,312	2,058
NO_3	--	<0.1	<0.1	--	<0.1	<0.1
As µg/L		5.7			3.0	
Fe µg/L		514			612	
Mn µg/L		772			2,287	
Pb µg/L		2.1			46	
Cr µg/L		2.4			19	

Well No.	BP-10	BP-10	BP-10	BP-11	BP-11	BP-11	BP-12
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$	6-12-85
Field Temp.	4.0	--		5.0	--		--
Field pH	7.52	7.24	7.38	7.44	7.23	7.34	7.17
Field Cond.	5,200	2,200		6,500	2,900		4,700
Lab pH	7.83	7.62	7.72	7.55	7.56	7.56	7.38
Lab Cond	2,144	2,559	2,352	2,923	3,703	3,313	6,926
TDS	1,703	1,940	1,822	2,494	3,630	3,062	7,520
Hardness	493	718	606	1,052	1,476	1,264	3,330
Alkalinity	254	463	359	357	390	374	462
Ca	88	70	79	221	130	176	321
Mg	66	134	100	121	280	201	615
Na	379	416	398	420	458	439	770
K	21	11	16	26	15	21	21
SO_4	913	978	946	1,412	1,862	1,637	3,767
Cl	47	43	45	62	86	74	129
NO_3	--	0.16	0.16	--	0.14	0.14	<0.1
As µg/L		7.8			2.1		<1
Fe µg/L		268			370		
Mn µg/L		1,063			637		
Pb µg/L		10.8			6.5		
Cr µg/L		8.5			21		

Well No.	BP-13	BP-13	BP-13	BP-14	BP-14	BP-14	BP-15
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{x}$	12-9-84	6-12-85	$\bar{x}$	6-12-85
Field Temp.	5.0	--		4.5	--		--
Field pH	7.45	7.21	7.34	7.23	7.22	7.23	6.5
Field Cond.	10,300	10,200		>20,000	36,000		108,000
Lab pH	7.47	7.13	7.39	7.31	7.3	7.3	6.8
Lab Cond	5,587	16,902	11,245	49,047	58,814	53,931	90,572
TDS	4,329	15,380	9,855	24,076	52,320	38,198	127,490
Hardness	1,727	5,741	3,734	10,332	16,958	13,645	20,134
Alkalinity	345	382	364	373	390	382	222
Ca	315	227	271	1,263	2,316	1,790	5,517
Mg	228	1,256	742	1,743	2,712	2,228	1,546
Na	754	2,286	1,520	4,101	8,274	6,188	35,764
K	37	36	37	123	62	93	621
SO_4	1,624	2,826	2,225	3,650	62,860	33,255	1,895
Cl	942	4,966	2,954	9,448	19,312	14,380	75,390
NO_3	--	0.34	0.34	--	21	21	0.2
As µg/L		<1	<1		<1	<1	<1
Fe µg/L		80			1,306		
Mn µg/L		2,620			11,740		
Pb µg/L		1.2			578		
Cr µg/L		35			24		

Well No.	BP-16	BP-16	BP-16	BP-17	BP-17	BP-17
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$
Field Temp.	5	--		4.5	--	4.5
Field pH	6.8	6.75	6.77	7.38	7.40	7.39
Field Cond.	720,000	45,000		6,300	2,400	
Lab pH	7.1	7.01	7.06	7.72	7.65	7.69
Lab Cond	73,300	60,695	66,998	2,848	3,082	2,965
TDS	58,490	50,010	54,250	2,357	2,670	2,514
Hardness	12,538	11,730	12,134	939	921	930
Alkalinity	22	343	285	337	465	401
Ca	3,191	3,727	3,459	192	86	139
Mg	1,109	588	849	112	172	142
Na	15,787	8,008	11,898	420	445	433
K	662	146	404	24	12	18
SO_4	1,820	2,040	1,930	1,180	1,112	1,146
Cl	31,259	20,871	26,065	154	158	156
NO_3	--	0.15	0.15	--	0.5	0.5
As µg/L		<1			<1	
Fe µg/L		1,232			344	
Mn µg/L		10,647			2,247	
Pb µg/L		36			1.3	
Cr µg/L		32			11	

Well No.	BP-18	BP-18	BP-18	BP-19	BP-20	BP-20	BP-20
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{x}$	6-12-85	12-9-84	6-12-85	$\bar{x}$
Field Temp.	5.0	--		--	5.0	--	
Field pH	7.55	7.59	7.57	7.99	7.36	7.43	7.40
Field Cond.	7,000	3,200		5,300	4,500	2,300	
Lab pH	7.77	7.64	7.71	7.80	7.76	7.73	7.75
Lab Cond	3,270	3,750	3,760	5,380	2,274	2,643	2,459
TDS	2,363	2,590	2,477	3,290	1,715	2,180	1,948
Hardness	611	830	721	193	584	735	660
Alkalinity	268	469	369	560	340	438	389
Ca	132	91	112	22	120	91	106
Mg	68	146	107	34	69	122	96
Na	552	467	510	1,118	389	409	399
K	23	11	17	9	20	11	16
SO_4	685	682	684	6	778	920	849
Cl	510	579	545	1,512	138	126	132
NO_3	--	<0.1	<0.1	<0.1	--	0.14	0.14
As µg/L		4.8		<1		3.6	
Fe µg/L		14				197	
Mn µg/L		313				1,064	
Pb µg/L		2				5.2	
Cr µg/L		16				21	

Well No.	BP-21	BP-21	BP-21	BP-22	BP-22	BP-22
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$
Field Temp.	6.0	--	6.0	5.0	--	5.0
Field pH	7.29	7.35	7.32	7.68	7.51	7.60
Field Cond.	16,400	3,800		6,800	3,600	
Lab pH	7.39	7.46	7.43	7.69	7.53	7.61
Lab Cond	10,481	5,025	7,753	3,042	4,941	3,992
TDS	9,122	3,960	6,541	2,102	3,390	2,746
Hardness	3,384	1,700	2,542	755	977	866
Alkalinity	314	460	387	344	418	381
Ca	458	118	288	132	96	114
Mg	544	343	444	103	180	142
Na	1,060	533	797	487	807	647
K	43	14	29	26	17	22
SO_4	914	721	818	615	766	691
Cl	2,686	1,102	1,894	470	1,020	745
NO_3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
As µg/L		2.8			11.4	
Fe µg/L		77			18	
Mn µg/L		714			420	
Pb µg/L		5.1			2.5	
Cr µg/L		15			23	

Well No.	BP-23	BP-23	BP-23	BP-24	BP-24	BP-24	BP-25
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{x}$	12-9-84	6-12-85	$\bar{x}$	6-12-85
Field Temp.	5.0	--		5.0	--		--
Field pH	7.38	7.31	7.35	7.57	7.42	7.50	7.17
Field Cond.	8,500	3,000		6,000	2,400		4,500
Lab pH	7.55	7.55	7.55	7.56	7.61	7.59	7.55
Lab Cond	4,060	3,531	3,796	2,609	2,904	2,757	6,487
TDS	2,937	2,640	2,789	2,056	2,550	2,303	6,100
Hardness	1,139	1,088	1,114	753	867	810	2,588
Alkalinity	360	506	433	355	478	417	478
Ca	196	101	149	142	91	117	154
Mg	158	204	181	97	156	127	535
Na	577	515	546	414	476	445	855
K	35	15	25	25	11	18	23
SO_4	926	952	939	964	999	982	3,050
Cl	715	414	565	165	143	154	469
NO_3	--	<0.1	<0.1	<0.1	0.96	0.98	0.77
As µg/L		<1					<1
Fe µg/L		450			265		
Mn µg/L		1,541			836		
Pb µg/L		2.4			1.6		
Cr µg/L		32			27		

Well No.	BP-26	BP-26	BP-26	BP-27	BP-27	BP-27
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{X}$	12-9-84	6-12-85	$\bar{X}$
Field Temp.	5.0	--		4.5	--	
Field pH	7.43	7.38	7.41	7.5	7.34	7.42
Field Cond.	5,700	2,500		6,400	2,700	
Lab pH	7.65	7.83	7.74	7.61	7.69	7.65
Lab Cond	2,328	2,883	2,606	2,739	3,050	2,895
TDS	1,811	2,580	2,196	2,012	2,210	2,111
Hardness	668	803	736	647	687	667
Alkalinity	364	460	412	390	447	419
Ca	114	89	102	116	91	104
Mg	93	141	117	86	112	99
Na	389	442	416	469	493	481
K	25	11	18	23	12	18
SO_4	918	1,055	987	772	772	772
Cl	78	79	79	305	329	317
NO_3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
As µg/L		2.9			8.0	
Fe µg/L		400			579	
Mn µg/L		716			695	
Pb µg/L		3			6.3	
Cr µg/L		25			23	

Well No.	BP-28	BP-28	BP-28
Sampling Date or Mean ($\bar{x}$)	12-9-84	6-12-85	$\bar{x}$
Field Temp.	4.5	--	--
Field pH	7.39	7.3	7.35
Field Cond.	6,100	2,400	
Lab pH	7.58	7.57	7.58
Lab Cond	2,739	2,946	2,843
TDS	2,249	2,160	2,205
Hardness	881	901	891
Alkalinity	399	473	436
Ca	173	106	140
Mg	109	156	133
Na	424	457	441
K	27	14	21
SO_4	1,135	1,089	1,112
Cl	110	103	107
NO_3	<0.1	<0.1	<0.1
As µg/L		7.0	
Fe µg/L		419	
Mn µg/L		1,250	
Pb µg/L		1.1	
Cr µg/L		18	

APPENDIX 4-2H

PORE WATER CHEMISTRY MAPS

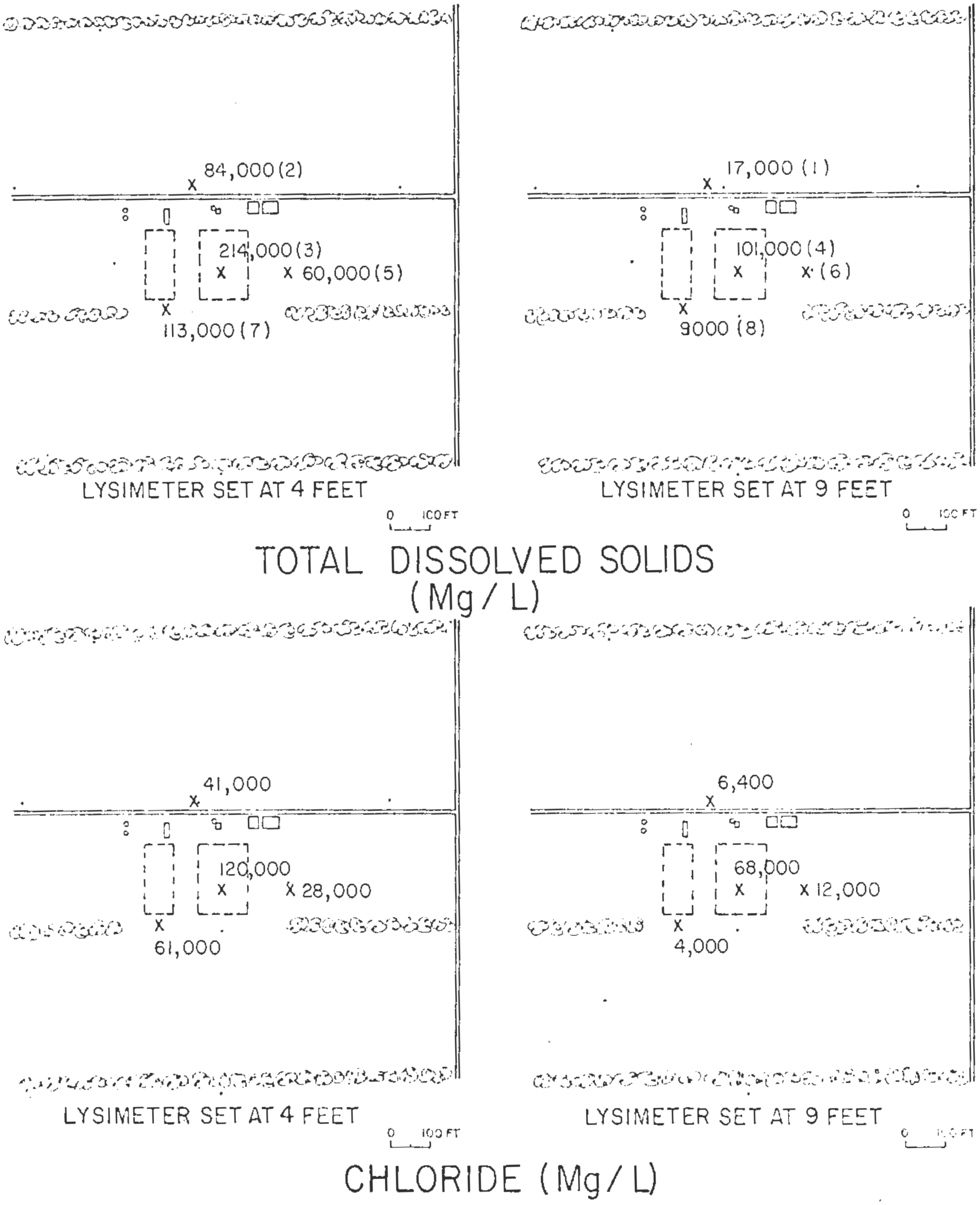
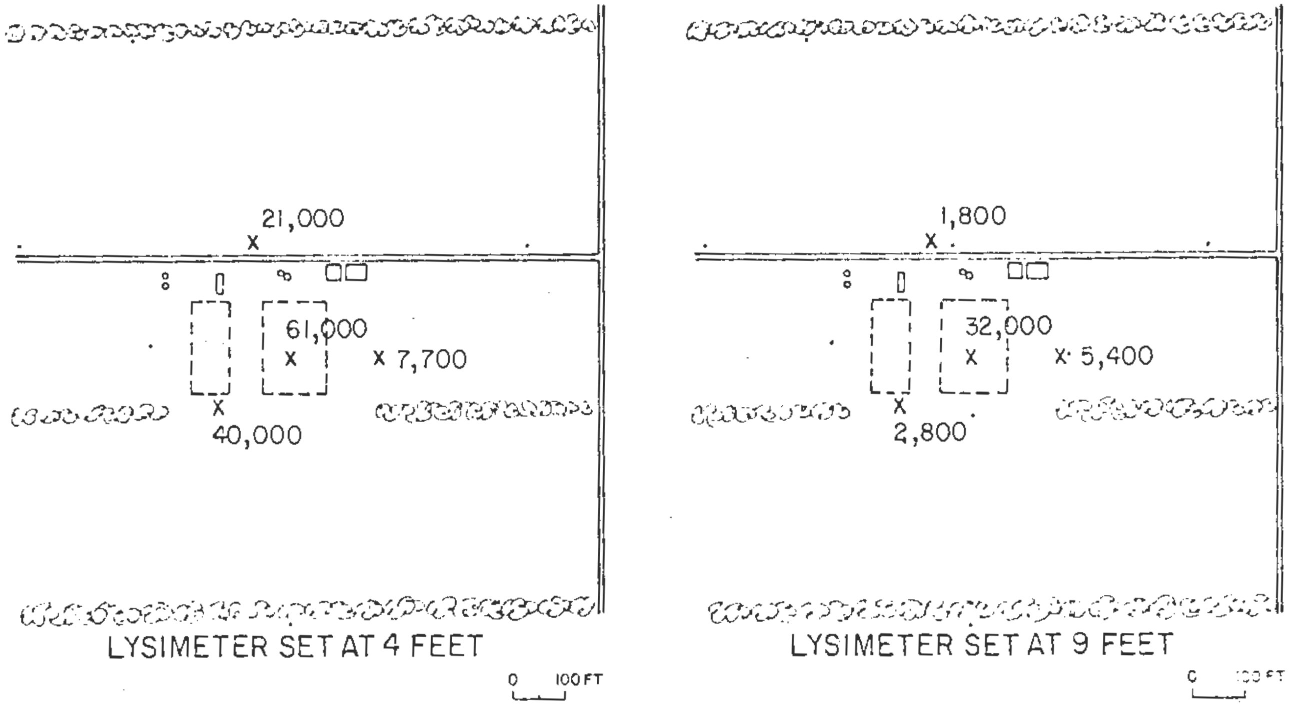
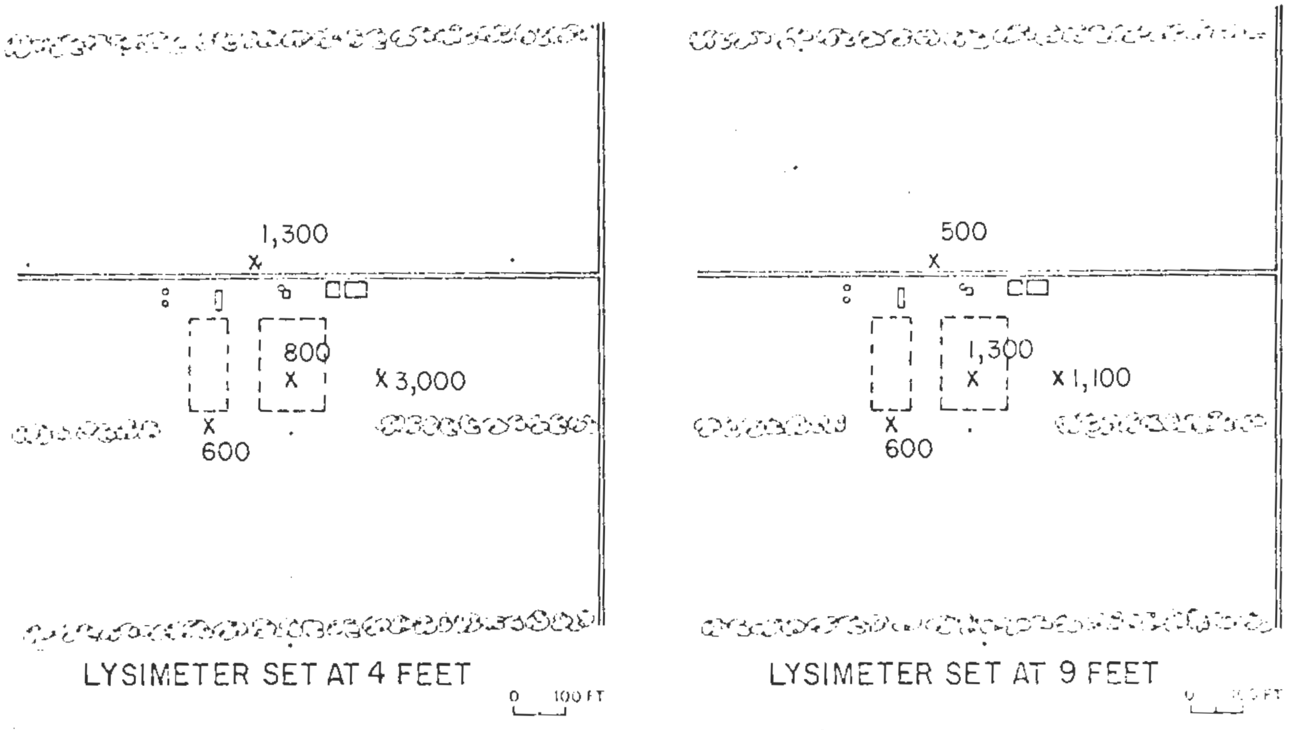


FIGURE 18 - TOTAL DISSOLVED SOLIDS AND CHLORIDE-ION CONCENTRATIONS IN THE VADOSE ZONE (1 foot = .3048 m).

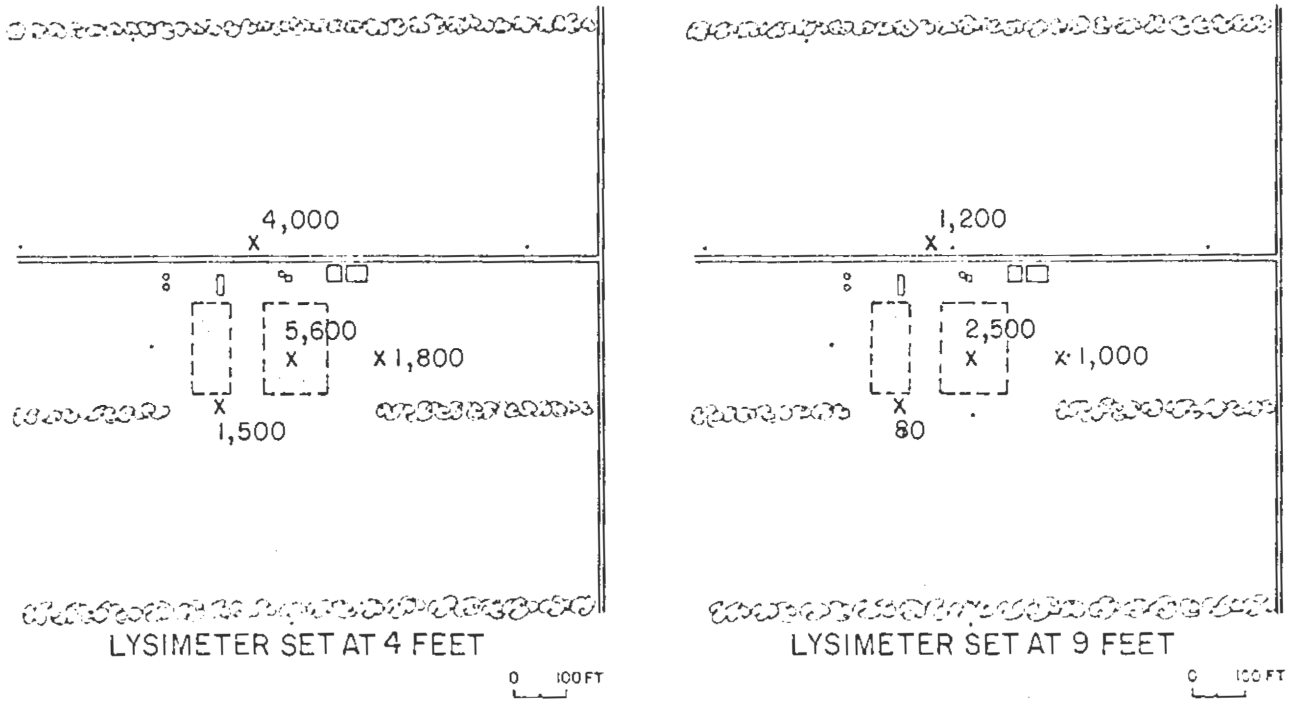


SODIUM (Mg/L)



SULFATE (Mg/L)

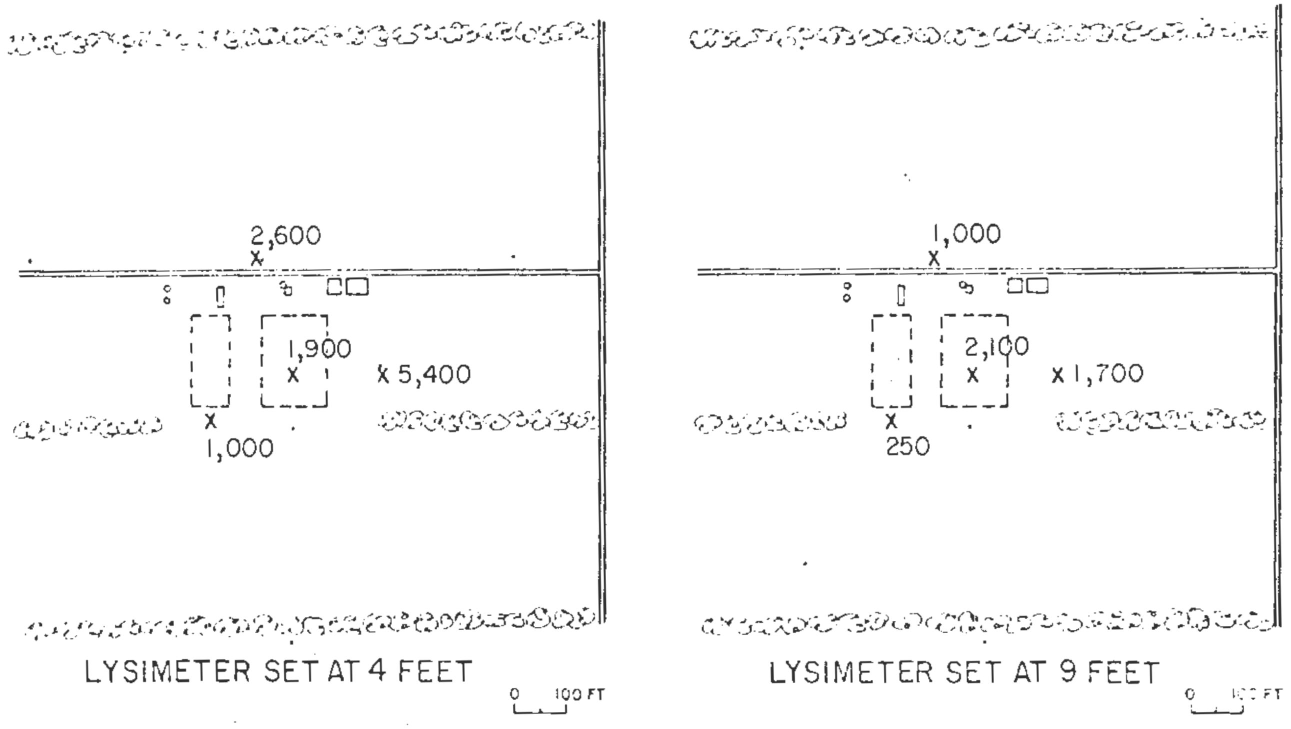
FIGURE 19 - SODIUM AND SULFATE CONCENTRATIONS IN THE VADOSE ZONE (1 foot = .3048 m).



LYSIMETER SET AT 4 FEET

LYSIMETER SET AT 9 FEET

CALCIUM (Mg/L)



LYSIMETER SET AT 4 FEET

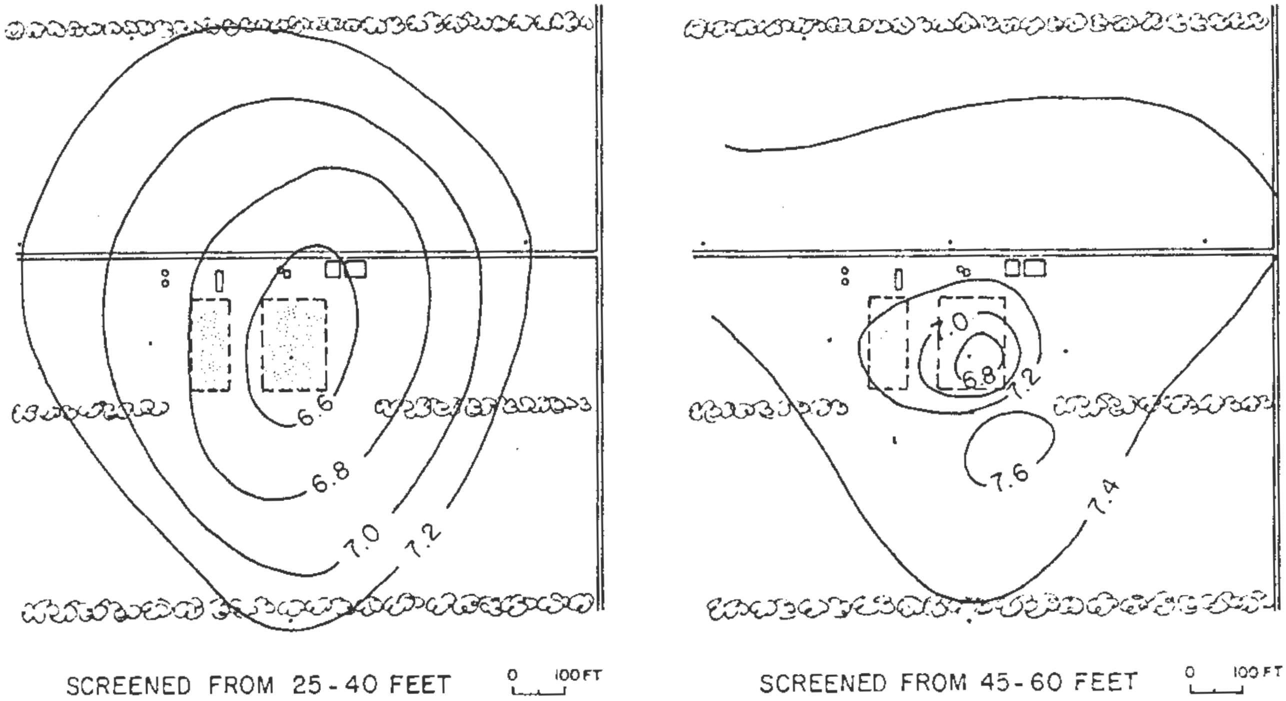
LYSIMETER SET AT 9 FEET

MAGNESIUM (Mg/L)

FIGURE 20 - CALCIUM AND MAGNESIUM CONCENTRATIONS IN THE VADOSE ZONE (1 foot = .3048 m).

APPENDIX 4-2I

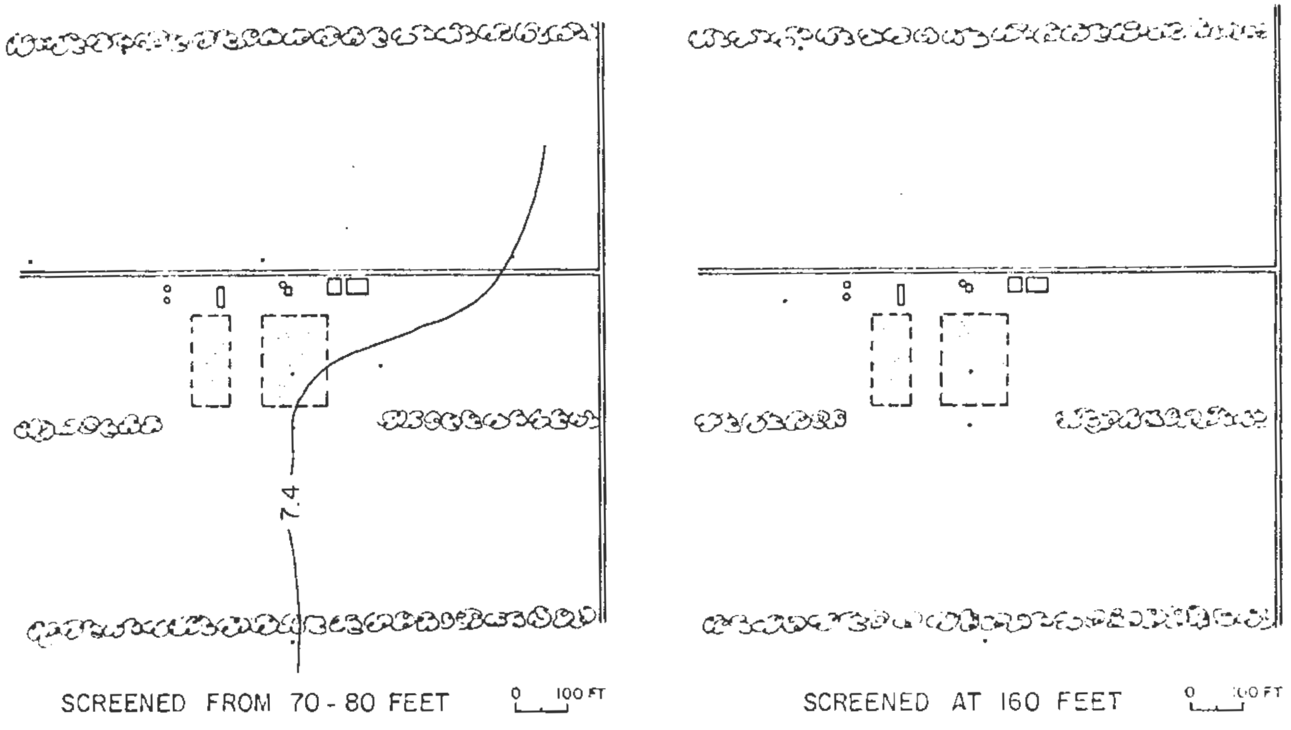
ISOCONCENTRATION MAPS



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

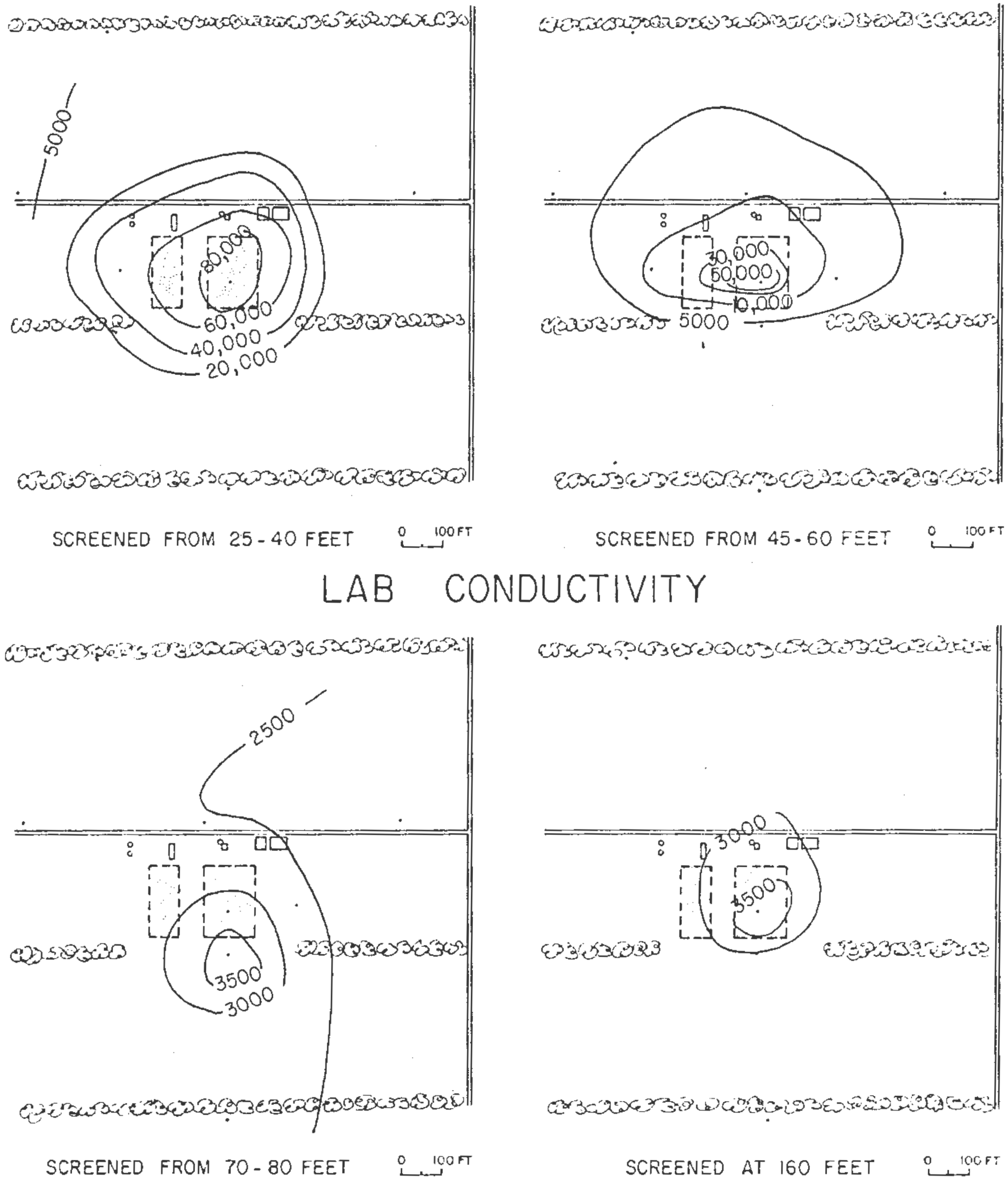
FIELD pH



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

<u>FIGURE 21</u> - THE ISOCONCENTRATION MAPS FOR FIELD pH IN THE FOUR INTERVALS (1 foot = .3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

LAB CONDUCTIVITY

SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

FIGURE 22 - THE ISOCONCENTRATION MAPS FOR LAB CONDUCTIVITY IN THE FOUR INTERVALS (1 foot = .3048 m).

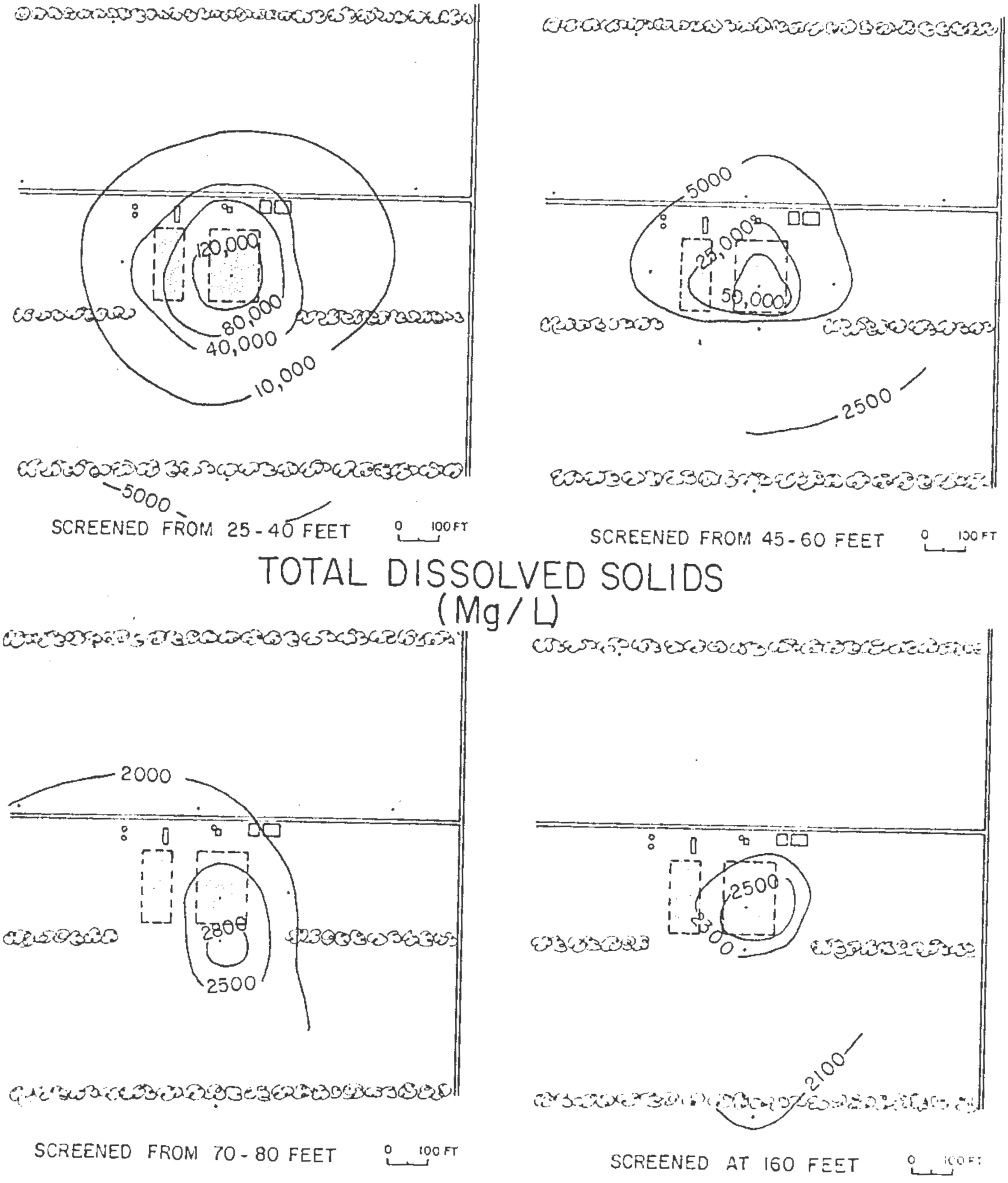
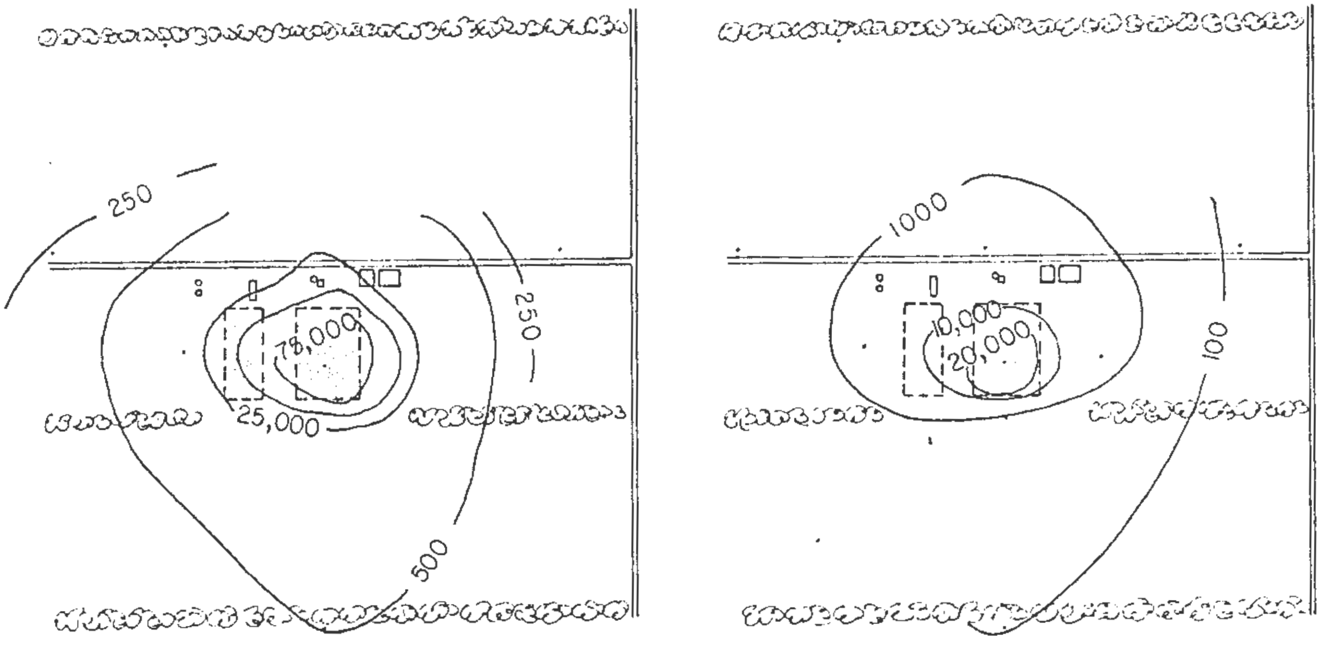


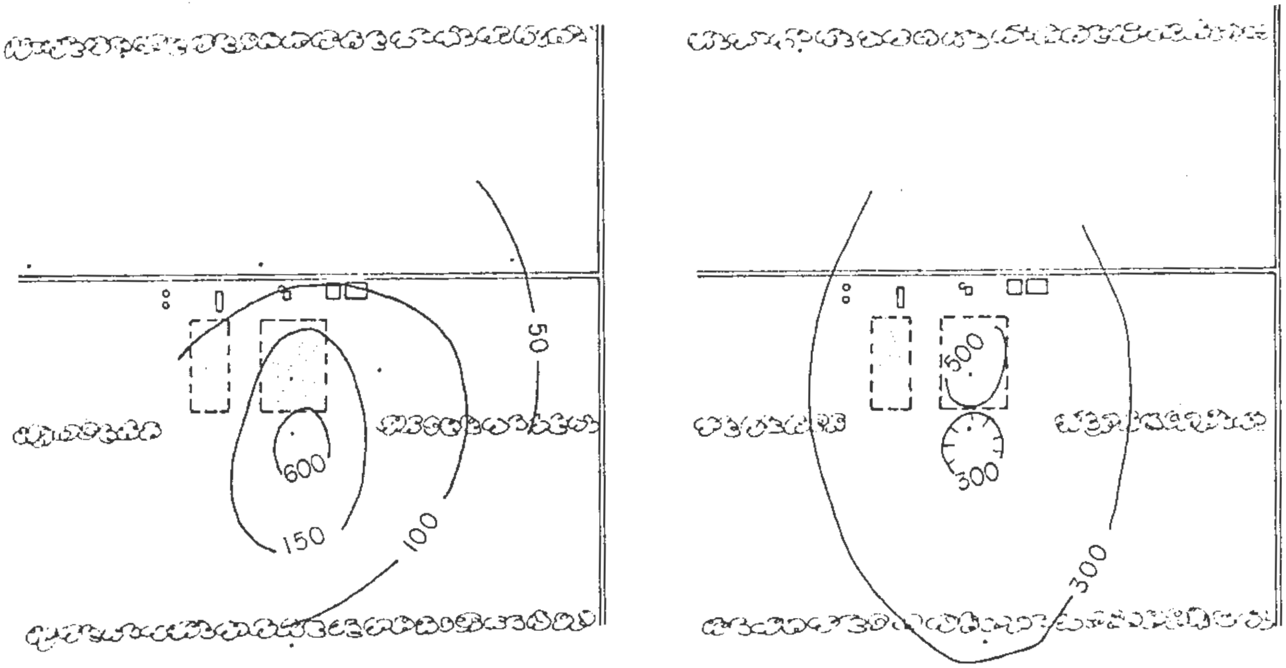
FIGURE 23 - THE ISOCONCENTRATION MAPS FOR TOTAL DISSOLVED SOLIDS IN THE FOUR INTERVALS (1 foot = .3048 m).



SCREENED FROM 25-40 FEET 0 100 FT

SCREENED FROM 45-60 FEET 0 100 FT

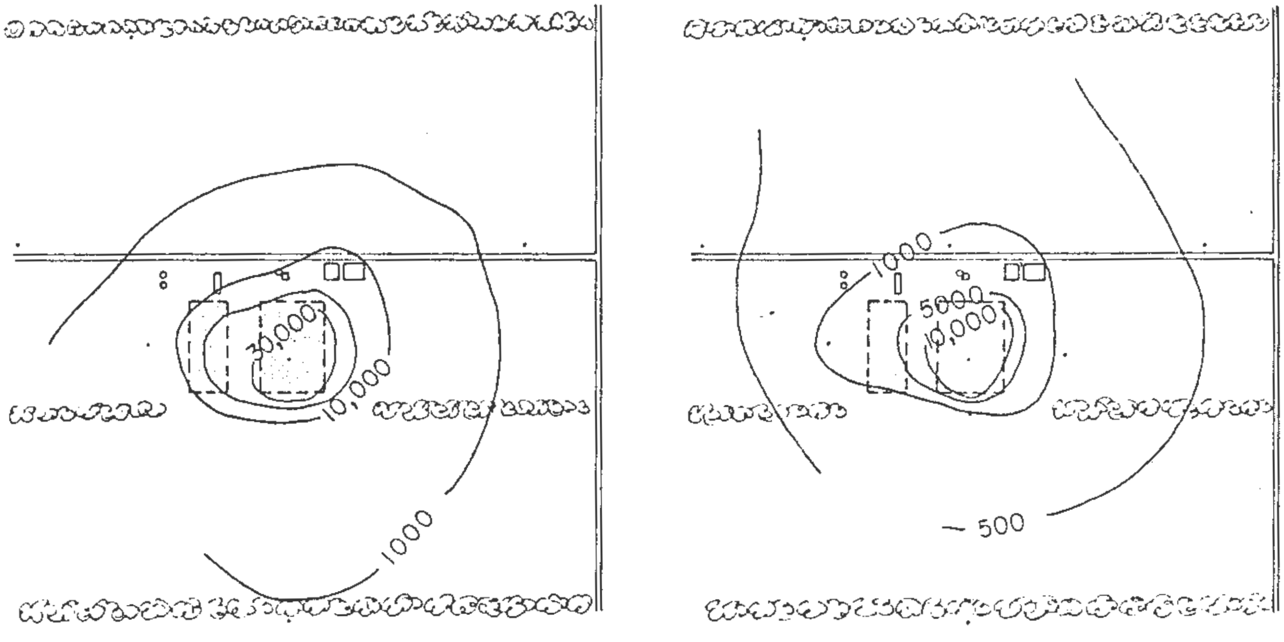
CHLORIDE (Mg/L)



SCREENED FROM 70-80 FEET 0 100 FT

SCREENED AT 160 FEET 0 100 FT

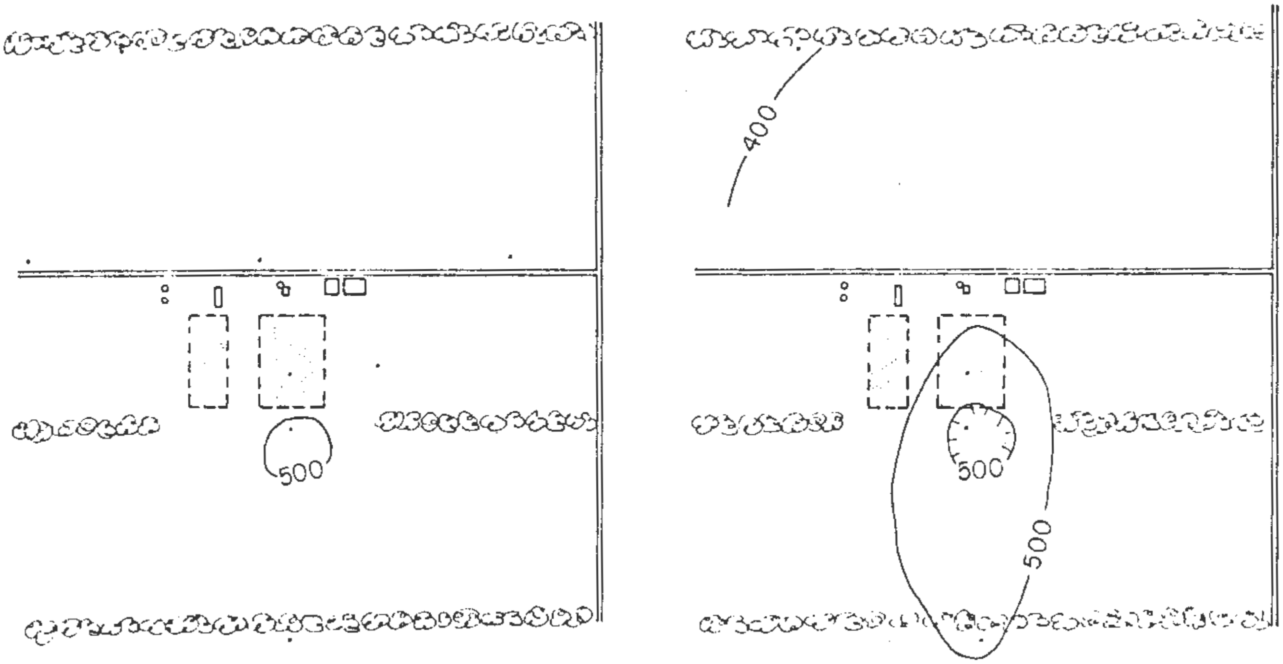
FIGURE 24 - THE ISOCONCENTRATION MAPS FOR CHLORIDE IN THE FOUR INTERVALS (1 foot = .3048 m).



SCREENED FROM 25-40 FEET 0 100 FT

SCREENED FROM 45-60 FEET 0 100 FT

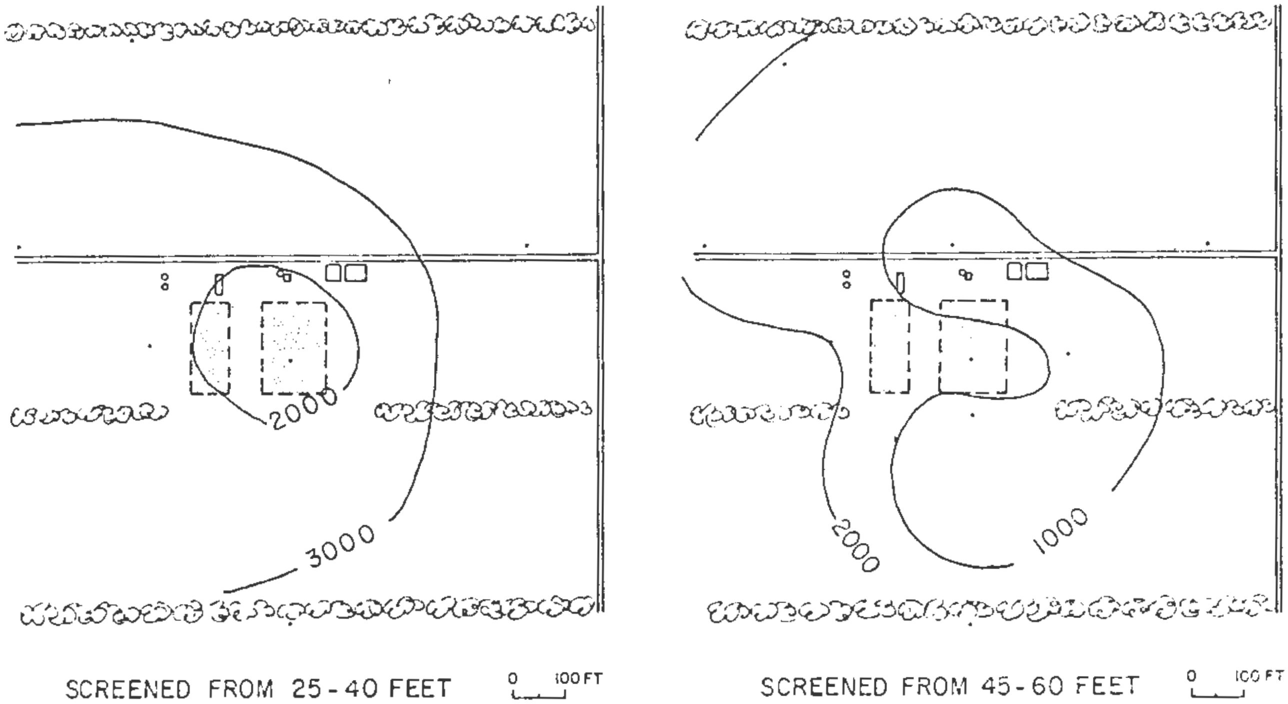
SODIUM (Mg/ L)



SCREENED FROM 70-80 FEET 0 100 FT

SCREENED AT 160 FEET 0 100 FT

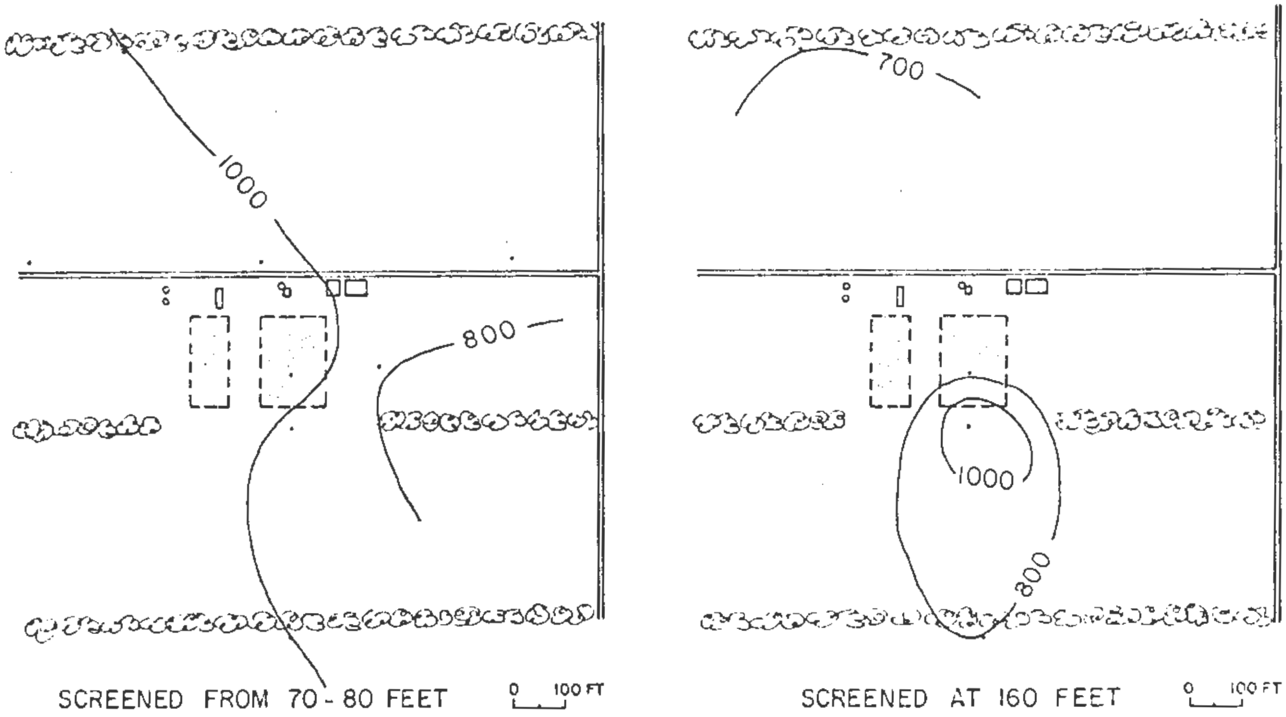
FIGURE 25 - THE ISOCONCENTRATION MAPS FOR SODIUM IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

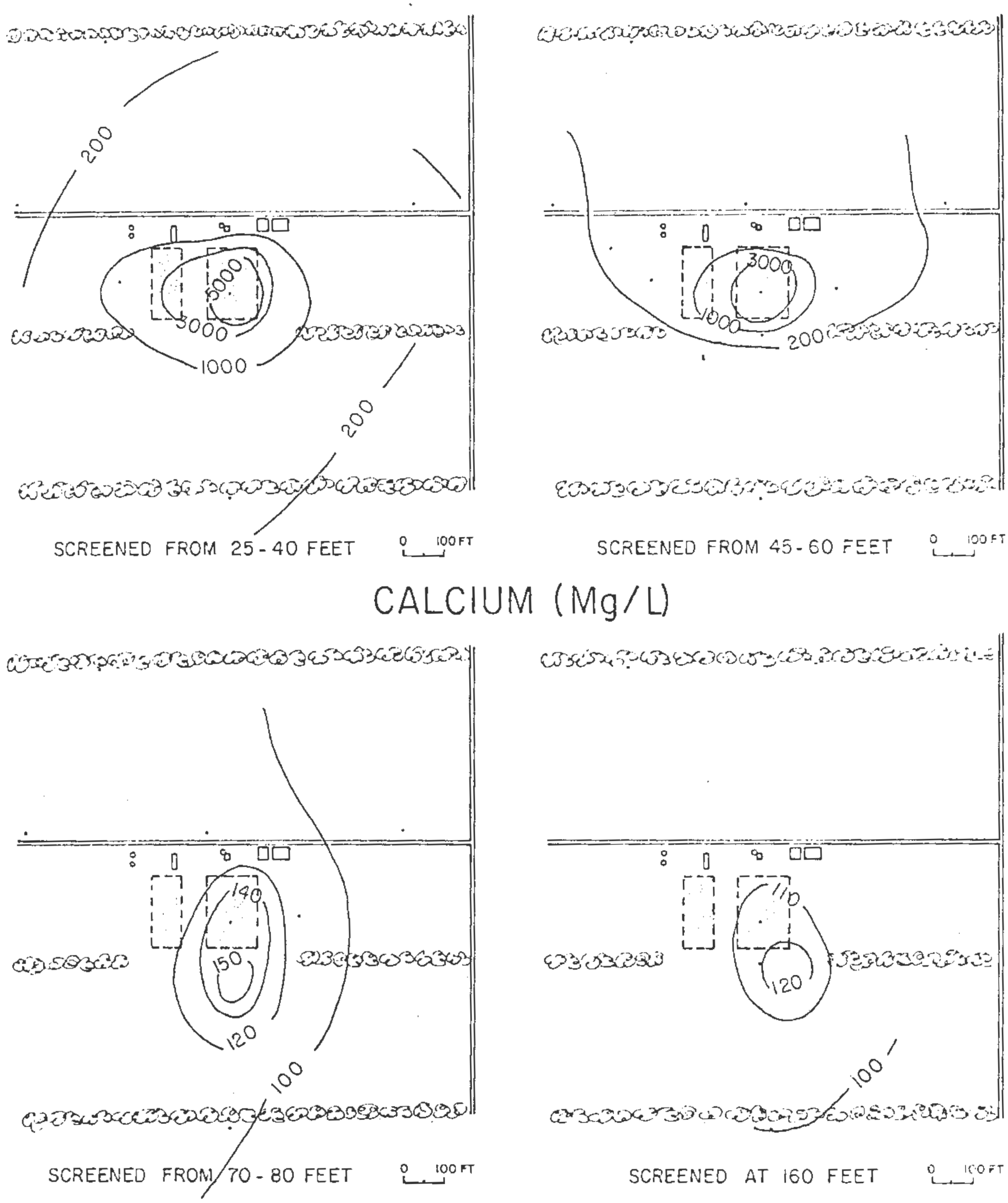
SULFATE (Mg/L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

FIGURE 26 - THE ISOCONCENTRATION MAPS FOR SULFATE IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

FIGURE 27 - THE ISOCONCENTRATION MAPS FOR CALCIUM IN THE FOUR INTERVALS (1 foot = 0.3048 m).

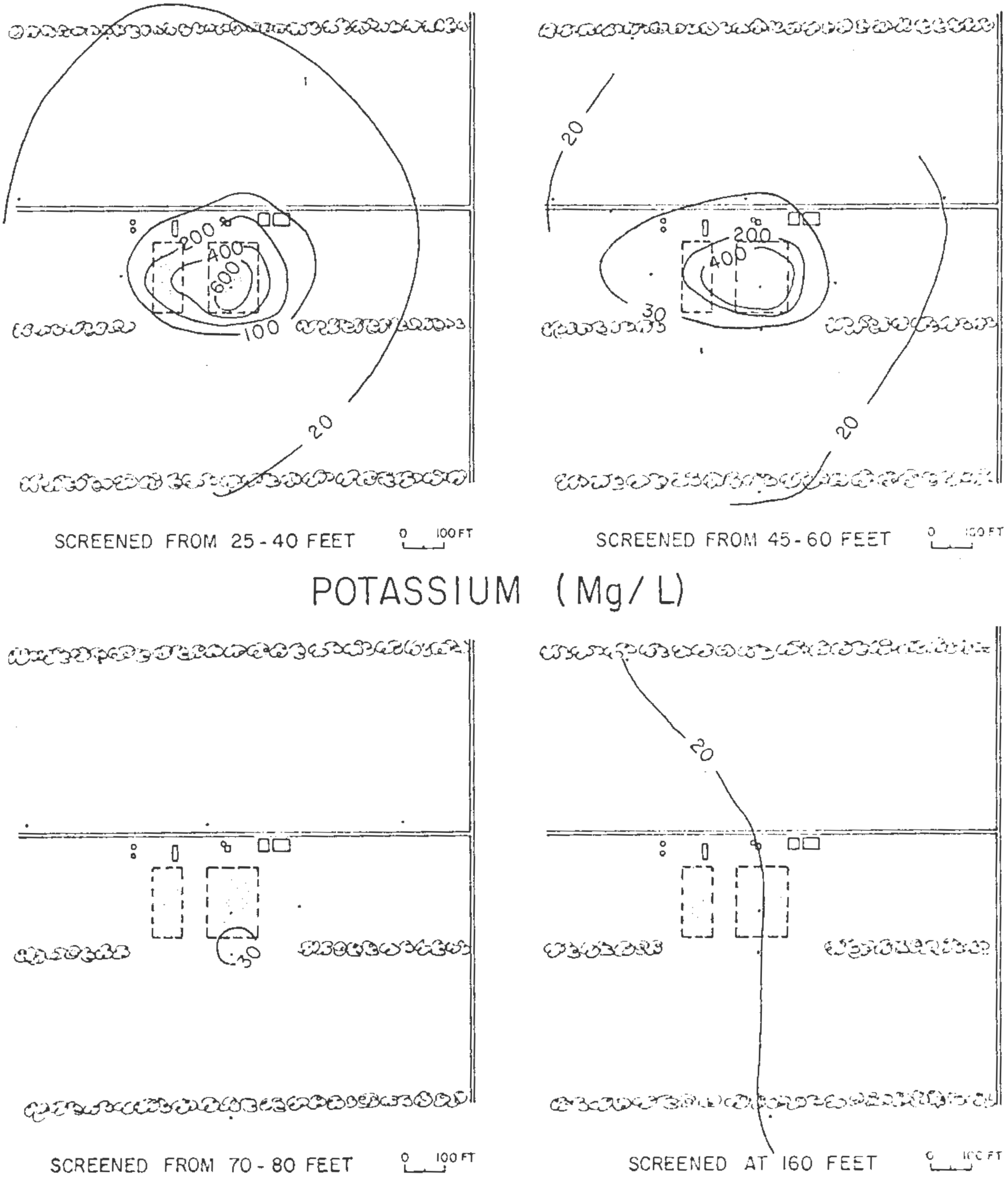
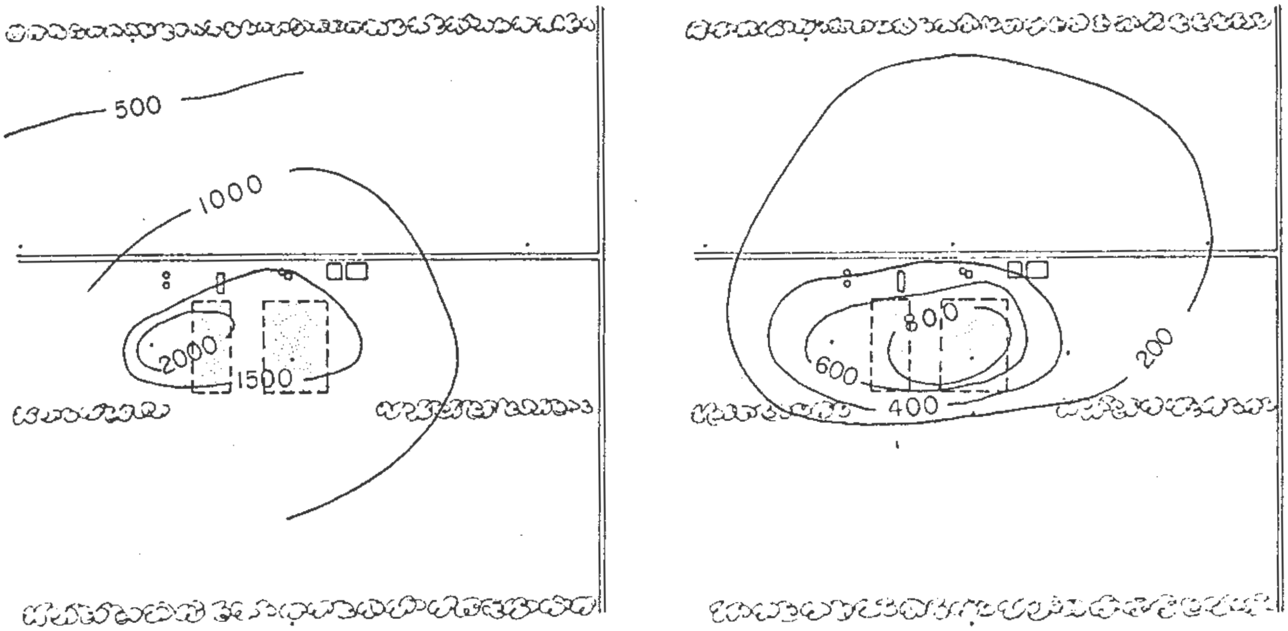


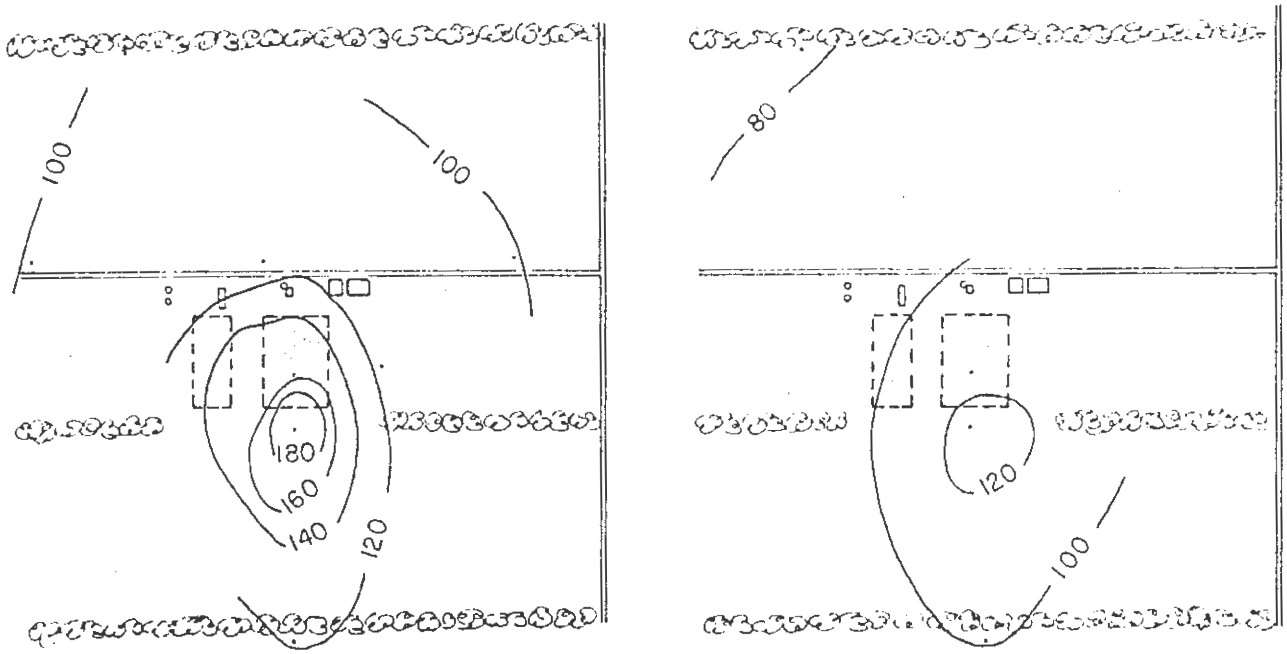
FIGURE 28 - THE ISOCONCENTRATION MAPS FOR POTASSIUM IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET 0 100 FT

SCREENED FROM 45-60 FEET 0 100 FT

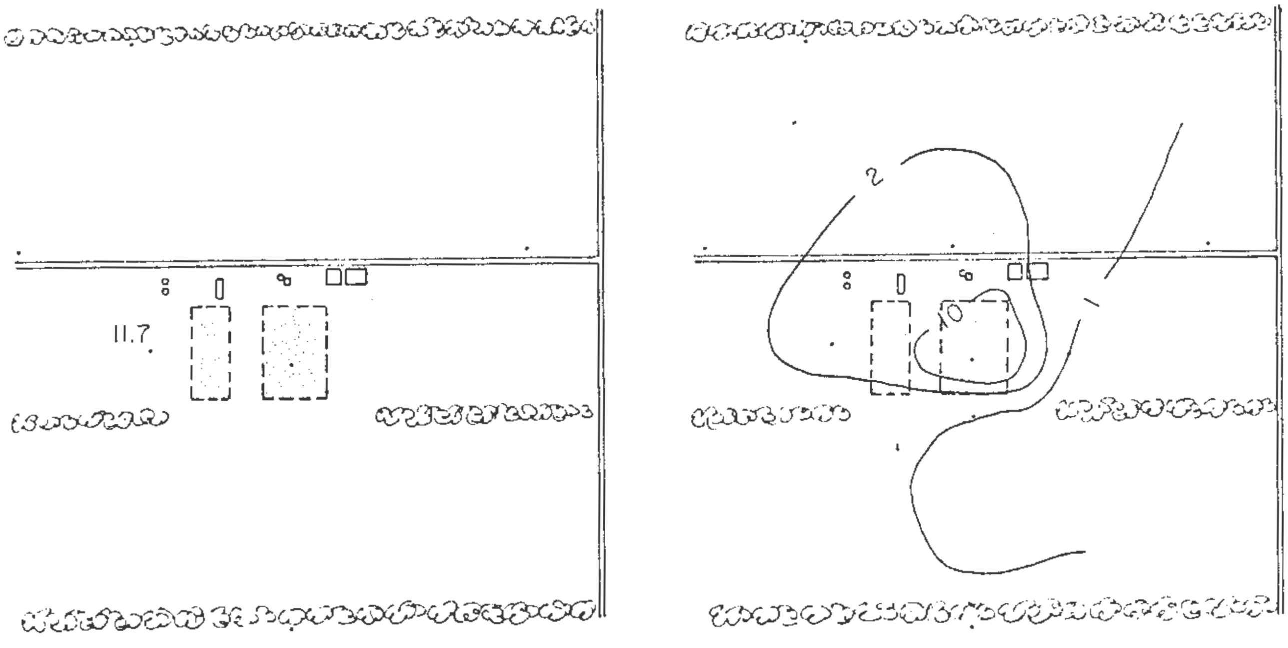
MAGNESIUM (Mg/L)



SCREENED FROM 70-80 FEET 0 100 FT

SCREENED AT 160 FEET 0 100 FT

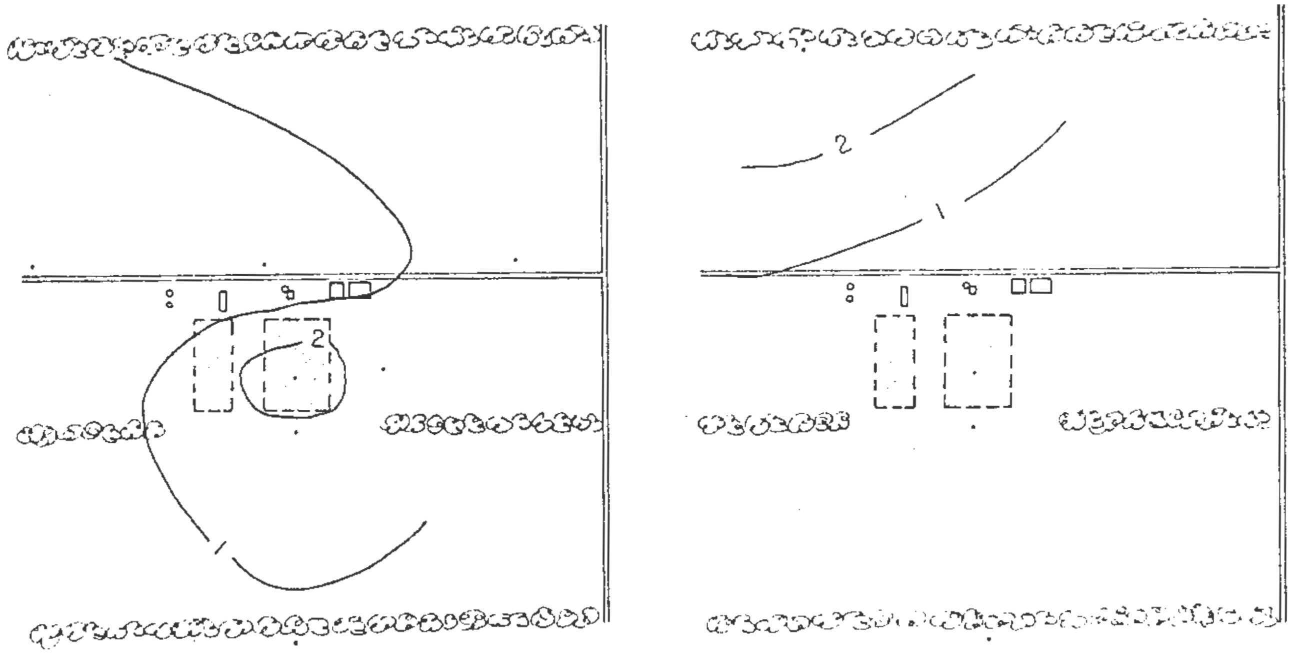
FIGURE 29 - THE ISOCONCENTRATION MAPS FOR MAGNESIUM IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

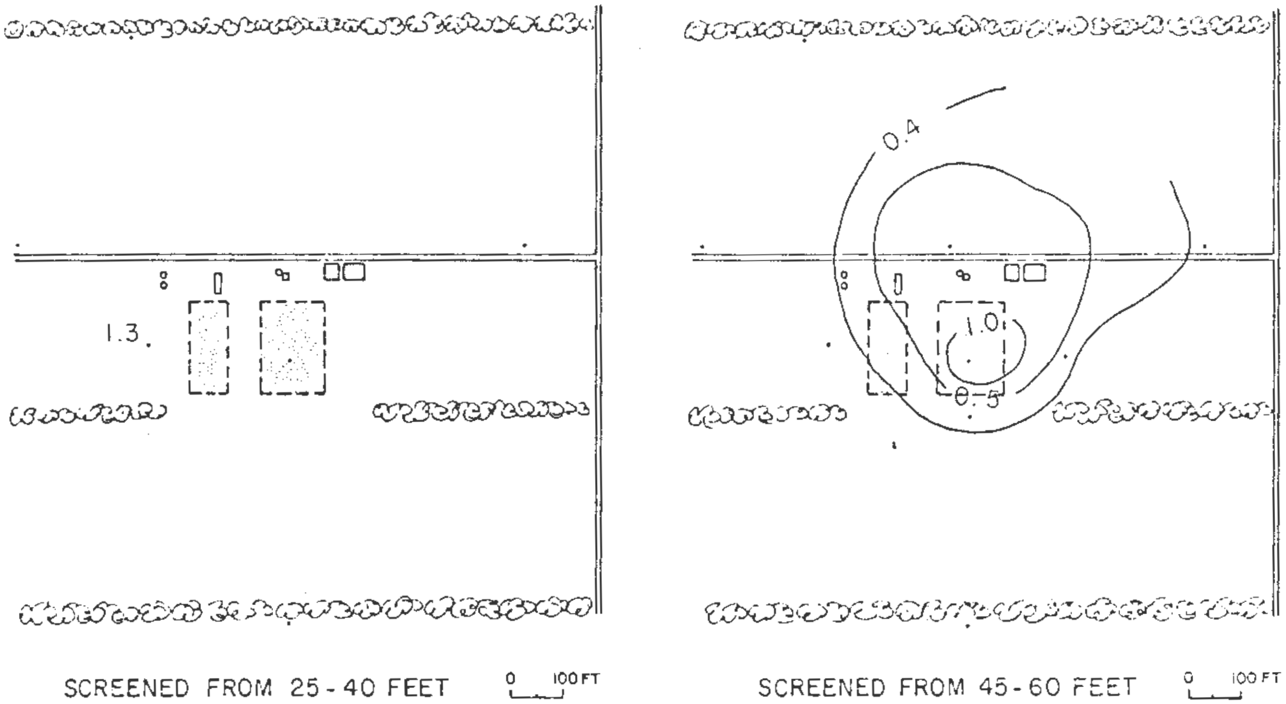
MANGANESE (Mg / L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

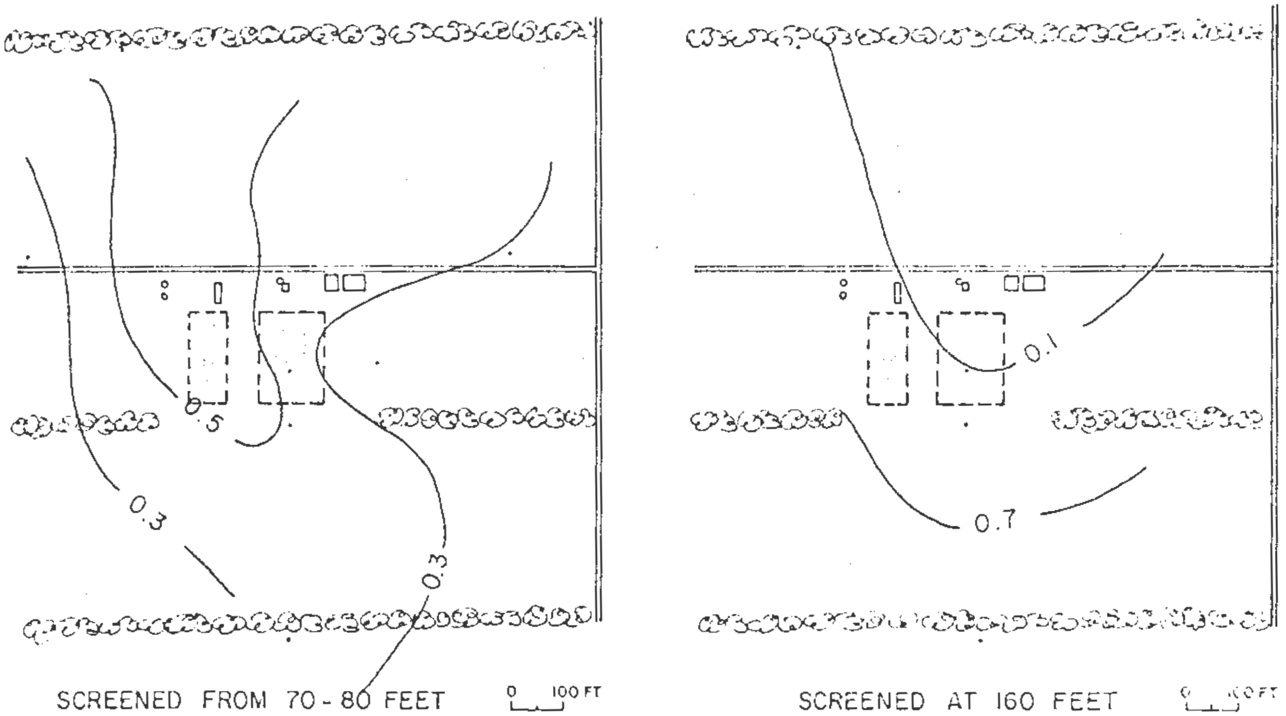
FIGURE 30 - THE ISOCONCENTRATION MAPS FOR MANGANESE IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

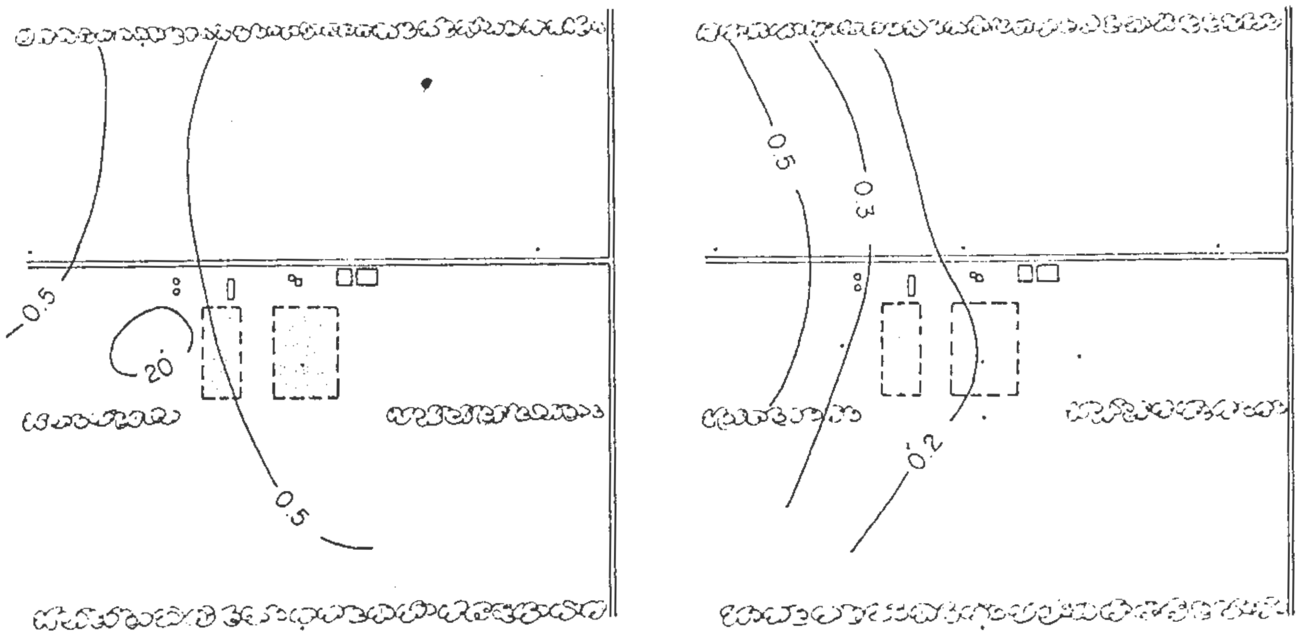
IRON (Mg/L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

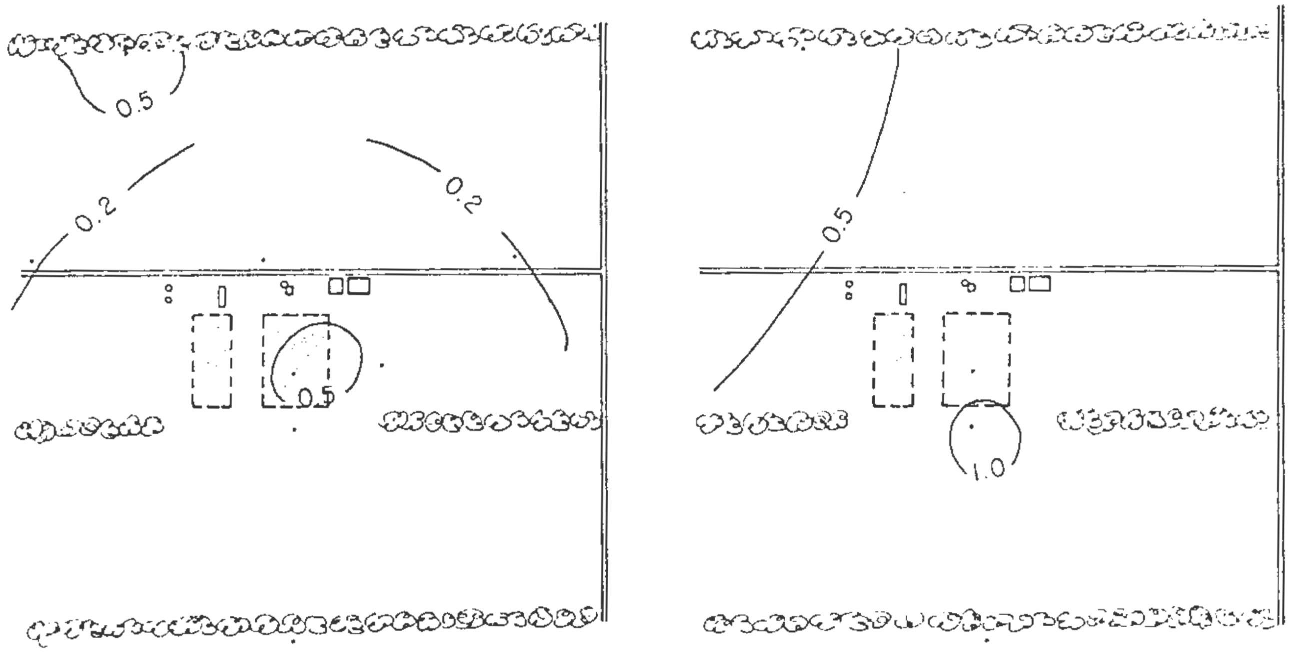
FIGURE 31 - THE ISOCONCENTRATION MAPS FOR IRON IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

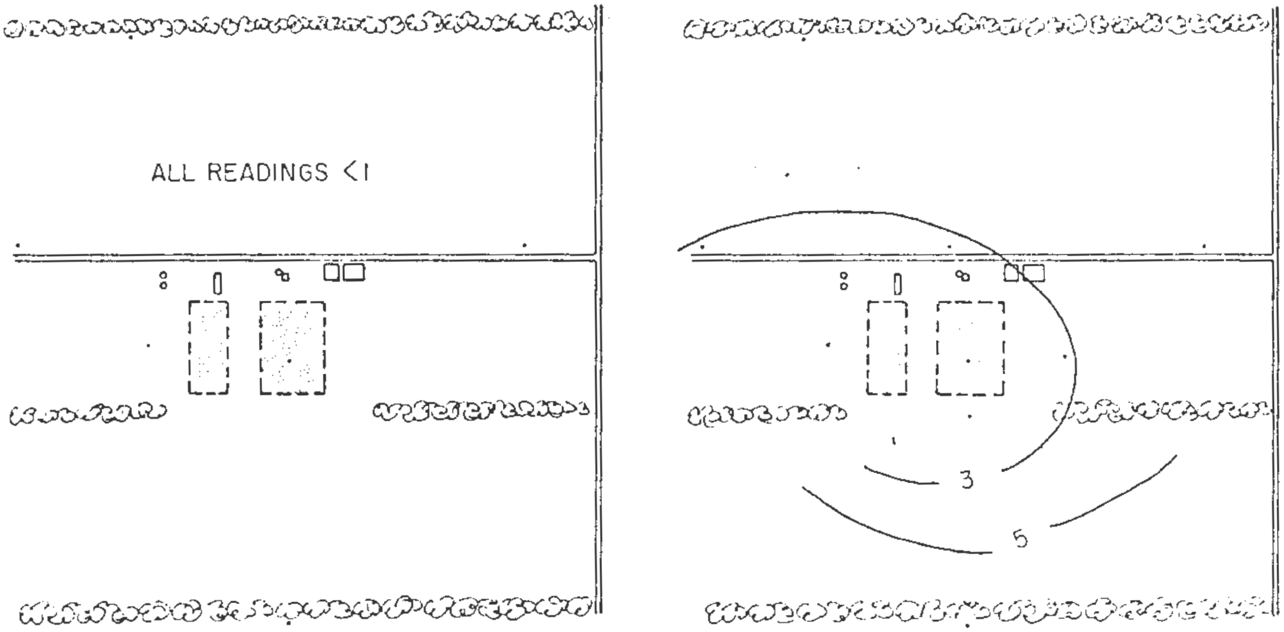
NITRATE (Mg/L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

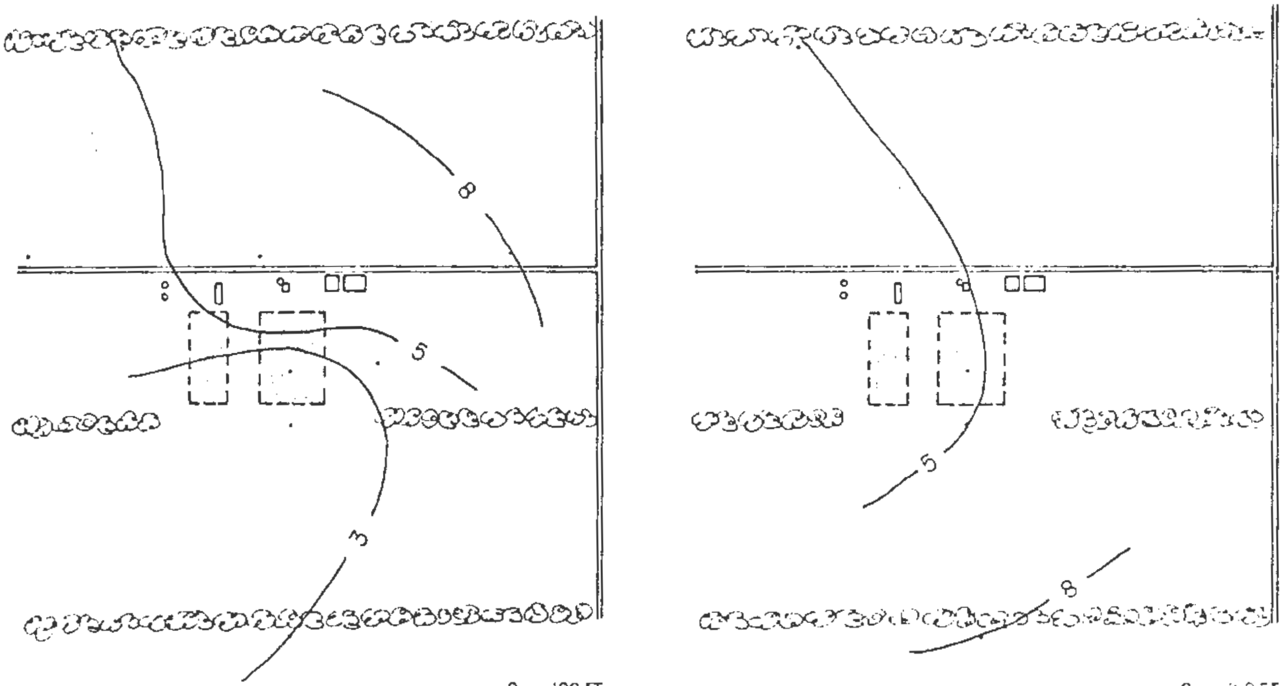
FIGURE 32 - THE ISOCONCENTRATION MAPS FOR NITRATE IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

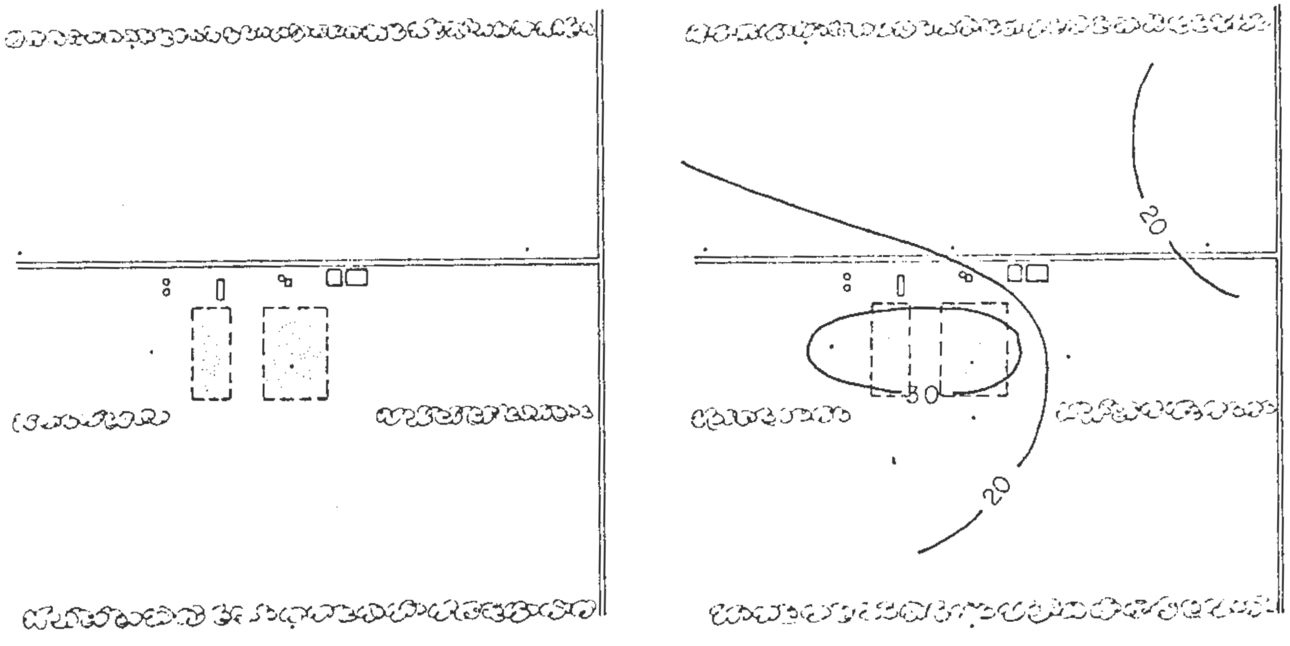
ARSENIC (µg/L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

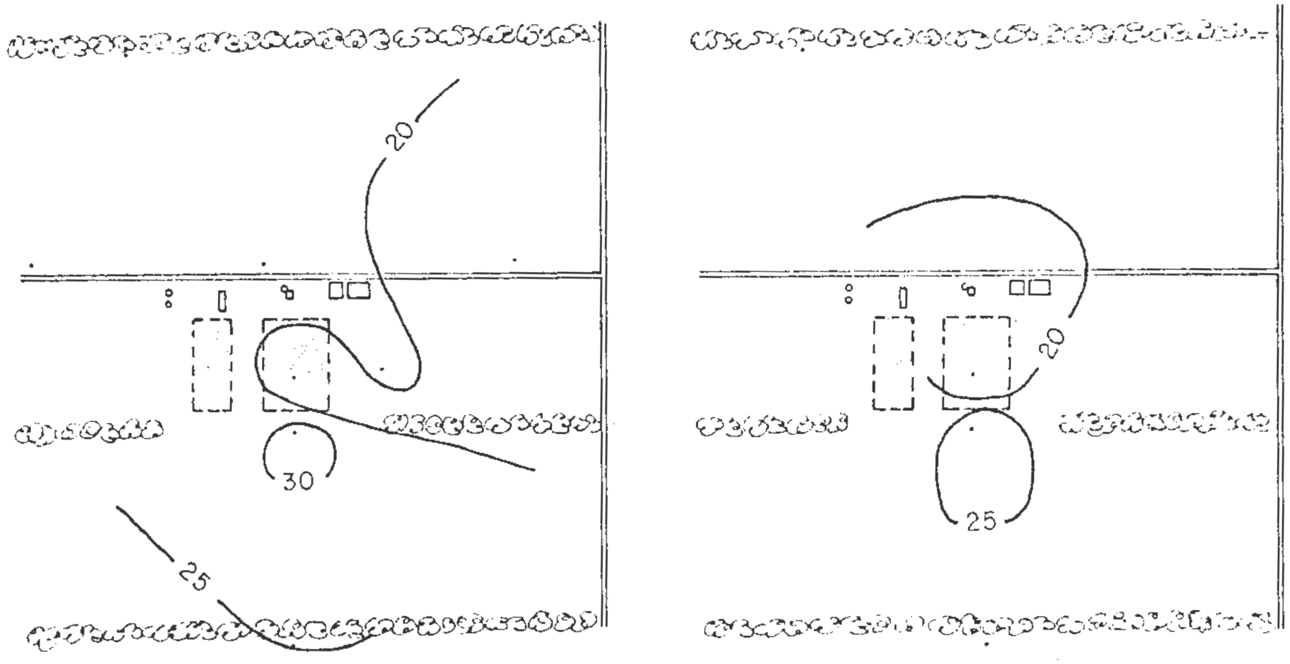
FIGURE 33 - THE ISOCONCENTRATION MAPS FOR ARSENIC IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

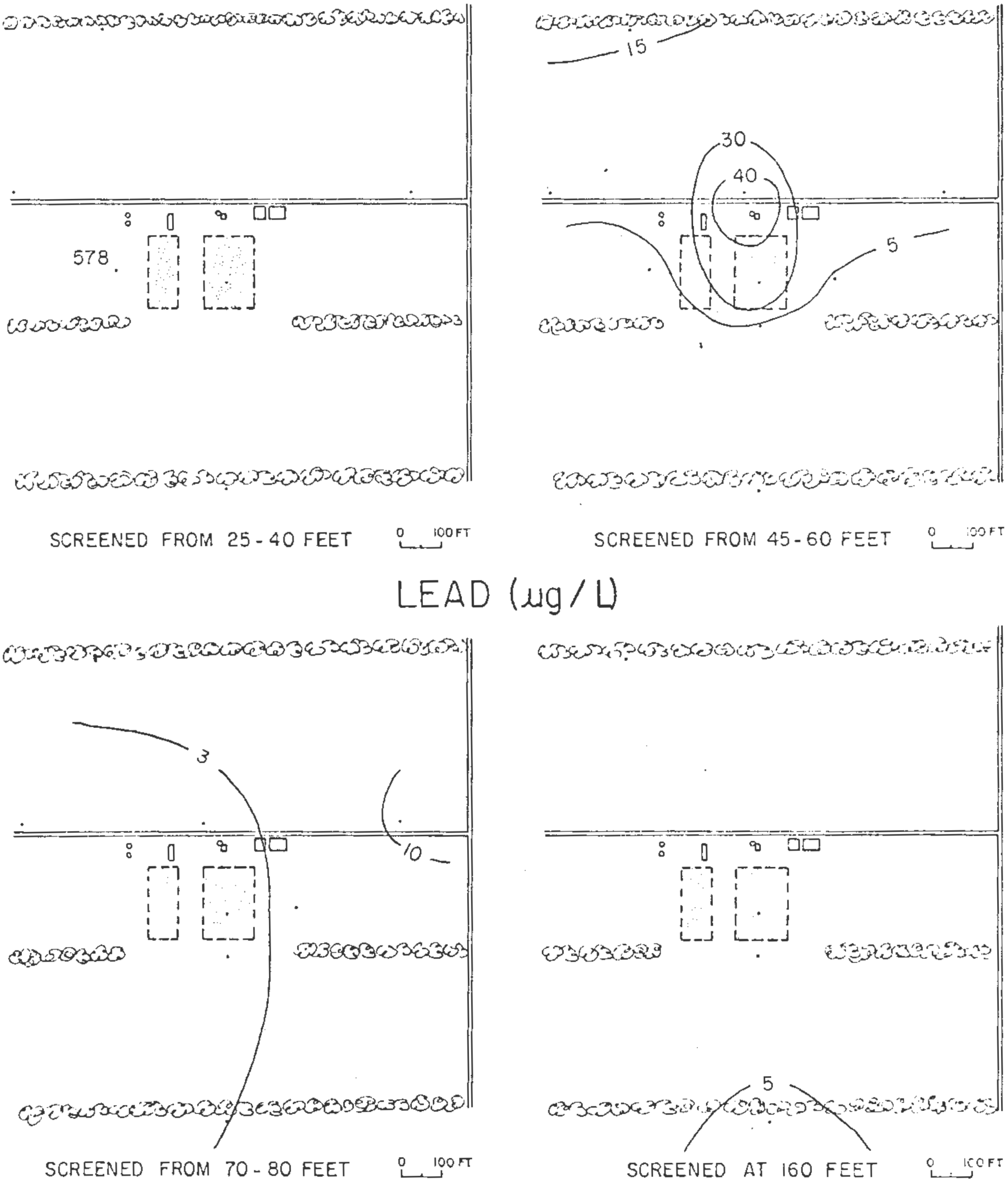
CHROMIUM (µg/L)



SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

FIGURE 34 - THE ISOCONCENTRATION MAPS FOR CHROMIUM IN THE FOUR INTERVALS (1 foot = 0.3048 m).



SCREENED FROM 25-40 FEET

SCREENED FROM 45-60 FEET

SCREENED FROM 70-80 FEET

SCREENED AT 160 FEET

FIGURE 35 - THE ISOCONCENTRATION MAPS FOR LEAD IN THE FOUR INTERVALS (1 foot = 0.3048 m).

APPENDIX 4-2J

CHEMICAL ANALYSES FROM ELUTRIATED SEDIMENT SAMPLES

mg/L

Hole #	Depth (ft.)	pH	EC	Satn %	Ca	Mg	Na	SAR	CO_3	HCO_3	Cl	SO_4
A	1	6.6	40.7	56	95.47	47.36	298.44	35		1.31	387.54	52.42
	3.5	7.4	43.2	52	29.55	8.84	402.74	92		4.15	410.85	26.13
	5	8.7	59.1	48	1.95	1.61	647.96	486	6.56	16.83	611.41	16.72
	7	7.1	63.8	49	90.38	16.30	607.36	83		2.40	741.56	0
	8	7.0	56.9	60	95.20	29.33	523.78	66		2.40	607.53	38.38
	10	6.7	77.3	59	133.93	32.41	789.10	87		1.53	984.86	0
	12	6.9	82.8	54	110.42	28.32	877.14	105		2.19	1057.71	0
	14	6.6	63.7	59	184.17	52.30	606.55	56		1.31	872.68	0
	17	7.0	73.1	57	154.13	48.07	657.64	65		1.97	844.03	13.84
	17.5	7.1	97.7	50	123.52	51.22	1347.98	144		2.19	1546.26	0
	18	7.3	22.5	51	87.10	41.54	89.72	11		0.87	198.62	18.87
	20	7.0	27.3	57	128.92	29.25	145.25	16		1.75	284.10	17.57
	25	7.2	27.4	55	80.12	35.69	204.16	27		1.53	290.41	28.03
	30	7.6	3.3	47	20.11	10.39	7.55	1.9		1.69	1.88	34.48
	32.5	7.5	3.0	50	19.59	8.96	9.07	2.4		1.69	4.71	31.22
B	5	7.1	44.1	62	74.20	17.68	489.57	72		1.97	570.62	8.86
	15	7.4	22.4	50	80.55	36.57	126.04	16		1.53	105.55	136.08
	25	7.5	3.48	46	27.43	12.14	4.53	1.0		1.71	6.19	36.20
	30	7.5	2.94	49	19.17	10.13	7.23	1.9		1.79	7.68	27.06
	32.5	7.5	2.38	53	16.66	8.43	4.16	1.2		1.81	1.10	26.34
C	5	7.8	7.63	55	22.42	74.08	36.78	5.3		2.12	1.88	129.28
	15	7.7	4.89	52	23.46	36.27	21.64	4.0		1.36	1.68	78.33
	20	7.6	4.15	52	24.51	23.44	17.45	3.6		3.24	1.49	60.67
	25	7.5	3.90	49	24.88	17.15	16.35	3.6		3.24	2.30	52.84
	30	7.6	2.33	48	7.37	5.44	12.19	4.8		1.81	2.64	20.55
	32.5	7.7	2.24	50	7.50	4.81	12.44	5.0		1.90	3.89	18.96
D	5	7.6	4.82	50	24.50	45.79	12.73	2.1		1.10	1.39	80.53
	10	7.6	3.83	51	25.35	27.17	8.14	1.6		1.27	0.72	58.67
	15	7.5	3.67	50	26.34	23.54	8.00	1.6		1.21	0.53	56.14
	25	7.7	2.45	52	9.82	8.91	9.04	3.0		1.27	0.38	26.12
	30	6.8	3.79	49	19.31	15.29	13.82	3.3		2.01	2.83	43.58
	32.5	7.1	3.52	49	18.92	12.96	12.48	3.1		1.90	0.34	42.12

Hole #	Depth (ft.)	pH	EC	Satn %	Ca	Mg	Na	SAR	CO_3	HCO_3	Cl	SO_4
E	5	7.3	9.08	57	30.21	71.69	23.93	3.4		1.80	97.47	26.56
	15	7.4	0.82	51	3.52	1.92	1.68	1.0		1.88	1.06	4.18
	20	7.3	2.78	49	19.78	10.86	5.35	1.4		1.88	2.83	31.28
	25	7.3	2.79	48	19.55	10.35	6.07	1.6		1.73	0.34	33.90
	27.5	7.4	2.80	48	19.41	10.13	6.43	1.7		1.58	0.38	34.01
I	5	7.4	4.10	94	17.21	18.62	10.71	2.5		1.17	18.19	27.18
	10	7.5	1.66	51	7.35	6.47	4.77	1.8		1.47	3.17	13.95
	15	7.4	2.87	51	20.53	10.45	5.47	1.4		1.23	0.86	34.36
	22.5	7.5	1.57	53	6.60	4.48	6.15	2.6		1.62	0.91	14.70
J	5	7.3	33.23	48	53.12	56.27	254.60	34		1.10	300.98	61.91
	10	7.6	3.82	50	12.34	11.95	7.91	2.3		1.38	27.31	3.51

APPENDIX 4-2K

TEXTURAL ANALYSES

Sample #	% Sand	% Silt	% Clay
A - 1.0'	37.3	40.1	22.6
A - 3.5'	39.5	36.5	24.0
A - 5.0'	37.3	37.4	25.3
A - 7.0'	45.1	30.3	24.6
A - 8.0'	34.6	36.1	29.3
A - 10.0'	35.1	35.7	29.2
A - 12.0'	33.1	37.7	29.0
A - 14.0'	35.1	35.3	29.6
A - 17.5'	35.5	35.4	29.1
A - 18.0'	33.7	36.3	30.0
A - 20.0'	38.7	35.4	25.9
A - 25.0'	35.8	36.9	27.3
A - 30.0'	35.3	37.0	27.7
A - 32.5'	35.4	36.4	28.2
	36.5	36.2	27.3
B - 2.5'	53.3	32.9	13.8
B - 5.0'	37.3	43.4	19.3
B - 7.5'	34.6	36.0	29.4
B - 12.5'	37.1	36.7	26.2
B - 15.0'	36.2	36.7	27.1
B - 22.5'	35.5	37.5	27.0
B - 25	35.4	37.5	27.1
B - 27.5'	35.0	35.8	29.2
B - 30.0'	35.4	37.7	26.9
B - 32.5'	34.1	37.2	28.1
C - 2.5'	24.9	50.5	24.6
C - 5.0'	32.2	39.3	28.5
C - 7.5'	37.4	38.8	23.8
C - 12.5'	37.6	36.0	26.4
C - 15.0'	37.2	36.7	26.1
C - 20.0'	36.4	36.7	26.9
C - 25.0'	36.7	36.3	27.0
C - 27.5'	35.9	35.8	28.3
C - 30.0'	34.7	39.1	26.2
C - 32.5'	35.5	36.4	28.1
D - 2.5'	39.0	35.4	25.6
D - 5.0'	36.7	36.2	27.1
D - 7.5'	37.8	34.1	28.1
D - 10.0'	36.3	35.8	27.9
D - 15.0'	36.2	35.7	28.1
D - 22.5'	38.3	33.7	28.0
D - 25'	35.5	37.0	27.5
D - 27.5'	34.3	38.6	27.1
D - 30.0'	35.4	37.7	26.9
D - 32.5'	34.5	38.4	27.1

Sample #	% Sand	% Silt	% Clay
E - 2.5'	5.2	58.0	36.8
E - 5.0'	35.5	34.2	30.3
E - 12.5'	36.5	34.3	29.2
E - 15.0'	36.4	34.6	29.0
E - 20.0'	35.5	35.3	29.2
E - 22.5'	35.3	36.5	28.2
E - 25.0'	34.2	36.2	29.6
E - 27.5	34.1	37.3	28.6
I - 2.5'	64.0	27.2	8.8
I - 5.0'	3.2	72.2	24.6
I - 7.5'	31.7	34.6	33.7
I - 10.0'	35.0	35.9	29.1
I - 12.5'	35.6	37.5	26.9
I - 15.0'	35.0	36.4	28.6
I - 20.0'	37.4	35.3	27.3
I - 22.5'	35.1	36.7	28.2
J - 1'	38.2	39.9	21.9
J - 2.5'	31.3	55.6	13.1
J - 5'	36.2	38.0	25.8
J - 7.5'	40.2	38.4	21.4
J - 10.0'	34.8	37.2	28.0
J - 12.5	35.1	36.7	28.2

APPENDIX 4-2L

CONSTRUCTION ESTIMATES FOR INFILTRATION GALLERY

OCTOBER 9, 1985

Trench	
2100'long 12' deep	45.00/hr. or 2.00/ft. = 4,200.00
Gravel	
2000/yd^3	
A) 3/4 crushed rock yd ≈ 3,000 lbs.	17.00/ton
B) gravel 8-10.00 yd^3	
	20,000.00
Drain Tile	0.30¢/foot
2-3' wide 2100' long Heavy Duty - Plastic	= \$630.00
Sump Pump	
1) 100 gpm submersible pump	1,200.00
Holding Tank (Fiberglass)	500.00

A local area contractor estimated the entire project at:
estimating \$10.00/foot ≈ \$21,000