1983

The effect of oil-and-gas well drilling fluids on shallow groundwater in western North Dakota

Edward C. Murphy
University of North Dakota

THE EFFECT OF OIL-AND-GAS WELL DRILLING FLUIDS ON SHALLOW GROUNDWATER IN WESTERN NORTH DAKOTA

by
Edward C. Murphy

Bachelor of Science in Geology,
University of North Dakota, 1979

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May
1983

This thesis submitted by Edward C. Murphy in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

Permission

Title The Effect of Oil-and-Gas Well Drilling Fluids on Shallow Groundwater in Western North Dakota

Department Geology

Degree Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairman of the Department or the Dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature Edward C. Murphy

Date April 11, 1983

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

Figure

Figure

Figure

Figure

Figure

LIST OF TABLES

Table

Table

ACKNOWLEDGEMENTS

I would like to express sincere appreciation to my advisory committee chairman, Dr. Alan E. Kehew, for his assistance in the field and his guidance throughout this project. I would like to also thank committee members Dr. Gerald H. Groenewold and Dr. Don L. Halvorson for their constructive criticisms and professional advice.

The staff of the North Dakota State Department of Health Environmental Laboratory is gratefully acknowledged for their assistance in this project. Special thanks are conveyed to Francis J. Schwindt, Rod Reetz, and Ken Kary.

Appreciation is extended to the members of the North Dakota Geological Survey for their help and support. A special thanks to David O. Lechner for his assistance in the earth resistivity survey. I am especially indebted to Mark Stadum, Daniel Pyle, and Bret Fossum (summer NDGS employees) for their assistance in instrumenting the sites and cheerfully working 12 to 16 hour days, while only being paid for 8.

Special gratitude is expressed to Norman Winter and family (Squaw Gap, Billings County) for their kindness and hospitality.

My greatest debt of gratitude is to my mother and father, Edward and Imogene, for their moral support and understanding.

I would like to also thank Mrs. Marlys Kennedy for her professional typing of this manuscript.

DEDICATED TO:

my father

Edward Paul Murphy

ABSTRACT

Upon completion of an oil-and-gas well in North Dakota the drilling fluid is buried in the reserve pit at the site. Reclamation of the drill site is expedited by digging a series of trenches which radiate out from the reserve pit. The majority of buried drilling fluid is ultimately contained within these 5-7 metre deep trenches. These fluids are commonly salt-based, i.e. they contain a concentration of 300,000±20,000 ppm NaCl. In addition, these drilling fluids also contain additives including toxic trace-metal compounds.

Four reclaimed oil-and-gas well sites were chosen for study in western North Dakota. The ages of these sites ranged from 2 to 23 years. These sites were chosen in an effort to encompass as many as possible of the geologic and geohydrologic variables that exist in this area. A total of 31 piezometers and 22 soil water samplers were installed in and around the drill sites and quarterly groundwater samples were obtained from these instruments. The local groundwater flow conditions were also determined at these sites.

Results of both the water analyses and earth resistivity surveys indicate that leachate is being generated at all of the study sites. Water obtained from the unsaturated zone beneath the buried drilling fluid at all of the four study sites exceeds some of the Recommended and Maximum Permissible Concentration Limits for trace elements and major ions (As, Cl^-, Pb, Se and NO_3^-). These values are greatly reduced in the unsaturated zone as the depth from

the buried drilling fluid increases. This reduction is assumed to be the result of attenuation of these ions by cation exchange on Na montmorillonitic clays.

Two of these study sites represent the typical geohydrologic setting for the majority of oil-and-gas well sites in this area. At these sites the saturated zone was not monitored. The reduction in ion concentration in the unsaturated zone suggests that there would be very little impact on the groundwater from this buried drilling fluid at these two sites.

The two other study sites were situated in geohydrologic settings that offered a great potential for leachate migration in the saturated zone. The chloride ion was chosen as an indicator of maximum leachate migration because of its high mobility and lack of attenuation other than by dispersion. The chloride concentrations returned to background levels within the saturated zone 60 to 90 metres downgradient of the buried drilling fluid at these two sites.

The consumption of shallow groundwater beneath one of the study sites constitutes a danger to human health. The Maximum Permissible Concentration Limits for Cd, Pb, and Se were exceeded in the shallow groundwater beneath the buried drilling fluid at this site. These limits were exceeded in an area approximately 60 by 110 m. The concentration level of NO_3^- ranged from 1310 to 12.2 mg/l (as N) throughout the groundwater at this study site. It is not known conclusively whether the buried drilling fluid at this site is the source of the NO_3^- contamination.

INTRODUCTION

History of Oil-and-Gas Drilling.--The first commercial oil well in the United States was drilled under the supervision of Colonel E. L. Drake and completed on August 28, 1859 in Titusville, Pennsylvania. However, the history of well drilling greatly precedes this event and can be traced as far back as China in 600 B.C. (Brantly, 1971). These early wells were drilled using a percussion method and it was not until the late 1880s that the present day method of rotary drilling began to develop (Chilingarian and Vorabutr, 1981).

As the drilling industry grew and advanced in technology, so also did its associated industries. An incident early in this developmental period gave rise to the drilling fluids industry. In October of 1900, Capt. Anthony F. Lucas and the Hamill Brothers were drilling the famous Spindletop well near Gladys, Texas. The drilling fluid at this location consisted of fresh water which was stored in a clay-lined pit adjacent to the well. Upon encountering a "caving sand" interval in the bore hole the drilling crew ran nearby cattle back and forth through the pit to produce a muddy fluid which enabled them to continue drilling and to complete the well (Chilingarian and Vorabutr, 1981). Drilling fluids remained virtually unchanged up until 1921 when the first attempt was made to control mud properties with the use of chemical additives (Rogers, 1953).

The drilling fluid industry has changed dramatically since those humble beginnings in east Texas. More than 700 U.S. patents were issued for drilling fluids between 1930-1979. Approximately 45 different chemical compounds are represented by over 500 trade name products. Out of these compounds only a dozen or so are used at a typical well site (Ranney, 1979).

The advent of deeper drilling within the last twenty to thirty years has necessitated the development of chemical drilling-fluid additives which enable the drilling fluid to perform its primary functions under higher temperatures and pressures. These primary functions are to lift formation cuttings to the surface, control subsurface pressures, lubricate the drill string, cool the drill bit, protect the formation productivity, and to provide an aid for formation evaluation (Moore, 1974). Drilling fluid additives can be grouped into a number of general categories according to purpose (table 1). Because of the great variability in chemical composition of drilling muds, the toxicity levels to both plant and animal varies widely between categories. This will be further discussed later in this report.

There are three types of oil-and-gas drilling fluid bases: fresh water, salt water, and oil. In North Dakota, salt-water based drilling muds are almost always used. The concentration of salt (NaCl) in these drilling fluids is commonly 300,000 ± 20,000 mg/1 (American Petroleum Institute, 1969). In comparison the average salinity of seawater is typically 35,000 mg/1 (Pearse and Gunther,

Table 1. Function and general purpose of drilling fluid additives (from Wright, 1978 and Collins, 1975).

Function	General Purpose	Common Additives
Weighting Material	Control formation pressure, check caving, fascilitate pulling dry pipe, & well completion operations	Barite, lead compounds, iron oxides
Viscosifier	Viscosity builders for fluids, for a high viscosity-solids relationship	Bentonite, attapulgite clays, all colloids, fiborous asbestos
Thinner Dispersant	Modify relationship between the viscosity and percentage of solids, vary gel strength, deflocculant	Tannins (quebracho), polyphosphates, lignitic materials
Filtrate Reducer	Cut the loss of the drilling fluid's liquid phase into the formation	Bentonite clays, sodium carboxymethyl cellulose (CMC), pregelatinized starch, various lignosulfonates
Lost Circulation Material	Primary function is to plug the zone of loss	Walnut shells, shredded cellophane flakes, thixotropic cement, shredded cane fiber, pig hair, chicken feathers etc.
Alkalinity, pH Control	Control the degree of acidity or alkalinity of a fluid	Lime, caustic soda, bicarbonate of soda
Emulsifier	Create a heterogeneous mixture of two liquids	lignosulfonates, mud detergent, petroleum sulfonate
Surfactant	Used to the degree of emulsification, aggregation, dispersion, interfacial tension, foaming, and defoaming (surface active agent)	Include additives used under emulsifier foamers, defoamers, & flocculators
Corrosion Inhibitor	Materials attempt to decrease the presence of such corrosive compounds as oxygen, carbon dioxide, and hydrogen sulfide	Cooper carbonate, sodium chromate, chromate-zinc solutions, chrome lignosulfonates, organic acids and amine polymers, sodium arsenite
Defoamer	Reduce foaming action especially in salt water based muds	Long chain alcohols, silicones, sulfonated oils
Foamer	Surfactants which foam in the presence of water and thus permit air or gas drilling in formations producing water	Organic sodium & sulfonates, alkyl benzene sulfonates
Flocculants	Used commonly for increases in gel strength	Salt, hydrated lime, gyosum, sodium tetraphosohates
Bactericides	Reduce bacteria count	Starch preservative, paraformaldehyde, caustic soda, lime, sodium pentachloraphenate
Lubricants	Reduce torque and increase horsepower at the bit by reducing the coefficient of friction	Graphite powder, soaps, certain oils
Calcium Remover	Prevent and overcome the contamination effects of anhydrite and gypsum	Caustic soda (NaOH), soda ash, bicarbonate of soda, barium carbonate
Shale Control Inhibitors	Used to control caving by swelling or hydrous disentegration	Gypsum, sodium silicate, calcium lignosulfonates, lime, salt

1957). The brines that are used to make up these salt-based muds are most commonly produced waters, i.e. they are produced along with the oil-and-gas at the well site. The concentration of many major ions in these "make up" waters is very high in comparison to their concentrations in shallow groundwater in western North Dakota. Therefore, in addition to the drilling fluid additives, these waters contain ions that have the potential to degrade the soil and shallow groundwater system.

Oil-and-Gas Drilling in North Dakota.—The completion of the Clarence Iverson #1 by Amerada in 1951 marked the beginning of oil production in North Dakota (fig. 1). To date, an estimated 9000 oil-and-gas wells have been drilled within the state.

Prior to drilling, a pit is excavated adjacent to the drill hole that serves to contain the drilling fluid as it is being circulated in and out of the bore hole. Mud or reserve pits in North Dakota are at present commonly constructed on the order of 150 feet in length, 60 feet in width, and 10 feet in depth (46m x 18m x 3m). The volume of drilling fluid maintained in each pit during drilling usually ranges from 54,000 to 90,000 cubic feet ((1530 to 2549 m^3) (400,000-675,000 gallons)). It can therefore be estimated that approximately 360 million cubic feet of drilling fluid have been buried in shallow pits in North Dakota.

Prior to the setting of surface casing, the drilling fluid is commonly a mixture of bentonite and fresh water, i.e. is devoid of most chemical additives. Just before setting the surface

Figure 1. The Amerada Clarence Iverson No. 1. The discovery well in North Dakota (photo by Mr. Bill Shemorry).

casing, the drilling fluid is "mudded up" and circulated in a closed system that no longer includes the reserve pit.

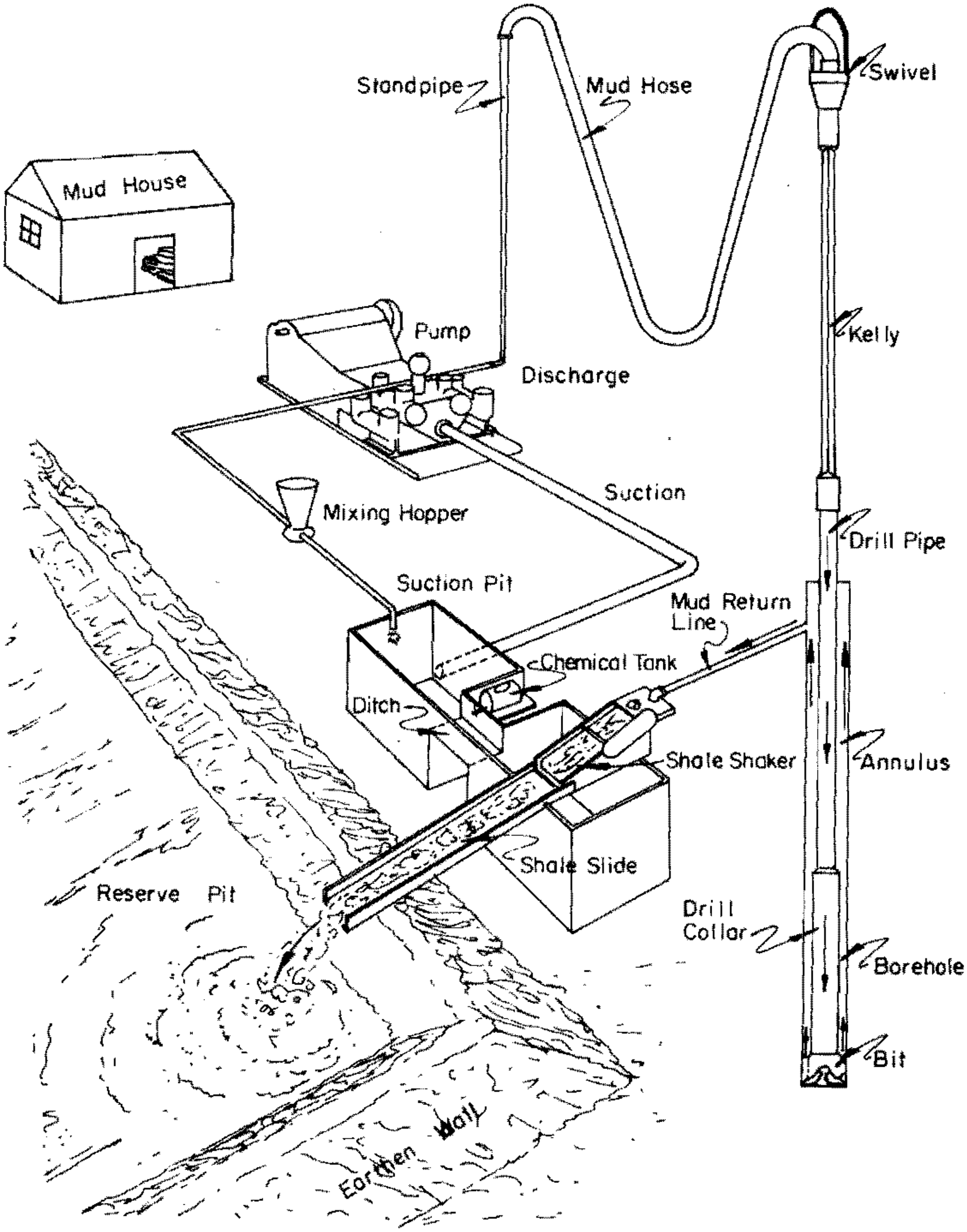
As the drilling fluid is circulated out of the bore hole, the suspended sediment cuttings are separated at the shale shaker and funneled into the reserve pit. The drilling fluid is then directed through a series of settling tanks designed to remove the remaining cuttings before being pumped back downhole (fig. 2). Although drilling fluid is no longer circulated into the pit, the fluid coating the cuttings at the shake shaker, along with that flushed out during periodic cleaning of the settling tanks, is deposited in the reserve pit.

Prior to 1974, reserve pits which had been excavated into permeable material (i.e., sand, gravel, and lignite) were often lined with bentonite clay to prevent loss of fluids during drilling. In recent years plastic liners have commonly replaced clay liners for seepage control (fig. 3).

At present the Oil-and-Gas Regulatory Division of the Industrial Commission of North Dakota has the authority to require that an operator install a plastic liner in reserve pits where it deems the surrounding sediment too permeable and would allow an excessive amount of liquid into the subsurface. This regulatory authority is provided by the General Rules and Regulations for the Conservation of Crude Oil and Natural Gas. The U.S. Forest Service has the same authority on federally-owned lands.

Reserve Pit Reclamation.--Shortly after completion of an oil-and-gas well in North Dakota, normally within a one-month period,

Figure 2. Closed-system circulation of drilling fluid.



Standpipe
Mud Hose
Swivel
Mud House
Pump
Kelly
Discharge
Suction
Mixing Hopper
Drill Pipe
Suction Pit
Mud Return Line
Chemical Tank
Ditch
Shale Shaker
Annulus
Shale Slide
Reserve Pit
Drill Collar
Borehole
Bit
Earthen Wall

Figure 3. A polyethylene lined reserve pit in western North Dakota. The depth of the pit is approximately 10 feet (3m).

Figure 4. Reclamation of a reserve pit by trenching in Billings County, North Dakota. The trenches are filled with drilling fluid from the pit in the background.

the reserve pit is reclaimed. Disposal procedures commonly consist of hauling away the less viscous portion of the drilling fluid for disposal in another reserve pit or injection well, or by spreading on roads to control dust. A series of trenches is excavated radiating outward from one side of the pit (fig. 4). Sediment is then pushed back into the pit from the opposite side thereby forcing the drilling fluid into these trenches (figs. 5 and 6). Finally, the pit and trenches are backfilled and leveled. In the 50s and 60s the pit was commonly reclaimed by pushing sediment in from all sides and the trenching method was uncommon. This earlier method required one month to a year to complete (Haugen, 1980). In comparison, a trenched pit can usually be reclaimed in a day or two. The trenching method of reclamation is intended to minimize the effects of drilling fluid on surface features (i.e. surface waters, soil, vegetation, and animals). However, in doing so the potential for degradation of the shallow groundwater is often greatly increased.

Drilling Fluid Chemistry.--In any study determining the effects of waste disposal on the shallow groundwater system, it is extremely important to know as precisely as possible the chemistry of the waste. This is essential to anticipate the chemical makeup of the leachate that will be generated.

There are a number of problems associated with obtaining the drilling fluid chemistry for a given drill site. The records of drilling activity and drilling fluid additives are often no longer available for sites that are twenty or thirty years old. Even

Figure 5. Reclamation of the reserve pit at the Apache Corp. Federal #1-5 re-entry. Sediment is being pushed into the pit and forcing the drilling fluid into the trenches. Photo is taken looking north.

Figure 6. Reclamation of the reserve pit at the Apache Corp. Federal #1-5 re-entry. Drilling fluid is filling the 21-foot (6.4m) deep trenches. Photo taken looking east.

when these records are available it is extremely difficult to determine the chemical composition of these drilling fluid additives. The drilling fluid industry is very competitive and the exact chemical composition of the product name additives is very difficult to obtain.

During the drilling of an oil well, a mud engineer monitors and records the concentrations of certain selected chemical parameters in the drilling fluid (commonly NaCl, NO_3^- and CrO_4^-). Although the concentration recorded in the circulating drilling fluid and that which is eventually buried at the site is not necessarily the same, it does give an approximation.

It should be noted that completion and workover fluids (including acidifying solutions) may also be discharged into the reserve pit, depending on whether or not an attempt is made to produce the well. The composition of these fluids is variable but predominantly they are acid. The volume of acid used in the acidizing of a well varies with subsurface conditions but commonly ranges from 500 ($1.9m^3$) to several thousand gallons (tens of m^3). The most common types of acids used are hydrochloric, formic, and acetic. During 1975, 87,000,000, 200,000, and 100,000 gallons of these acids, respectively, were used for oil-and-gas well treatments in the U.S. (Collins, 1975).

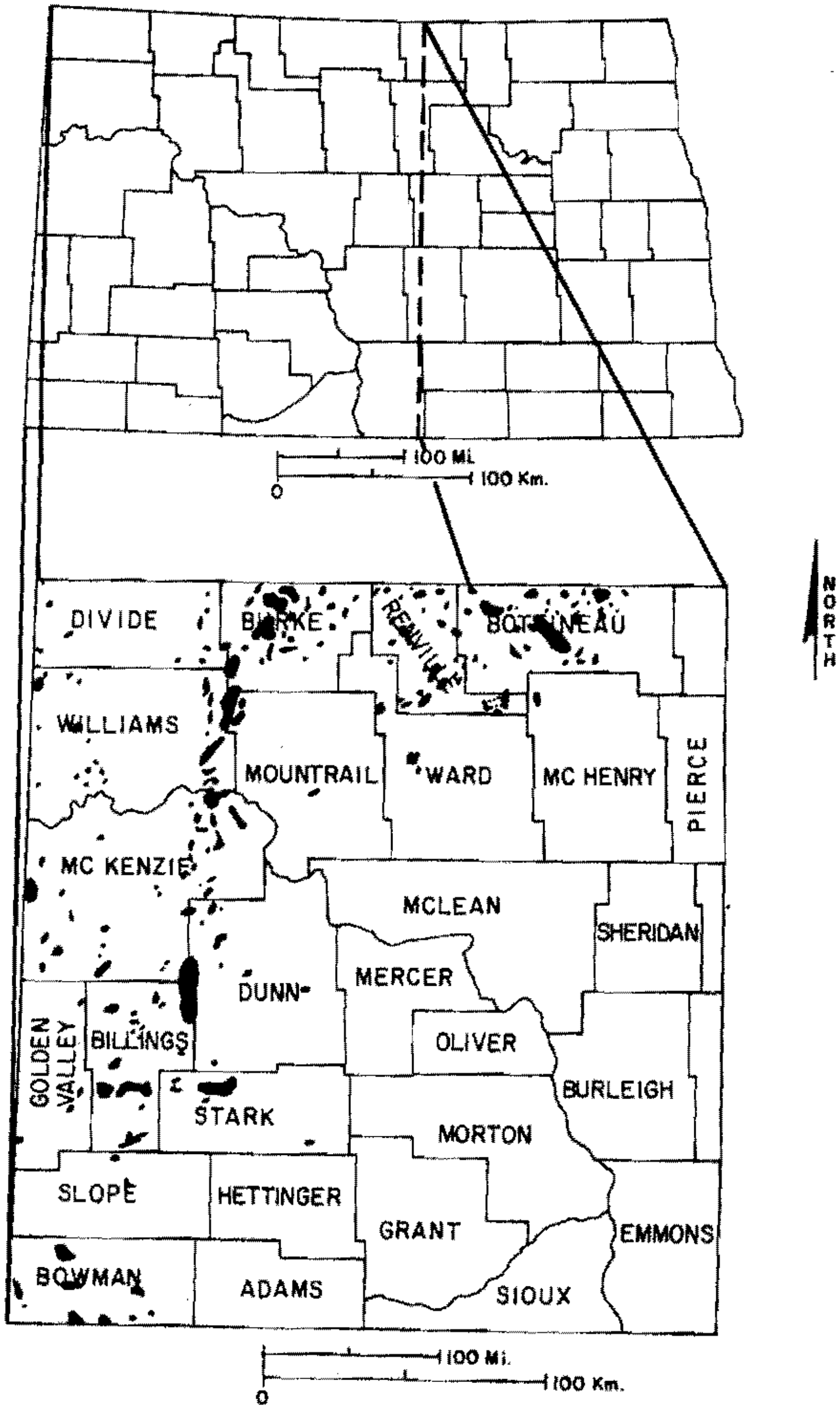
Project Inception.--On September 26, 1979 the State Geologist of North Dakota (Dr. Lee C. Gerhard) drafted a letter to the Governor of North Dakota (Arthur A. Link) and the North Dakota Industrial Commission requesting that they direct the North Dakota

Geological Survey (NDGS) and the North Dakota State Department of Health (NDSDH) to study the toxicity of drilling fluids and their disposal effects. This letter was the result of concern expressed by ranchers in western North Dakota in regard to the protection of the shallow groundwater systems in these areas from potential degradation by chemicals (especially chromium) leached from oil-and-gas well drilling fluid pits and the virtual absence of scientific data on this subject. These concerns culminated in a special hearing before the Industrial Commission of the State of North Dakota on January 8, 1980 in Dickinson, North Dakota. The purpose of the hearing was to determine if the use of sodium chromate (a commonly used drilling fluid additive in western North Dakota) (table 1) should be prohibited in North Dakota.

In response to Dr. Gerhard's letter, Dr. Alan E. Kehew (formerly with the NDGS) and Francis J. Schwindt (Assistant Director-Division of Water Supply and Pollution Control (NDSDH) became co-investigators in a project designed to study the migration of oil-and-gas well drilling fluids from reserve pits. This project was funded by the NDGS and a grant from the Environmental Protection Agency.

In April of 1980, I became the principal investigator of this project and decided to focus the investigation and research in western North Dakota because of the concentration of drilling activity in this area of the state (fig. 7) and the frequent use of sodium chromate as a drilling fluid additive in this area.

Figure 7. Oil fields in North Dakota (Gerhard and Anderson, 1981, p. 17).


100 Mi.
100 Km.
0
NORTH
DIVIDE
BURKE
RENVILLE
BOTTINEAU
WILLIAMS
MOUNTRAIL
WARD
MC HENRY
PIERCE
MC KENZIE
MCLEAN
SHERIDAN
DUNN
MERCER
GOLDEN VALLEY
BILLINGS
OLIVER
BURLEIGH
STARK
MORTON
SLOPE
HETTINGER
GRANT
EMMONS
BOWMAN
ADAMS
SIOUX
100 Mi.
100 Km.
0

These additives are commonly used in this area to reduce the corrosion of the drill pipe by the high H_2S content in the subsurface.

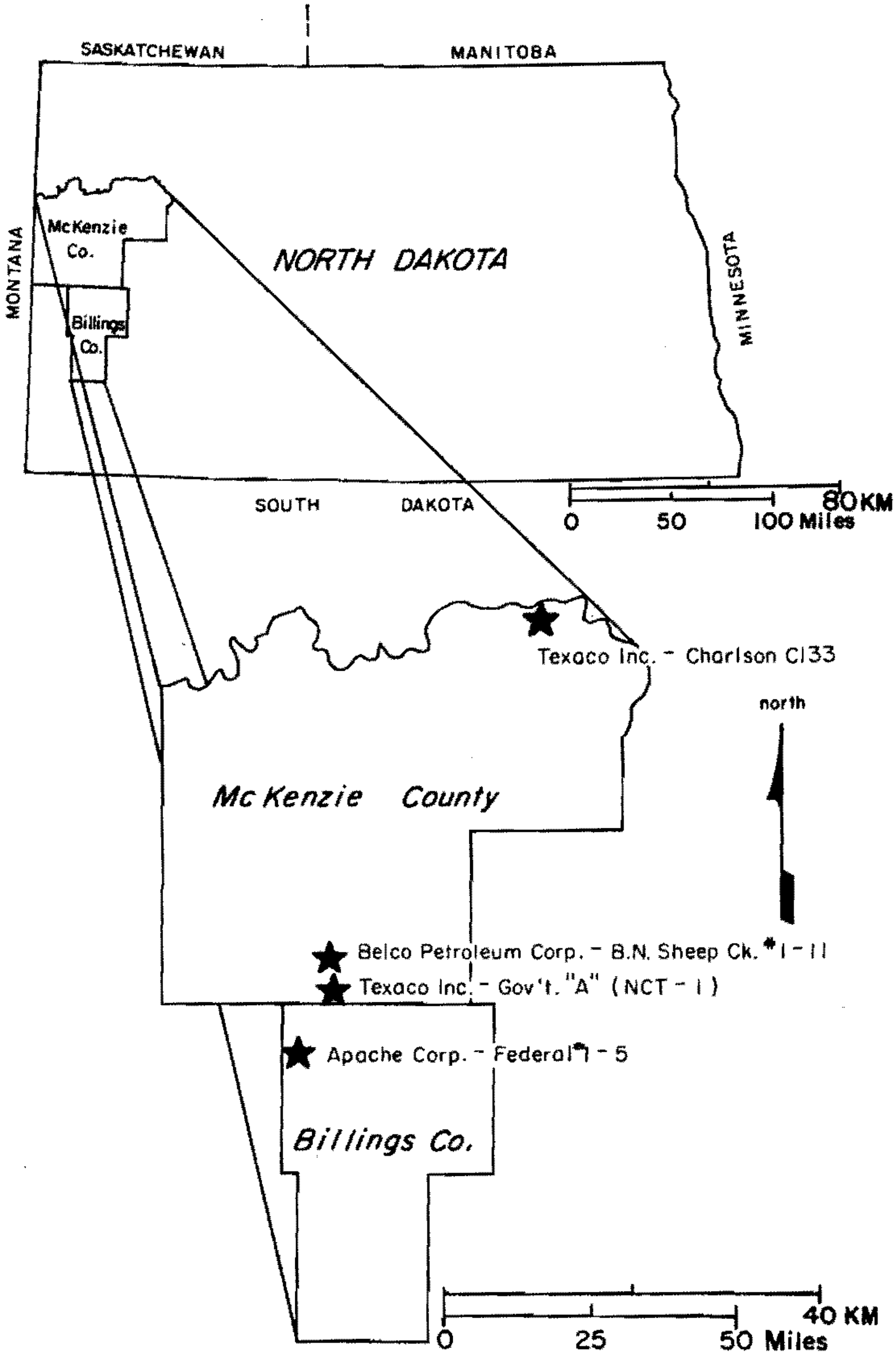
Purpose.--Rule number (43-02-03-19) of the General Rules and Regulations for the Conservation of Crude Oil and Natural Gas states that "....no pit shall be constructed so as to allow surface or subsurface contamination by seepage or flowage from said pit..." (Appendix A).

The purpose of this study is to:

1) determine whether or not chemical components are being leached out of reclaimed drilling sites in western North Dakota.
2) if so, to investigate the extent, character, and geochemical controls influencing the movement or attenuation of the leachate;
3) evaluate the potential health risks to both humans and livestock resulting from consumption of shallow groundwater within an area surrounding these reclaimed drilling pits; and
4) suggest, if appropriate, alternative methods of drilling fluid pit reclamation.

Location and History of Study Sites.--A total of four reclaimed oil-and-gas reserve pits were selected for monitoring in western North Dakota (fig. 8). Three of these sites are located within the nonglaciated portion of the state in close proximity to the center of the Williston Basin. The fourth site is located along

Figure 8. The location of the four study sites.


SASKATCHEWAN
MANITOBA
MONTANA
McKenzie Co.
Billings Co.
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
0 50 100 Miles
80 KM
Texaco Inc. - Charlson C133
north
Mc Kenzie County
Belco Petroleum Corp. - B.N. Sheep Ck. #1-11
Texaco Inc. - Gov't. "A" (NCT-1)
Apache Corp. - Federal #1-5
Billings Co.
0 25 50 Miles
40 KM

the margin of maximum glacial extent but is not situated upon glacially derived sediments (Clayton et al., 1980). All sites lie within the Missouri River Drainage Basin, the major drainage basin in this area.

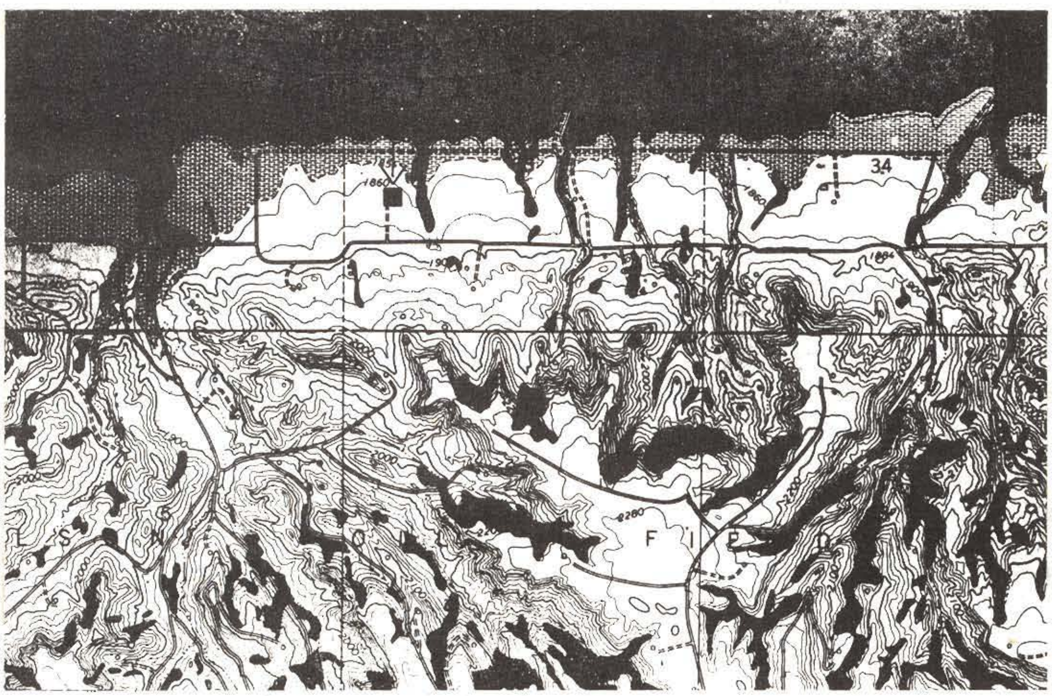
In choosing these four sites an attempt was made to encompass the major variables which effect reclaimed drilling fluid pits; the age of the pit, the geologic and geohydrologic conditions, the chemical drilling fluid additives used, the use of workover and completion fluids, the presence or absence of a pit liner, and the method of pit reclamation.

The oldest drill site is located in the Charlson oil field in northeastern McKenzie County along the southern shore of Lake Sakakawea (T154N, R95W, C NW/SW Sec. 33) (figs. 9 and 10). This site is identified as the "Charlson C133." Amerada Petroleum Corporation began drilling (spudded) the well (Steve Yttredahl "B" #2) on November 19, 1955 and began producing oil from it in 1956. The well was turned over to Texaco Inc. in the mid-60s and converted to a water injection well in 1966 (Madison North Unit C133). The well operated in this capacity until the late 1970s. From August of 1974 through January of 1977, compressed nitrogen gas was added to the injected fresh water as part of Texaco's enhanced secondary recovery program. The reserve pit did not have a plastic liner and, although data are inconclusive, most likely was not trenched during reclamation.

Two additional sites are located about a mile apart in the Roughrider oil field in southern McKenzie County. These sites are

Figure 9. Photograph of Texaco Charlson Madison North Unit C-133. Photo is taken looking north.

Figure 10. Topographic map of Texaco Charlson Madison North Unit C133 (T154N, R95W, c nw/sw sec. 33). Scale is 1.9 inches = 1 mile (1.6 km).


34

identified as "Govt. A (NCT-1)" and "B.N. Sheep Creek #1-11," and are situated within highly dissected badland topography in the Little Missouri Drainage Basin, 4.5 airmiles (7.2 km) east of the Little Missouri River. Texaco Inc. spudded the Government "A" (NCT-1) (T145N., R101W, SE/NE Sec. 14) on December 29, 1960 (figs. 11 and 12). The well was temporarily abandoned in April of the following year and plugged on October 24, 1964. The reserve pit was not lined with a plastic liner and apparently was pushed in during reclamation. Belco Petroleum Corporation spudded the Sheep Creek Burlington Northern #1-11 (T145N, R101W, SW/NE Sec. 11) on March 21, 1977 and plugged and abandoned the well on April 19 of the same year (figs. 13 and 14). The well site is bounded to the west by a stock pond and to the north by an intermittent fork of the Little Beicegal Creek. The reserve pit did not have a plastic liner and was apparently trenched to the west.

The fourth study site is located approximately 1200 feet (366m) west of the Little Missouri River in northwestern Billings County (T145N, R102W, NE/SE Sec. 5) (figs. 15 and 16). This site is identified as the "Apache Federal #1-5." It is situated upon the Little Missouri flood plain 2400 feet (732m) southwest of the Theodore Roosevelt National Memorial Park (Elkhorn Ranch Site). Apache Corporation spudded the Federal #1-5 on June 7, 1979 and plugged it on the 30th of the month. On May 2, 1981, Apache re-entered the well and drilled approximately 1000 feet (305m) deeper (figs. 17 and 18). This well is presently producing

Figure 11. Photograph of Texaco Inc. Government "A" (NCT-1). Note absence of vegetation over reserve pit. Photo taken looking northeast.

Figure 12. Topographic map of Texaco Inc. Government "A" (NCT-1) study site (T145N, R101W, se/ne sec. 14). Scale is 2.0 inches = 1 mile (1.6 km).

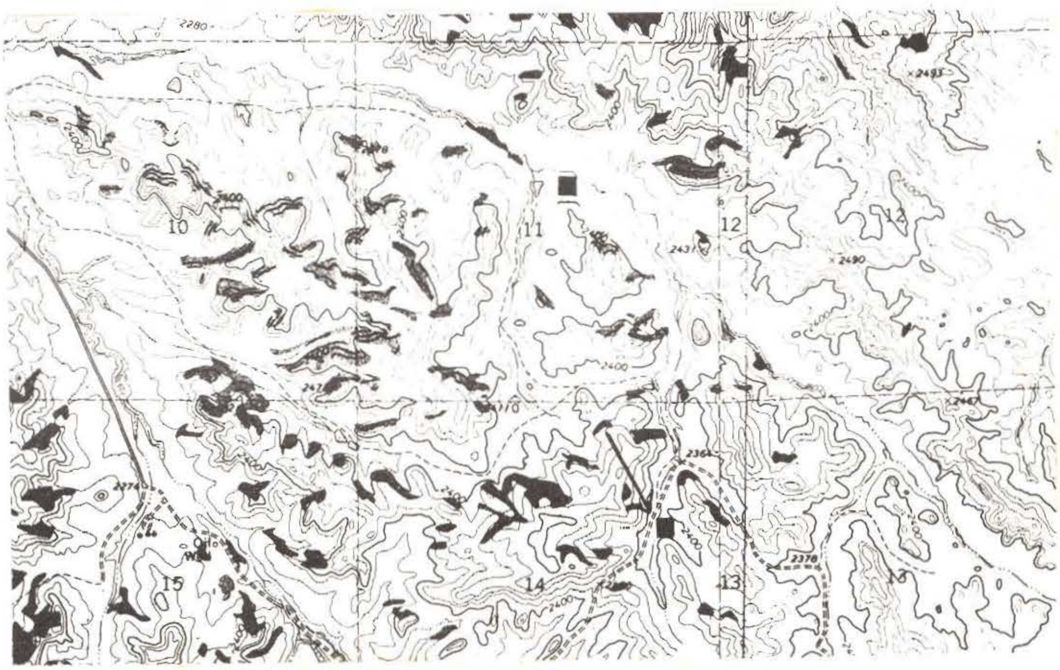

2280
10
11
12
13
14
15
2400

Figure 13. Photograph of Belco Petroleum B.N. Sheep Creek #1-11. Stock pond is located along right-hand border. Photo is taken looking south.

Figure 14. Topographic map of Belco Petroleum B.N. Sheep Creek #1-11 study site (T145N, R101W, sw/ne sec. 11). Scale is 2.0 inches = 1 mile (1.6 km).


2280
10
11
12
13
14
15
2378

Figure 15. Photograph of Apache Corp. Federal #1-5 study site. Note vegetation above reclaimed reserve pit (arrow). Photo was taken prior to the drilling of the re-entry well. Photo is looking northeast.

Figure 16. Topographic map of Apache Corp. Federal #1-5 study site (T145N, R102W, ne/se sec. 5). Scale is 1.9 inches = 1 mile (1.6 km).

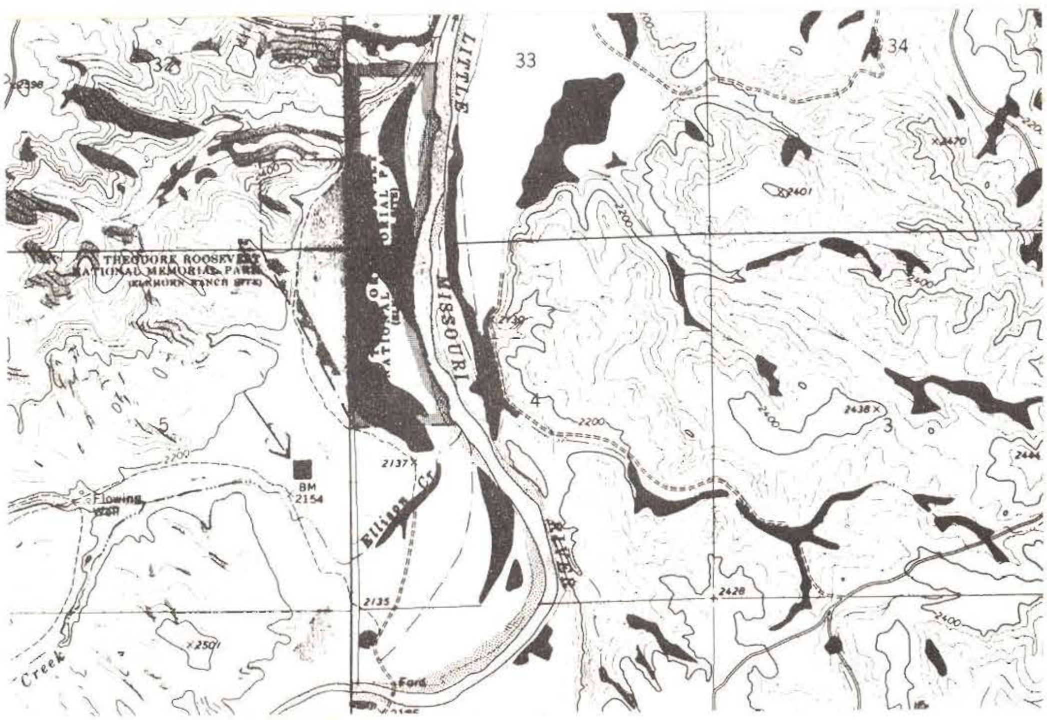

33
34
LITTLE
MISSOURI
RIVER
THEODORE ROOSEVELT
NATIONAL MEMORIAL PARK
4
5
3
2200
2400
2401
2470
2438
2428
2137
2135
2501
BM
2154
Flowing Well
Ellison Cr
Ford
Creek

Figure 17. The Cardinal Rig #7 drilling the Apache Corp. Federal #1-5 re-entry. The reserve pit is located between the rig and the sediment pile. Photo taken looking east-northeast.

Figure 18. The reserve pit from the Apache Corp. Federal #1-5 upon completion of drilling. Note the extensive tear in the pit liner along the entire north face of the pit. Photo is taken looking north.

oil. This site has two separate reserve pits on location because of the 1981 re-entry. Both mud pits were lined with a plastic liner and trenched during reclamation.

Climate.--The climate in the area of study is continental, semi-arid, characterized by long cold winters and short warm to hot summers (Anna, 1981). Precipitation averages slightly higher than fifteen inches (38 cm) annually, fifty percent of this typically coming during the months of May, June, and July. The average annual snowfall is between 30 and 35 inches (76-89 cm) (Goodman and Eidem, 1976). The ground in this area is normally frozen three to five months of the year. (National Oceanic and Atmospheric Administration, 1981).

PREVIOUS WORK

An extensive library search and a nationwide computer search through the Georef system produced less than a dozen articles on the disposal of drilling fluids, none of which provided quantitative geochemical data. A few drilling-fluid-related studies either began after the inception of this project or were in progress and have not as yet been published. Foremost among these is a project similar to this one sponsored by the American Petroleum Institute (API). It involves the field monitoring of twenty reclaimed reserve pits from Texas to North Dakota. The North Dakota site is located a few miles north of Dickinson. This (API) project began early in 1980 in response to an attempt by the U.S. Environmental Protection Agency to have drilling fluids classified as hazardous wastes.

The U.S. Bureau of Land Management (BLM) has been testing the effects of drilling fluid on soils in Wyoming. In this cooperative project, BLM has been spreading drilling fluid over test plots and planting numerous species of grass and shrubs. The plants are later tissue-tested to determine their uptake of salts and trace minerals. A similar project was recently conducted by Utah State University, and another is currently in progress at Purdue University (Lenzini, 1980). The drilling fluids being tested are fresh-water based and, therefore, such a test would not be practical with the salt-water based drilling fluids that are used in North Dakota.

The dumping of drilling fluid into oceanic waters upon completion of an offshore drilling program has long been an area of primary concern. Laboratory research into the effects of drilling fluids on marine organisms began as early as the 1950s. Prior to 1977, drilling fluid waste had been discharged into the marine environment from over 20,000 offshore wells (Ranney, 1979). The majority of environmental studies on offshore drilling fluid disposal involve the determination of toxicity levels to marine organisms. Unfortunately, these data are not applicable to on-shore studies.

METHOD OF INVESTIGATION

Reconnaissance Study.--During the month of April, 1980, sixty well sites were chosen for potential monitoring in western North Dakota. The Geologic Map of North Dakota (Clayton et al., 1980) was used in combination with geologic and geohydrologic interpretation of 1:20,000 aerial photographs to narrow the list to a dozen sites. These sites were situated within either Tertiary bedrock or colluvial and alluvial sediments.

Initial site investigation occurred during the last week in May, 1980. A North Dakota Geological Survey truck-mounted auger (4 3/4 inch diameter) was used to obtain subsurface geologic information at each of these sites. Four study sites were chosen for groundwater monitoring based upon the results of this reconnaissance study. Two of these sites represent the typical geohydrologic conditions within which the majority of oil-and-gas well sites in this area are situated. The other two sites were chosen because of their relatively permeable sediments and high water table.

Field Methods.--The North Dakota Geological Survey's truck-mounted hollow stem 8" auger (Mobil B-50) was used to drill holes to provide geologic and geohydrologic data as well as to enable installation of monitoring equipment at each of these four sites during the periods of June 16-26 and August 11-15 in 1980 and May 26 -

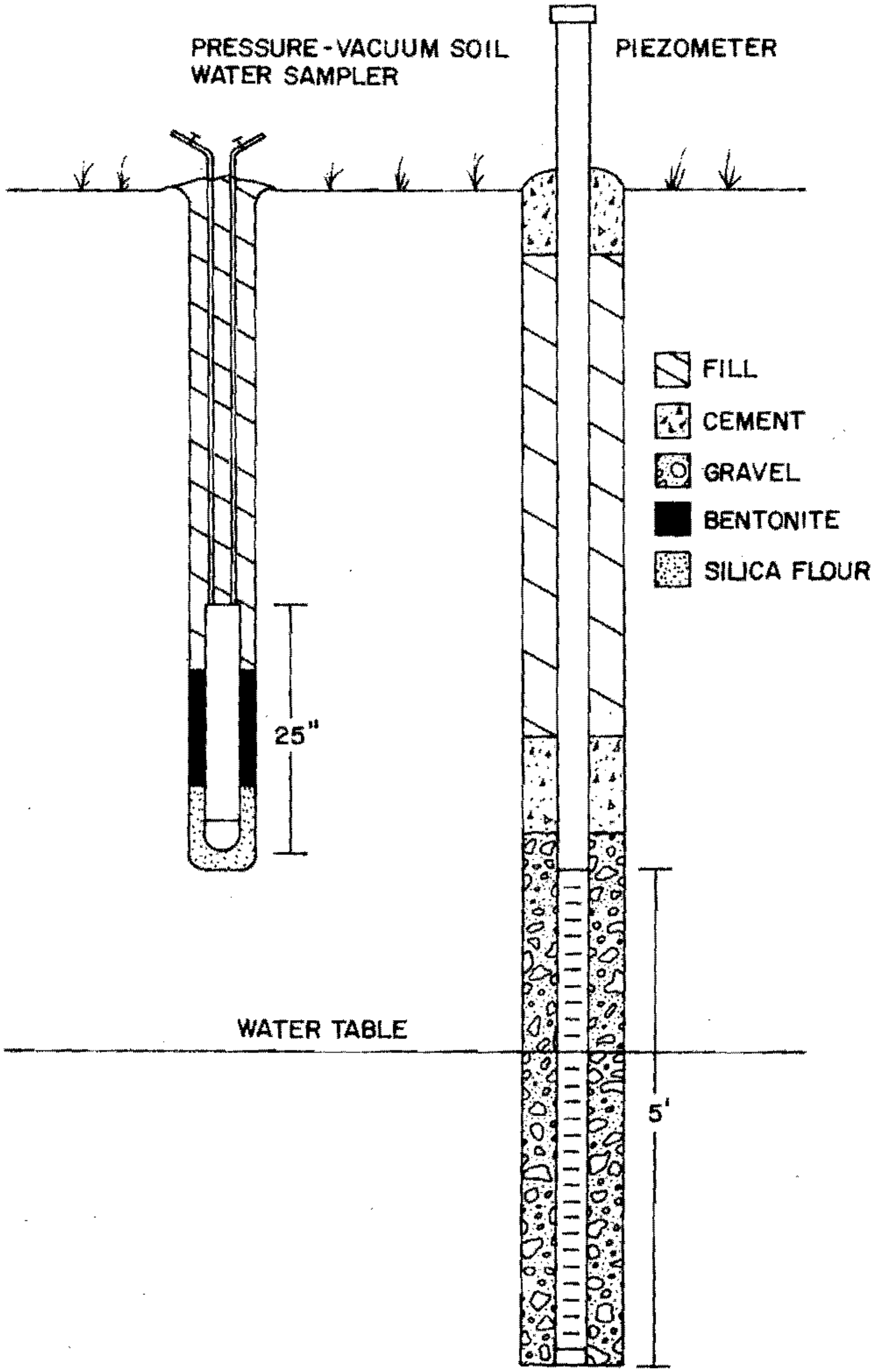
June 6 of 1981 (Appendix B). The maximum depth of penetration obtained with this auger was 72 feet (22m). The limitations this imposed upon the groundwater monitoring affected, but were not detrimental to, the overall project.

Shelby tube sediment samples were taken at each site in addition to the collection of sample drill cuttings. These 2.5 foot (0.762m) by 3 inch (7.62 cm) sediment cores provided detailed lithologic and stratigraphic information as well as relatively undisturbed samples for textural analysis. A total of 160 feet (48.8m) of shelby tube sediment cores was retrieved from the four sites.

Piezometers were one of two types of instruments installed to monitor the groundwater system at each site. They provided water samples from within the zone of saturation, enabled a determination of the elevation and gradient of the water table, and enabled 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 a 5 foot (1.52m) preslotted 0.02 inch (5.1 mm) pvc screen. A washed gravel pack was placed around the screen and the holes were sealed with approximately 10 feet of cement and then back-filled to the surface with drill cuttings (fig. 19).

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 sampler is 3 inches (7.6 cm) in diameter and 25 inches (0.64m) in length (fig. 19). A 2 inch

Figure 19. A profile of a soil water sampler (lysimeter) and piezometer as used in this study.


PRESSURE-VACUUM SOIL
WATER SAMPLER
PIEZOMETER
FILL
CEMENT
GRAVEL
BENTONITE
SILICA FLOUR
25"
WATER TABLE
5'

(5.08 cm) ceramic cup is attached to the bottom of the pvc body. This cup forms the porous membrane through which soil water is drawn into the device. Vacuums of 50-85 centibars are normally applied. 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. Access tubes were run to the surface to enable the application of a vacuum and collection of the water sample at the surface. The maximum sample obtainable is one quart (0.946 litre).

A number of studies have shown that Ca, Na, and K can be leached out of the ceramic cup of this device and thus produce values of these ions in excess of their true concentration (Johnson et al., 1981). To prevent this the ceramic cups were first rinsed with approximately 8N HCl and then rinsed twice with distilled water.

Water samples were collected on a quarterly basis. Two to four weeks prior to collection, the wells were bailed dry in order to provide a representative sample. At this time, a vacuum was also induced into the soil water samplers to allow sufficient time for the soil water to be drawn into the sample chamber.

The temperature, pH, and electrical conductivity of the water samples were determined in the field at the time of sample collection. The dissolved-oxygen content of each of these water samples was determined only once (Nov. 3, 1981) due to equipment malfunction and inaccessibility. 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) containers, and were packed in ice during transportation to the lab. The water samples in the pint (473 ml) bottles were analyzed for trace metal content. Five milliliters of concentrated nitric acid was added to these samples after filtering to prevent the trace metals from precipitating out of solution. The water samples in the quart (0.946 litre) containers were analyzed for major ions. All water samples were analyzed by the North Dakota State Department of Health Environmental Laboratory in Bismarck.

A detailed description of the field equipment used and the precise methods of field sampling is provided in Groenewold et al. (1979).

Each 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 determination is made by displacing the hydraulic head (water level) and measuring the time required for it to return to equilibrium. In this study a slug was used to raise the water level in a 2 inch (5 cm) pvc pipe 3.3 feet (1.0m). 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 this 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).

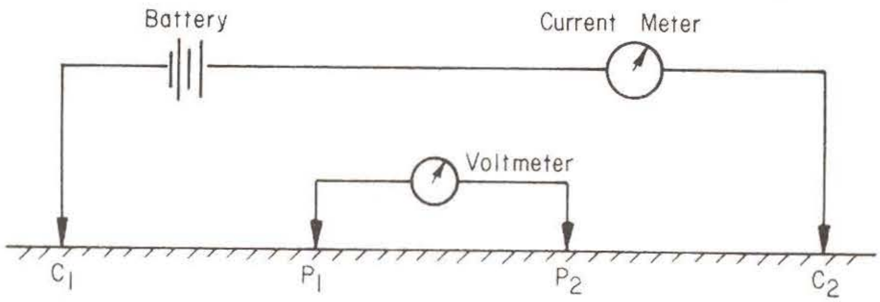
Single-well-response tests were conducted on piezometers at the Texaco Charlson C133 and Apache Federal 1-5 sites. A total of 7 piezometers was tested. The remaining piezometers were not tested because either the slug could not be lowered into the well due to constrictions and bends in the pipe or there was not sufficient water in the well.

Electrical earth resistivity surveys were conducted at two of the study sites (fig. 20). Electrical earth resistivity is a surface geophysical technique used to interpret subsurface geophysical conditions based upon changes in the conduction of an induced electrical current. The electrical current is passed into the ground through a pair of current electrodes (C_1 and C_2) and the resulting potential drop is measured across a pair of potential electrodes (P_1 and P_2) (fig. 21). A Soil Test R-50 stratameter, in combination with the R-65 voltmeter, was used in this project. A thorough explanation of resistivity theories and equations is presented in Van Nostrand and Cook (1966) and an excellent summary is provided by Kehew and Groenewold (1982).

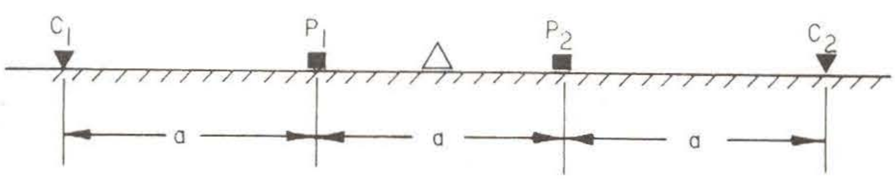
The Wenner electrode configuration was used in the earth resistivity surveys of the Apache Federal 1-5 and the Texaco Charlson

Figure 20. The electrical earth resistivity survey equipment at resistivity station 18 of the Apache Federal #1-5 site. The electrode spacing of the array is 12 feet (3.7m). The photo is taken looking west-northwest.

Figure 21. Configuration of the four-electrode array used in the electrical earth resistivity survey. Current is passed through electrodes C_1 and C_2 and potential difference readings are made between electrodes P_1 and P_2. Equal electrode spacings (a) were used in the Wenner electrode configuration.



WENNER CONFIGURATION



△ RESISTIVITY STATION

C133 sites. In this method the four electrodes are equally spaced along a line. The distance between adjacent electrodes or 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 (fig. 21).

The Vertical Electrical Sounding method (VES) was used in this project. It involves a fixed center of the electrode array (resistivity station) and expansion of the electrodes about this point. Stations were spaced approximately 100 feet (30.5m) apart. Readings were taken at successive electrode spacings ("a") of 12, 30, 40, 60, and 80 feet.

Laboratory Work.--Microscopic mineral evaluation and wet and dry sieve analyses were performed on sandy gravel layers at the Texaco Charlson C133 and Apache Federal 1-5 sites. Sand, silt, and clay contents were determined with the use of a hydrometer for shelby tube samples at each of the study sites. The procedure used is outlined in Appendix C.

A second method of hydraulic conductivity determination was based upon textural analysis. A simple equation relating effective grain size to permeability was used (Freeze and Cherry, 1979):

$$K = A\, d_{10}^{2}$$

$A = 1$ for K in cm/s and d_{10} in mm

d_{10} = effective grain size at which 10% by weight of the sediment particles are finer and 90% are coarser.

This equation is suitable for textural approximation of hydraulic conductivity for sediment in the range of fine sand to gravel.

Eleven shelby tube sediment samples were added to distilled water (35 grams sediment to 1000 ml H_2O) and stirred for four hours. These samples were elutriated to determine the variability in relative concentrations of ions that would readily go into solution. The results of this elutriation were compared with analyses of water samples from the unsaturated zone at the Texaco Gov't. (NCT-1) and Apache Federal 1-5 sites to assist in determination of the depth of leachate migration. The fluids derived from the elutriation of sediment samples were chemically analyzed by the North Dakota State Department of Health Laboratory.

OVERVIEW OF GEOLOGY AND GEOHYDROLOGY IN WESTERN NORTH DAKOTA

Regional Geology and Geohydrology.--Billings and McKenzie Counties are located near the center of the Williston Basin and are underlain by 15,000 feet (4570m) of sedimentary rocks ranging in age from Cambrian to Recent. These strata overlie Precambrian igenous and metamorphic basement rocks (Groenewold et al., 1979).

The surface and near-surface stratigraphy of southwestern North Dakota is comprised largely of sediments of Paleocene age. These sediments consist of alternating sands, silts, clays, and lignites. The majority of drilling fluid pits in western North Dakota are situated within either the Bullion Creek or Sentinel Butte Formations, which include sediments that are fluvial, lacustrine, and paludal in origin. The maximum thickness for each of these formations is about 600 feet (200m) (Clayton et al., 1980).

Holocene alluvium, comprised of cross-bedded sands and obscurely bedded silts and clays, is present along stream channels. These deposits are of local importance along the major drainage systems, such as the Little Missouri River.

The major aquifers in Billings and McKenzie Counties are the Fox Hills-lower Hell Creek aquifer system, the upper Hell Creek-lower Ludlow aquifer system, aquifers within the upper Ludlow-Bullion Creek Formations, aquifers within the Sentinel Butte Formation, and aquifers within alluvial deposits (Anna, 1981).

Clays in Western North Dakota.--The surface and near-surface Tertiary sediments of western North Dakota are extremely clay rich. Clay and silty clay are the dominant sedimentological units. Jacob (1972) determined that only 10% of the Bullion Creek Formation is comprised of sand units. The silt and clay content of these sands ranges from 1.4 to 89.8% with a mean of 22.4%. Preliminary work by Forsman (in preparation) indicates that many of the sand grains contain thin coatings of authigenic Na montmorillonite. Groenewold et al. (in press) performed textural analyses on 79 sediment samples from the Sentinel Butte Formation. The resulting mean textural analyses for these sediments were:

	% sand	% silt	% clay
$\bar{X}$	19.4	44.8	35.8

Studies by Royse (1967), Jacob (1975), and Moran et al. (1978b) have shown that the dominant clay mineral group in the upper Paleocene sediments in western North Dakota is smectite, specifically Na montmorillonite. The results of 79 clay analyses by Groenewold et al. (in press) indicate a clear dominance of smectite (normally Na montmorillonite) and illite-mica clays.

The smectite (montmorillonite) group consists of 2:1 clay minerals, i.e. their structure is two tetrahedral layers separated by a single octahedral layer. Isomorphous substitution of ions in either of the two layers results in a deficiency of positive charge for the structure (Birkeland, 1974). This charge is balanced by either ion substitution in the octahedral layer or more commonly by adsorption of cations into the interlayer positions between the sheets. These cations are held rather loosely in the structure and are exchangeable. This explains the smectite clay's relatively large cation exchange capacity (Krauskopf, 1979).

Divalent ions such as Ba^{2+}, Ca^{2+}, and Mg^{2+} normally have a stronger adsorption affinity than do monovalent ions such as K^{+} and Na^{+}. The strongest affinity is for the smaller hydrated ions and the weakest is for the largest ions. Laboratory experiments have shown that Ca^{2+} is adsorbed in strong preference to both Na^{+} and Mg^{2+}, and Mg^{2+} is selected in preference to Na^{+}. These affinities are highly dependent upon relative concentration levels of the interacting ions (Moran et al., 1978b).

The exchange reactions between cations proceed very quickly (Freeze and Cherry, 1979). These reactions continue until the concentration of cations in the pore water and the cations adsorbed onto the adjacent clay surfaces are in equilibrium. As the pore water flows through the clay or clayey sediments there is continual readjustment by cation exchange to maintain this equilibrium. This adjustment is relatively fast in comparison to normal subsurface flow rates (Moran et al., 1978b).

Groundwater Recharge.--The unsaturated zone is the interval between the surface and the water table. The saturated zone lies beneath the groundwater table. Groundwater recharge is defined as that portion of infiltrating water which reaches the saturated zone and begins to flow downward from the water table. In the Northern Great Plains the depth to the saturated zone is often several tens of metres (Rehm et al., 1982).

Water at the surface (either from recent precipitation or snow melt) can either evaporate, transpire from vegetation, pond, or infiltrate into the subsurface. The major controlling factors are the permeability and moisture content of the sediment and the amount of water available.

Water which has infiltrated into the unsaturated zone can either continue its downward movement to the saturated zone or remain within this zone. This water will eventually either move down to the saturated zone with subsequent infiltrating water or be removed from this zone by evapotranspiration.

Groundwater recharge can occur any time during the year. In a recent study in west-central North Dakota it was shown that the majority of groundwater recharge occurred during the months of March and April when the concurrent evapotranspiration rates were very small and runoff maximized (Rehm et al., 1982). Evapotranspiration rates are lowest to nonexistent in the late fall and throughout the winter but precipitation is low or in the form of snow. These rates slowly increase during the spring and normally reach peak amounts during August.

Potential spring recharge is directly related to the accumulation of snow from the previous 4 to 5 months and recent precipitation. The accumulated snow is often not available for groundwater recharge until the last week of March when the mean daily air temperatures rise above the freezing point (Rehm et al., 1982).

Commencing in November, the ground normally begins to freeze from the surface downward. The maximum depth of frost is normally 5 to 8 feet (1.5-2.5m) below a vegetated surface and 9 feet (2.7m) beneath a vegetation free surface. This frozen soil is not necessarily impermeable as evidenced by observed rises in the water table during spring melt. The rise often precedes the completion of thawing in the shallow subsurface. Frozen soil exists as four major structures, the least porous of which is normally found beneath vegetation free soil. This frost will begin to melt when the air and soil temperatures rise above $0^{\circ}C$ and will be completely thawed within a thirty- to fifty-day period (Rehm, et al., 1982).

Hydraulic Conductivity.--Hydraulic conductivity is a quantitative measurement of the ability of a material to transmit a fluid. Within the saturated zone this measurement is a function of the permeability of the sediment and the density and viscosity of the fluid.

Within the saturated zone of a shallow unconfined aquifer there are normally two major components of flow. One of the components of flow is lateral and in the direction of decreasing water table elevation. The second is a downward component (for a recharge area) and is commonly the dominant flow direction (Moran et al., 1978a).

Water within the unsaturated zone is held in the soil pores by surface tension forces. As the moisture content of the sediment increases, this holding force decreases. When this force is exceeded, the water will flow downward under the force of gravity or laterally if a perched saturated zone forms above a horizontal zone of low permeability. The hydraulic conductivity of unsaturated sediment increases as the moisture content increases. The hydraulic conductivity is also a function of the pressure head (Freeze and Cherry, 1979).

The determination of hydraulic conductivity within the unsaturated zone requires a pressure head measuring device, such as a tensiometer, and measurement of the moisture content of the sediment. These values are extremely variable with time and create a wide range of hydraulic conductivity values for a given sediment within this zone.

Hydraulic conductivity values have been established for the major sediments within the Bullion Creek and Sentinel Butte Formations by studies in western North Dakota. Groenewold et al. (1979) determined the following range in hydraulic conductivity values in this area: silt and clay (5×10^{-9} - 5×10^{-10} m/s), sand (2×10^{-5} - 2×10^{-7} m/s), sand and gravel (2×10^{-5} - 3×10^{-6} m/s) and lignite (3×10^{-5} - 1×10^{-8} m/s).

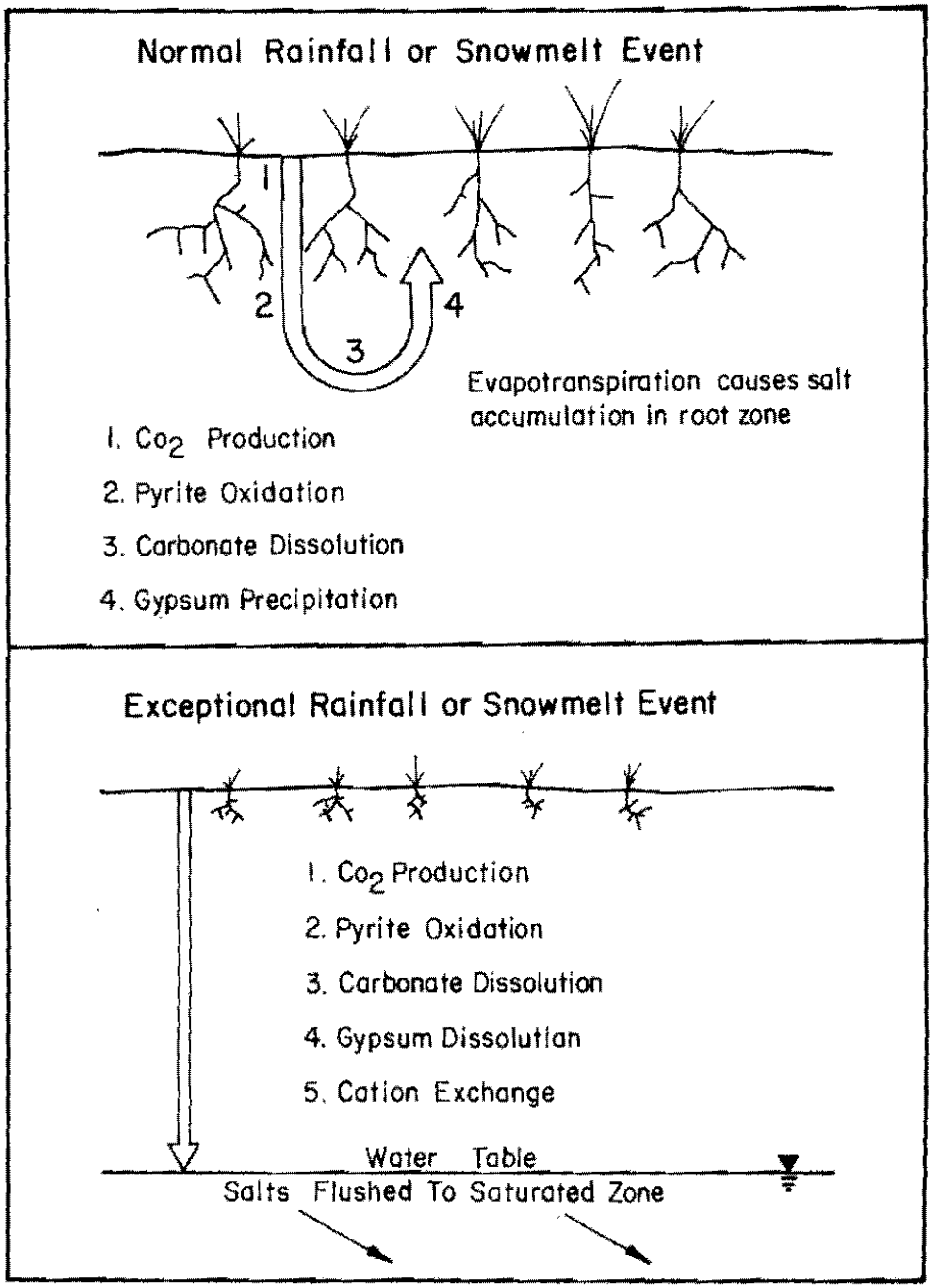
<u>Chemical Evolution of Groundwater in Western North Dakota</u>.--Groundwater in western North Dakota is characterized by dominant concentrations of Na^+, HCO_3^-, and SO_4^{2-}. A hydrogeochemical model has been developed by Moran et al. (1978b) and refined by Groenewold et al. (in press) to explain the chemical evolution of groundwater in this region. These studies have shown that the chemistry of the water is largely determined by geochemical processes that take place

in the unsaturated zone. These processes are dependent upon the recharge pattern and mineral content of the sediment in this portion of the landscape.

In western North Dakota, most of the rainfall and snowmelt infiltrates into the unsaturated zone only a short distance before it is removed by evapotranspiration. The oxidation of both organic matter in the soil and iron sulfide by this infiltrating water produces hydrogen ions and SO_4^{2-}. The oxidation of organic matter is by far the dominant source of the H^+ ion. Weathered sediments appear to be the dominant source of the sulfate ions. This water is now acidic, as a result of the H^+ ion, and will dissolve any carbonate mineral with which it comes in contact. The dissolution of calcite and dolomite will release Ca^{2+} and HCO_3^- into the pore water. Most of this pore water in the unsaturated zone will eventually return to the atmosphere by evapotranspiration. This will cause the supersaturation level of $CaSO_4$ to be reached and gypsum will precipitate in the shallow subsurface. This geochemical model is also applicable in the absence of organic matter in the soil (Groenewold et al., in press) (fig. 22).

During exceptional infiltration events, water will pass through the geochemically critical near-surface zone and dissolve a portion of the accumulated gypsum. This will add high concentrations of Ca^{2+} ans SO_4^{2-} ions to the solution. HCO_3^- ions will also be added from carbonate mineral dissolution. As this water infiltrates through the unsaturated zone the Ca^{2+} ion will normally be replaced by Na^+ due to exchange on sodium montmorillonitic clays. The resulting

Figure 22. A hydrogeochemical model for the chemical evolution of groundwater in western North Dakota. The predominant chemical reactions are presented for both the normal and exceptional rainfall and snowmelt events (from Moran et al., 1978b and Groenewold et al., in press).


Normal Rainfall or Snowmelt Event
1
2
3
4
Evapotranspiration causes salt accumulation in root zone
1. Co2 Production
2. Pyrite Oxidation
3. Carbonate Dissolution
4. Gypsum Precipitation
Exceptional Rainfall or Snowmelt Event
1. Co2 Production
2. Pyrite Oxidation
3. Carbonate Dissolution
4. Gypsum Dissolutian
5. Cation Exchange
Water Table
Salts Flushed To Saturated Zone

water is now characterized by dominant concentrations of Na^+, SO_4^{2-}, and HCO_3^- ions. This basic chemistry will change little after migration to the saturated zone (fig. 22). A detailed discussion of this geochemical model is presented in Moran et al. (1978b) and Groenewold et al. (in press).

GEOLOGY AND GEOHYDROLOGY OF STUDY SITES

<u>Texaco Charlson C133 Well Site</u>.--The site is underlain by at least 60 feet (18m) of colluvium and alluvium (figs. 23 and 24). Fluvial sediments include gravel composed entirely of subrounded to sub-angular pebbles 0.16 to 2.4 inches (0.4 to 6.0 cm) in diameter. The pebble lithologies include clinker, siltstone, and claystone and appear to have been derived from the Bullion Creek and Sentinel Butte Formations.

Overlying the gravel layer is 30-40 feet (9.1-12.2m) of colluvium and slopewash sediment eroded from steep slopes underlain by the Bullion Creek Formation just to the south of the site. This sediment includes sandy gravel, gravelly sand, sandy silt, and silty clay. Fragments of both clinker and lignite range from common to locally abundant and vary in grain size, corresponding to the dominant grain size of the specific horizon. The source location is substantiated by the general decrease in grain size from south to north and a decrease in abundance of the more unstable fragments (i.e., lignite and poorly cemented sandstone pebbles) in this same direction.

The water table of the unconfined aquifer beneath this study site, which fluctuated over a range of 10 feet (3.05m) in elevation during the monitoring period between August of 1980 and November of

Figure 23. Map view of the Texaco Inc. Charlson Madison North Unit C133 Site. Water sampling instrumentation and earth resistivity stations are depicted.

LEGEND

Drilling fluid

Silty clay (or)

Sandy silt

Sand

Sandy gravel

Lignite

Fill

	Map View	Profile
Piezometer	D_{12}	
Soil water sampler	D_6	
Resistivity station		St. 16
Oil-and-gas borehole		

Reserve pit outline

Reclamation trenches

Groundwater table

Water level

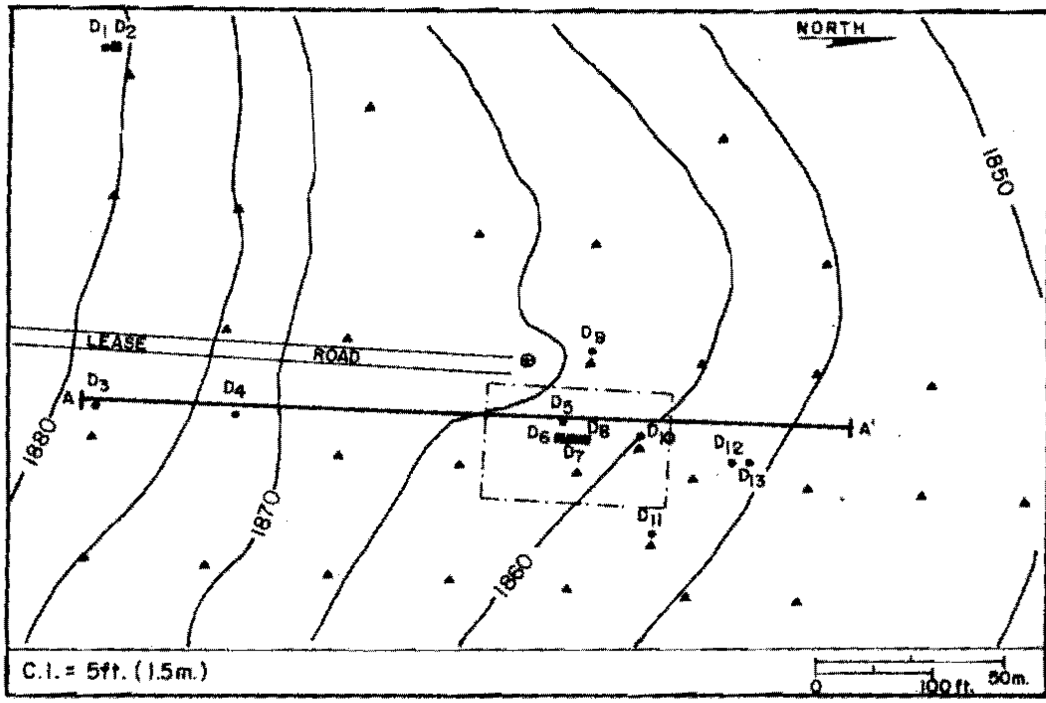
Elevation contours, (ft. above sea level) 1870

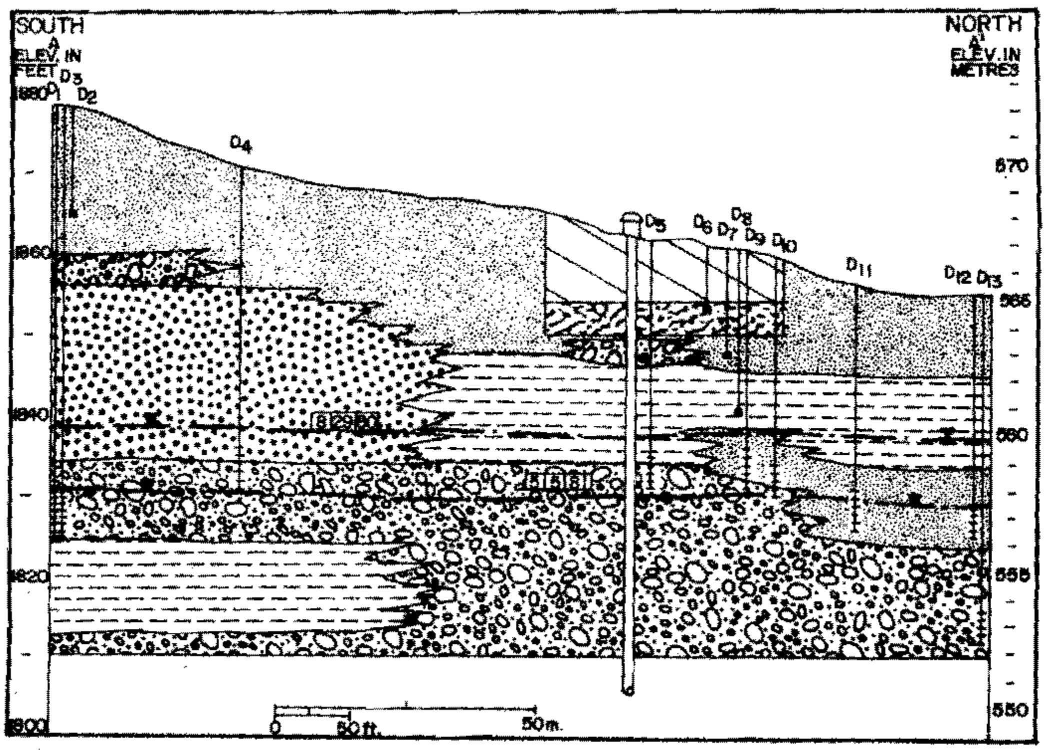
Profile line of cross-section A A'

Contact of alluvium and underlying bedrock $\frac{QA}{TSB}$

Contact of colluvium and underlying bedrock $\frac{QC}{TBC}$

Figure 24. Geologic cross-section of the Texaco Inc. Charlson Madison North Unit C133 site. The configuration of the water table is shown for two separate periods. The line of profile is depicted in figure 23.


NORTH
LEASE ROAD
D1 D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
A
A'
1880
1870
1860
1850
C.I. = 5ft. (1.5m.)
0
100 ft.
50m.


SOUTH
A
ELEV. IN FEET
NORTH
A'
ELEV. IN METRES
1880
1860
1840
1820
1800
570
565
560
555
550
0
50 ft.
50m.

1981 (fig. 25), is directly related to the level of Lake Sakakawea. The fluctuating reservoir level correlates exactly with the elevation of the water table which ranged in elevation from 1840 feet (560m) above sea level down to 1831 feet (557.5m). Beneath the bottom of the drilling-fluid pit the depth to the water table fluctuated from 13-21 feet (4.0-6.4m) during this study period.

The direction of groundwater flow in this area is from south to north. The gradient of the water table is 3×10^{-3} ft/ft (3×10^{-4} m/m) in a direction normal to the shoreline of Lake Sakakawea.

Texaco (Gov't. NCT) Well Site.--This site is underlain by approximately 20 feet (6m) of colluvium (figs. 26 and 27) which varies in grain size from medium sand to clay but consists predominantly of silt. Fragments of lignite and clinker are common throughout this deposit.

Underlying the colluvium are sediments of the lower Sentinel Butte Formation. The dominant Sentinel Butte lithologies are sands, clays, and lignites. The sands are comprised of poorly cemented fine- to medium-size sand grains with varying percentages of silt.

The clays range from silty to very silty and vary in color from light gray to light blue-green. The degree of induration is highly variable, ranging from extremely well to poor. The lignites vary in both induration and in percentage of clay partings. The middle coal (2351-2355 ft. [717-718m] above sea level) is highly indurated.

Monitoring of the five piezometers installed indicates that the water table was never reached at this site. Two piezometers (A_3 and

Figure 25. Correlation of the Lake Sakakawea water level and the groundwater table elevations at the Texaco Charlson Madison North Unit C133 site. Data is presented for August of 1980 through November of 1981 (from National Oceanic and Atmospheric Administration, 1981 and U.S. Army Corps of Engineers, 1981).

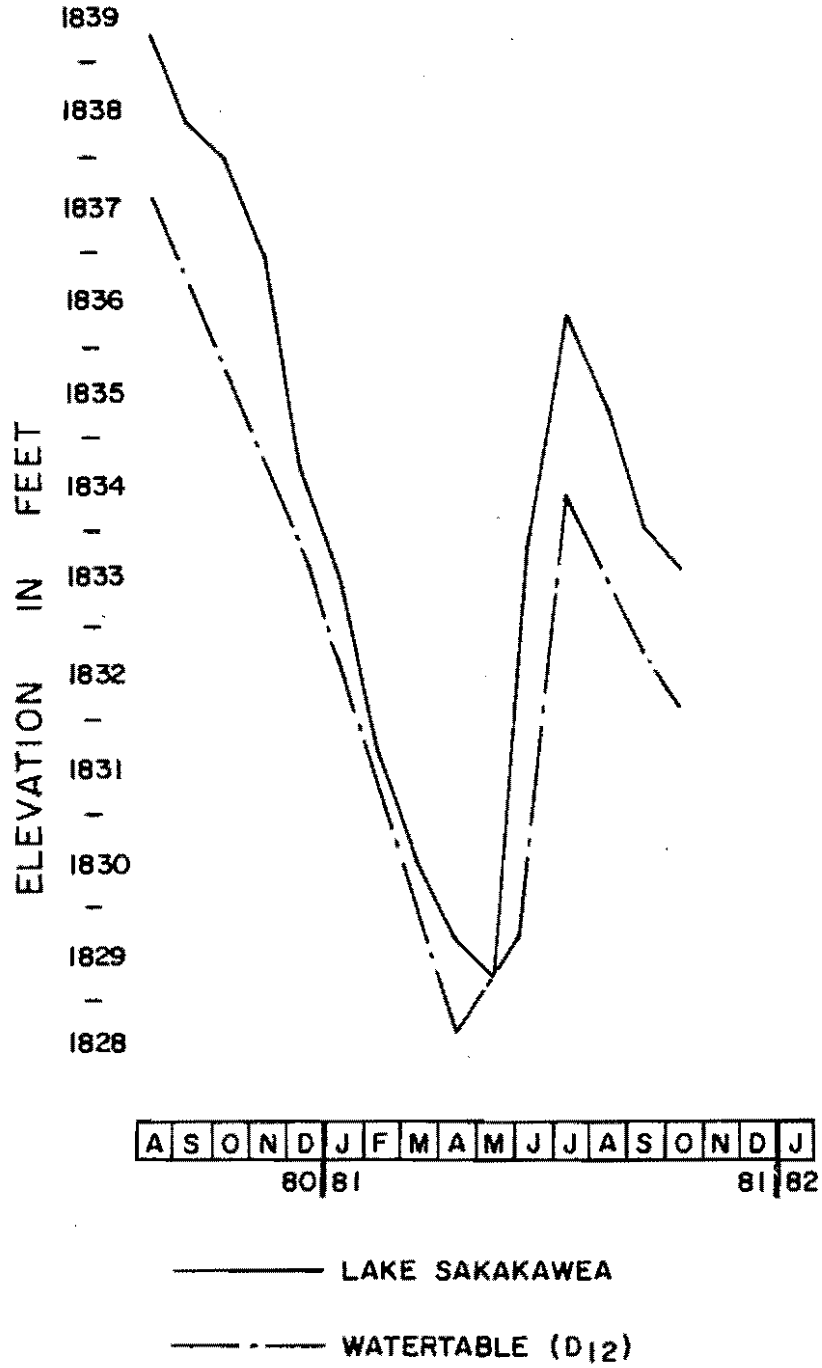
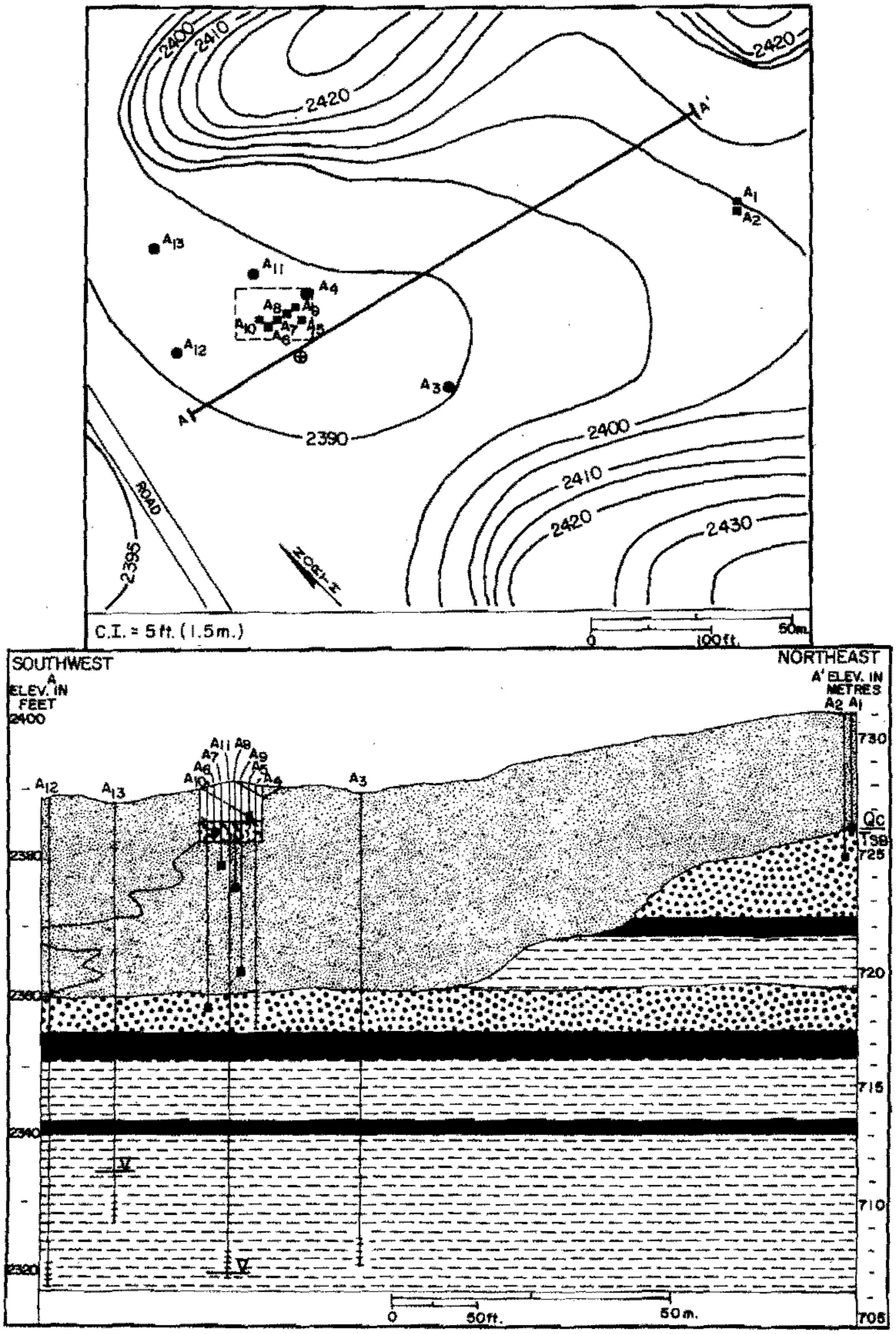

ELEVATION IN FEET
1839
1838
1837
1836
1835
1834
1833
1832
1831
1830
1829
1828
A S O N D J F M A M J J A S O N D J
80 81
81 82
LAKE SAKAKAWEA
WATERTABLE (D12)

Figure 26. Map view of the Texaco Inc. Government "A" (NCT-1) site. Water sampling devices are depicted (for legend see figs. 23 and 24).

Figure 27. Geologic cross-section of the Texaco Inc. Government "A" (NCT-1) site. The water levels for A_{10} and A_{13} are depicted (not groundwater table). The line of profile is shown in figure 26 (for legend see figs. 23 and 24).


2400
2410
2420
2420
2420
A'
A1
A2
A13
A11
A4
A8
A9
A10
A7
A5
A6
A12
A3
A
2390
2400
2410
2420
2430
ROAD
2395
NORTH
C.I. = 5 ft. (1.5 m.)
0
100 ft.
50 m.
SOUTHWEST
A
ELEV. IN FEET
2400
2380
2360
2340
2320
NORTHEAST
A' ELEV. IN METRES
730
725
720
715
710
705
Qc
TSB
0
50 ft.
50 m.

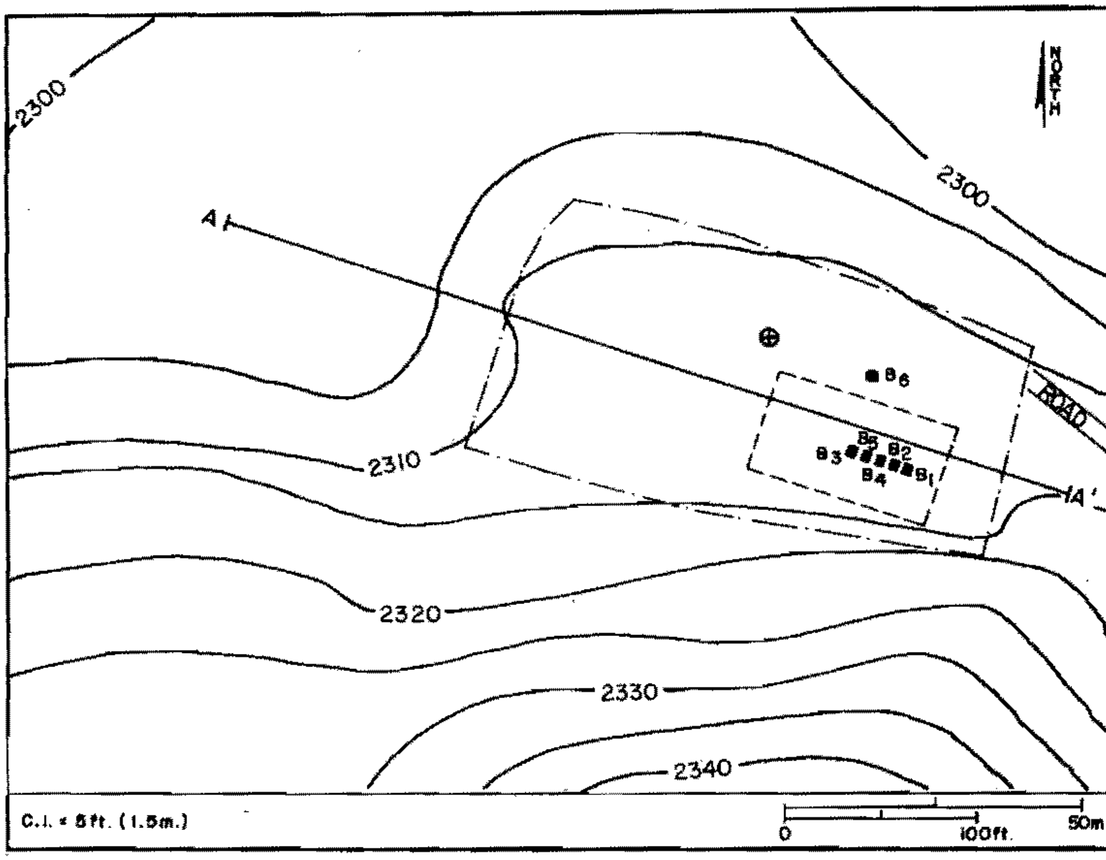
A_{12}) have never contained water indicating that, barring improper installation, the screened intervals are above the zone of saturation. The elevation difference between water levels in two other piezometers (A_{11} and A_{13}) ranges from 10 feet (3m) up to 16 feet (5m) (fig. 27). Given the close proximity of these piezometers, a possible explanation is that the screened intervals intercept perched saturated zones in the clay. Joints and fractures may result in differences in hydraulic conductivity in the unsaturated zone and the formation of a perched water table; therefore, the position of the true water table is unknown. Another possible explanation is that the cement plugs were not properly installed in either A_{11} and/or A_{13} and therefore allowed water from the perched water table to travel down the outside of the pvc and into the screen interval.

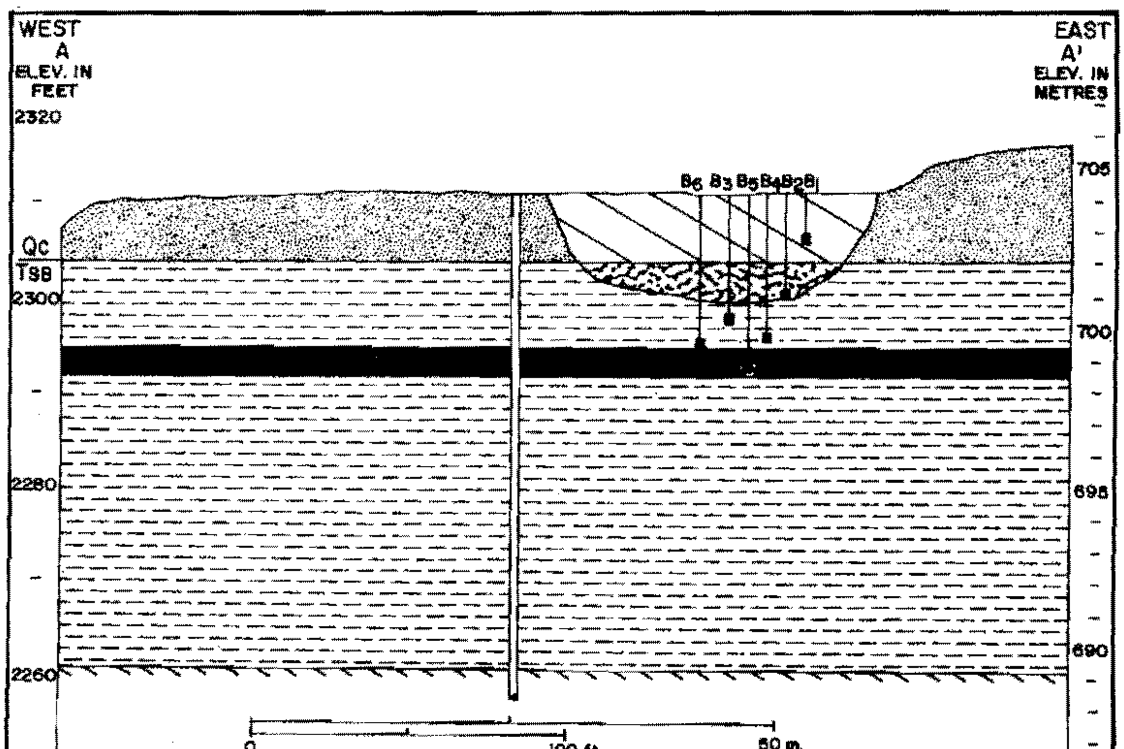
A temporary perched water table (at a depth of 30 feet [9.2m]) was found to exist in the silty sand layer above the middle coal. The fifth piezometer (A_4) was installed with a ten foot (3m) screen through this interval in a successful attempt to obtain water samples after periods of high precipitation.

Belco Petroleum (Sheep Creek #1-11) Well Site.--The reserve pit was constructed in 6 to 7 feet (1.8-2.1m) of silt (figs. 28 and 29) overlying sediments of the Sentinel Butte Formation. An underlying 9 foot (2.7m) orange to gray silty clay layer contains plant fossils. Below the silty clay layer is a 3 foot (0.9m) coal seam that is moderately to well indurated and contains clay partings. The underlying 30 foot (9.1m) clay is light gray to

Figure 28. Map view of the Belco Petroleum B.N. Sheep Creek #1-11 site. The reserve pit is outlined with dashes and the oil well pad with dot and dashes (for legend see figs. 23 and 24).

Figure 29. Geologic cross-section of the Belco Petroleum B.N. Sheep Creek #1-11 site. The line of profile is shown in figure 28 (for legend see figs. 23 and 24).


2300
2300
NORTH
A
A'
ROAD
B6
B5 B2
B3
B1
B4
2310
2320
2330
2340
C.I. = 5 ft. (1.5m.)
0
100ft.
50m


WEST
A
ELEV. IN
FEET
EAST
A'
ELEV. IN
METRES
2320
2300
2280
2260
705
700
695
690
Qc
TSB
B6 B3 B5 B4 B2 B1
0
100 ft.
50 m.

blue-gray in color and varies from extremely well to moderately indurated.

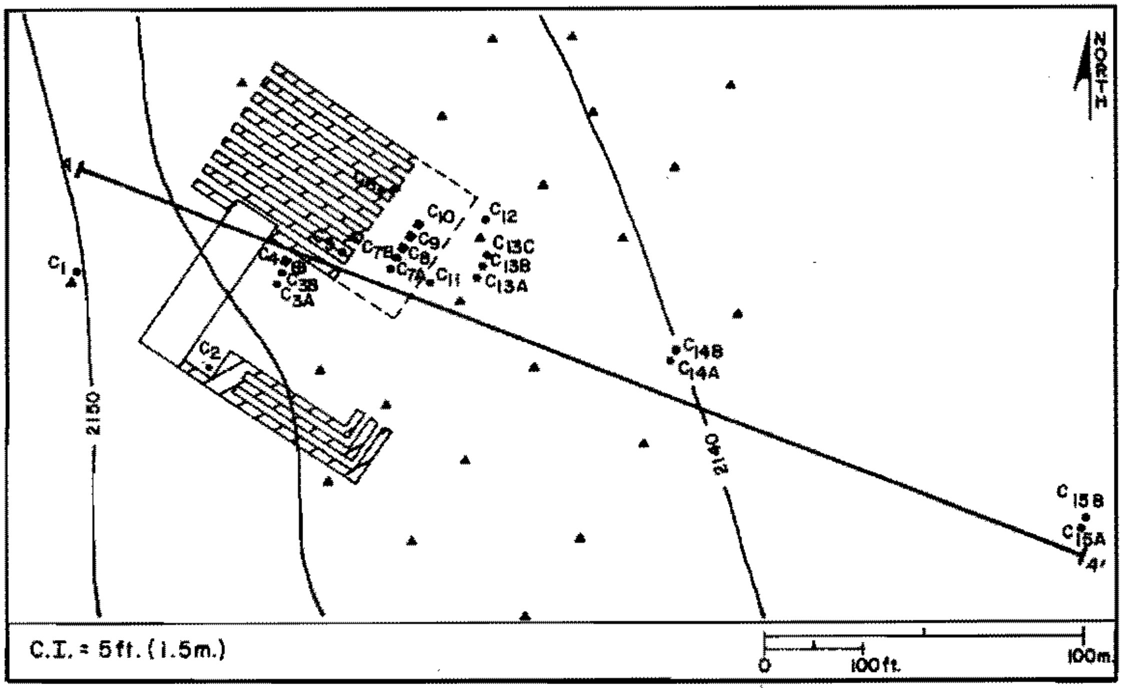
A cemented zone was encountered in the subsurface at a depth of 50 feet (15.2m). The auger was only able to penetrate this zone a few inches, in spite of four separate attempts. The holes were left open for two days but never contained any water, indicating the saturated zone was not reached. Because of this barrier the water table could not be reached during drilling and, therefore, only soil water samplers were installed.

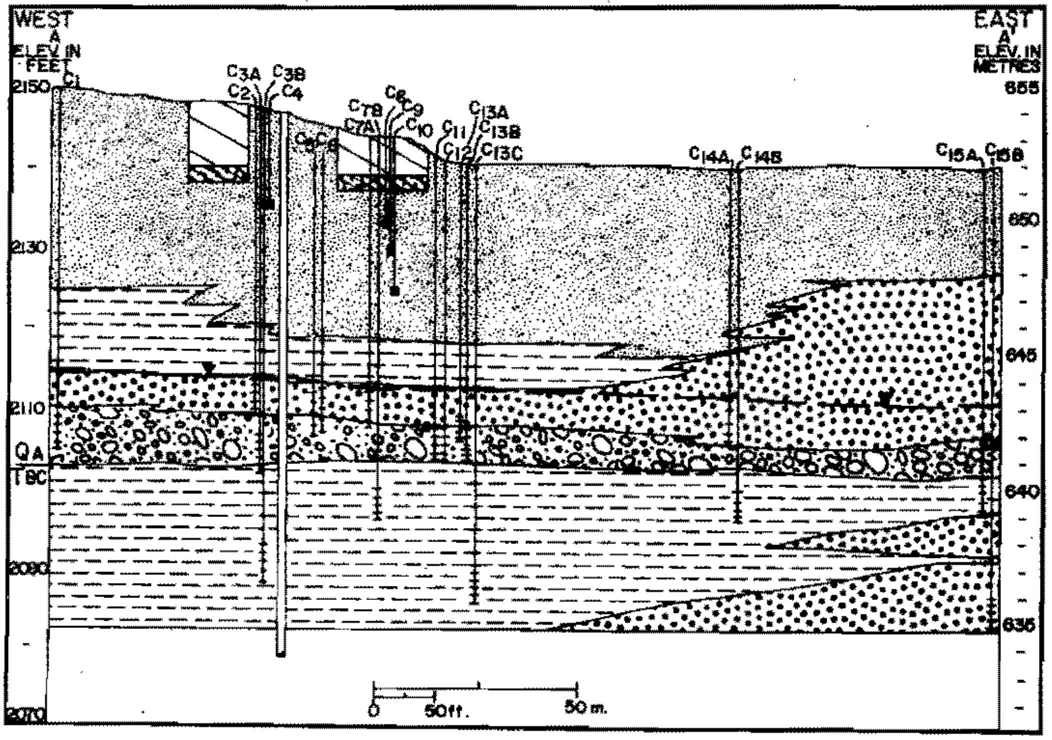
Apache (Federal #1-5) Well Site.—The Apache site is located upon 40-45 feet (12.2-13.7m) of Holocene alluvium (figs. 30 and 31) on the flood plain of the Little Missouri River. At the base of the alluvium a 3 to 7 foot (0.9-2.1m) basal gravel unit consists of subrounded 0.2 to 3.2 inch (0.4-8.0 cm) diameter pebbles comprised predominantly of clinker, siltstone, and claystone derived from Paleocene formations. The gravel layer is moderately to poorly sorted. The alluvium sediments form a fining upward sequence from the basal gravel layer to a sandy clayey silt. The amount of lignite and clinker fragments is extremely variable throughout these deposits.

The alluvial deposits are underlain by sediments of the Bullion Creek Formation. The upper part of the section consists of at least 20 feet (6.1m) of light blue-gray to light blue-green silty clay in the area beneath the drilling pad. Two lenticular beds of medium-grained sand are located at this horizon east of the drill pad. The lower sand bed is most likely present at a greater depth

Figure 30. Map view of the Apache Corp. Federal #1-5 site. The 1979 reserve pit is shown in dashed outline, the 1981 reserve pit is shown with a solid line (for legend see figs. 23 and 24).

Figure 31. Geologic cross-section of the Apache Corp. Federal #1-5 site. Piezometers C_5, C_6, and C_{11} were destroyed during reconstruction of the pad for the 1981 re-entry. The line of profile is shown in figure 30 (for legend see figs. 23 and 24).


NORTH
A
A'
C1
C2
C3A
C3B
C4
C7A
C7B
C8
C9
C10
C11
C12
C13A
C13B
C13C
C14A
C14B
C15A
C15B
2150
2140
C.I. = 5 ft. (1.5 m.)
0
100 ft.
100 m.


WEST
A
ELEV. IN FEET
EAST
A'
ELEV. IN METRES
C1
C3A C3B
C2 C4
C5 C6
C7B
C7A
C8 C9
C10
C11
C12
C13A
C13B
C13C
C14A C14B
C15A C15B
2150
2130
2110
2090
2070
QA
TBC
655
650
645
640
635
0
50 ft.
50 m.

to the west.

The depth to the water table ranges from 35.5 feet (10.8m) along the western edge of the study area to 28 feet (8.5m) in the eastern portion. The depth to the water table from beneath the two drilling fluid pit bottoms is approximately 23 feet (7.0m). The depth of the water table from the bottom of the unlined drilling-fluid filled trenches varies from approximately 15 feet (4.6m) for the 1979 trenches to 10 feet (3.0m) for those excavated in 1981. The water table of the unconfined aquifer beneath the study site has declined an average of 6 inches (15 cm) during this project. This minor decline is apparently due to the abnormally low amount of precipitation recorded over the period of study.

The direction of groundwater flow is from southwest to northeast. The gradient of the water table averages 2×10^{-3} ft/ft (2×10^{-4} m/m) within the area of study.

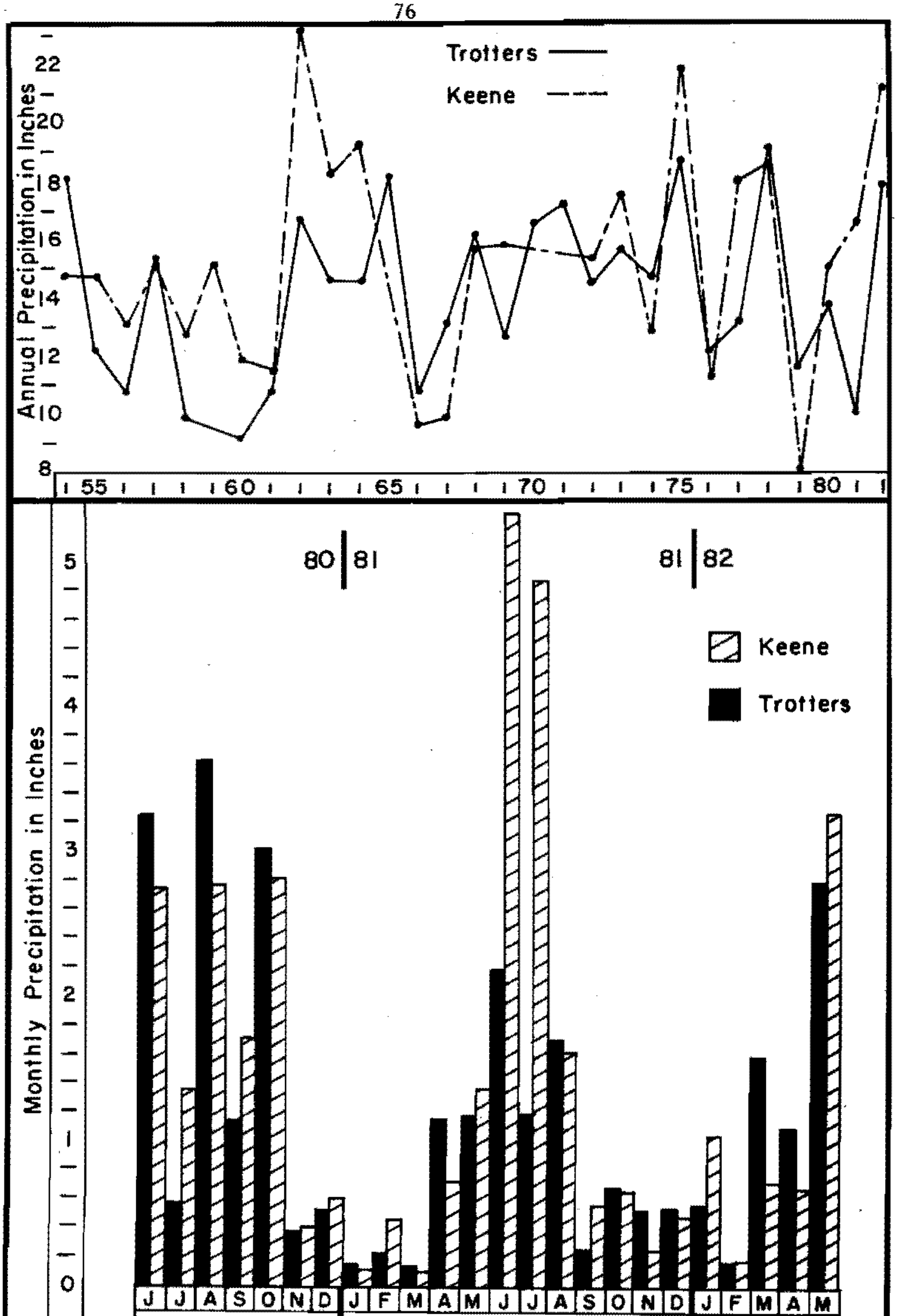
RESULTS

Precipitation at Sites During Study Period.—Precipitation was estimated at the four study sites between August of 1980 and November of 1981 using monthly totals from nearby U.S. Weather Bureau gauging stations. Three of the monitored sites (Belco Corp., Texaco-NCT, and Apache Corp.) are in close proximity to the Trotters 3 se gauging station. The Texaco Charlson site is in an area monitored by the Keene gauging station.

During 1981 the Keene station recorded 16.52 inches (41.96 cm) of precipitation (fig. 32). The mean annual precipitation for this station over the last twenty-eight years has been 15.35 inches (38.99 cm). Therefore, the amount of precipitation that fell in and around the Texaco Charlson C133 site during the study period was slightly more than an inch (2.5 cm) above normal. Ten inches (25.4 cm) of this moisture fell during the months of June and July (fig. 32).

The Trotters 3 se station recorded only 9.87 inches (25.07 cm) of precipitation during 1981. This was nearly five inches (12.7 cm) less than the twenty-eight year annual mean of 14.36 inches (36.47 cm). The precipitation that fell on the Texaco NCT, Belco Corp., and Apache Corp. study sites during this period was the fifth lowest amount in the last twenty-nine years (fig. 32).

Figure 32. Annual and monthly precipitation totals from the Trotters 3se and Keene gauging stations. Annual precipitation is for the years of 1954-1982. Monthly precipitation is for the period of June 1980 through May 1982 (from National Oceanic and Atmospheric Administration, 1981).


Trotters
Keene
Annual Precipitation in Inches
8
10
12
14
16
18
20
22
55
60
65
70
75
80
Monthly Precipitation in Inches
0
1
2
3
4
5
80 | 81
81 | 82
Keene
Trotters
J J A S O N D J F M A M J J A S O N D J F M A M

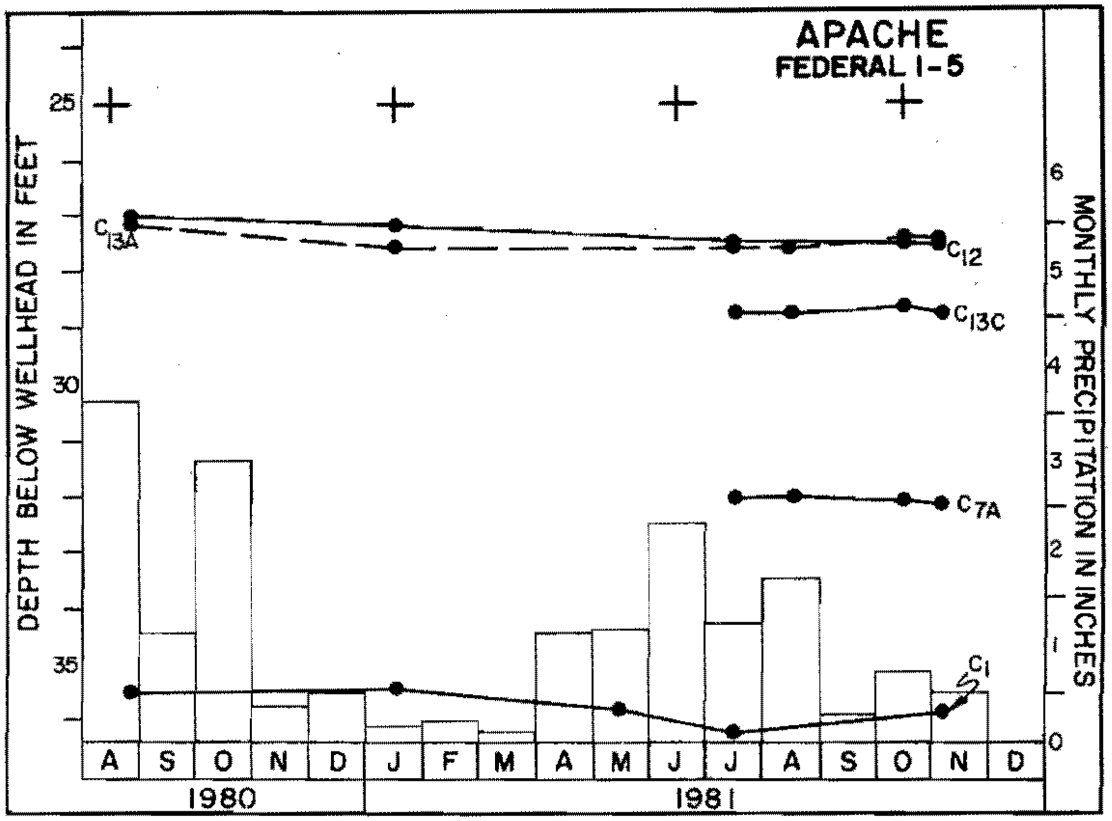
Groundwater Recharge at Sites During Study Period.--Groundwater was monitored at the two study sites which have shallow groundwater tables (Apache Federal 1-5 and Texaco Charlson C133). Water-level readings were taken a total of 8 times over a span of 16 months. Difficulties in travel to each site and the frequent inaccessibility of water level tapes made monthly readings impractical. In the absence of monthly control, quantitative recharge data could not be determined for each site.

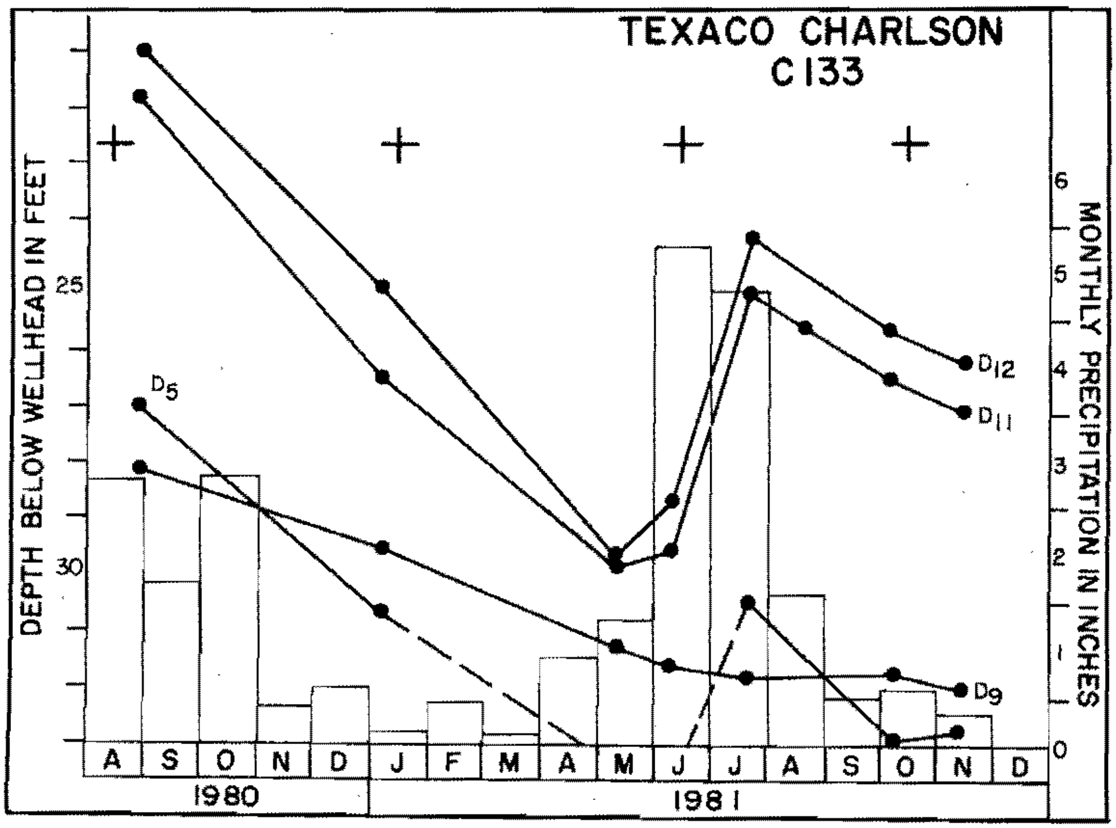
The water table remained relatively constant during the period of study at the Apache Federal 1-5 site (fig. 33). Most of the water levels declined slightly during the interim from August of 1980 through July of 1981. The levels then slightly increased through the end of the monitoring period. A portion of the October 1981 precipitation could have resulted in groundwater recharge because of the coinciding low to negligible evapotranspiration rates. Below-average recharge is believed to have taken place in the spring of 1981 and very little, if any, took place again until October of that year.

The water table at the Texaco Charlson C133 site fluctuated significantly during the study period (fig. 34). As previously discussed, these changes correlated precisely with the fluctuating water levels of the adjacent Sakakawea Reservoir (fig. 25). The water table fluctuations also correlate with precipitation during the months of June and July. Although significant amounts of precipitation infiltrated to the saturated zone during this time, the 5 foot (1.5m) water table rise is attributed to the adjacent

Figure 33. Water table levels and monthly precipitation totals for the Apache Corp. Federal #1-5 site. Monitored from August of 1980 through December of 1981. Quarterly water sampling dates indicated by (+).

Figure 34. Water table levels and monthly precipitation totals for the Texaco Inc. Charlson Madison North Unit C133 site. Monitored from August of 1980 through December of 1981. Quarterly water sampling dates indicated by (+). Well number D_9 is believed to have a faulty screened interval.


APACHE
FEDERAL 1-5
DEPTH BELOW WELLHEAD IN FEET
MONTHLY PRECIPITATION IN INCHES
25
30
35
0
1
2
3
4
5
6
C13A
C12
C13C
C7A
C1
A S O N D J F M A M J J A S O N D
1980
1981


TEXACO CHARLSON
C133
DEPTH BELOW WELLHEAD IN FEET
MONTHLY PRECIPITATION IN INCHES
25
30
0
1
2
3
4
5
6
D5
D12
D11
D9
A S O N D J F M A M J J A S O N D
1980
1981

rise of the reservoir.

During the study period the shallow groundwater flow at the Texaco Charlson C133 site was to the north. The relationship between the local water table and the reservoir level could produce a reduction in gradient and even a reversal in the groundwater flow direction. This could occur as a result of a higher lake level.

No recharge data is available for the Texaco Gov't. (NCT-1) and Belco Petroleum Sheep Creek 1-11 sites because the saturated zone could not be reached to be monitored. Considerably less recharge is believed to have occurred at these two sites, in comparison to the Apache Federal 1-5 sites, because of their greater depth to the water table.

Textural Analyses.--A total of 57 sediment samples from the four study sites was texturally analyzed (Appendix C). The mean sand, silt, and clay ratios for each site are:

	% Sand	% Silt	% Clay
Texaco Gov't. NCT-1	14.7	43.7	41.6
Belco B.N. #1-11	5.8	50.5	43.7
Apache Federal #1-5	15.6	55.8	28.6
Texaco Charlson C133	22.8	44.6	32.6

The mean and effective grain sizes were determined for the sand and sandy gravel layer at both the Apache and Texaco Charlson site. The resulting sediment size in mm is:

	d_{10}	d_{50}
Apache Federal #1-5	0.177	3.0
Texaco Charlson C133	0.153	3.9

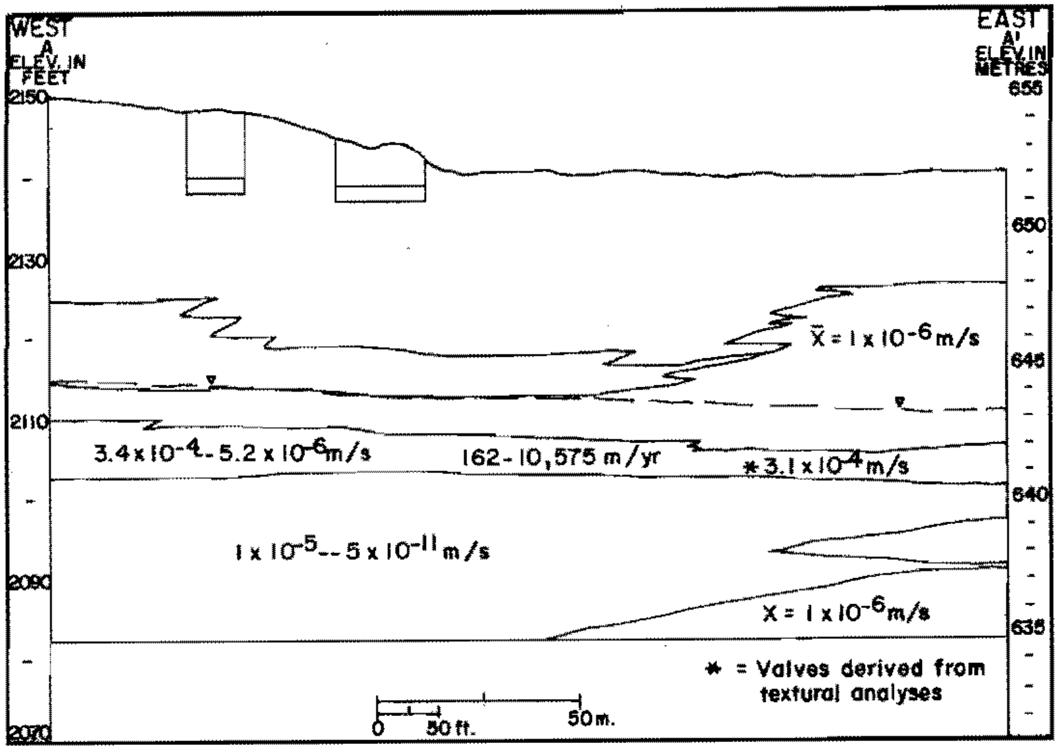
Hydraulic Conductivity.--Hydraulic conductivity values for sediment within the saturated zone at the Apache Federal #1-5 and Texaco Charlson C133 sites are presented in figures 35 and 36. These values were derived from single-well-response tests, textural analyses, and from published data on similar sediments in this area. The saturated hydraulic conductivity values for the sandy gravel layers at these two sites ranged from 2.0×10^{-4} to 5.2×10^{-6} m/s. The values for the silty sand deposits ranged from 1.0×10^{-5} to 1.0×10^{-6} m/s.

Water Analyses from the Unsaturated Zone.--A total of 119 individual water samples was analyzed by the North Dakota State Department of Health. One hundred of these were analyzed for both trace metal and major ion content. The water sample analyses are listed for each study site in Appendix D. These samples were obtained from the unsaturated and saturated zones.

Profiles of 20 chemical parameters from the Texaco Gov't. (NCT-1) site are presented in figure 37. The values plotted are the means of quarterly water samples from the unsaturated zone. A number of parameters had extremely high concentrations in the pore water beneath the reserve pits: TDS (152,000 mg/L), Cl^- (91,250 mg/L), Na (60,300 mg/L), NO_3^- (264 mg/L as N), As (93 ug/L), Cr (98.2 ug/L), and Pb (619 ug/L). These maximum concentration levels were attained by most constituents (excluding NO_3^-) 4 to 6 feet (1.2-1.8m) beneath the bottom of the buried drilling fluid. Most of these concentrations had been reduced significantly in pore

Figure 35. Ranges and means of hydraulic conductivities at the Apache Corp. Federal #1-5 site. The values presented are for sediment under saturated conditions (for lithology see figure 31).

Figure 36. Ranges and means of hydraulic conductivities at the Texaco Inc. Charlson Madison North Unit C133 site. The values presented are for sediment under saturated conditions (for lithology see figure 24).


WEST
A
ELEV. IN
FEET
EAST
A'
ELEV. IN
METRES
2150
2130
2110
2090
2070
655
650
645
640
635
X̄ = 1 x 10-6 m/s
3.4 x 10-4 - 5.2 x 10-6 m/s
162 - 10,575 m/yr
* 3.1 x 10-4 m/s
1 x 10-5 -- 5 x 10-11 m/s
X = 1 x 10-6 m/s
* = Valves derived from textural analyses
0
50 ft.
50 m.

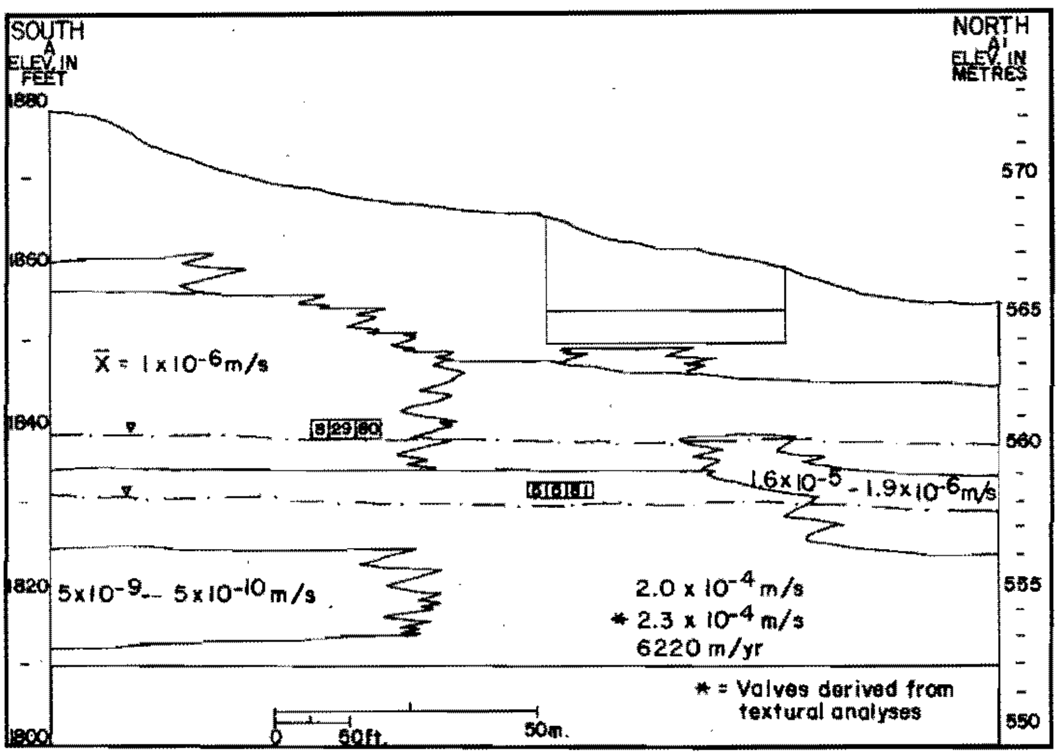
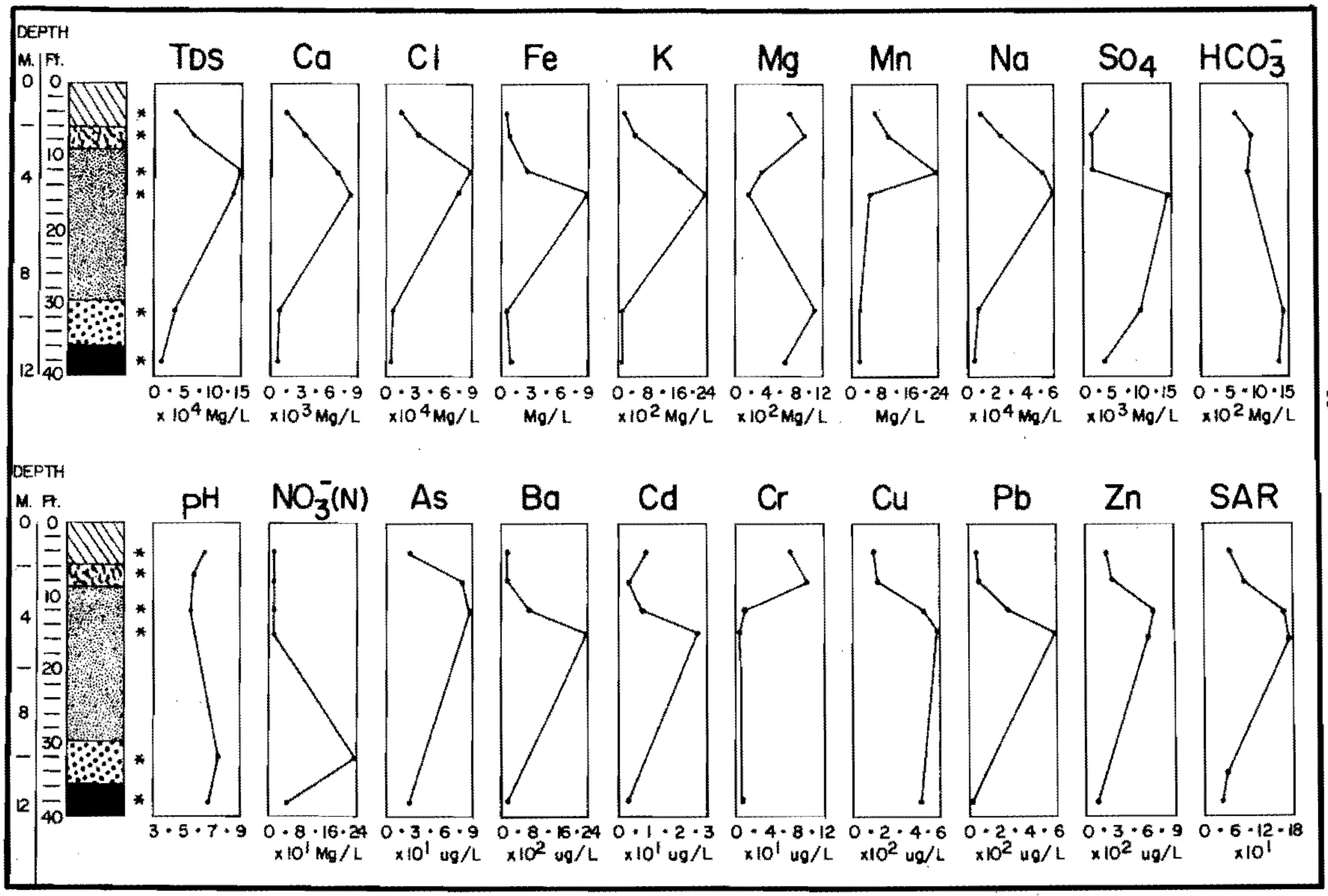

SOUTH
A
ELEV. IN
FEET
NORTH
A'
ELEV. IN
METRES
1880
1860
1840
1820
1800
570
565
560
555
550
X̄ = 1 x 10-6 m/s
8 29 80
8 6 81
1.6 x 10-5 - 1.9 x 10-6 m/s
5 x 10-9 -- 5 x 10-10 m/s
2.0 x 10-4 m/s
* 2.3 x 10-4 m/s
6220 m/yr
* = Valves derived from textural analyses
0
50 ft.
50 m.

Figure 37. Concentration profiles for various parameters in pore water within the unsaturated zone at the Texaco Inc. Government "A" (NCT-1) site. Position of soil water samplers indicated by (*). For lithology see legend for figure 24.


DEPTH
M. Ft.
TDS
Ca
Cl
Fe
K
Mg
Mn
Na
SO4
HCO3-
0 • 5 • 10 • 15 x 10^4 Mg/L
0 • 3 • 6 • 9 x 10^3 Mg/L
0 • 3 • 6 • 9 x 10^4 Mg/L
0 • 3 • 6 • 9 Mg/L
0 • 8 • 16 • 24 x 10^2 Mg/L
0 • 4 • 8 • 12 x 10^2 Mg/L
0 • 8 • 16 • 24 Mg/L
0 • 2 • 4 • 6 x 10^4 Mg/L
0 • 5 • 10 • 15 x 10^3 Mg/L
0 • 5 • 10 • 15 x 10^2 Mg/L
DEPTH
M. Ft.
pH
NO3-(N)
As
Ba
Cd
Cr
Cu
Pb
Zn
SAR
3 • 5 • 7 • 9
0 • 8 • 16 • 24 x 10^1 Mg/L
0 • 3 • 6 • 9 x 10^1 ug/L
0 • 8 • 16 • 24 x 10^2 ug/L
0 • 1 • 2 • 3 x 10^1 ug/L
0 • 4 • 8 • 12 x 10^1 ug/L
0 • 2 • 4 • 6 x 10^2 ug/L
0 • 2 • 4 • 6 x 10^2 ug/L
0 • 3 • 6 • 9 x 10^2 ug/L
0 • 6 • 12 • 18 x 10^1

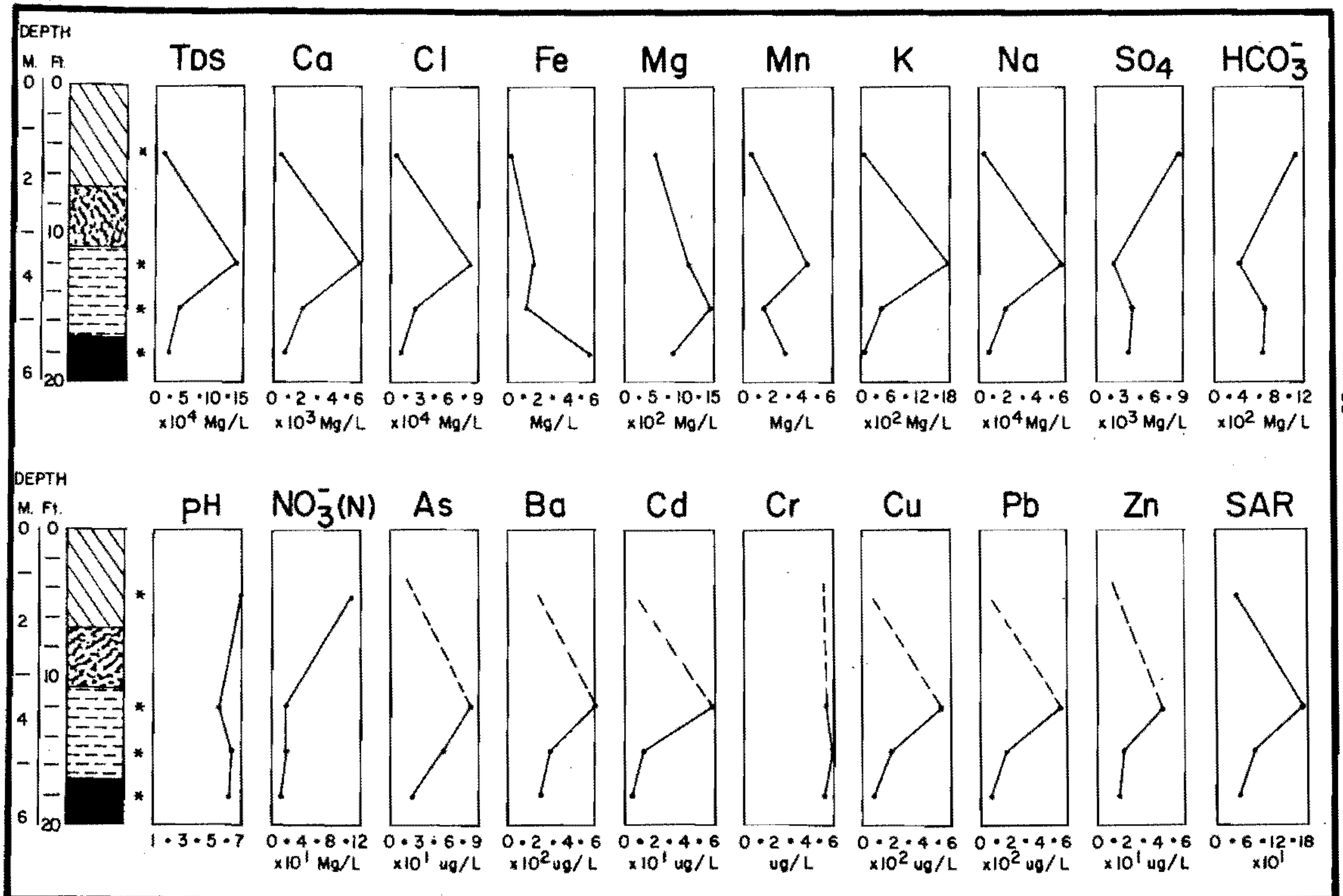
water within 20 feet (6.1m) of the base of the buried fluid; TDS (17,300 mg/L), Cl^- (2750 mg/L), Na (5355 mg/L), As (26 ug/L), Cr (3.2 ug/L), and Pb (8.5 ug/L). The pore water in the unsaturated zone at this site is slightly acidic.

Profiles for chemical parameters from the Belco Petroleum B.N. Sheep Creek #1-11 are presented in figure 38. The values plotted for the 20 chemical parameters are the mean values of quarterly water samples from the unsaturated zone. The maximum concentration levels of most of these ions were found at a level 2 feet (0.6m) beneath the bottom of the buried drilling fluid: TDS (136,000 mg/L), Cl^- (81,250 mg/L), Na (57,950 mg/L), As (80.4 ug/L), Cr (5.6 ug/L), and Pb (540 ug/L). Most of these concentrations had been significantly reduced within a depth of 8 feet (2.4m) beneath the drilling fluid: TDS (29,950 mg/L), Cl^- (13,133 mg/L), Na (8800 mg/L), As (24.3 ug/L), Cr (5.4 ug/L), and Pb (93 ug/L). The pore water throughout the unsaturated zone at this site is slightly acidic.

Only one water sample was recovered from the unsaturated zone at the Apache Federal 1-5 site (C_{10}, Appendix D). This sample was obtained from 10 feet (3m) beneath the bottom of the reserve pit, 20 feet (6m) beneath the surface. The concentrations of many parameters were very high at this depth: TDS (53,200 mg/L), Cl^- (25,000 mg/L), Na (17,900 mg/L), NO_3^- (203 mg/L as N), As (43.3 ug/L), Cr (18.9 ug/L), and Pb (188 ug/L). The pH of this pore water was 6.5.

At the Texaco Charlson C133 site water samples were recovered from depths of 3 feet (1m) and 10 feet (3m) beneath the base of the

Figure 38. Concentration profiles for various parameters in pore water in the unsaturated zone at the Belco Petroleum B.N. Sheep Creek #1-11. Position of soil water samplers indicated by (*). See legend of figure 24 for lithology.


DEPTH
M. Ft.
TDS
Ca
Cl
Fe
Mg
Mn
K
Na
SO4
HCO3-
0 • 5 • 10 • 15
x10^4 Mg/L
0 • 2 • 4 • 6
x10^3 Mg/L
0 • 3 • 6 • 9
x10^4 Mg/L
0 • 2 • 4 • 6
Mg/L
0 • 5 • 10 • 15
x10^2 Mg/L
0 • 2 • 4 • 6
Mg/L
0 • 6 • 12 • 18
x10^2 Mg/L
0 • 2 • 4 • 6
x10^4 Mg/L
0 • 3 • 6 • 9
x10^3 Mg/L
0 • 4 • 8 • 12
x10^2 Mg/L
DEPTH
M. Ft.
pH
NO3-(N)
As
Ba
Cd
Cr
Cu
Pb
Zn
SAR
1 • 3 • 5 • 7
0 • 4 • 8 • 12
x10^1 Mg/L
0 • 3 • 6 • 9
x10^1 ug/L
0 • 2 • 4 • 6
x10^2 ug/L
0 • 2 • 4 • 6
x10^1 ug/L
0 • 2 • 4 • 6
ug/L
0 • 2 • 4 • 6
x10^2 ug/L
0 • 2 • 4 • 6
x10^2 ug/L
0 • 2 • 4 • 6
x10^1 ug/L
0 • 6 • 12 • 18
x10^1

reserve pit (D_7 and D_8, Appendix D). The concentrations of many parameters did not decrease as expected but commonly increased within this interval; TDS (19,000-26,200 mg/L), Cl^- (10,000-12,000 mg/L), Na (5970-7470 mg/L), NO_3^- (47.1-138 mg/L), As (18.5-26.5 ug/L), Cr (2.9-22.4 ug/L), and Pb (35-33 ug/L). The pore water within this interval is slightly acidic.

Elutriation Experiment.--Ten sediment samples from the unsaturated zones at the Texaco (NCT-1) and Apache Corp. Federal #1-5 were elutriated. The test was performed to obtain additional pore water chemistry at these sites. Distilled water was used at a sufficiently high solution-to-sediment ratio to minimize the possibility of ions reaching the saturation point.

The concentrations of seven selected parameters in fluids separated by elutriation of sediment samples at the Apache Corp. Federal 1-5 site is presented in figure 39. The maximum-concentration-levels of many parameters were in fluids that had either been mixed with drilling fluid or sediment that was from 3 feet (1m) beneath the base of the reserve pit. In this analysis Cr ranged from 26.6 ug/L in the drilling fluid to 6.3 ug/L in fluid mixed with sediment 7.5 feet (2.3m) beneath the reserve pit. Chloride was reduced from 350 mg/L to 64 mg/L within this same interval.

The water analyses of the elutriation experiments from the Texaco Gov't. (NCT-1) site demonstrate a maximum concentration of most of these parameters within the drilling fluid (fig. 40). Some of the parameters reach maximum concentrations in sediment 14 feet

Figure 39. Concentration profiles for various parameters in elutriated sediment samples from the Apache Corp. Federal #1-5 site. Textural analyses were determined by the hydrometer method (Appendix C). The (*) indicates the depth the elutriated sample was taken from, (·) indicates the depth of the sediment for hydrometer textural analyses. See legend of figure 24 for lithology.

Figure 40. Concentration profiles for various parameters in elutriated sediment samples from the Texaco Inc. Government "A" (NCT-1) site. Textural analyses were determined by the hydrometer method (Appendix C). The depth of the elutriated sample indicated by (*) and the depth of the sediment samples for hydrometer textural analyses indicated by (·). See legend of figure 24 for lithology.

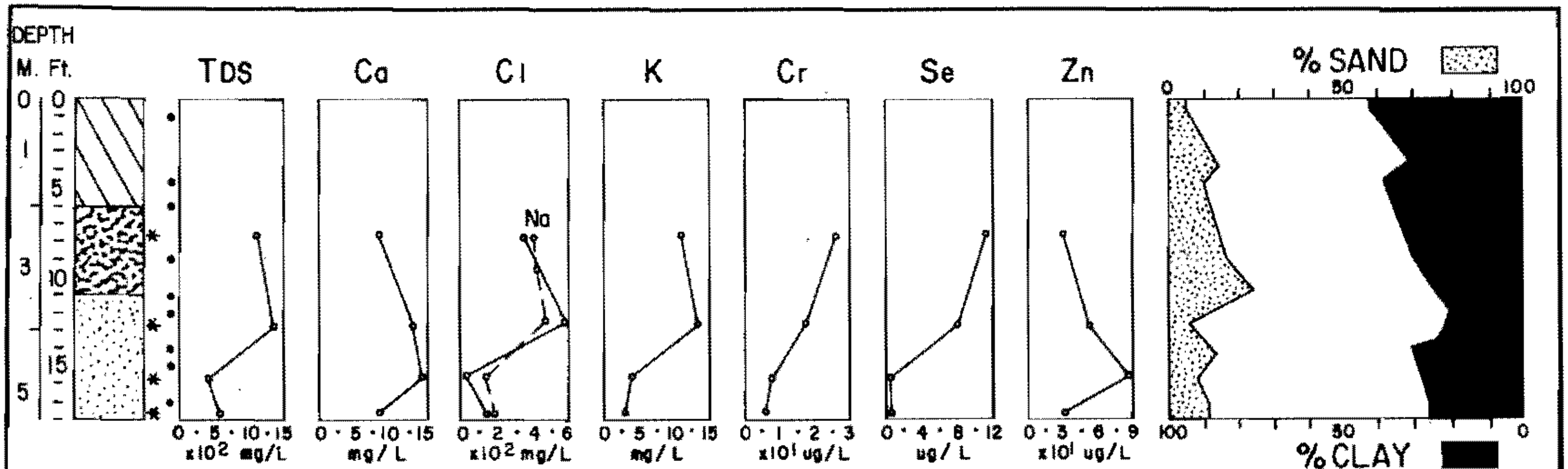

DEPTH
M. Ft.
TDS
Ca
Cl
K
Cr
Se
Zn
Na
% SAND
% CLAY
x10² mg/L
mg/L
x10² mg/L
mg/L
x10¹ ug/L
ug/L
x10¹ ug/L

Fig. 39

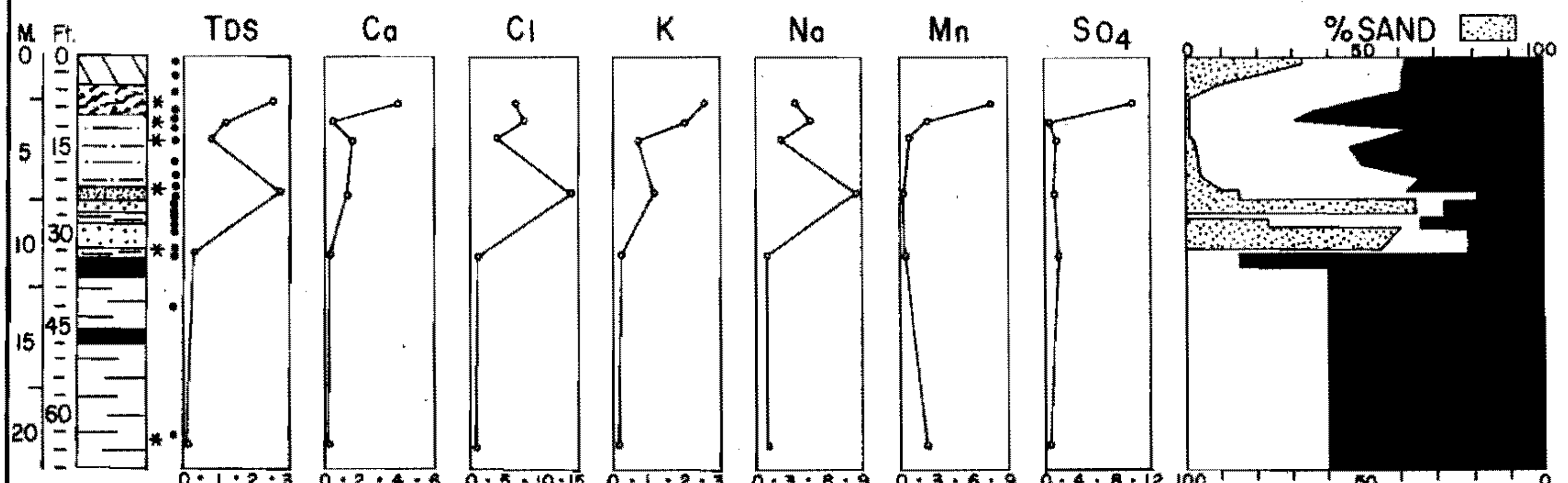

M. Ft.
TDS
Ca
Cl
K
Na
Mn
SO4
% SAND
% CLAY
x10³ mg/L
x10² mg/L
x10² mg/L
x10¹ mg/L
x10² mg/L
x10⁻¹ mg/L
x10² mg/L

Fig. 40

(4.3m) beneath the base of the reserve pit: TDS (2540 mg/L), Cl^- (1380 mg/L), and Na (947 mg/L). The concentration of all of the measured parameters was very low in the fluid mixed with sediment from a depth of 64 feet (19.5m): TDS (264 mg/L), Cl^- (5 mg/L), and Na (104 mg/L).

The ion profiles (figs. 39 and 40) from the elutriation experiment demonstrate a general decrease in concentration with increased depth from the buried drilling fluid. Although the results from this method do not necessarily represent the actual pore water chemistry in the unsaturated zone, they do demonstrate the reduction in leachate concentration as the distance from the reserve pit increases.

Water Analysis from the Saturated Zone.--Isoconcentration maps of 24 chemical parameters from the Apache Federal #1-5 site are presented in Appendix E. These maps represent the groundwater chemistry for the upper 10 feet (3m) of the saturated zone at this site. These isoconcentration maps were constructed to enable determination of the lateral extent of leachate migration within this zone. The values plotted are the mean of quarterly water samples from the saturated zone. The background chemical concentration levels were obtained from piezometers and shallow water wells upgradient from the site. The highest concentrations recorded for most parameters in the saturated zone were beneath the reserve pit: TDS (12,100 mg/L), Cl^- (4500 mg/L), Na (3520 mg/L), NO_3^- (< 2 mg/L as N), As (15 ug/L), Cr (1.8 ug/L), and Pb (26 ug/L). The concentrations of all parameters returned to background levels within 200 feet (61m) downgradient from the reserve pit: TDS (3610 mg/L), Cl^- (13 mg/L), Na (944 mg/L), As (4.6 ug/L), Cr (2.6 ug/L), and Pb (9.0 ug/L). The pH is slightly acidic (6.4) within the effected zone to slightly alkaline (7.2) outside of this area.

Isoconcentration maps of 24 chemical parameters from the Texaco Charlson C133 site are presented in Appendix E. These maps represent the groundwater chemistry for the upper 15 feet (4.6m) of the saturated zone at this site. Background chemical concentration levels were obtained from piezometers and shallow water wells upgradient from the site. The highest concentrations recorded for most parameters in the saturated zone, with the exception of NO_3^-, were recorded beneath the reserve pit: TDS (16,100 mg/L), Cl^- (4875 mg/L), Na (3940 mg/L), NO_3^- (1160 mg/L as N), As (22 ug/L), Pb (53 ug/L), and Se (272 ug/L). Most of these parameters returned to background concentrations within a 300 to 400 foot (91-122m) radius of the reserve pit: TDS (4810 mg/L), Cl^- (38 mg/L), Na (766 mg/L), NO_3^- (35.1 mg/L as N), As (6.2 ug/L), Pb (14 ug/L), and Se (<2 ug/L). The pH of the groundwater is slightly acidic (6.5-6.8) within the effected area.

No water samples were obtained from the saturated zone at either the Texaco Gov't. (NCT-1) or Belco Petroleum B.N. Sheep Creek 1-11 study sites.

Apparent Resistivity.--Apparent resistivity values for the Apache Federal #1-5 and Texaco Charlson C133 sites are plotted vertically in Appendix F. Some of the lithologies and the water table depth are discernible from the resistivity values of these profiles. However, their detection is a function of the electrode spacing. The effect of the drilling fluid in reducing the apparent resistivity values can be observed in stations 16 and 21 of the Texaco Charlson site (Appendix F).

These same apparent resistivity values are presented in iso-resistivity maps of the five electrode spacings at each site (figs. 41-44). At the Apache site a plume of low resistivity originates in the reserve pit and extends in the direction of groundwater flow. The low resistivity plume at the Texaco Charlson C133 site is large and extends both upgradient and downgradient from the local groundwater flow direction.

In the presentation of the apparent resistivity profiles the electrode spacing and depth of current penetration are depicted as equal. This has been found to be generally true for electrode spacings of less than 100 feet (30.5m) (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).

Chemical Composition of Drilling Fluid at Study Sites.--The records of drilling activity and drilling fluid additives were no longer available for the two oldest sites, Texaco Charlson C133 (1955) and Texaco Gov't. NCT-1 (1960). The records (mud

Figure 41. Apparent resistivity stations and isoresistivity maps for electrode spacings of 12 and 30 feet (3.7 and 9.1m) for the Apache Federal #1-5 site. The values for each station are given in Appendix F. See legend of figure 23 for symbols.

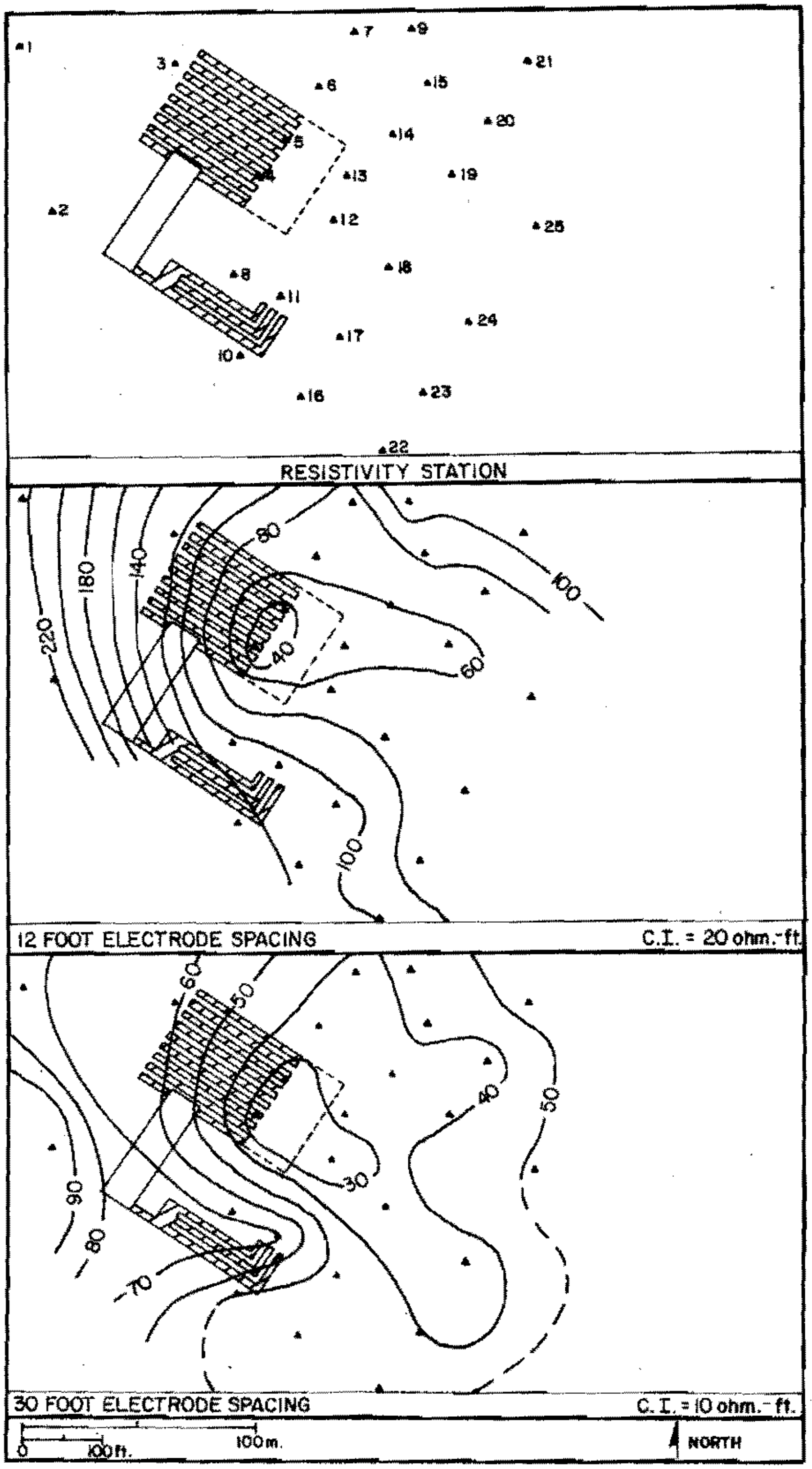

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
RESISTIVITY STATION
220
180
140
80
100
40
60
100
12 FOOT ELECTRODE SPACING
C.I. = 20 ohm.-ft.
60
50
40
50
30
90
80
70
30 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
0
100 ft.
100 m.
NORTH

Figure 42. Apparent isoresistivity maps for electrode spacings of 40, 60, and 80 feet (12.2, 18.3, and 24.4m) at the Apache Federal #1-5 site. The values for each resistivity station are given in Appendix F. See legend of figure 23 for symbols.

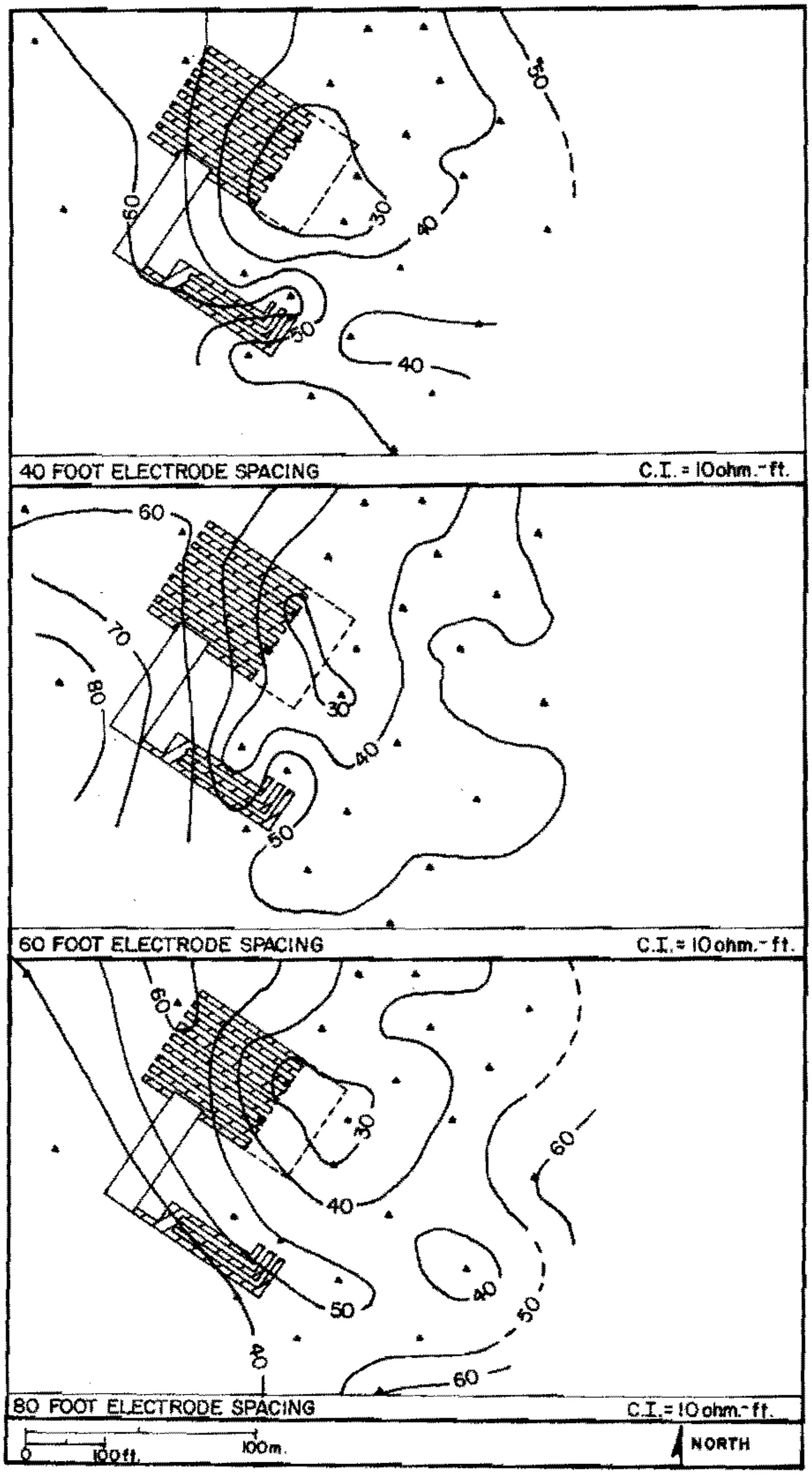

40 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
60 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
80 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
0
100 ft.
100 m.
NORTH

Figure 43. Apparent resistivity stations and isoresistivity maps for electrode spacings of 12 and 30 feet (3.7 and 9.1m) at the Texaco Charlson Madison North Unit C133 site. Values for each resistivity station are plotted in Appendix F. See legend of figure 23 for symbols.

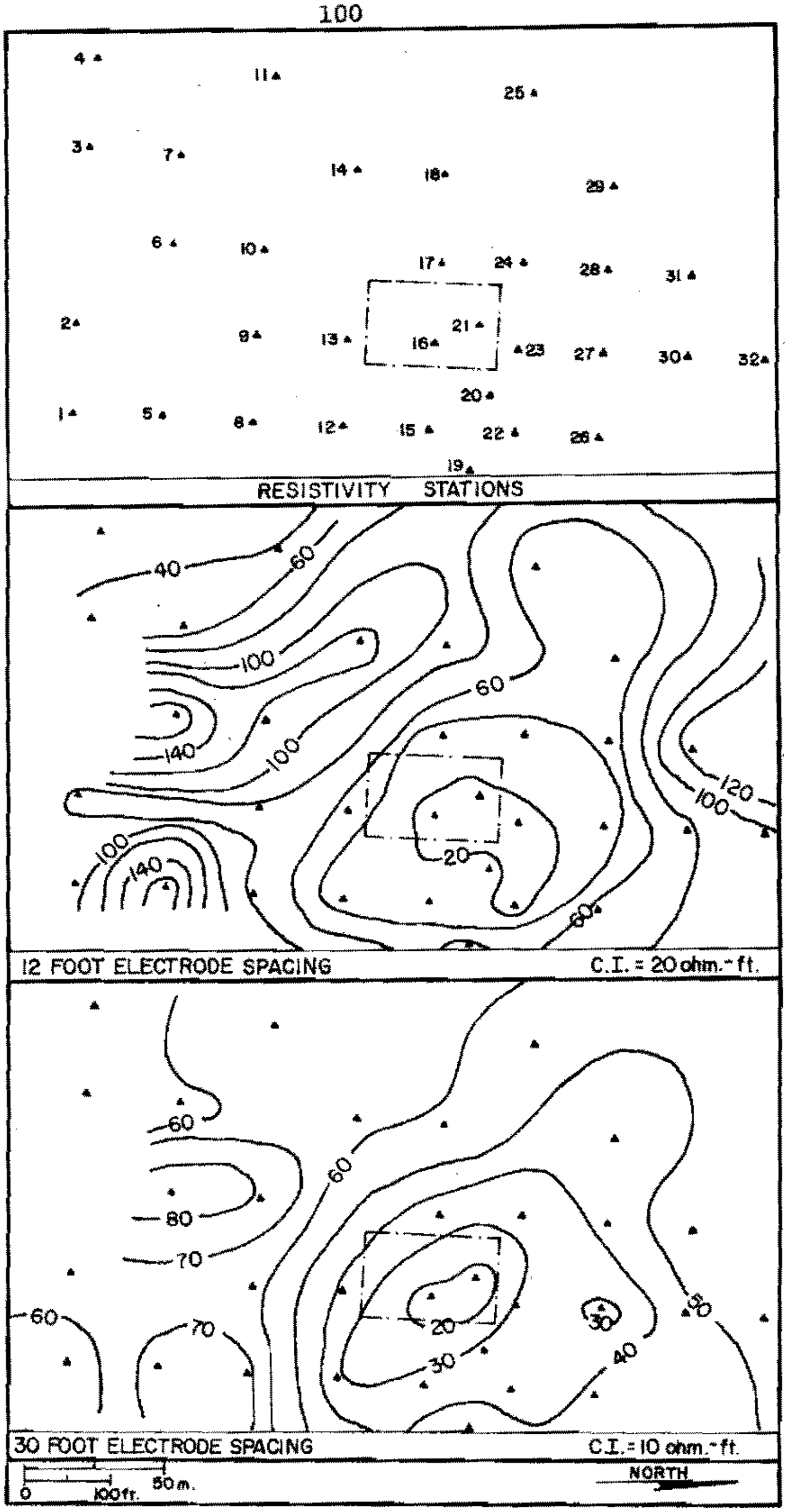
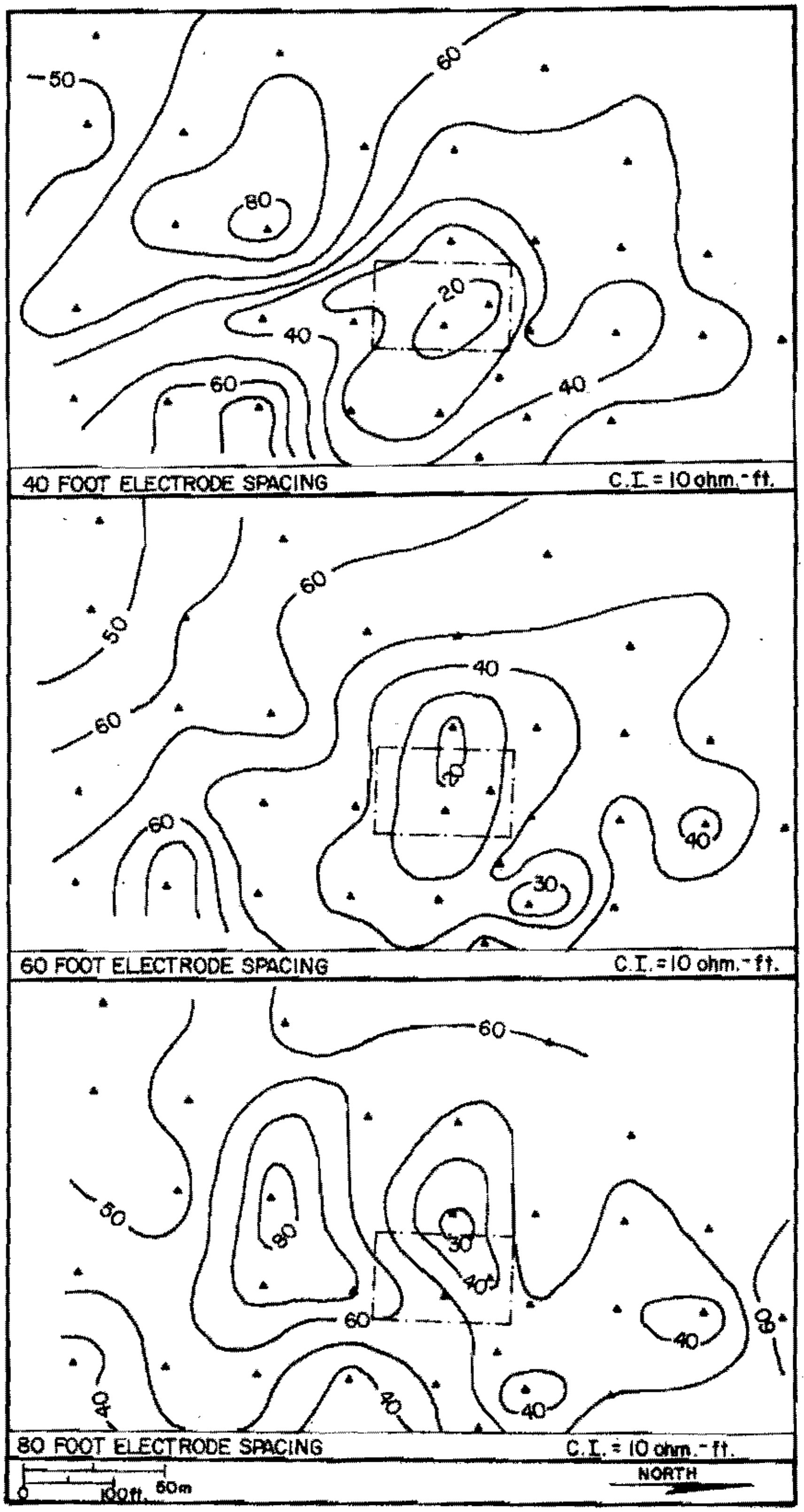

RESISTIVITY STATIONS
12 FOOT ELECTRODE SPACING
C.I. = 20 ohm.-ft.
30 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
0
100 ft.
50 m.
NORTH

Figure 44. Apparent isoresistivity maps for electrode spacings of 40, 60, and 80 feet (12.2, 18.3, and 24.4m) at the Texaco Charlson Madison North Unit C133 site. Values for each resistivity station are plotted in Appendix F. See legend of figure 23 for symbols.



50
60
80
20
40
60
40
40 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
60
50
60
40
20
60
40
30
60 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
60
50
80
30
40
60
40
60
40
40
40
80 FOOT ELECTRODE SPACING
C.I. = 10 ohm.-ft.
0
100ft.
50m
NORTH

recapitulation sheets) were obtained for the Belco Petroleum and Apache Corp. sites. The type and quantity of drilling additives were estimated from these reports (Appendix G).

The concentration range for the chemical parameters from the mud engineer's report at the Belco Petroleum and Apache Corp. study sites is given in table 2. A sample of drilling fluid was taken from the Apache Corp. Federal #1-5 just prior to the reclamation of the site. The analysis of the fluid indicates that the majority of the chemical parameters measured exceed the background levels at this site by factors of 10 to 10,000 (table 2).

Sources of Error in Study.--There has been concern in recent years for potential chemical biassing of water samples collected by soil water samplers. The concern is with the ceramic cup through which the water sample is drawn. The effective pore diameter of this cup is approximately one micron, too small to allow the passage of some colloids and bacteria. The concentration levels of some trace elements and NO_3^- in the water samples may be limited or reduced by adsorption by the ceramic matrix. Because of the extremely high ion concentrations of the pore water sampled by these devices, the effects of the ceramic cup were considered to be negligible. The soil water samplers function irregularly and the ceramic cup pores can become irreversibly plugged if not properly installed. The water sample recovery success was 39% during this study.

The sand and sandy gravel layers at the Apache and Texaco Charlson sites posed a significant problem to piezometer installation.

Table 2. The range of selected chemical concentrations in drilling fluid and chemical analyses of the Apache re-entry drilling fluid. The concentration ranges were obtained from mud engineer reports. The sample of Apache re-entry drilling fluid was taken from the reserve pit 48 hours prior to reclamation.

	NaCl (ppm)	Chromate (ppm)	Nitrates (mg/L)
Belco Petro.	135,000 - 197,000	*	*
Apache Corp.	277,000 - 300,000	735-950	65-198
Apache Re-entry	297,000 - 318,000	500-1500	25-175
Rec. Conc.	320,000	400-800	*

	Apache Re-entry Drilling Fluid	Background Level
Cond. mhos/cm.	203,000	4500-6500
TDS mg/L	257,000	3500-5000
Fe mg/L	4.5	0.14.0.16
Mn mg/L	0.92	1-3
Ca mg/L	8250	150-200
Mg mg/L	166	80-100
K mg/L	1510	16-20
Na mg/L	70,500	1000-1200
Cl mg/L	175,000	15-30
SO_4 mg/L	887	2000-2500
HCO_3 mg/L	213	1200-1400
F mg/L	0	0.5-0.7
% Na	87.7	75-78
As ug/L	451	5-8
Ba ug/L	0	200-250
Cd ug/L	59.2	0.5-1.5
Cr ug/L	331	1-3
Cu ug/L	650	10-50
Pb ug/L	346	3-10
pH	7.2	7.0-7.2
Se ug/L	0	<2
Zn ug/L	300	30-80
No_3 mg/L	1030	<2

The majority of auger holes collapsed and the piezometers had to be pounded through these intervals. The thickness of these collapsed intervals ranged from 5 to 20 feet (1.5-6.1m). Because of this collapsed sediment, the cement plugs could not be properly installed above the screened interval. The improper sealing of these piezometers allowed the leachate in the gravel layers to travel unobstructed through the auger hole backfill and into the screened interval. This was apparently the case with piezometers C_{7B} and C_{13C} at the Apache study site.

The basis for clay percentage determination by the hydrometer method is the change in water density due to the suspended clay particles. A very high NaCl content was found in the pore water and sediments beneath the reclaimed reserve pits. There was concern that this salt content would be sufficiently high to substantially increase the density of the hydrometer tested water. This would result in erroneously high clay percentages. A series of liquid decantations was suggested to reduce the NaCl content but was not attempted because of possible loss of clay particles. The sediment percentages obtained in this study are thought to be within the normal margin of error for the hydrometer method.

DISCUSSION

Attenuation of Dispersion of Leachate.--There are two main types of drilling fluid leachate. The first is the initial less viscous fluid component of the buried waste. This is the portion that is supposed to be sucked out of the pit prior to reclamation. The other is the leachate generated by infiltrating precipitation. Both of these leachates are subject to the controls of the hydrogeochemical model that was described earlier. Evapotranspiration of this leachate will cause the near surface accumulation of NaCl crystals.

Exceptional precipitation events will flush the salt and leach other soluble constituents from the buried drilling fluid. This leachate will eventually reach the saturated zone and will flow along with the groundwater. The nonreactive solutes, generally the dissolved anions, will be carried at a rate equal to the average linear velocity of the groundwater. Unless there is a constant influx of leachate, the leachate plume in the saturated zone will become increasingly dilute away from the source. This dilution is largely a result of hydrodynamic dispersion, a mixing process caused by the differences in flow velocity in the saturated porous medium. Molecular diffusion is another dispersive process where the ions or molecules migrate under a chemical gradient from regions of high concentrations to regions of low concentrations. This is a relatively slow process and is only important under low groundwater velocity conditions (Freeze and Cherry, 1979).

Transfer of the solutes from the porewater to the porous medium retards the movement of the leachate plume. Chief among these transfer processes is adsorption by clay minerals. A landfill study in Illinois concluded that leachate had to travel through 700 feet (213.4m) of sand to achieve the same attenuation provided by 5 feet (1.5m) of clay till (Cartwright and Sherman, 1972). As discussed earlier, these dissolved ions are discriminately adsorbed as a function of concentration, charge, and ionic radius. Foremost among the most highly attenuated ions are the trace metals.

Initially, burial of the drilling fluid in the unlined trenches produces leachate at a near-constant rate from the desiccation of this drilling mud and the downward migration of the less viscous part of the fluid. If emplaced above the water table, the buried drilling fluid eventually will desiccate, after which leachate will normally be generated only after exceptional rainfall or snowmelt events. This infrequently (seasonally) generated leachate will normally be subject to attenuation on clay minerals in the unsaturated and saturated zones and by dispersion in the saturated zone.

At both the Apache and Texaco Charlson sites the high clay content in the unsaturated zone should retard movement of most of the ions by adsorption onto the sediment matrix. Mechanical dispersion is assumed to be the dominant dilution process in the saturated sandy gravel zones. Longitudinal dispersion is the prevalent dispersive process in the sandy gravel layer at the Apache site (Appendix E). A groundwater gradient reduction or flow reversal at the Texaco C133 site would explain the shape and location of the leachate plume at this site. If the groundwater flow has remained constant at this site, the configuration of the leachate plume is most likely a result of longitudinal and transverse dispersion in the saturated zone (Appendix E).

The chloride ion was selected for special attention during this project for a number of reasons. The normal concentration level for the chloride ion in the shallow groundwater systems of western North Dakota commonly ranges from a few to several tens of milligrams per litre (Groenewold et al., 1979). The average concentration of the chloride ion in oil-and-gas well drilling fluids in North Dakota is 150,000 mg/L (table 2). In addition, the chloride ion is a mobile anion in the soil system. This low susceptibility to attenuation is attributed to the relative noninteraction between clay minerals and the chloride ion (Griffin et al., 1976). The extremely high concentration of chloride ions in drilling fluid and its mobility in the subsurface make it an excellent indicator of leachate migration. This ion can generally be used to monitor the maximum extent of a drilling fluid generated leachate plume in western North Dakota.

Leachate Migration at the Texaco (NCT-1) Site.--The chemical profiles from the Texaco (NCT-1) site (figs. 37 and 40) indicate that many of the ions are being leachated out of the buried drilling fluid. There are a number of trace elements present in high concentrations in the pore water from the buried drilling fluid to a depth of 5 feet (1.5m) beneath the reserve pit: As (93-88 ug/L), Pb (619-253 ug/L), and Zn (726-655 ug/L). These elements are assumed to have been adsorbed onto clay surfaces within the clayey silt interval and are much reduced in concentration in pore water samples from a depth of 30 feet (9.1m): As (26 ug/L), Pb (8.5 ug/L), and Zn (125 ug/L).

Relatively high concentrations of Pb (104-137 ug/L) and Cl^- (9250-5250 mg/L) are present in groundwater from piezometer A_{11} at a depth of 72 feet (21.9m). These concentrations are believed to be the result of leachate traveling down through the annulus to the screened interval in the improperly sealed bore hole and do not represent the true pore water at this level. This assumption is substantiated by analyses of pore water collected at depths of 20 feet (6m) beneath the reserve pit. This pore water contained Cl^- concentrations of only 2750 mg/L.

Leachate Migration at the Belco Petroleum B.N. Sheep Creek #1-11 Site.--The chemical profiles for the Belco Petroleum study site indicate a maximum concentration of most of the ions within a depth of 2 feet (0.6m) of the buried drilling fluid. The chloride ion content is reduced from 93,700 to 12,000 mg/L within the zone from the buried drilling fluid to a depth of 8 feet (2.4m). Within this same interval As is reduced from 163 to 24 ug/L and Pb from 1320 to 93 ug/L. The reduction in concentration of these and other ions in the pore water within the unsaturated zone is attributable to attenuation by clay adsorption.

The Texaco (NCT-1) and Belco Petroleum B.N. Sheep Creek #1-11 study sites are very similar geologically and geohydrologically. As the distance away from the reserve pit is increased in the subsurface, there is a significant reduction in ion concentration in the pore water. This reduction is assumed to be the result of ion attenuation by exchange on clay minerals. This reduction should continue throughout the thick unsaturated zones and, therefore, very little if any leachate should reach the water table at these sites.

Leachate Migration at the Apache Federal #1-5.--The water sample from the unsaturated zone at the Apache site contained high concentrations of Cl^- (25,000 mg/L), NO_3^- (203 mg/L as N), and Pb (188 ug/L). The elutriation experiment demonstrated that leachate decreased in concentration as the depth from the reserve pit increased. In the saturated zone beneath the reserve pit the concentrations of these ions are much reduced: Cl^- (3750 mg/L), NO_3^- (<2 mg/L as N), and Pb (10.0 ug/L). The attenuation of these and other ions in the unsaturated zone, along with dispersion in the upper saturated zone, is believed to be responsible for limiting the drilling fluid leachate to a very small area (250 x 250 feet [76 x 76m]) (Appendix E).

The effect of layered heterogeneities in the subsurface is to focus the leachate migration in the zone of highest hydraulic conductivity. This will occur if the hydraulic conductivity in one zone is at least 100 times that in the others (Freeze and Cherry, 1979). The hydraulic conductivity in the saturated sandy gravel layer at the Apache site is 10^2 to 10^7 times greater than that of the underlying bedrock silty clay. Large concentrations of Cl^-

in samples from piezometers C_{7B}, C_{13B}, and C_{13C} suggest that leachate is not being focused in the gravel layer but is moving through the underlying silty clay. However, these concentrations are believed to be the result of an inadequate seal in the bore hole between the screened interval and the gravel layer. The leachate may have traveled down the outside of the pvc pipe through the gravel backfill. If, on the contrary, these ion concentrations are indeed a true reflection of the groundwater chemistry at this depth, the density of the leachate plume would have to be large enough to overcome the effects of lateral groundwater flow and hydraulic conductivity variations.

Leachate Migration at the Texaco Charlson C133 Site.—Analyses of water samples from the unsaturated zone beneath the reserve pit at this site indicate a high concentration of some parameters and relatively low concentrations of trace elements: TDS (26,200 mg/L), Cl^- (12,500 mg/L), NO_3^- (138 mg/L as N), Pb (17-33 ug/L) and Se (<2 ug/L). The concentrations of most of these parameters are reduced in the saturated zone: TDS (16,100 mg/L) and Cl^- (5000 mg/L). However, for a few parameters the concentrations are increased in this zone: Pb (85 ug/L), Se (260 ug/L), and NO_3^- (818 mg/L as N) (Appendix D and E). The shape and position of the plumes on the isoconcentration maps for Pb and Se indicate that the reserve pit is the source. The decreased concentration of Pb and Se in the unsaturated zone, relative to the saturated zone, is most likely a local phenomenon. This is probably due to the heterogeneity of the buried drilling fluid both in its chemical composition and relative thickness.

The leachate from the reserve pit has created a plume approximately 400 x 300 feet (122 x 91m) within the upper saturated zone at this site. This plume extends both upgradient and downgradient with respect to the local groundwater flow direction (Appendix E). The configuration of this plume is assumed to be the result of either a gradient reduction or reversal in the local groundwater table in recent years or longitudinal and transverse dispersion in the saturated zone.

Extremely high levels of NO_3^-, a very mobile anion, were found in the shallow groundwater at this site. The maximum concentration recorded was 1310 mg/L (reported as N) in the saturated zone and 138 mg/L (reported as N) in the unsaturated zone beneath the reserve pit. The maximum concentration recorded in the saturated zone was 250 feet (76.2m) upgradient from the reserve pit. The shape of the plume seems to indicate a source other than the reserve pit. However, nitrate levels from the drilling fluid at the Apache re-entry are sufficiently high to indicate that buried drilling fluid is a potential source (table 2). The reserve pit could be the source if the adjacent reservoir has caused a groundwater flow reversal in this area.

If the NO_3^- is not being leached from the reserve pit, then alternative sources must be proposed. A small undetected pit to the south of the reserve pit may contain discarded nitrate fertilizer or drilling fluid additives. The source could also be from a surface spill of nitric acid or some other nitrogen compound. However, there is no evidence to support the existence of either of these possible sources. As mentioned in the history section of this site, this well was used for nitrogen injection between 1974 and 1977. The injection line runs parallel to the access road and it was initially theorized that a rupture in this line could be the source of nitrate pollution. However, under normal circumstances the nitrogen gas will not produce NO_3^- (Koob, 1981). Two wells were sampled upgradient from the site and were found to contain normal NO_3^- background levels (T154N, T95W, Sec. 32 C/SE/SE and Sec. 33 SW/SW/SE). The first well tested is a farm well located approximately one quarter of a mile south of the study site. It was initially speculated that either barnyard wastes or a faulty septic system at this farmstead might explain the high NO_3^- level in the study area. However, this source was considered unlikely because of the high nitrate concentrations of the leachate and was completely dismissed when the farm well was found to only have normal background concentrations of this ion. If the reserve pit is not the source of NO_3^- pollution at this site, no viable alternative has yet been determined.

Comparison of water chemistry from piezometers D_{12} and D_{13} (Appendix D) suggest that the major zone of leachate migration at this site does not correspond to the top of the saturated zone. This could be the result of preferential migration of the leachate due to lenses of high hydraulic conductivity in the sand and sandy gravel deposits (fig. 36). A greater density of the leachate in in comparison to the local groundwater could also create a vertical component of transport. Whether these two factors act in combination or separately the maximum migration of leachate at this site is occurring within the sandy gravel layer.

The geologic and geohydrologic conditions at the Apache Corporation Federal 1-5 and Texaco Charlson C133 study sites are very similar. At both sites the unsaturated zones have moderate percentages of clay which has the capacity to attenuate the leachate. The upper portions of the saturated zones at these sites have very high hydraulic conductivities. Leachate migration at the Apache site corresponds to the direction of groundwater flow (fig. 45). The leachate plume at the Texaco Charlson site has a stronger upgradient component than it does in the direction of groundwater flow (fig. 45). This is believed to be the result of a reduction in, or a reversal of, the groundwater flow direction in recent time due to a higher water level in the adjacent reservoir.

Apparent Resistivity.--Leachate distribution was estimated using apparent resistivity values. These values were compared with water analyses to determine leachate indicators. An apparent resistivity value of 30 ohm-ft. or less was chosen as an indicator of leachate at the Apache Corp. Federal 1-5 site. A comparison of the four electrode spacings, at or below the water table, indicates the maximum extent of leachate migration to be at a depth of 30 to 40 feet (9.1-12.2m) (fig. 46). A sandy gravel layer lies within this interval. This supports the hypothesis that maximum migration of the leachate would take place within the zone of highest hydraulic conductivity.

An apparent resistivity value of 30 ohm-ft. or less was also chosen as an indicator of leachate at the Texaco Charlson C133 site.

Figure 45. Profiles of leachate migration at the Apache Corp. Federal #1-5 and Texaco Charlson Madison North Unit C133 sites. There is no upgradient component of leachate migration at the Apache site. An upgradient component of leachate is present at the Texaco site. The configuration at the Texaco site is also a reflection of control. The arrows point in the direction of shallow groundwater flow. The Texaco Charlson C133 profile supports the theory that groundwater flow at this site had been from north to south in the immediate past.

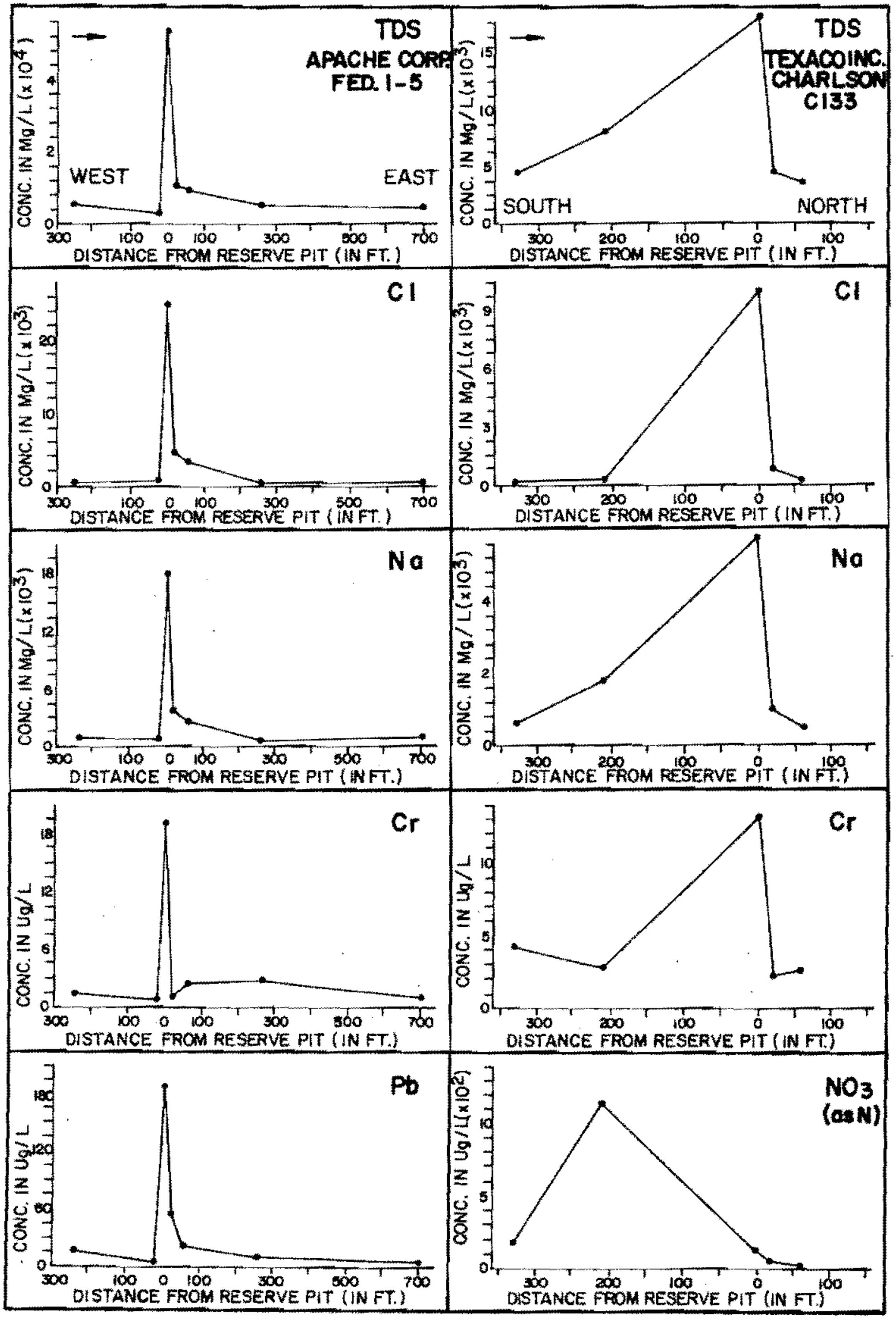
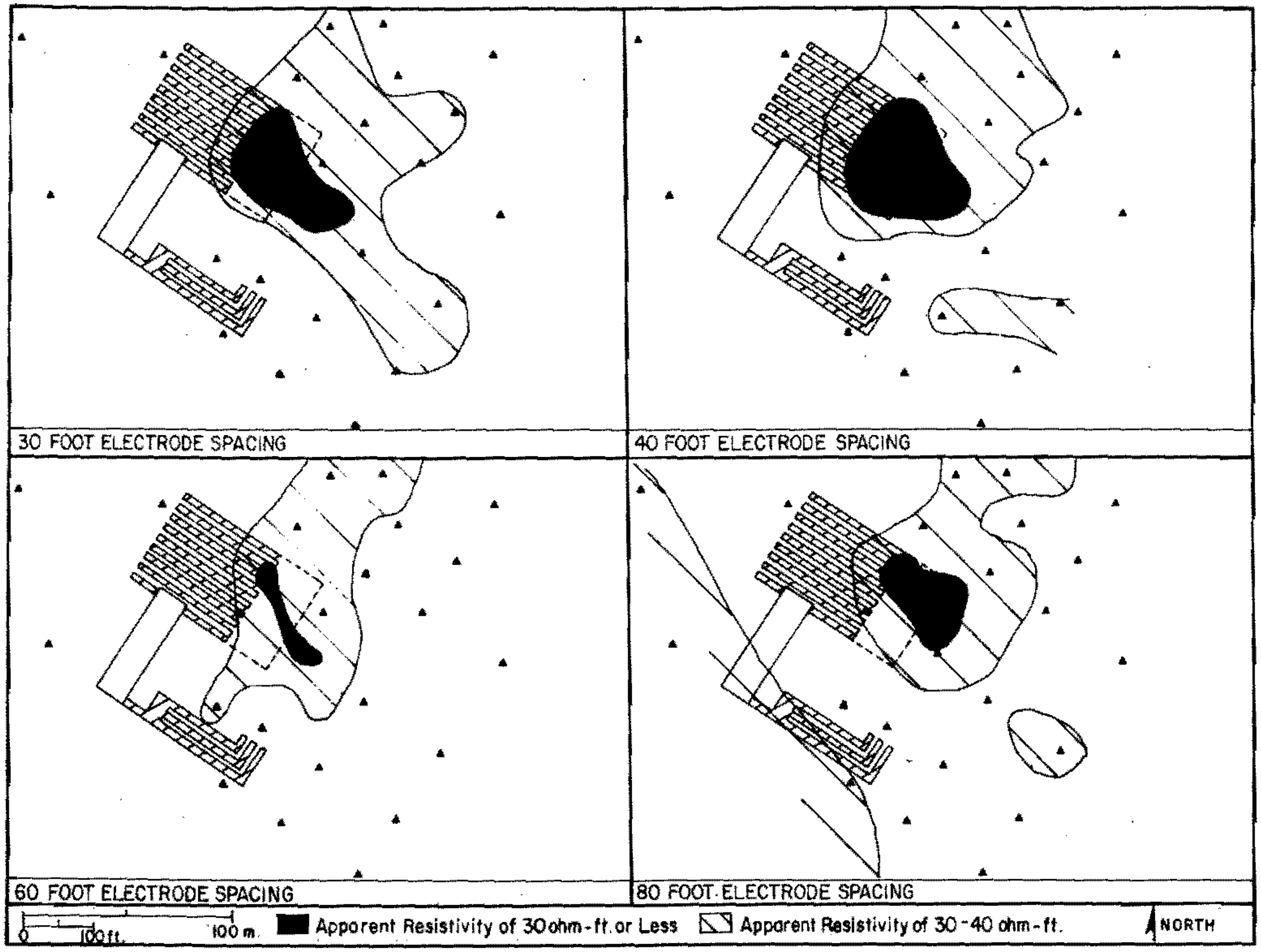

TDS
APACHE CORP.
FED. 1-5
WEST
EAST
CONC. IN Mg/L (x 10⁴)
DISTANCE FROM RESERVE PIT (IN FT.)
TDS
TEXACO INC.
CHARLSON
C133
SOUTH
NORTH
CONC. IN Mg/L (x 10³)
Cl
Na
Cr
CONC. IN Ug/L
Pb
NO3
(as N)
CONC. IN Ug/L (x 10²)

Figure 46. Apparent isoresistivity maps for Apache Corp. Federal #1-5 site. Selected ohm-ft. values indicate leachate distribution. Electrode spacings of 30, 40, 60, and 80 feet (9.1, 12.2, 18.3, and 24.4m). See figure 23 for legend.

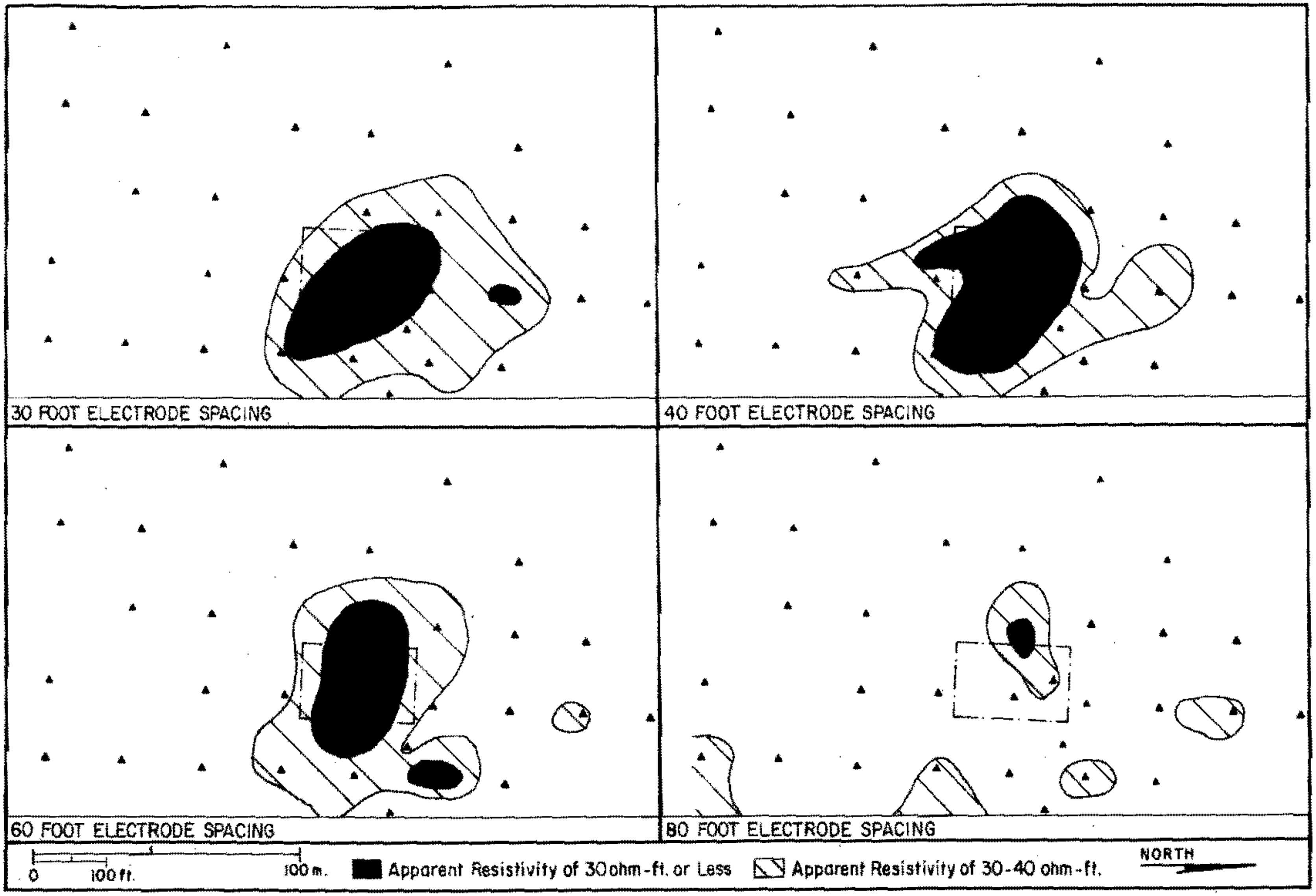

30 FOOT ELECTRODE SPACING
40 FOOT ELECTRODE SPACING
60 FOOT ELECTRODE SPACING
80 FOOT ELECTRODE SPACING
0
100 ft.
100 m.
Apparent Resistivity of 30 ohm-ft. or Less
Apparent Resistivity of 30-40 ohm-ft.
NORTH

A comparison of the four electrode spacings, at or below the water table, indicate the maximum extent of leachate migration to be at a depth of 30 to 60 feet (9.1-18.3m) (fig. 47). The thick gravel unit is within this interval. These results again support the interpretation of maximum migration of the leachate in the zone of highest hydraulic conductivity. The reduction of leachate at the 80 foot electrode spacing is theorized to be the result of Tertiary bedrock sediments. This low hydraulic conductivity layer would have an upper boundary between a depth of 60 and 80 feet (18.3-24.4m). This depth was not reached during augering and the resistivity data are the only basis for speculation regarding the presence of such a unit at this depth.

Interpreted Resistivity.--The measurements obtained by surface resistivity methods correspond to the true resistivity of the geologic sediments if they are homogeneous and isotropic. However, as a rule geologic materials are nonhomogeneous and anisotropic. The values recorded are, therefore, apparent resistivities (Yazicigil and Sendlein, 1982).

The apparent resistivity values for the two monitored sites were plotted against electrode spacing to obtain qualitative information on the subsurface geological conditions (Appendix F). Subsurface control from auger hole data was used for correlation with the apparent resistivity curves. In addition, stratigraphic data were compared with automatically interpreted resistivity curves using a computer program developed by Zohdy and Bisdorf (1975),

Figure 47. Apparent isoresistivity maps for Texaco Charlson C133 site. Selected ohm-ft. values indicate leachate distribution. Electrode spacings of 30, 40, 60, and 80 feet (9.1, 12.2, 18.3, and 24.4m). For legend see figure 23.


30 FOOT ELECTRODE SPACING
40 FOOT ELECTRODE SPACING
60 FOOT ELECTRODE SPACING
80 FOOT ELECTRODE SPACING
0
100 ft.
100 m.
Apparent Resistivity of 30 ohm-ft. or Less
Apparent Resistivity of 30-40 ohm-ft.
NORTH

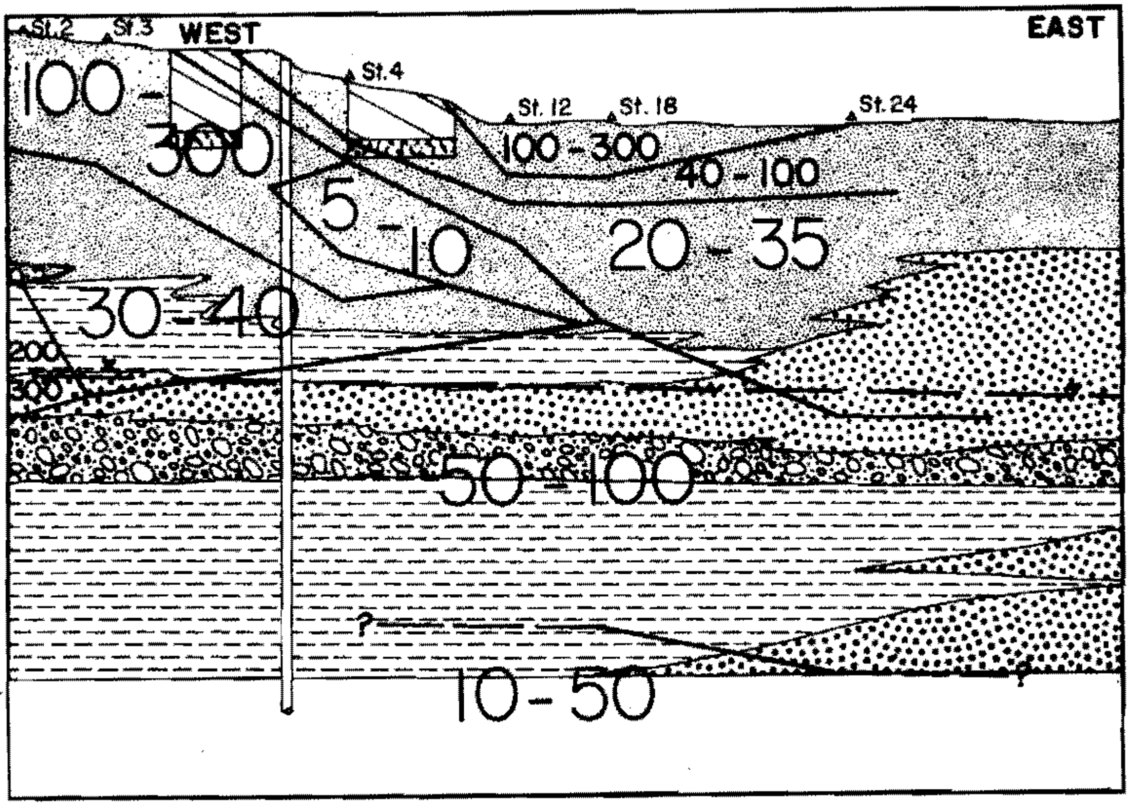
which calculates layer thicknesses and resistivities (Appendix F). There are a few inherent problems with this computer program. The program cannot interpret VES curves that have a slope which exceeds 45° (as was the case for stations 9, 13, 15, 16, 17, 22, and 24 for the Texaco Charlson C133 site). In addition, the program assumes horizontally and laterally homogeneous layers. Neither of the two sites surveyed has much lateral continuity. Interpretations can still be made successfully as long as the lateral heterogeneity is not excessive (Kehew and Groenewold, 1982).

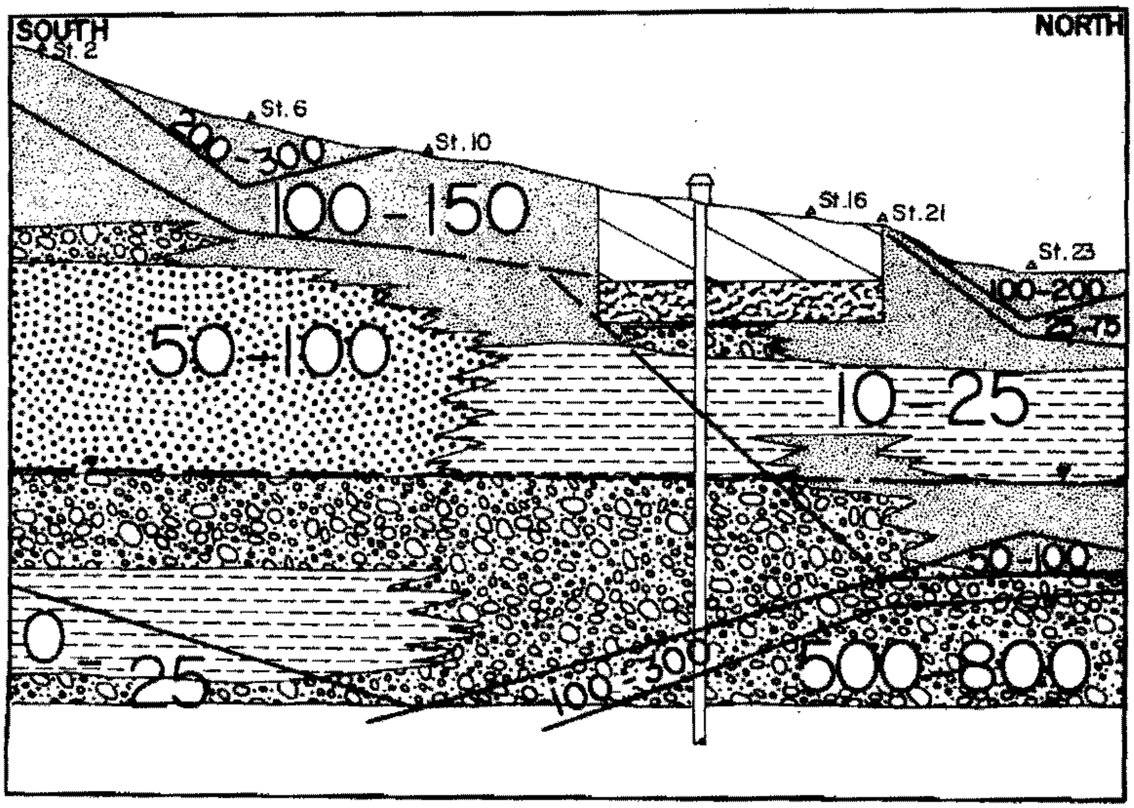
Profiles of interpreted resistivity values for the Apache Federal 1-5 and Texaco Charlson C133 sites are presented in figures 48 and 49. Both depict a zone of low interpreted resistivity underlying the buried drilling fluid. The apparent resistivity curves (field values) and the interpreted resistivity values do not correlate well at the Apache site. A much better correlation between the two exists at the Texaco site. Correlation between interpreted resistivity and sediment boundaries are, at best, tenuous at the Apache site. These same correlations agree very well for the Texaco site.

Variables in Earth Resistivity Surveying.--The earth resistivity surveys were used in this study to obtain additional data on the migration of leachate from the reserve pit and trenches. The optimum conditions, for which the most favorable results would be obtained, include a high water table, a thick relatively homogeneous sediment layer of moderate to high resistivity, and a leachate of low resistivity.

Figure 48. A profile of interpreted resistivity values at the Apache Corp. Federal #1-5. The reduction in apparent resistivity caused by the leachate can be seen in the silt layer beneath the reserve pit. The interpreted resistivity boundaries do not correlate well with lithologic changes. Values are in ohm-ft. See legend of figure 24 for lithologic symbols.

Figure 49. A profile of interpreted resistivity values at the Texaco Inc. Charlson Madison North Unit C133. The reduction in apparent resistivity caused by the leachate created the 10-25 ohm-ft. zone beneath the reserve pit. The interpreted resistivity boundaries correlate well at this site with both the leachate boundaries and lithologic changes. See legend of figure 24 for lithologic symbols.


St.2
St.3
WEST
EAST
St.4
St.12
St.18
St.24
100-300
100-300
40-100
5-10
20-35
30-40
200
300
50-100
?
10-50


SOUTH
St.2
NORTH
St.6
200-300
St.10
100-150
St.16
St.21
St.23
100-200
25-75
50-100
10-25
50-100
0-25
100-300
100
500-800

The two sites which were VES surveyed are characterized by both lateral and vertical discontinuity. The sediment size in the deposits ranges from clay to gravel. The high silt percentage and the degree of unconsolidation of these deposits resulted in poor definition of the layer boundaries (Appendix F). Fortunately, the resistivity values of the leachate at these sites were sufficiently low to permit detection by this method.

The two remaining study sites were not surveyed with the resistivity technique even though they were sedimentologically more laterally continuous. It was felt that the depth to the water table was too great and that leachate in the saturated zone would not be detected.

At the Apache site vegetation was absent on the highly compacted pad. This caused a slight reduction in resistivity over this area. This reduction was greatly overshadowed by the much greater influence of the leachate.

The lines of electrodes were oriented east-west at the Apache site and north-south at the Texaco Charlson site. At each site the arrays approximately paralleled the direction of shallow groundwater flow. Studies have shown that the apparent resistivity is variable and dependent upon the orientation of the electrode array. Anomolies are therefore abnormally elongated in the direction of traverse (Van Nostrand and Cook, 1966). The resulting resistivity patterns on isoresistivity maps for the sites (figs. 41-44) are somewhat elongated parallel to the direction of the electrode lines. However, this appears to be largely a result of leachate dispersion by groundwater flow in this same direction.

The assumption has been made in the presentation of both the apparent and interpreted resistivity data that the electrode spacings (a) and depth of current penetration are equivalent. This was assumed even though both sites contain zones of high salinity pore water which could reduce current penetration. The depth of current penetration and the electrode spacing are considered equal in this study because no observable pattern was detected to indicate otherwise.

Effect of Pit Reclamation on Precipitation Infiltration.--As previously discussed, the most common method of pit reclamation today is by trenching. A series of trenches, ranging in depth from 14 to 21 feet (4.3 to 6.4m), are constructed to radiate out from one side of the pit (fig. 50-B). Simultaneously, or shortly after completion of trench construction, the pit is pushed in from the opposite side by a bulldozer. As the fill is pushed toward the trenches it forces the drilling fluid into them. When the pit is completely filled with sediment most of the drilling fluid is contained in the trenches. The final stage of reclamation is to cover the trenches with fill and to level and compact the site (fig. 50-C).

Prior to the drilling of an oil well, an area (pad) is leveled and highly compacted to minimize settling due to the weight of the oil rig and associated heavy equipment. This compaction creates an area of high potential runoff and very low infiltration capacity.

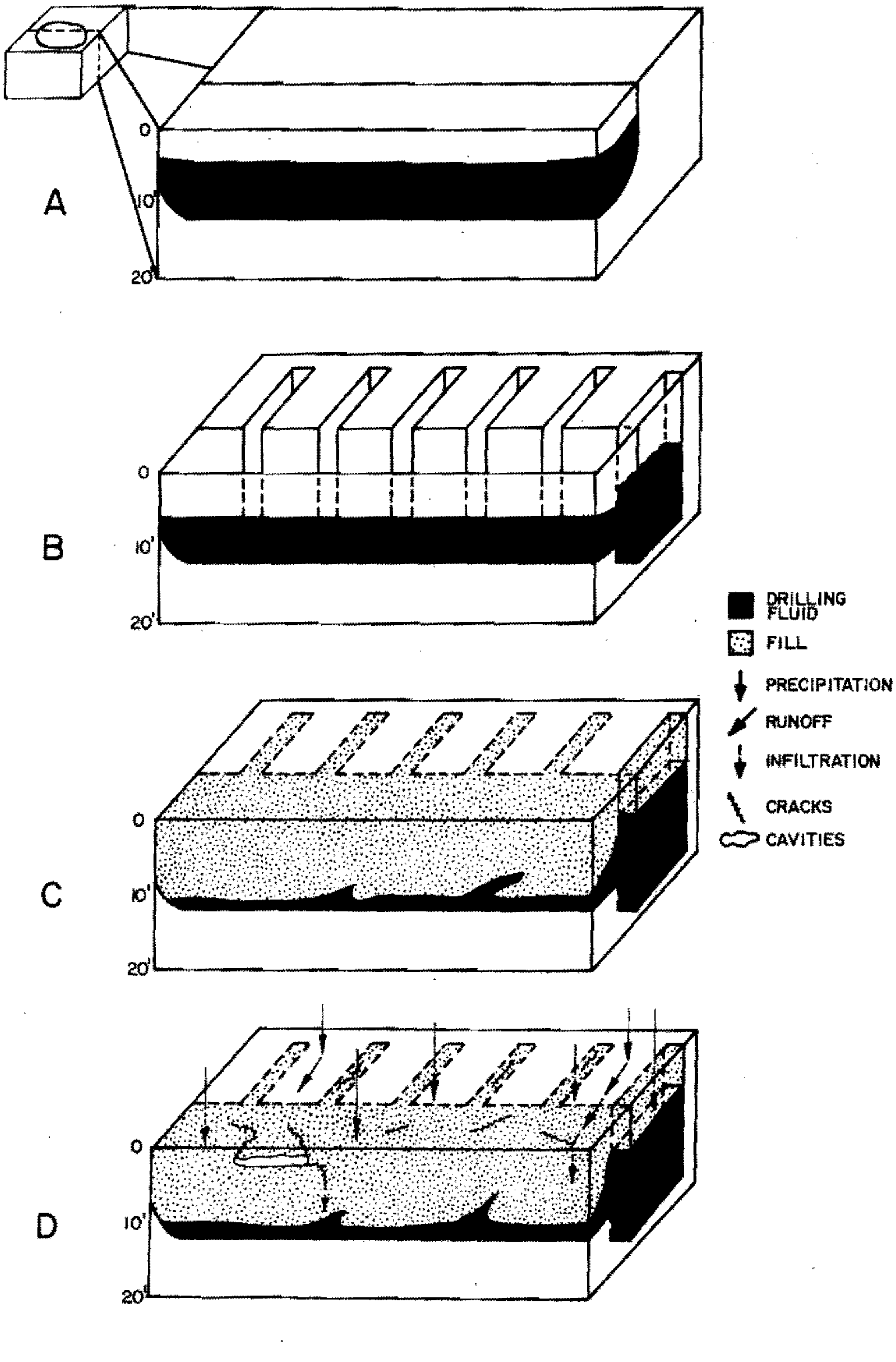
During reclamation the fill in the reserve pit and trenches is

Figure 50a. A cross-section of an active drilling fluid pit.

Figure 50b. A drilling fluid pit upon completion of the trenching operation and prior to back filling. Note the depth of the drilling fluid in the trenches in comparison to the reserve pit.

Figure 50c. A drilling fluid pit upon completion of reclamation. Sediment has been spread over the pit and the area has been leveled. Note that the majority of the drilling fluid is now in the unlined trenches.

Figure 50d. The results of subsidence within the pit and trenches. This increases the infiltration in this area.


A
B
C
D
0
10'
20'
DRILLING FLUID
FILL
PRECIPITATION
RUNOFF
INFILTRATION
CRACKS
CAVITIES

compacted to a lesser extent than the surrounding sediment on the pad. In addition, desiccation of the drilling fluid over time reducesits volume and causes settling of the overlying fill. The settling of the fill is most prevalent over the trenches (due to the greater drilling fluid/fill ratio) but also occurs throughout the pit area. This settling creates cavities and surface cracks which act as preferred avenues for infiltration. In addition, ponding of water in surface depressions is caused by subsidence of all or parts of the trench surfaces. This ponding, along with the presence of surface cracks, results in greatly increased infiltration above the fluid filled trenches (figs. 50-D, 51, and 52). This, therefore, increases the amount of leachate that is produced. The highly compacted sediment between the trenches and throughout the rest of the drill pad (not including the area above the reserve pit) often funnels runoff into the surface cracks, cavities, and depressions of the fill in the pit and trenches. Infiltration is also increased by the lack of vegetation over the reserve pit and trenches. Moisture that could be taken up by plants and recirculated to the atmosphere is now available for infiltration to the buried drilling fluid (fig. 50-D).

Health Effects of Drilling Fluid Leachate.--Much concern has been expressed about the toxicity and mobility of the chromium ion, a component of certain drilling fluids. Chromium exists in three forms: pure elemental chromium metal, hexavalent chromium (Cr^{+6}) and trivalent chromium (Cr^{+3}). Trivalent chromium is very insoluble and immobile but becomes highly mobile when oxidized to the hexavalent

Figure 51. A collapsed trench surface at the Apache Federal #1-5 site (this trench is from the reclamation of the original reserve pit). The collapsed surface is due to desiccation of buried drilling fluid. The maximum depth of the depression is 2.4 feet (0.7m). The photo is looking east towards the buried reserve pit.

Figure 52. Desiccation and settling cracks developed on the surface of the reclaimed reserve pit at Apache Federal #1-5 re-entry. The photo was taken 5 weeks after the pit was reclaimed. The knife is 9 inches (22.9 cm) in length.

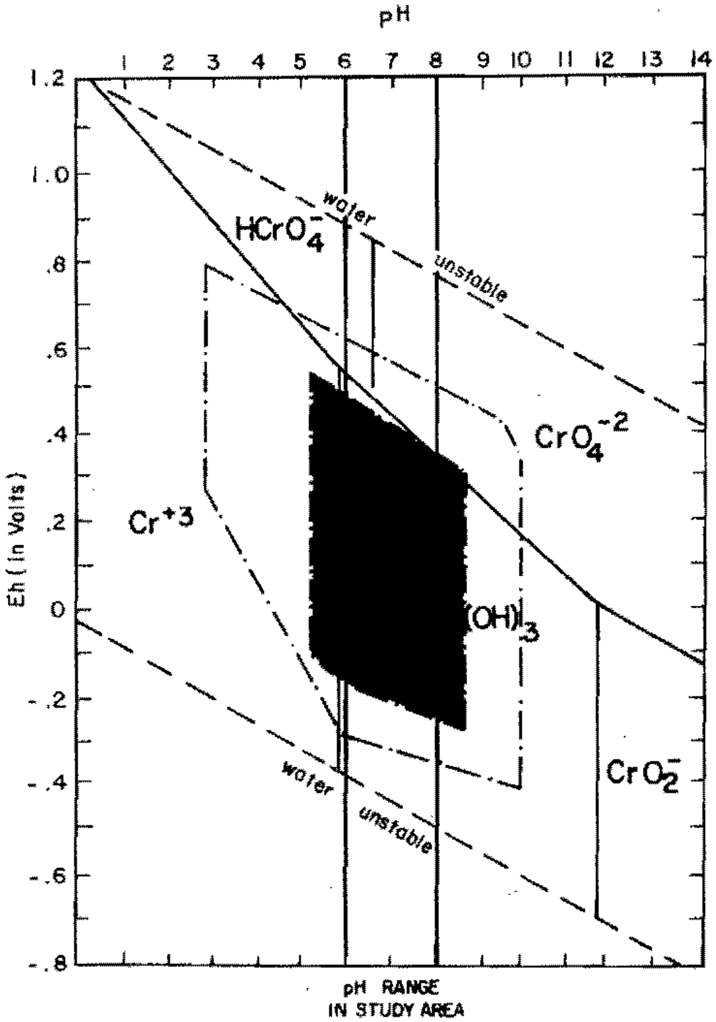
state (Robertson, 1975). The hexavalent chromium ion is also much more toxic than is the trivalent ion (Valkovic', 1975). The valence state of chromium is largely dependent upon the Eh and the pH of the surrounding environment.

The Eh-pH stability field diagram for chromium in natural waters at a temperature at 25°C and one atmosphere is shown in figure 53. The diagram indicates that there is only a small portion of the typical groundwater field within which Cr^{+6} is stable. The conversion of chromium to the hexavalent state requires strongly oxidizing conditions.

The North Dakota State Department of Health Lab analyzed the groundwater samples for 29 chemical parameters. The Recommended Concentration Limit and Maximum Permissible Concentration Limit for human, livestock uses, and irrigation purposes for a number of these parameters are presented in table 3.

The Maximum Permissible Concentration Limit of 50 ug/L was determined for chromium in its hexavalent state. This limit was exceeded in only two of the water samples from the four study sites. Both of these samples were obtained from soil water samplers emplaced in the reserve pit at the Texaco Gov't. NCT-1 site (fig. 37). The water samples from the saturated zones at the Apache Federal 1-5 and Texaco Charlson C133 sites contained Cr concentrations far below the Maximum Permissible Concentration. Even if this ion is in its hexavalent state in this groundwater, which is highly unlikely (fig. 53), it does not pose a health threat at these concentrations.

Figure 53. Stability-field diagram for trivalent and hexavalent chromium compounds in water at 25°C and one atmosphere. Hexavalent chromium normally exists over a small Eh-pH range in natural groundwaters. The pH range for the groundwater at the study sites is shown in the diagram (from Robertson, 1975, p. 522).



— · — MOST NATURAL SURFACE WATERS WITHIN THIS ZONE

■ MOST NATURAL GROUNDWATER WITHIN THIS ZONE

Table 3. Recommended Concentration Limits and Maximum Permissible Concentrations for human, livestock, and irrigation crop consumption of some selected chemical parameters (Freeze and Cherry, 1979).

PARAMETER	Human in mg/L	Livestock in mg/L	Crops in mg/L
Total dissolved solids *	500	7000	700
Chloride *	250		
Sulfate *	250		
Nitrate **	45	45	
Iron *	0.3		
Manganese *	0.05		
Copper *	1.0		
Zinc *	5.0		
	in ug/L	in ug/L	in ug/L
Arsenic **	50	200	100
Barium **	1000		
Cadmium **	10	50	10
Chromium **	50	1000	100
Selenium **	10	50	20
Lead **	50	100	5000
Silver **	50	2000	1000

* Recommended Concentration Limit based upon taste and esthetic appearance.

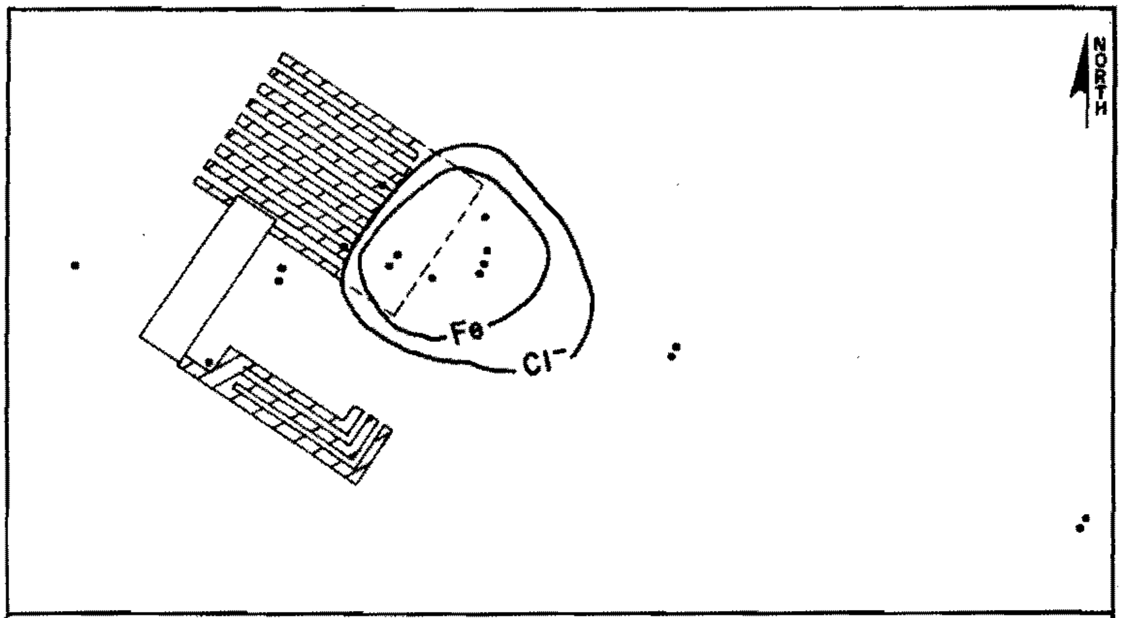
** Maximum Permissible Concentration based upon health effects.

At the Apache Federal 1-5 site only five parameters (TDS, Cl^-, SO_4^{2-}, Fe and Mn) exceeded the Recommended Concentration Limits in the saturated zone. The background concentration levels of TDS, SO_4^{2-}, and Mn also exceed these limits at this site. The Recommended Concentration Limits for Cl^- and Fe are exceeded in an area approximately 150 x 120 feet (46 x 37m) within the upper saturated zone at this site (fig. 54). The limits for these ions are set for taste and aesthetics of the water. The consumption of water from the saturated zone at this site did not pose a health threat to humans or livestock during the sampling period.

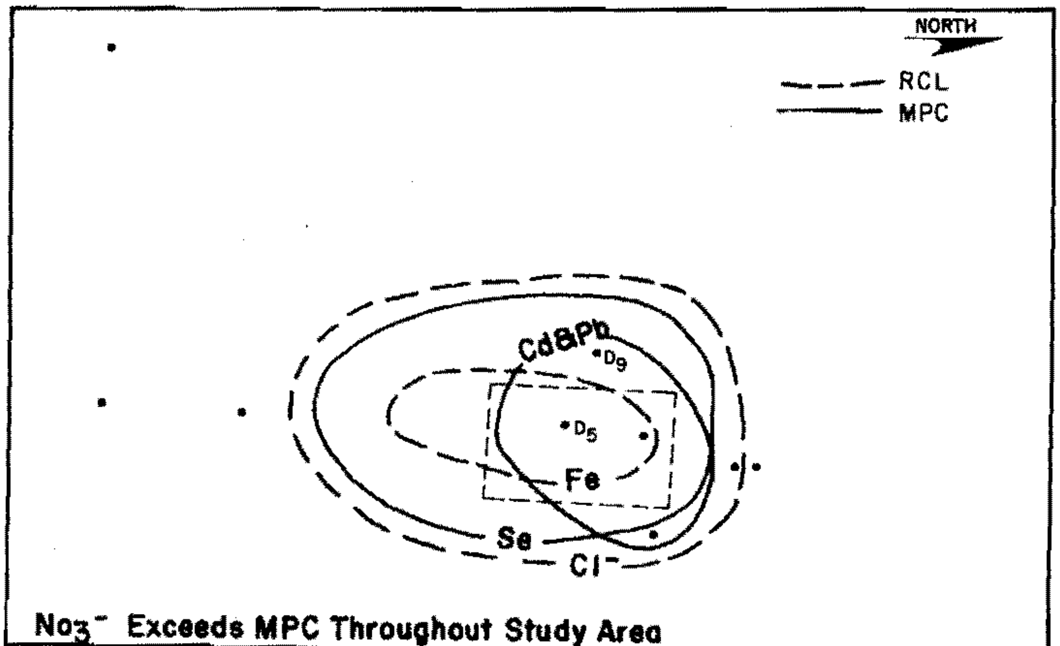
A number of parameters in groundwater at the Texaco Charlson C133 site exceed the drinking water standards. The Recommended Concentration Limits for TDS, Cl^-, SO_4^{2-}, Fe, and Mn were exceeded but do not pose health threats (Appendix E). The background concentration levels of TDS, SO_4^{2-}, and Mn also exceed the limits at this site. The Recommended Concentration Limits for Cl^- and Fe are exceeded in an area approximately 400 x 300 feet (122 x 91m) within the upper saturated zone at this site (fig. 55). Maximum Permissible Concentration Limits for Cd, Pb, NO_3^-, and Se were exceeded in the groundwater at this site (fig. 55). Groundwater samples periodically exceeded the Maximum Concentration Limits for Cd and Pb in an area approximately 200 x 200 feet (61 x 61m) in the upper saturated zone. The mean of the quarterly water samples exceeded the limits at only two piezometers, D_9 for Cd and D_5 for Pb (Appendix E). These two ions are potential carcinogenics in concentrations exceeding the Maximum Concentration Limits

Figure 54. Approximate limits of groundwater which exceeds the Recommended Concentration Limits for Cl^- and Fe at the Apache Corp. Federal #1-5 site. The upper 10 feet (3m) of the saturated zone was monitored.

Figure 55. Approximate limit of groundwater which exceeds the Recommended Concentration Limit and Maximum Permissible Concentration Limit at the Texaco Charlson C133 site. The upper 15 feet (4.6m) of the saturated zone was monitored.



APACHE FEDERAL 1-5



NO_3^- Exceeds MPC Throughout Study Area

TEXACO CHARLSON C133

(Valkovic', 1975).

Se exceeds the Maximum Permissible Concentration Limit by a factor of 25X over an area approximately 350 x 200 feet (107 x 61m) in the upper saturated zone (fig. 55). There has been some question as to whether or not the 10 ug/L limit for Se is justifiable. The health effects of this ion are not known at low concentrations and 50 ug/L might be a more realistic limit (Hammer, 1981). At the high concentration observed at this site, Se is a potential carcinogen.

The concentration of NO_3^- in groundwater at the Texaco Charlson C133 exceeds the Maximum Permissible Concentration Limit by a factor of up to 110X (Appendix E). All of the water samples analyzed from the saturated zone at this site exceed the 10 mg/L limit for NO_3^- (as N). The health effects of this ion are well known at concentrations exceeding this limit. Adults can tolerate higher concentrations of NO_3^- but it is often fatal to infants by inducing methemoglobinemia ("blue baby disease"). The human and livestock consumption of shallow groundwater in the immediate area of the Texaco Charlson C133 site constitutes a danger to health.

As assessment of the groundwater quality at the Texaco Gov't. (NCT-1) and Belco Petroleum B.N. Sheep Creek 1-11 sites could not be made. The pore water in the unsaturated zone beneath these reserve pits contained a number of parameters which exceeded drinking water standards. However, this pore water will not be consumed by humans or livestock and does not therefore constitute a health hazard. The concern at these two sites is for the quality of water that will reach the saturated zone where it has the potential to be consumed. The reduction in ion concentrations in the pore water through the unsaturated zone (figs. 37-40) is the basis for the assumption that this water will be sufficiently reduced in these concentrations and will not adversely affect the groundwater beneath these two sites.

CONCLUSIONS

The following can be concluded from the results of this study:

1. Leachate is being generated from the buried drilling fluid at each of the four western North Dakota study sites. The amount of leachate generated is relatively small because of the small volume of buried drilling fluid and the normally low amounts of subsurface infiltration of precipitation. However, infiltration is increased by the improper compaction of sediments over the buried drilling fluid and by improper leveling of the site during reclamation.
2. The amount of drilling-fluid-generated leachate that reaches the groundwater table is assumed minimized by adsorption onto the commonly abundant Na montmorillonitic clays within the normally thick unsaturated zone. The portion of leachate which enters the saturated zone is often diluted by mechanical dispersion.
3. Two of the study sites (Texaco Gov't. "A" (NCT-1) and Belco Petroleum B.N. Sheep Creek 1-11) were chosen because they represent typical geologic and geohydrologic conditions for the majority of reserve pits in western North Dakota. The saturated zone was not monitored at these two sites but the reduction in ion concentrations in the leachate as it moved through the unsaturated zone is the basis for assuming that very little leachate is reaching the groundwater table. The two other sites (Apache Corp. Federal 1-5 and Texaco Charlson

Madison North Unit (C133) were chosen because they represented the "highest potential" for leachate migration. At these sites leachate plumes were detected within the saturated zone. The chemical concentrations within the saturated zones at these sites returned to background levels within a maximum radius of 400 feet (122m) from the reserve pit.

4. The consumption of shallow groundwater within the immediate vicinity of the reserve pit at one of the four study sites (Texaco Charlson C133) constitutes a danger to health.
5. Reserve pits are most often reclaimed by the trenching method regardless of whether or not the pit was lined. The majority of drilling fluid is disposed of in these unlined trenches and not in the reserve pit.
6. The chloride ion is the best single indicator of the maximum extent of leachate migration because of its high concentration in drilling fluid, its low concentration in the shallow groundwater in this area, and its mobility in the subsurface.
7. Electrical earth resistivity was used to successfully outline the drilling-fluid-generated leachate plume at two of the study sites.
8. Chromate drilling fluid additives were constituents of the buried drilling fluid at two of the study sites (Apache Federal 1-5 and Texaco Gov't. "A" NCT-1). The chromium ion was greatly reduced in concentration in the pore water as the depth in the unsaturated zone increased at these sites. The shallow groundwater beneath the buried drilling fluid at the Apache Federal 1-5 showed no increase in chromium concentration.

RECOMMENDATIONS

Pit Reclamation.--Unfortunately, the disposal of discarded drilling fluid over the years has been one of the most neglected areas of shallow waste disposal within the state of North Dakota. The reserve pits have been trenched regardless of whether or not they had been lined and in total disregard to the local geohydrologic conditions. In addition, the liners in the pits have often not been properly maintained and generally have substantial tears in them (fig. 56). There have also been cases where the reclamation trenches have been improperly constructed (fig. 57). The less viscous ("fluid") portion of the drilling fluid is supposed to be removed from the pit prior to site reclamation. This did not occur at many of the reserve pit reclamations that I witnessed.

In certain geohydrologic settings, i.e. a high water table and sediment with high hydraulic conductivities, the drilling fluid should not be disposed of "on site". At such locations the drilling fluid should be removed and disposed of in an approved site.

In a few isolated sites the reserve pit has been reclaimed by alternative methods. Drilling fluid has been collected from the pit and disposed in the deep subsurface by injection wells. This method is rarely used because of the difficulties associated with the very viscous nature of the fluid.

A few "toxic-free additives" have been developed by drilling

Figure 56. The reserve pit at the Apache Federal #1-5 site (re-entry). Note the substantial tear in the pit liner. Photo taken looking south.

Figure 57. A reserve pit in northern Billings County. The reclamation trench is leading down the hillside into the ravine.

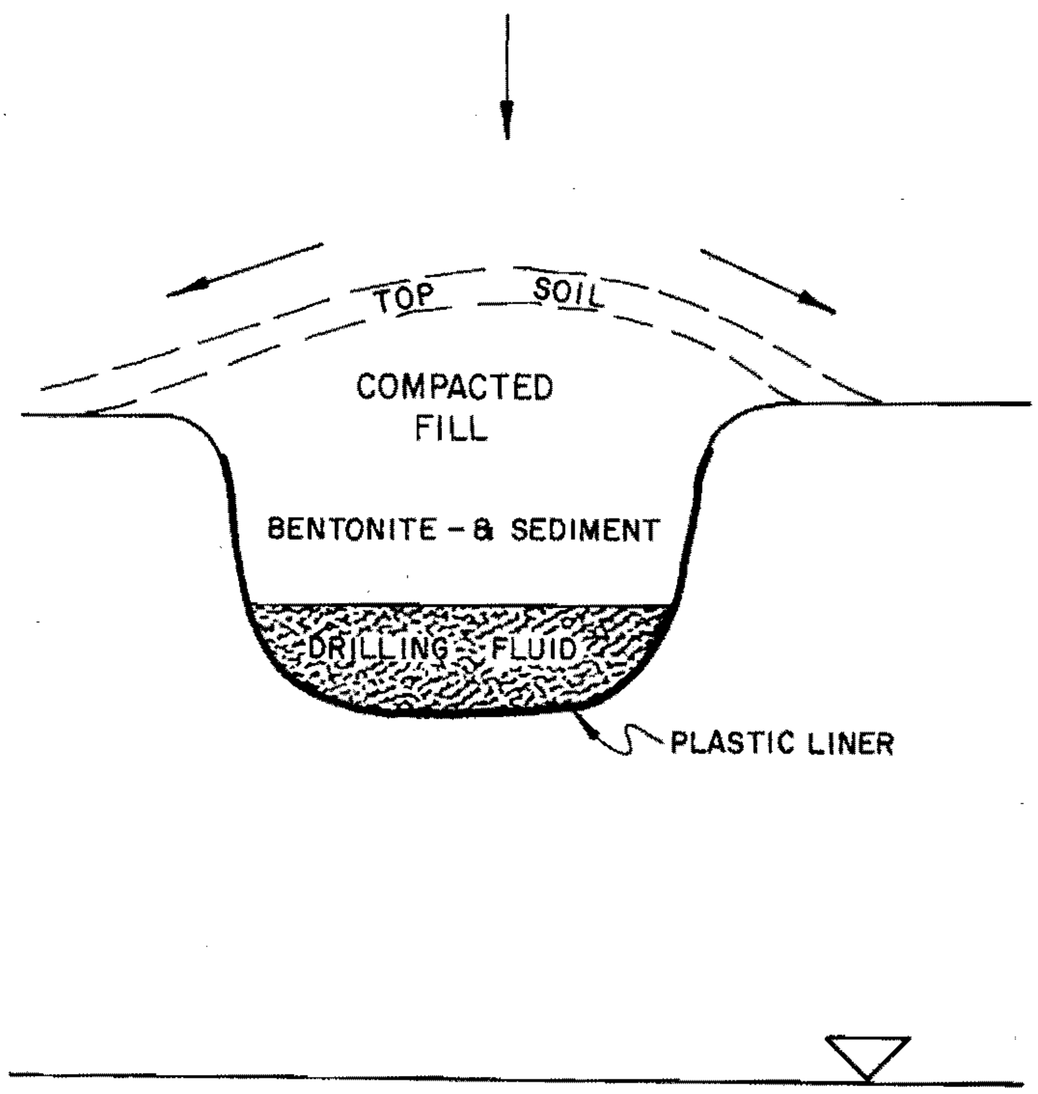
fluid companies. These additives perform the same service as their toxic counterparts, for example, Chrome Free Lignosulfonate. These were developed because of the banning of some additives (i.e., chromates) in certain areas of the country. The use of such additives reduces the potential health risk.

One solution discussed has been the sealing off of the buried drilling fluid from infiltrating water by incapsulation in relatively impermeable sediment. One such method has been designed by (Hicks, in preparation) (fig. 58). The mounding of sediment would increase precipitation runoff and thereby reduce infiltration and consequential leachate. If a method can be devised to desiccate the drilling fluid prior to pit reclamation, this method of incapsulation and mounding will have more merit. Desiccation would also eliminate the volume of leachate generated.

The lithology of the upper 200 feet (61m) of sediment at each drill site should be determined. In addition, the depth to the water table should be determined. This determination could be made while the oil-and-gas well was being spudded. This information should be sent to the state or federal agency in charge of site reclamation to enable the selection of the proper reclamation method.

Further Study.--This study has determined that leachate will be generated by the current method of reserve pit reclamation. Therefore, it is important to focus interest in areas where this leachate will degrade the local groundwater. This concern should now be focused

Figure 58. Alternative method of reserve pit reclamation (from Hicks, in preparation). This method should increase surface runoff and decrease leachate generated by the buried drilling fluid.


TOP SOIL
COMPACTED FILL
BENTONITE - & SEDIMENT
DRILLING FLUID
PLASTIC LINER

on oil-and-gas well sites in north-central North Dakota. Sites situated upon permeable glacial meltwater channels have a high potential for large-scale leachate contamination of the shallow groundwater. The sites in this area should be monitored in both the saturated and unsaturated zones with piezometers and soil water samplers.

Future studies in the semi-arid climate of western North Dakota and eastern Montana should focus upon the migration and attenuation mechanisms of the drilling fluid leachate in the unsaturated zone. Soil water samplers should be placed in the unsaturated zone both beneath and adjacent to the buried drilling fluid to enable determination of lateral and vertical leachate migration. Any future study should also incorporate the use of x-ray fluorescence (XRF), scanning electron microscopy (SEM), and/or other geochemical techniques to accurately determine the attenuating mechanisms.

Alternative methods of reserve pit reclamation should be studied. If a method can be devised to desiccate the drilling fluid prior to burial, it can be confined to the lined pit. This confinement will greatly reduce the amount of leachate that will be generated.

APPENDICES

APPENDIX A

RULES AND REGULATIONS FOR RESERVE PIT RECLAMATION

43-02-03-19. PIT FOR DRILLING MUD AND DRILL CUTTINGS, AND RESTORATION OF SURFACE. In order to assure a supply of proper material or mud-laden fluid to confine oil, gas, or water to their native strata during the drilling of any well, each operator shall provide, before drilling is commenced, a container or pit of sufficient size to contain said material or fluid, and the accumulation of drill cuttings. The pit shall be leveled and the surface restored within a reasonable time after the well has been completed.

(((No pit shall be constructed so as to allow surface or subsurface contamination by seepage or flowage from said pit.)))

Pits shall not be located in, or hazardously near, stream courses, nor shall they block natural drainages, and shall be constructed in such a manner so as to prevent contamination of surface or subsurface waters by seepage or flowage therefrom.

In the construction of a drill site or production facility, the topsoil shall be removed, stockpiled, and stabilized for later redistribution on the surface of the location when it is reclaimed. "Topsoil" means the suitable plant growth material on the surface, however, in no event shall this be deemed to be more than the top 8" of soil.

Within a reasonable time, normally no more than one year, after the completion of a well, pits shall be pushed in and levelled, or in the case of abandonment, the site shall be restored. Prior to the commencement of such operations, the operator or the operator's agent shall file a notice of intention (Form 4) to level pits or restore site with the State Geologist and obtain approval from the State Geologist or his representative. Verbal approval to commence operations may be given, in which case the operator shall file a subsequent notice with the State Geologist reporting the work performed. Any operator who obtains verbal approval may be required by the State Geologist to perform additional work if the State Geologist determines that the work performed does not constitute proper restoration, or does not comport with the subsequent notice of intention submitted. The notice shall state the name and location of the well, the name of the operator, and the method of restoration, and shall include a statement of proposed work. Such work shall include, but not be limited to the following:

(1) The location or unused portion shall be restored as close as possible to original condition. This work will be done within a reasonable time after plugging or setting production casing.

(2) The stockpiled topsoil will be evenly distributed over the location, and revegetation will be native species or to the specifications of the appropriate government representative and the landowner.

(3) If required by the State Geologist, the reserve pit will have fencing on three sides during drilling operations, and prior to rig release the fourth side will be fenced. The pit fence will maintain until the pit is dry.

(4) If there is any oil on the pits when drilling is completed, it will be removed immediately or the pits will be flagged overhead.

General Authority
NDCC 38-08-04

Law Implemented
NDCC 38-08-04

APPENDIX B

LITHOLOGIC DESCRIPTION OF DRILL HOLES

Abbreviations used in the lithologic auger hole descriptions.

Word	Abbreviation	Word	Abbreviation
alternating	altg	light	lt
black	blk	lignite (-itic)	Lig, lig
blue	bl	ligmonite (-itic)	Lim, lim
brown	brn	lithic	lit
carbonaceous	carb	medium	med
cement	Cmt	moderate	mod
clay (-ey)	Cl, cl	nodules	Nod
concretion	Conc	orange (-ish)	or, orsh
dark	dk	parting	ptg
fossil (-iferous)	Foss, foss	pebble (-ly)	Pbl, pbl
fragment	Frag, frag	rock	Rk
gravel	Grv	sand (-y)	Sd, sdy
gray (-ish)	gry, grysh	silt (-y)	Slt, slty
green (-ish)	gn, gnsh	stringer	strgr
high (-ly)	hi	subangular	sbang
indurated	ind	subrounded	sbrndd
interval	Intvl	yellow (-ish	yel, yelsh
laminated	lam		

(Swanson, 1981)

TABLE 4

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT TEXACO GOV'T. "A" (NCT-1).

Auger Hole No. A1

Interval (in ft.)	Lithologic Description
0-13	Silt, lt gry, Cl Ptgs.
13-19	Silt, lt brn, Clinker Frags.
19-23.5	Sand, lt grn-gry, f gr, sbrndd.
23.5-24	Concretion.
24-28.5	Sand, yel-brn, mod cmt.
28.5-32	Lignite.
32-38	Clay, lt gry-bl.
38-45	Clay, lt gry, slty.
45-47	Lignite.
47-58	Clay, dk gry.
58-59	Lignite.
59-62	Clay, lt grn, hi ind, Lig Strgrs.
TD	

Auger Hole No. A3

Interval (in ft.)	Lithologic Description
0-18	Silt, brn-drk brn, Cl, Clinker Frags.
18-20	Clay, lt brn-gry, silty.
20-21	Concretion.
21-29	Clay, lt brn-gry, slty.
29-34.5	Lignite.
34.5-39.5	Clay, lt grn-gry, slty.
39.5-41	Clay, dk brn, silty, Clinker Frags.
41-44	Clay, lt bl, slty.
44-45	Lignite.
45-51	Clay, lt grn-gry, slty.
51-68	Clay, lt bl-gry.
TD	

Auger Hole No. A11

Interval (in ft.)	Lithologic Description
0-19	Clay, dk brn, slty.
19-31	Clay, lt brn, slty, Clinker Frags.
31-34	Sand, lt brn-yel, f gr.
34-37	Lignite.
37-46	Clay, med gry.
46-46.5	Lignite.
46.5-50	Clay, lt gry, lig.
50-72	Clay, lt bl-gry, Lim Nod.
TD	

TABLE 4 (CONT.)

Auger Hole No. A12

Interval (in ft.)	Lithologic Description
0-19	Silt, yel-brn to dk brn, sdy, cl.
19-22	Clay, bry, slty, lam.
22-33	Silt, yel-brn to brn.
33-43	Sand, brn, v f gr, slty.
43-45	Lignite.
45-55	Clay, bl, altg lig Cl, dk gry-blk.
55-64	Clay, bl-gry.
64-67	Lignite.
67-72	Clay, bl-gry.
TD	

Auger Hole No. A14

Interval (in ft.)	Lithologic Description
0-24	Clay, yel-brn, slty, carb.
24-30	Silt, brn to yel-brn, cl.
30-34	Clay, yel-brn, slty.
34-36	Clay, gry, lig.
36-40	Lignite.
40-48	Clay, gry-bl.
48-50	Lignite.
50-62	Clay, gry-bl.
TD	

TABLE 5

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT BELCO PETROLEUM
B.N. SHEEP CK. #1-11.

Auger Hole No. B6

Interval (in ft.)	Lithologic Description
0-12	Silt, gry-brn.
12-16	Clay, or-gry, foss.
16-19	Lignite.
19-50	Clay, bl-gry, altg. brn Cl, foss.
50-50.5	Cemented zone, auger could not penetrate.
TD	

Auger Hole No. B7

Interval (in ft.)	Lithologic Description
0-13	Clay, lt gry, slty.
13-25	Silt, lt gry-brn, Clinker Frags, Lig Frags.
25-28	Silt, dk brn, sdy.
28-30	Clay, gry.
30-30.5	Lignite.
30.5-43	Clay, bl-gry.

TABLE 5 (CONT.)

43-43.5 TD	Cemented zone, auger could not penetrate.

TABLE 6

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT APACHE FEDERAL #1-5.

Auger Hole No. C1

Interval (in ft.)	Lithologic Description
0-25	Silt, lt brn-brn, sdy, Cl Intvls.
25-34.5	Clay, brn-dk brn, slty.
34.5-40	Sand, brn, med. gr.
40-47.5 TD	Gravel, sdy, Clinker & Lig Frags.

Auger Hole No. C5

Interval (in ft.)	Lithologic Description
0-14	Silt, lt yel-brn, cl.
14-28	Clay, lt brn, slty, Lig & Clinker Frags.
28-32.5	Sand, brn, med-f gr.
32.5-37.5 TD	Gravel, sdy, Clinker & Lig Frags.

Auger Hole No. C6

Interval (in ft.)	Lithologic Description
0-14	Silt, lt yel-brn, cl.
14-29	Clay, brn-lt brn, Lig & Clinker Frags.
29-36.5	Sand, brn, med-f gr.
36.5-38 TD	Gravel, sdy, Clinker & Lig Frags.

Auger Hole No. C11

Interval (in ft.)	Lithologic Description
0-11	Silt, lt yel-brn, cl.
11-29	Clay, yel-brn, slty, Clinker & Lig Frags.
29-37.5	Sand, lt-dk gry, med-f gr, Clinker & Lig Frags.
37.5-38.5 TD	Gravel, sdy.

TABLE 6 (CONT.)

Auger Hole No. C13

Interval (in ft.)	Lithologic Description
0-9	Silt, lt yel-brn, cl.
9-24	Clay, yel-brn, slty, Clinker & Lig Frags.
24-27.5	Sand, lt-dk gry, med-f gr, Clinker & Lig Frags.
27.5-38	Gravel, sdy.
38-55	Clay, gry-lt bl, slty.
TD	

Auger Hole No. C14

Interval (in ft.)	Lithologic Description
0-19	Silt, lt yel-brn, sdy.
19-30	Sand, med gr.
30-42	Gravel, sdy.
42-47	Clay, lt bl to grn-bl.
TD	

Auger Hole No. C15

Interval (in ft.)	Lithologic Description
0-14	Silt, lt yel-brn, sdy.
14-22	Sand, med brn, med gr.
22-35	Sand, gry, med gr, Clinker & Lig Frags, Grv.
35-39	Gravel, sdy.
39-42	Clay, lt bl.
42-47	Sand, gry, med gr.
47-49	Clay, lt gry-bl.
49-62	Sand, gry, med gr.
TD	

TABLE 7

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT TEXACO CHARLSON C133.

Auger Hole No. D1

Interval (in ft.)	Lithologic Description
0-14	Silt, lt yel-brn, sdy, cl.
14-26	Sand, med brn, med gr, slty, Clinker & Lig Frags.
26-29	Clay, lt yel, slty.
29-40	Clay, drk brn, slty, Clinker Frags.
40-52	Sand, med-dk brn, slty, Clinker & Lig Frags.

TABLE 7 (CONT.)

52-65	Gravel sdy.
TD	

Auger Hole No. D3

Interval (in ft.)	Lithologic Description
0-18	Sand, lt yel-brn, slty, cl, Clinker & Lig Frags.
18-23	Gravel.
23-33	Sand, med-dk brn, slty, Clinker & Lig Frags.
33-42	Clay, dk brn-brn, slty, lit RK & Lig Frags.
42-45	Gravel.
45-54	Clay, dk brn-brn, slty, lit Rk & Lig Frags.
54-66	Clay, blk-dk brn, slty, Clinker & Lig Frags.
66-72	Gravel, sdy.
TD	

Auger Hole No. D4

Interval (in ft.)	Lithologic Description
0-5	Silt, lt gry, cl.
5-26	Sand, yel-brn, slty, cl, Clinker Frags.
26-31	Clay, dk brn, slty.
31-36	Clay, yel-brn, slty, Lig Frags.
36-42	Gravel, sdy.
TD	

Auger Hole No. D5

Interval (in ft.)	Lithologic Description
0-7	Clay, lt brn, slty.
7-11	Drilling Fluid.
11-13	Silt, lt brn-brn, slty, Clinker Frags.
13-28	Clay, brn-dk brn, slty, Sd Strgr.
28-32.5	Gravel, sdy, sbrndd.
TD	

Auger Hole No. D9

Interval (in ft.)	Lithologic Description
0-10	Silt, lt yel-brn, sdy.
10-18	Sand, lt yel-brn, v f gr, slty.
18-23	Gravel, sdy, sbang lit Rk pbls.
23-31	Clay, brn-dk brn, slty, Sd Strgr.
31-37.5	Gravel, sdy.
TD	

TABLE 7 (CONT.)

Auger Hole No. D10

Interval (in ft.)	Lithologic Description
0-7	Clay, lt brn, slty.
7-11	Drilling Fluid.
11-15	Sand, lt brn-brn, slty, Clinker Frags.
15-28	Clay, brn-dk brn, slty.
28-32.5	Gravel, sdy.
TD	

Auger Hole No. D11

Interval (in ft.)	Lithologic Description
0-9	Silt, lt yel-brn, cl.
9-29	Clay, brn, slty, Clinker Frags.
29-32.5	Gravel.
TD	

Auger Hole No. D12

Interval (in ft.)	Lithologic Description
0-11	Silt, lt brn-brn, cl, sdy.
11-22	Clay, brn-lt gry, slty, Clinker Frags.
22-31	Sand, lt brn-gry, slty, Cl strgr.
31-37.5	Gravel, sdy, lit Rk sbrndd-sbang pbl.
TD	

APPENDIX C

TEXTURAL ANALYSES

HYDROMETER METHOD OF TEXTURAL ANALYSES

The sample was air-dried and placed on a thin cardboard box lid on a wooden surface. The blunt end of a rock chisel was dropped on the sample with just enough force to disaggregate the sample. This was done until the pieces were approximately 15 mm or smaller. The day before analyses were run, a batch of 4 percent Calgon solution was mixed and placed in a carboy. At the same time, two distilled water carboys were filled and all three were left overnight to attain room temperature. Approximately 45 grams of a sample were weighed and put in a beaker (pint jar). The sample was soaked overnight in 125 ml of 4 percent Calgon solution. A test cylinder of 125 ml 4 percent Calgon solution was prepared to determine the hydrometer weight of the Calgon. After soaking, the sample was put in the mechanical analysis stirred with some distilled water and agitated for one to two minutes. It was then decanted into a settling cylinder. If any clay balls coated with sand grains were present, they were gently flattened with a glass stirring rod and agitated in the stirrer with additional distilled water until completely dispersed before being added to the settling cylinder. The cylinder was topped off with distilled water and agitated for about 45 seconds with a rubber stopper full of holes attached to an iron rod. Any sand or gravel clinging to the stopper was washed off with distilled water into the soaking beaker and added to the sample during wet-sieving. The sample was left to settle for approximately two and one-half hours depending on the water (room) temperature (two hours thirty-three minutes for 22°C). The hydrometer reading was recorded and the test Calgon reading subtracted from it to obtain the clay weight. The sample was then wet-sieved and the sand and gravel was returned to the soaking beaker. The sample was dried overnight in an oven at 100°C. The sample was then put on the Ro-Tap mechanical shaker for ten minutes with No. 10 (2 mm), No. 18 (1 mm), and No. 230 (63 microns) sieves. The sand envelopes were weighed during sieving then filled with the sand and gravel fraction and weighed again subtracting the envelope weight to obtain the sand and gravel weight. The gravel was subtracted from the original sample weight and the corrected weight was used to calculate the sand, silt, and clay percentages. All weight not accounted for by the gravel, sand, and clay was considered silt.

Table 8. TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO GOVERNMENT "A" (NCT-1) SITE.

Depth	General Description	% Sand	% Silt	% Clay
1'	Fill	31.1	33.2	35.7
4'	Fill	12.3	48.9	38.8
6'	Fill	3.3	56.9	39.8
9.5'	Fill	0.6	36.2	63.2
11'	Silty clay	0.4	31.3	68.3
12'	Clayey silt	0.2	66.4	33.4
14.5'	Silty clay	1.2	44.5	54.3
17'	Silty clay	2.0	48.0	50.0
19.5'	Clayey silt	3.1	63.6	33.3
22'	Clayey silt	7.4	56.1	36.5
22.5'	Laminated clayey silt	15.0	66.2	18.8
24.5'	V. F. sand	64.6	9.9	25.5
25.5'	Clayey silt	12.8	62.8	24.4
27'	Clayey silt	0.7	66.0	33.3
28'	Laminated clayey silt	23.1	50.3	26.6
29'	V. F. sand	61.4	16.4	22.2
32'	V.F. sand	55.0	18.2	26.8
33.5'	Clay	0.2	15.6	84.2
42'	Silty clay	0.1	41.1	58.8
64'	Silty clay	0.4	40.8	58.8
	Mean	14.7	43.7	41.6

TABLE 9. TEXTURAL ANALYSES OF SEDIMENT AT THE BELCO PETROLEUM B.N. SHEEP CK. #1-11 SITE

Depth	General Description	% Sand	% Silt	% Clay
1'	Fill	11.1	53.2	35.7
4.5'	Fill	14.9	51.0	34.1
6'	Fill	7.6	54.6	37.8
9.5'	Drilling Fluid & Fill	12.8	52.6	34.6
11'	Silt	0.2	74.3	25.5
12'	Silt	0.2	64.3	35.5
13.5'	Silt	1.0	55.7	43.3
15'	Silty Clay	4.6	41.8	53.6
19.5'	Silty Clay	2.5	31.0	66.5
22'	Clayey Silt	4.7	57.6	37.7
25'	Clay	0.3	33.2	66.5
28'	Clay	1.7	31.7	66.6
31'	Clayey Silt	1.8	58.2	40
43'	Clayey Silt	17.7	47.9	34.4
	Mean	5.8	50.5	43.7

TABLE 10. TEXTURAL ANALYSES OF SEDIMENT AT THE APACHE CORP. FEDERAL #1-5 SITE

Depth	General Description	% Sand	% Silt	% Clay
1'	Fill	5.6	52.2	42.2
4.5'	Fill	10.9	58.0	31.1
6'	Fill	8.3	54.0	37.7
9'	Fill	17.0	50.8	32.2
11'	Fill	25.2	47.0	27.8
12'	Silt	6.4	66.9	26.7
14'	Silt	18.6	55.8	25.6
15'	Silt	8.1	59.7	32.2
17'	Silt	11.6	61.7	26.7
26'	Clayey Silt	4.0	63.7	32.3
28'	Silt	19.4	60.5	20.1
30'	Silty Sand	59.6	29.3	11.1
45'	Silt	8.1	66.3	25.6
	Mean	15.6	55.8	28.6

TABLE 11. TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO CHARLSON MADISON NORTH UNIT C133 SITE

Depth	General Description	% Sand	% Silt	% Clay
1'	Fill	20.7	51.5	27.8
4.5'	Fill	24.1	37.4	38.5
6'	Fill	18.3	35.1	46.6
8'	Fill	46.0	37.0	17.0
11'	Sandy Silt	41.4	43.1	15.5
13'	Silty Sand	44.2	40.9	14.9
15'	Clayey Silt	17.5	57.0	25.5
16.5'	Clayey Silt	7.9	64.4	27.7
18'	Sandy Silt	27.7	52.3	20.0
28'	Clayey Silt	1.1	50.1	48.8
32'	Silty Clay	1.5	21.9	76.6
	Mean	22.8	44.6	32.6

APPENDIX D

WATER ANALYSES

Sta.	Instrumentation Number
Date-$\bar{X}$	Sampling date or mean
Cond.	Specific conductance in micromhos/cm.
TDS	Total dissolved solids in milligrams/litre
Fe	Iron in milligrams/litre
Mn	Manganese in milligrams/litre
Ca	Calcium in milligrams/litre
Mg	Magnesium in milligrams/litre
Total H.	Total hardness in milligrams/litre
K	Potassium in milligrams/litre
Na	Sodium in milligrams/litre
Cl	Chloride in milligrams/litre
SO_4	Sulfate in milligrams/litre
Total A.	Total alkalinity ($CaCO_3$) in milligrams/litre
HCO_3	Bicarbonate in milligrams/litre
CO_3	Carbonate in milligrams/litre
F	Fluoride in milligrams/litre
% Na	Percent sodium
As	Arsenic in micrograms/litre
Ba	Barium in micrograms/litre
Cd	Cadmium in micrograms/litre
Cr	Chromium in micrograms/litre
Cu	Copper in micrograms/litre
Pb	Lead in micrograms/litre
pH	Field pH
Se	Selenium in micrograms/litre
Temp.	Field temperature in degrees Celsius
Turb.	Turbidity
Zn	Zinc in micrograms/litre
SAR	Sodium absorption ratio
NO_3	Nitrate reported as N in milligrams/litre

TABLE 12. RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT TEXACO INC. GOV'T. "A" (NCT-1) SITE

Instr. No.	Sampling Date			
	9/3/80	1/7/81	6/8/81	10/9/81
A_1*	0	0	0	0
A_2*	0	0	0	0
A_3*	0	0	0	0
A_4	–	–	X	X
A_5*	X	0	X	X
A_6*	X	0	0	X
A_7*	X	X	X	X
A_8*	0	X	0	0
A_9*	0	0	0	0
A_{10}*	–	–	X	–
A_{11}	X	X	X	0
A_{12}	0	0	0	0
A_{13}	X	X	X	X

X Water sample obtained from instrument

0 No sample obtained from instrument

– Sampling device not yet instrumented

* Soil water sampler

Sta.	A_4	A_4	A_4	A_5	A_5	A_5
Date-X	6/27/81	10/9/81	$\bar{x}$	9/30/80	7/17/81	10/9/81
Cond.	18,200	23,100	20,650	49,800	44,000	44,100
TDS	17,300	22,400	19,850	32,700	32,000	32,200
Fe	0.42	0.67	0.55	0.30	0.30	0.54
Mn	1.77	2.49	2.13	8.70	6.03	5.16
Ca	565	532	549	1570	1460	1480
Mg	522	707	615	760	760	770
Total H.	3560	4240	3900	7060	6770	6860
K	77.7	59.2	68.5	148	152	133
Na	4080	6630	5355	11,400	---	10,300
Cl	2000	3500	2750	14,000	16,200	15,000
SO_4	9550	10,100	9825	4480	3590	4260
Total A.	911	1220	1066	587	520	564
HCO_3	1110	1490	1300	717	636	689
CO_3	0	0	0	0	0	0
F	0.2	0.2	0.2	0.3	0.2	0.2
% Na	71.2	77.1	74.2	77.8	75.2	76.4
As	22	29	26	---	24	24.7
Ba	260	60	160	---	160	50
Cd	3.2	4.0	3.6	---	8.5	10.4
Cr	1.5	4.9	3.2	---	74.4	78.0
Cu	74.0	19.6	46.8	---	141	111
Pb	4	13	8.5	---	36	34
pH	7.2	6.5	6.9	6.7	6.8	6.1
Se	---	<2	<2	---	---	<2
Temp.	11.0	10.0	11.0	18.0	14.0	15
Turb.	1.0	5.0	3.0	5.00	2.0	4.0
Zn	103	145	124	---	158	175
SAR	29.7	44.2	37.0	59.2	50.3	54.0
NO_3	<2	85.6	42.8	2.00	5.0	2.00

Sta.	A_5	A_6	A_6	A_6	A_7	A_7
Date-X	$\bar{x}$	9/3/80	10/9/81	$\bar{x}$	9/3/80	1/7/81
Cond.	45,967	95,000	75,700	85,350	272,800	180,000
TDS	32,350	67,800	59,500	63,650	169,000	135,000
Fe	0.38	0.80	0.72	0.76	2.1	8.08
Mn	6.63	5.30	16.1	10.7	9.8	8.68
Ca	1503	3170	3250	2310	7940	6550
Mg	763	990	940	965	174	360
Total H.	6897	11,900	11,900	11,900	20,500	17,800
K	144	475	430	453	1660	1580
Na	10,850	24,000	20,000	22,000	62,600	49,900
Cl	15,100	37,500	32,500	35,000	95,000	75,000
SO_4	4110	1260	1940	1600	1690	2160
Total A.	557	719	736	728	579	675
HCO_3	681	879	899	889	708	825
CO_3	0	0	0	0	0	0
F	0.2	0.1	0.1	0.1	0.0	0.0
% Na	76.5	81.2	78.3	79.8	86.8	85.8
As	24.4	--	88.1	88.1	--	48
Ba	105	--	120	120	--	970
Cd	9.5	--	3.0	3.0	--	13.9
Cr	86.2	--	98.8	98.9	--	10.4
Cu	126	--	161	161	--	653
Pb	35	--	62	62	--	607
pH	6.5	5.8	6.0	5.9	5.6	--
Se	<2	--	<2	<2	--	--
Temp.	--	17	15	16	15	8
Turb.	--	3.0	480	--	3.0	2.0
Zn	167	--	211	211	--	715
SAR	54.5	95.4	79.4	87.4	189	162
NO_3	3.0	2.0	<2	<2	<2	<2

Sta.	A_7	A_7	A_7	A_8	A_{10}	A_{11}
Date-X	7/17/81	10/9/81	$\bar{x}$	1/7/81	6/27/81	9/3/80
Cond.	167,500	165,000	173,750	165,000	34,200	35,100
TDS	153,000	146,000	149,500	132,000	32,200	21,800
Fe	1.81	3.54	2.82	9.72	0.36	0.1
Mn	13.7	13.8	23.5	5.73	2.77	0.3
Ca	6660	7100	6880	8250	562	437
Mg	390	515	375	197	1050	515
Total H.	18,200	19,800	19,000	21,400	5740	323
K	1610	1820	1635	2430	117	43.7
Na	55,300	35,400	52,611	60,300	8320	7760
Cl	87,500	100,000	91,250	75,000	6500	9250
SO_4	1690	1580	1690	728	14,700	3630
Total A.	630	657	666	—	1150	323
HCO_3	770	803	787	—	1410	395
CO_3	0	0	0	—	0	0
F	0.0	0.0	0.0	0.0	0.4	0.4
% Na	86.7	79.4	86.3	85.8	75.8	83.9
As	217	14.0	93	68	—	12
Ba	580	—	775	2550	—	360
Cd	8.3	2.0	8.1	26.3	—	5.0
Cr	8.1	9.9	9.5	1.1	—	1.1
Cu	510	275	480	586	—	270
Pb	122	30	253	619	—	104
pH	6.4	5.5	5.8	—	7.4	6.6
Se	—	<2	<2	—	—	<3
Temp.	11	13	12	8	11.0	11.0
Turb.	1.0	3.0	—	—	3.0	5.0
Zn	1030	433	726	655	—	156
SAR	178	109	170	179	47.7	59.5
NO_3	<2	<2	<2	<2	264	7.92

Sta.	A_{11}	A_{11}	A_{11}	A_{13}	A_{13}	A_{13}
Date-X	1/7/81	6/27/81	$\bar{x}$	9/3/80	1/7/81	6/8/81
Cond.	22,500	19,800	25,800	21,000	15,000	15,400
TDS	13,200	13,200	16,067	14,400	12,500	12,100
Fe	0.58	1.54	.74	0.8	0.34	0.32
Mn	0.6	0.600	0.5	1.8	0.71	1.21
Ca	266	187	297	256	192	171
Mg	305	186	335	252	153	121
Total H.	1920	1230	1158	1670	1100	926
K	39.8	33.2	38.9	31.2	33.5	26.1
Na	4890	4310	5653	5120	3980	3560
Cl	5250	5250	6583	2750	1700	1000
SO_4	2300	2970	2967	5420	5820	6590
Total A.	347	486	385	1010	1110	1160
HCO_3	424	594	471	1240	1360	1420
CO_3	0	0	0	0	0	0
F	0.5	0.5	0.5	0.5	0.4	0.5
% Na	84.6	88.3	85.6	86.8	88.5	89.2
As	11	--	12	16	16	25
Ba	130	--	245	--	260	250
Cd	3.1	--	4.1	5.6	8.5	5.9
Cr	8.8	--	5.0	6.0	2.3	10.4
Cu	77.0	--	174	204	127	135
Pb	137	--	121	23	64	29
pH	--	7.8	7.2	6.9	--	7.6
Se	--	--	<3	<3	--	--
Temp.	8.0	13	11	11	8	11
Turb.	3.0	44	--	50	3.0	5.0
Zn	110	--	133	211	102	272
SAR	48.5	53.3	--	54.3	51.9	50.8
NO_3	2.0	<2	3.97	21.6	<2	<2

Sta.	A_{13}	A_{13}
Date-X	10/9/81	$\bar{x}$
Cond.	14,200	15,200
TDS	12,500	12,500
Fe	0.31	0.33
Mn	1.13	1.17
Ca	148	182
Mg	119	137
Total H.	859	1013
K	20.8	28.7
Na	4420	4200
Cl	875	1350
SO_4	6260	6040
Total A.	1160	1160
HCO_3	1420	1390
CO_3	0	0
F	0.4	0.5
% Na	91.7	88.9
As	24.3	21
Ba	30	145
Cd	7.3	6.6
Cr	6.1	5.6
Cu	57.6	131
Pb	7.0	26
pH	6.8	7.1
Se	<2	<2
Temp.	10	11
Turb.	4.0	--
Zn	162	187
SAR	65.5	53.1
NO_3	<2	<2

TABLE 13. RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT BELCO PETROLEUM B.N. SHEEP CREEK #1-11 SITE.

Instr. No.	Sampling Date			
	9/3/80	1/7/81	6/29/81	10/4/81
B_1*	0	0	X	X
B_2*	0	0	0	0
B_3*	X	X	X	X
B_4*	X	X	X	X
B_5*	0	X	X	X
B_6*	0	0	0	0

X Water sample obtained from instrument

0 No sample obtained from instrument

* Soil water sampler

Sta.	B_1	B_1	B_1	B_3	B_3	B_3
Date-X	6/29/81	10/4/81	$\bar{x}$	9/3/80	1/7/81	6/8/81
Cond.	22,500	--	22,500	269,200	150,000	161,000
TDS	19,000	--	19,000	167,000	137,000	135,000
Fe	0.22	0.42	0.32	1.8	6.32	1.06
Mn	0.780	0.24	0.51	3.2	3.11	5.08
Ca	467	550	509	6760	6100	5500
Mg	597	637	617	960	995	1150
Total H.	3620	3990	3805	20,800	19,300	18,400
K	47.5	74.0	61	2200	2010	1770
Na	4300	6170	5235	61,600	56,000	50,100
Cl	4500	4750	4625	93,700	70,000	75,000
SO_4	8510	8000	8255	2190	1880	1790
Total A.	882	--	882	241	294	294
HCO_3	1070	--	1070	295	359	360
CO_3	0	--	0	0	0	0
F	0.2	--	0.2	0.0	0.0	0.0
% Na	71.9	76.9	74.4	86.4	86.2	85.4
As	--	--	--	--	38	163
Ba	--	--	--	--	780	420
Cd	--	--	--	--	76.3	51.3
Cr	--	--	--	--	2.6	5.4
Cu	--	--	--	--	557	491
Pb	--	--	--	--	1320	216
pH	7.6	7.6	7.1	5.5	--	5.7
Se	--	--	--	--	--	--
Temp.	12	12	12	13	8	9
Turb.	4.0	--	4.0	2.0	2.0	0.00
Zn	--	--	--	--	569	440
SAR	31.0	42.4	36.6	185	175	160
NO_3	--	106	106	2.0	2.0	2.0

Sta.	B_3	B_3	B_4	B_4	B_4	B_4
Date-X	10/6/81	$\bar{x}$	9/3/80	1/7/81	6/8/81	10/6/81
Cond.	158,000	159,500	82,200	63,000	73,200	71,800
TDS	158,000	136,000	55,100	46,000	52,900	57,200
Fe	2.13	1.96	0.30	2.3	0.32	8.41
Mn	4.99	4.095	0.80	1.21	1.08	6.41
Ca	6070	6085	2190	2090	1870	1920
Mg	1450	1073	1430	1540	1440	1570
Total H.	21,100	20,050	11,300	11,500	10,600	11,200
K	1850	1930	377	490	385	369
Na	59,900	57,950	18,100	18,400	16,500	19,500
Cl	87,500	81,250	29,000	20,000	28,700	30,000
SO_4	1740	1835	3760	3160	3630	3460
Total A.	332	294	366	542	523	552
HCO_3	406	360	448	662	639	675
CO_3	0	0	0	0	0	0
F	0.0	0.0	0.1	0.0	0.0	0.1
% Na	85.9	86.1	77.5	77.5	77.1	78.9
As	40.2	80.4	--	17	56	89.6
Ba	70	600	--	270	450	100
Cd	2.3	63.8	--	8.6	13.7	--
Cr	5.8	5.6	--	6.8	1.4	10.0
Cu	138	524	--	274	140	133
Pb	84.2	540	--	353	27	166
pH	5.2	5.6	6.2	--	6.2	5.7
Se	<2	<2	--	--	--	<2
Temp.	12	11	13	8	9	10
Turb.	4.0	--	3.0	2.0	1.0	45
Zn	296	435	--	225	183	180
SAR	179	177	74	74.3	69.7	80.1
NO_3	2.0	2.0	5.0	2.0	2.0	2.0

Sta.	B_4	B_5	B_5	B_5	B_5
Date-X	$\bar{x}$	1/7/81	6/8/81	10/6/81	$\bar{x}$
Cond.	72,500	41,000	41,000	39,400	41,000
TDS	54,000	32,800	27,100	28,200	29,950
Fe	1.35	1.62	4.89	11.4	5.97
Mn	1.15	3.31	2.55	2.85	2.90
Ca	2005	1060	900	950	970
Mg	1490	810	750	830	797
Total H.	11,250	5980	5330	5790	5700
K	381	99.5	92.0	65.5	86.0
Na	18,250	9010	7980	9410	8800
Cl	28,750	12,000	13,700	13,700	13,133
SO_4	3545	3210	3360	2910	3160
Total A.	533	—	517	515	516
HCO_3	651	—	632	629	631
CO_3	0	—	0	0	0
F	0.1	0.1	0.1	0.1	0.1
% Na	77.5	76.5	76.3	77.8	76.9
As	54.2	12	21	40.0	24.3
Ba	273	150	260	—	205
Cd	11.15	9.7	1.8	4.8	5.4
Cr	6.1	5.2	2.3	8.6	5.4
Cu	182	133	81.0	41.1	85.0
Pb	182	205	38	36	93
pH	6.2	—	6.2	5.9	6.1
Se	<2	—	—	<2	<2
Temp.	—	8	10	10	9
Turb.	—	—	50	90.0	—
Zn	196	158	137	164	153
SAR	74.2	50.6	47.4	53.7	50.6
NO_3	2.0	2.0	<2	<2	<2

TABLE 14. RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT APACHE CORP. FEDERAL #1-5 SITE

Instr. No.	Sampling Date			
	9/30/80	1/7/81	6/29/81	10/12/81
C_1	X	X	X	X
C_2	–	–	X	X
C_{3a}	–	–	X	X
C_{3b}	–	–	X	X
C_4*	–	–	0	0
C_5	X	X	–	–
C_6	X	X	–	–
C_{7a}	–	–	X	X
C_{7b}	–	–	X	X
C_8*	–	–	0	0
C_9*	–	–	0	0
C_{10}*	–	–	0	X
C_{11}	X	X	–	–
C_{12}	X	X	X	X
C_{13a}	–	–	X	X
C_{13b}	X	X	X	X
C_{13c}	–	–	X	X
C_{14a}	–	–	X	X
C_{14b}	–	–	X	X
C_{15a}	–	–	X	X
C_{15b}	–	–	X	X

X Water sample obtained from instrument
0 No water sample obtained from instrument
– Sampling device not yet instrumented or was destroyed
* Soil water sampler

Sta.	C_1	C_1	C_1	C_1	C_1	C_2
Date-X	9/3/80	1/7/81	6/29/81	10/12/81	$\bar{x}$	6/29/81
Cond.	6200	5400	4460	5280	5340	4230
TDS	4630	4840	4060	4550	4590	3740
Fe	0.12	0.2	1.3	2.47	0.75	0.25
Mn	2.44	2.66	2.69	2.85	2.68	2.82
Ca	188	181	150	177	179	154
Mg	107	106	89	103	105	80.0
Total H.	910	888	742	867	878	714
K	18.8	17.8	16.2	19.0	18.3	16.6
Na	1310	1130	1030	1400	1220	965
Cl	25	11	13	30	19	55
SO_4	2260	2650	2130	2130	2195	1850
Total A.	1180	1240	1040	1120	1150	1030
HCO_3	1440	1520	1270	1370	1405	1250
CO_3	0	0	0	0	0	0
F	0.6	0.7	0.5	0.5	0.6	0.6
% Na	75.8	73.3	75	77.7	75	74.5
As	7.0	14	21	7.5	11	11
Ba	260	160	240	0	200	360
Cd	5.6	0.5	2.8	1.5	2.2	2.0
Cr	1.2	1.4	2.6	1.6	1.5	6.8
Cu	134	95.0	26.0	12.3	60.5	94
Pb	27	7.0	36	6.0	17.0	6
pH	7.1	--	6.8	7.5	7.1	6.8
Se	<3	--	--	<2	<2	--
Temp.	10.1	8	11	10	--	11
Turb.	3.0	--	5.0	22.0	--	7.0
Zn	120	119	35	49	84	169
SAR	19.0	16.4	16.4	20.7	17.7	15.6
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_2	C_2	C_{3A}	C_{3A}	C_{3A}	C_{3B}
Date-X	10/12/81	$\bar{x}$	6/29/81	10/12/81	$\bar{x}$	6/29/81
Cond.	4180	4205	4320	4410	4365	4050
TDS	3470	3605	3720	3790	3755	3650
Fe	0.08	0.17	0.47	1.27	0.87	0.24
Mn	0.14	1.48	1.81	1.86	1.84	1.27
Ca	80.0	117	150	149	150	143
Mg	76.5	78.3	76.5	79.0	78	66.0
Total H.	514	614	689	698	694	630
K	14.2	15.4	17.3	13.8	15.6	16.8
Na	1040	1003	1050	1130	1090	1040
Cl	13	34	33	33	33	23
SO_4	1680	1765	1740	1730	1735	1740
Total A.	929	951	1020	1080	1075	1020
HCO_3	1130	1190	1300	1330	1315	1250
CO_3	0	0	0	0	0	0
F	0.4	0.5	0.8	0.8	0.8	1.3
% Na	81.3	77.9	76.8	77.8	77.3	78.2
As	6.7	8.9	9	5.0	7.0	7
Ba	—	360	340	—	340	170
Cd	0.9	1.5	1.7	1.1	1.4	1.8
Cr	2.3	4.6	2.0	1.4	1.7	2.0
Cu	6.1	50.5	46.0	6.3	26.2	52
Pb	9.0	7.5	8	4.0	6.0	21
pH	7.5	7.1	6.9	7.7	7.3	7.0
Se	<2	<2	—	<2	<2	—
Temp.	10	—	11	10	—	11
Turb.	3.0	—	4.0	10.0	—	2.0
Zn	65	117	47.0	29.0	38.0	34
SAR	19.9	17.8	17.5	18.6	18.1	18.1
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{3B}	C_{3B}	C_5	C_5	C_5	C_6
Date-X	10/12/81	$\bar{x}$	9/3/80	1/7/81	$\bar{x}$	9/3/80
Cond.	3840	3945	4680	4000	4340	5820
TDS	3200	3425	3420	3360	3390	4130
Fe	0.21	0.23	0.06	1.06	0.56	0.04
Mn	0.98	1.13	2.72	3.19	3.0	2.84
Ca	109	126	147	148	148	193
Mg	54	60	75.0	82.0	79	105
Total H.	494	562	677	707	692	917
K	12.4	14.6	15.1	76.5	45.8	16.5
Na	1010	1025	998	899	949	1250
Cl	28	26	105	70	88	150
SO_4	1380	1560	1480	1470	1475	1760
Total A.	999	1010	981	1010	996	1080
HCO_3	1220	1235	1190	1230	1210	1330
CO_3	0	0	0	0	0	0
F	1.3	1.3	0.6	0.6	0.6	0.6
% Na	81.6	79.9	76.1	73.3	73.7	74.6
As	6.8	6.9	3.0	8.0	5.5	4.0
Ba	60	110	120	180	150	20
Cd	0.7	1.3	1.9	0.7	1.3	1.0
Cr	2.1	2.1	0.0	0.8	0.4	0.4
Cu	6.9	29.5	63.0	16.0	40.0	99.0
Pb	5	13	7.0	7.0	7.0	3.0
pH	7.8	7.4	6.8	—	6.8	6.6
Se	<2	<2	<3	—	<3	<3
Temp.	10	—	10.5	8	—	10.5
Turb.	4.0	—	2.0	—	—	2.0
Zn	24.0	29.0	136	48	92	206
SAR	19.8	19.0	16.6	14.6	15.6	17.9
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_6	C_6	C_{7A}	C_{7A}	C_{7A}	C_{7B}
Date-X	1/7/81	$\bar{x}$	6/29/81	10/12/81	$\bar{x}$	6/29/81
Cond.	4500	5160	18,400	10,100	14,250	22,600
TDS	4330	4230	12,700	7530	10,115	13,100
Fe	0.47	0.26	1.19	4.2	2.7	10.5
Mn	3.64	3.24	6.54	3.6	5.1	9.23
Ca	175	184	585	274	430	775
Mg	98.0	102	280	148	214	370
Total H.	840	879	2610	1290	1950	3460
K	18.2	17.4	61.5	36.6	49	61.0
Na	1120	1185	3680	2460	3070	4120
Cl	53	102	5500	2000	3750	5000
SO_4	2200	1980	2170	2000	2085	2280
Total A.	1110	1095	803	1000	902	817
HCO_3	1360	1345	981	1220	1101	998
CO_3	0	0	0	0	0	0
F	0.5	0.6	0.3	0.4	0.4	0.3
% Na	74.2	74.4	75.3	80.4	77.9	72
As	9.0	7.0	19	11.3	15.2	15
Ba	90	55	410	170	290	400
Cd	0.9	1.0	2.3	1.1	1.7	2.0
Cr	0.9	0.7	1.5	4.2	2.9	3.0
Cu	21.0	60	48	7.9	28	82.0
Pb	3.0	3.0	26	11.0	19	10.0
pH	—	6.6	7.0	7.3	7.2	6.8
Se	—	<3	—	<2	<2	—
Temp.	8	—	12	10	11	12
Turb.	—	—	15.0	33.0	—	83.0
Zn	52	129	90.0	137	113.5	104
SAR	16.7	17.3	31.3	29.7	30.5	30.4
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{7B}	C_{7B}	C_{10}	C_{11}	C_{11}	C_{11}
Date-X	10/12/81	$\bar{x}$	10/12/81	9/3/80	1/7/81	$\bar{x}$
Cond.	18,100	20,350	65,500	19,500	21,000	20,250
TDS	12,400	12,750	53,200	11,500	12,100	11,800
Fe	2.29	6.17	0.75	3.10	0.84	1.97
Mn	6.49	7.9	4.03	6.10	12.9	9.5
Ca	650	713	1440	520	717	619
Mg	350	360	2100	277	347	302
Total H.	3060	3260	12,200	2440	3220	2830
K	45.2	53.1	144	39.0	44.7	41.9
Na	3520	3820	17,900	3520	3490	3505
Cl	5500	5250	25,000	4000	4500	4250
SO_4	1850	2065	5750	2570	2500	2535
Total A.	817	817	1140	968	923	946
HCO_3	998	998	1400	1180	1120	1150
CO_3	0	0	0	0	0	0
F	0.3	0.3	0.0	0.3	0.3	0.3
% Na	71.3	71.8	76.0	75.7	70.1	72.7
As	15.6	15.3	43.3	9	15	12
Ba	20	210	90	380	300	340
Cd	4.6	3.3	16.3	3.1	0.6	1.9
Cr	3.0	3.0	18.9	1.8	0.5	1.2
Cu	10.2	46.1	125	68.0	52.0	60
Pb	50	30	188	92	19	56
pH	6.8	6.8	6.5	6.4	--	6.4
Se	<2	<2	2.6	<3	--	<3
Temp.	10	--	10	10.7	8	--
Turb.	34.0	--	3.0	50.0	3.0	--
Zn	53	79	172	132	85.0	109
SAR	27.6	29.0	70.4	30.9	26.7	28.8
NO_3	<2	<2	203	<2	<2	<2

Sta.	C_{12}	C_{12}	C_{12}	C_{12}	C_{12}	C_{13A}
Date-X	9/3/80	1/7/81	6/29/81	10/12/81	$\bar{x}$	6/29/81
Cond.	14,200	12,000	14,600	15,800	14,400	13,600
TDS	8590	9660	11,000	11,500	10,330	10,000
Fe	0.7	0.54	10.7	15.6	5.6	0.25
Mn	5.6	8.28	9.86	11.0	9.1	5.0
Ca	525	680	715	745	698	515
Mg	287	372	385	455	379	267
Total H.	2490	3230	3370	3730	3300	2380
K	38.7	34.7	33	35.7	35.2	33.5
Na	2120	2310	2660	3000	2485	2660
Cl	2750	2750	3500	3750	3125	3250
SO_4	2360	3030	3290	3060	3045	2820
Total A.	846	814	811	804	813	761
HCO_3	1030	994	991	982	993	930
CO_3	0	0	0	0	0	0
F	0.3	0.3	0.3	0.2	0.3	0.4
% Na	64.7	60.7	63.1	63.5	63.3	70.7
As	10.0	17.0	11.0	3.9	10.5	8
Ba	160	140	150	--	150	470
Cd	2.4	0.5	1.3	0.5	0.9	3.9
Cr	2.3	1.2	1.9	2.0	2.0	2.6
Cu	76	41.0	54	10.3	48	72
Pb	26	11	13	6.0	12	27
pH	6.5	--	6.9	7.2	6.9	7.1
Se	<3	--	--	<2	<2	--
Temp.	9.7	8.0	12.0	10	--	11.0
Turb.	25	2.0	85	112	--	3.0
Zn	144	67.0	76.0	79	78	114
SAR	18.4	17.6	19.9	21.3	19.2	23.7
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{13A}	C_{13A}	C_{13B}	C_{13B}	C_{13B}	C_{13B}
Date-X	10/12/81	$\bar{x}$	9/3/80	1/7/81	6/29/81	10/12/81
Cond.	13,800	13,700	18,800	17,500	14,000	12,700
TDS	9810	9905	11,600	11,600	9580	9080
Fe	1.58	0.92	0.10	1.93	0.75	1.53
Mn	6.13	5.6	9.10	14.7	11.2	9.9
Ca	515	515	760	780	565	495
Mg	285	276	400	390	280	265
Total H.	2460	2420	3540	3550	2560	2320
K	31.7	32.6	37.5	39.5	29.5	28.5
Na	2780	2720	3130	2930	2510	2510
Cl	3250	3250	4250	4650	3250	3250
SO_4	2480	2650	2610	2370	2390	1970
Total A.	781	771	819	814	914	939
HCO_3	954	942	1000	994	1110	1140
CO_3	0	0	0	0	0	0
F	0.4	0.4	0.3	0.2	0.3	0.3
% Na	70.9	70.8	65.6	64	67.9	70.0
As	9.6	8.8	7	13	14	9.1
Ba	110	290	240	190	310	90
Cd	0.4	2.2	5.8	0.8	1.8	2.0
Cr	3.2	2.9	2.0	0.7	4.2	3.5
Cu	9.2	40.6	106	73.0	49.0	12.6
Pb	7	17	78	25	10	21.0
pH	7.4	7.3	6.3	--	6.8	7.1
Se	<2	<2	<3	--	--	<2
Temp.	10.0	--	10.0	8	11	10
Turb.	25	--	4.0	23.0	5.0	12
Zn	69	92	124	138	88	50.0
SAR	24.3	24	22.8	21.3	21.5	22.6
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{13B}	C_{13C}	C_{13C}	C_{13C}	C_{14A}	C_{14A}
Date-X	$\bar{x}$	6/29/81	10/12/81	$\bar{x}$	6/29/81	10/12/81
Cond.	15,750	13,800	9400	12,100	4040	4060
TDS	10,590	9670	6640	8155	3610	6640
Fe	1.1	0.60	0.68	0.64	0.10	0.26
Mn	10.6	5.43	3.59	4.51	0.880	0.80
Ca	663	487	281	384	148	126
Mg	335	245	155	200	77.0	71.0
Total H.	3050	2220	1340	1780	688	607
K	33.5	32.7	22.9	27.8	19.4	15.7
Na	2720	2590	2080	2335	973	944
Cl	3750	3250	1750	2500	13	10
SO_4	2380	2610	1880	2245	1890	1640
Total A.	867	748	764	756	804	829
HCO_3	1055	914	933	924	982	1010
CO_3	0	0	0	0	0	0
F	0.3	0.4	0.5	0.5	0.6	0.5
% Na	66.8	71.5	77.0	74.7	75.3	77.1
As	11.1	16	0.0	8.0	11	4.6
Ba	215	450	20	235	460	40
Cd	1.9	1.9	0.9	2.4	0.9	0.6
Cr	2.8	1.6	2.3	2.0	3.1	2.6
Cu	61	56.0	9.4	32.7	50.0	10.0
Pb	23	12.0	10.0	11.0	14	4.0
pH	6.7	7.0	7.2	7.1	7.1	7.2
Se	<2	--	<2	<2	--	<2
Temp.	--	11	10	--	11	10
Turb.	--	3.0	6.0	--	5.0	3.0
Zn	106	65.0	38	52	78	30
SAR	22.1	23.8	24.7	24.3	16.1	16.6
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{14A}	C_{14B}	C_{14B}	C_{14B}	C_{15A}	C_{15A}
Date-X	$\bar{x}$	6/29/81	10/12/81	$\bar{x}$	6/29/81	10/12/81
Cond.	4050	3680	3710	3695	5220	5430
TDS	5125	3310	2980	3145	5040	4820
Fe	0.18	0.07	0.22	0.15	0.14	0.13
Mn	0.84	0.690	0.49	0.59	1.60	1.54
Ca	137	115	88.5	102	186	177
Mg	74.0	51.0	45.0	48.0	88.5	91.5
Total H.	648	497	406	452	830	820
K	17.6	17.4	13.7	15.6	21.0	18.4
Na	959	933	895	914	1260	1350
Cl	12	10	10	10	18	20
SO_4	1765	1670	1440	1555	2930	2650
Total A.	817	843	808	826	874	841
HCO_3	996	1030	987	1009	1060	1020
CO_3	0	0	0	0	0	0
F	0.6	0.8	0.7	0.8	0.7	0.6
% Na	76.2	80.2	82.6	81.4	76.7	78.1
As	7.8	8.0	5.2	6.6	11.0	0.0
Ba	250	420	70	245	370	150
Cd	0.8	0.7	0.7	0.7	1.3	0.7
Cr	2.9	1.9	2.4	2.2	1.1	1.7
Cu	30.0	37.0	6.9	22	47.0	10.3
Pb	9.0	--	5.0	5.0	5	3.0
pH	7.2	7.0	7.1	7.1	7.3	7.3
Se	<2	--	<2	<2	--	<2
Temp.	--	10	10	--	10	10
Turb.	--	1.0	4.0	--	1.0	2.0
Zn	54	37.0	34	35.5	80.0	48.0
SAR	16.4	18.1	19.3	18.7	19.1	20.5
NO_3	<2	<2	<2	<2	<2	<2

Sta.	C_{15A}	C_{15B}	C_{15B}	C_{15B}	Winter Stock Well
Date-X	$\bar{x}$	6/29/81	10/12/81	$\bar{x}$	1/7/81
Cond.	5325	5300	5080	5190	1700
TDS	4930	4820	4370	4590	1200
Fe	0.14	0.25	0.08	0.17	0.09
Mn	1.57	1.03	0.830	0.93	0.02
Ca	181	161	118	140	1.5
Mg	90	79.5	61.0	70.3	1.0
Total H.	825	730	546	656	8.0
K	19.7	19.6	13.5	16.6	2.4
Na	1305	1260	1370	1315	477
Cl	19	18	3.0	11	6.0
SO_4	2790	2760	2280	2520	169
Total A.	858	847	863	855	903
HCO_3	1040	1030	1050	1040	1060
CO_3	0	0	0	0	17
F	0.7	0.8	0.9	0.9	4.5
% Na	77.4	78.9	84.4	82.2	99.2
As	5.5	9	0.0	4	--
Ba	260	350	120	235	--
Cd	1.0	1.0	0.3	0.7	--
Cr	1.4	1.8	2.3	2.1	--
Cu	28.7	32.0	5.4	18.7	--
Pb	4.0	5.0	4.0	5.0	--
pH	7.3	7.2	7.5	7.4	8.5
Se	<2	--	<2	<2	--
Temp.	--	10	10	--	11.0
Turb.	--	1.0	1.0	--	1.0
Zn	64	45.0	27.0	36	--
SAR	19.8	20.3	25.4	22.4	73.9
NO_3	<2	<2	<2	<2	2.0

TABLE 15. RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT TEXACO INC. CHARLSON MADISON NORTH UNIT C133 SITE.

Instr. No.	Sampling Date			
	9/3/81	1/7/81	6/8/81	10/6/81
D_1	–	–	X	X
D_2*	–	–	0	0
D_3	–	–	X	X
D_4	X	X	0	X
D_5	X	X	0	0
D_6*	0	0	0	0
D_7*	–	–	0	X
D_8*	–	–	X	X
D_9	X	X	X	X
D_{10}	X	X	0	X
D_{11}	X	X	X	X
D_{12}	X	X	X	X
D_{13}	–	–	X	X

X Water sample obtained from instrument

0 No water sample obtained from instrument

– Sampling device not yet instrumented

* Soil water sampler

Sta.	D_1	D_1	D_1	D_3	D_3	D_3
Date-X	6/8/81	10/6/81	$\bar{x}$	6/8/81	10/6/81	$\bar{x}$
Cond.	5480	5410	5445	5540	5420	5480
TDS	5040	4970	5035	4940	4680	4810
Fe	0.05	0.07	0.06	0.06	0.07	0.07
Mn	0.53	1.49	1.01	1.22	1.97	1.60
Ca	397	502	450	445	595	520
Mg	167	200	184	155	212	184
Total H.	1680	2070	1785	1750	2360	2055
K	23.3	21.9	22.6	31.9	27.7	29.8
Na	843	899	871	785	747	766
Cl	63	23	43	35	40	38
SO_4	3040	2790	2915	2930	2490	2710
Total A.	683	753	718	614	647	631
HCO_3	834	920	877	750	790	770
CO_3	0	0	0	0	0	0
F	0.3	0.3	0.3	0.3	0.2	0.3
% Na	52	48.3	50.1	49.2	40.6	44.9
As	5.0	7.6	6.3	8.0	4.3	6.2
Ba	170	170	170	410	200	303
Cd	2.8	1.6	2.2	18	2.0	10
Cr	2.5	4.2	3.3	5.9	2.3	4.1
Cu	90	26.2	58.1	237	35.0	136
Pb	8.0	6.0	7.0	22	5.0	14
pH	6.9	6.7	6.8	7.0	6.7	6.9
Se	--	<2	<2	--	<2	<2
Temp.	10	9.0	9.5	10	9.0	10
Turb.	1.0	3.0	2.0	1.0	3.0	2.0
Zn	94	112	103	181	86	134
SAR	8.93	8.57	8.70	8.16	6.68	7.42
NO_3	95.9	83.0	89.5	185	176	181

Sta.	D_4	D_4	D_4	D_4	D_5	D_5
Date-X	9/3/80	1/7/81	10/6/81	$\bar{x}$	9/3/80	1/7/81
Cond.	11,200	12,500	11,700	11,800	16,500	26,000
TDS	6980	8930	7830	7913	11,000	21,200
Fe	0.0	0.42	0.11	0.18	0.0	1.46
Mn	0.2	0.42	0.11	0.18	0.6	0.77
Ca	542	725	757	675	510	675
Mg	352	477	472	434	667	1240
Total H.	2800	3770	3820	3467	4020	6790
K	21.2	31.3	21.2	24.6	26.7	54.7
Na	1580	1980	1890	1817	2830	5050
Cl	68	60	70	66	1750	4150
SO_4	3220	3960	2960	3380	4420	8520
Total A.	542	642	554	580	598	678
HCO_3	663	784	677	708	731	828
CO_3	0	0	0	0	0	0
F	0.2	0.2	0.2	0.2	0.3	0.2
% Na	54.9	53.1	51.6	53.2	60.3	61.6
As	6	12	1.1	6.4	15	28
Ba	400	150	150	233	180	170
Cd	3.7	2.1	1.5	2.4	7.3	10.4
Cr	4.4	1.0	3.0	2.8	3.8	7.0
Cu	82.0	85.0	56.0	74	164	160
Pb	18	5.0	5.0	9.3	20	85
pH	6.4	--	6.5	6.5	6.6	--
Se	260	--	<2	<2	272	--
Temp.	9.0	6.0	9	8	11	6
Turb.	3.0	2.0	2.0	2.0	5.0	5.0
Zn	99	75	82	85	132	160
SAR	12.9	14.0	13.3	13.4	19.4	26.6
NO_3	861	1310	1310	1160	496	1140

Sta.	D_5	D_7	D_8	D_8	D_8	D_9
Date-X	$\bar{x}$	10/6/81	6/29/81	10/6/81	$\bar{x}$	9/3/80
Cond.	21,250	27,600	27,500	36,400	31,950	19,600
TDS	6100	19,000	15,500	26,200	20,850	21,600
Fe	0.73	0.25	0.18	0.32	0.25	0
Mn	0.68	0.13	0.78	0.66	0.72	0.2
Ca	593	575	700	1000	850	725
Mg	954	705	855	1390	1123	647
Total H.	5405	4330	5260	8210	6735	4470
K	40.7	34.2	37.7	36.0	36.9	18.2
Na	3940	5970	4430	7470	5950	2810
Cl	2950	10,000	7500	12,500	10,000	3750
SO_4	6470	1170	1440	3160	2300	3970
Total A.	638	829	775	972	874	485
HCO_3	780	1010	947	1180	1064	593
CO_3	0	0	0	0	0	0
F	0.3	0.0	0.1	0.0	0.1	0.3
% Na	61	74.8	64.5	66.3	65.4	57.6
As	22	18.5	16	26.5	21.3	29
Ba	175	260	830	130	480	240
Cd	8.9	4.0	9.8	4.4	7.1	19.1
Cr	5.4	2.9	3.7	22.4	13.1	13.4
Cu	162	40.9	69.0	74.7	71.9	338
Pb	53	35	17	33	25	63
pH	6.6	6.4	7.0	6.2	6.6	6.5
Se	272	<2	--	<2	<2	136
Temp.	9.7	13	10	12	11	10
Turb.	--	15	3.0	4.0	3.5	11
Zn	146	120	77	111	94	454
SAR	23	39.4	26.5	35.8	31.2	18.2
NO_3	818	47.1	103	138	121	396

Sta.	D_9	D_9	D_9	D_9	D_{10}	D_{10}
Date-X	1/7/81	6/8/81	10/6/81	$\bar{x}$	9/3/80	1/7/81
Cond.	19,000	20,600	19,800	19,700	9260	19,000
TDS	15,100	14,000	14,600	14,300	6040	16,000
Fe	0.64	0.11	0.19	0.15	0.12	0.70
Mn	0.16	0.14	0.15	0.15	0.40	0.91
Ca	942	780	850	815	440	702
Mg	840	765	865	803	272	1070
Total H.	5810	5090	5680	5385	2220	6150
K	28.8	24.1	18.0	21.2	20.2	33.0
Na	3540	3180	3610	3360	1490	3470
Cl	5100	4750	5000	4875	950	4600
SO_4	3920	3770	3510	3845	2450	5270
Total A.	480	490	466	483	283	571
HCO_3	587	599	570	590	346	698
CO_3	0	0	0	0	0	0
F	0.2	0.2	0.2	0.2	0.6	0.3
% Na	56.8	57.4	57.8	57.5	59.2	54.9
As	12	24	15.3	19.7	6	18
Ba	270	620	300	285	240	260
Cd	9.6	9.2	13.6	11.6	2.9	5.4
Cr	1.2	4.6	4.4	4.4	2.3	1.6
Cu	73	69	50.8	71	124	114
Pb	106	8.0	8.0	36	9.0	79
pH	--	6.6	5.7	6.3	6.5	--
Se	--	--	<2	<2	132	--
Temp.	8	11	10	10	11	7
Turb.	2.0	3.0	4.0	4	15.0	3.0
Zn	124	171	275	223	94	188
SAR	20.1	19.3	20.8	19.7	13.7	19.2
NO_3	518	483	540	512	244	576

Sta.	D_{10}	D_{10}	D_{11}	D_{11}	D_{11}	D_{11}
Date-X	10/6/81	$\bar{x}$	9/3/80	1/7/81	6/8/81	10/6/81
Cond.	15,100	14,453	7590	6400	6670	6220
TDS	10,600	10,880	4760	5390	5010	4900
Fe	0.14	0.32	0.04	0.23	0.04	0.09
Mn	0.07	0.46	0.64	0.880	0.53	0.51
Ca	450	531	407	442	451	450
Mg	635	659	237	225	235	235
Total H.	3730	4033	1990	2030	2090	2090
K	22.2	25.1	17.5	26.3	25.3	19.2
Na	2810	2590	995	905	1040	890
Cl	2500	2683	775	700	750	875
SO_4	3340	3687	1950	2710	2150	2070
Total A.	535	463	479	530	490	475
HCO_3	654	566	585	648	599	580
CO_3	0	0	0	0	0	0
F	0.4	0.4	0.2	0.2	0.2	0.2
% Na	61.9	58.7	51.8	49.0	51.9	47.9
As	14.4	12.8	8	17	9	0.0
Ba	100	200	180	90	310	60
Cd	2.8	3.7	5.5	15.6	9.4	1.6
Cr	3.8	2.6	1.8	1.5	2.8	3.0
Cu	35.7	91.2	58	52	80.0	43.9
Pb	5.0	31	26	43	3.0	3.0
pH	6.5	6.5	6.6	—	7.2	6.4
Se	<2	<2	28	—	—	<2
Temp.	10	9.3	9	7	11	9
Turb.	2.0	6.7	5.0	2.0	0.0	3.0
Zn	104	129	61.0	56.0	104	66
SAR	20.0	17.6	9.68	8.73	9.93	8.46
NO_3	522	447	83.6	57.8	61.3	82.3

Sta.	D_{11}	D_{12}	D_{12}	D_{12}	D_{12}	D_{12}
Date-X	$\bar{x}$	9/3/80	1/7/81	6/8/81	10/6/81	$\bar{x}$
Cond.	6535	5430	4200	4160	3970	4180
TDS	4955	3880	4370	3570	3480	3725
Fe	0.04	0.04	0.18	0.06	0.12	0.09
Mn	0.59	1.48	1.52	1.49	2.0	1.51
Ca	446	432	437	370	435	434
Mg	235	162	180	150	157	160
Total H.	2060	1740	1830	1540	1730	1735
K	22.3	22.7	22.7	19.5	16.7	21.1
Na	950	600	606	521	528	564
Cl	763	225	125	95	100	113
SO_4	2110	2090	2680	2140	1960	2115
Total A.	485	405	445	437	437	437
HCO_3	592	495	544	534	534	534
CO_3	0	0	0	0	0	0
F	0.2	0.3	0.2	0.3	0.2	0.3
% Na	50.4	42.5	41.7	42.2	39.7	42.0
As	11	4.0	4.0	5.0	1.3	4.0
Ba	135	180	180	450	50	180
Cd	7.5	3.4	2.5	3.3	1.7	2.9
Cr	2.3	3.1	0.8	2.8	2.9	2.9
Cu	53	64	37.0	44.0	17.3	41
Pb	15	17	---	18.0	4.0	18
pH	6.7	6.5	---	7.4	6.5	6.8
Se	---	27	---	---	<2	---
Temp.	9.0	10	7.0	10.0	8.0	9.0
Turb.	3.0	2.0	1.0	0.0	2.0	2.0
Zn	64	58.0	45.0	114	73	66
SAR	9.20	6.23	6.15	5.77	5.51	5.96
NO_3	71.9	99.6	53.7	16.5	12.2	35.1

Sta.	D_{13}	D_{13}	D_{13}
Date-X	6/8/81	10/6/81	$\bar{x}$
Cond.	5320	4280	4300
TDS	4120	3230	3675
Fe	.02	0.07	0.05
Mn	1.55	1.48	1.52
Ca	412	375	394
Mg	132	127	130
Total H.	1570	1460	1515
K	37.9	28.0	33
Na	709	624	667
Cl	425	350	388
SO_4	2100	1420	1760
Total A.	420	382	401
HCO_3	514	467	491
CO_3	0	0	0
F	0.4	0.3	0.4
% Na	49.3	48	49
As	5.0	3.0	4
Ba	410	150	280
Cd	6.5	5.2	5.9
Cr	4.3	3.1	3.7
Cu	69.0	31.6	50.3
Pb	44	3.0	23.5
pH	7.4	6.6	7.0
Se	—	<2	—
Temp.	9	8	90
Turb.	1.0	2.0	2.0
Zn	102	125	114
SAR	7.76	7.10	7.43
NO_3	46.2	71.4	58.8

TABLE 16. ELUTRIATION EXPERIMENT SEDIMENT SAMPLES FROM STUDY SITES.

Sample No.	Study Site	Depth from surface
E1	Texaco Gov't "A" NCT-1	8.0 ft. (2.4m)
E2	Texaco Gov't "A" NCT-1	11.5 ft. (3.5m)
E3	Texaco Gov't "A" NCT-1	14.5 ft. (4.4m)
E4	Texaco Gov't "A" NCT-1	22.3 ft. (6.8m)
E5	Texaco Gov't "A" NCT-1	33.5 ft. (10.2 m)
E6	Texaco Gov't "A" NCT-1	64.5 ft. (19.7m)
E7	Belco Petro. B.N. #1-11	9.5 ft. (2.9m)
E8	Apache Federal #1-5	7.5 ft. (2.3m)
E9	Apache Federal #1-5	12.5 ft. (3.8m)
E10	Apache Federal #1-5	15.5 ft. (4.7m)
E11	Apache Federal #1-5	17.5 ft. (5.3m)
E12	Texaco Charlson C133	14.0 ft. (4.2m)

Sta.	E_1	E_2	E_3	E_4	E_5	E_6
Date-X						
Cond.	3160	2420	1420	4474	411	369
TDS	2450	1300	833	2540	334	264
Fe	0.07	1.01	0.06	0.22	0.65	7.04
Mn	0.77	0.21	0.1	0.06	0.04	0.14
Ca	388	36.5	66.5	52.5	4.5	6.5
Mg	13	10.0	16.5	13.0	2.0	6.5
Total H.	1020	132	234	184	19	43
K	25.8	19.5	6.45	11.7	3.3	3.85
Na	328	457	222	947	102	104
Cl	650	720	340	1380	6.0	5.0
SO_4	1010	24	151	92	179	23
Total A.	43	54	43	63	60	187
HCO_3	53	66	53	77	73	229
CO_3	0	0	0	0	0	0
F	0.4	0.3	0.6	0.2	0.3	--
% Na	40.9	88.1	67.2	91.7	91.8	84
As	--	--	--	--	4.0	6.0
Ba	--	--	--	--	190	220
Cd	--	--	--	--	2.1	3.0
Cr	--	--	--	--	9.7	18.8
Cu	--	--	--	--	135	158
Pb	--	--	--	--	28	35
pH	7.5	8.1	7.5	8.2	9.4	9.4
Se	--	--	--	--	2.0	5.0
Temp.	--	--	--	--	--	--
Turb.	2.0	22.0	1.0	8.0	7.0	92.0
Zn	--	--	--	--	83.0	192
SAR	4.46	17.2	6.3	30.3	10.0	6.92
NO_3	<2	<2	5.0	<2	2.0	<2

Sta.	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}
Date-X						
Cond.	1380	1830	2620	675	800	253
TDS	797	1150	1230	371	542	143
Fe	0.04	0.1	10.7	6.84	2.59	0.04
Mn	0.08	0.02	0.14	0.12	0.04	0.01
Ca	51.0	8.0	13.0	14.0	8.0	8.0
Mg	16.0	1.0	6.0	6.0	3.0	5.5
Total H.	193	24	57	60	32	43
K	7.2	11.9	12.7	3.45	2.8	1.4
Na	212	390	473	135	164	45
Cl	290	350	590	5.0	64	48
SO_4	186	291	45	88	250	7.0
Total A.	54	163	158	195	81	45
HCO_3	66	200	179	235	99	55
CO_3	0	0	7.0	2.0	0	0
F	0.2	0.4	0.1	0.1	0.2	0.1
% Na	70.4	97.2	94.7	83.0	91.6	69.5
As	3.0	5.0	10.0	9.0	7.0	--
Ba	420	320	200	230	210	--
Cd	0.8	1.0	2.6	2.8	1.2	--
Cr	1.2	26.6	17.6	7.4	6.3	--
Cu	19.0	60.0	101	142	60.0	--
Pb	5.0	15.0	23.0	14.0	13.0	--
pH	8.2	8.6	9.8	10.0	9.6	9.1
Se	0	11.0	8.0	0	0	--
Temp.	--	--	--	--	--	--
Turb.	1.0	1.0	35.0	4.0	15.0	3.0
Zn	24	30	52.0	94.0	30.0	--
SAR	6.64	34.5	27.2	7.62	12.5	2.99
NO_3	<2	<2	<2	<2	2.0	<2

APPENDIX E

ISOCONCENTRATION MAPS OF SELECTED PARAMETERS FROM WITHIN THE SATURATED ZONES AT THE APACHE FEDERAL #1-5 AND TEXACO CHARLSON C133 SITES.

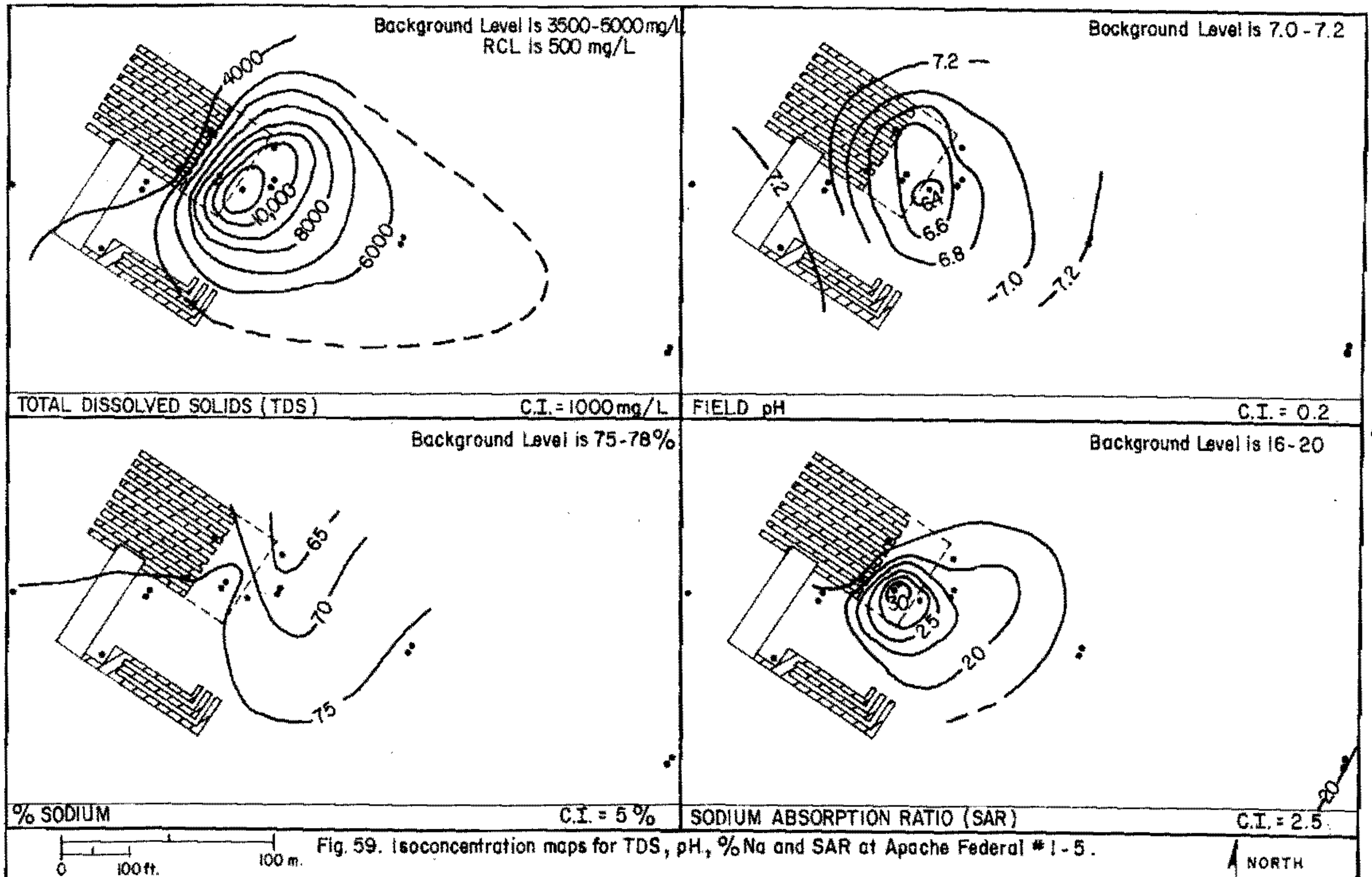


Fig. 59. Isoconcentration maps for TDS, pH, %Na and SAR at Apache Federal # 1-5.

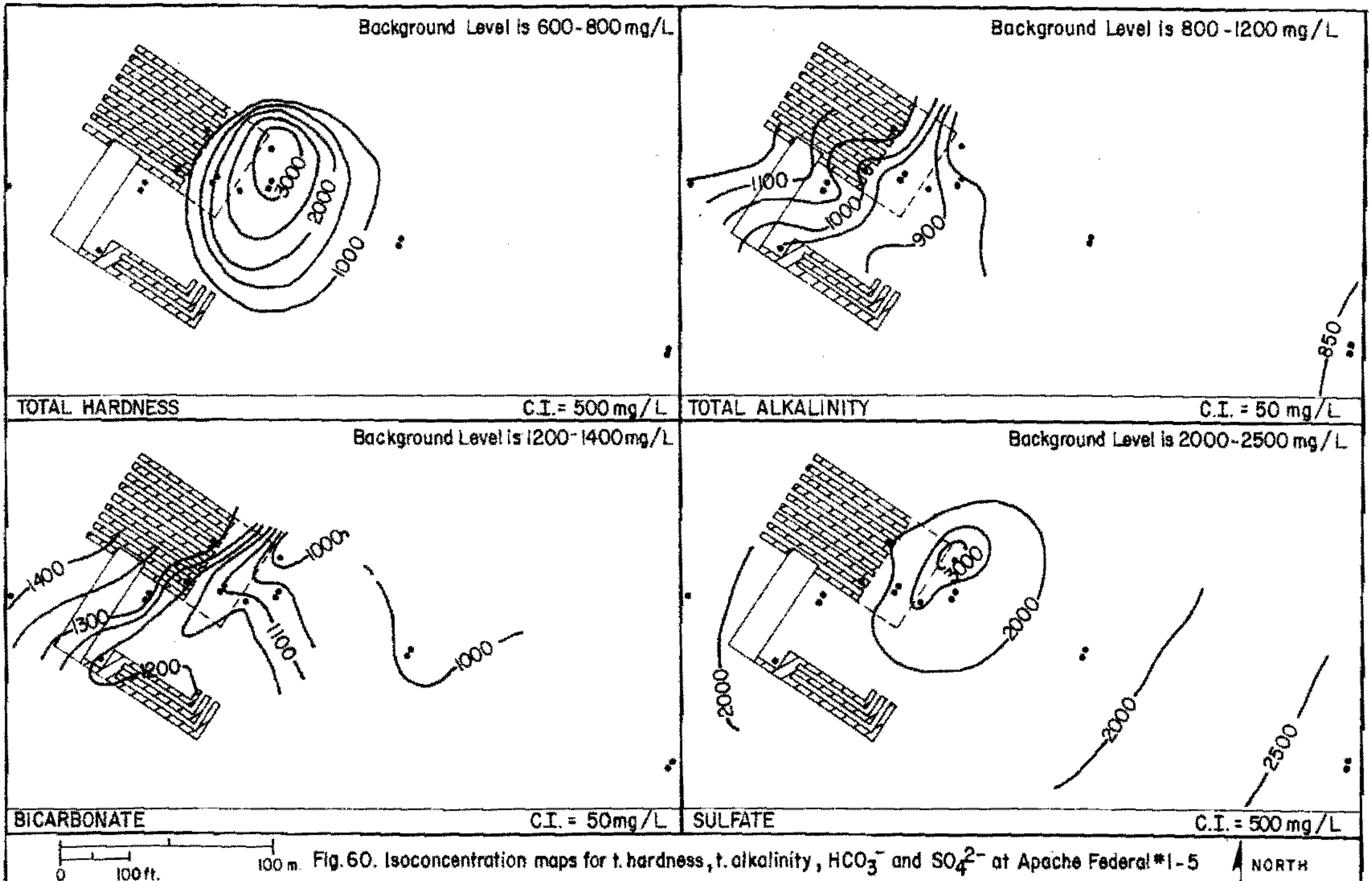


Fig. 60. Isoconcentration maps for t. hardness, t. alkalinity, HCO_3^- and SO_4^{2-} at Apache Federal #1-5

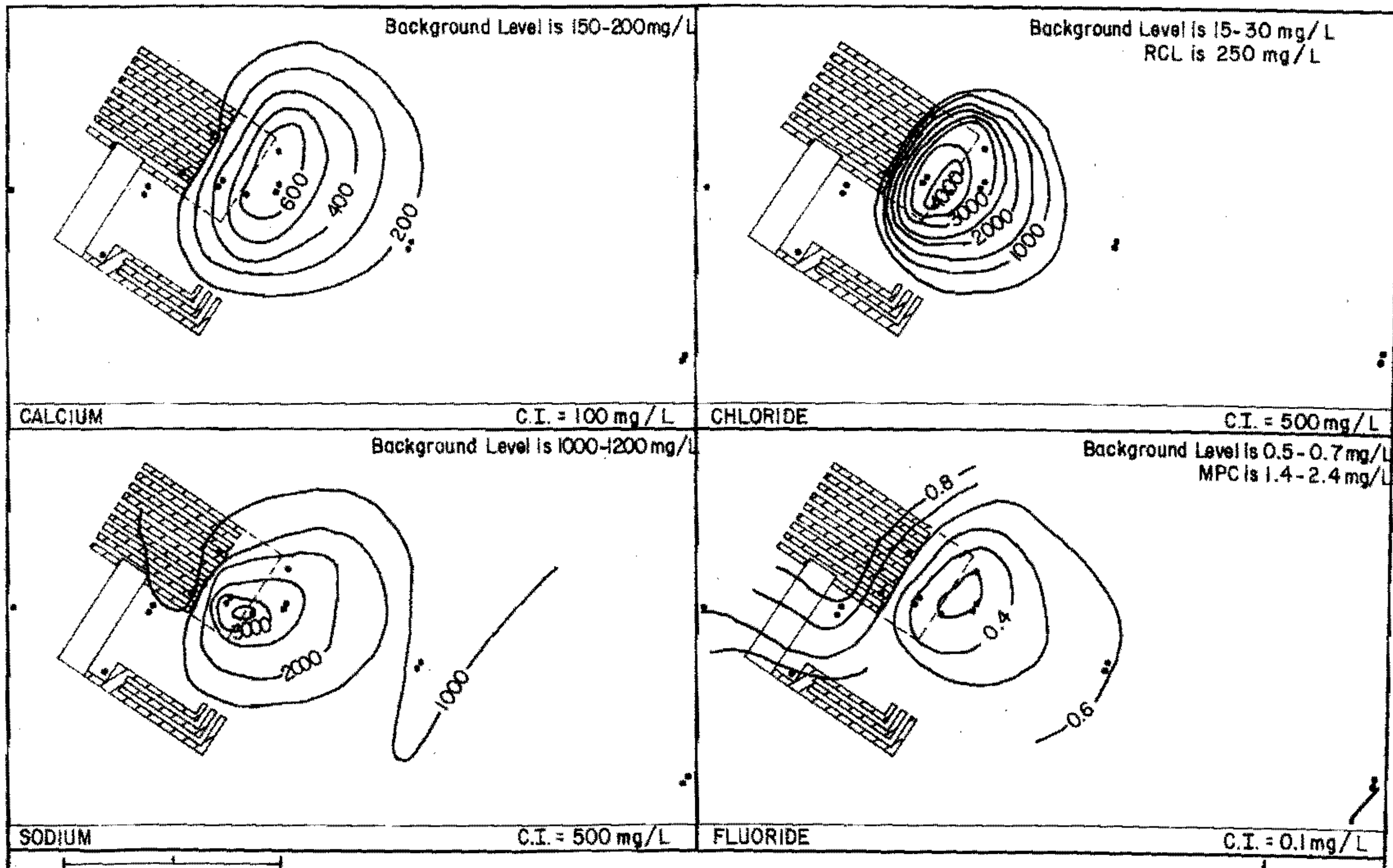
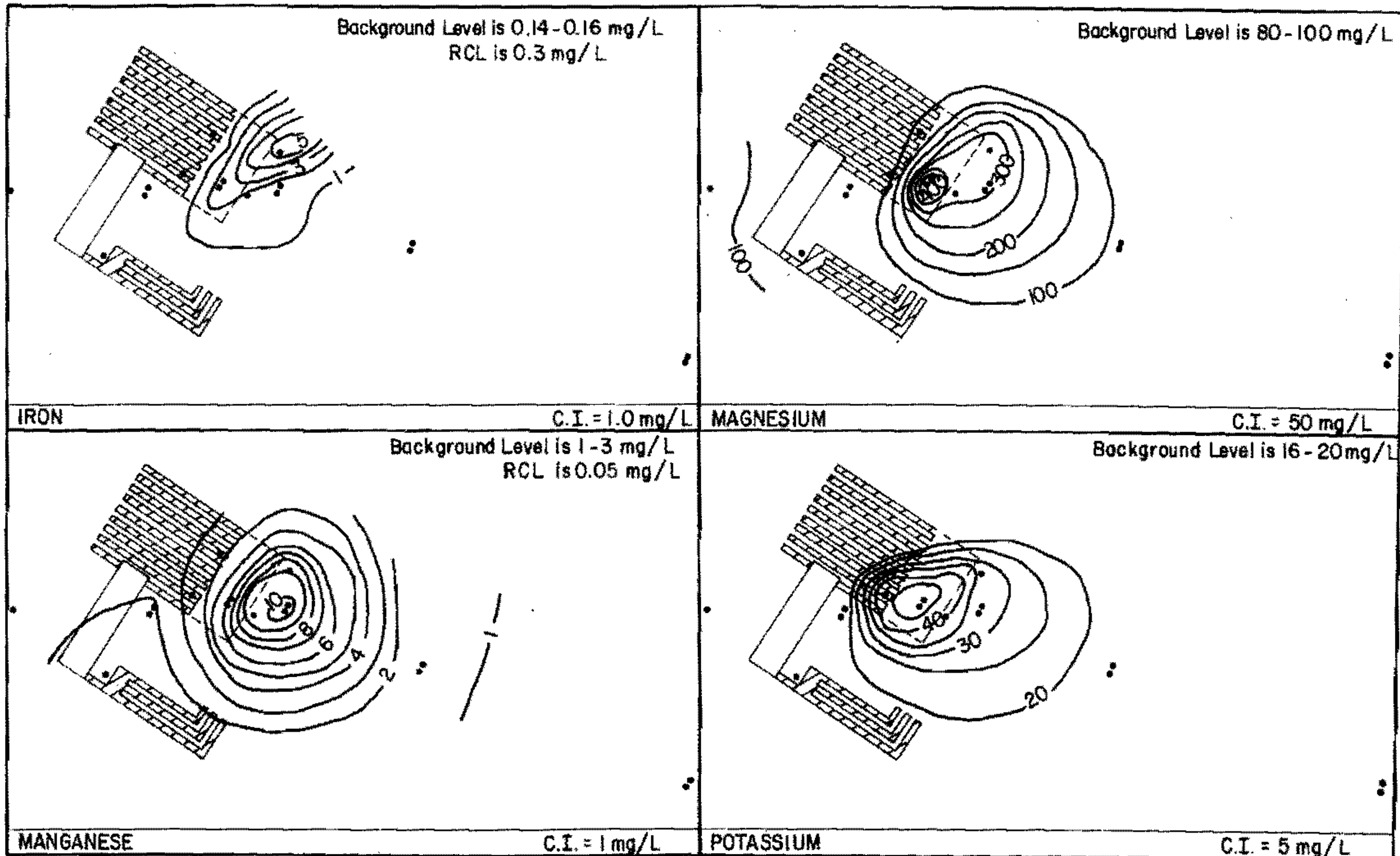
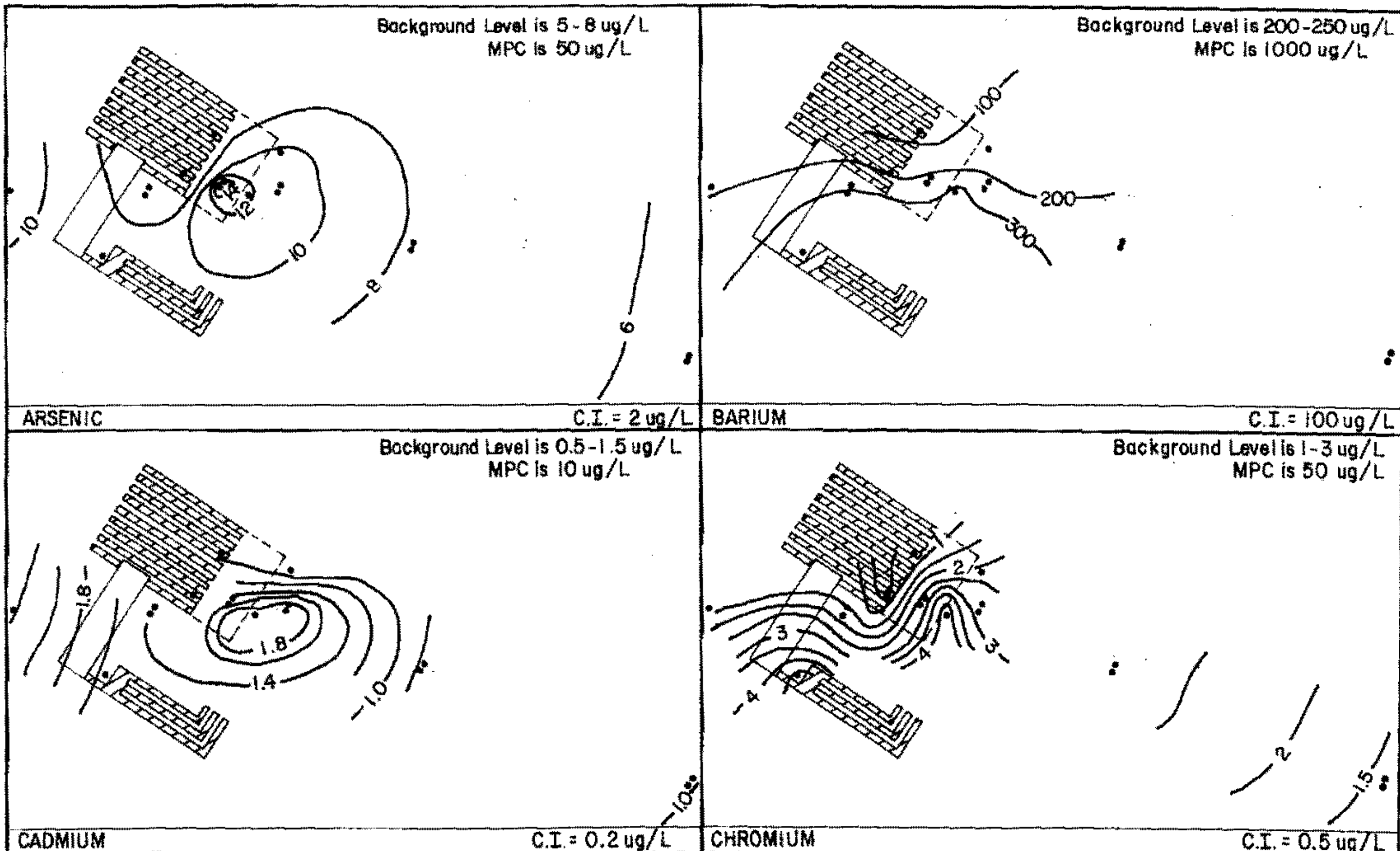


Fig. 61. Isoconcentration maps for Ca, Cl^-, Na and Fluoride at Apache Federal #1-5.



0 100 ft. 100 m. Fig. 62. Isoconcentration maps for Fe, Mg, Mn and K at Apache Federal # 1-5. NORTH



0 100 ft. 100 m. Fig. 63. Isoconcentration maps for As, Ba, Cd and Cr at Apache Federal # 1-5. NORTH

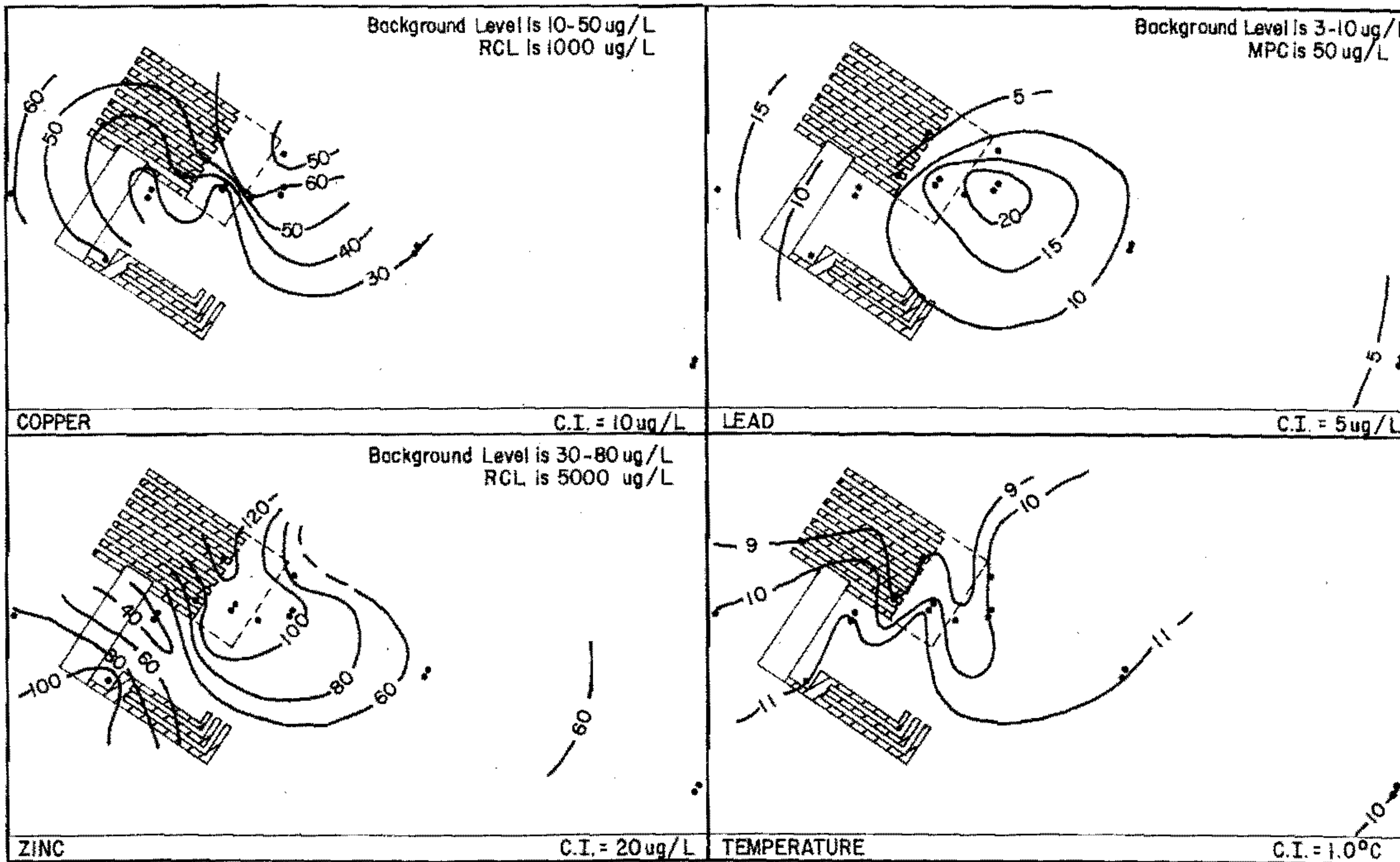


Fig. 64. Isoconcentration maps for Cu, Pb, Zn and Temp. at Apache Federal #1-5

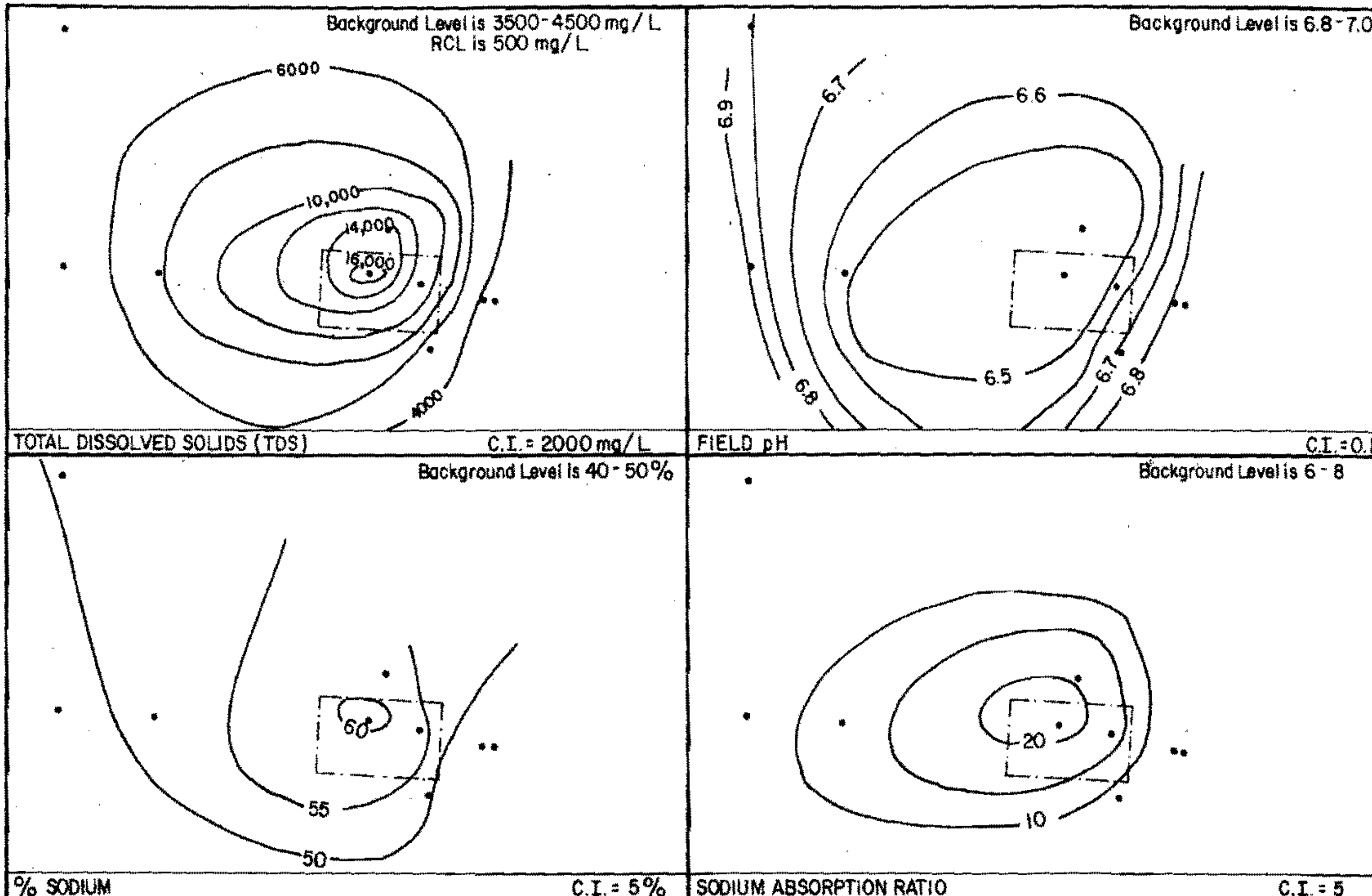


Fig. 65. Isoconcentration maps for TDS, pH, % Na and SAR at Texoco Charlson C133

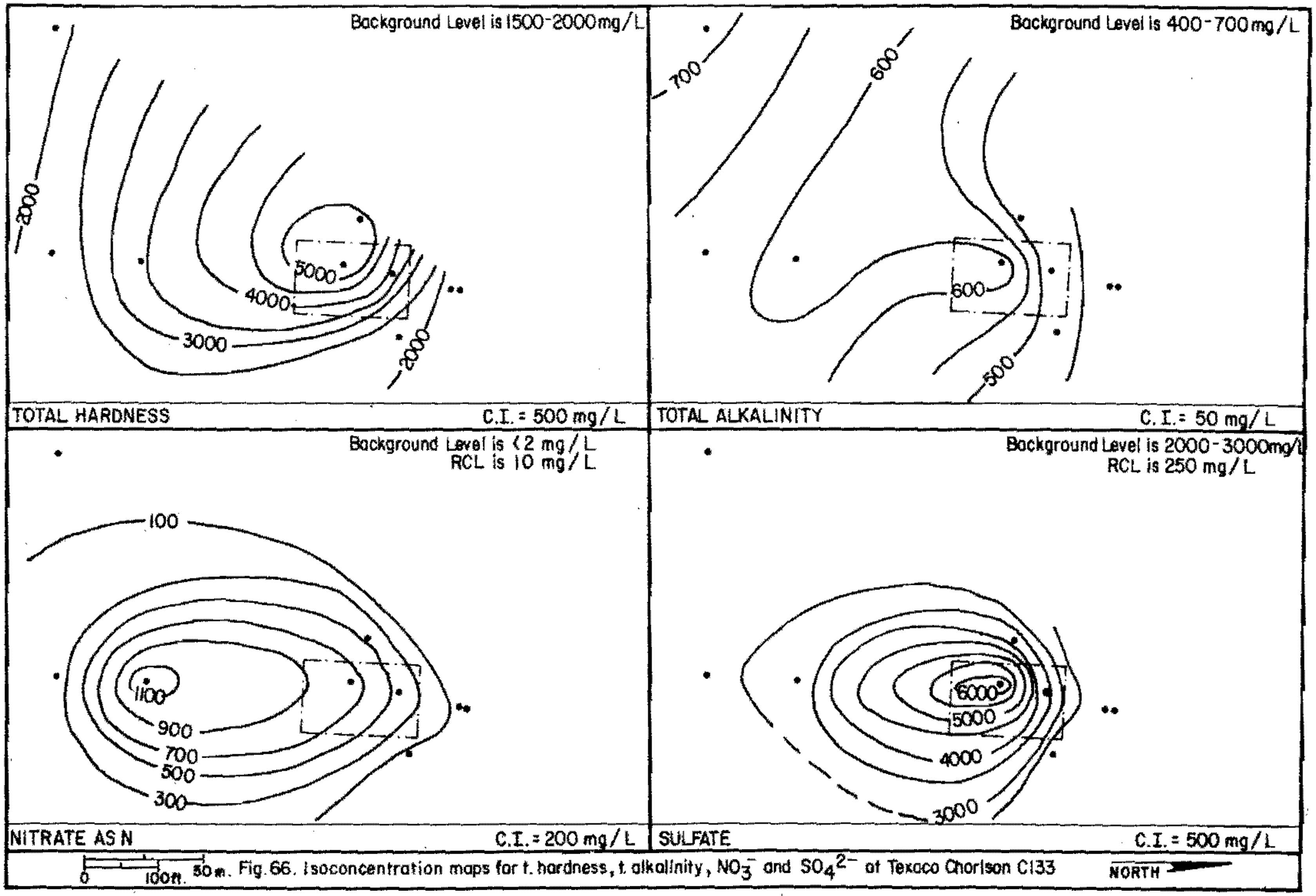


Fig. 66. Isoconcentration maps for t. hardness, t. alkalinity, NO_3^- and SO_4^{2-} at Texaco Charlson C133

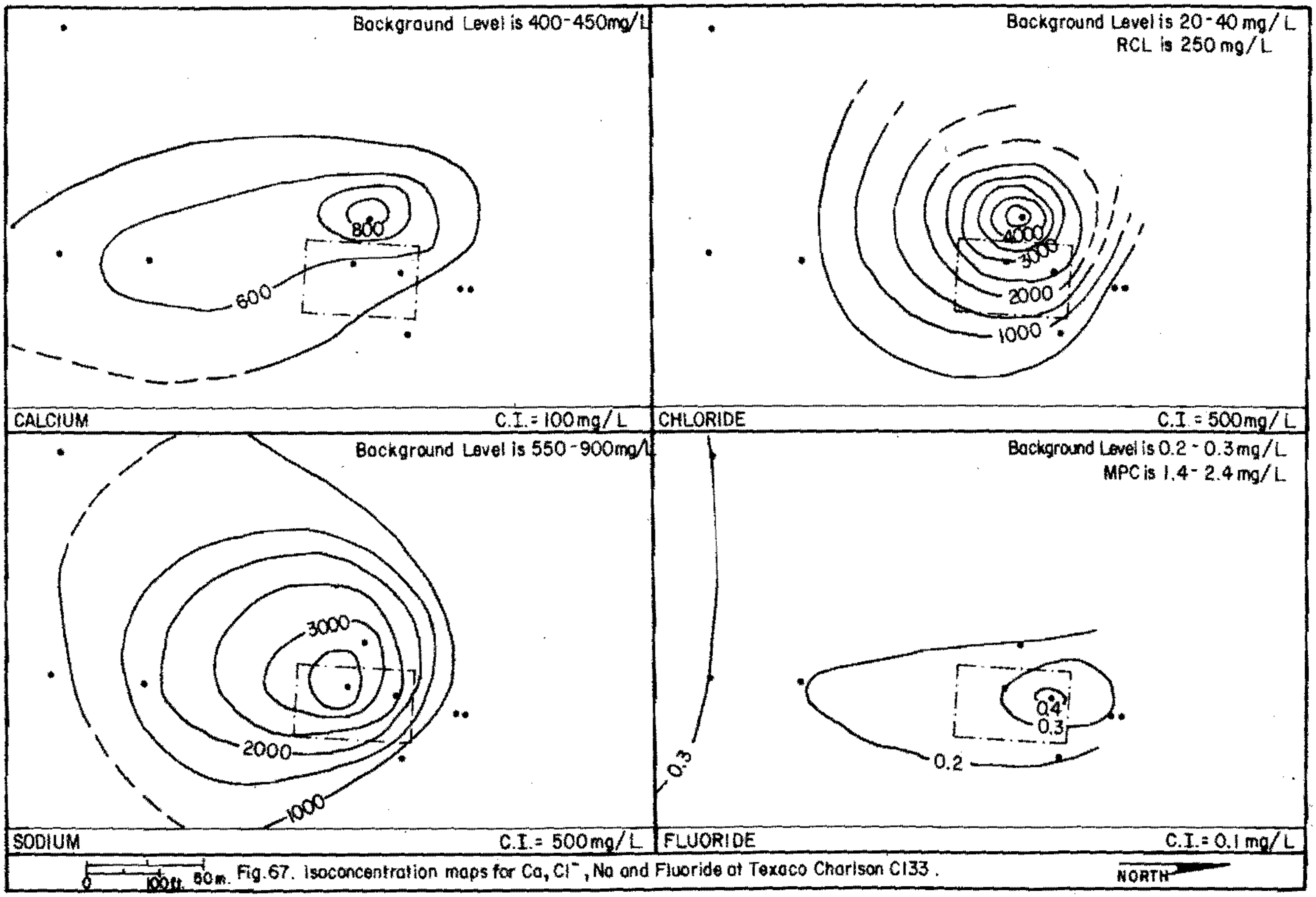


Fig. 67. Isoconcentration maps for Ca, Cl^-, Na and Fluoride at Texaco Charlson C133.

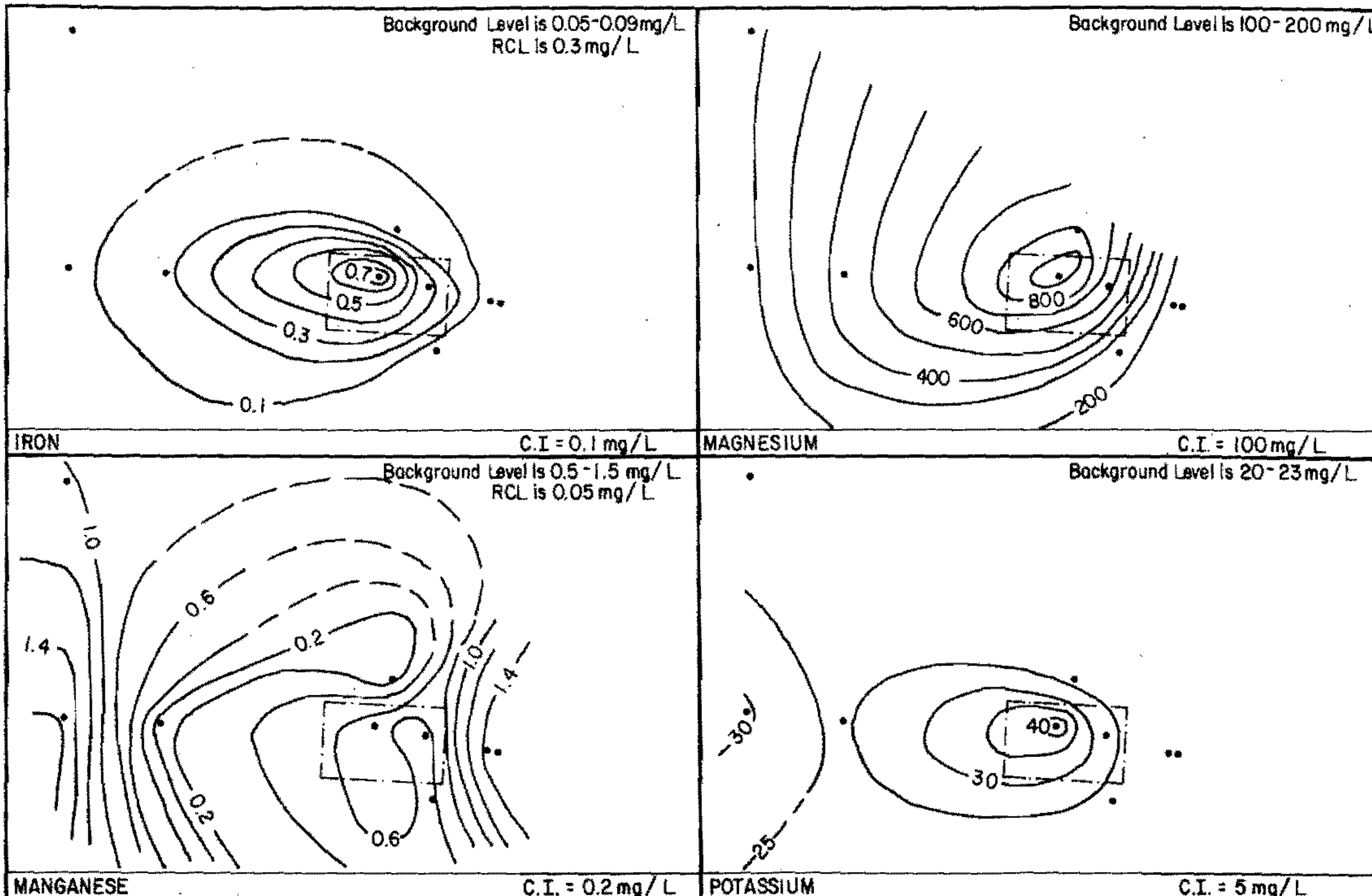


Fig. 68. Isoconcentration maps for Fe, Mg, Mn and K at Texaco Charlson C133.

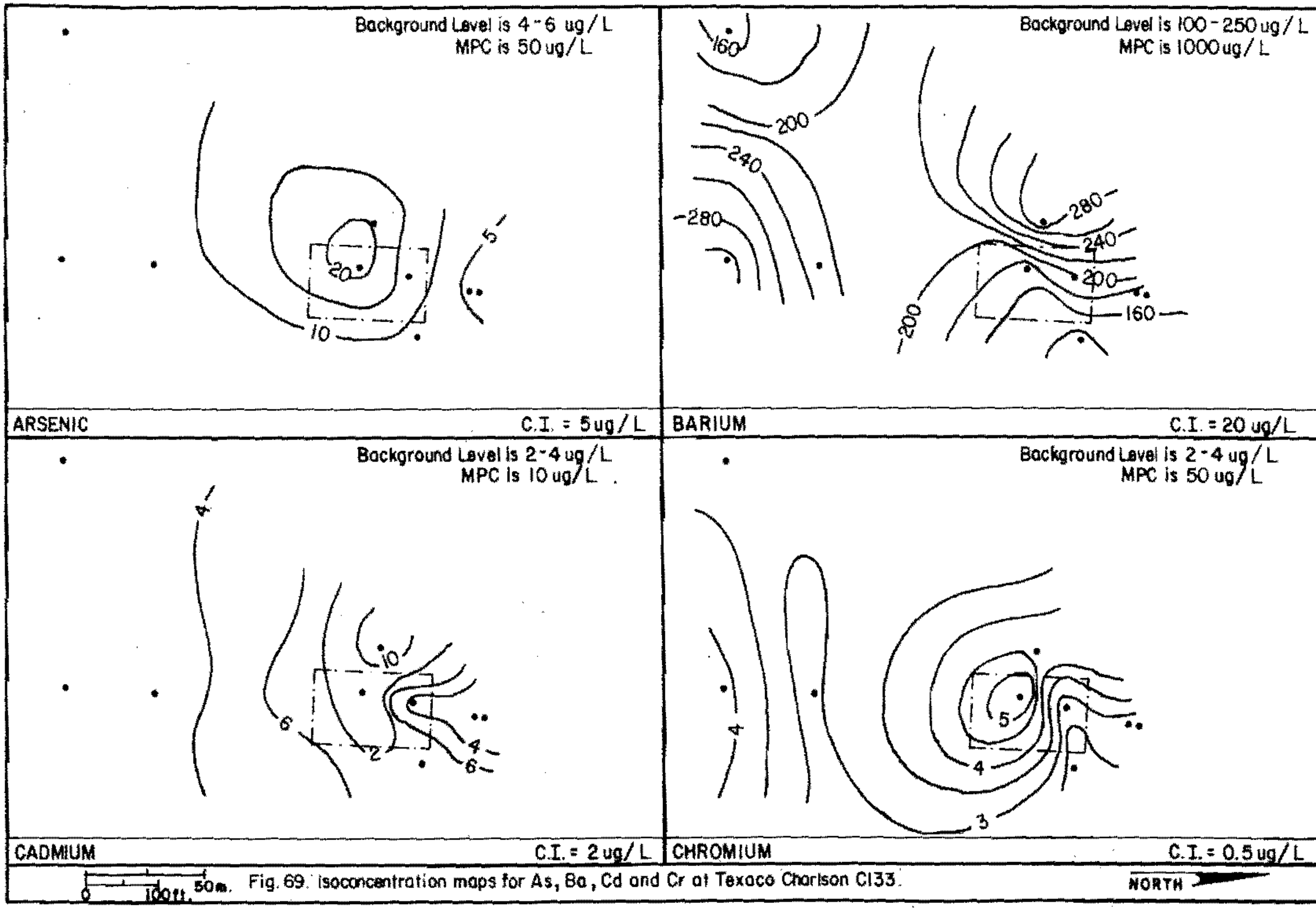
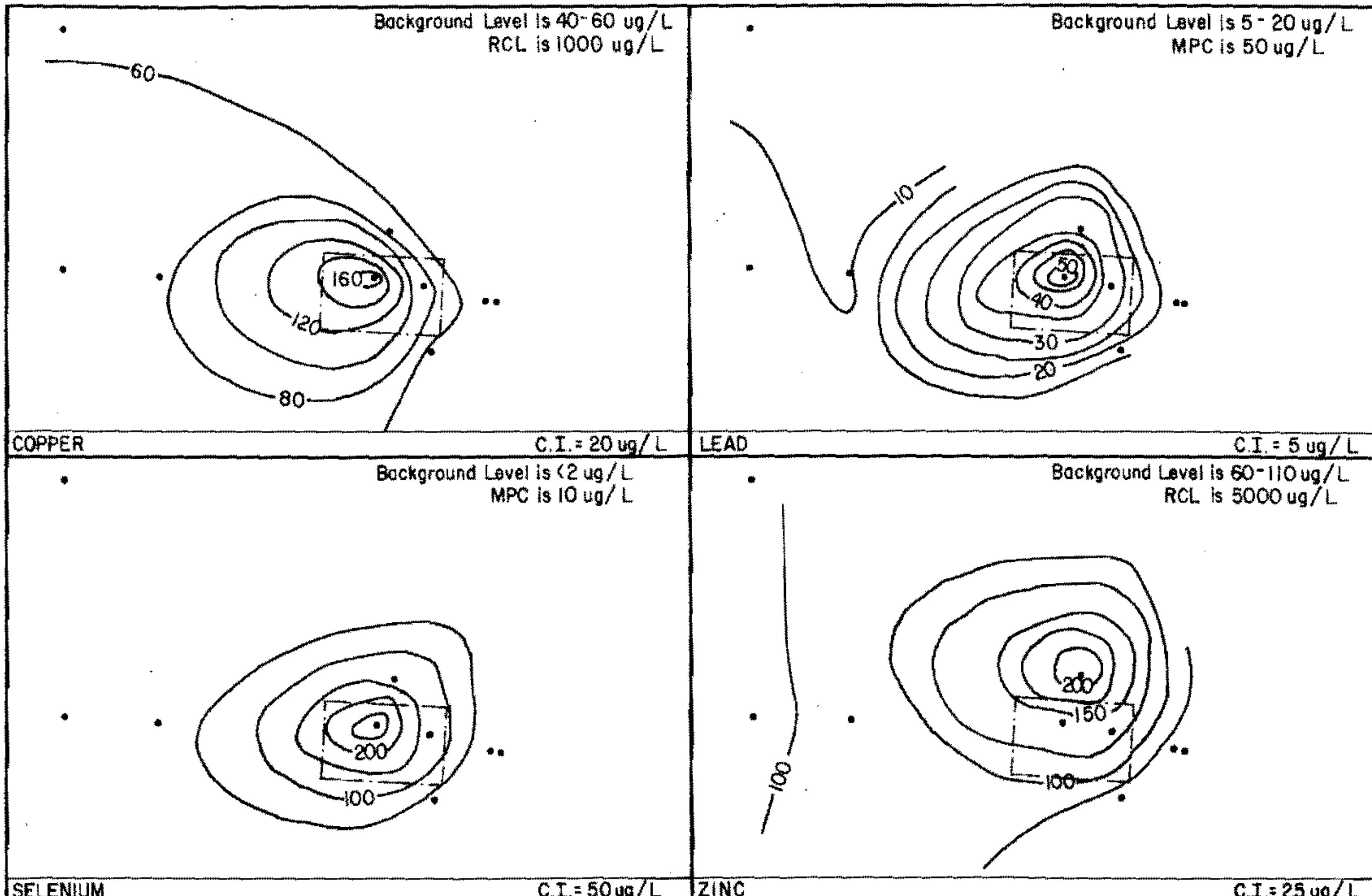


Fig. 69. Isoconcentration maps for As, Ba, Cd and Cr at Texaco Charlson C133.



0 100ft. 50m. Fig. 70. Isoconcentration maps for Cu, Pb, Se and Zn at Texaco Charlson C133. NORTH

APPENDIX F

APPARENT AND INTERPRETED RESISTIVITY PROFILES FOR THE APACHE FEDERAL #1-5 AND TEXACO CHARLSON C133 SITES.

Each resistivity station profile includes the field curve plotted as apparent resistivity versus electrode spacing, the depths and resistivities obtained by automatic interpretation (this data was unobtainable when the slope of the apparent resistivity field curve exceeded 45^{o}), lithology, and water table level on the date the resistivity readings were taken. A lithologic column is presented for each resistivity station and corresponds to the station that it is adjacent to. When the lithology is the same for the two adjacent stations only one lithologic column is presented.

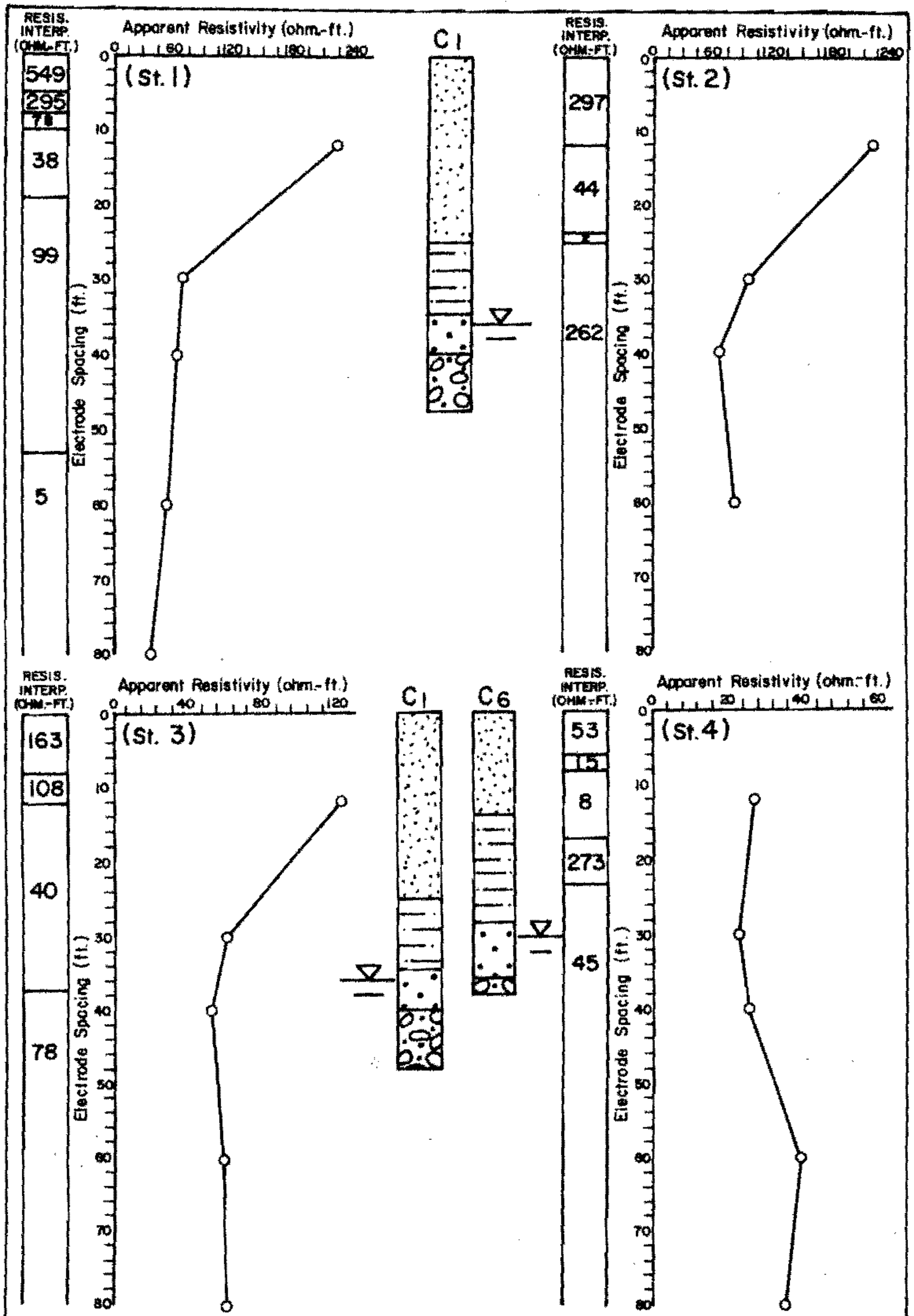


Fig. 71. Apparent and Interpreted Resistivity Profiles for Sts. 1-4 at Apache Federal # 1-5

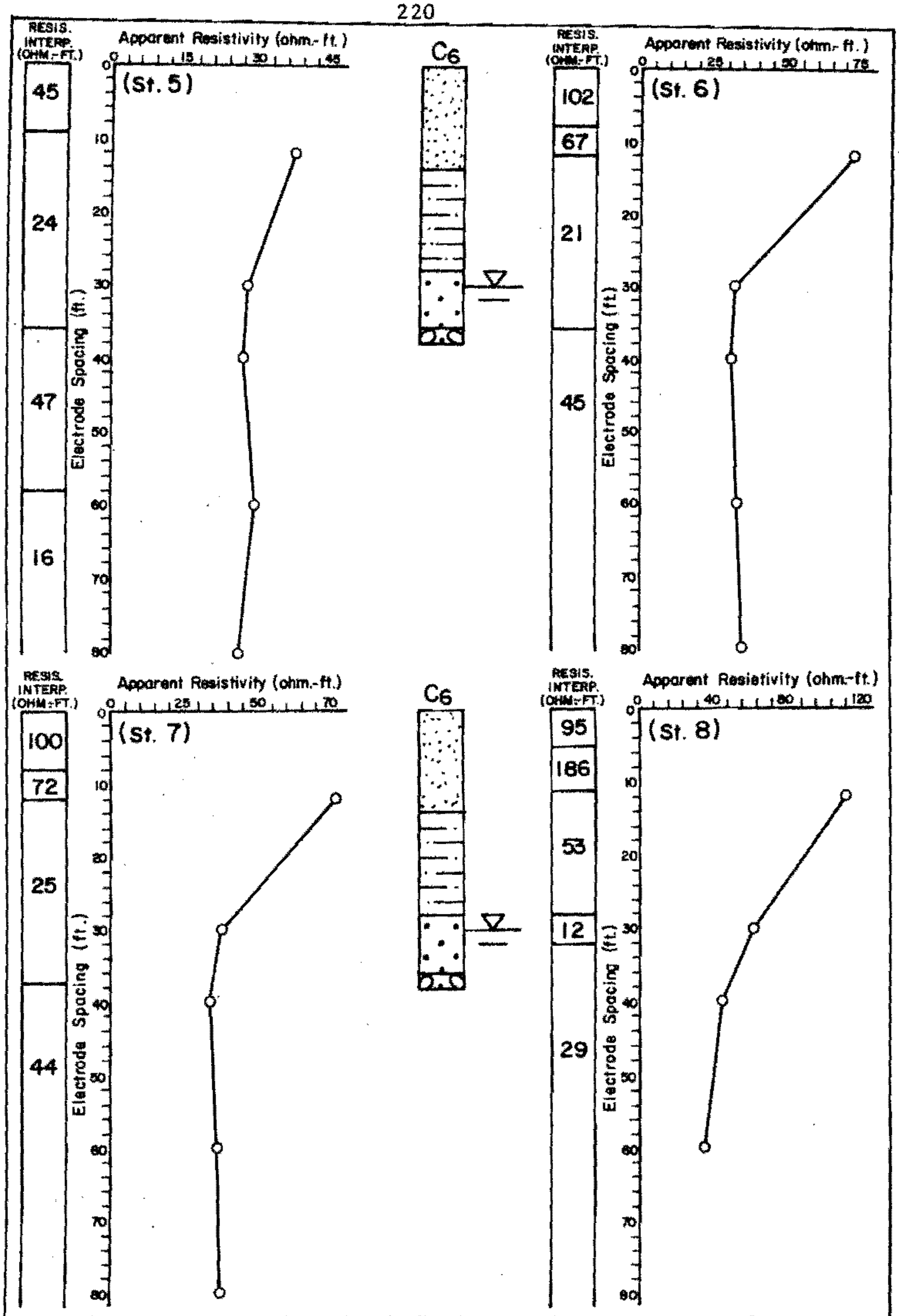


Fig. 72. Apparent and Interpreted Resistivity Profiles for Sts. 5-8 at Apache Federal #1-5.

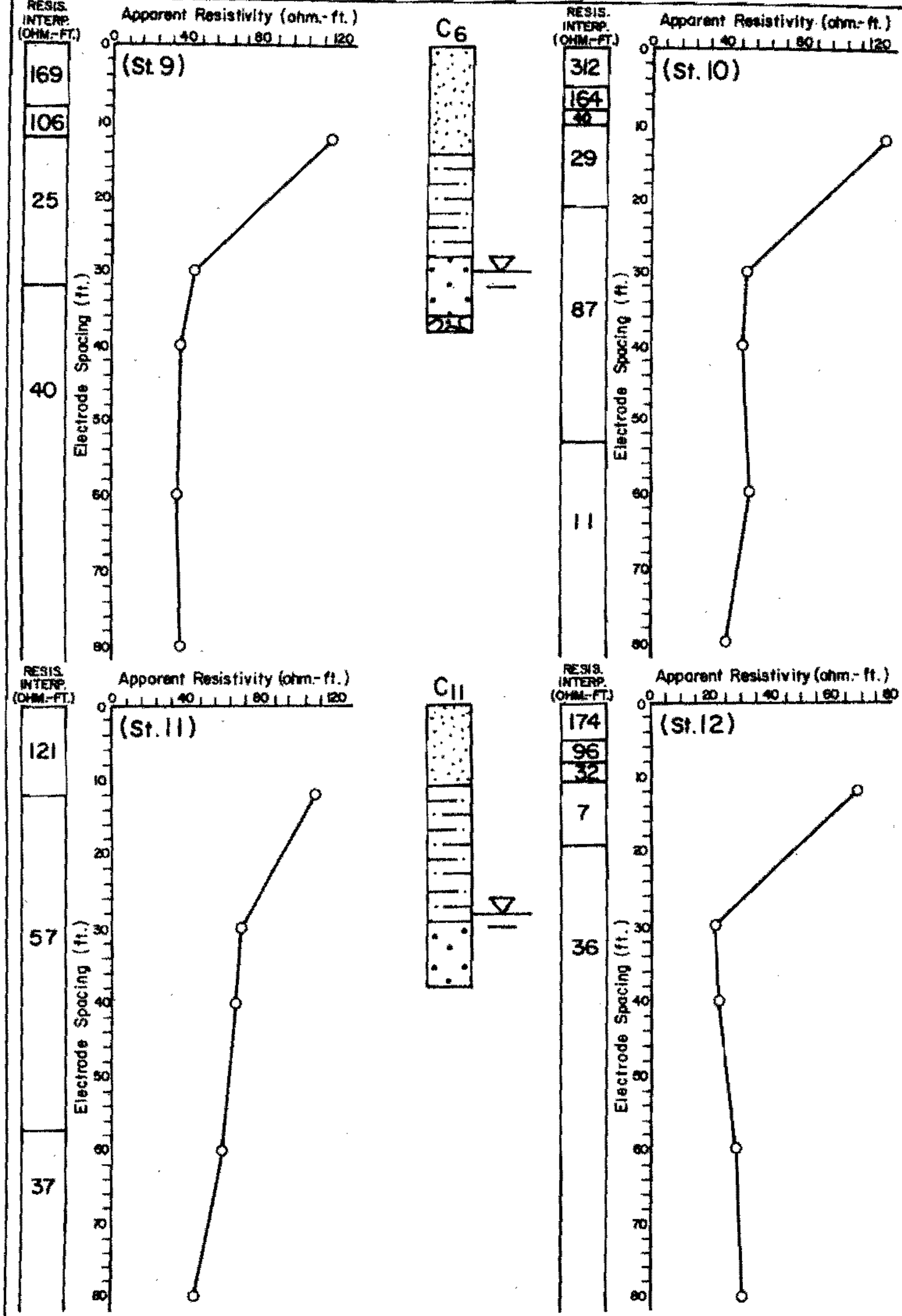


Fig. 73. Apparent and Interpreted Resistivity Profiles for Sts. 9 - 12 at Apache Federal #1-5.

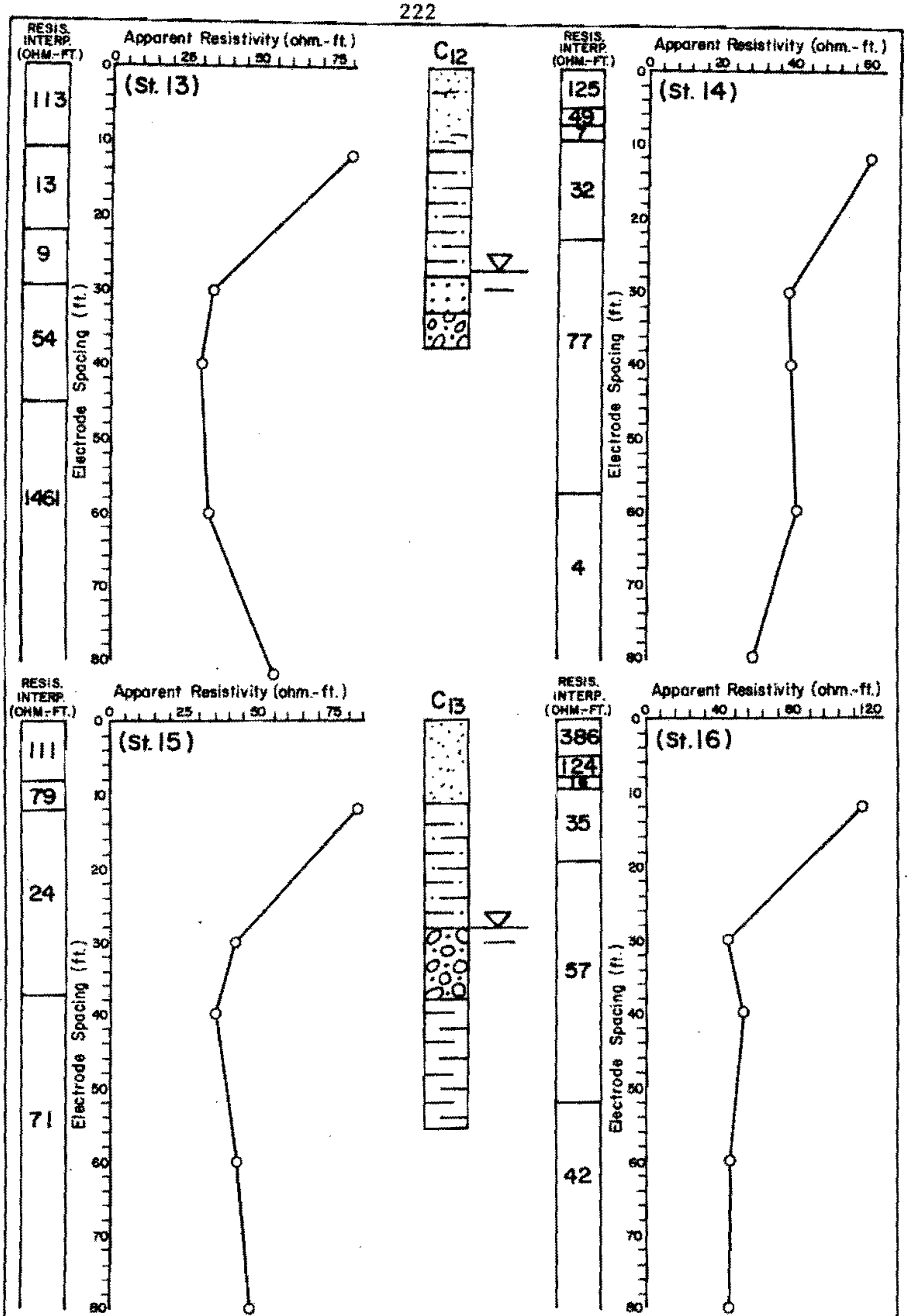


Fig. 74. Apparent and Interpreted Resistivity Profiles for Sts. 13 - 16 at Apache Federal #1-5.

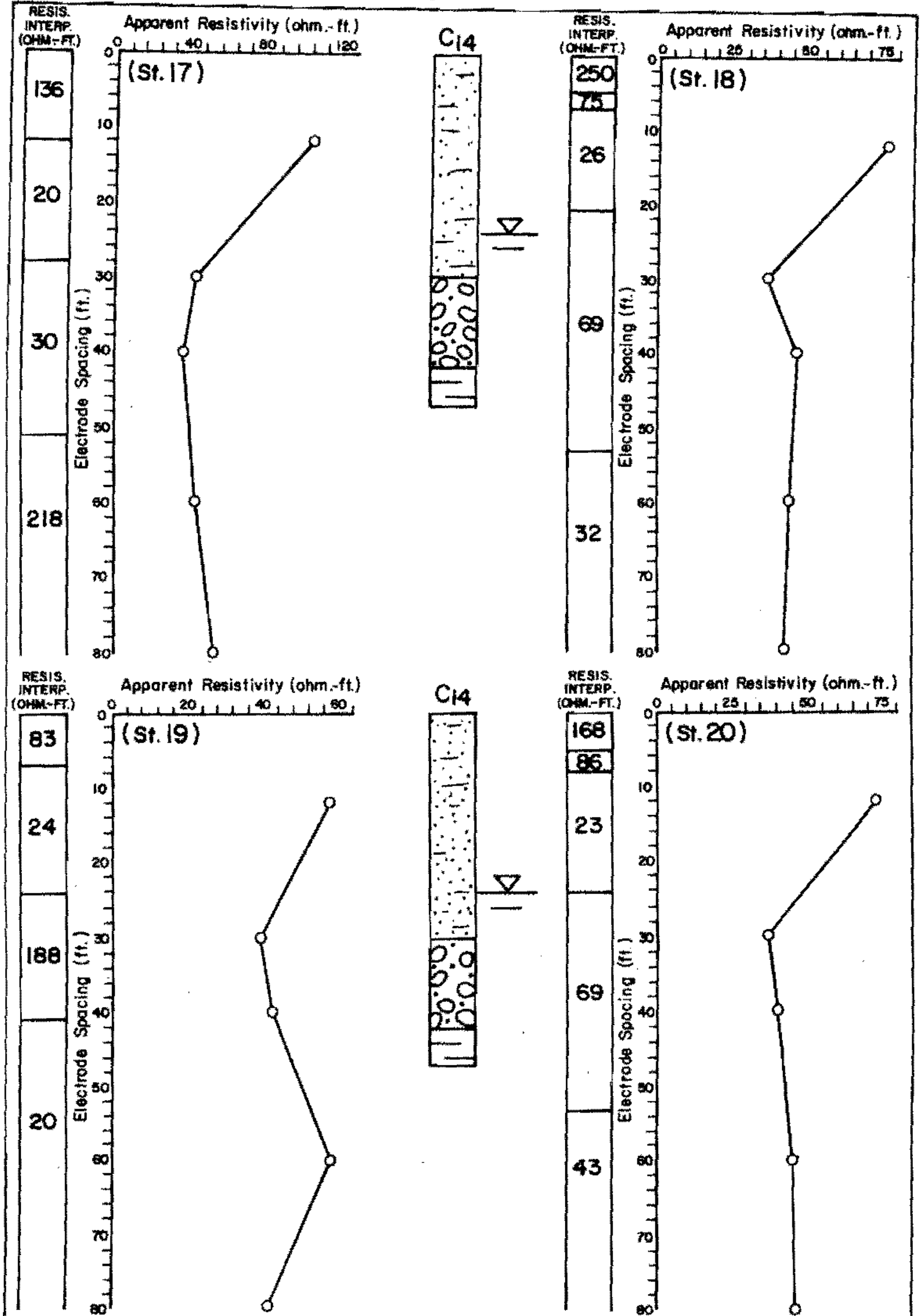


Fig. 75. Apparent and Interpreted Resistivity Profiles for Sts. 17 - 20 at Apache Federal #1-5.

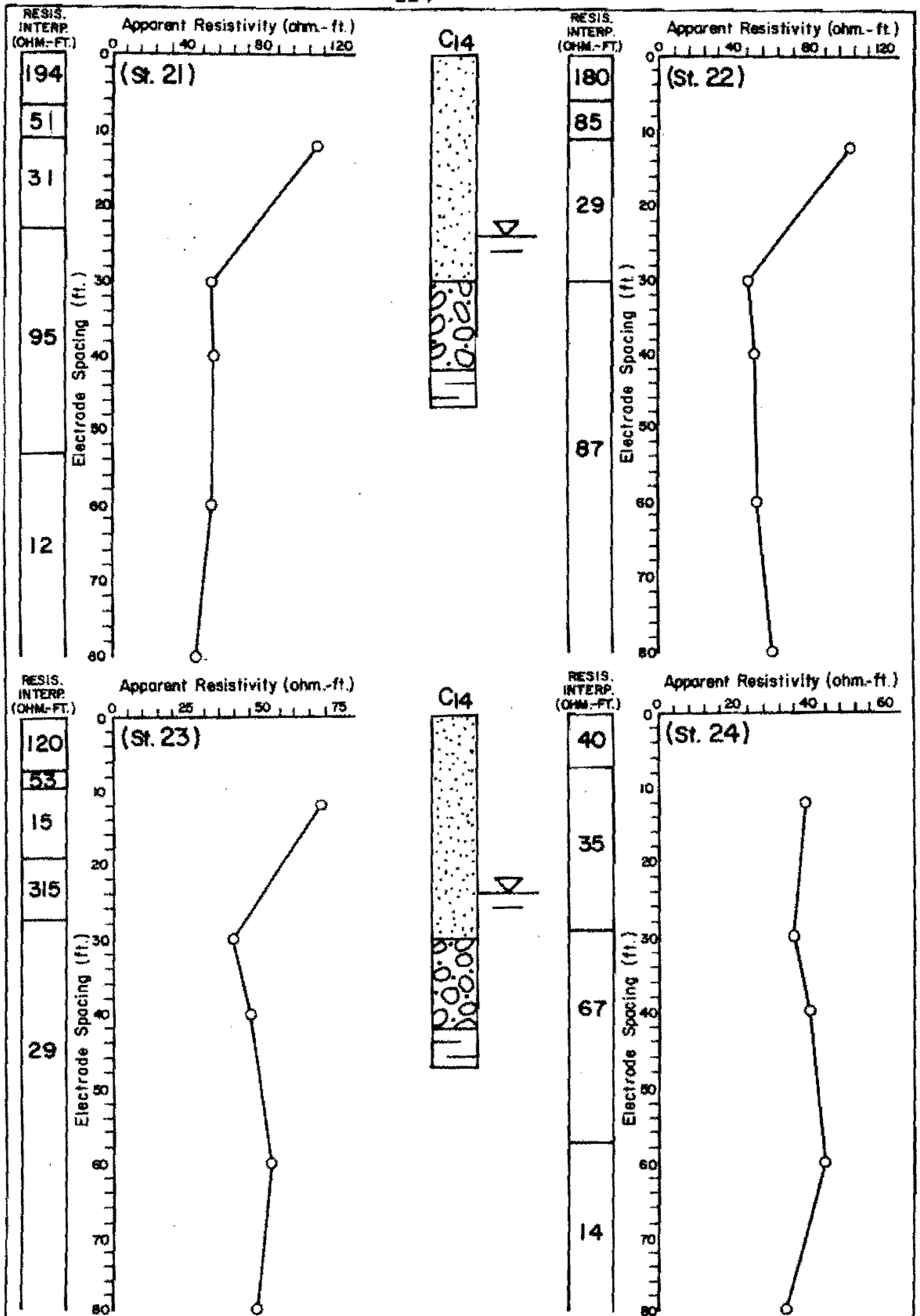


Fig. 76. Apparent and Interpreted Resistivity Profiles for Sts. 21 - 24 at Apache Federal # 1-5.

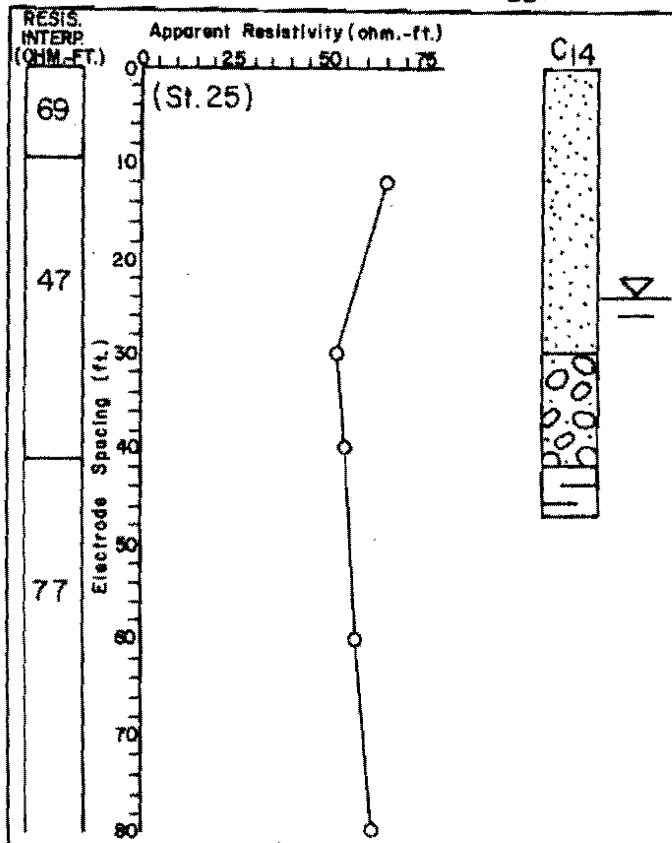


Fig. 77. Apparent and Interpreted Resistivity Profiles for St. 25 at Apache Federal #1-5.

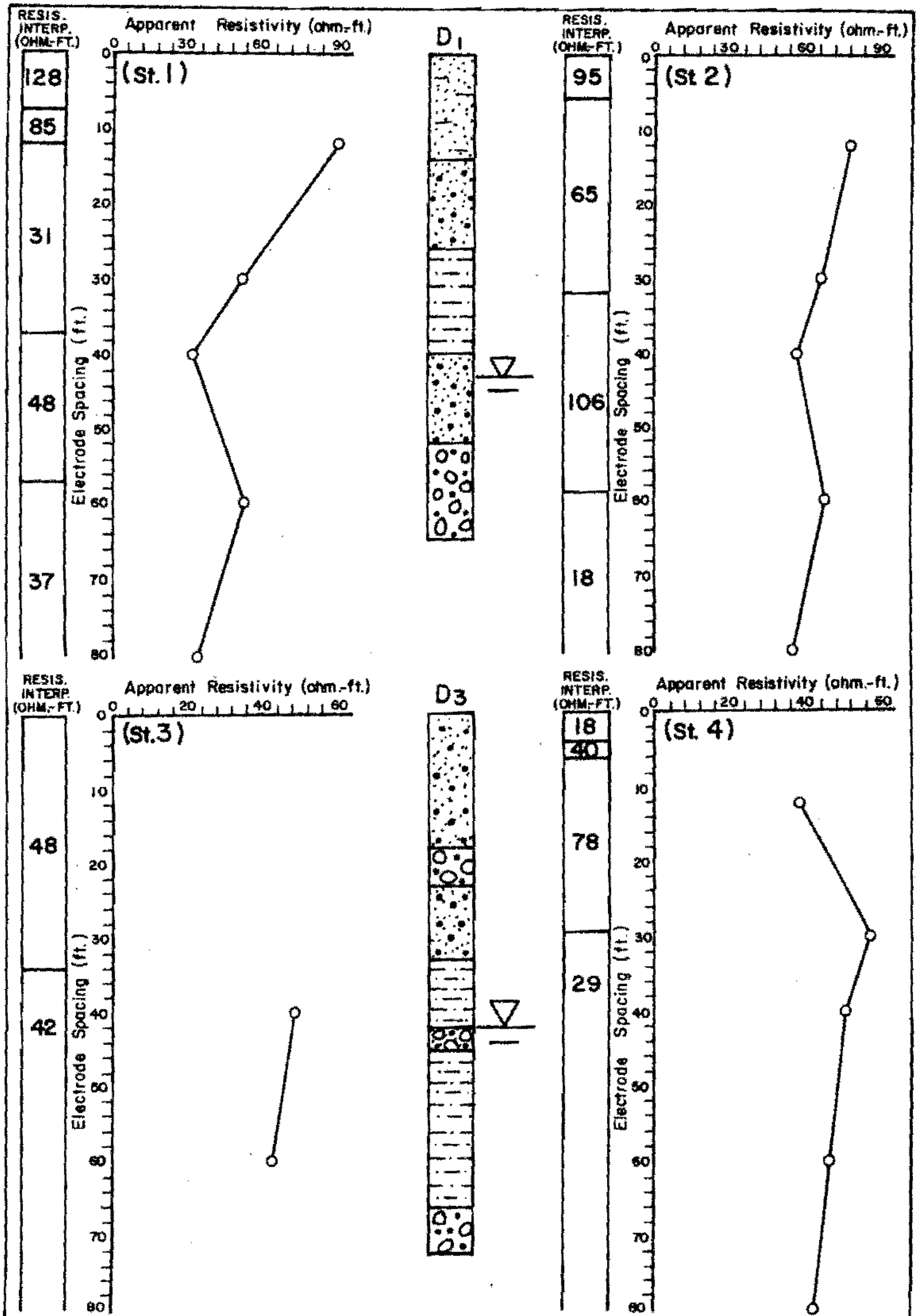


Fig. 78. Apparent and Interpreted Resistivity Profiles for Sts. 1 - 4 at Texaco Charlson C133.

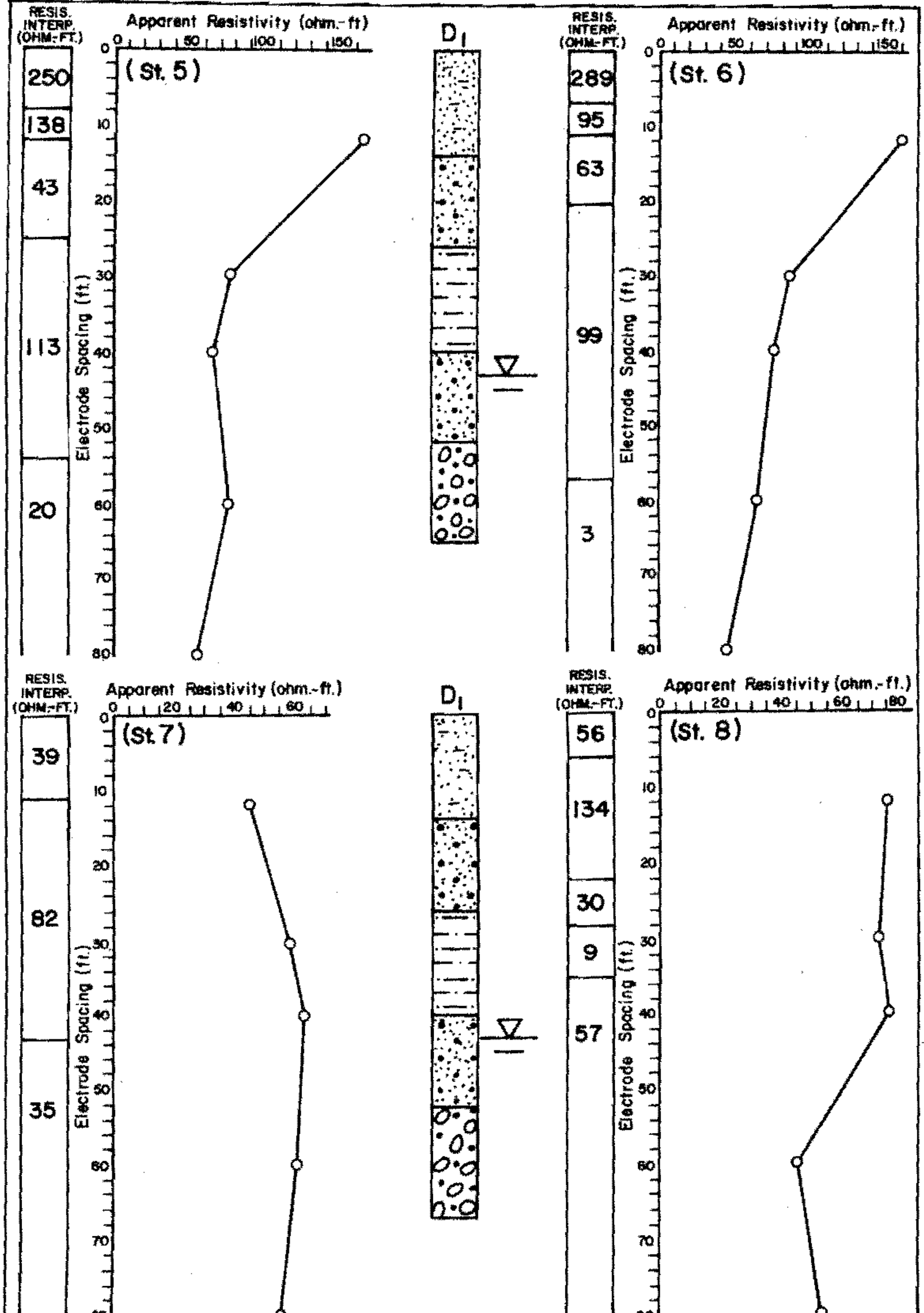


Fig. 79. Apparent and Interpreted Resistivity Profiles for Sts. 5 - 8 of Texaco Charlson C133.

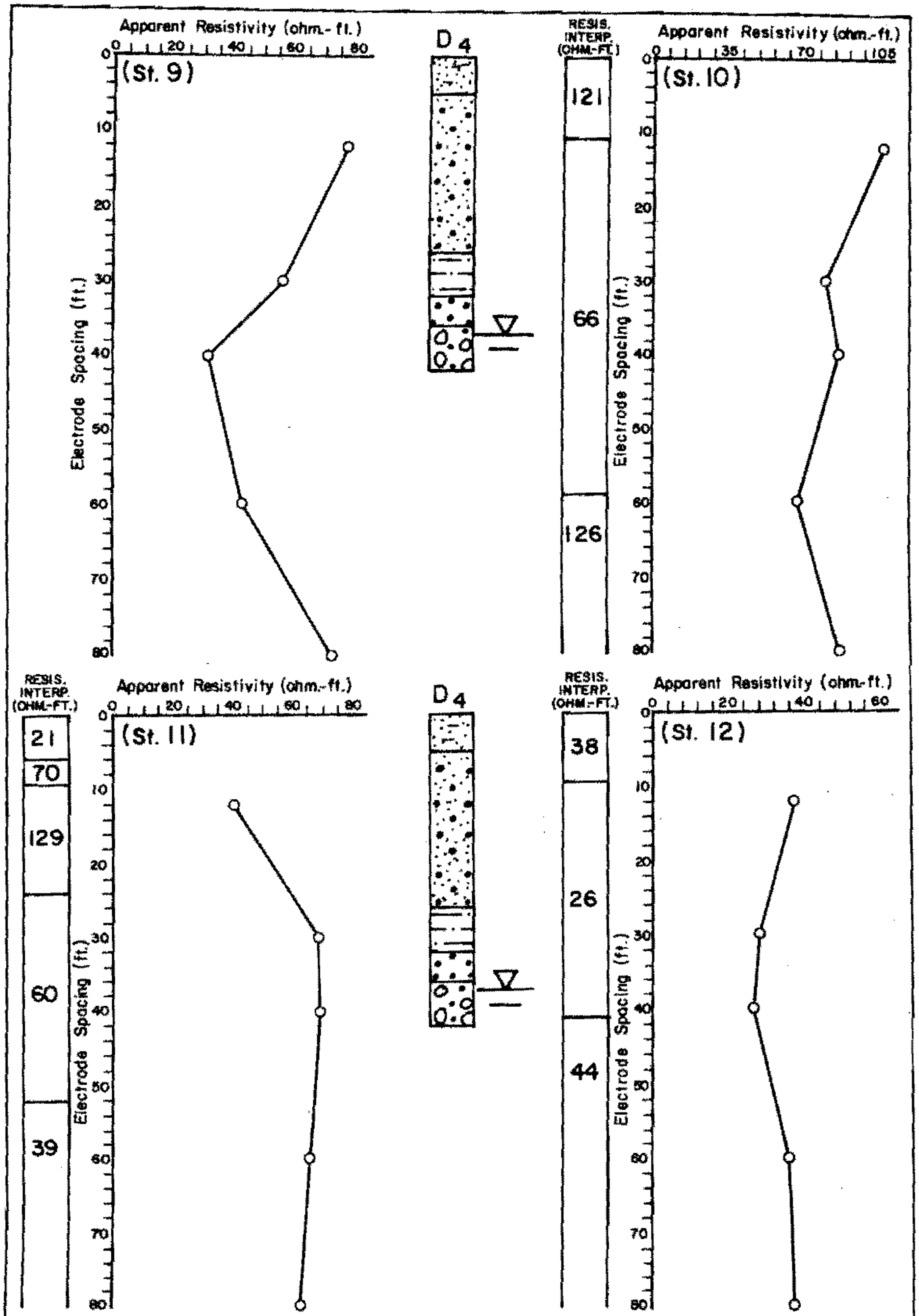


Fig. 80. Apparent and Interpreted Resistivity Profiles for Sts. 9 - 12 at Texaco Charlson C133.

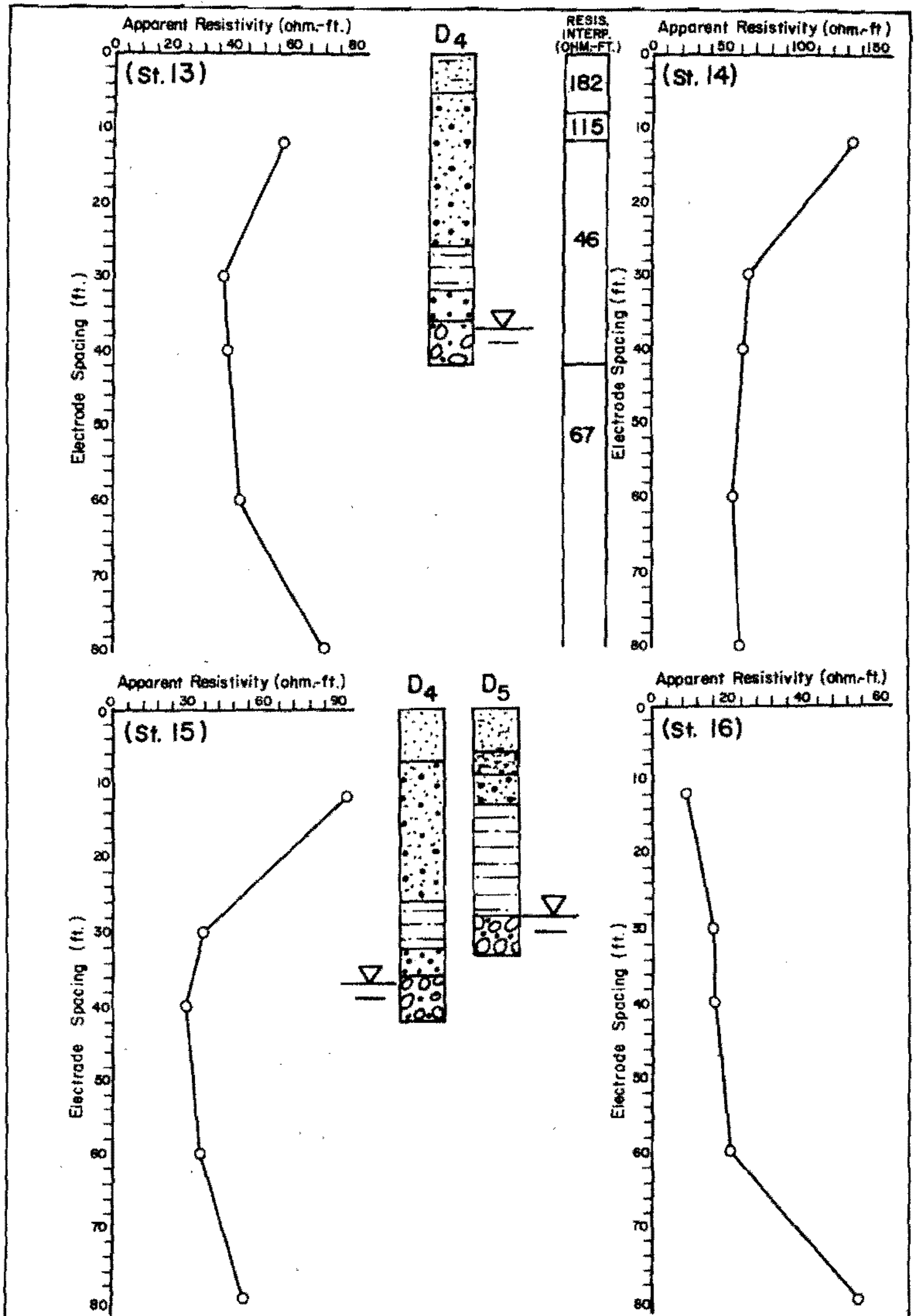


Fig. 81. Apparent and Interpreted Resistivity Profiles for Sts. 13 - 16 at Texaco Charlson C133.

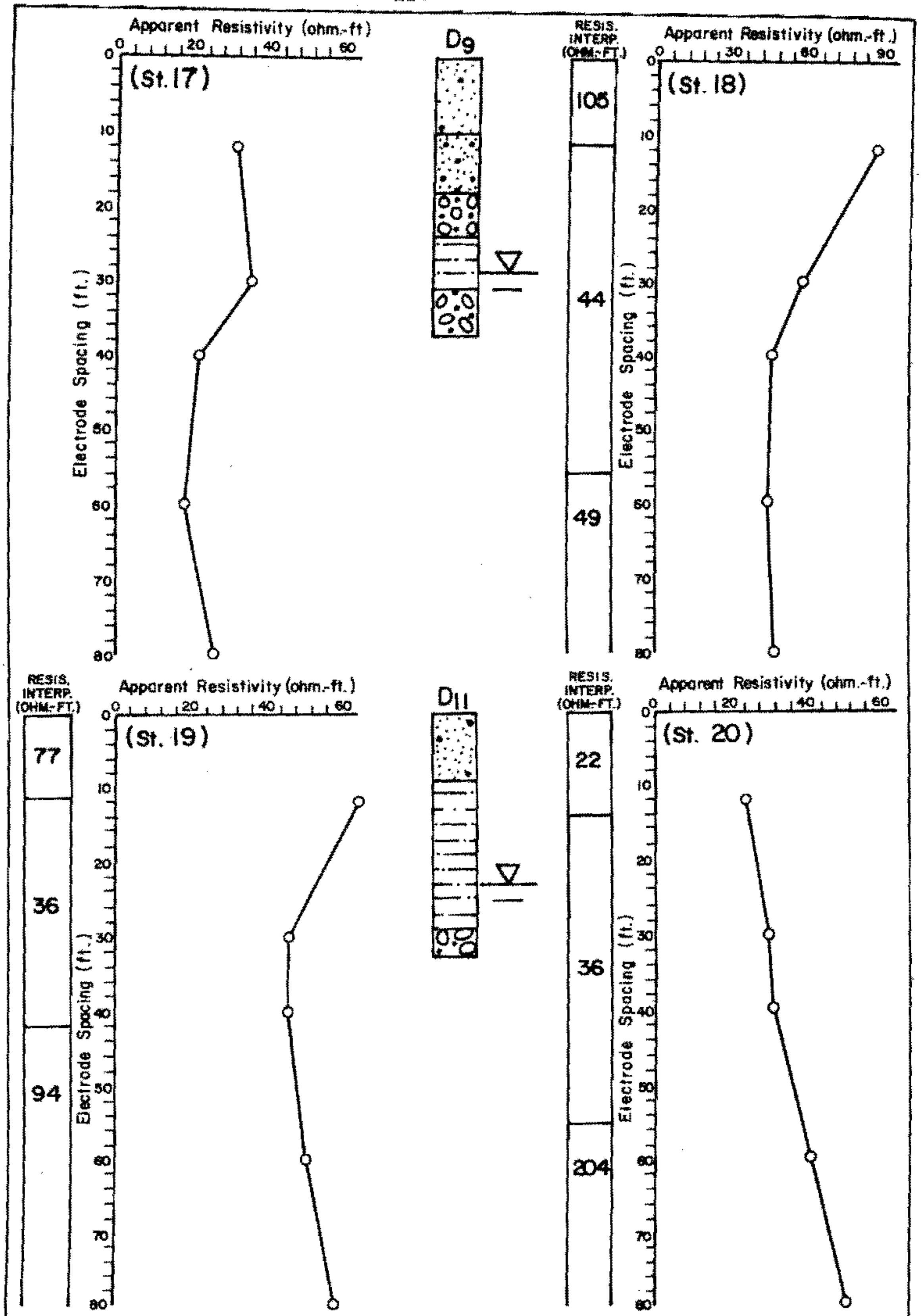


Fig. 82. Apparent and Interpreted Resistivity Profiles for Sts. 17 - 20 at Texoco Charlson C133.

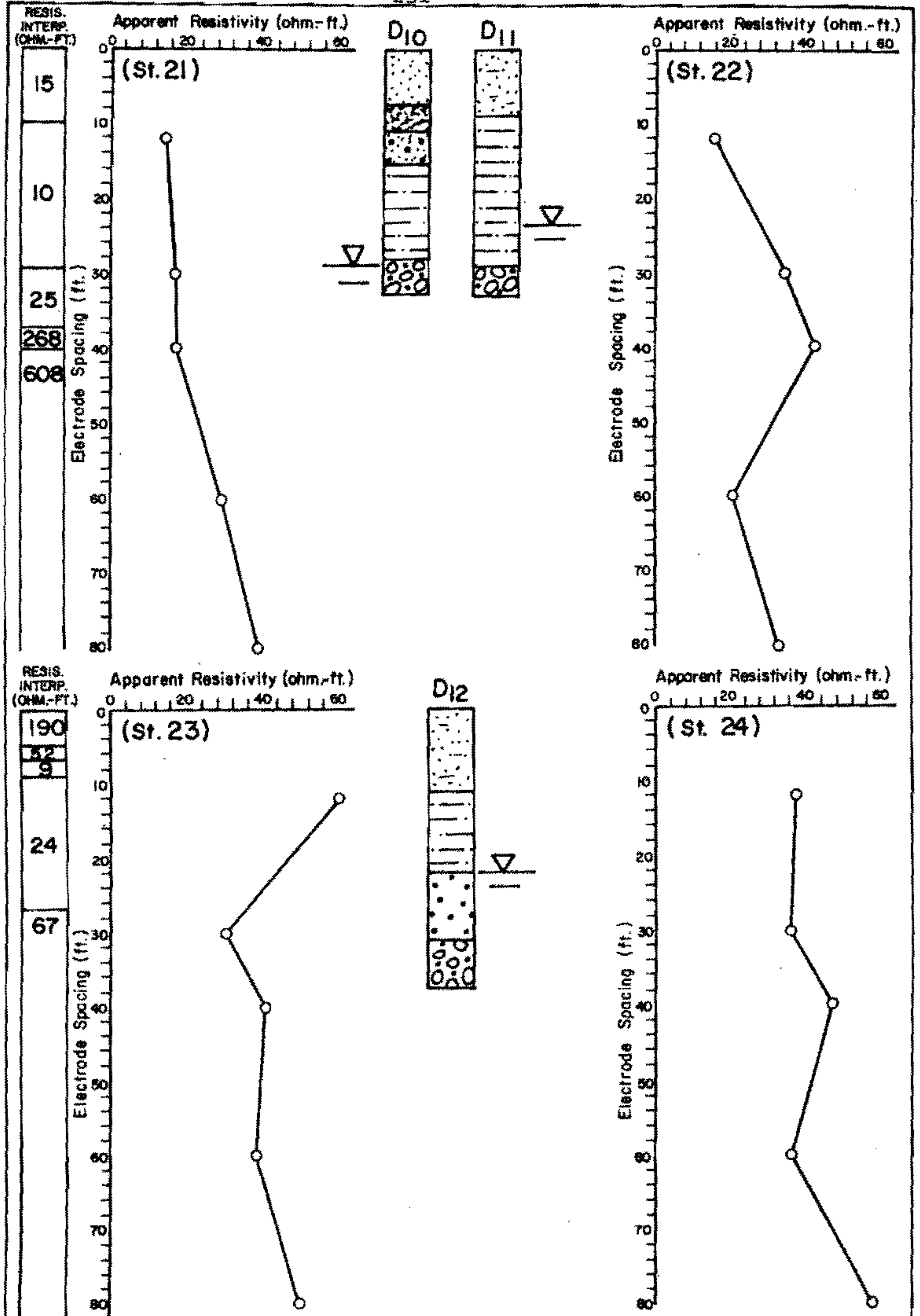


Fig. 83. Apparent and Interpreted Resistivity Profiles for Sts. 21 - 24 at Texaco Charlson C133.

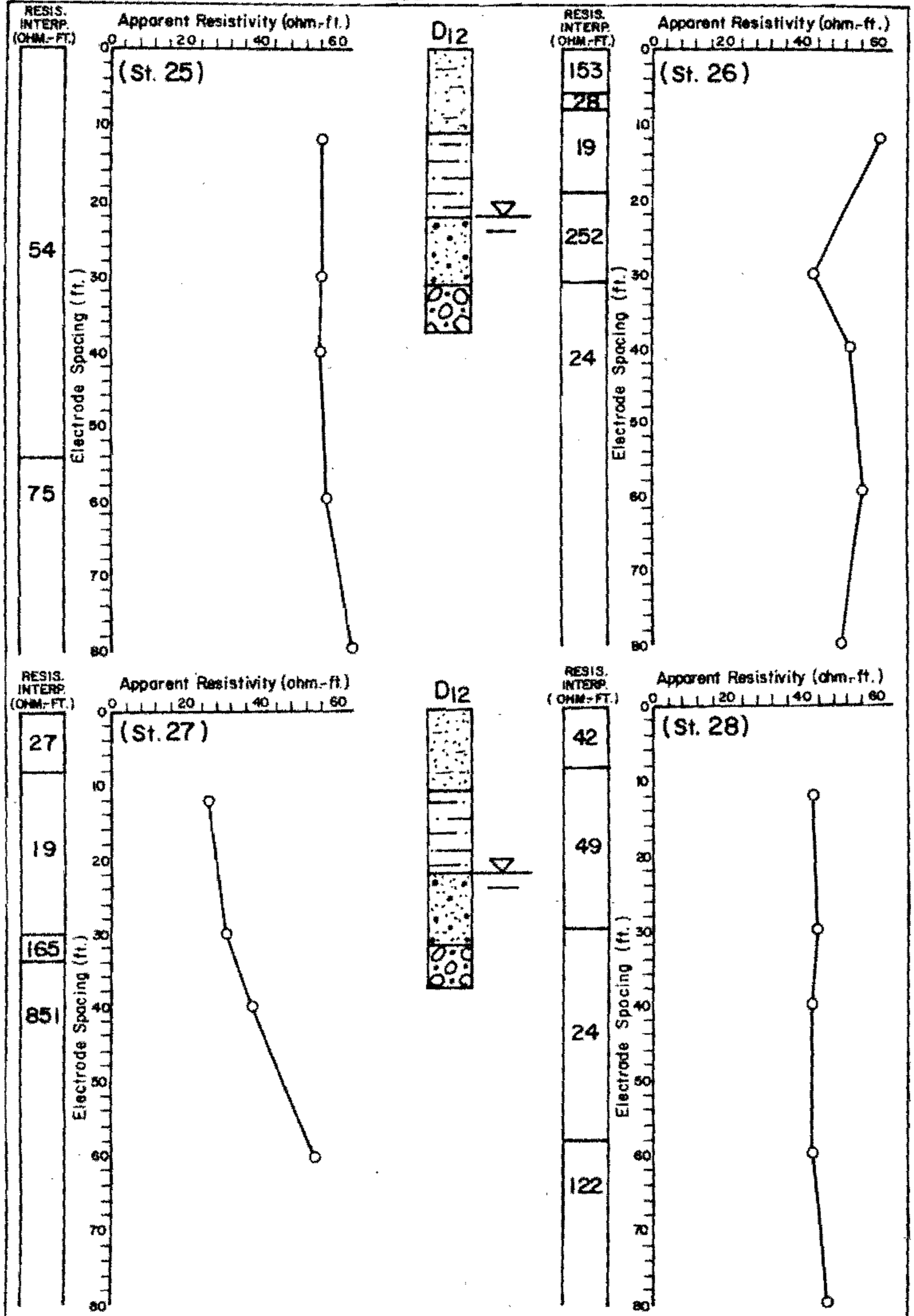


Fig. 84. Apparent and Interpreted Resistivity Profiles for Sts. 25-28 at Texaco Charlson C133.

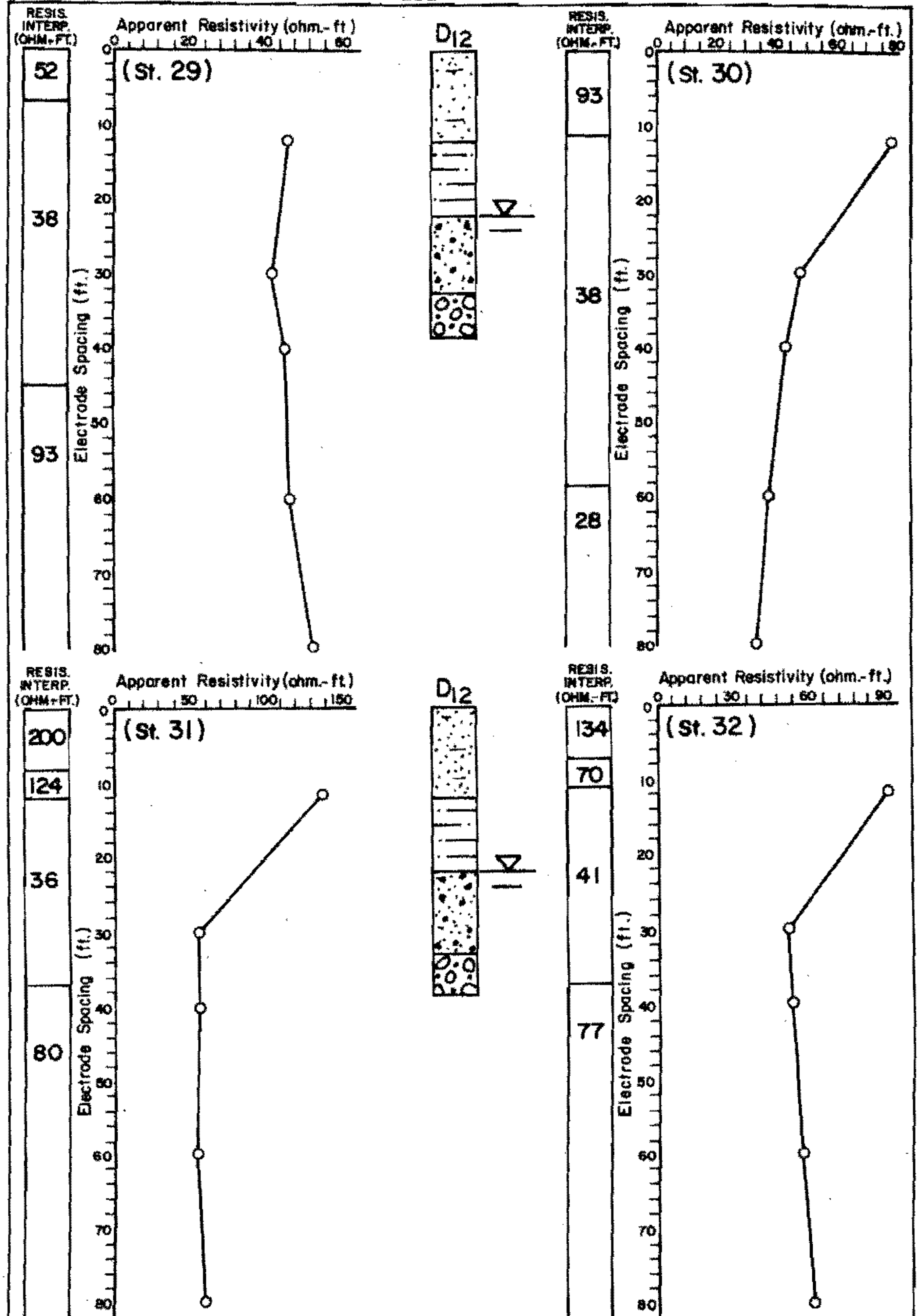


Fig.85. Apparent and Interpreted Resistivity Profiles for Sts. 29 - 32 at Texaco Charlson C133.

APPENDIX G

DRILLING FLUID ADDITIVES USED AT THE BELCO PETROLEUM
B.N. SHEEP CK. #1-11 AND APACHE FEDERAL #1-5 SITES.

TABLE 17. DRILLING FLUID ADDITIVES USED AT THE BELCO PETROLEUM B.N. SHEEP CK. #1-11 SITE.

Drilling Fluid Additives
Belco Petroleum Corp. Sheep Creek B.N. #1-11
Drilling Dates: 3/27/77 thru 4/18/77

Quantity	Product Name	Physical or Chemical Composition
385 sacks	Geogel	Sepiolite (chain lattice clay)
305 sacks	My-Lo-Jel	Corn starch
227 sacks	Salt Gel	Attapulgite clay, Fuller's Earth
43 sacks	Scav 730	Organic
36 sacks	Poly Sol	Potato starch
27 sacks	Preservative	Paraformaldehyde
25 sacks	Drillaid 421	Selective flocculant polymer
20 sacks	Select Floc	Blend of selective flocculants
16 sacks	Super Visbestos	Asbestos
11 sacks	Pipe-Lax	Surfactants in a naptha base
10 sacks	Ammonium Nitrate	NH_4NO_3
8 sacks	Mud Fiber	Bagasse-cane fiber
7 sacks	Mica, Fine	Mica flakes
4 sacks	A-40	Alkyl-aryl sulfonate

(sacks are commonly 100 lbs.)

TABLE 18. DRILLING FLUID ADDITIVES USED AT THE APACHE FEDERAL #1-5 SITE.

Drilling Fluid Additives
Apache Corp. Federal #1-5
Drilling Dates: 6/7/79 thru 6/30/79

Quantity	Product Name	Physical or Chemical Composition
674 sacks	Salt Gel	Attapulgite clay, Fuller's Earth
383 sacks	Magco-Poly-Sol	Pregelatinized starch
105 sacks	My-Lo-Jel	Corn starch
105 gallons	X-100	Zinc-chromium solution
40 sacks	Magcogel	Sodium montmorillonite
14 sacks	Magco-Mica	Mica flakes
11 sacks	Sodium Dichromate	$Na_2Cr_2O_7 \cdot 2H_2O$
8 sacks	Ammonium Nitrate	NH_4NO_3
6 sacks	Lime	CaO
2 sacks	Selec Floc	Selective flocculants
2 sacks	Dow G	Preservative
1 can	Magco-Poly-Defoamer	Polyalkylene glycols

(sacks are commonly 100 lbs.

TABLE 19. DRILLING FLUID ADDITIVES USED AT THE APACHE FEDERAL #1-5 RE-ENTRY.

Drilling Fluid Additives
Apache Corp. Federal #1-5 (Re-entry)
Drilling Dates: 4/2/81 thru 4/15/81

Quantity	Product Name	Physical or Chemical Composition
397 sacks	My-Lo-Jel	Corn starch
124 sacks	Sea Mud	Sepiolite
122 sacks	Salt Gel	Attapulgite clay, Fuller's Earth
21 sacks	TDF-Gel	* *
10 sacks	Preservative	Paraflormaldehyde
9 sacks	Desco	Sulfomethylated tannin-sodium dichromate mixture
6 sacks	Sodium Dichromate	$Na_2Cr_2O_7 \cdot 2H_2O$
4 sacks	HME	* *
4 cans	Magco-Poly-Defoamer	Polyalkylene glycols

(sacks are commonly 100 lbs.)

* * Composition unknown

REFERENCES CITED

REFERENCES CITED

American Petroleum Institute, 1969, Principles of drilling fluid control (12th ed): University of Texas-Austin, Petroleum Extension Service, 215 p.

Anna, L.O., 1981, Ground-water resources of Billings, Golden Valley, and Slope Counties, North Dakota: North Dakota Geological Survey Bulletin 76, no. 3, 56 p.

Birkeland, P.W., 1974, Pedology, weathering, and geomorphological research: New York, Oxford University Press, 285 p.

Brantly, J.E., 1971, History of oil well drilling: Houston, Texas, Gulf Publishing, 1525 p.

Cartwright, K., and Sherman, F.B., Jr., 1972, Electrical earth resistivity surveying in landfill investigations, in Engineering and Soils Engineering Symposium, 10th, Moscow, Idaho, p. 77-92.

Chilingarian, G.V., and Vorabutr, P., 1981, Drilling and drilling fluids-development in petroleum science 11: New York, Elsevier, 767 p.

Clayton, L., Moran, S.R., Bluemle, J.P., and Carlson, C.G., 1980, Geologic map of North Dakota: U.S. Geological Survey, scale 1:500,000.

Collins, A.G., 1975, Possible contamination of groundwaters by oil-and-gas well drilling fluids: U.S. Department of Commerce, NTIS Report No. CONF75051331, 37 p.

Forsman, N.F., (in preparation), Petrology and geochemistry of the Sentinel Butte Formation (Paleocene): PhD Dissertation, University of North Dakota.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater, Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

Gerhard, L.C., and Anderson, S.B., 1981, Oil exploration and development in the North Dakota Williston Basin-1980 update: North Dakota Geological Survey Miscellaneous Series 59, 19 p.

Goodman, L.R., and Eidem, R.J., 1976, The atlas of North Dakota: Fargo, North Dakota, North Dakota Studies, Inc., 111 p.

Griffin, R.A., Cartwright, K., Shimp, N.F., Steele, J.D., Ruch, R.R., White, W.A., Hughes, G.M., and Gilkeson, R.H., 1976, Attenuation of pollutants in municipal landfill leachate by clay minerals-part 1: Illinois State Geological Survey Envrionmental Geology Notes No. 78, 34 p.

Groenewold, G.H., Hemish, L.A., Cherry, J.A., Rehm, B.W., Meyer, G.N., Winczewski, L.M., 1979, Geology and Geohydrology of the Knife River Basin and adjacent areas of west-central North Dakota: North Dakota Geological Survey Report of Investigation No. 64, 402 p.

Groenewold, G.H., Koob, R.D., McCarthy, G.J., Rehm, B.W., and Peterson, W.M., (in press), Geological and geochemical controls on the chemical evolution of subsurface water in the undisturbed and surface-mined landscape in western North Dakota: Report to U.S. Department of the Interior-Bureau of Mines, Contract No. J0275010, 166 p.

Hammer, M.J., 1981, An assessment of current standards for selenium in drinking water: Groundwater, v. 19, no. 4, p. 366-369.

Haugen, Gary, 1980, personal communications, Haugen Construction Service, Minot, North Dakota, July 11.

Hicks, B.L., (in preparation), Saltwater seeps: a preliminary investigation of reserve pit closure problems: U.S. Department of Agriculture, Forest Service, Northern Region Office, Missoula, Montana.

Hvorslev, M.J., 1951, Time lag and soil permeability in groundwater observations: Waterways Experiment Station, Corps of Engineers, U.S. Army, Bulletin no. 36, Vicksburg, Mississippi, 47 p.

Jacob, A.F., 1972, Depositional environments of parts of the Tongue River Formation, western North Dakota, in Ting, F.T.C., ed., Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geological Survey Miscellaneous Series no. 50, 134 p.

______, 1975, Criteria for differentiating the Tongue River and Sentinel Butte Formations (Paleocene), North Dakota: North Dakota Geological Survey Report of Investigations no. 53, 55 p.

Johnson, T.M., Cartwright, K., and Schuller, R.M., 1981, Monitoring of leachate migration in the unsaturated zone in the vicinity of sanitary landfills: Ground Water Monitoring Review, v. 1, no. 3, p. 55-63.

Kehew, A.E., and Groenewold, G.H., 1982, Earth resistivity investigations in reclaimed surface lignite mine spoils: U.S. Department of the Interior, Bureau of Mines, Contract no. J0275010, 98 p.

Koob, R.D., 1981, personal communications, Dean of the College of Science and Mathematics, North Dakota State University, Fargo, North Dakota, December 2.

Krauskopf, K.B., 1979, Introduction to geochemistry (2nd ed): New York, McGraw-Hill, 617 p.

Lenzini, Doug, 1980, BLM testing of drilling muds on Wyoming soils: Western Oil Reporter, v. 37, no. 7, p. 120-121.

Moore, P.L., 1974, Drilling practices manual: Tulsa, Oklahoma, Petroleum Publishing, 448 p.

Moran, S.R., Cherry, J.A., Fritz, P., Peterson, W.M., Sommerville, M.H., Stancel, S.A., and Ulmer, J.H., 1978a, Geology, groundwater hydrology, and hydrochemistry of a proposed surface mine and lignite gasification site near Dunn Center, North Dakota: North Dakota Geological Survey Report of Investigation, no. 61, 263 p.

Moran, S.R., Groenewold, G.H., and Cherry, J.A., 1978b, Geologic, hydrologic, and geochemical concepts and techniques in overburden characterization for mined-land reclamation: North Dakota Geological Survey Report of Investigation no. 63, 152 p.

National Oceanic and Atmospheric Administration, 1981, Climatological data and monthly precipitation data: National Weather Service, U.S. Department of Commerce, Bismarck, North Dakota.

Pearse, A.S., and Gunther, G., 1957, Salinity, in Hedgepeth, J.W., ed, Treatise on marine ecology and paleocology: Geological Society of America, Memoir 67, v. 1, p. 129-157.

Ranney, M.W., 1979, Crude oil drilling fluids: Park Ridge, New Jersey, Noyes Data Corp., 348 p.

Reed, P.C., Cartwright, K., and Osby, D., 1981, Electrical resistivity surveys near brine holding ponds in Illinois: Illinois State Geological Survey Geology Notes no. 95, 30 p.

Rehm, B.W., Groenewold, G.H., and Peterson, W.M., 1982, Mechanisms, distribution and frequency of groundwater recharge in an upland area of western North Dakota: North Dakota Geological Survey Report of Investigation no. 75, 72 p.

Robertson, F.R., 1975, Hexavalent chromium in the groundwater in Paradise Valley, Arizona: Groundwater, v. 13, no. 6, p. 516-527.

Rogers, W.F., 1953, Composition and properties of oil well drilling fluids: Houston, Texas, Gulf Publishing, 670 p.

Royse, C.F., Jr., 1967, A stratigraphic and sedimentologic analysis of the Tongue River and Sentinel Butte Formations (Paleocene), western North Dakota: PhD Dissertation, University of North Dakota, 312 p.

Soiltest Inc., 1968, Earth resistivity manual: Evanston, Illinois, Soiltest Inc., 52 p.

Swanson, R.G., 1981, Sample examination manual, methods in exploration series: Tulsa, Oklahoma, American Association of Petroleum Geologists, 6 p.

U.S. Army Corps of Engineers, 1981, Daily water levels for the Garrison Dam Reservoir: Riverdale, North Dakota, Omaha Division.

Valkovic', Vlado, 1975, Trace element analysis: London, Taylor and Francis, 229 p.

Van Nostrand, R.G., and Cook, K.L., 1966, Interpretation of resistivity data: U.S. Geological Survey Professional Paper 499, 310 p.

Wright, T.R., ed., 1978, Guide to drilling, workover, and completion fluids: World Oil, no. 6, p. 53-96.

Yazicigil, Hasan, and Sendlein, L.V.A., 1982, Surface geophysical techniques in groundwater monitoring-part 2: Ground Water Monitoring Review, v. 2, no. 1, p. 56-62.

Zohdy, A.A.R., and Bisdorf, R.J., 1975, Computer programs for the forward calculation and automatic inversion of Wenner sounding curves: U.S. Department of Commerce, NTIS Publication no. PB-247 265, 47 p.