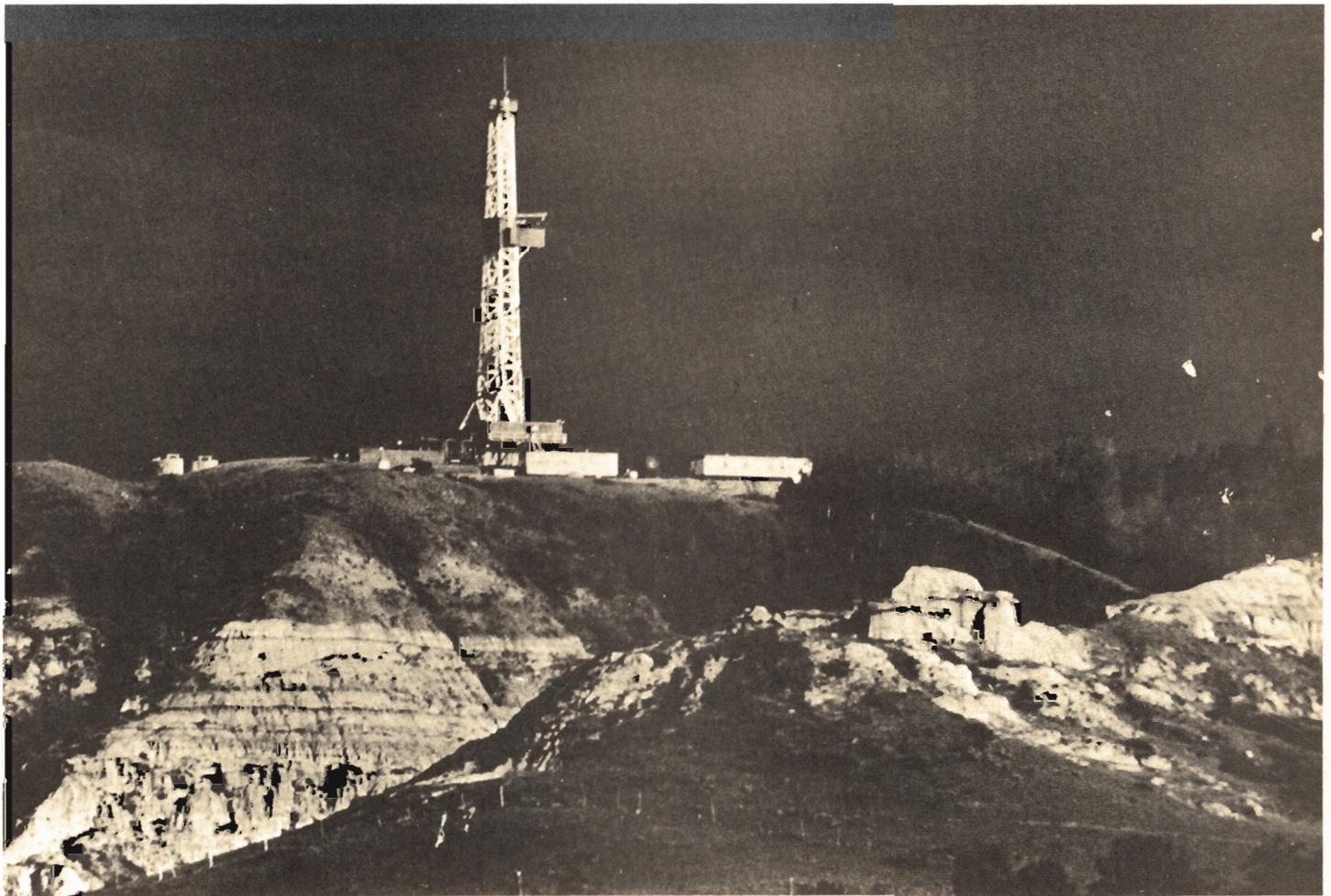


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THE EFFECT OF OIL AND GAS WELL DRILLING
FLUIDS ON SHALLOW GROUNDWATER IN
WESTERN NORTH DAKOTA

by

Edward C. Murphy and Alan E. Kehew



REPORT OF INVESTIGATION NO. 82

NORTH DAKOTA GEOLOGICAL SURVEY

Don L. Halvorson, State Geologist

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This report is 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 $300,000 \pm 20,000$ 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 concentration limits 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 1,310 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, Captain 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.

Three types of oil and gas drilling fluid bases are used: 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 $300,000 \pm 20,000$ mg/l (American Petroleum Institute, 1969). In comparison the average salinity of seawater is typically 35,000 mg/l (Pearse and Gunther, 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 9,000 oil and gas wells have been drilled within the state.

Prior to drilling, a pit is excavated adjacent to the drill hole. This pit 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 commonly constructed on the order of 150 feet in length, 60 feet in width, and 10 feet in depth (46 m x 18 m x 3 m). The volume of drilling fluid maintained in each pit during drilling usually ranges from 54,000 to 90,000 cubic feet ((1,530 to 2,549 m³) (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,

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

<u>Function</u>	<u>General Purpose</u>	<u>Common Additives</u>
Weighting Material	Control formation pressure, check caving, facilitate pulling dry pipe, and well completion operations	Barite, lead compounds, iron oxides
Viscosifier	Viscosity builders for fluids, for a high viscosity-solids relationship	Bentonite, attapulgite clays, all colloids, fibrous 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, and flocculators
Corrosion Inhibitor	Materials attempt to decrease the presence of such corrosive compounds as oxygen, carbon dioxide, and hydrogen sulfide	Copper 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
Foamer	Surfactants which foam in the presence of water and thus permit air or gas drilling in formations producing water	Organic sodium and sulfonates, alkyl benzene sulfonates
Flocculants	Used commonly for increases in gel strength	Salt, hydrated lime, gypsum, sodium tetraphosphates
Bactericides	Reduce bacteria count	Starch preservative, paraformaldehyde, caustic soda, lime, sodium pentachlorophenate
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 disintegration	Gypsum, sodium silicate, calcium lignosulfonates, lime, salt

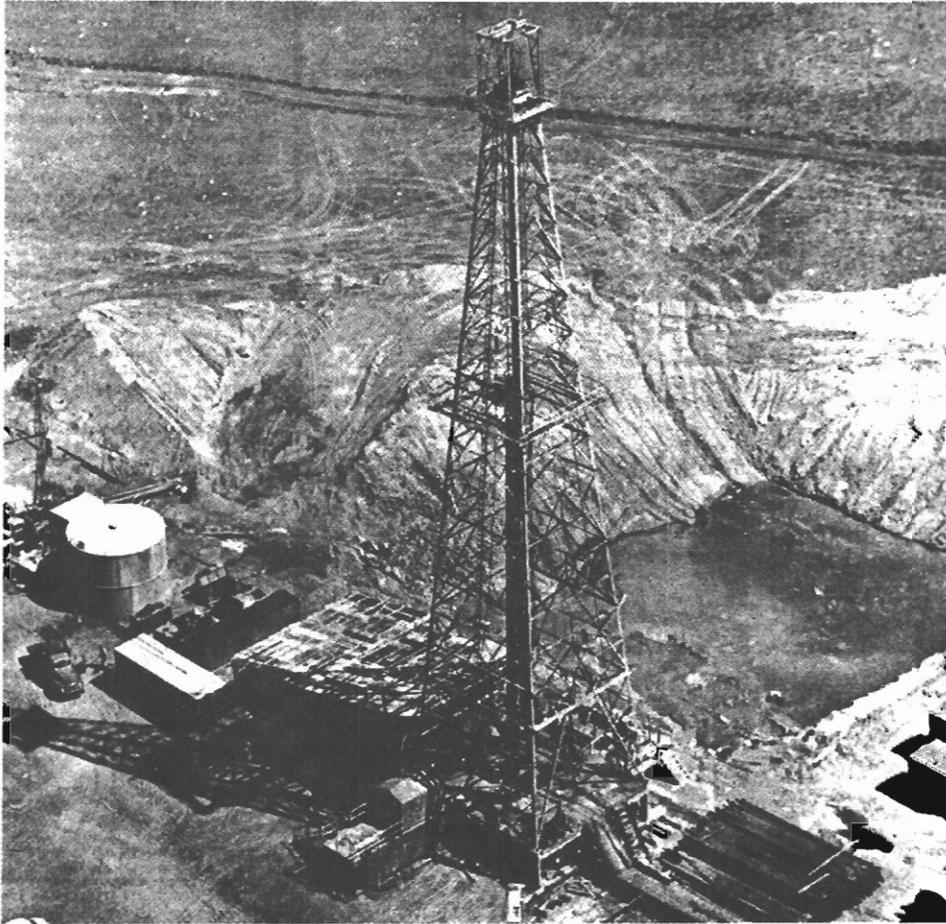


Figure 1. The Amerada Clarence Iverson #1. The discovery well in North Dakota (photo by Mr. Bill Shemorry).

i.e., is devoid of most chemical additives. Just before setting the surface 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 shale 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).

The Oil and Gas Regulatory Division of the Industrial Commission of North Dakota has the authority to require an operator to install a plastic liner in reserve pits if the surrounding sediment is so permeable that it 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, the reserve pit is reclaimed. Disposal procedures

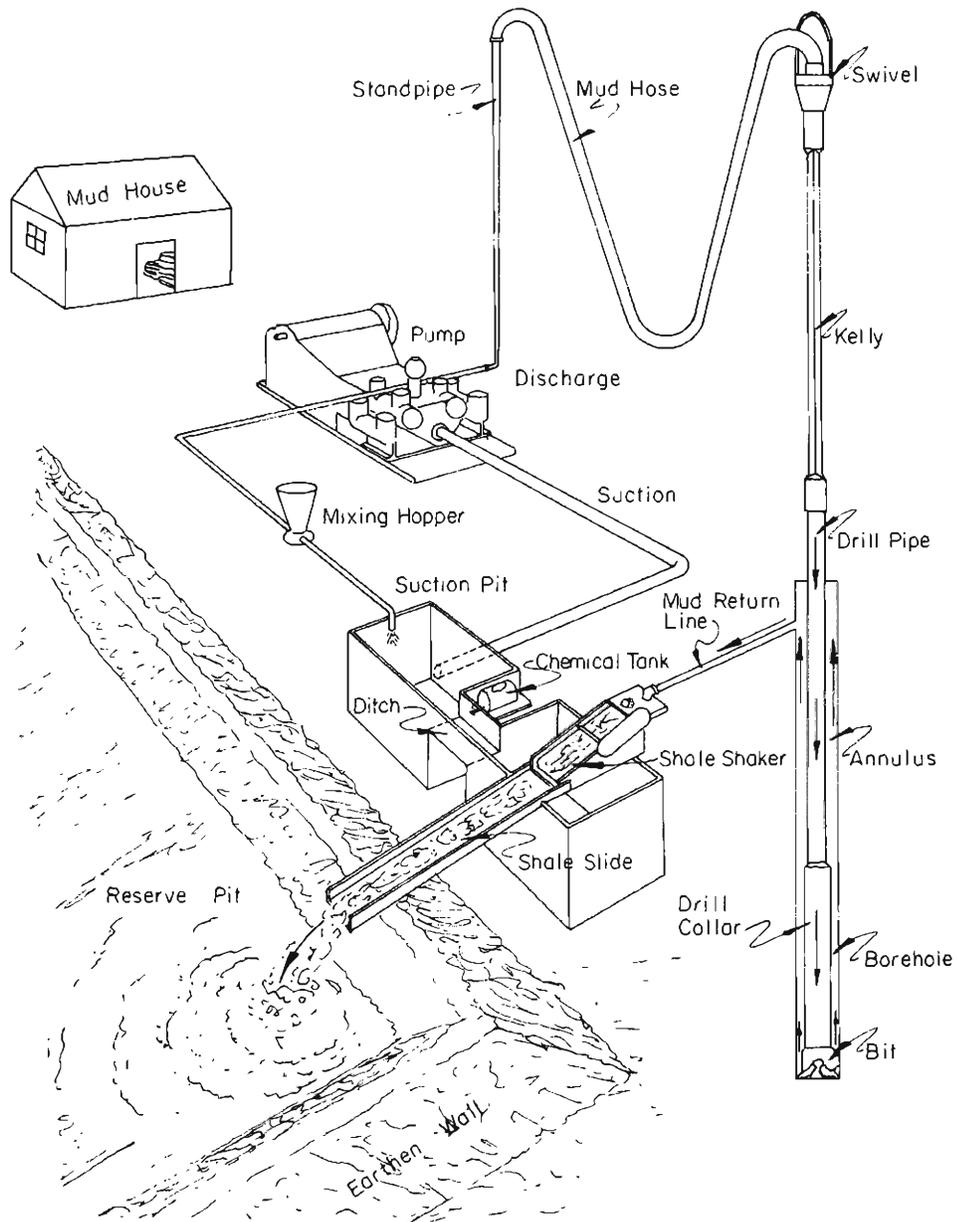


Figure 2. Closed system circulation of drilling fluid.

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 make-up 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 20 or 30 years old. Even 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 (1.9 m) to several thousand gallons (tens of m). 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 United States (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 (NDS DH) to study the toxicity of drilling fluids and their disposal effects. This letter was written because 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 (NDS DH) 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



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



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.



Figure 5. Reclamation of the reserve pit at the Apache 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.

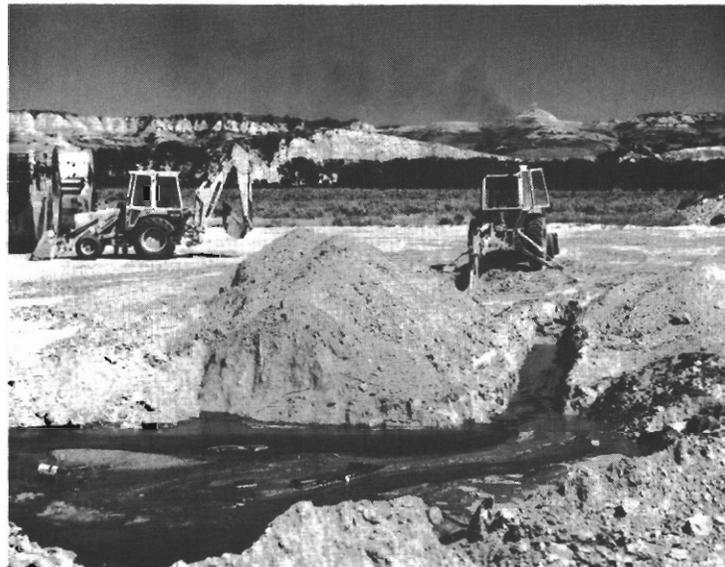


Figure 6. Reclamation of the reserve pit at the Apache Federal #1-5 re-entry. Drilling fluid is filling the 21-foot (6.4 m) deep trenches. Photo is taken looking east.

by the NDGS and a grant from the Environmental Protection Agency.

In April of 1980, Edward Murphy 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. These additives are commonly used in this area to reduce the corrosion of the drill pipe by the high H₂S content in the subsurface.

Purpose of Study

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" (app. 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; and, if so, investigate the extent, character, and geochemical controls influencing the movement or attenuation of the leachate;
2. 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
3. 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 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 affect 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 (C NWSWsec 33, T154N, R95W) (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 identified as "Gov't. "A" (NCT-1) #1" and "Sheep Creek BN #1-11," and are situated within highly dissected badland topography in the Little Missouri Drainage Basin, 4.5 air miles (7.2 km) east of the Little Missouri River. Texaco Inc. spudded the Gov't "A" (NCT-1) #1 (SENEsec 14, T145N, R101W) 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 BN #1-11 (SWNEsec 11, T145N, R101W) 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 on the west by a stock pond and on 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

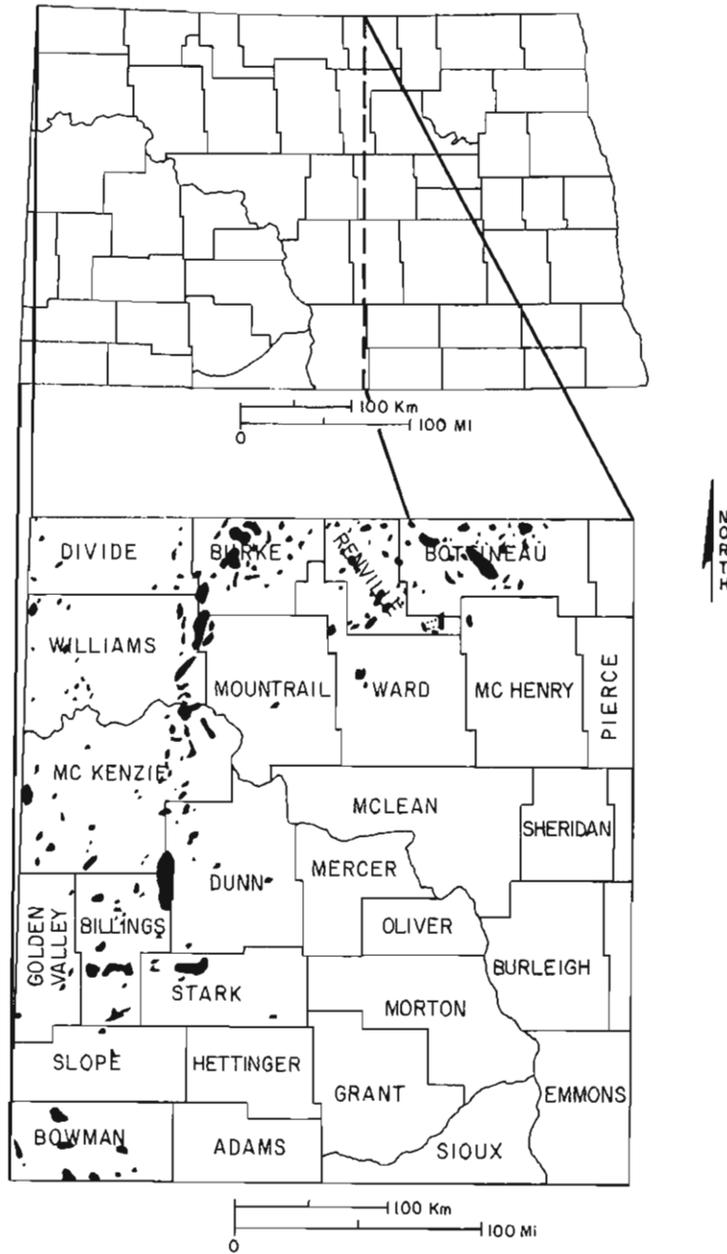


Figure 7. Oil fields in North Dakota (Gerhard and Anderson, 1981, p. 17).

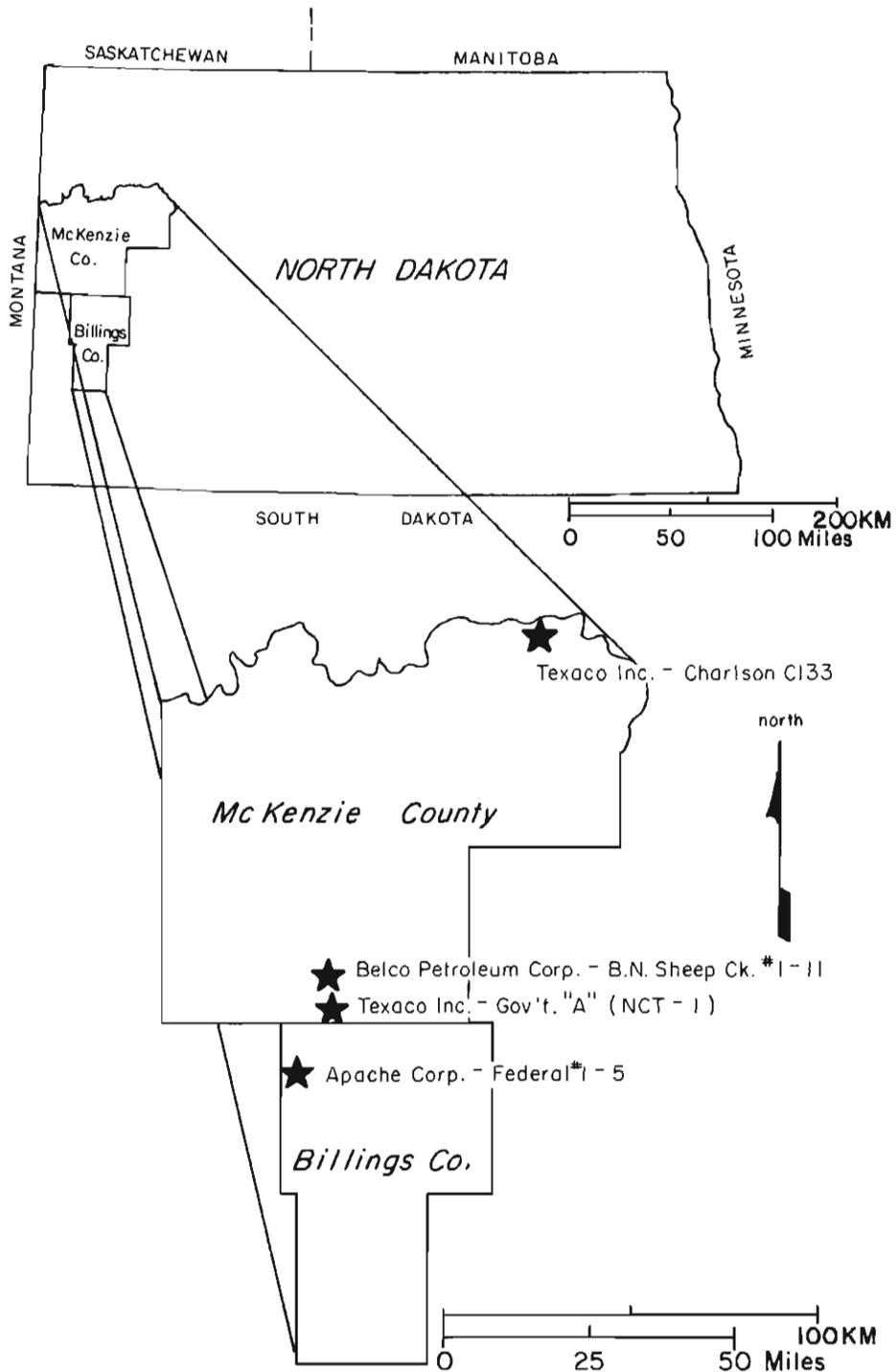


Figure 8. The location of the four study sites.

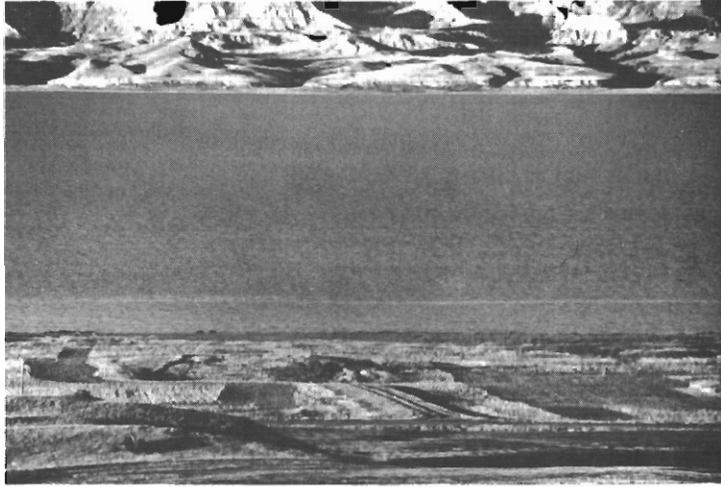


Figure 9. Photograph of Texaco Charlson Madison (North) Unit #C133. Photo is taken looking north.

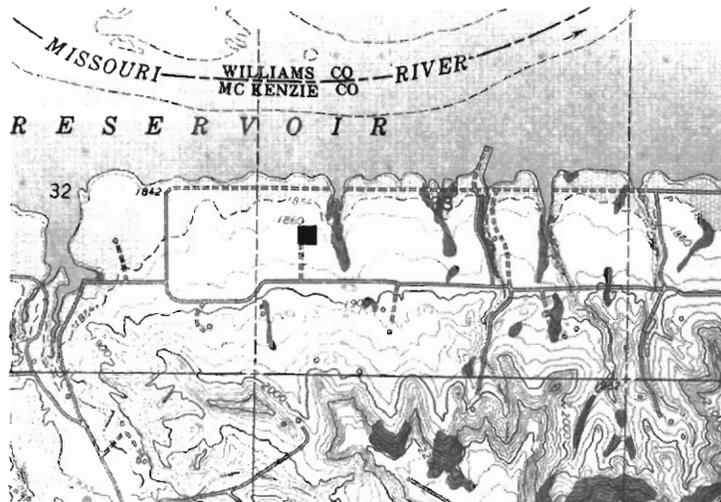


Figure 10. Topographic map of Texaco Charlson Madison (North) Unit #C133 (C NWSWsec 33, T154N, R95W). Scale is 2.3 inches = 1 mile (1.6 km).



Figure 11. Photograph of Texaco Gov't. "A" (NCT-1)#1. Note absence of vegetation over reserve pit. Photo is taken looking northeast.

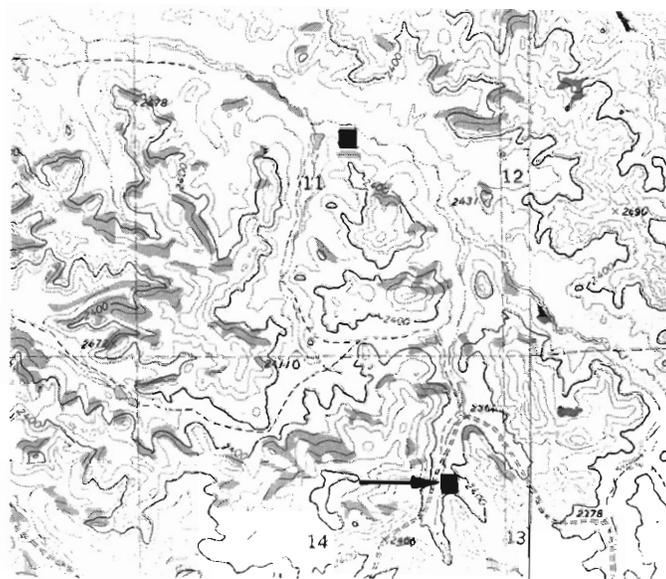


Figure 12. Topographic map of Texaco Gov't. "A" (NCT-1)#1 study site (SENEsec 14, T145N, R101W). Scale is 2.3 inches = 1 mile (1.6 km).



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

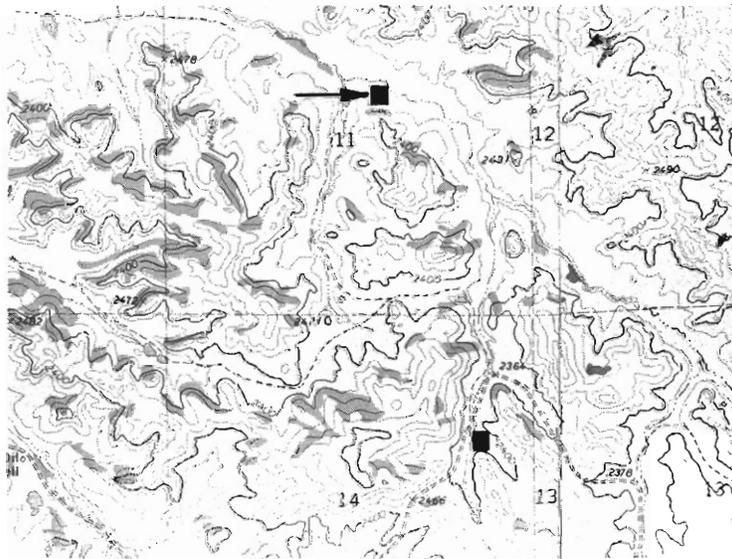


Figure 14. Topographic map of Belco Petroleum Sheep Creek BN #1-11 study site (SWNEsec 11, T145N, R101W). Scale is 2.3 inches = 1 mile (1.6 km).

approximately 1,200 feet (366 m) west of the Little Missouri River in northwestern Billings County (NESEsec 5, T145N, R102W) (figs. 15 and 16). This site is identified as the "Apache Federal #1-5." It is situated upon the Little Missouri flood plain, 2,400 feet (732 m) 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 1,000 feet (305 m) deeper (figs. 17 and 18). This well is presently producing 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 15 inches (38 cm) annually, 50 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 haz-

ardous wastes. Another study on the effects of buried drilling fluid on shallow groundwater has recently been completed in eastern Montana (Dewey, 1984).

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, (Lenzini, 1980). The drilling fluids being tested are fresh-water based; such a test would not be practical with the salt-water based drilling fluids 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. These data are not applicable to onshore 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-in. 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



Figure 15. Photograph of Apache 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.

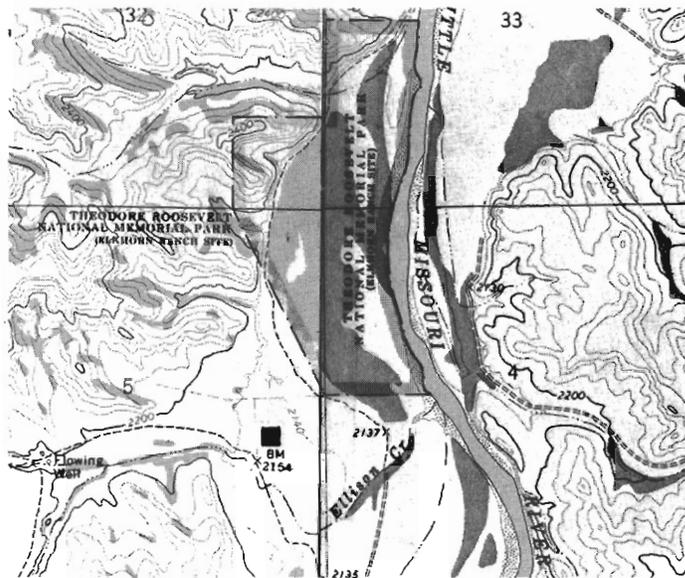


Figure 16. Topographic map of Apache Federal #1-5 study site (NESEsec 5, T145N, R102W). Scale is 2.3 inches = 1 mile (1.6 km).

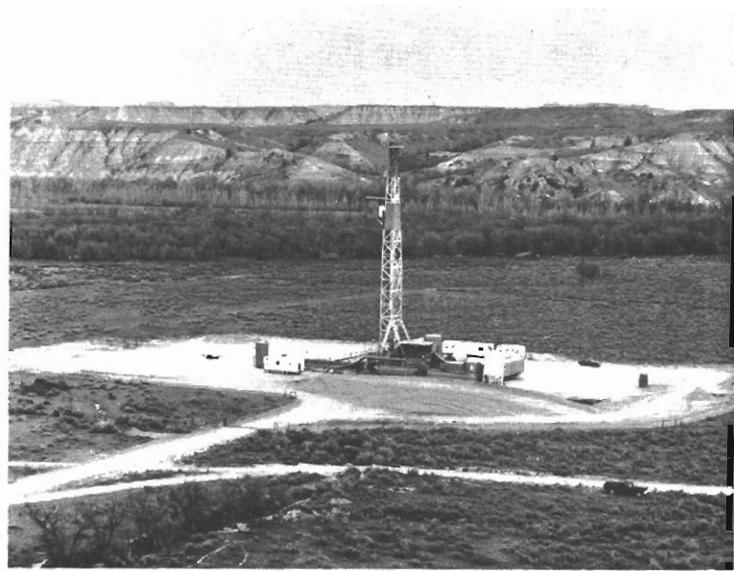


Figure 17. The Cardinal Rig #7 drilling the Apache Federal #1-5 re-entry. The reserve pit is located between the rig and the sediment pile. Photo is taken looking east-northeast.



Figure 18. The reserve pit from the Apache 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.

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-inch 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 (app. B). The maximum depth of penetration obtained with this auger was 72 feet (22 m). 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 (0.762 m) 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 (48.8 m) 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 (1.52 m) 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 backfilled 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 (0.64 m) in length (fig. 19). A 2-inch (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 millilitres 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

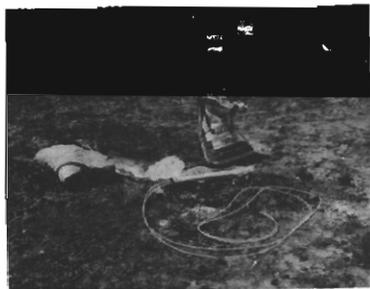
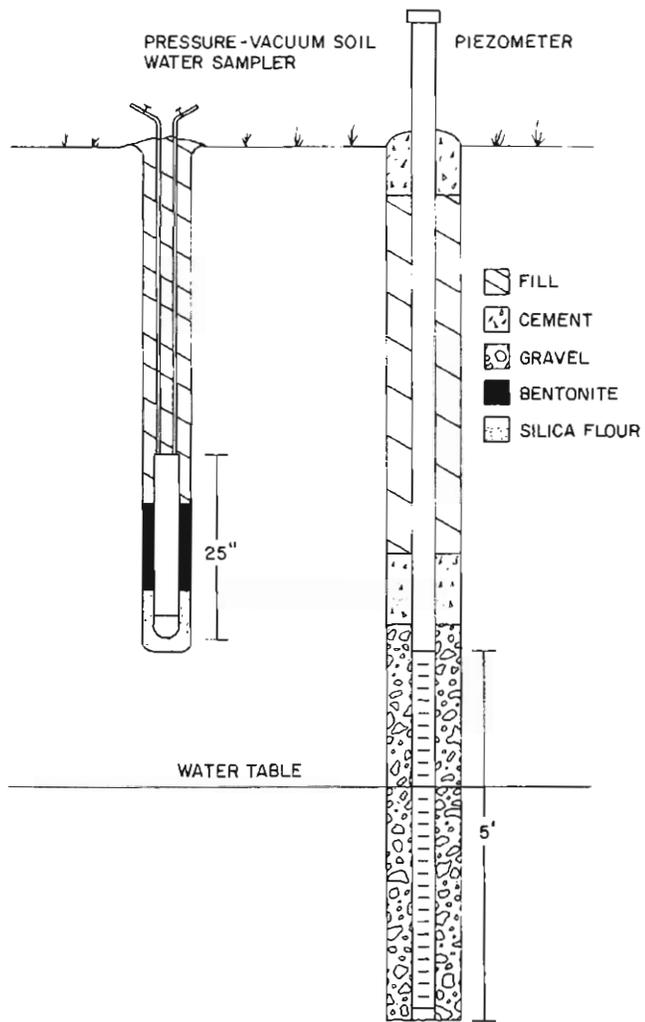


Figure 19. A profile of a soil water sampler (lysimeter) and piezometer as used in this study.

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 (1.0 m). Upon insertion of the slug, the time was recorded for the water level to return to its original equilibrium level (falling head test). The time was also recorded for the water level to return to equilibrium when the slug was withdrawn (rising head test). Hydraulic conductivities were determined for the tested intervals by analysis of 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 were tested. The remaining piezometers were not tested either because the slug could not be lowered into the well due to constrictions and bends in the pipe or because there was insufficient 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 #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 (30.5 m) 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 and Apache Federal sites. Sand, silt, and clay contents were determined with the use of a hydrometer for shelly 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):

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

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

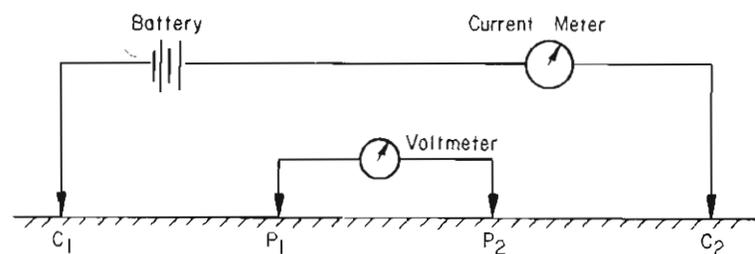
d_{10} = effective grain size at which 10% by weight of the sediment particles are finer and 90% are coarser.

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

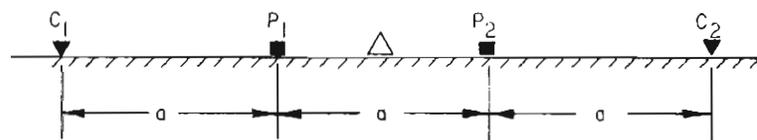
Eleven shelly tube sediment samples were added to distilled water (35 grams sediment to 1,000 ml H_2O) and stirred for four hours. These samples were elutriated to determine the variability in relative concentrations of ions that would readily go into solution. The results of this elutriation



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 (3.7 m). The photo is taken looking west-northwest.



WENNER CONFIGURATION



△ RESISTIVITY STATION

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.

were compared with analyses of water samples from the unsaturated zone at the Texaco Gov't. "A" (NCT-1) #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 (4,570 m) of sedimentary rocks ranging in age from Cambrian to Recent. These strata overlie Precambrian igneous and metamorphic basement rocks.

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 (200 m) (Clayton et al., 1980).

Holocene alluvium, comprised of crossbedded 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) deter-

mined that only 10 percent 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 percent with a mean of 22.4 percent. Preliminary work by Forsman (in preparation) indicates that many of the sand grains contain thin coatings of authigenic Na montmorillonite. Groenewold et al. (1983) performed textural analyses on 79 sediment samples from the Sentinel Butte Formation. The resulting mean textural analyses for these sediments were:

	% Sand	% Silt	% Clay
X̄	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. (1983) 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 either by 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 Ba²⁺, Ca²⁺, and Mg²⁺ 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 Ca²⁺ is adsorbed in strong preference to both Na⁺ and Mg²⁺, and Mg²⁺ 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 snowmelt) 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 four to five 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 (1.5-2.5 m) below a vegetated surface and 9 feet (2.7 m) 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°C and will be completely thawed within a 30- to 50-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).

Chemical Evolution of Groundwater in Western North Dakota

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. (1983) 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 appli-

cable in the absence of organic matter in the soil (Groenewold et al., 1983) (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+} and 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 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. (1983).

GEOLOGY AND GEOHYDROLOGY OF STUDY SITES

Texaco Charlson Madison (North) Unit #C133 Well Site

The site is underlain by at least 60 feet (18 m) of colluvium and alluvium (figs. 23 and 24). Fluvial sediments include gravel composed entirely of subrounded to subangular 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 (9.1-12.2 m) 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

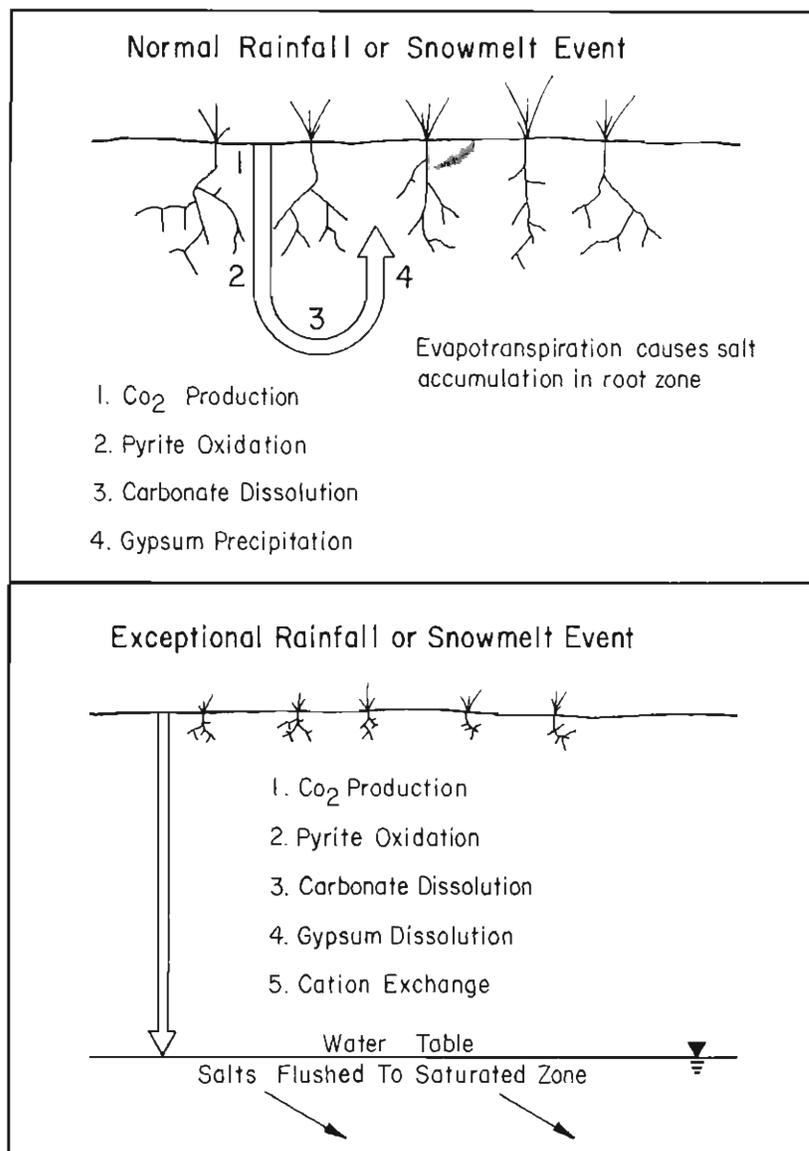


Figure 22. A hydrogeochemical model for the chemical evolution of groundwater in western North Dakota. The predominant chemical reactions are presented for both the normal and exceptional rainfall and snowmelt events (from Moran et al., 1978b and Groenewold et al., 1983).

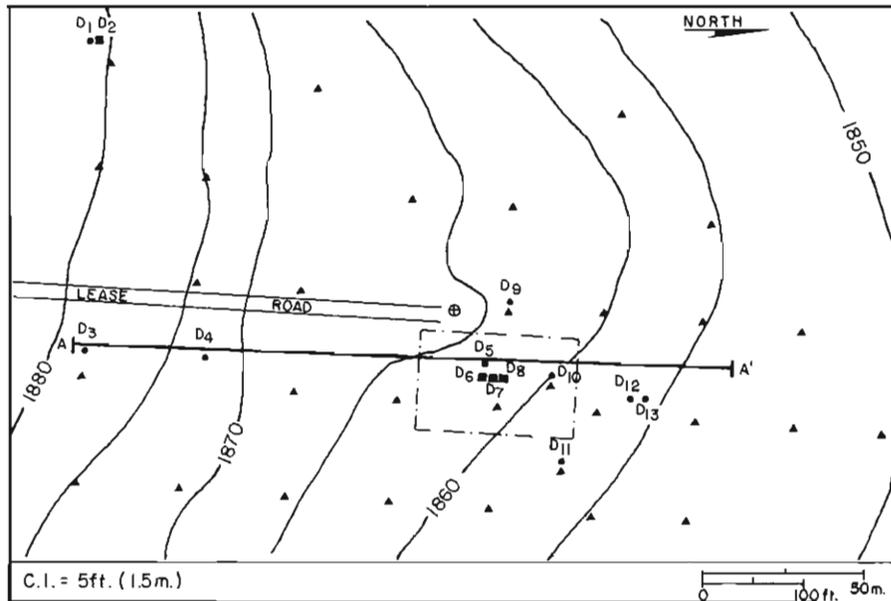
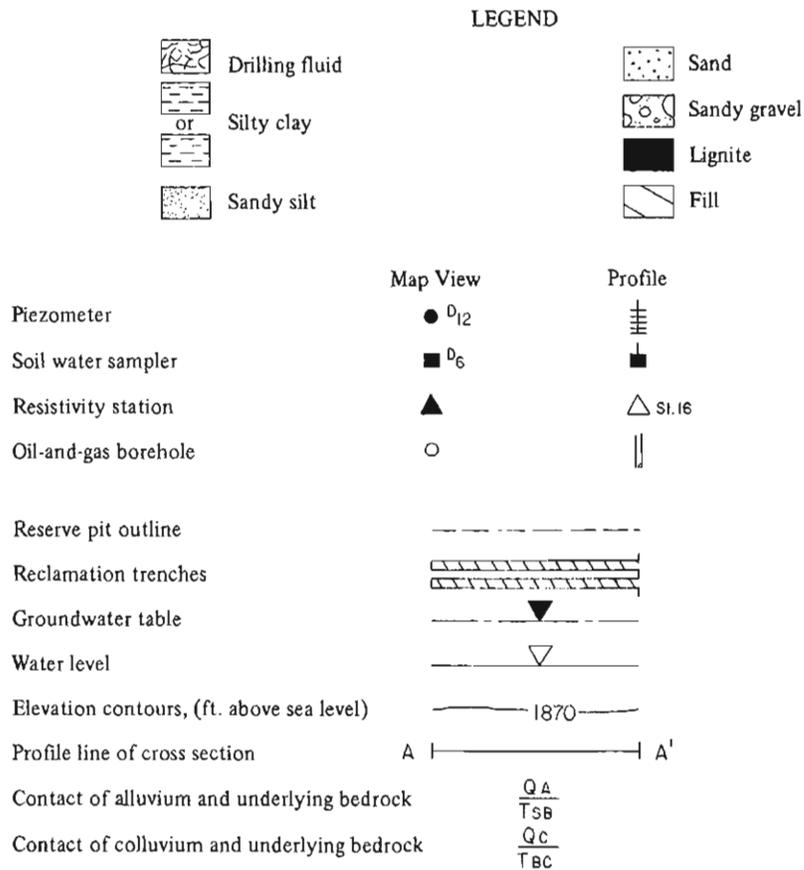


Figure 23. Map view of the Texaco Charlson Madison (North) Unit #C133 site. Water sampling instrumentation and earth resistivity stations are depicted.

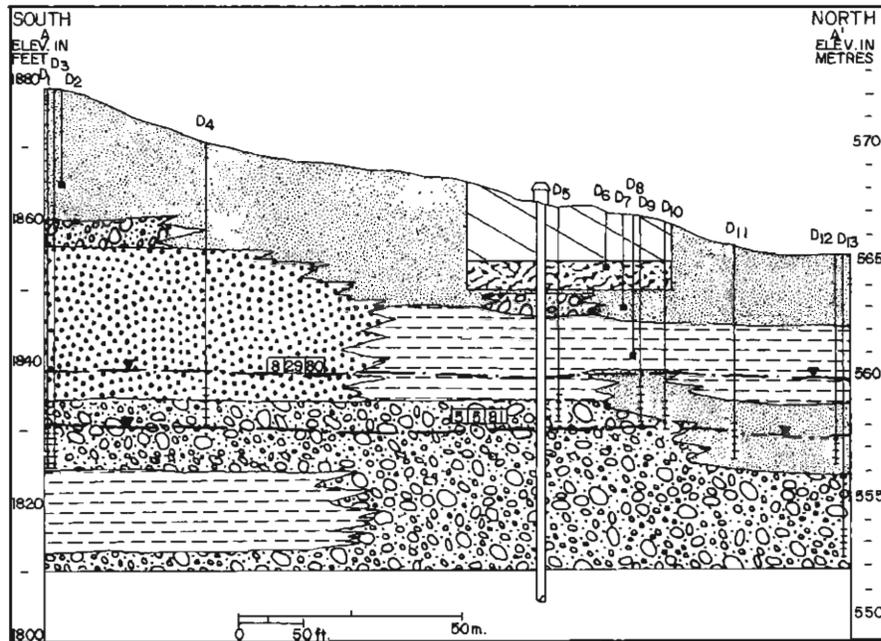


Figure 24. Geologic cross section of the Texaco Charlson Madison (North) Unit #C133 site. The configuration of the water table is shown for two separate periods. The line of profile is depicted in figure 23.

aquifer beneath this study site, which fluctuated over a range of 10 feet (3.05 m) in elevation during the monitoring period between August of 1980 and November of 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 (560 m) above sea level down to 1831 feet (557.5 m). Beneath the bottom of the drilling fluid pit the depth to the water table fluctuated from 13-21 feet (4.0-6.4 m) 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. "A" (NCT-1)
#1 Well Site

This site is underlain by approximately 20 feet (6 m) of colluvium (figs. 26 and 27) which ranges 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 (2,351-2,355 ft. [717-718 m] 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 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 (3 m) up to 16 feet (5 m) (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 [9.2 m]) was found to exist in the silty sand layer above the middle coal. The fifth piezometer (A_4) was installed with a 10-foot (3 m) screen through this interval in a successful attempt to obtain water samples after periods of high precipitation.

Belco Petroleum Sheep Creek
BN #1-11 Well Site

The reserve pit was constructed in 6 to 7 feet (1.8-2.1 m) of silt (figs. 28 and 29) overlying sediments of the Sentinel Butte Formation. An underlying 9-foot (2.7 m) orange to gray silty clay layer contains plant fossils. Below the silty clay layer is a 3-foot (0.9 m) coal seam that is moderately to well indurated and contains clay partings. The underlying 30-foot (9.1 m) clay is light gray to 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 (15.2 m). The auger was able to penetrate this zone only 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 (12.2-13.7 m) 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 (0.9-2.1 m) basal gravel unit consists of subrounded 0.2- to 3.2-inch (0.4-8.0 cm) diameter pebbles comprised

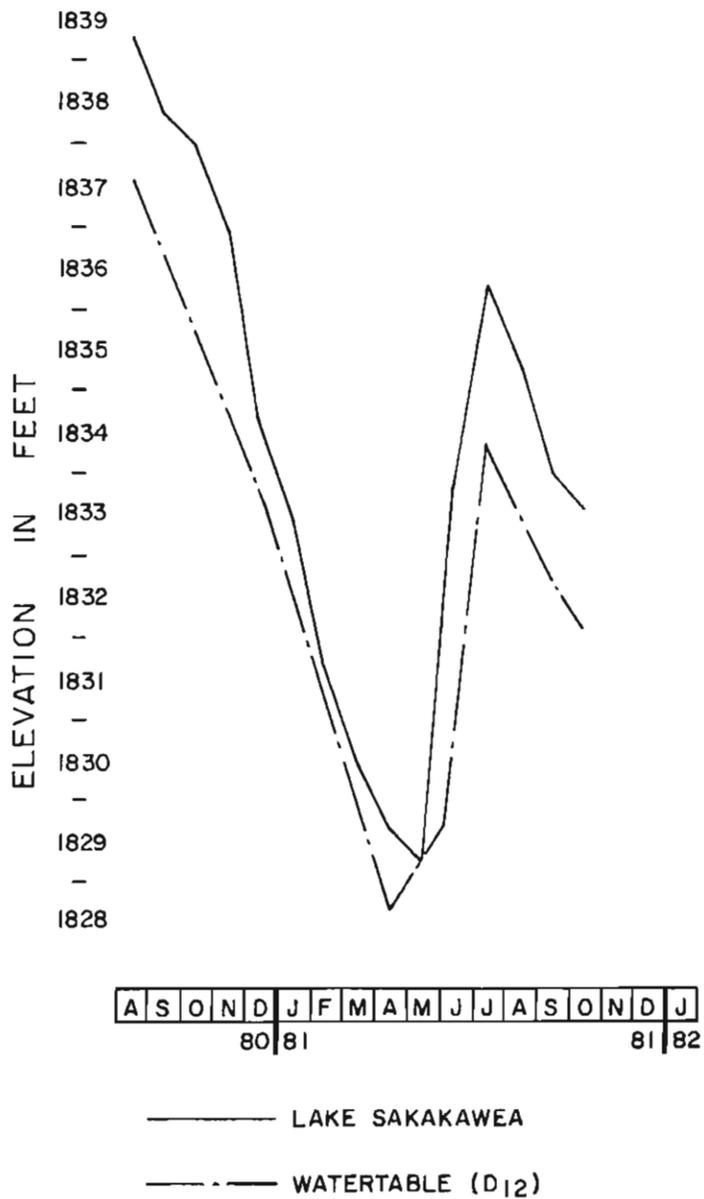


Figure 25. Correlation of the Lake Sakakawea water level and the groundwater table elevations at the Texaco Charlson Madison (North) Unit #C133 site. Data is presented for August of 1980 through November of 1981 (from National Oceanic and Atmospheric Administration, 1981 and U.S. Army Corps of Engineers,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

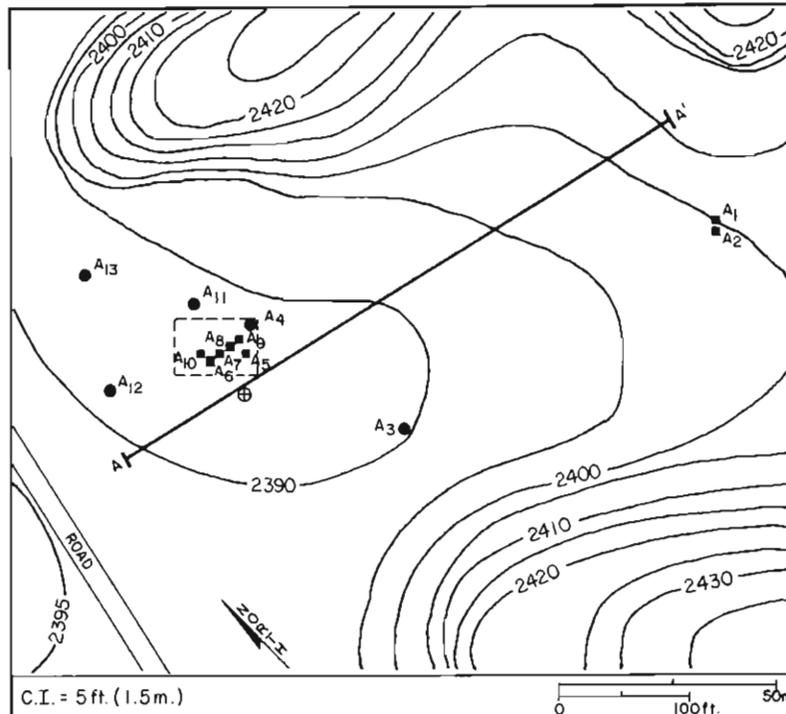


Figure 26. Map view of the Texaco Gov't. "A" (NCT-1) #1 site. Water sampling devices are depicted. For legend see figure 23.

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 (6.1 m) 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 to the west.

The depth to the water table ranges from 35.5 feet (10.8 m) along the western edge of the study area to 28 feet (8.5 m) in the eastern portion. The depth to the water table from beneath the two drilling fluid pit bottoms is approximately 23 feet (7.0 m). The depth of the water table from the bottom of the unlined drilling fluid filled trenches varies from approximately 15 feet (4.6 m) for the 1979 trenches to 10 feet (3.0 m) 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 Sheep Creek, Texaco Gov't. "A," and Apache Federal) are in close proximity to the Trotters 3 se gauging station. The Texaco Charlson site is 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 28 years has been 15.35 inches (38.99 cm). Therefore, the

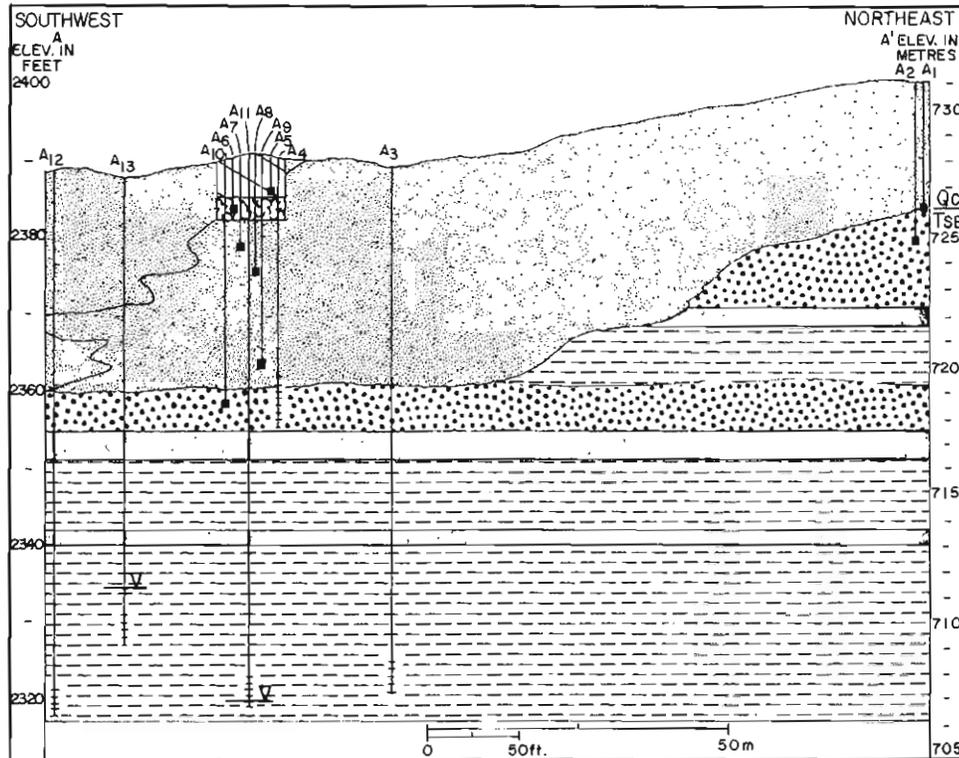


Figure 27. Geologic cross section of the Texaco Gov't. "A" (NCT-1) #1 site. The water levels for A10 and A13 are depicted (not groundwater table). The line of profile is shown in figure 26. For legend see figure 23.

amount of precipitation that fell in and around the Texaco Charlson 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 5 inches (12.7 cm) less than the 28-year annual mean of 14.36 inches (36.47 cm). The precipitation that fell on the Belco Sheep Creek, Texaco Gov't. "A," and Apache Federal study sites during this period was the fifth lowest amount in the last 29 years (fig. 32).

Groundwater Recharge at Sites During Study Period

Groundwater was monitored at the two study sites which have shallow groundwater tables (Apache Federal and Texaco Charlson). Water-level readings were taken a total of eight 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 site (fig. 33). Most of the water levels declined slightly during the interim from August of 1980 through July of 1981. The levels then increased slightly 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 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 (1.5 m) water-table rise is attributed to the adjacent rise of the reservoir.

During the study period the shallow groundwater flow at the Texaco Charlson site was to the north. The relationship between the local water

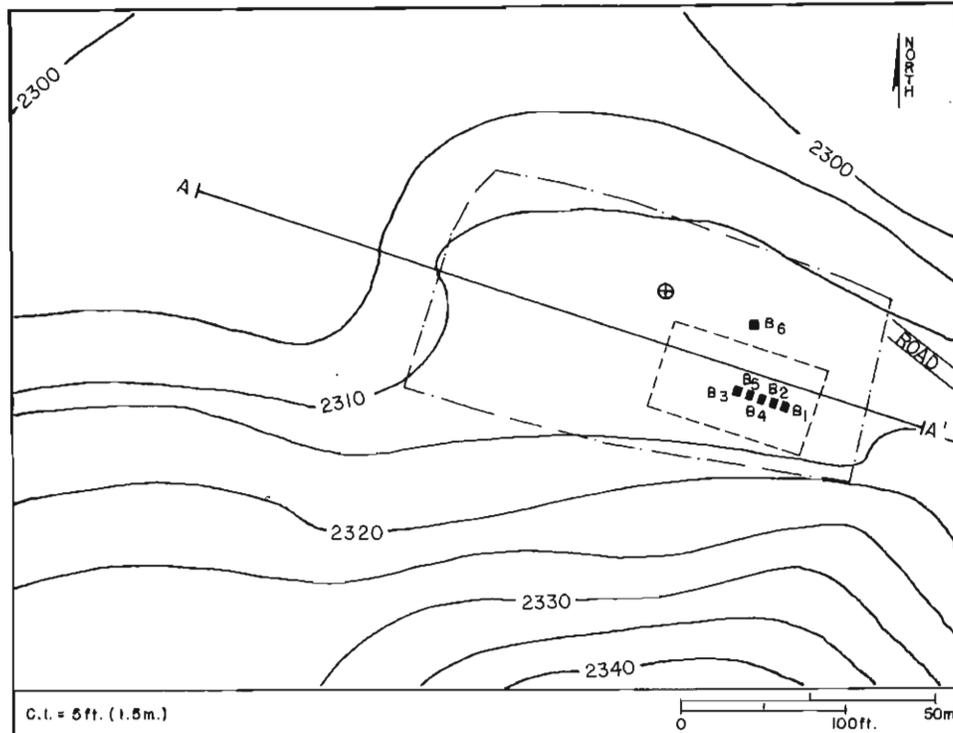


Figure 28. Map view of the Belco Petroleum Sheep Creek BN #1-11 site. The reserve pit is outlined with dashes and the oil well pad with dot and dashes. For legend see figure 23.

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. "A" and Belco Sheep Creek 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 site, because of their greater depth to the water table.

Textural Analyses

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

Texaco Gov't. "A" (NCT-1) #1
%Sand-14.7, %Silt-43.7, %Clay-41.6

Belco Petroleum Sheep Creek BN #1-11
%Sand-5.8, %Silt-50.5, %Clay-43.7

Apache Federal #1-5
%Sand-15.6, %Silt-55.8, %Clay-28.6

Texaco Charlson Madison (North)
Unit #C133

%Sand-22.8, %Silt-44.6, %Clay-32.6

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

	d_{10}	d_{50}
Apache Federal #1-5	0.177	3.0

Texaco Charlson Madison (North) Unit #C133	0.153	3.9
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Hydraulic Conductivity

Hydraulic conductivity values for sediment within the saturated zone at the Apache Federal and Texaco Charlson 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

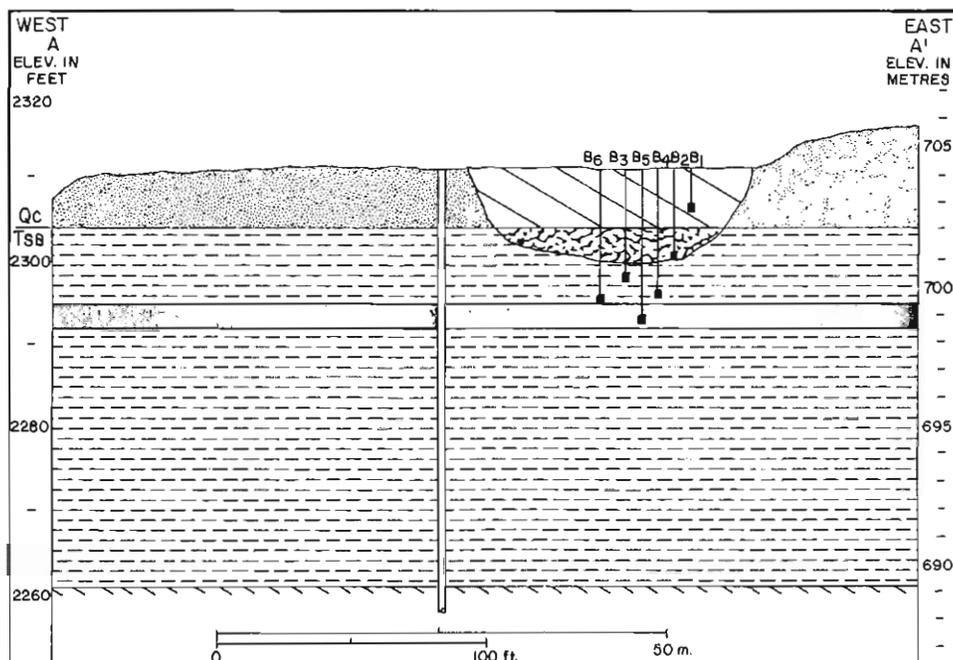


Figure 29. Geologic cross section of the Belco Petroleum Sheep Creek BN#1-11 site. The line of profile is shown in figure 28. For legend see figure 23.

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. "A" 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 (1.2-1.8 m) beneath the bottom of the buried drilling fluid. Most of these concentrations had been reduced significantly in pore water within 20 feet (6.1 m) of the base of the buried fluid; TDS (17,300 mg/l); Cl^- (2,750 mg/l), Na

(5,355 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 BN 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 (0.6 m) 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 (2.4 m) beneath the drilling fluid: TDS (29,950 mg/l), Cl^- (13,133 mg/l), Na (8,800 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 site (C₁₀, app. D). This sample was obtained from 10 feet (3 m) beneath the bottom of the reserve pit, 20 feet (6 m) beneath the surface. The concentrations of many parameters were very high at this depth: TDS (53,200 mg/l), Cl^- (25,000

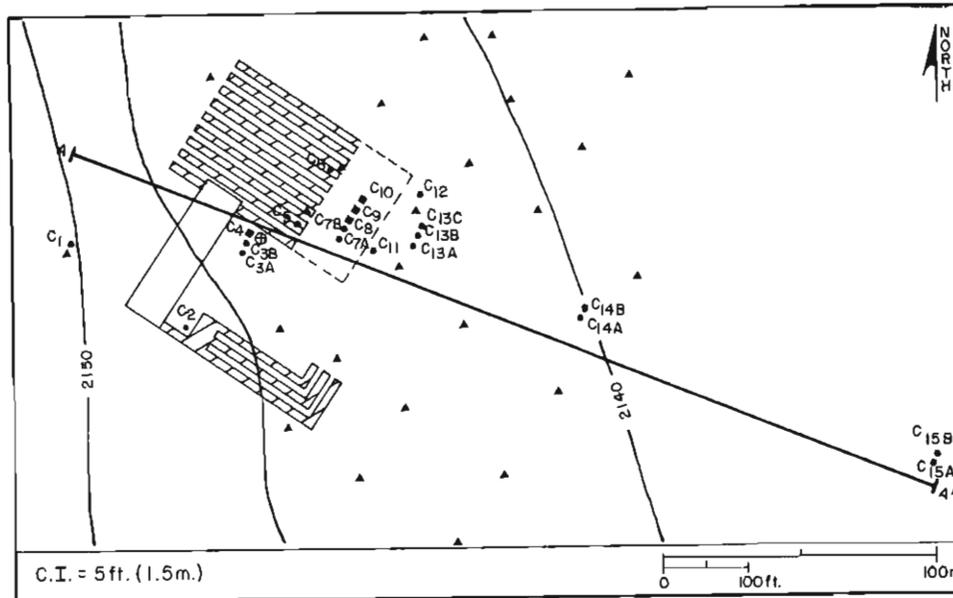


Figure 30. Map view of the Apache Federal #1-5 site. The 1979 reserve pit is shown in dashed outline, the 1981 reserve pit is shown with a solid line. For legend see figure 23.

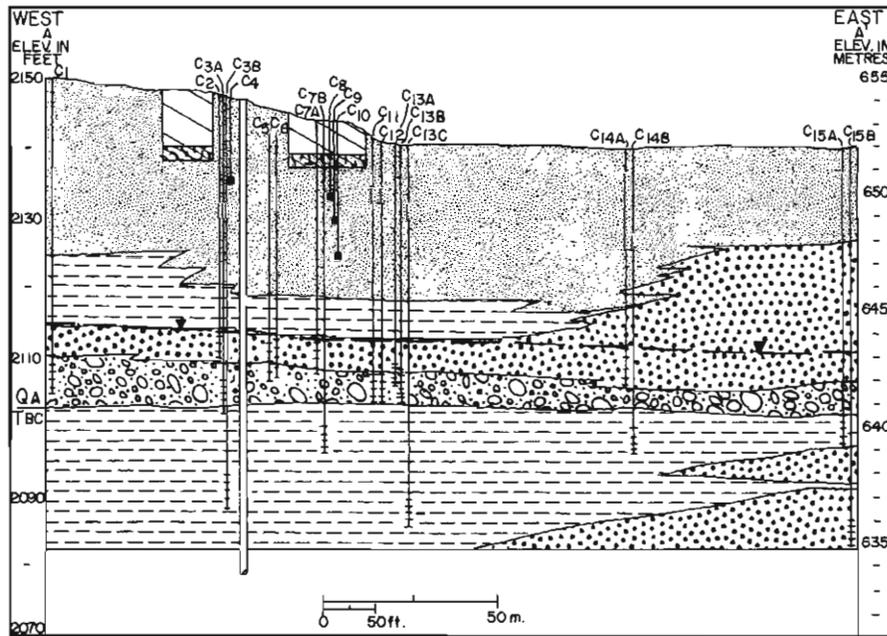


Figure 31. Geologic cross section of the Apache Federal #1-5 site. Piezometers C5, C6, and C11 were destroyed during reconstruction of the pad for the 1981 re-entry. The line of profile is shown in figure 30. For legend see figure 23.

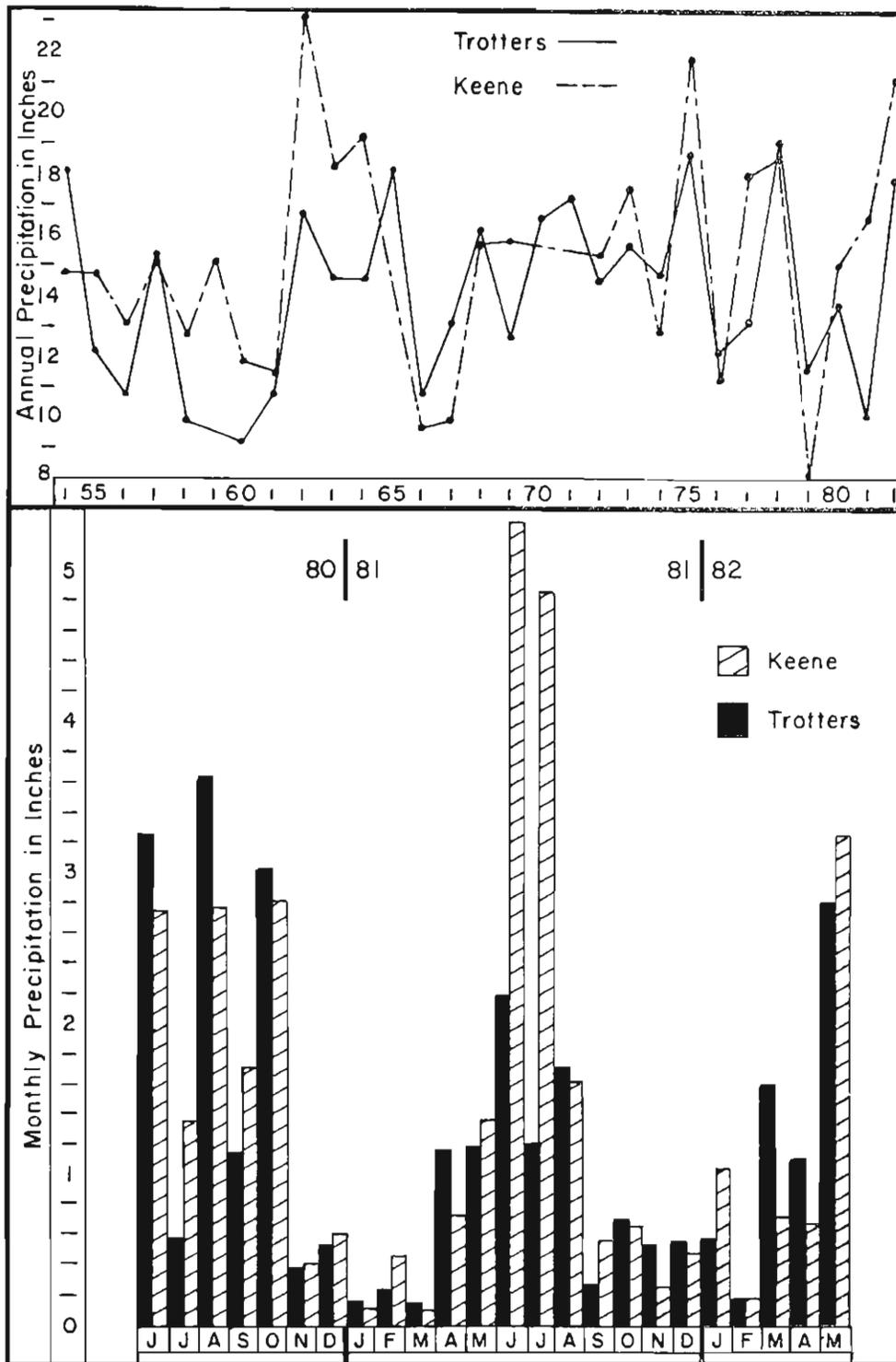


Figure 32. Annual and monthly precipitation totals from the Trotters 3 se and Keene gauging stations. Annual precipitation is for the years of 1954-1982. Monthly precipitation is for the period of June 1980 through May 1982 (from National Oceanic and Atmospheric Administration, 1981).

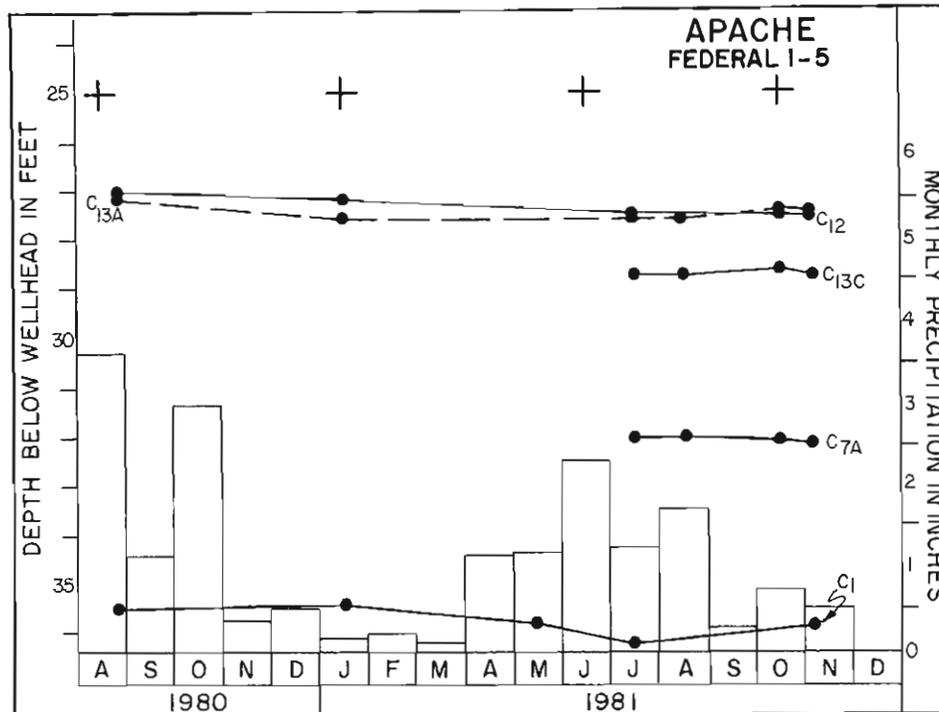


Figure 33. Water-table levels and monthly precipitation totals for the Apache Federal #1-5 site. Monitored from August of 1980 through December of 1981. Quarterly water sampling dates indicated by (+).

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 site water samples were recovered from depths of 3 feet (1 m) and 10 feet (3 m) beneath the base of the reserve pit (D₇ and D₈, app. 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 (5,970-7,470 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 Gov't. "A" and Apache Federal 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 Federal 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 (1 m) 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 (2.3 m) 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. "A" 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 (4.3 m) beneath the base of the reserve pit: TDS (2,540 mg/l), Cl^- (1,380 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 (19.5 m): 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

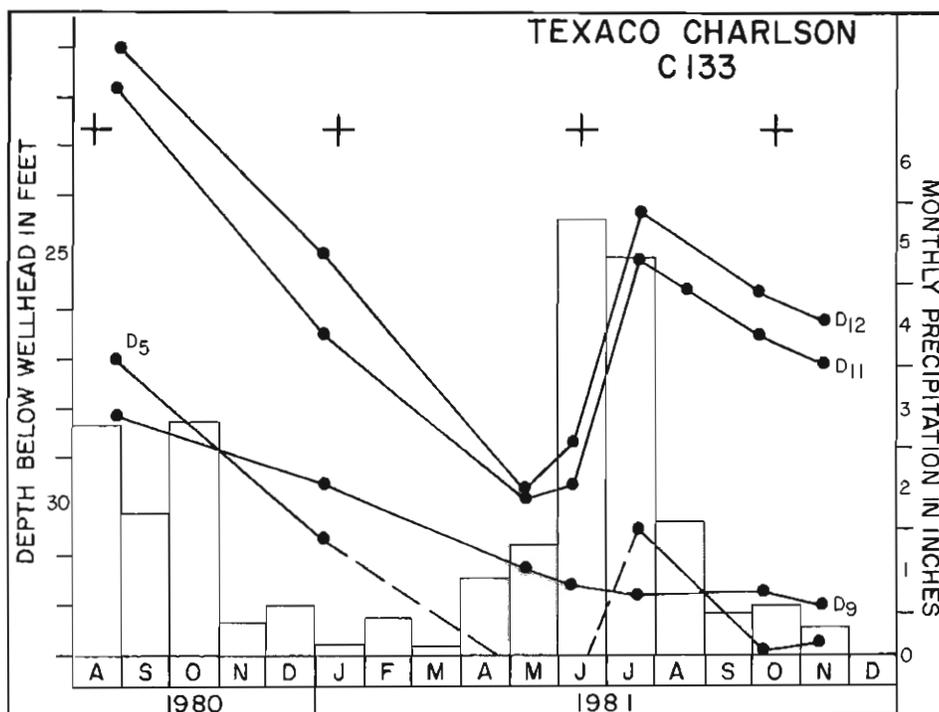


Figure 34. Water-table levels and monthly precipitation totals for the Texaco Charlson Madison (North) Unit #C133 site. Monitored from August of 1980 through December of 1981. Quarterly water sampling dates indicated by (+). Well number D9 is believed to have a faulty screened interval.

chemistry in the unsaturated zone, they do demonstrate the reduction in leachate concentration as the distance from the reserve pit increases.

Water Analyses from the Saturated Zone

Isoconcentration maps of 24 chemical parameters from the Apache Federal site are presented in appendix E. These maps represent the groundwater chemistry for the upper 10 feet (3 m) 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⁻ (4,500 mg/l), Na (3,520 mg/l), NO₃⁻ (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 (61 m) downgradient from the reserve pit: TDS (3,610 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 affected zone to slightly alkaline (7.2) outside of this area.

Isoconcentration maps of 24 chemical parameters from the Texaco Charlson site are presented in appendix E. These maps represent the groundwater chemistry for the upper 15 feet (4.6 m) 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 NO₃⁻, were recorded beneath the reserve pit: TDS (16,100 mg/l), Cl⁻ (4,875 mg/l), Na (3,940 mg/l), NO₃⁻ (1,160 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 (91-122 m) radius of the reserve pit: TDS (4,810 mg/l), Cl⁻ (38 mg/l), Na (766 mg/l), NO₃⁻ (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 affected area.

No water samples were obtained from the saturated zone at either the Texaco Gov't. "A" or Belco Sheep

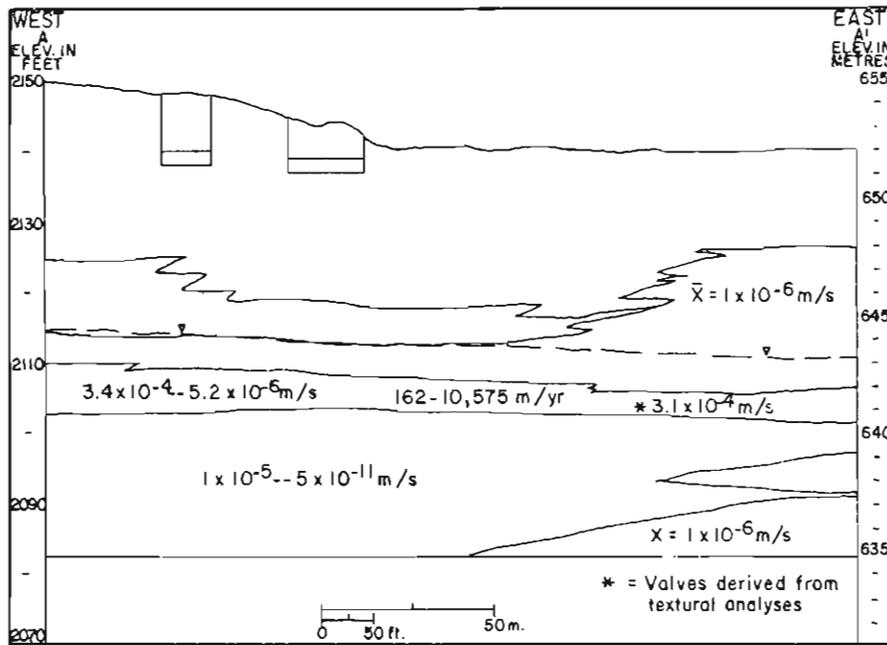


Figure 35. Ranges and means of hydraulic conductivities at the Apache Federal #1-5 site. The values presented are for sediment under saturated conditions. For lithology see legend for figure 31.

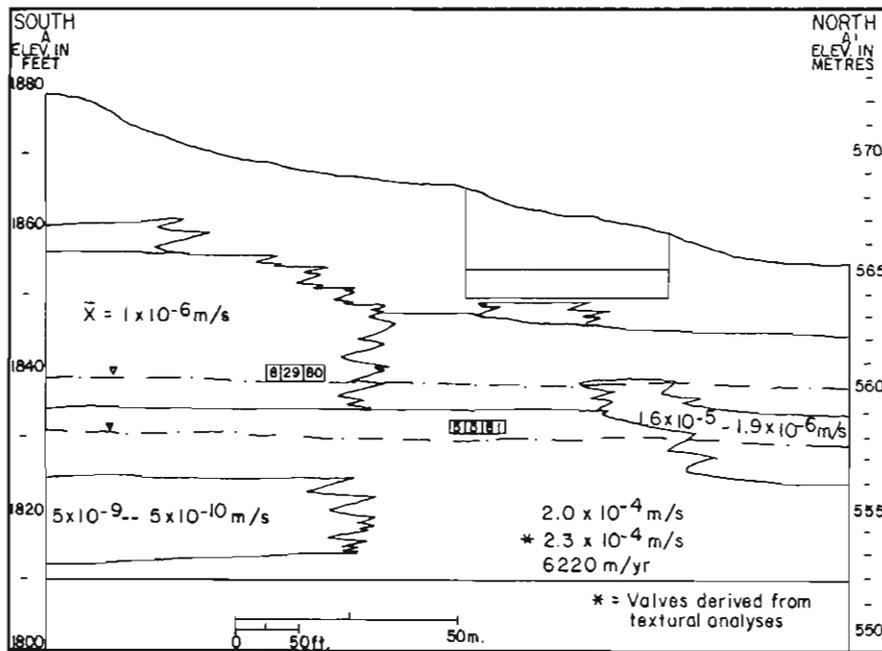


Figure 36. Ranges and means of hydraulic conductivities at the Texaco Charlson Madison (North) Unit #C133 site. The values presented are for sediment under saturated conditions. For lithology see legend for figure 24.

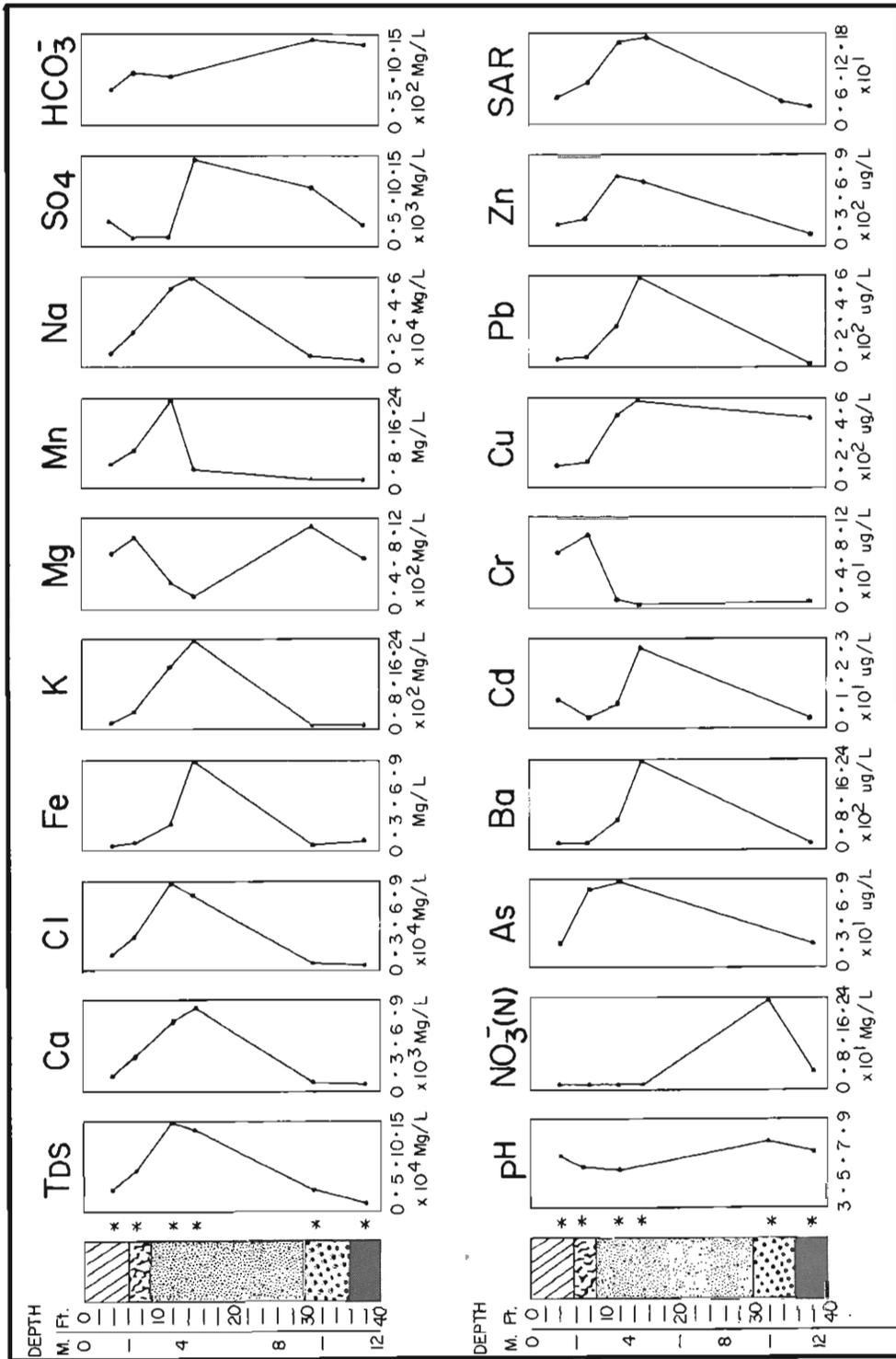


Figure 37. Concentration profiles for various parameters in pore water within the unsaturated zone at the Texaco Gov't. "A" (NCT-1)#1 site. Position of soil water samplers indicated by (*). For lithology see legend for figure 24.

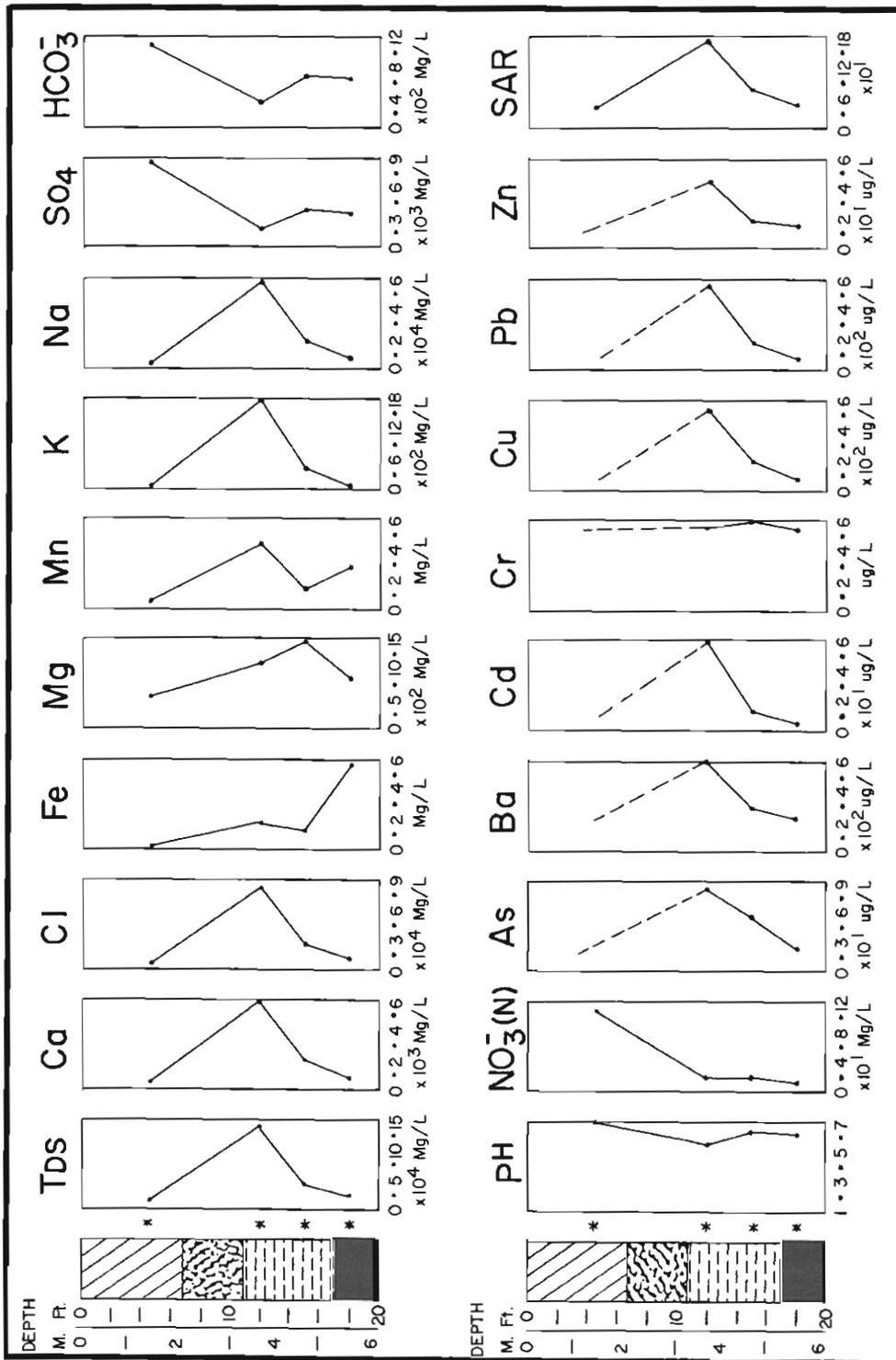


Figure 38. Concentration profiles for various parameters in pore water in the unsaturated zone at the Belco Petroleum Sheep Creek BN #1-11. Position of soil water samplers indicated by (*). For lithology, see legend for figure 24.

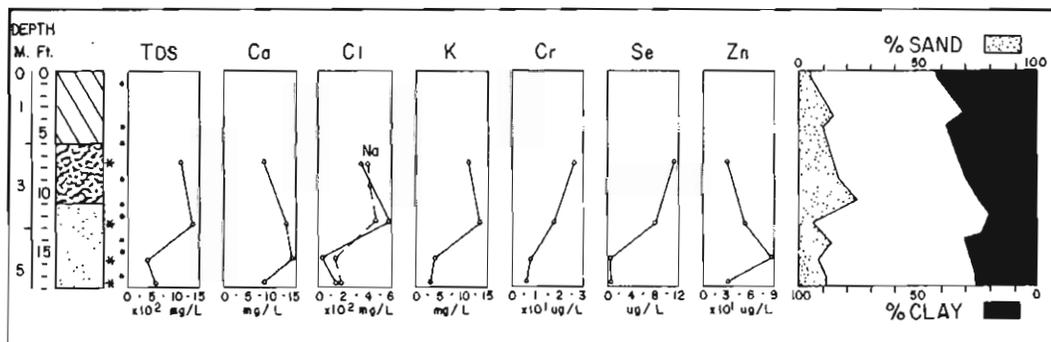


Figure 39. Concentration profiles for various parameters in elutriated sediment samples from the Apache Federal #1-5 site. Textural analyses were determined by the hydrometer method (app. C). The (*) indicates the depth the elutriated sample was taken from, (·) indicates the depth of the sediment for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

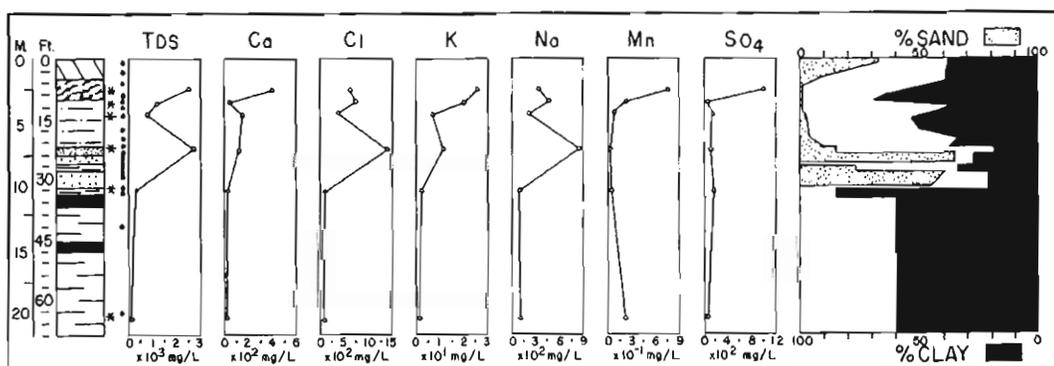


Figure 40. Concentration profiles for various parameters in elutriated sediment samples from the Texaco Gov't. "A" (NCT-1) #1 site. Textural analyses were determined by the hydrometer method (app. C). The depth of the elutriated sample indicated by (*) and the depth of the sediment samples for hydrometer textural analyses indicated by (·). For lithology, see legend for figure 24.

Creek study sites.

Apparent Resistivity

Apparent resistivity values for the Apache Federal and Texaco Charlson 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 (app. 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 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 (30.5 m) (Soiltest, 1968). This 1:1 ratio of depth to electrode spacing has been demonstrated by a number of VES projects in Illinois (Cartwright and Sherman, 1972). However, the presence of sedimentary layers with greatly differing resistivities and/or saline pore water has been shown to distort the electrical field and reduce the depth of current penetration (Reed et al., 1981).

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 (1955) and Texaco Gov't. "A" (1960). The records (mud recapitulation sheets) were obtained for the Belco Sheep Creek and Apache Federal sites. The type and quantity of drilling additives were estimated from these reports (app. G).

The concentration range for the chemical parameters from the mud engineer's report at the Belco Sheep Creek and Apache Federal study sites is given in table 2. A sample of drill-

ing fluid was taken from the Apache Federal 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 biasing 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 percent during this study.

The sand and sandy gravel layers at the Apache Federal and Texaco Charlson sites posed a significant problem to piezometer installation. 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 (1.5-6.1 m). 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 C7B and C13C at the Apache Federal 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

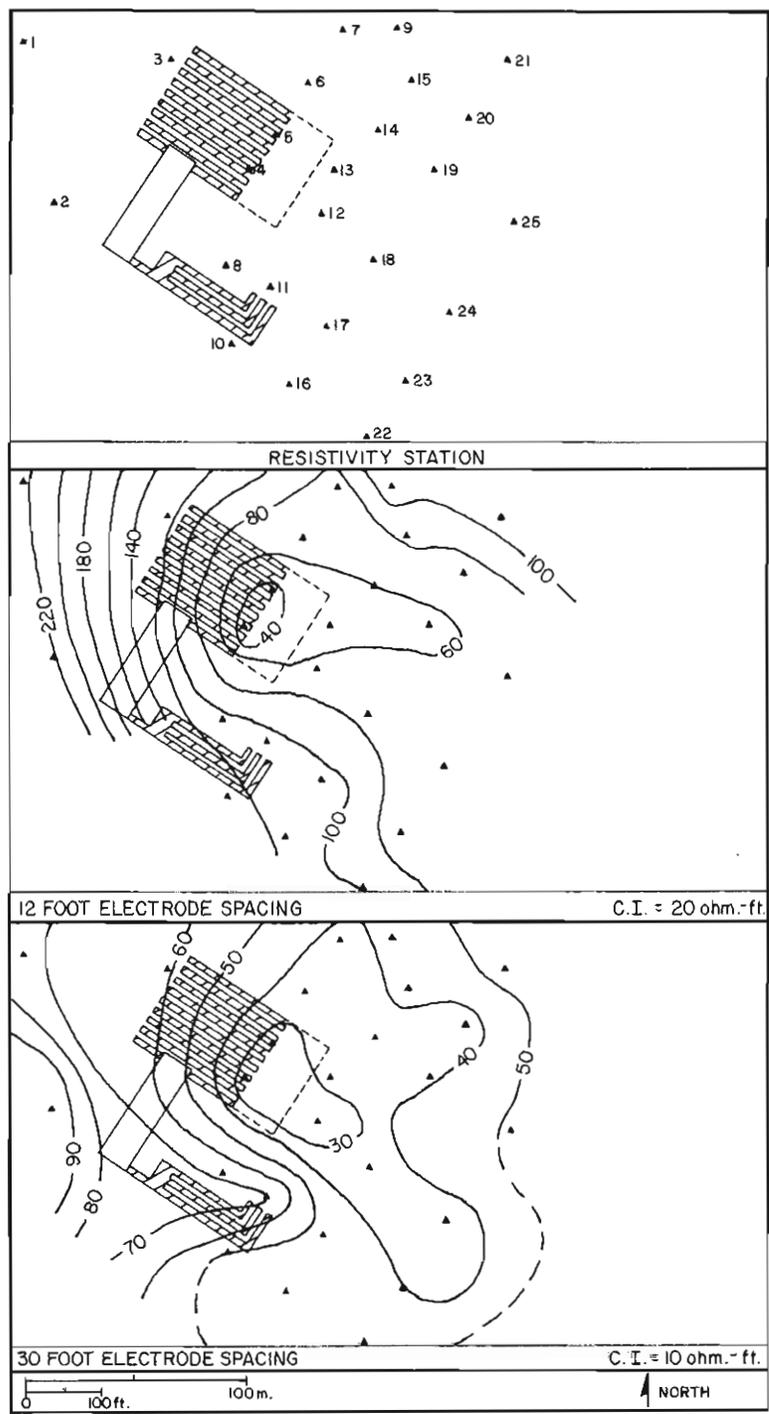


Figure 41. Apparent resistivity stations and isoresistivity maps for electrode spacings of 12 and 30 feet (3.7 and 9.1 m) for the Apache Federal #I-5 site. The values for each station are given in appendix F. For symbols, see legend for figure 23.

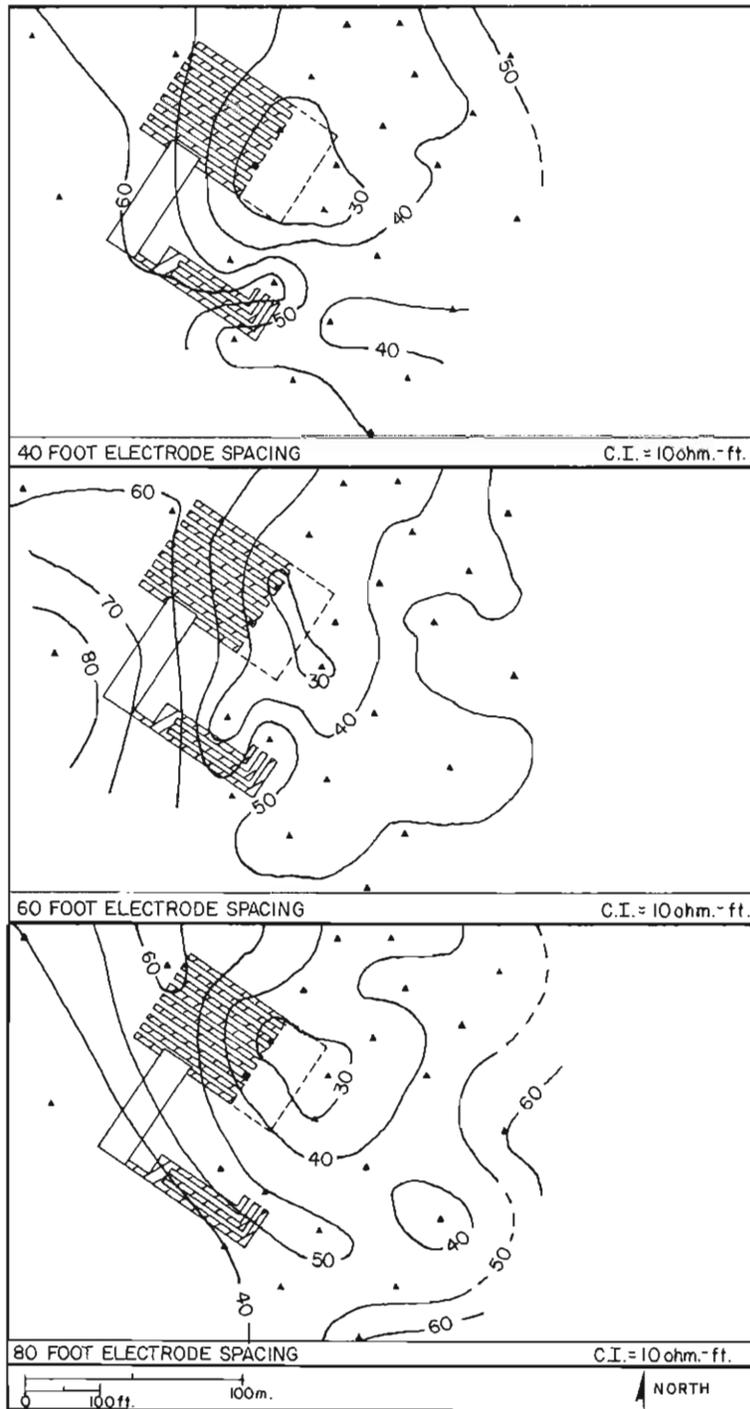


Figure 42. Apparent isoresistivity maps for electrode spacings of 40, 60, and 80 feet (12.2, 18.3, and 24.4 m) at the Apache Federal #1-5 site. The values for each resistivity station are given in appendix F. For symbols see legend for figure 23.

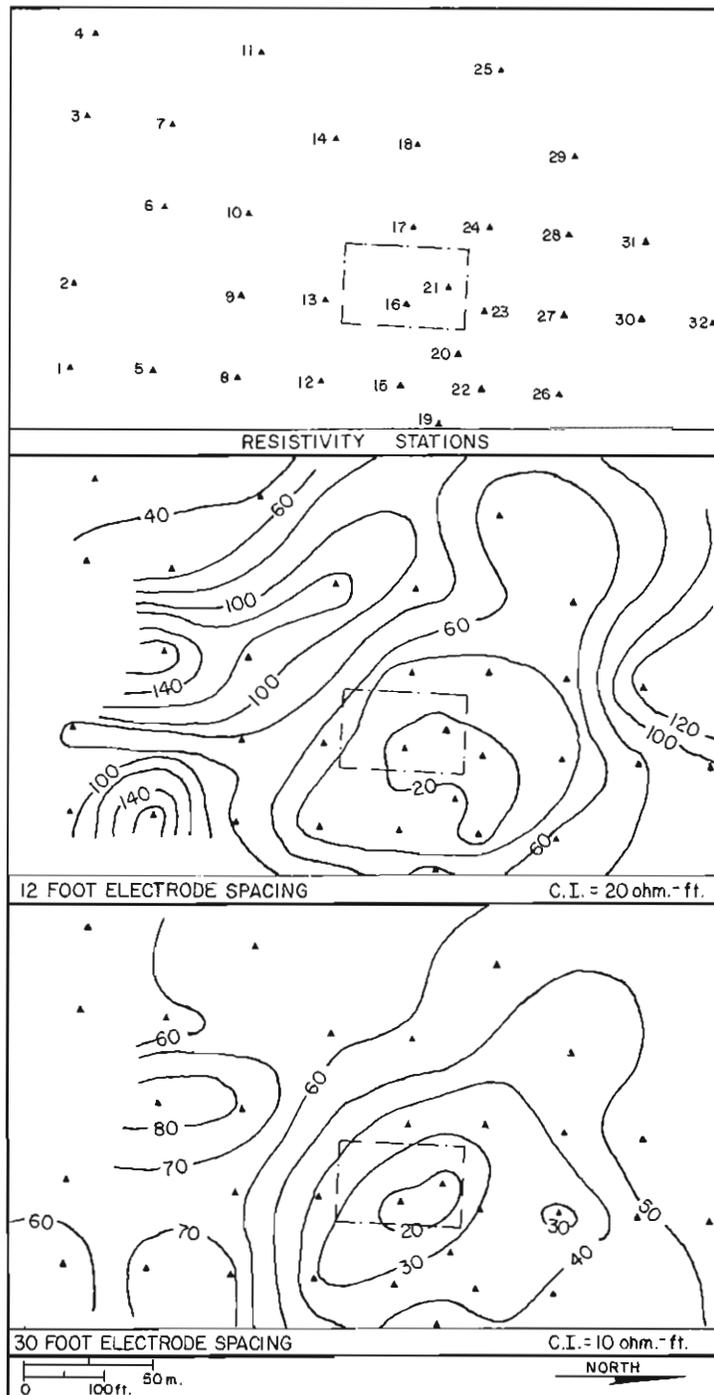


Figure 43. Apparent resistivity stations and isoresistivity maps for electrode spacings of 12 and 30 feet (3.7 and 9.1 m) at the Texaco Charlson Madison (North) Unit #C133 site. Values for each resistivity station are plotted in appendix F. For symbols see legend for figure 23.

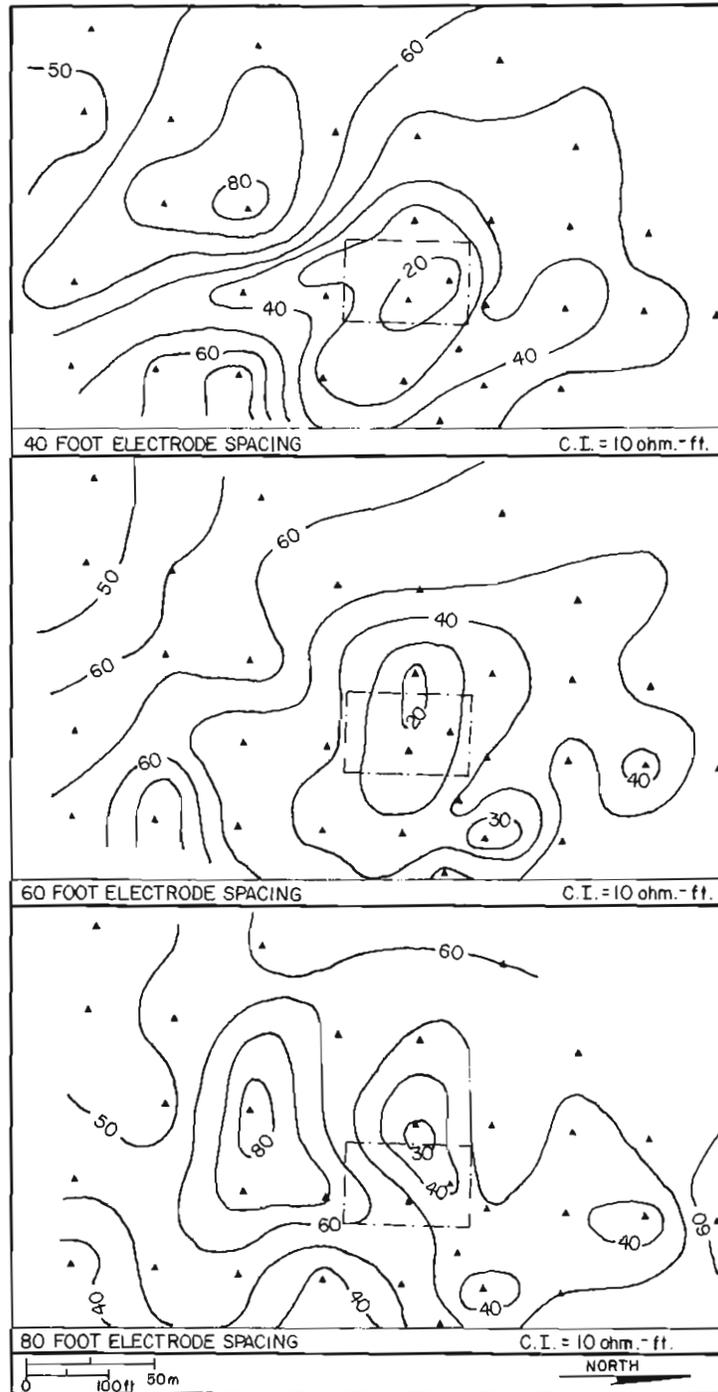


Figure 44. Apparent isoresistivity maps for electrode spacings of 40, 60, and 80 feet (12.2, 18.3, and 24.4 m) at the Texaco Charlson Madison (North) Unit #C133 site. Values for each resistivity station are plotted in appendix F. For symbols, see legend for figure 23.

TABLE 2 -- The range of selected chemical concentrations in drilling fluid and chemical analyses of the Apache Federal #1-5 re-entry drilling fluid. The concentration ranges were obtained from mud engineer reports. The sample of Apache Federal re-entry drilling fluid was taken from the 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 mg/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 (reported as N)	1030	< 2

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 and 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 important only under low groundwater velocity conditions (Freeze and Cherry, 1979).

Transfer of the solutes from the pore water 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 (213.4 m) of sand to achieve the same attenuation provided by 5 feet (1.5 m) of clay till (Cart-

wright 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 Federal 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 Federal site (app. E). A groundwater gradient reduction or flow reversal at the Texaco Charlson 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 (app. 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 Gov't. "A" (NCT-1) #1 Site

The chemical profiles from the Texaco Gov't. "A" site (figs. 37 and 40) indicate that many of the ions are being leached 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 (1.5 m) 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 (9.1 m): 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^- (9,250-5,250 mg/l) are present in groundwater from piezometer A₁₁ at a depth of 72 feet (21.9 m). 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 (6 m) beneath the reserve pit. This pore water contained Cl^- concentrations of only 2,750 mg/l.

Leachate Migration at the Belco Petroleum Sheep Creek BN #1-11 Site

The chemical profiles for the Belco Sheep Creek study site indicate a maximum concentration of most of the ions within a depth of 2 feet (0.6 m) 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 (2.4 m). Within this same interval As is reduced from 163 to 24 ug/l and Pb from 1,320 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 or by the removal of the leachate by evapo-

transpiration.

The Texaco Gov't. "A" and Belco Sheep Creek study sites are 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 can also be attributed to the removal of leachate by evapotranspiration. 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 Site

The water sample from the unsaturated zone at the Apache Federal 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^- (3,750 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 evapotranspiration in the unsaturated zone and 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 76 m]) (app. 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 Federal 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 Madison (North) Unit
#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^- (5,000 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) (apps. 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 91 m) within the upper saturated zone at this site. This plume extends both upgradient and downgradient with respect to the local groundwater flow direction (app. 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 1,310 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 concen-

tration recorded in the saturated zone was 250 feet (76.2 m) 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 Federal 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 (C SESEsec 32, T154N, R95W, and SWSWSEsec 33). 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 D₁₂ and D₁₃ (app. 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 con-

ductivity in the sand and sandy gravel deposits (fig. 36). A greater density of the leachate 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 Federal and Texaco Charlson study sites are 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 Federal 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 Federal 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 (9.1-12.2 m) (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 site. 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 (9.1-18.3 m) (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 (18.3-24.4 m). 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 (app. 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), which calculates layer thicknesses and resistivities (app. 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 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 and Texaco Charlson 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 Federal site. A much better

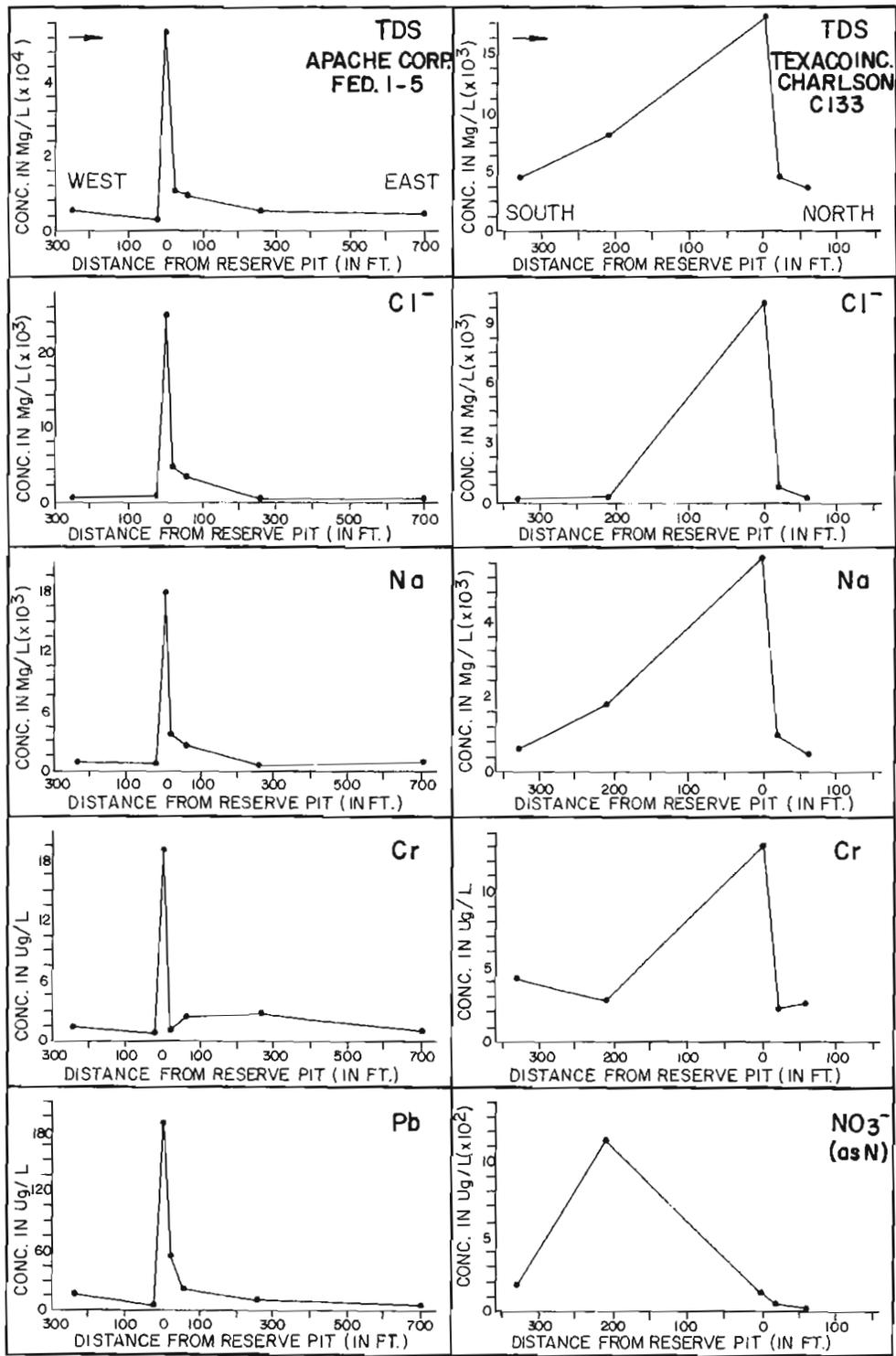


Figure 45. Profiles of leachate migration at the Apache Federal #1-5 and Texaco Charlson Madison (North) Unit #C133 sites. There is no upgradient component of leachate migration at the Apache Federal site. An upgradient component of leachate is present at the Texaco Gov't. "A" site. The configuration at the Texaco Gov't. "A" site is also a reflection of control. The arrows point in the direction of shallow groundwater flow. The Texaco Charlson Madison (North) Unit #C133 profile supports the theory that groundwater flow at this site had been from north to south in the immediate past.

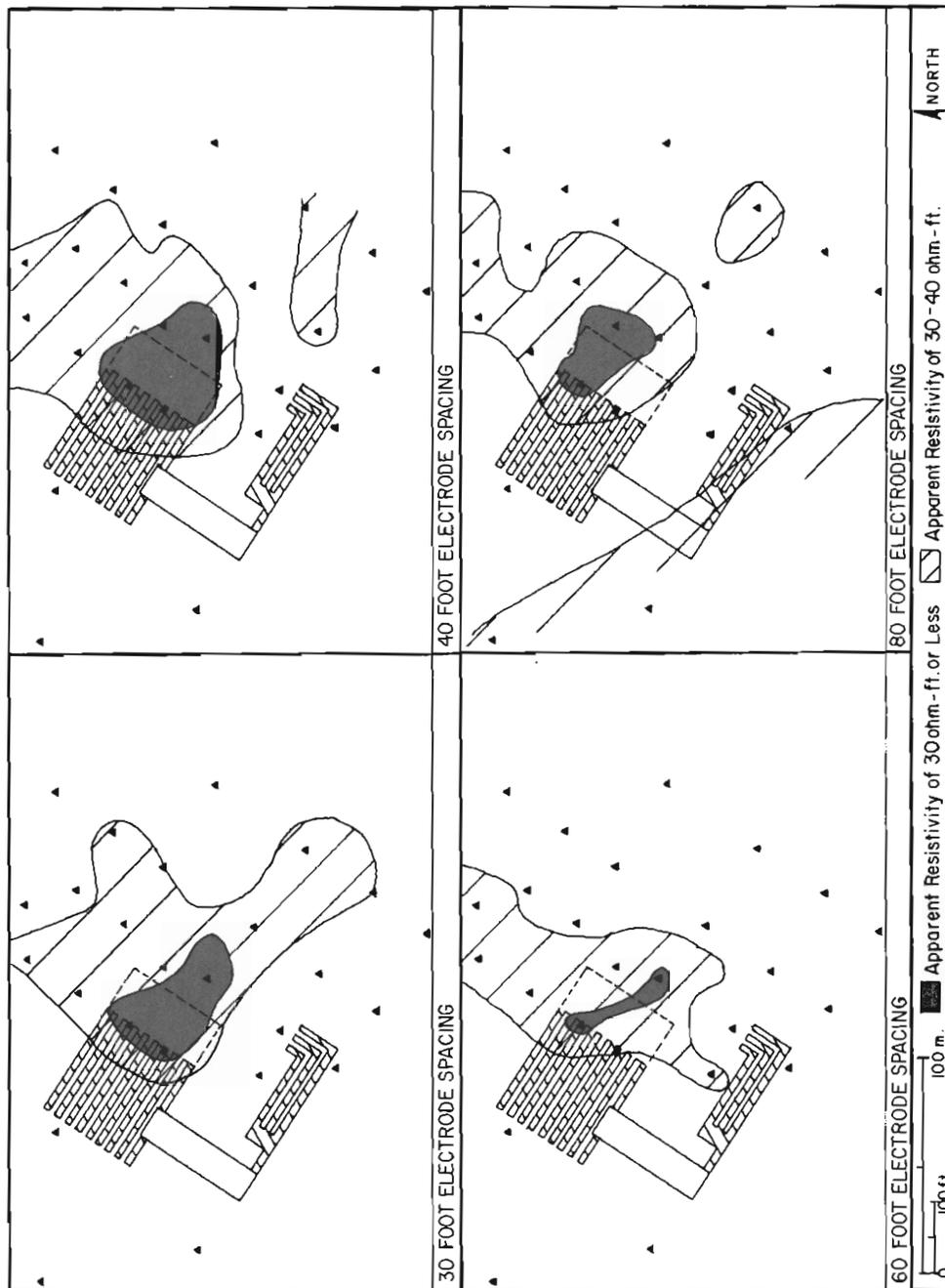


Figure 46. Apparent isoresistivity maps for Apache Federal #1-5 site. Selected ohm-ft. values indicate leachate distribution. Electrode spacings of 30, 40, 60, and 80 feet (9.1, 12.2, 18.3, and 24.4 m). For legend see figure 23.

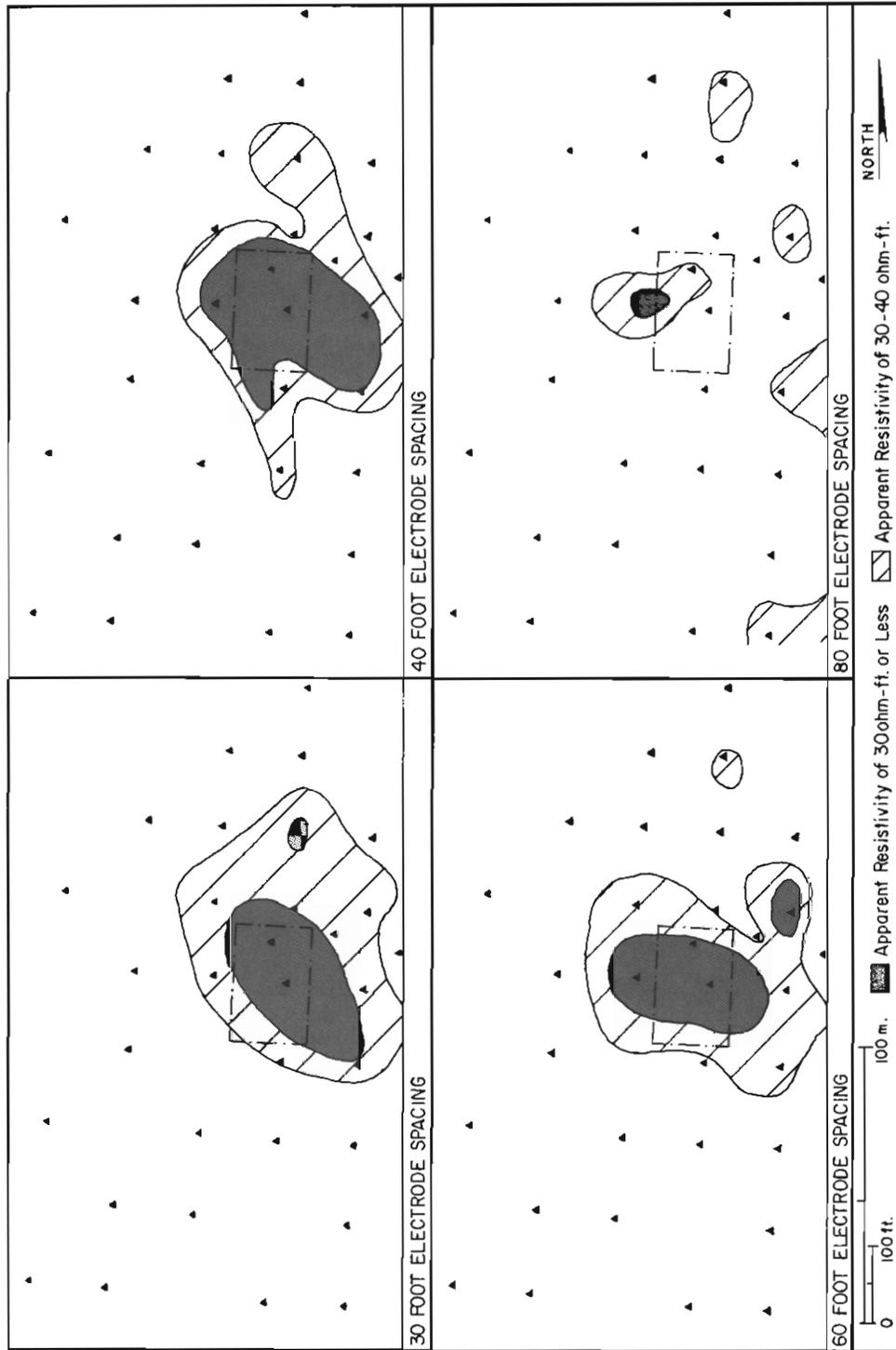


Figure 47. Apparent resistivity maps for Texaco Charlson Madison (North) Unit #C133 site. Selected ohm-ft. values indicate leachate distribution. Electrode spacings of 30, 40, 60, and 80 feet (9.1, 12.2, 18.3, and 24.4 m). For legend see figure 23.

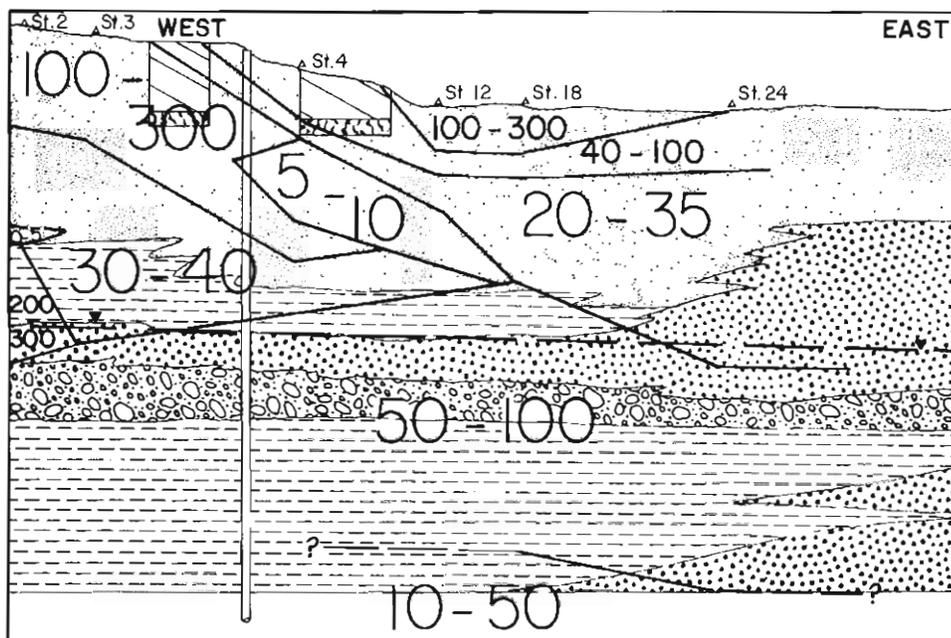


Figure 48. A profile of interpreted resistivity values at the Apache Federal #1-5. The reduction in apparent resistivity caused by the leachate can be seen in the silt layer beneath the reserve pit. The interpreted resistivity boundaries do not correlate well with lithologic changes. Values are in ohm-ft.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

correlation between the two exists at the Texaco Charlson site. Correlation between interpreted resistivity and sediment boundaries are, at best, tenuous at the Apache Federal site. These same correlations agree very well for the Texaco Charlson 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.

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 (app. 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 Federal 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 Federal 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. Anomalies are therefore abnormally elongated in the direction of traverse (Van Nostrand and Cook, 1966). The resulting resistivity patterns on iso-resistivity 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.

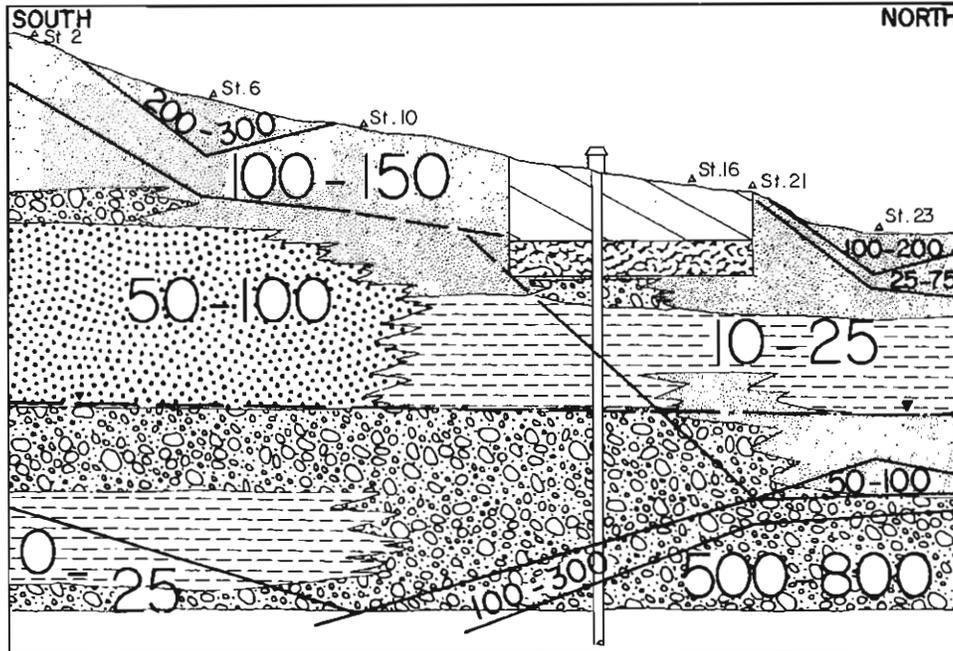


Figure 49. A profile of interpreted resistivity values at the Texaco Charlson Madison (North) Unit #C133. The reduction in apparent resistivity caused by the leachate created the 10-25 ohm-ft. zone beneath the reserve pit. The interpreted resistivity boundaries correlate well at this site with both the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

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 6.4 m), are constructed to radiate out from one side of the pit (figs. 50-A and 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 compacted to a lesser extent than the surrounding sediment on the pad. In addition, desiccation of the drilling fluid over time reduces its 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

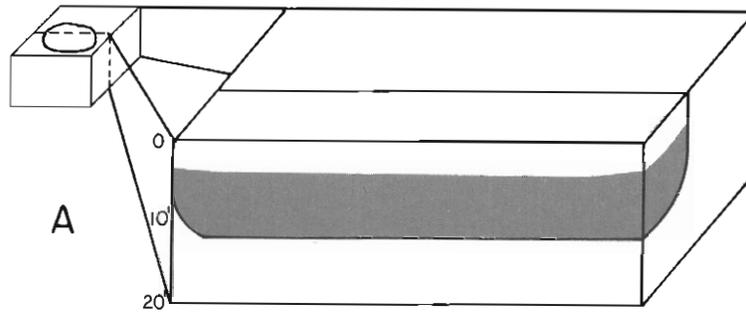


Figure 50A. A cross section of an active drilling fluid pit.

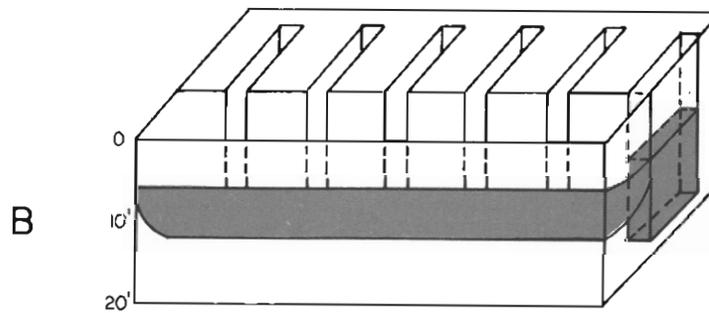


Figure 50B. A drilling fluid pit upon completion of the trenching operation and prior to backfilling. Note the depth of the drilling fluid in the trenches in comparison to the reserve pit.

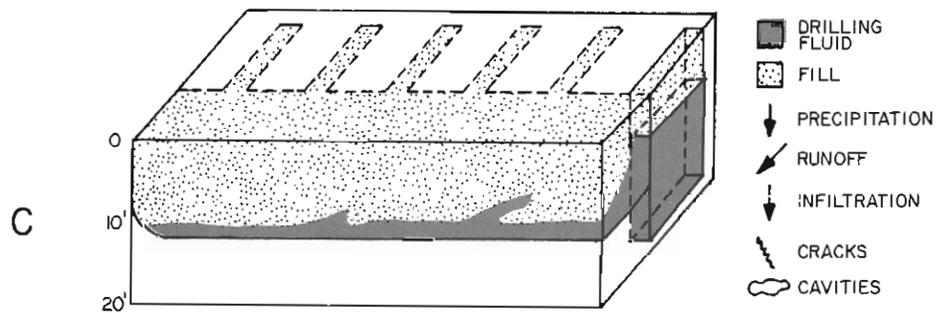


Figure 50C. A drilling fluid pit upon completion of reclamation. Sediment has been spread over the pit and the area has been leveled. Note that the majority of the drilling fluid is now in the unlined trenches.

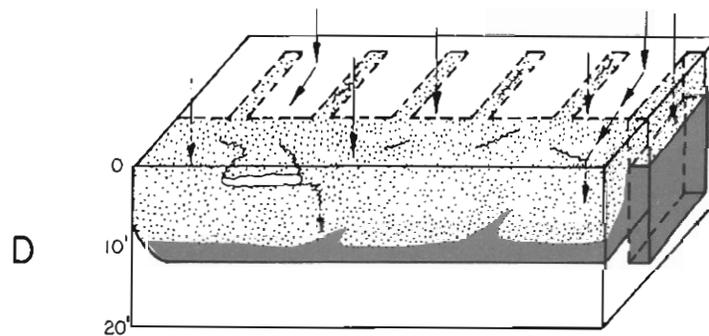


Figure 50D. The results of subsidence within the pit and trenches. This increases the infiltration in this area.

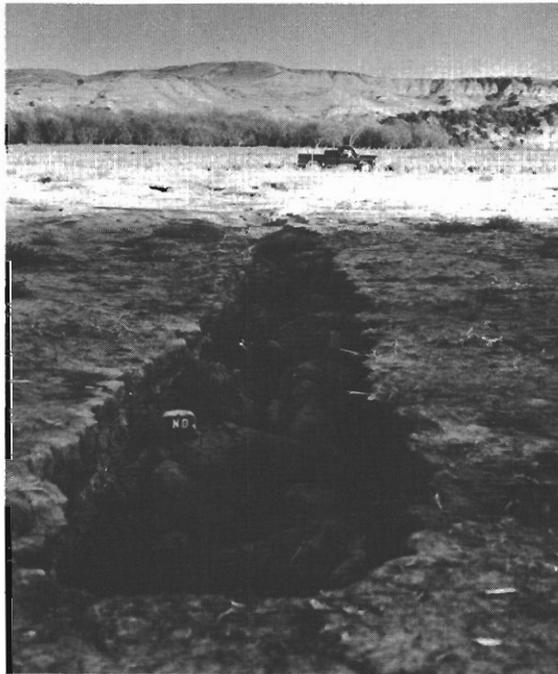


Figure 51. A collapsed trench surface at the Apache Federal #1-5 site (this trench is from the reclamation of the original reserve pit). The collapsed surface is due to desiccation of buried drilling fluid. The maximum depth of the depression is 2.4 feet (0.7 m). The photo is looking east towards the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

(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 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 Cr^{+6} is stable only within a small portion of the typical groundwater field. The conversion of chromium to the hexavalent state requires strongly oxidizing conditions.

The North Dakota State Department of Health Laboratory 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. "A" site (fig. 37). The water samples from the saturated zones at the Apache Federal and Texaco Charlson sites contained Cr concentrations far below the maximum permissible

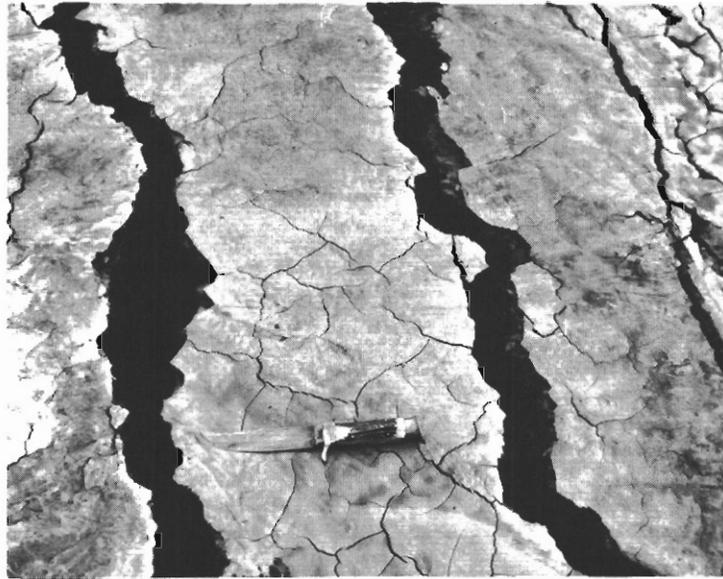


Figure 52. Desiccation and settling cracks developed on the surface of the reclaimed reserve pit at Apache Federal #1-5 re-entry. The photo was taken 5 weeks after the pit was reclaimed. The knife is 9 inches (22.9 cm) in length.

concentration limit. 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.

At the Apache Federal 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 exceeded 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 37 m) 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 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 (app. E). The background concentration levels of TDS, SO_4^{2-} , and Mn also exceeded 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 91 m) within the upper satu-

rated 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 61 m) in the upper saturated zone. The mean of the quarterly water samples exceeded the limits at only two piezometers, D₉ for Cd and D₅ for Pb (app. E). These two ions are potential carcinogenics in concentrations exceeding the maximum concentration limits (Valkovic', 1975).

Se exceeds the maximum permissible concentration limit by a factor of 25X over an area approximately 350 x 200 feet (107 x 61 m) 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 exceeds the maximum permissible concentration limit by a factor of up to 110X (app. E). All of the water samples analyzed from the saturated zone at this site exceeded the 10 mg/l limit

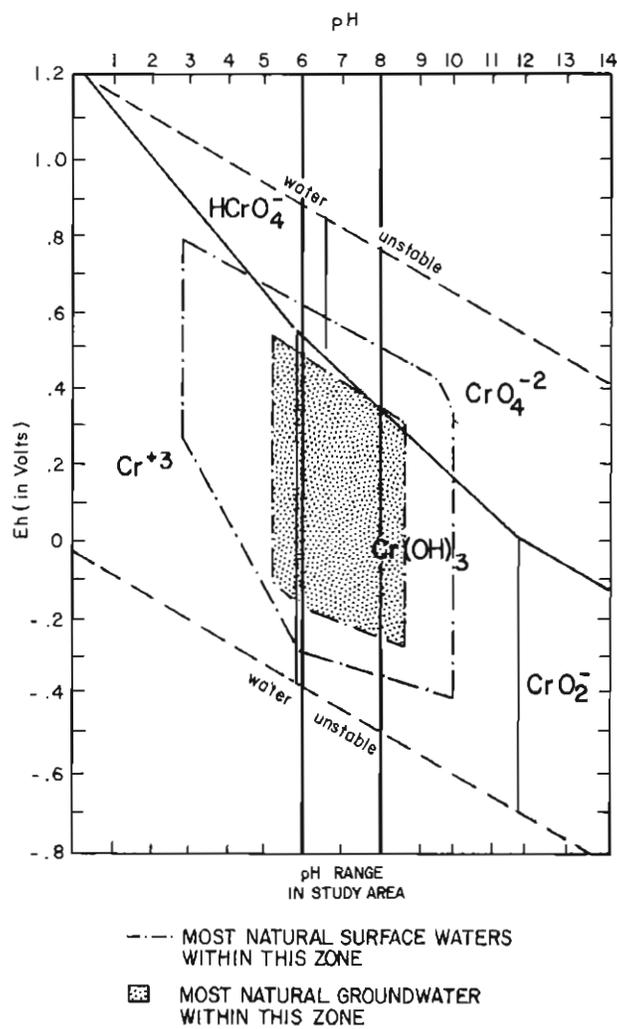


Figure 53. Stability-field diagram for trivalent and hexavalent chromium compounds in water at 25°C and one atmosphere. Hexavalent chromium normally exists over a small Eh-pH range in natural groundwaters. The pH range for the groundwater at the study sites is shown in the diagram (from Robertson, 1975,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

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).

	Human	Livestock	Crops
PARAMETER	in mg/L	in mg/L	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
<p>* Recommended Concentration Limit based upon taste and esthetic appearance.</p> <p>** Maximum Permissible Concentration based upon health effects.</p>			

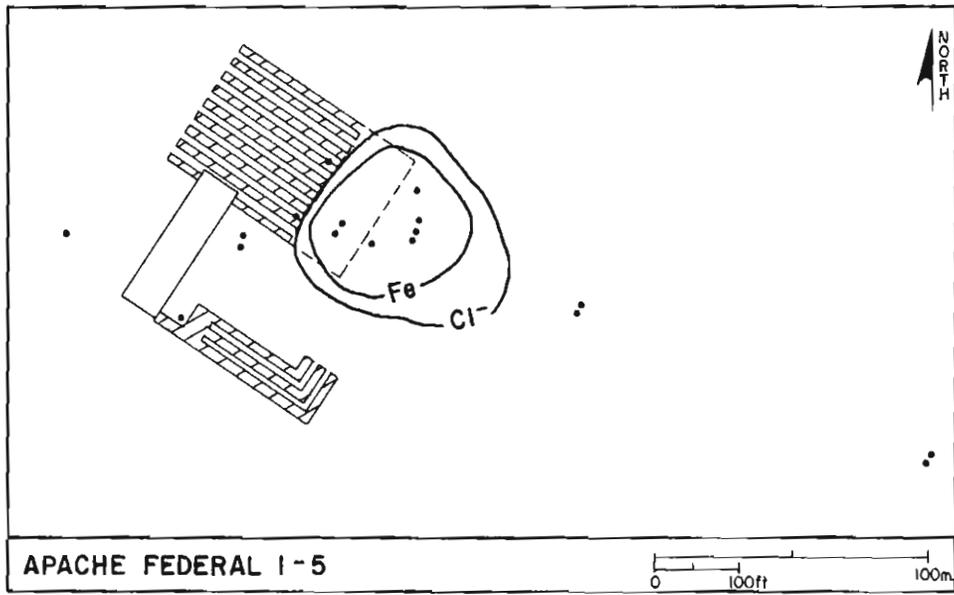


Figure 54. Approximate limits of groundwater which exceeds the recommended concentration limits for Cl⁻ and Fe at the Apache Federal #1-5 site. The upper 10 feet (3 m) of the saturated zone was monitored.

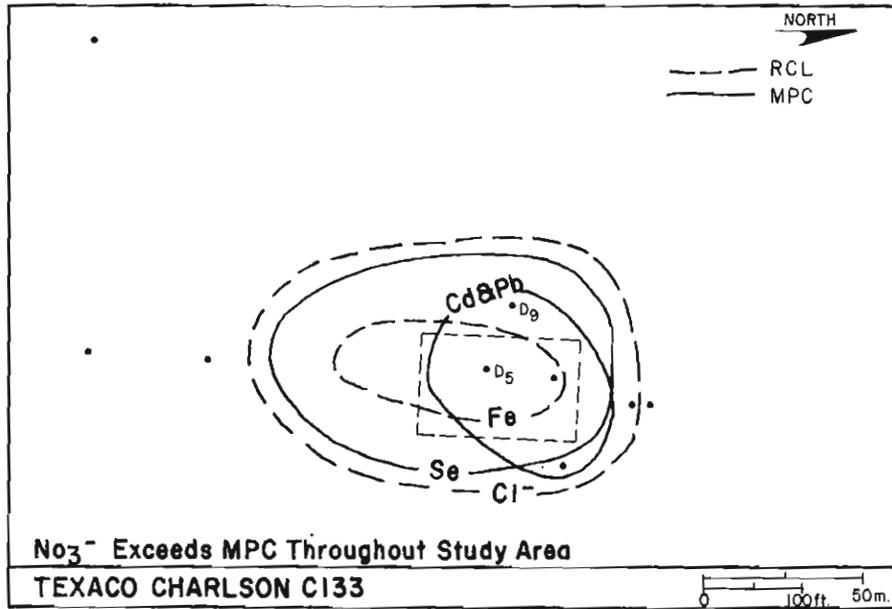


Figure 55. Approximate limit of groundwater which exceeds the recommended concentration limit and maximum permissible concentration limit at the Texaco Charlson Madison (North) Unit #C133 site. The upper 15 feet (4.6 m) of the saturated zone was monitored.

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 site constitutes a danger to health.

As assessment of the groundwater quality at the Texaco Gov't. "A" and Belco Sheep Creek 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 both adsorption onto the commonly abundant Na montmorillonitic clays within the normally thick unsaturated zone and evapotranspiration. 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" and Belco Sheep Creek) 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 Federal and Texaco Charlson) 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 (122 m) 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) 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 and Texaco Gov't. "A"). The chromium ion was

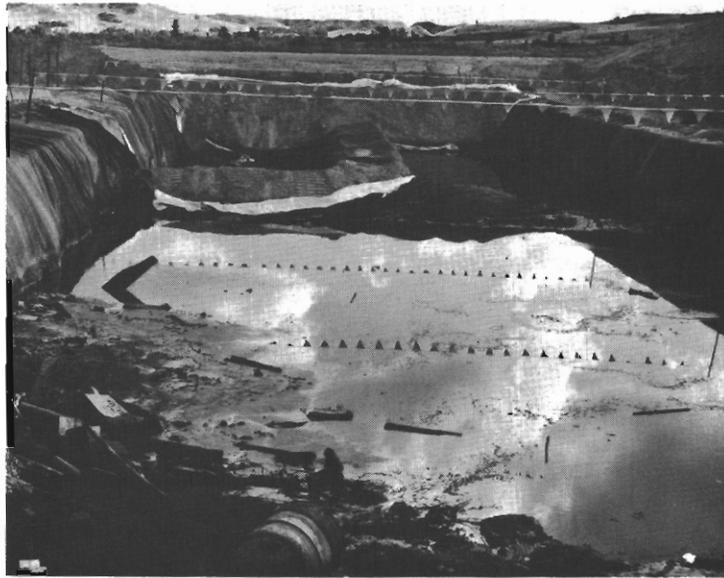


Figure 56. The reserve pit at the Apache Federal #1-5 site (re-entry). Note the substantial tear in the pit liner. Photo is taken looking south.

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 showed no increase in chromium concentration.

RECOMMENDATIONS

Pit Reclamation

The fieldwork for this report was done during the summers of 1980 and 1981. This corresponded with the peak of oil activity in western North Dakota. During this time the oil and gas field inspectors (at that time employed by the North Dakota Geological Survey and now employees of the Oil and Gas Regulatory Division of the Industrial Commission) were kept constantly busy by oil rig activities (i.e., the setting of surface casing, routine inspection, hole plugging, etc.) and had very little time to oversee pit reclamation. As a result of this understaffing a number of poorly maintained sites and improperly constructed reclamation trenches went undetected (figs. 56 and 57). In addition, 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 were witnessed.

A number of these pit maintenance and pit reclamation problems have been corrected by an increase in oil and gas inspector personnel and by the recent decrease in oil activity in the state. The pit location is now subject to approval prior to construction as are the reclamation procedures upon hole completion.

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.

One solution discussed has been the sealing off of the buried drilling fluid from infiltrating water by incapsulation in relatively impermeable sediment. One proposed method would mix bentonite and sediment in the compacted fill above the buried drilling fluid (Hicks, 1983). The drilling fluid would be confined to the plastic lined pit and the overlying fill would be mounded at the surface to decrease infiltration. Dessication of the drilling fluid prior to burial would greatly increase the stability. This method could be used in the badlands areas, but the mounding would be inappropriate for farmland or hayland.

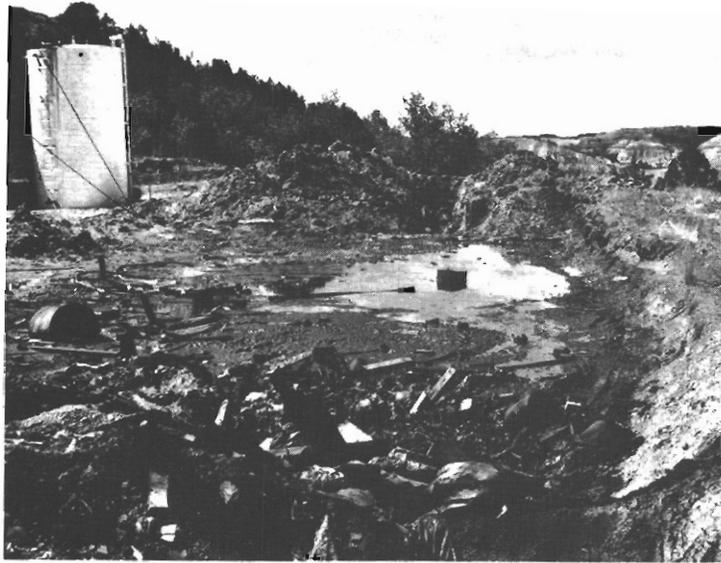


Figure 57. A reserve pit in northern Billings County. The reclamation trench is leading down the hillside into the ravine.

A new method of pit reclamation is currently being experimented with in western North Dakota. Al's Construction, of Regent, North Dakota, is using a machine to blow sediment into the reserve pit (fig. 58). The drilling fluid can be confined to the reserve pit using this method of reclamation. An average pit can reportedly be "blown in" in 18 hours and can then be compacted by heavy equipment. Preliminary results indicate that this method of pit reclamation is successful.

The lithology of the upper 200 feet (61 m) 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.

In western North Dakota there are a very few settings, occasionally found along the Little Missouri River and associated tributaries, where the local geohydrologic conditions (i.e., a high water table and sediment with high hydraulic conductivities) are not favorable for disposal of waste drilling fluids. At these unique locations the drilling fluid should be removed and disposed of in an approved site.

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 is now being focused on oil and gas well sites in north-central North Dakota in a project funded by the North Dakota Water Resources Research Institute. Sites situated upon permeable glacial melt-water channels have a high potential for large-scale leachate contamination of the shallow groundwater. Two sites in this area are being 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 geo-

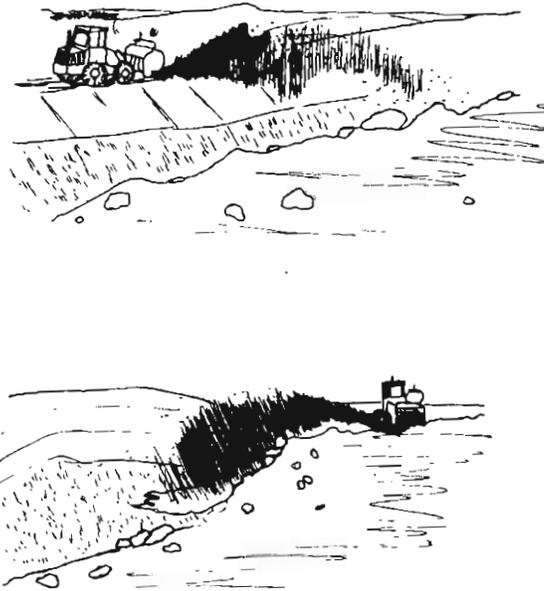


Figure 58. A sketch of Al's Construction machinery blowing fill into a reserve pit in western North Dakota.

chemical techniques to accurately determine the attenuating mechanisms.

A number of oil and gas well sites within the Little Missouri River badlands are situated upon the tops or sides of hills and buttes. Such locations decrease the possibility of leachate interaction with groundwater, but they are more likely to result in surface problems. Hicks (1983) demonstrates that drilling-fluid leachate is migrating to the surface at some of the reclaimed drill sites he studied. Most of these seeps are occurring along the

contact between the base of the compacted fill of the drill pad and the hillside. Based upon Hicks' (1983) results, a further study of the surface effects of buried drilling fluid seems warranted.

Alternative methods of reserve pit reclamation that would confine the buried drilling fluid to the lined pit should be studied. Methods, such as the one shown in figure 58, would eliminate the need for trenching and greatly reduce the amount of leachate that would be generated.

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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 leveled, 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

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

APPENDIX B-II
LITHOLOGIC DESCRIPTION OF DRILL HOLES AT BELCO PETROLEUM
SHEEP CREEK BN #1-11

APPENDIX B-III
LITHOLOGIC DESCRIPTION OF DRILL HOLES AT APACHE FEDERAL #1-5

APPENDIX B-IV
LITHOLOGIC DESCRIPTION OF DRILL HOLES AT
TEXACO CHARLSON MADISON (NORTH) UNIT #C133

APPENDIX B-I

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

Auger Hole No. A1

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-13	Silt; light-gray, clay partings
13-19	Silt; light-brown, clinker fragments
19-23.5	Sand; light-green-gray, fine-grained, subrounded
23.5-24	Concretion
24-28.5	Sand; yellow-brown, moderate cement
28.5-32	Lignite
32-38	Clay; light-gray-blue
38-45	Clay; light-gray, silty
45-47	Lignite
47-58	Clay; dark-gray
58-59	Lignite
59-62	Clay; light-green, highly indurated, lignite stringers
TD	

Auger Hole No. A3

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-18	Silt; brown to dark-brown, clayey, clinker fragments
18-20	Clay; light-brown-gray, silty
20-21	Concretion
21-29	Clay; light-brown-gray, silty
29-34.5	Lignite
34.5-39.5	Clay; light-green-gray, silty
39.5-41	Clay; dark-brown, silty, clinker fragments
41-44	Clay; light-blue, silty
44-45	Lignite
45-51	Clay; light-green-gray, silty
51-68	Clay; light-blue-gray
TD	

Auger Hole No. A11

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-19	Clay; dark-brown, silty
19-31	Clay; light-brown, silty, clinker fragments
31-34	Sand; light-brown-yellow, fine-grained
34-37	Lignite
37-46	Clay; medium-gray
46-46.5	Lignite
46.5-50	Clay; light-gray, lignitic
50-72	Clay; light-blue-gray, ligmonitic nodules
TD	

Auger Hole No. A12

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-19	Silt; yellow-brown to dark-brown, sandy, clayey
19-22	Clay; gray, silty, laminated
22-33	Silt; yellow-brown to brown
33-43	Sand; brown, very fine grained, silty
43-45	Lignite
45-55	Clay; blue, alternating lignitic clay, dark-gray-black
55-64	Clay; blue-gray
64-67	Lignite
67-72	Clay; blue-gray
TD	

Auger Hole No. A14

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-24	Clay; yellow-brown, silty, carbonaceous
24-30	Silt; brown to yellow-brown, clayey
30-34	Clay; yellow-brown, silty
34-36	Clay; gray, lignitic
36-40	Lignite
40-48	Clay; gray-blue
48-50	Lignite
50-62	Clay; gray-blue
TD	

APPENDIX B-II

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT BELCO
 PETROLEUM SHEEP CREEK BN #1-11

Auger Hole No. B6

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-12	Silt; gray-brown
12-16	Clay; orange-gray, fossiliferous
16-19	Lignite
19-50	Clay; blue-gray, alternating brown clay, fossiliferous
50-50.5	Cemented zone, auger could not penetrate.
TD	

Auger Hole No. B7

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-13	Clay; light-gray, silty
13-25	Silt; light-gray-brown, clinker fragments, lignite fragments
25-28	Silt; dark-brown, sandy
28-30	Clay; gray
30-30.5	Lignite
30.5-43	Clay; blue-gray
43-43.5	Cemented zone, auger could not penetrate.
TD	

APPENDIX B-III

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

Auger Hole No. C1

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-25	Silt; light-brown to brown, sandy, clay intervals
25-34.5	Clay; brown to dark-brown, silty
34.5-40	Sand; brown, medium-grained
40-47.5	Gravel; sandy, clinker fragments, lignite fragments
TD	

Auger Hole No. C5

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-14	Silt; light-yellow-brown, clayey
14-28	Clay; light-brown, silty, lignite fragments, clinker fragments
28-32.5	Sand; brown, medium- to fine-grained
32.5-37.5	Gravel; sandy, clinker fragments, lignite fragments
TD	

Auger Hole No. C6

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-14	Silt; light-yellow-brown, clayey
14-29	Clay; brown to light-brown, lignite fragments, clinker fragments
29-36.5	Sand; brown, medium- to fine-grained
36.5-38	Gravel; sandy, clinker fragments, lignite fragments
TD	

Auger Hole No. C11

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-11	Silt; light-yellow-brown, clayey
11-29	Clay; yellow-brown, silty, clinker fragments, lignite fragments
29-37.5	Sand; light- to dark-gray, medium- to fine-grained, clinker fragments, lignite fragments
37.5-38.5	Gravel; sandy
TD	

Auger Hole No. C13

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-9	Silt; light-yellow-brown, clayey
9-24	Clay; yellow-brown, silty, clinker fragments, lignite fragments
24-27.5	Sand; light-gray to dark-gray, medium- to fine-grained, clinker fragments, lignite fragments
27.5-38	Gravel; sandy
38-55	Clay; gray to light-blue, silty
TD	

Auger Hole No. C14

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-19	Silt; light-yellow-brown, sandy
19-30	Sand; medium-grained
30-42	Gravel; sandy
42-47	Clay; light-blue to gray-blue
TD	

Auger Hole No. C15

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-14	Silt; light-yellow-brown, sandy
14-22	Sand; medium-brown, medium-grained
22-35	Sand; gray, medium-grained, clinker fragments, lignite fragments, gravel
35-39	Gravel; sandy
39-42	Clay; light-blue
42-47	Sand; gray, medium-grained
47-49	Clay; light- to gray-blue
49-62	Sand; gray, medium-grained
TD	

APPENDIX B-IV

LITHOLOGIC DESCRIPTION OF DRILL HOLES AT
TEXACO CHARLSON MADISON (NORTH) UNIT #C133

Auger Hole No. D1

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-14	Silt; light-yellow-brown, sandy, clayey
14-26	Sand; medium-brown, medium-grained, silty, clinker fragments, lignite fragments
26-29	Clay; light-yellow, silty
29-40	Clay; dark-brown, silty, clinker fragments
40-52	Sand; medium-dark-brown, silty, clinker fragments, lignite fragments
52-65	Gravel; sandy
TD	

Auger Hole No. D3

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-18	Sand; light-yellow-brown, silty, clayey, clinker fragments, lignite fragments
18-23	Gravel
23-33	Sand; medium-dark-brown, silty, clinker fragments, lignite fragments
33-42	Clay; dark-brown to brown, silty, lithic rock, lignite fragments
42-45	Gravel
45-54	Clay; dark-brown to brown, silty, lithic rock, lignite fragments
54-66	Clay; black to dark-brown, silty, clinker fragments, lignite fragments
66-72	Gravel; sandy
TD	

Auger Hole No. D4

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-5	Silt; light-gray, clayey
5-26	Sand; yellow-brown, silty, clayey, clinker fragments
26-31	Clay; dark-brown, silty
31-36	Clay; yellow-brown, silty, lignite frag- ments
36-42	Gravel; sandy
TD	

Auger Hole No. D5

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-7	Clay; light-brown, silty
7-11	Drilling fluid
11-13	Silt; light-brown to brown, silty, clinker fragments
13-28	Clay; brown to dark-brown, silty, sand stringer
28-32.5	Gravel; sandy, subrounded
TD	

Auger Hole No. D9

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-10	Silt; light-yellow-brown, sandy
10-18	Sand; light-yellow-brown, very fine grained, silty
18-23	Gravel; sandy, subangular lithic rock pebbles
23-31	Clay; brown to dark-brown, silty, sand stringer
31-37.5	Gravel; sandy
TD	

Auger Hole No. D10

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-7	Clay; light-brown, silty
7-11	Drilling fluid
11-15	Sand; light-brown to brown, silty, clinker fragments
15-28	Clay; brown to dark-brown, silty
28-32.5	Gravel; sandy
TD	

Auger Hole No. D11

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-9	Silt; light-yellow-brown, clayey
9-29	Clay; brown, silty, clinker fragments
29-32.5	Gravel
TD	

Auger Hole No. D12

<u>Interval (in feet)</u>	<u>Lithologic Description</u>
0-11	Silt; light-brown to brown, clayey, sandy
11-22	Clay; brown to light-gray, silty, clinker fragments
22-31	Sand; light-brown to gray, silty, clay stringer
31-37.5	Gravel; sandy, lithic rock subrounded-subangular pebbly
TD	

APPENDIX C
TEXTURAL ANALYSES

APPENDIX C-I
TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO
GOV'T. "A" (NCT-1) #1 SITE

APPENDIX C-II
TEXTURAL ANALYSES OF SEDIMENT AT THE BELCO
PETROLEUM SHEEP CREEK BN #1-11 SITE

APPENDIX C-III
TEXTURAL ANALYSES OF SEDIMENT AT THE APACHE
FEDERAL #1-5 SITE

APPENDIX C-IV
TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO CHARLSON
MADISON (NORTH) UNIT #C133 SITE

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.

APPENDIX C-1

TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO
GOV'T. "A" (NCT-1) #1 SITE

<u>Depth</u>	<u>General Description</u>	<u>% Sand</u>	<u>% Silt</u>	<u>% Clay</u>
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'	Very fine 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'	Very fine sand	61.4	16.4	22.2
32'	Very fine 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

APPENDIX C-II

TEXTURAL ANALYSES OF SEDIMENT AT THE BELCO
PETROLEUM SHEEP CREEK BN #1-11 SITE

<u>Depth</u>	<u>General Description</u>	<u>% Sand</u>	<u>% Silt</u>	<u>% Clay</u>
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 and 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

APPENDIX C-III
 TEXTURAL ANALYSES OF SEDIMENT AT THE APACHE
 FEDERAL #1-5 SITE

<u>Depth</u>	<u>General Description</u>	<u>% Sand</u>	<u>% Silt</u>	<u>% Clay</u>
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

APPENDIX C-IV

TEXTURAL ANALYSES OF SEDIMENT AT THE TEXACO
CHARLSON MADISON (NORTH) UNIT #C133 SITE

<u>Depth</u>	<u>General Description</u>	<u>% Sand</u>	<u>% Silt</u>	<u>% Clay</u>
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

APPENDIX D-I

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

Instrument Number	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	0
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 water 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- \bar{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	1,570	1,460	1,480
Mg	522	707	615	760	760	770
Total H.	3,560	4,240	3,900	7,060	6,770	6,860
K	77.7	59.2	68.5	148	152	133
Na	4,080	6,630	5,355	11,400	---	10,300
Cl	2,000	3,500	2,750	14,000	16,200	15,000
SO ₄	9,550	10,100	9,825	4,480	3,590	4,260
Total A.	911	1,220	1,066	587	520	564
HCO ₃	1,110	1,490	1,300	717	636	689
CO ₃	0.0	0.0	0.0	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	22.0	29.0	26.0	---	24.0	24.7
Ba	260	60.0	160	---	160	50.0
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	4.0	13.0	8.5	---	36.0	34.0
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	15.0
Turb.	1.0	5.0	3.0	5.0	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	2.0	5.0	2.0

Sta.	A ₅	A ₆	A ₆	A ₆	A ₇	A ₇
Date- \bar{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	1,503	3,170	3,250	2,310	7,940	6,550
Mg	763	990	940	965	174	360
Total H.	6,897	11,900	11,900	11,900	20,500	17,800
K	144	475	430	453	1,660	1,580
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	4,110	1,260	1,940	1,600	1,690	2,160
Total A.	557	719	736	728	579	675
HCO ₃	681	879	899	889	708	825
CO ₃	0.0	0.0	0.0	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	---	48.0
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	35.0	---	62.0	62.0	---	607
pH	6.5	5.8	6.0	5.9	5.6	---
Se	2	---	2	2	---	---
Temp.	---	17.0	15.0	16.0	15.0	8.0
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- \bar{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	6,660	7,100	6,880	8,250	562	437
Mg	390	515	375	197	1,050	515
Total H.	18,200	19,800	19,000	21,400	5,740	323
K	1,610	1,820	1,635	2,430	117	43.7
Na	55,300	35,400	52,611	60,300	8,320	7,760
Cl	87,500	100,000	91,250	75,000	6,500	9,250
SO ₄	1,690	1,580	1,690	728	14,700	3,630
Total A.	630	657	666	---	1,150	323
HCO ₃	770	803	787	---	1,410	395
CO ₃	0.0	0.0	0.0	---	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	93.0	68.0	---	12.0
Ba	580	---	775	2,550	---	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	30.0	253	619	---	104
pH	6.4	5.5	5.8	---	7.4	6.6
Se	---	2	2	---	---	3
Temp.	11.0	13.0	12.0	8.0	11.0	11.0
Turb.	1.0	3.0	---	---	3.0	5.0
Zn	1,030	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- \bar{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	0.6	0.5	1.8	0.71	1.21
Ca	266	187	297	256	192	171
Mg	305	186	335	252	153	121
Total H.	1,920	1,230	1,158	1,670	1,100	926
K	39.8	33.2	38.9	31.2	33.5	26.1
Na	4,890	4,310	5,653	5,120	3,980	3,560
Cl	5,250	5,250	6,583	2,750	1,700	1,000
SO ₄	2,300	2,970	2,967	5,420	5,820	6,590
Total A.	347	486	385	1,010	1,110	1,160
HCO ₃	424	594	471	1,240	1,360	1,420
CO ₃	0.0	0.0	0.0	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	11.0	---	12.0	16.0	16.0	25.0
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	23.0	64.0	29.0
pH	---	7.8	7.2	6.9	---	7.6
Se	---	---	3	3	---	---
Temp.	8.0	13.0	11.0	11.0	8.0	11.0
Turb.	3.0	44.0	---	50.0	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- \bar{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	4,420	4,200
Cl	875	1,350
SO ₄	6,260	6,040
Total A.	1,160	1,160
HCO ₃	1,420	1,390
CO ₃	0.0	0.0
F	0.4	0.5
% Na	91.7	88.9
As	24.3	21.0
Ba	30.0	145
Cd	7.3	6.6
Cr	6.1	5.6
Cu	57.6	131
Pb	7.0	26.0
pH	6.8	7.1
Se	2	2
Temp.	10.0	11.0
Turb.	4.0	---
Zn	162	187
SAR	65.5	53.1
NO ₃	2	2

APPENDIX D-II

RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT BELCO PETROLEUM SHEEP CREEK BN #1-11 SITE

Instrument Number	Sampling Date			
	<u>9/3/80</u>	<u>1/7/81</u>	<u>6/29/81</u>	<u>10/4/81</u>
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 water sample obtained from instrument
 * Soil water sampler

Sta.	B ₁	B ₁	B ₁	B ₃	B ₃	B ₃
Date- \bar{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	6,760	6,100	5,500
Mg	597	637	617	960	995	1,150
Total H.	3,620	3,990	3,805	20,800	19,300	18,400
K	47.5	74.0	61.0	2,200	2,010	1,770
Na	4,300	6,170	5,235	61,600	56,000	50,100
Cl	4,500	4,750	4,625	93,700	70,000	75,000
SO ₄	8,510	8,000	8,255	2,190	1,880	1,790
Total A.	882	---	882	241	294	294
HCO ₃	1,070	---	1,070	295	359	360
CO ₃	0.0	---	0.0	0.0	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	---	---	---	---	38.0	163
Ba	---	---	---	---	780	420
Cd	---	---	---	---	76.3	51.3
Cr	---	---	---	---	2.6	5.4
Cu	---	---	---	---	557	491
Pb	---	---	---	---	1,320	216
pH	7.6	7.6	7.1	5.5	---	5.7
Se	---	---	---	---	---	---
Temp.	12.0	12.0	12.0	13.0	8.0	9.0
Turb.	4.0	---	4.0	2.0	2.0	0.0
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- \bar{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	6,070	6,085	2,190	2,090	1,870	1,920
Mg	1,450	1,073	1,430	1,540	1,440	1,570
Total H.	21,100	20,050	11,300	11,500	10,600	11,200
K	1,850	1,930	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	1,740	1,835	3,760	3,160	3,630	3,460
Total A.	332	294	366	542	523	552
HCO ₃	406	360	448	662	639	675
CO ₃	0.0	0.0	0.0	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	---	17.0	56.0	89.6
Ba	70.0	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	27.0	166
pH	5.2	5.6	6.2	---	6.2	5.7
Se	2	2	---	---	---	2
Temp.	12.0	11.0	13.0	8.0	9.0	10.0
Turb.	4.0	---	3.0	2.0	1.0	45.0
Zn	296	435	---	225	183	180
SAR	179	177	74.0	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- \bar{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	2,005	1,060	900	950	970
Mg	1,490	810	750	830	797
Total H.	11,250	5,980	5,330	5,790	5,700
K	381	99.5	92.0	65.5	86.0
Na	18,250	9,010	7,980	9,410	8,800
Cl	28,750	12,000	13,700	13,700	13,133
SO ₄	3,545	3,210	3,360	2,910	3,160
Total A.	533	---	517	515	516
HCO ₃	651	---	632	629	631
CO ₃	0.0	---	0.0	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	12.0	21.0	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	38.0	36.0	93.0
pH	6.2	---	6.2	5.9	6.1
Se	2	---	---	2	2
Temp.	---	8.0	10.0	10.0	9.0
Turb.	---	---	50.0	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

APPENDIX D-III

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

Instrument Number	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- \bar{X}	9/3/80	1/7/81	6/29/81	10/12/81	\bar{X}	6/29/81
Cond.	6,200	5,400	4,460	5,280	5,340	4,230
TDS	4,630	4,840	4,060	4,550	4,590	3,740
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	89.0	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	1,310	1,130	1,030	1,400	1,220	965
Cl	25.0	11.0	13.0	30.0	19.0	55.0
SO ₄	2,260	2,650	2,130	2,130	2,195	1,850
Total A.	1,180	1,240	1,040	1,120	1,150	1,030
HCO ₃	1,440	1,520	1,270	1,370	1,405	1,250
CO ₃	0.0	0.0	0.0	0.0	0.0	0.0
F	0.6	0.7	0.5	0.5	0.6	0.6
% Na	75.8	73.3	75.0	77.7	75.0	74.5
As	7.0	14.0	21.0	7.5	11.0	11.0
Ba	260	160	240	0.0	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	94.0
Pb	27.0	7.0	36.0	6.0	17.0	6.0
pH	7.1	---	6.8	7.5	7.1	6.8
Se	3	---	---	2	2	---
Temp.	10.1	8.0	11.0	10.0	---	11.0
Turb.	3.0	---	5.0	22.0	---	7.0
Zn	120	119	35.0	49.0	84.0	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- \bar{X}	10/12/81	\bar{X}	6/29/81	10/12/81	\bar{X}	6/29/81
Cond.	4,180	4,205	4,320	4,410	4,365	4,050
TDS	3,470	3,605	3,720	3,790	3,755	3,650
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	78.0	66.0
Total H.	514	614	689	698	694	630
K	14.2	15.4	17.3	13.8	15.6	16.8
Na	1,040	1,003	1,050	1,130	1,090	1,040
Cl	13.0	34.0	33.0	33.0	33.0	23.0
SO ₄	1,680	1,765	1,740	1,730	1,735	1,740
Total A.	929	951	1,020	1,080	1,075	1,020
HCO ₃	1,130	1,190	1,300	1,330	1,315	1,250
CO ₃	0.0	0.0	0.0	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	9.0	5.0	7.0	7.0
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	52.0
Pb	9.0	7.5	8.0	4.0	6.0	21.0
pH	7.5	7.1	6.9	7.7	7.3	7.0
Se	2	2	---	2	2	---
Temp.	10.0	---	11.0	10.0	---	11.0
Turb.	3.0	---	4.0	10.0	---	2.0
Zn	65.0	117	47.0	29.0	38.0	34.0
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- \bar{X}	10/12/81	\bar{X}	9/3/80	1/7/81	\bar{X}	9/3/80
Cond.	3,840	3,945	4,680	4,000	4,340	5,820
TDS	3,200	3,425	3,420	3,360	3,390	4,130
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	54.0	60.0	75.0	82.0	79.0	105
Total H.	494	562	677	707	692	917
K	12.4	14.6	15.1	76.5	45.8	16.5
Na	1,010	1,025	998	899	949	1,250
Cl	28.0	26.0	105	70.0	88.0	150
SO ₄	1,380	1,560	1,480	1,470	1,475	1,760
Total A.	999	1,010	981	1,010	996	1,080
HCO ₃	1,220	1,235	1,190	1,230	1,210	1,330
CO ₃	0.0	0.0	0.0	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	60.0	110	120	180	150	20.0
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	5.0	13.0	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.	10.0	---	10.5	8.0	---	10.5
Turb.	4.0	---	2.0	---	---	2.0
Zn	24.0	29.0	136	48.0	92.0	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- \bar{X}	1/7/81	\bar{X}	6/29/81	10/12/81	\bar{X}	6/29/81
Cond.	4,500	5,160	18,400	10,100	14,250	22,600
TDS	4,330	4,230	12,700	7,530	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	2,610	1,290	1,950	3,460
K	18.2	17.4	61.5	36.6	49.0	61.0
Na	1,120	1,185	3,680	2,460	3,070	4,120
Cl	53.0	102	5,500	2,000	3,750	5,000
SO ₄	2,200	1,980	2,170	2,000	2,085	2,280
Total A.	1,110	1,095	803	1,000	902	817
HCO ₃	1,360	1,345	981	1,220	1,101	998
CO ₃	0.0	0.0	0.0	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	72.0
As	9.0	7.0	19.0	11.3	15.2	15.0
Ba	90.0	55.0	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	60.0	48.0	7.9	28.0	82.0
Pb	3.0	3.0	26.0	11.0	19.0	10.0
pH	---	6.6	7.0	7.3	7.2	6.8
Se	---	3	---	2	2	---
Temp.	8.0	---	12.0	10.0	11.0	12.0
Turb.	---	---	15.0	33.0	---	83.0
Zn	52.0	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- \bar{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	1,440	520	717	619
Mg	350	360	2,100	277	347	302
Total H.	3,060	3,260	12,200	2,440	3,220	2,830
K	45.2	53.1	144	39.0	44.7	41.9
Na	3,520	3,820	17,900	3,520	3,490	3,505
Cl	5,500	5,250	25,000	4,000	4,500	4,250
SO ₄	1,850	2,065	5,750	2,570	2,500	2,535
Total A.	817	817	1,140	968	923	946
HCO ₃	998	998	1,400	1,180	1,120	1,150
CO ₃	0.0	0.0	0.0	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	9.0	15.0	12.0
Ba	20.0	210	90.0	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	60.0
Pb	50.0	30.0	188	92.0	19.0	56.0
pH	6.8	6.8	6.5	6.4	---	6.4
Se	2	2	2.6	3	---	3
Temp.	10.0	---	10.0	10.7	8.0	---
Turb.	34.0	---	3.0	50.0	3.0	---
Zn	53.0	79.0	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- \bar{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	8,590	9,660	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.	2,490	3,230	3,370	3,730	3,300	2,380
K	38.7	34.7	33.0	35.7	35.2	33.5
Na	2,120	2,310	2,660	3,000	2,485	2,660
Cl	2,750	2,750	3,500	3,750	3,125	3,250
SO ₄	2,360	3,030	3,290	3,060	3,045	2,820
Total A.	846	814	811	804	813	761
HCO ₃	1,030	994	991	982	993	930
CO ₃	0.0	0.0	0.0	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	8.0
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	76.0	41.0	54	10.3	48.0	72.0
Pb	26.0	11.0	13.0	6.0	12.0	27.0
pH	6.5	---	6.9	7.2	6.9	7.1
Se	3	---	---	2	2	---
Temp.	9.7	8.0	12.0	10.0	---	11.0
Turb.	25.0	2.0	85.0	112	---	3.0
Zn	144	67.0	76.0	79.0	78.0	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- \bar{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	9,810	9,905	11,600	11,600	9,580	9,080
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.	2,460	2,420	3,540	3,550	2,560	2,320
K	31.7	32.6	37.5	39.5	29.5	28.5
Na	2,780	2,720	3,130	2,930	2,510	2,510
Cl	3,250	3,250	4,250	4,650	3,250	3,250
SO ₄	2,480	2,650	2,610	2,370	2,390	1,970
Total A.	781	771	819	814	914	939
HCO ₃	954	942	1,000	994	1,110	1,140
CO ₃	0.0	0.0	0.0	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	64.0	67.9	70.0
As	9.6	8.8	7.0	13.0	14.0	9.1
Ba	110	290	240	190	310	90.0
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	7.0	17.0	78.0	25.0	10.0	21.0
pH	7.4	7.3	6.3	---	6.8	7.1
Se	2	2	3	---	---	2
Temp.	10.0	---	10.0	8.0	11.0	10.0
Turb.	25.0	---	4.0	23.0	5.0	12.0
Zn	69.0	92.0	124	138	88.0	50.0
SAR	24.3	24.0	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- \bar{X}	\bar{X}	6/29/81	10/12/81	\bar{X}	6/29/81	10/12/81
Cond.	15,750	13,800	9,400	12,100	4,040	4,060
TDS	10,590	9,670	6,640	8,155	3,610	6,640
Fe	1.1	0.60	0.68	0.64	0.10	0.26
Mn	10.6	5.43	3.59	4.51	0.88	0.8
Ca	663	487	281	384	148	126
Mg	335	245	155	200	77.0	71.0
Total H.	3,050	2,220	1,340	1,780	688	607
K	33.5	32.7	22.9	27.8	19.4	15.7
Na	2,720	2,590	2,080	2,335	973	944
Cl	3,750	3,250	1,750	2,500	13.0	10.0
SO ₄	2,380	2,610	1,880	2,245	1,890	1,640
Total A.	867	748	764	756	804	829
HCO ₃	1,055	914	933	924	982	1,010
CO ₃	0.0	0.0	0.0	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	0.0	8.0	11.0	4.6
Ba	215	450	20.0	235	460	40.0
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	61.0	56.0	9.4	32.7	50.0	10.0
Pb	23.0	12.0	10.0	11.0	14.0	4.0
pH	6.7	7.0	7.2	7.1	7.1	7.2
Se	2	---	2	2	---	2
Temp.	---	11.0	10.0	---	11.0	10.0
Turb.	---	3.0	6.0	---	5.0	3.0
Zn	106	65.0	38.0	52.0	78.0	30.0
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- \bar{X}	\bar{X}	6/29/81	10/12/81	\bar{X}	6/29/81	10/12/81
Cond.	4,050	3,680	3,710	3,695	5,220	5,430
TDS	5,125	3,310	2,980	3,145	5,040	4,820
Fe	0.18	0.07	0.22	0.15	0.14	0.13
Mn	0.84	0.69	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	1,260	1,350
Cl	12.0	10.0	10.0	10.0	18.0	20.0
SO ₄	1,765	1,670	1,440	1,555	2,930	2,650
Total A.	817	843	808	826	874	841
HCO ₃	996	1,030	987	1,009	1,060	1,020
CO ₃	0.0	0.0	0.0	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	70.0	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	22.0	47.0	10.3
Pb	9.0	---	5.0	5.0	5.0	3.0
pH	7.2	7.0	7.1	7.1	7.3	7.3
Se	2	---	2	2	---	2
Temp.	---	10.0	10.0	---	10.0	10.0
Turb.	---	1.0	4.0	---	1.0	2.0
Zn	54.0	37.0	34.0	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- \bar{X}	\bar{X}	6/29/81	10/12/81	\bar{X}	1/7/81
Cond.	5,325	5,300	5,080	5,190	1,700
TDS	4,930	4,820	4,370	4,590	1,200
Fe	0.14	0.25	0.08	0.17	0.09
Mn	1.57	1.03	0.83	0.93	0.02
Ca	181	161	118	140	1.5
Mg	90.0	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	1,305	1,260	1,370	1,315	477
Cl	19.0	18.0	3.0	11.0	6.0
SO ₄	2,790	2,760	2,280	2,520	169
Total A.	858	847	863	855	903
HCO ₃	1,040	1,030	1,050	1,040	1,060
CO ₃	0.0	0.0	0.0	0.0	17.0
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	0.0	4.0	---
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.	---	10.0	10.0	---	11.0
Turb.	---	1.0	1.0	---	1.0
Zn	64.0	45.0	27.0	36.0	---
SAR	19.8	20.3	25.4	22.4	73.9
NO ₃	2	2	2	2	2.0

APPENDIX D-IV

RESULTS OF QUARTERLY WATER SAMPLING FROM INSTRUMENT STATIONS AT TEXACO CHARLSON MADISON (NORTH) UNIT #C133 SITE

<u>Instrument Number</u>	<u>Sampling Date</u>			
	<u>9/3/81</u>	<u>1/7/81</u>	<u>6/8/81</u>	<u>10/6/81</u>
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- \bar{X}	6/8/81	10/6/81	\bar{X}	6/8/81	10/6/81	\bar{X}
Cond.	5,480	5,410	5,445	5,540	5,420	5,480
TDS	5,040	4,970	5,035	4,940	4,680	4,810
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.	1,680	2,070	1,785	1,750	2,360	2,055
K	23.3	21.9	22.6	31.9	27.7	29.8
Na	843	899	871	785	747	766
Cl	63.0	23.0	43.0	35.0	40.0	38.0
SO ₄	3,040	2,790	2,915	2,930	2,490	2,710
Total A.	683	753	718	614	647	631
HCO ₃	834	920	877	750	790	770
CO ₃	0.0	0.0	0.0	0.0	0.0	0.0
F	0.3	0.3	0.3	0.3	0.2	0.3
% Na	52.0	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	18.0	2.0	10.0
Cr	2.5	4.2	3.3	5.9	2.3	4.1
Cu	90.0	26.2	58.1	237	35.0	136
Pb	8.0	6.0	7.0	22.0	5.0	14.0
pH	6.9	6.7	6.8	7.0	6.7	6.9
Se	---	2	2	---	2	2
Temp.	10.0	9.0	9.5	10.0	9.0	10.0
Turb.	1.0	3.0	2.0	1.0	3.0	2.0
Zn	94.0	112	103	181	86.0	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- \bar{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	6,980	8,930	7,830	7,913	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	1,240
Total H.	2,800	3,770	3,820	3,467	4,020	6,790
K	21.2	31.3	21.2	24.6	26.7	54.7
Na	1,580	1,980	1,890	1,817	2,830	5,050
Cl	68.0	60.0	70.0	66.0	1,750	4,150
SO ₄	3,220	3,960	2,960	3,380	4,420	8,520
Total A.	542	642	554	580	598	678
HCO ₃	663	784	677	708	731	828
CO ₃	0.0	0.0	0.0	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	6.0	12.0	1.1	6.4	15.0	28.0
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	74.0	164	160
Pb	18.0	5.0	5.0	9.3	20.0	85.0
pH	6.4	---	6.5	6.5	6.6	---
Se	260	---	2	2	272	---
Temp.	9.0	6.0	9.0	8.0	11.0	6.0
Turb.	3.0	2.0	2.0	2.0	5.0	5.0
Zn	99.0	75.0	82.0	85.0	132	160
SAR	12.9	14.0	13.3	13.4	19.4	26.6
NO ₃	861	1,310	1,310	1,160	496	1,140

Sta.	D ₅	D ₇	D ₈	D ₈	D ₈	D ₉
Date- \bar{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	6,100	19,000	15,500	26,200	20,850	21,600
Fe	0.73	0.25	0.18	0.32	0.25	0.0
Mn	0.68	0.13	0.78	0.66	0.72	0.2
Ca	593	575	700	1,000	850	725
Mg	954	705	855	1,390	1,123	647
Total H.	5,405	4,330	5,260	8,210	6,735	4,470
K	40.7	34.2	37.7	36.0	36.9	18.2
Na	3,940	5,970	4,430	7,470	5,950	2,810
Cl	2,950	10,000	7,500	12,500	10,000	3,750
SO ₄	6,470	1,170	1,440	3,160	2,300	3,970
Total A.	638	829	775	972	874	485
HCO ₃	780	1,010	947	1,180	1,064	593
CO ₃	0.0	0.0	0.0	0.0	0.0	0.0
F	0.3	0.0	0.1	0.0	0.1	0.3
% Na	61.0	74.8	64.5	66.3	65.4	57.6
As	22.0	18.5	16.0	26.5	21.3	29.0
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	53.0	35.0	17.0	33.0	25.0	63.0
pH	6.6	6.4	7.0	6.2	6.6	6.5
Se	272	2	---	2	2	136
Temp.	9.7	13.0	10.0	12.0	11.0	10.0
Turb.	---	15.0	3.0	4.0	3.5	11.0
Zn	146	120	77.0	111	94.0	454
SAR	23.0	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- \bar{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	9,260	19,000
TDS	15,100	14,000	14,600	14,300	6,040	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	1,070
Total H.	5,810	5,090	5,680	5,385	2,220	6,150
K	28.8	24.1	18.0	21.2	20.2	33.0
Na	3,540	3,180	3,610	3,360	1,490	3,470
Cl	5,100	4,750	5,000	4,875	950	4,600
SO ₄	3,920	3,770	3,510	3,845	2,450	5,270
Total A.	480	490	466	483	283	571
HCO ₃	587	599	570	590	346	698
CO ₃	0.0	0.0	0.0	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	12.0	24.0	15.3	19.7	6.0	18.0
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	73.0	69.0	50.8	71.0	124	114
Pb	106	8.0	8.0	36.0	9.0	79.0
pH	---	6.6	5.7	6.3	6.5	---
Se	---	---	2	2	132	---
Temp.	8.0	11.0	10.0	10.0	11.0	7.0
Turb.	2.0	3.0	4.0	4.0	15.0	3.0
Zn	124	171	275	223	94.0	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- \bar{X}	10/6/81	\bar{X}	9/3/80	1/7/81	6/8/81	10/6/81
Cond.	15,100	14,453	7,590	6,400	6,670	6,220
TDS	10,600	10,880	4,760	5,390	5,010	4,900
Fe	0.14	0.32	0.04	0.23	0.04	0.09
Mn	0.07	0.46	0.64	0.88	0.53	0.51
Ca	450	531	407	442	451	450
Mg	635	659	237	225	235	235
Total H.	3,730	4,033	1,990	2,030	2,090	2,090
K	22.2	25.1	17.5	26.3	25.3	19.2
Na	2,810	2,590	995	905	1,040	890
Cl	2,500	2,683	775	700	750	875
SO ₄	3,340	3,687	1,950	2,710	2,150	2,070
Total A.	535	463	479	530	490	475
HCO ₃	654	566	585	648	599	580
CO ₃	0.0	0.0	0.0	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	8.0	17.0	9.0	0.0
Ba	100	200	180	90.0	310	60.0
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	58.0	52.0	80.0	43.9
Pb	5.0	31.0	26.0	43.0	3.0	3.0
pH	6.5	6.5	6.6	---	7.2	6.4
Se	2	2	28.0	---	---	2.0
Temp.	10.0	9.3	9.0	7.0	11.0	9.0
Turb.	2.0	6.7	5.0	2.0	0.0	3.0
Zn	104	129	61.0	56.0	104	66.0
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- \bar{X}	\bar{X}	9/3/80	1/7/81	6/8/81	10/6/81	\bar{X}
Cond.	6,535	5,430	4,200	4,160	3,970	4,180
TDS	4,955	3,880	4,370	3,570	3,480	3,725
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.	2,060	1,740	1,830	1,540	1,730	1,735
K	22.3	22.7	22.7	19.5	16.7	21.1
Na	950	600	606	521	528	564
Cl	763	225	125	95.0	100	113
SO ₄	2,110	2,090	2,680	2,140	1,960	2,115
Total A.	485	405	445	437	437	437
HCO ₃	592	495	544	534	534	534
CO ₃	0.0	0.0	0.0	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	11.0	4.0	4.0	5.0	1.3	4.0
Ba	135	180	180	450	50.0	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	53.0	64.0	37.0	44.0	17.3	41.0
Pb	15.0	17.0	---	18.0	4.0	18.0
pH	6.7	6.5	---	7.4	6.5	6.8
Se	---	27.0	---	---	2.0	---
Temp.	9.0	10.0	7.0	10.0	8.0	9.0
Turb.	3.0	2.0	1.0	0.0	2.0	2.0
Zn	64.0	58.0	45.0	114	73.0	66.0
SAR	9.2	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- \bar{X}	6/8/81	10/6/81	\bar{X}
Cond.	5,320	4,280	4,300
TDS	4,120	3,230	3,675
Fe	0.02	0.07	0.05
Mn	1.55	1.48	1.52
Ca	412	375	394
Mg	132	127	130
Total H.	1,570	1,460	1,515
K	37.9	28.0	33.0
Na	709	624	667
Cl	425	350	388
SO ₄	2,100	1,420	1,760
Total A.	420	382	401
HCO ₃	514	467	491
CO ₃	0.0	0.0	0.0
F	0.4	0.3	0.4
% Na	49.3	48.0	49.0
As	5.0	3.0	4.0
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	44.0	3.0	23.5
pH	7.4	6.6	7.0
Se	---	2	---
Temp.	9.0	8.0	90.0
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

APPENDIX D-V

ELUTRIATION EXPERIMENT SEDIMENT SAMPLES FROM STUDY SITES

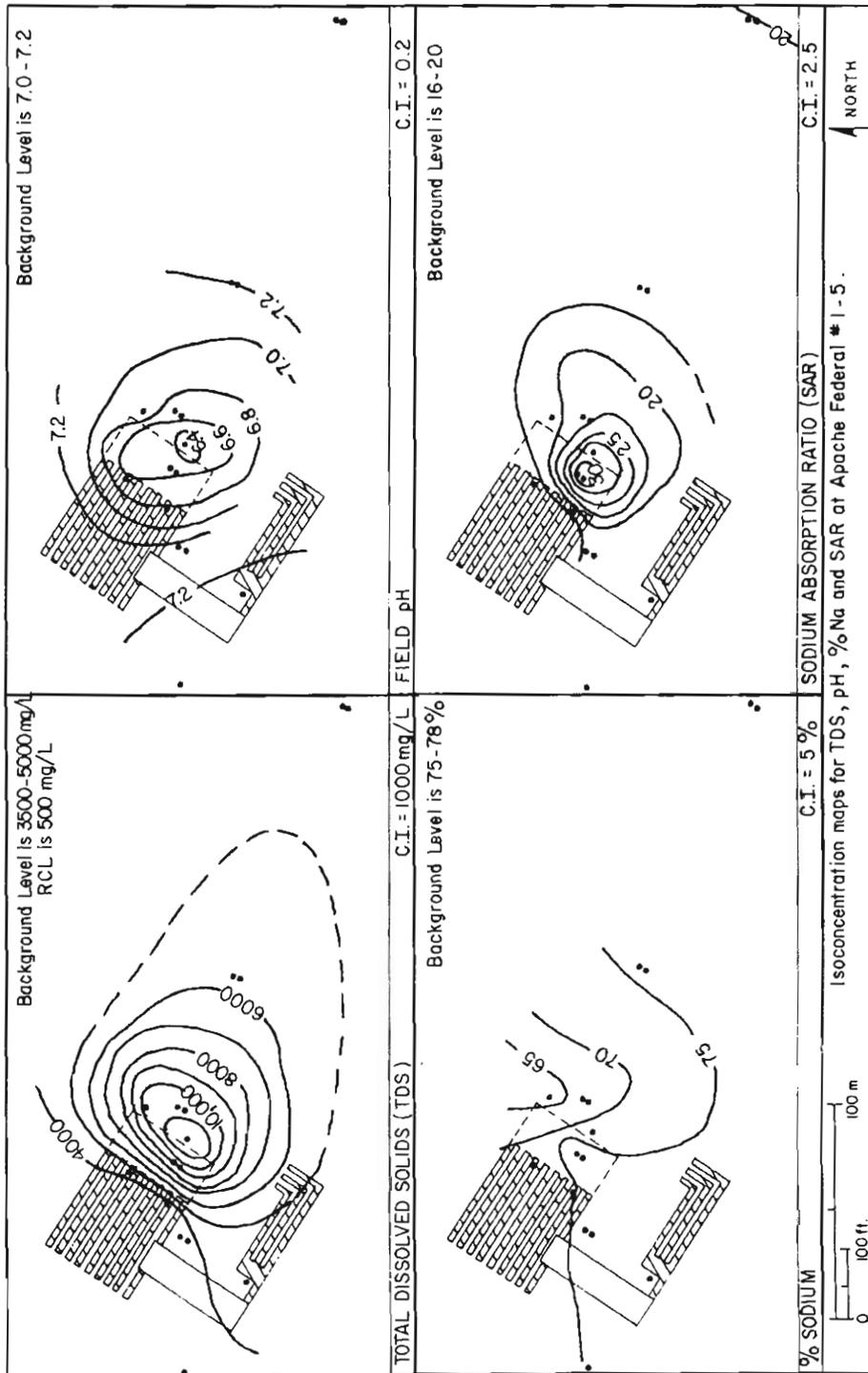
<u>Sample No.</u>	<u>Study Site</u>	<u>Depth from Surface</u>
E1	Texaco Gov't. "A" (NCT-1) #1	8.0 ft. (2.4 m)
E2	Texaco Gov't. "A" (NCT-1) #1	11.5 ft. (3.5 m)
E3	Texaco Gov't. "A" (NCT-1) #1	14.5 ft. (4.4 m)
E4	Texaco Gov't. "A" (NCT-1) #1	22.3 ft. (6.8 m)
E5	Texaco Gov't. "A" (NCT-1) #1	33.5 ft. (10.2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

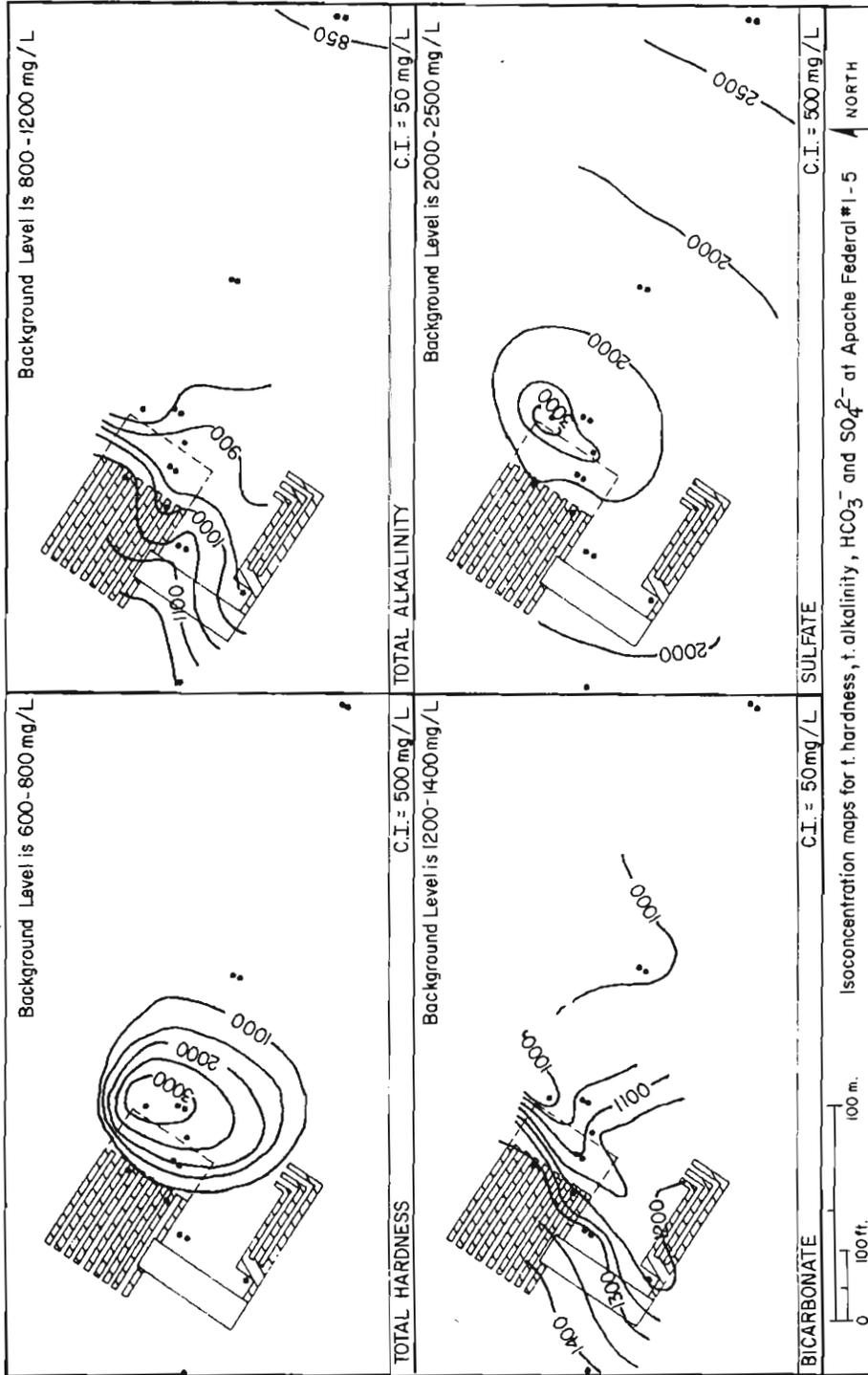
Sta. Date- \bar{X}	E ₁	E ₂	E ₃	E ₄	E ₅	E ₆
Cond.	3,160	2,420	1,420	4,474	411	369
TDS	2,450	1,300	833	2,540	334	264
Fe	0.07	1.01	0.06	0.22	0.65	7.04
Mn	0.77	0.21	0.1	0.06	0.04	0.14
Ca	388	36.5	66.5	52.5	4.5	6.5
Mg	13.0	10.0	16.5	13.0	2.0	6.5
Total H.	1,020	132	234	184	19.0	43.0
K	25.8	19.5	6.45	11.7	3.3	3.85
Na	328	457	222	947	102	104
Cl	650	720	340	1,380	6.0	5.0
SO ₄	1,010	24.0	151	92.0	179	23.0
Total A.	43.0	54.0	43.0	63.0	60.0	187
HCO ₃	53.0	66.0	53.0	77.0	73.0	229
CO ₃	0.0	0.0	0.0	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	84.0
As	---	---	---	---	4.0	6.0
Ba	---	---	---	---	190	220
Cd	---	---	---	---	2.1	3.0
Cr	---	---	---	---	9.7	18.8
Cu	---	---	---	---	135	158
Pb	---	---	---	---	28.0	35.0
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

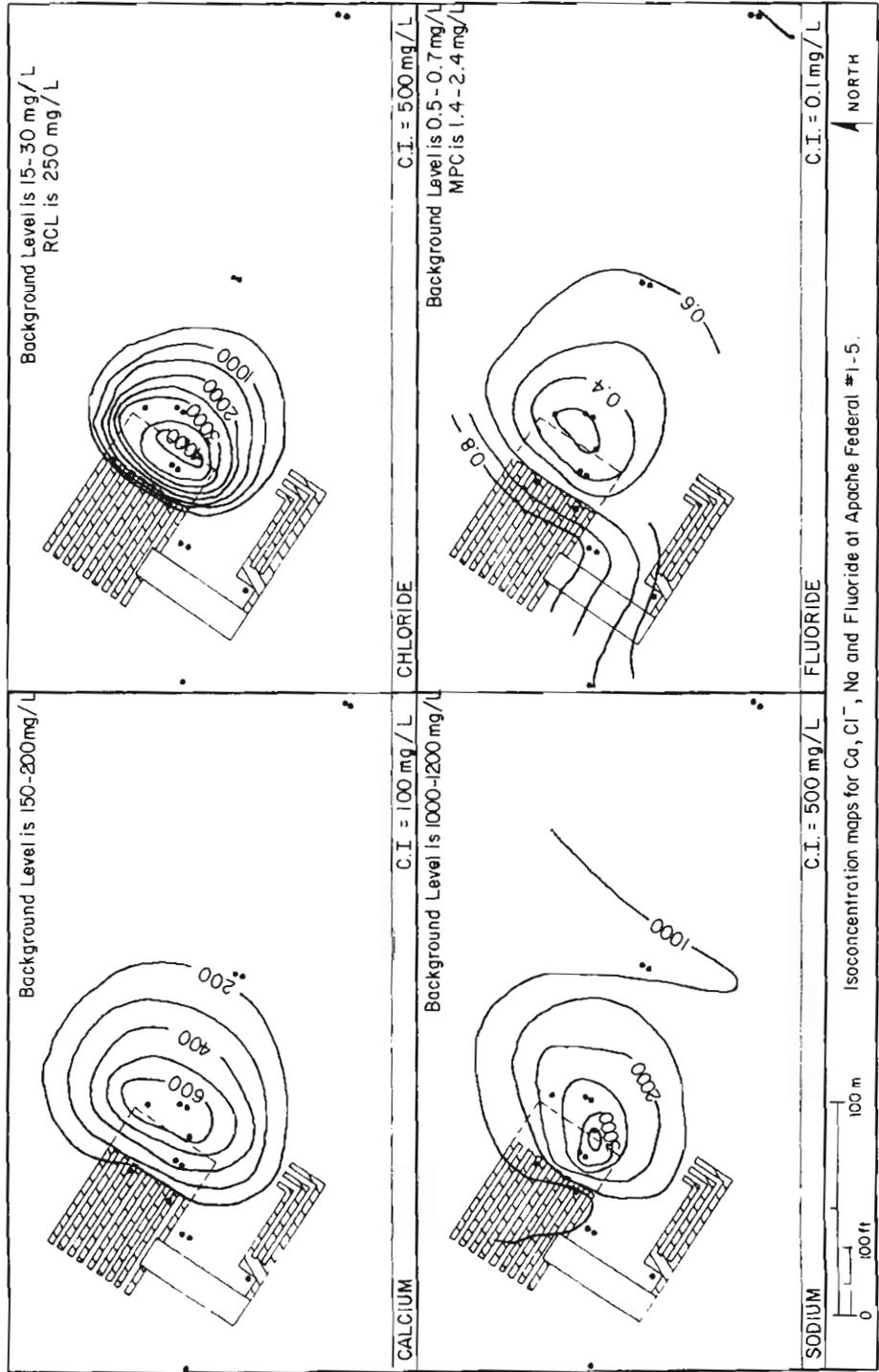
Sta. Date- \bar{X}	E ₇	E ₈	E ₉	E ₁₀	E ₁₁	E ₁₂
Cond.	1,380	1,830	2,620	675	800	253
TDS	797	1,150	1,230	371	542	143
Fe	0.04	0.1	10.7	6.84	2.59	0.04
Mn	0.08	0.02	0.14	0.12	0.04	0.01
Ca	51.0	8.0	13.0	14.0	8.0	8.0
Mg	16.0	1.0	6.0	6.0	3.0	5.5
Total H.	193	24.0	57.0	60.0	32.0	43.0
K	7.2	11.9	12.7	3.45	2.8	1.4
Na	212	390	473	135	164	45.0
Cl	290	350	590	5.0	64.0	48.0
SO ₄	186	291	45.0	88.0	250	7.0
Total A.	54.0	163	158	195	81.0	45.0
HCO ₃	66.0	200	179	235	99.0	55.0
CO ₃	0.0	0.0	7.0	2.0	0.0	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	0.0	11.0	8.0	0.0	0.0	---
Temp.	---	---	---	---	---	---
Turb.	1.0	1.0	35.0	4.0	15.0	3.0
Zn	24.0	30.0	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

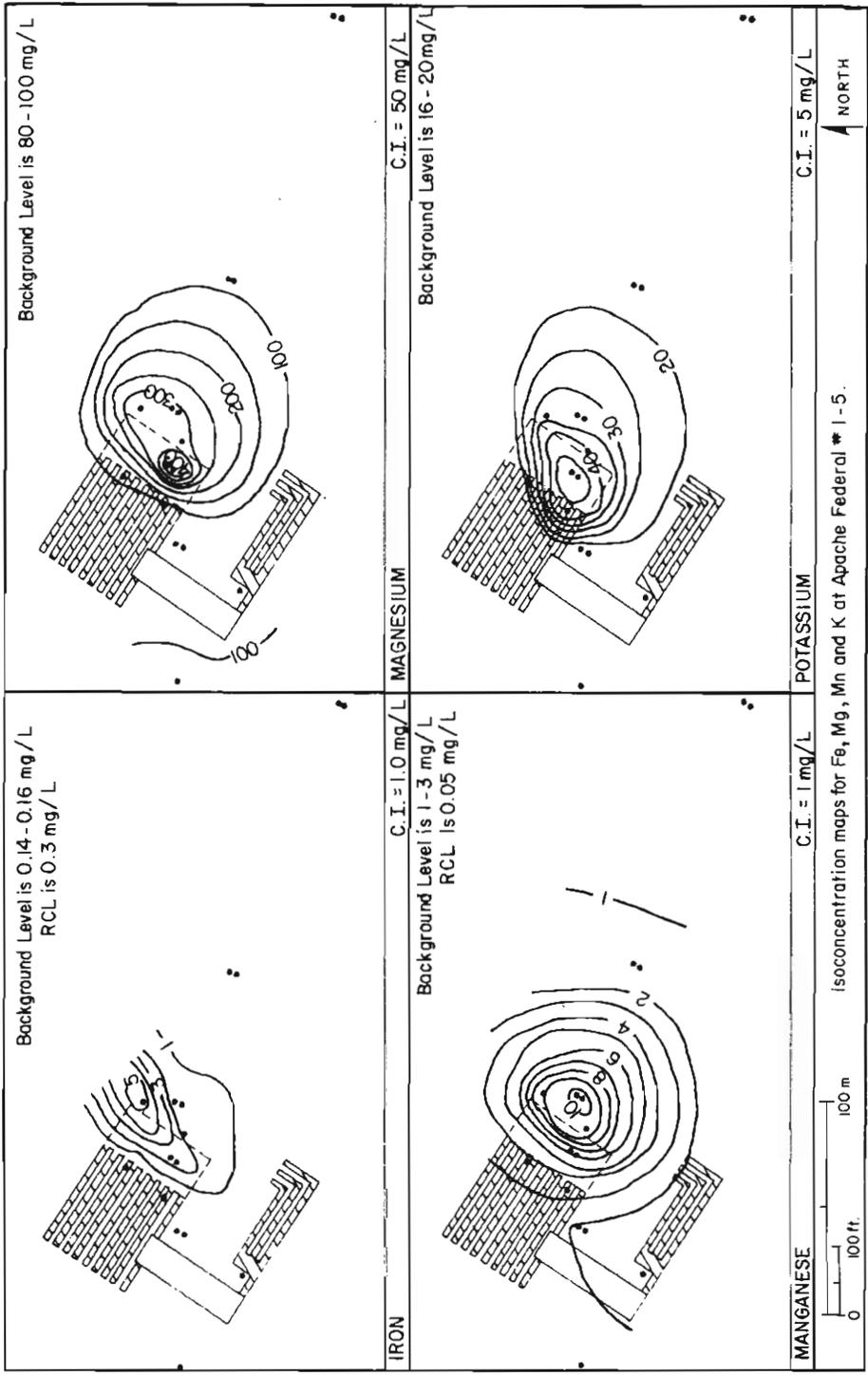
APPENDIX E

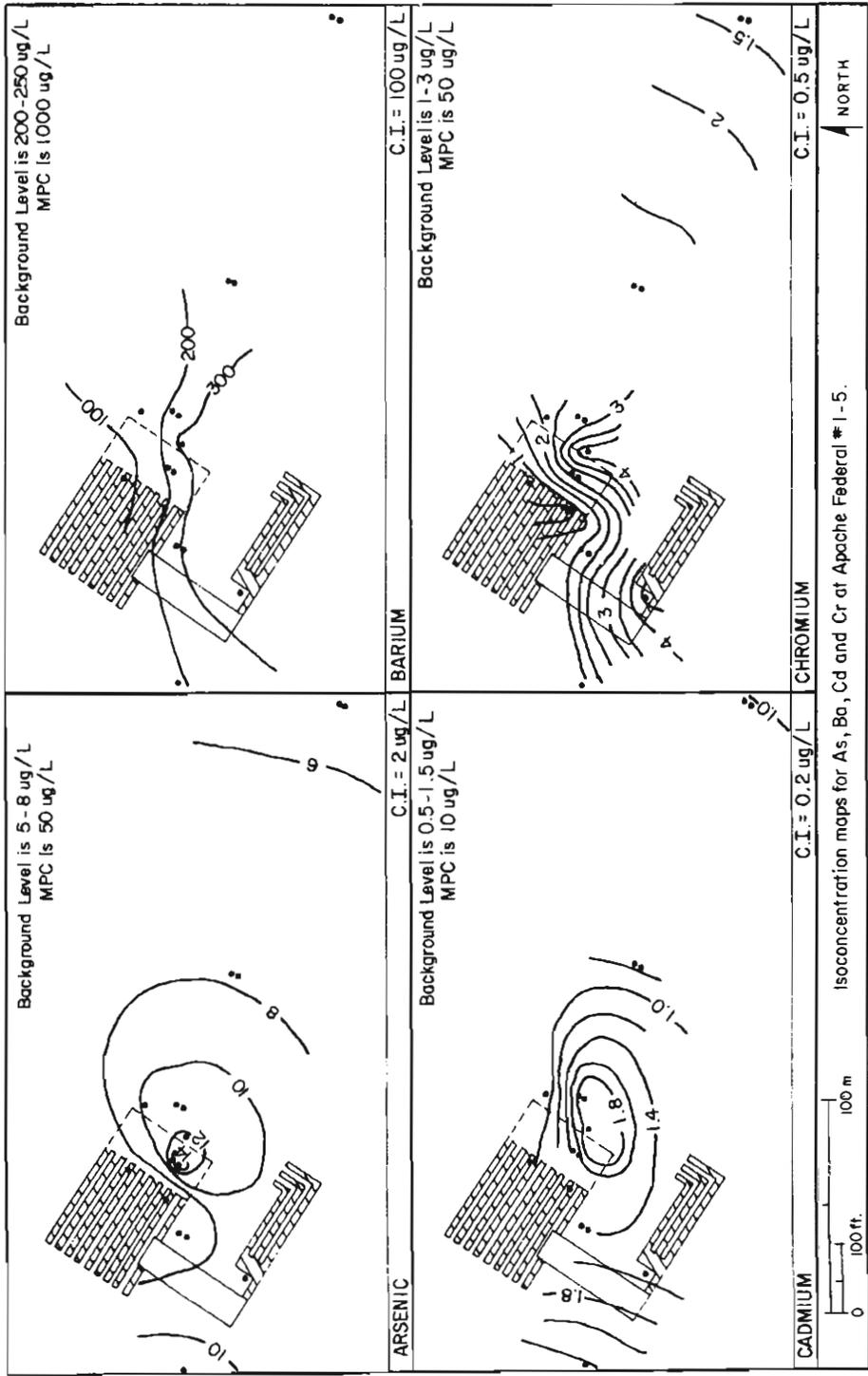
ISOCONCENTRATION MAPS OF SELECTED PARAMETERS FROM WITHIN
THE SATURATED ZONES AT THE APACHE FEDERAL #1-5
AND TEXACO CHARLSON MADISON (NORTH) UNIT #C133 SITES



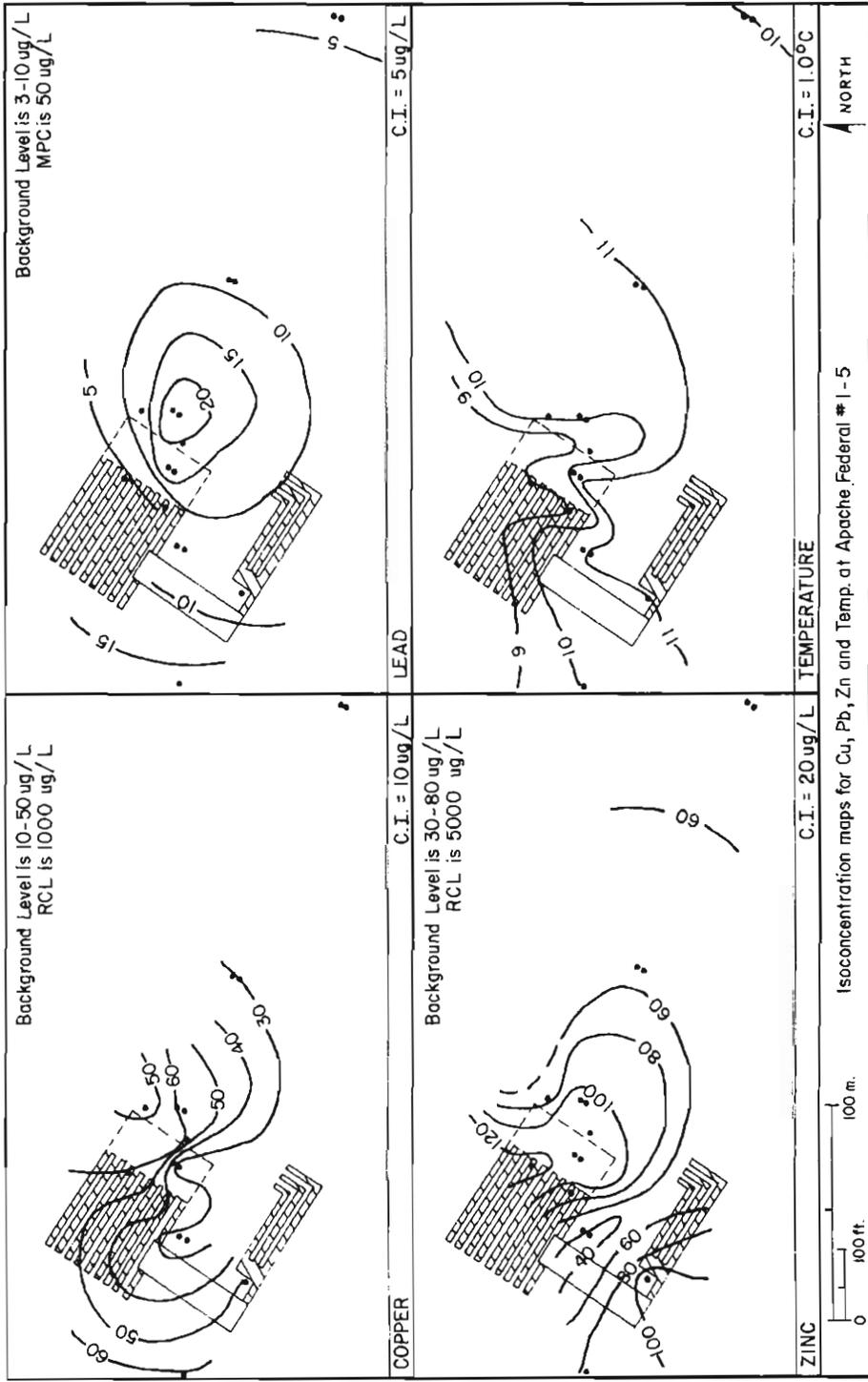


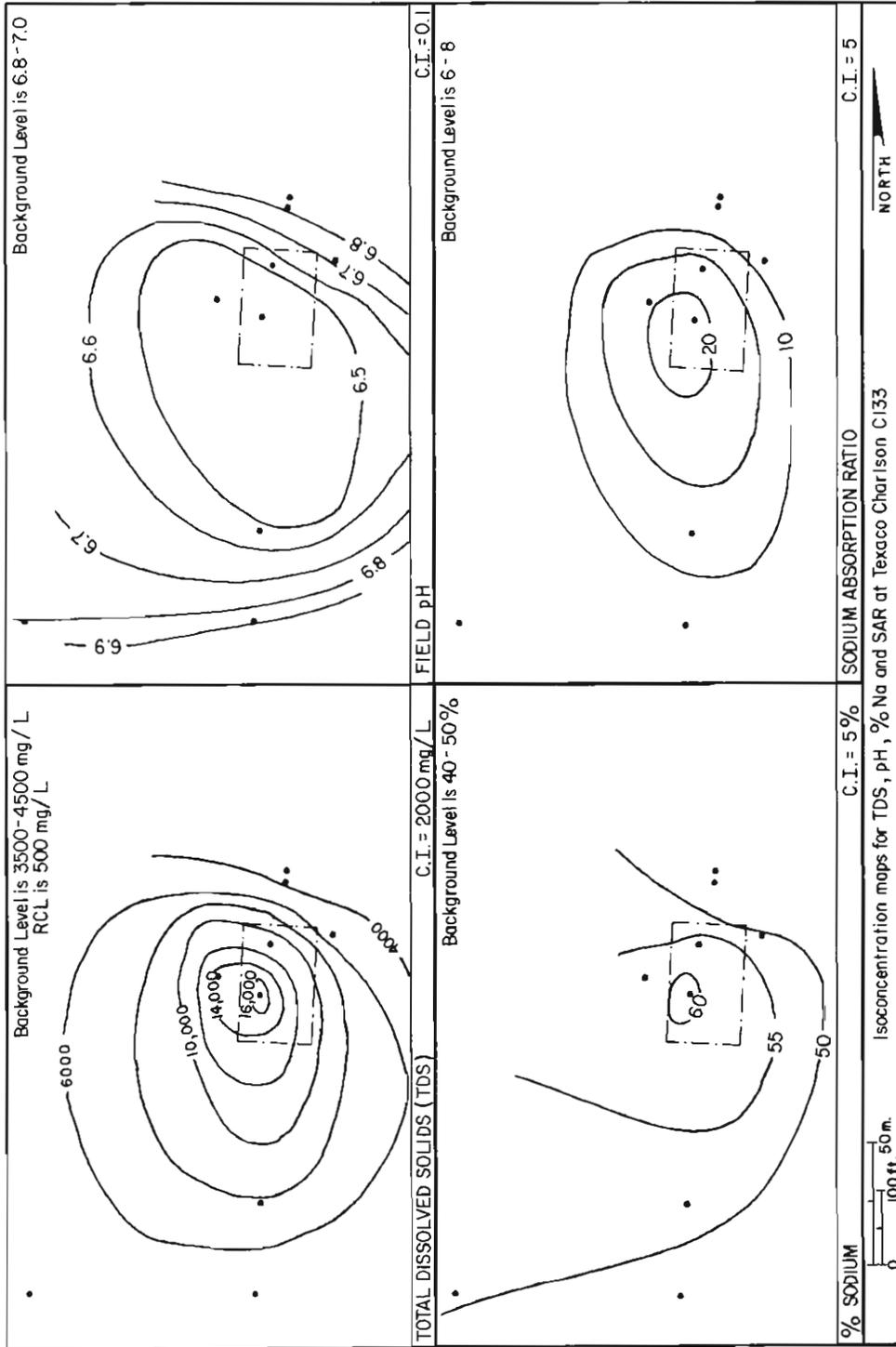


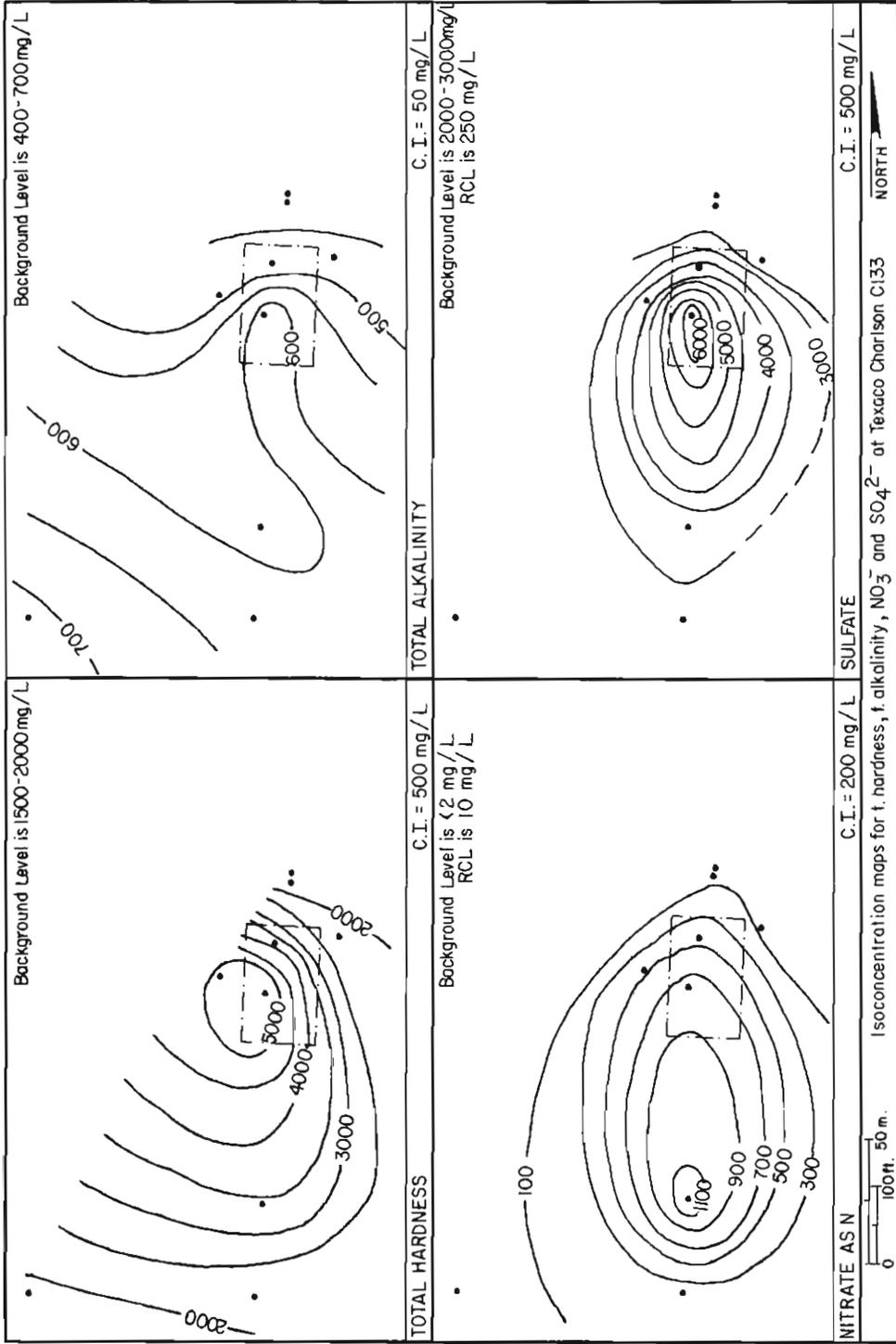


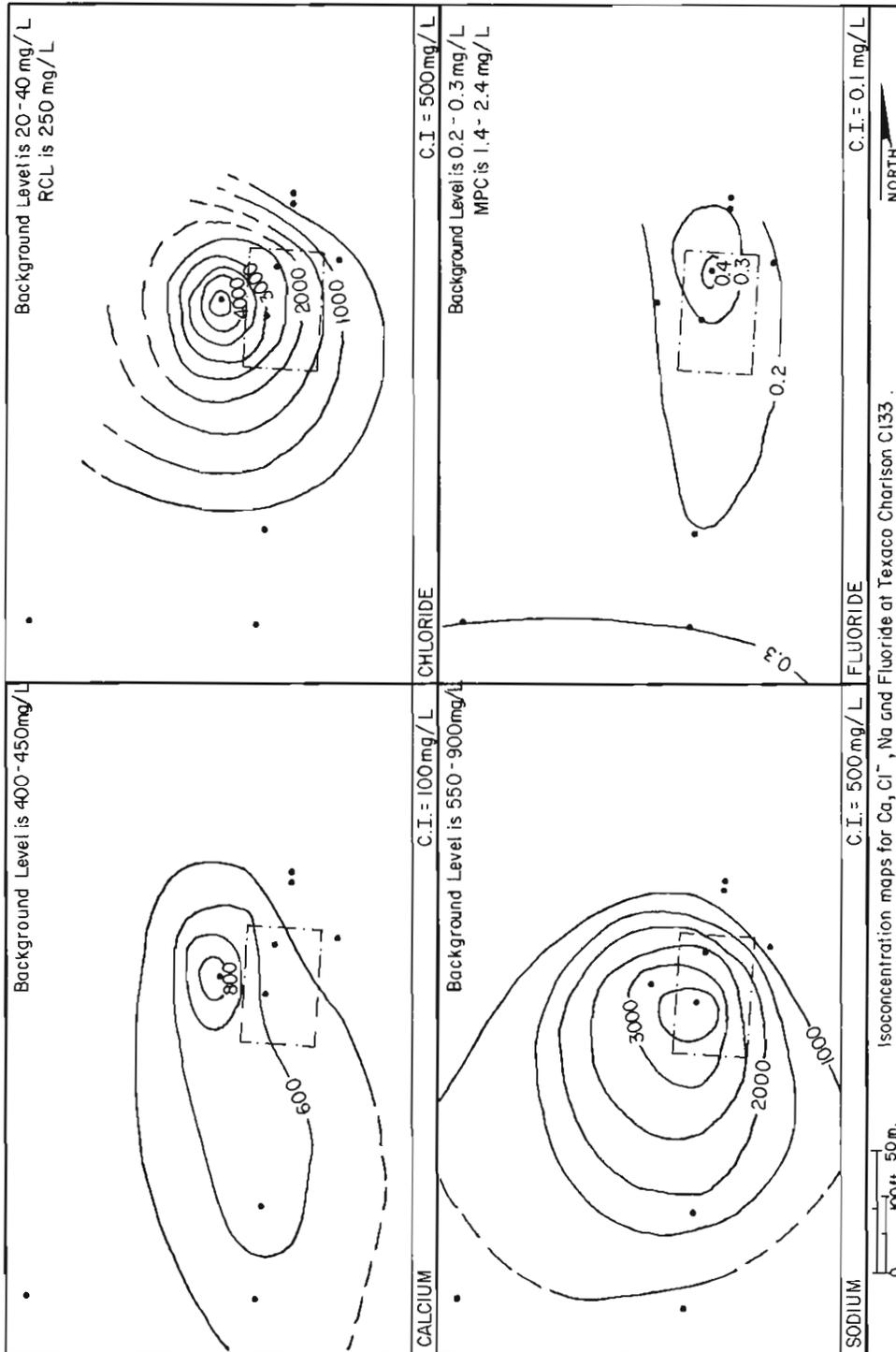


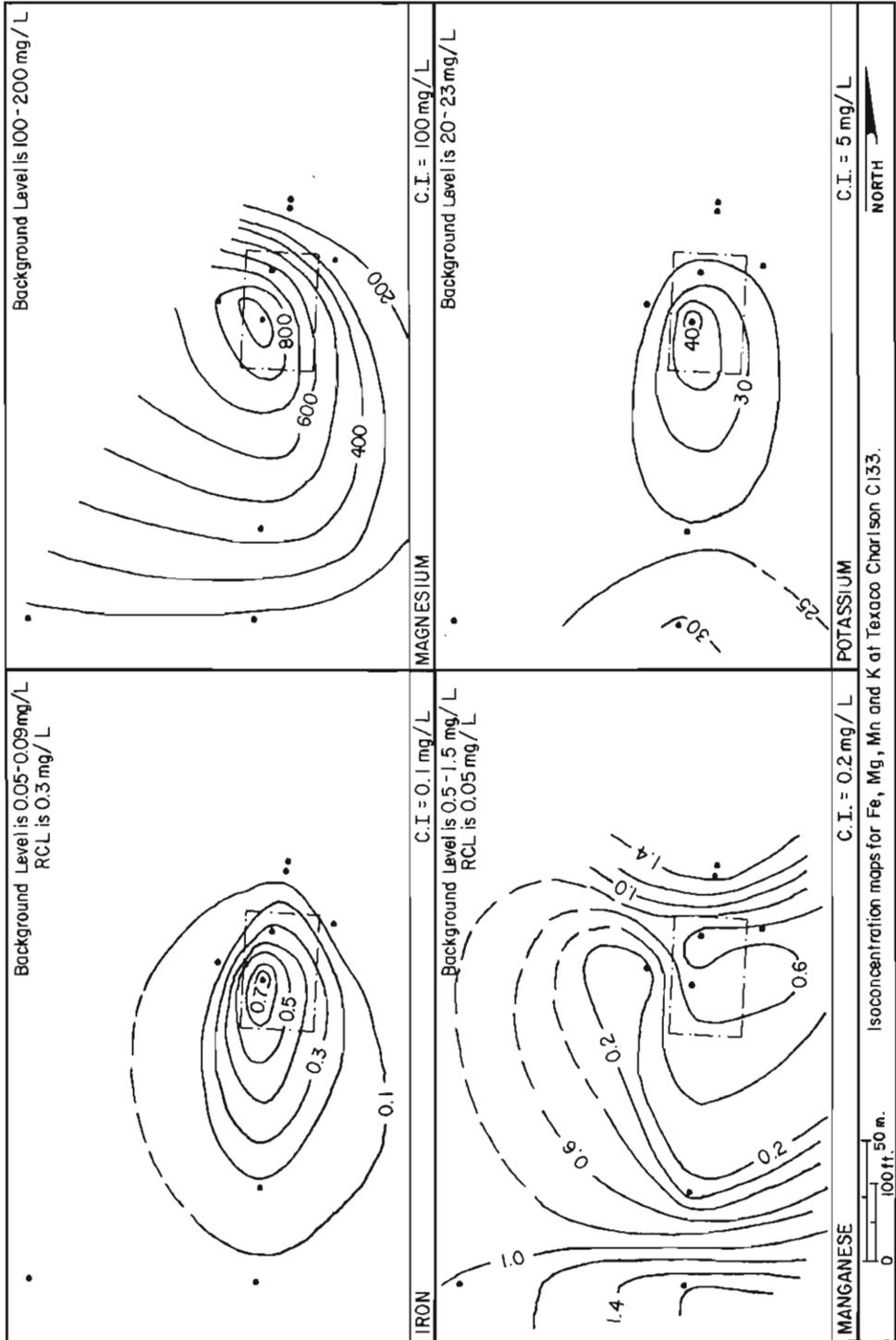
Isoconcentration maps for As, Ba, Cd and Cr at Apache Federal #1-5.

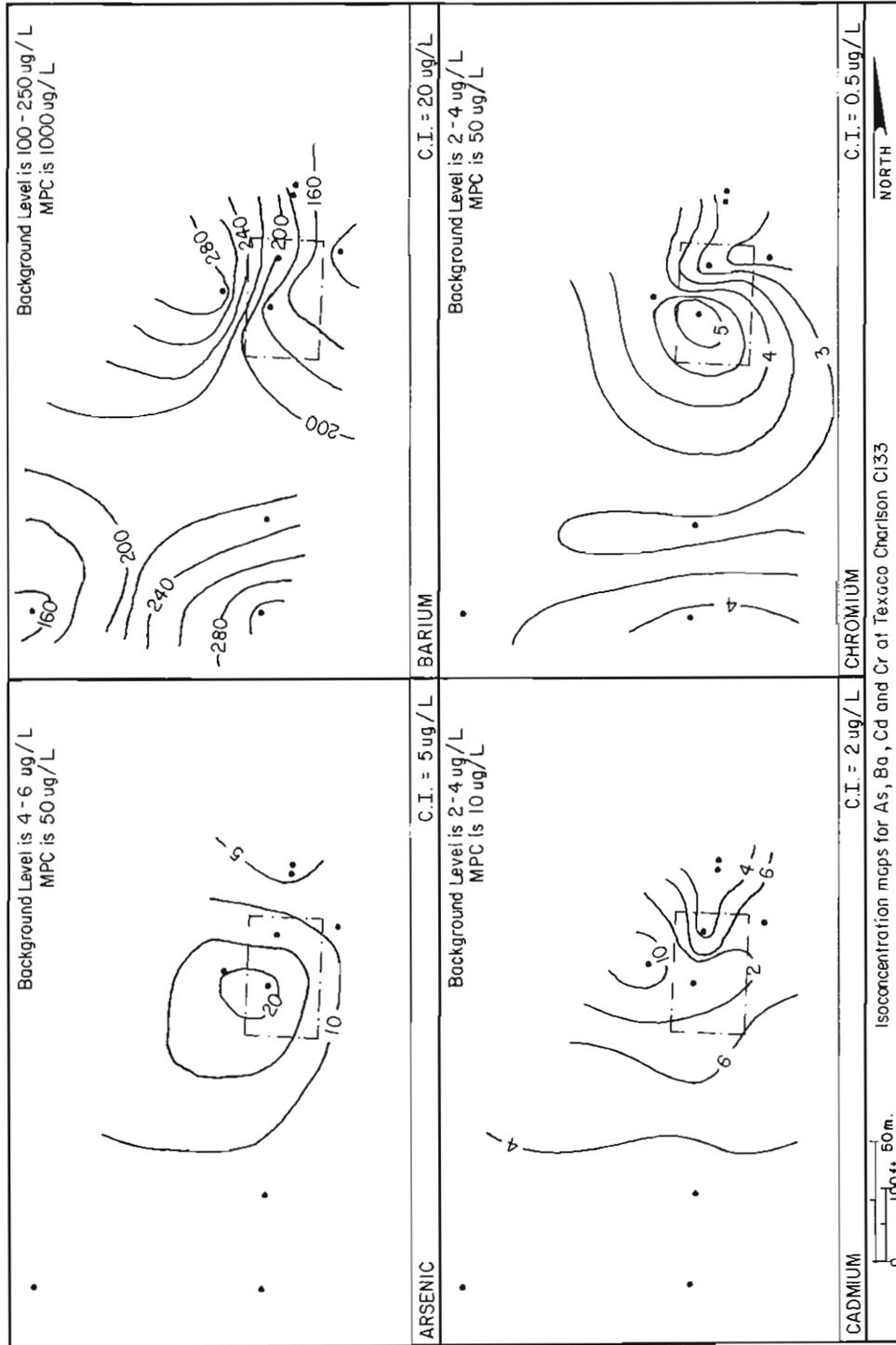


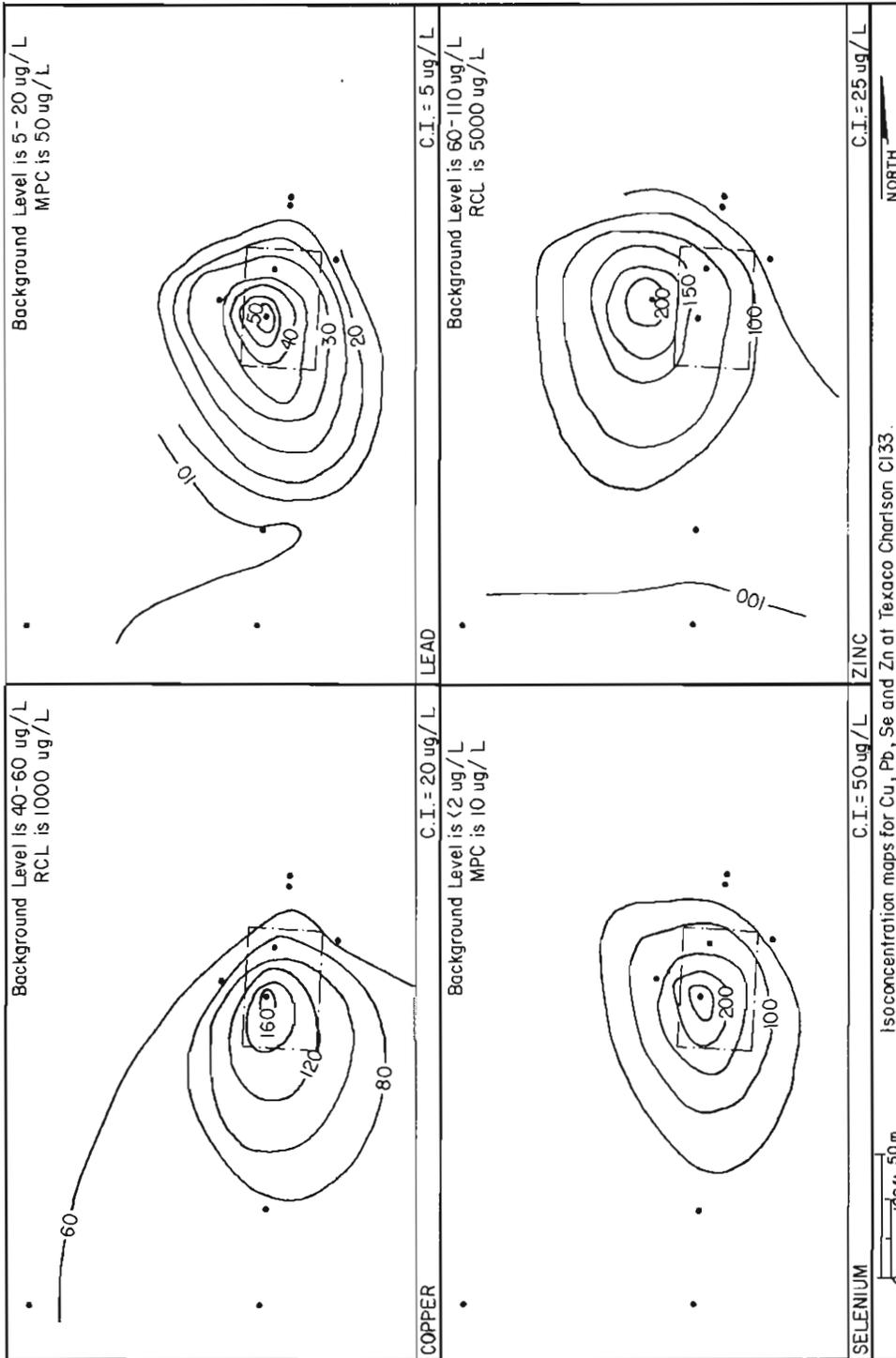








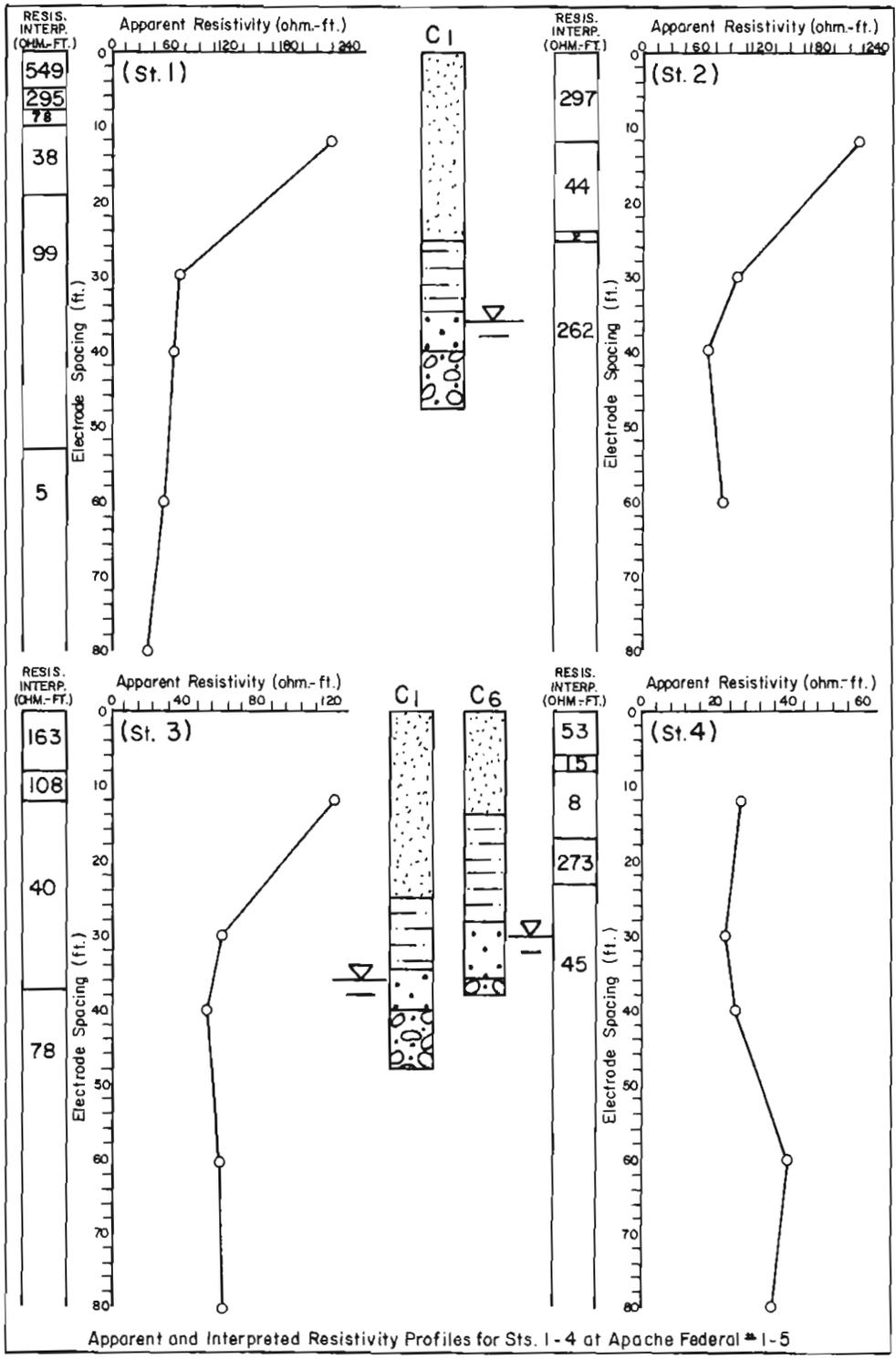




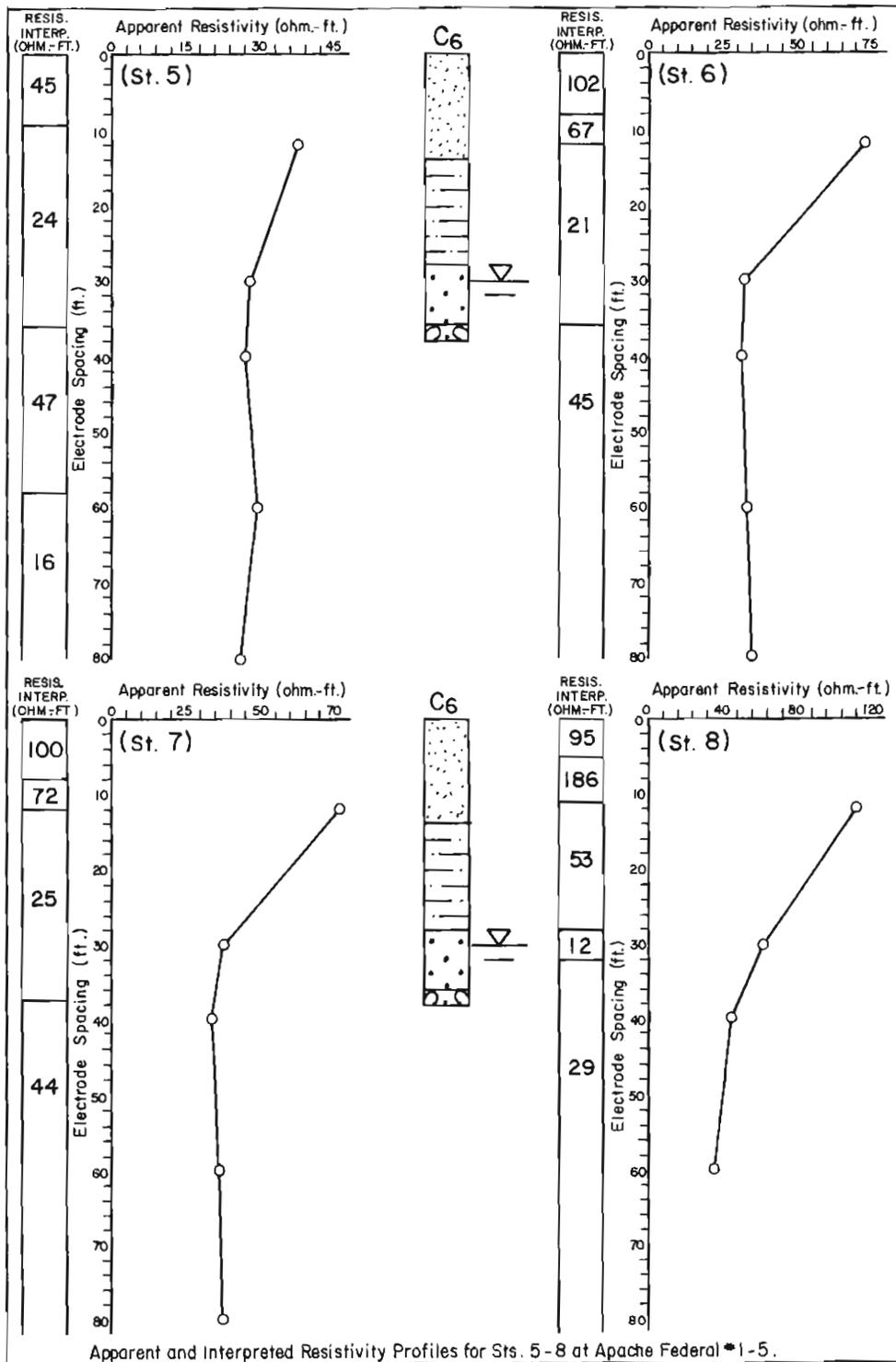
APPENDIX F

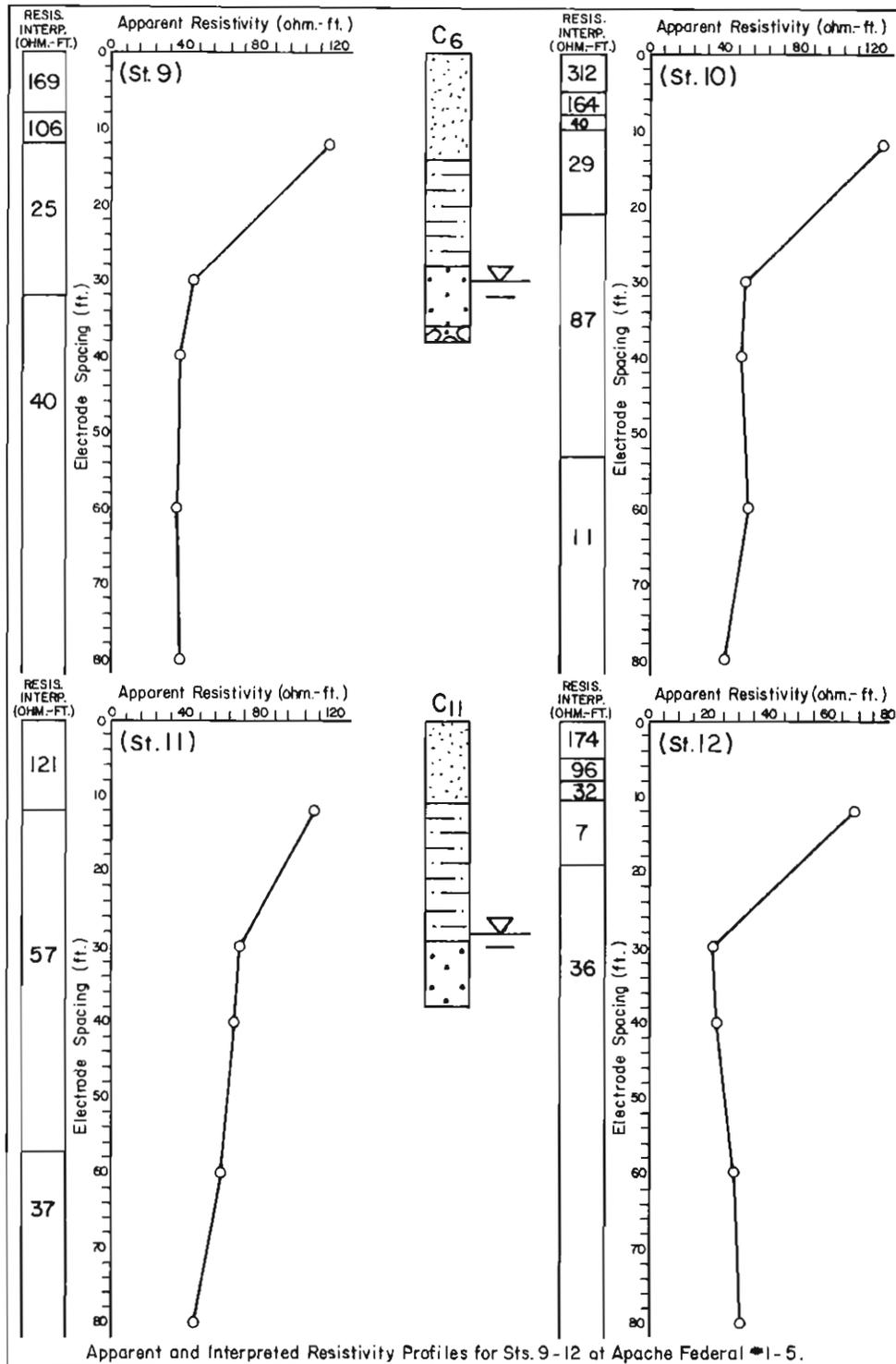
APPARENT AND INTERPRETED RESISTIVITY PROFILES FOR
THE APACHE FEDERAL #1-5 AND TEXACO CHARLSON
MADISON (NORTH) UNIT #C133 SITES

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°), 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.

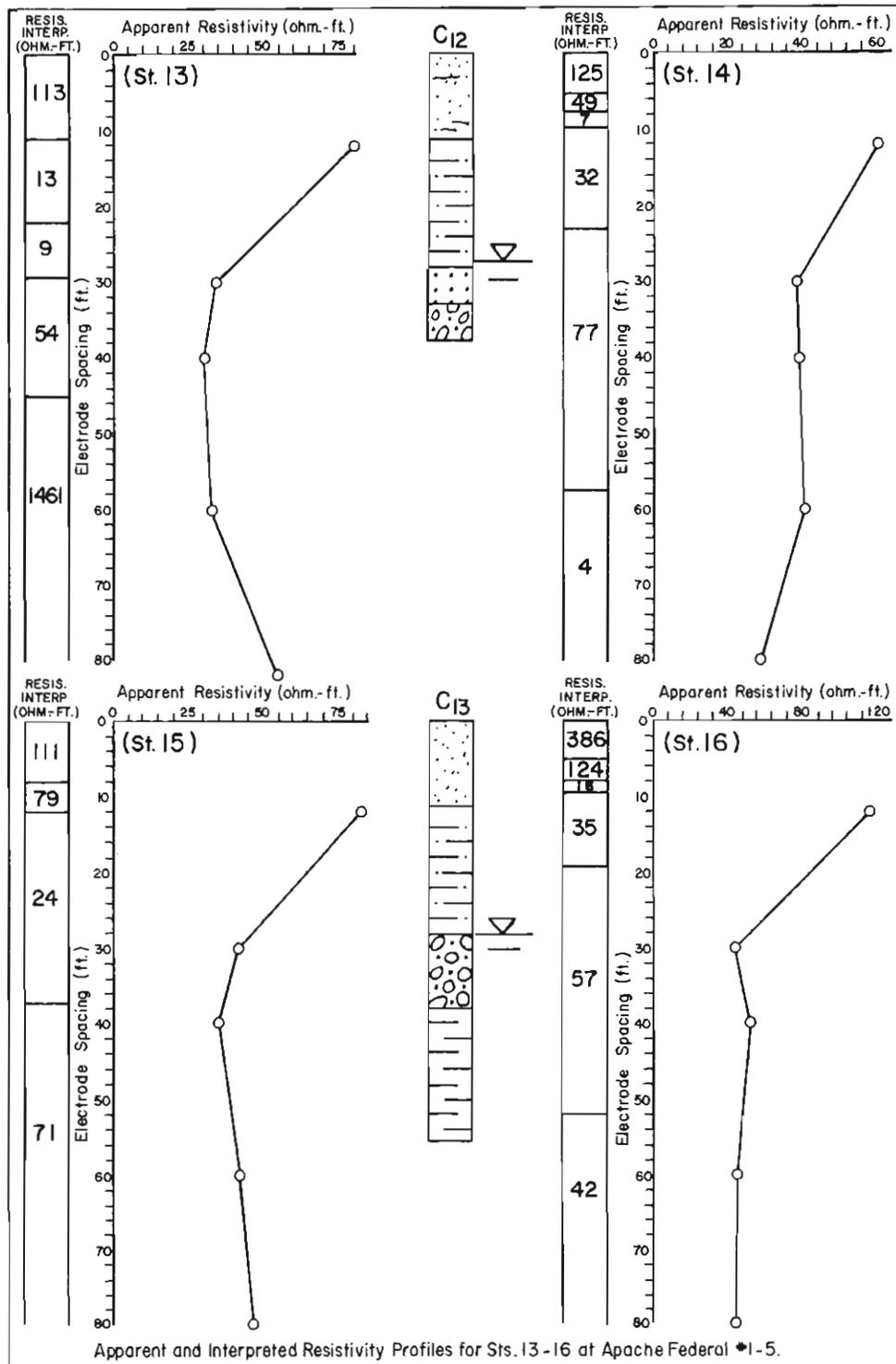


Apparent and Interpreted Resistivity Profiles for Sts. 1-4 at Apache Federal # 1-5

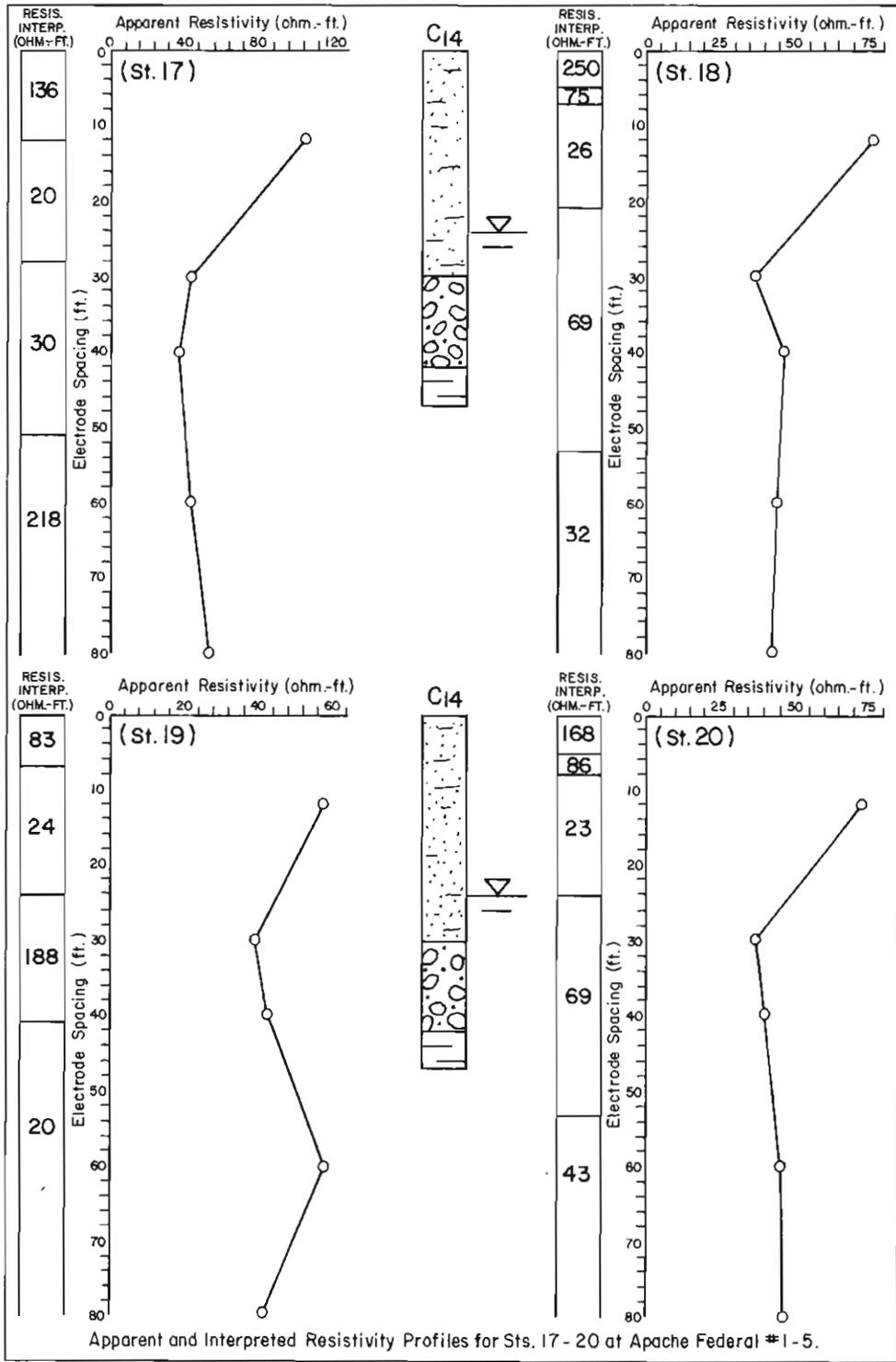




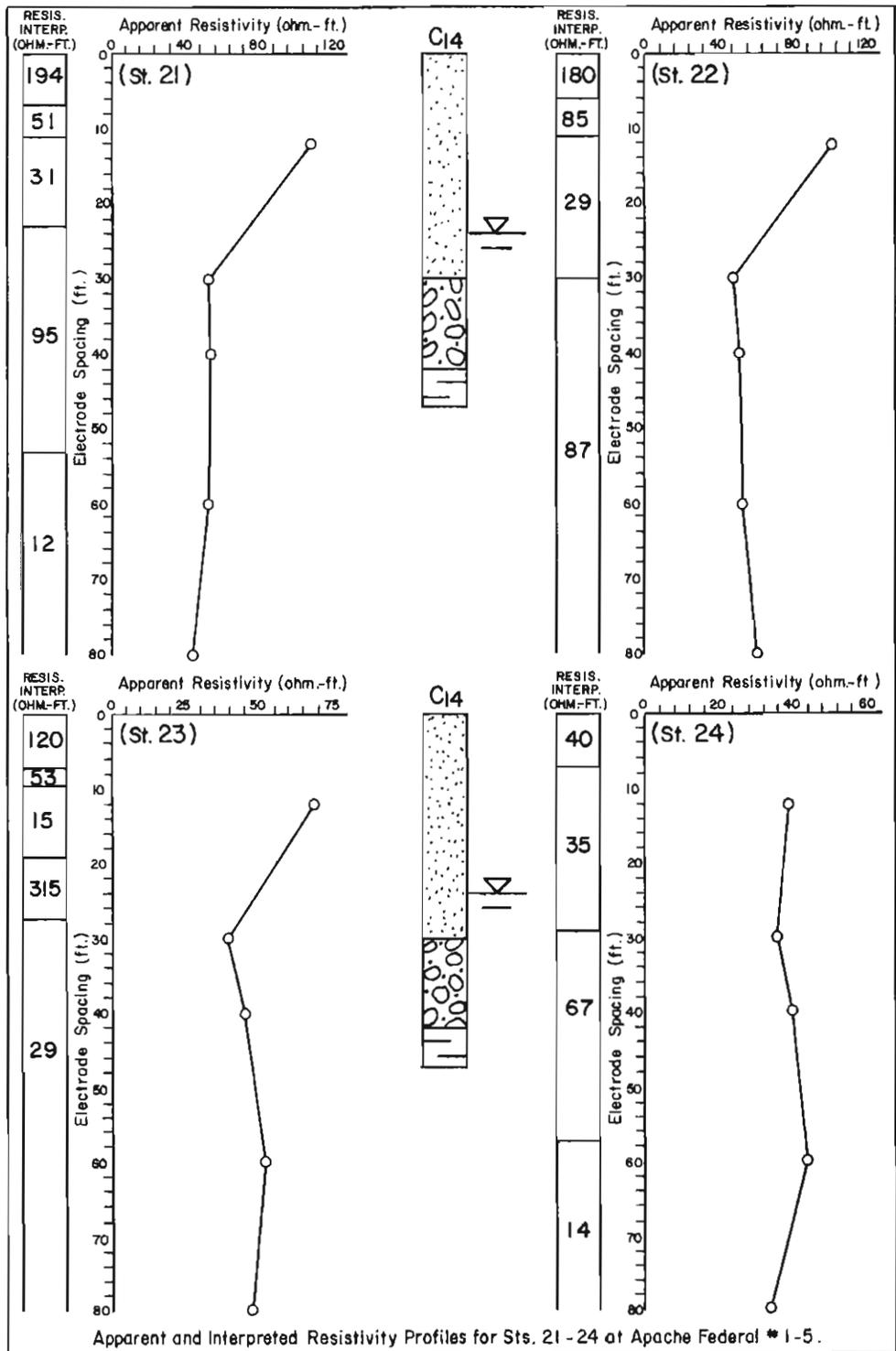
Apparent and Interpreted Resistivity Profiles for Sts. 9-12 at Apache Federal #1-5.

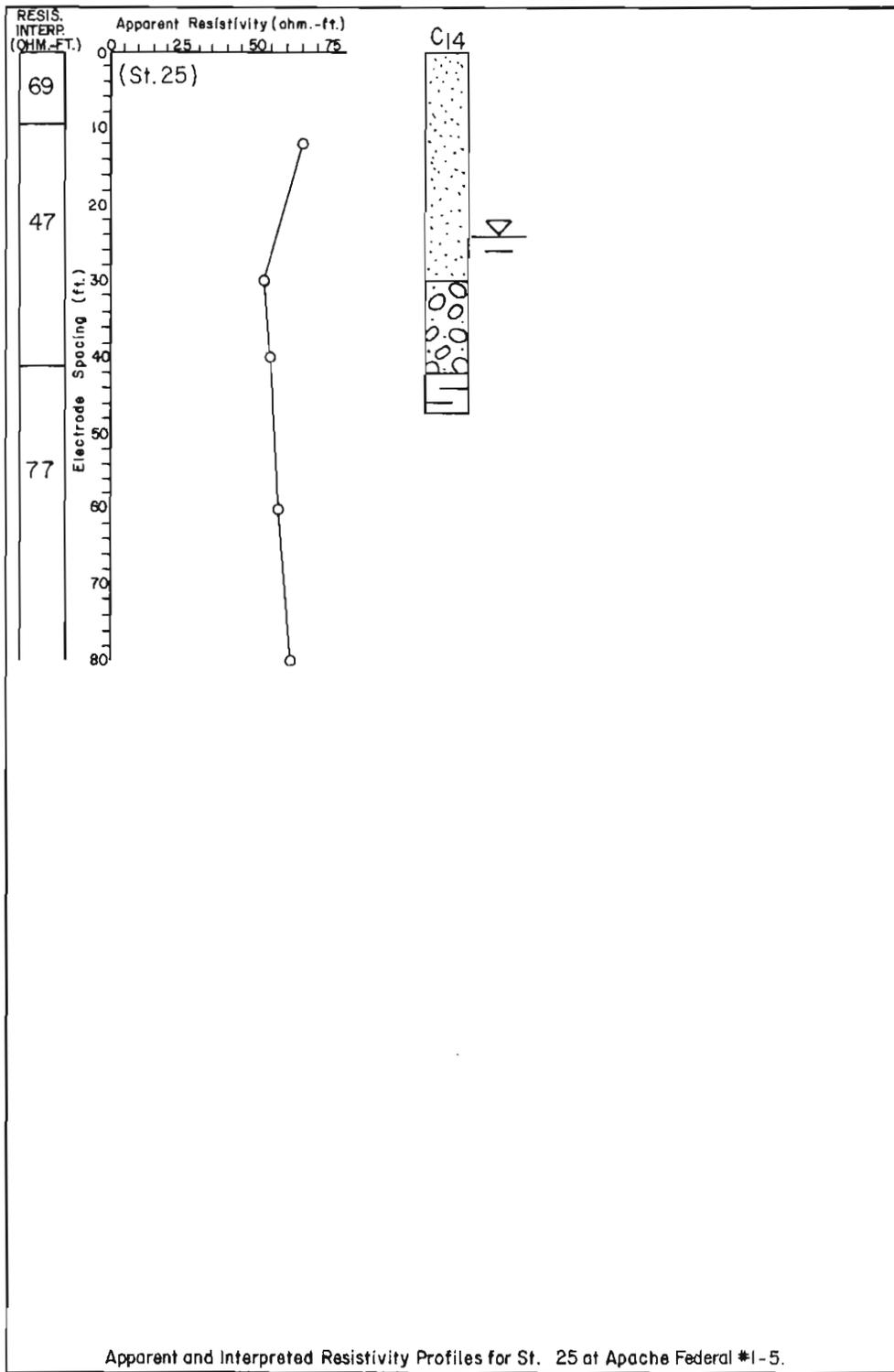


Apparent and Interpreted Resistivity Profiles for Sts. 13-16 at Apache Federal *1-5.

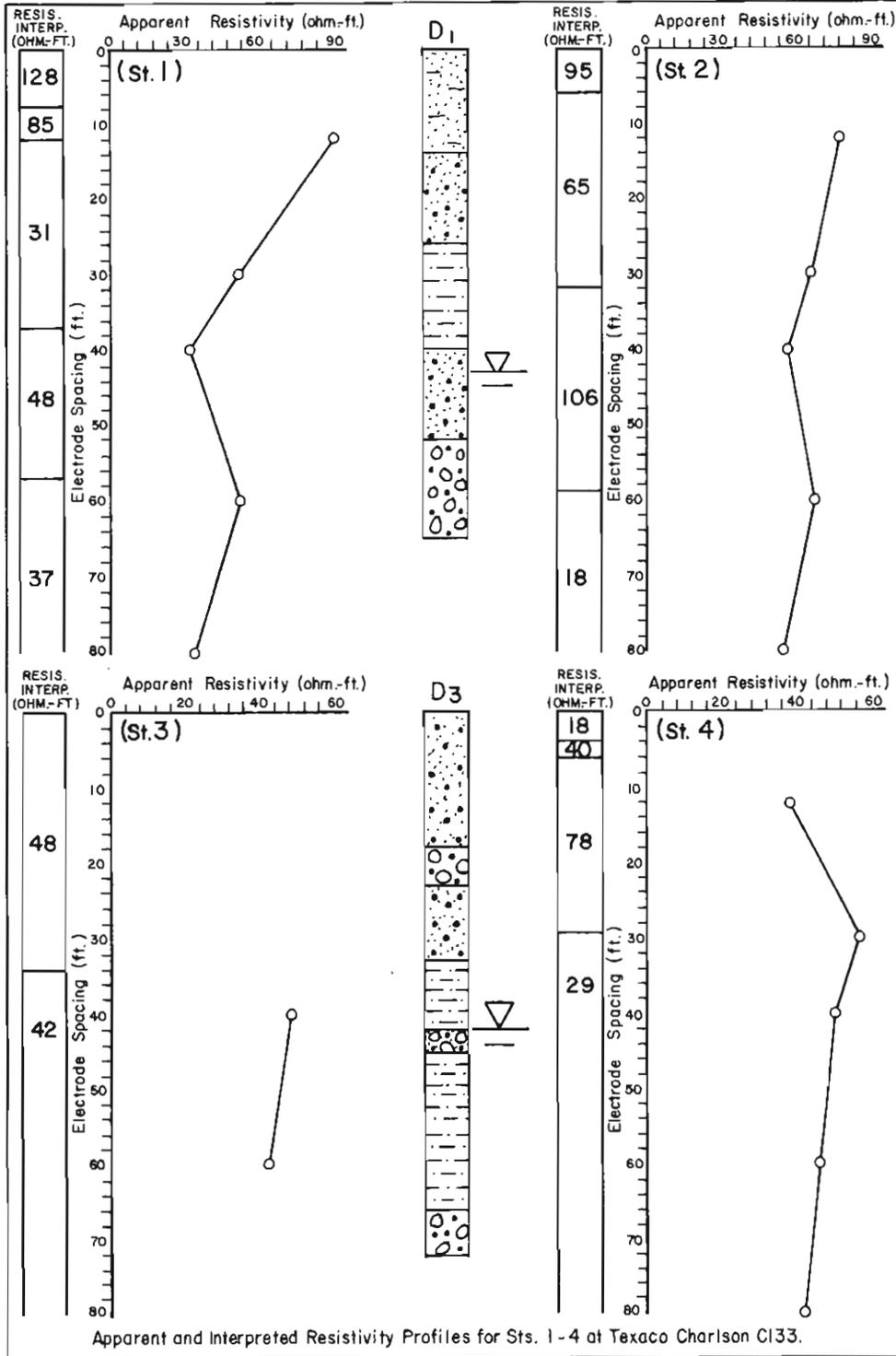


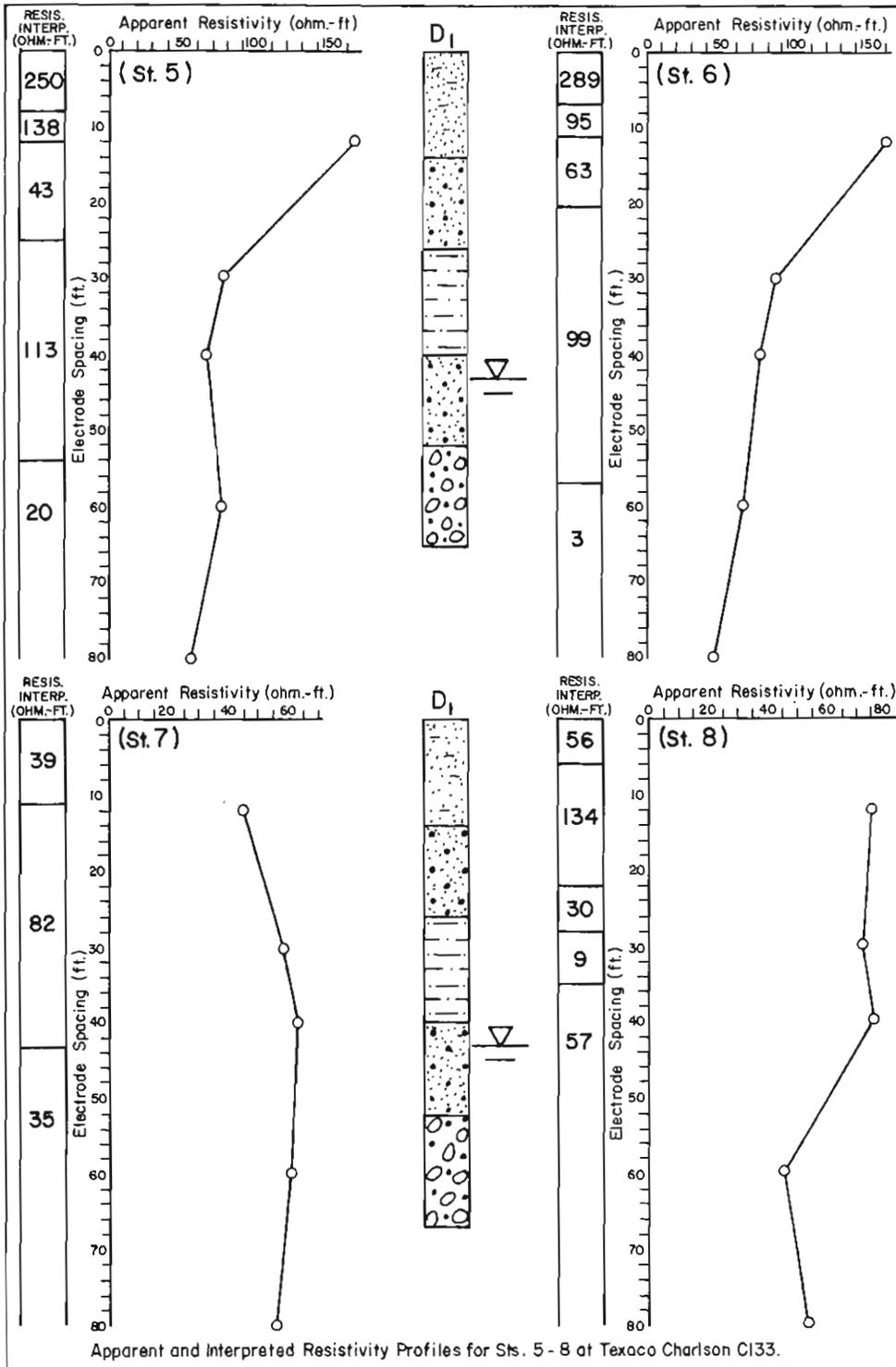
Apparent and Interpreted Resistivity Profiles for Sts. 17 - 20 at Apache Federal #1-5.

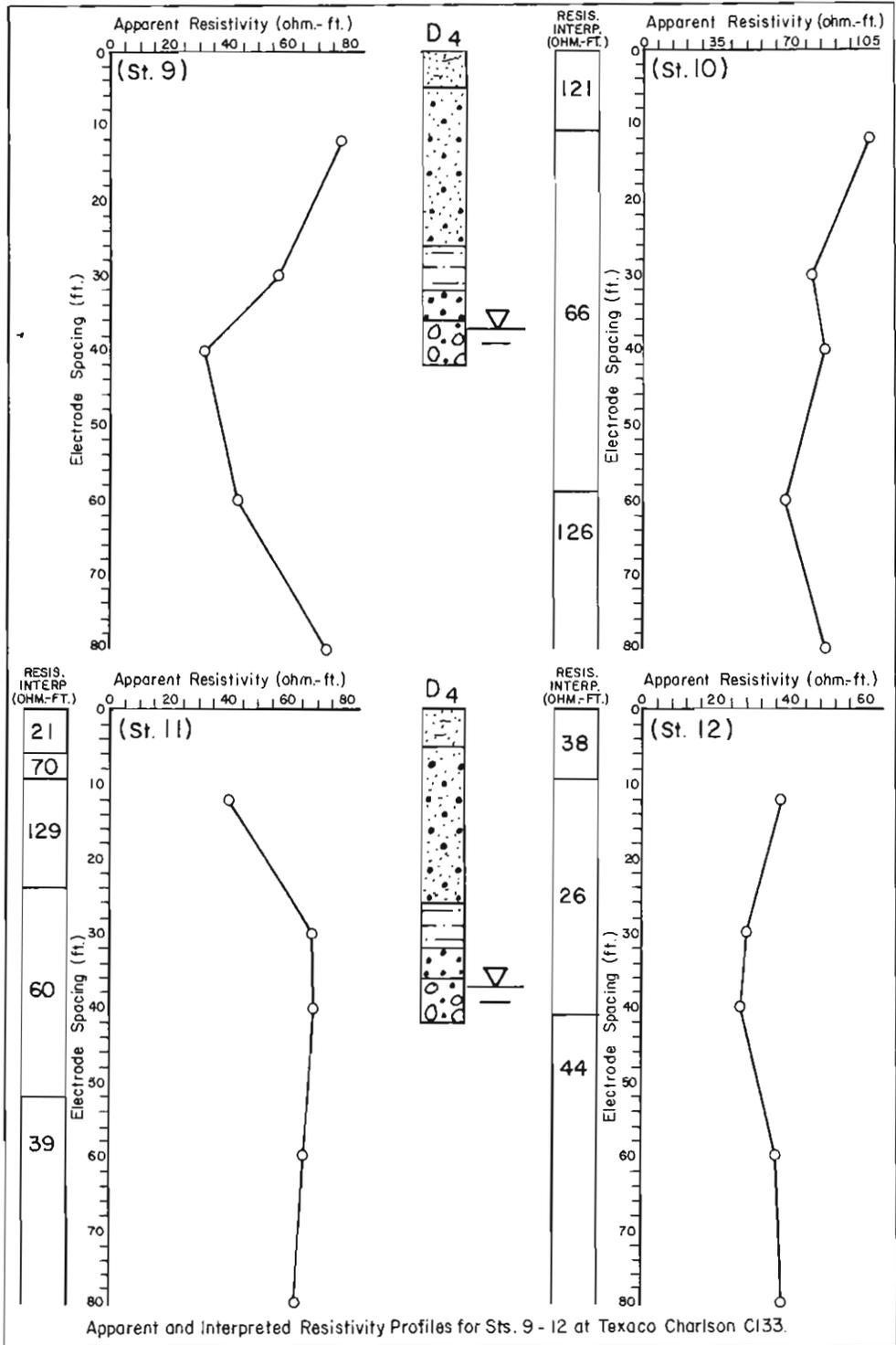




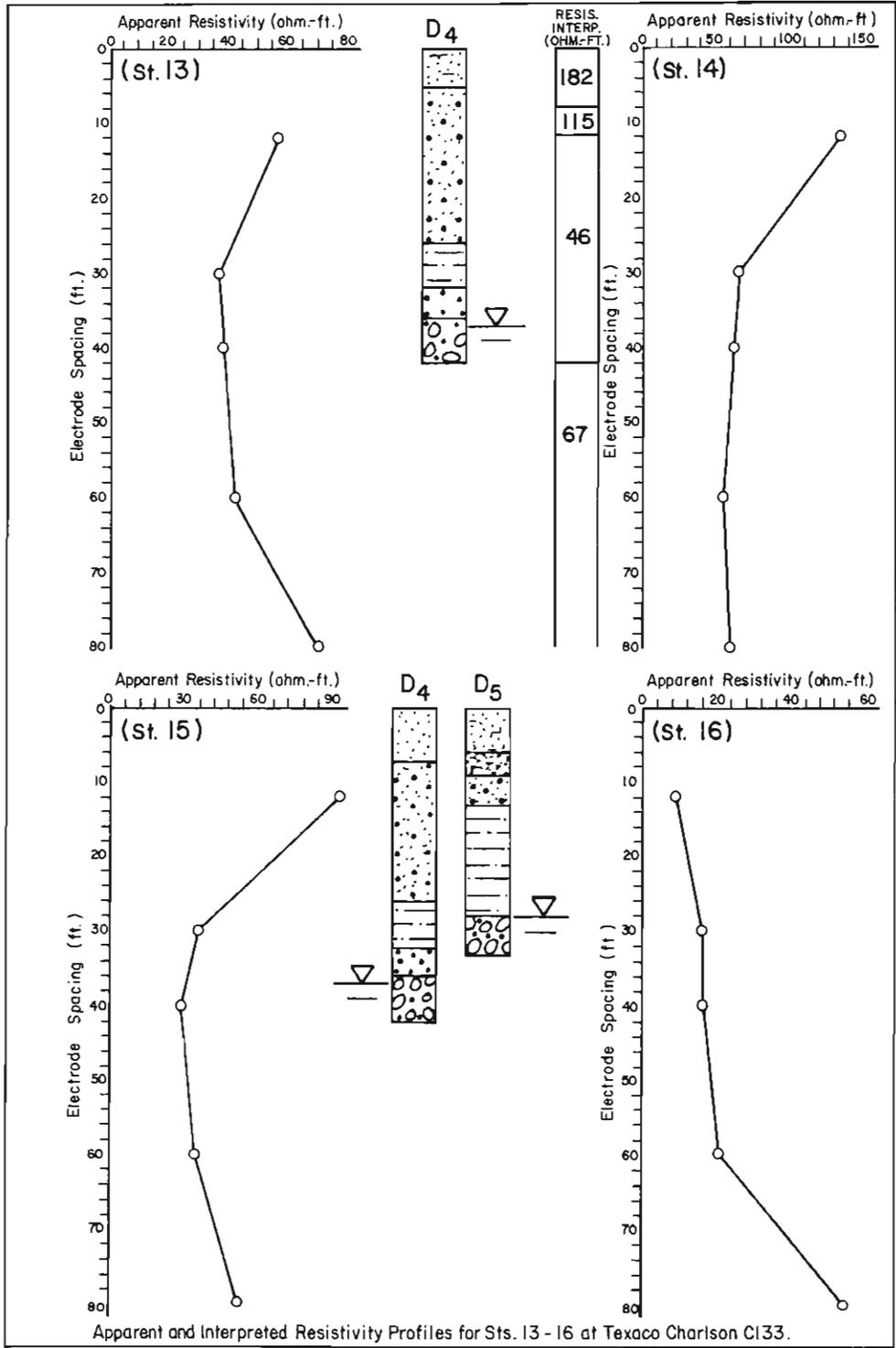
Apparent and Interpreted Resistivity Profiles for St. 25 at Apache Federal #1-5.

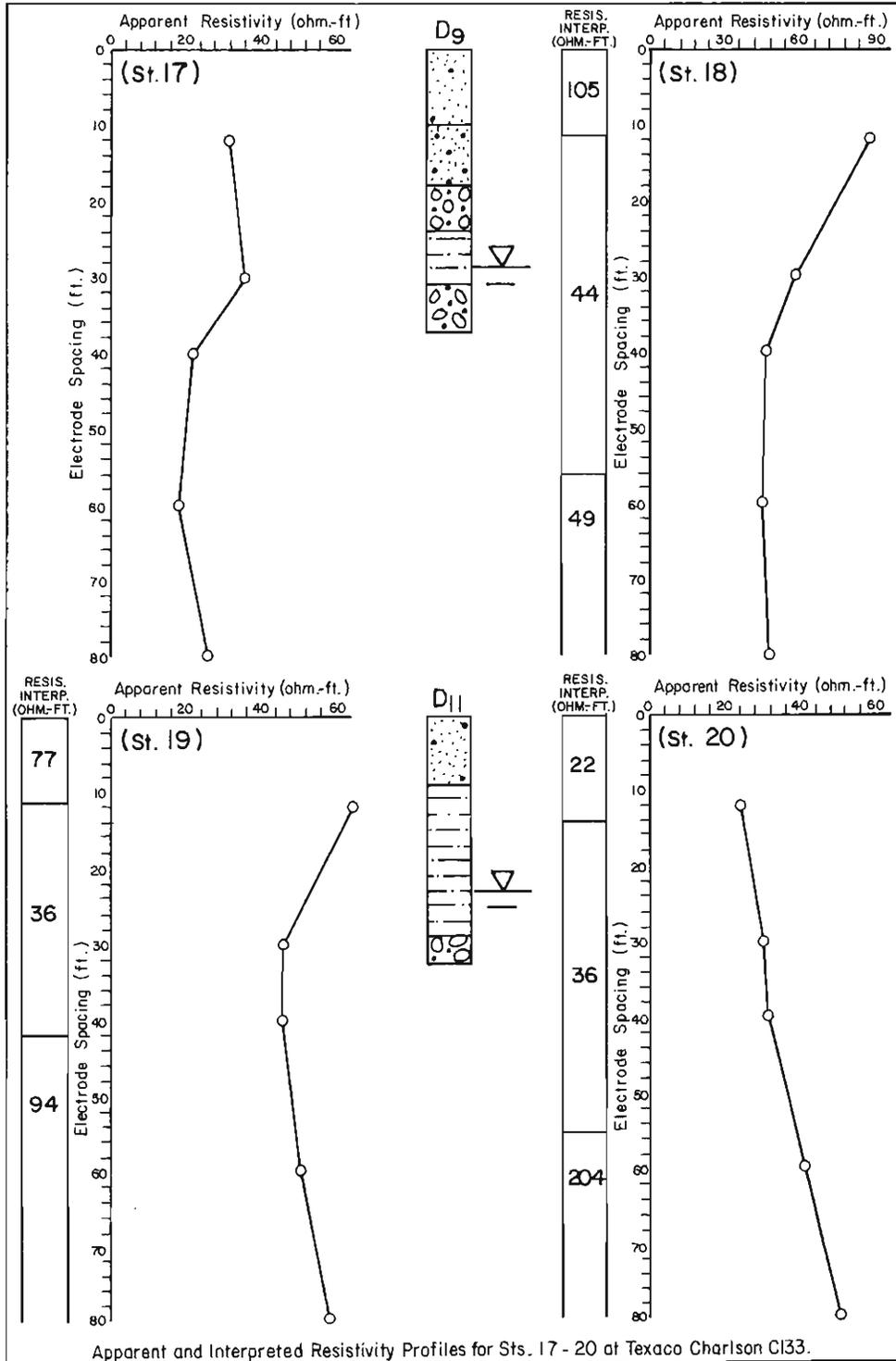




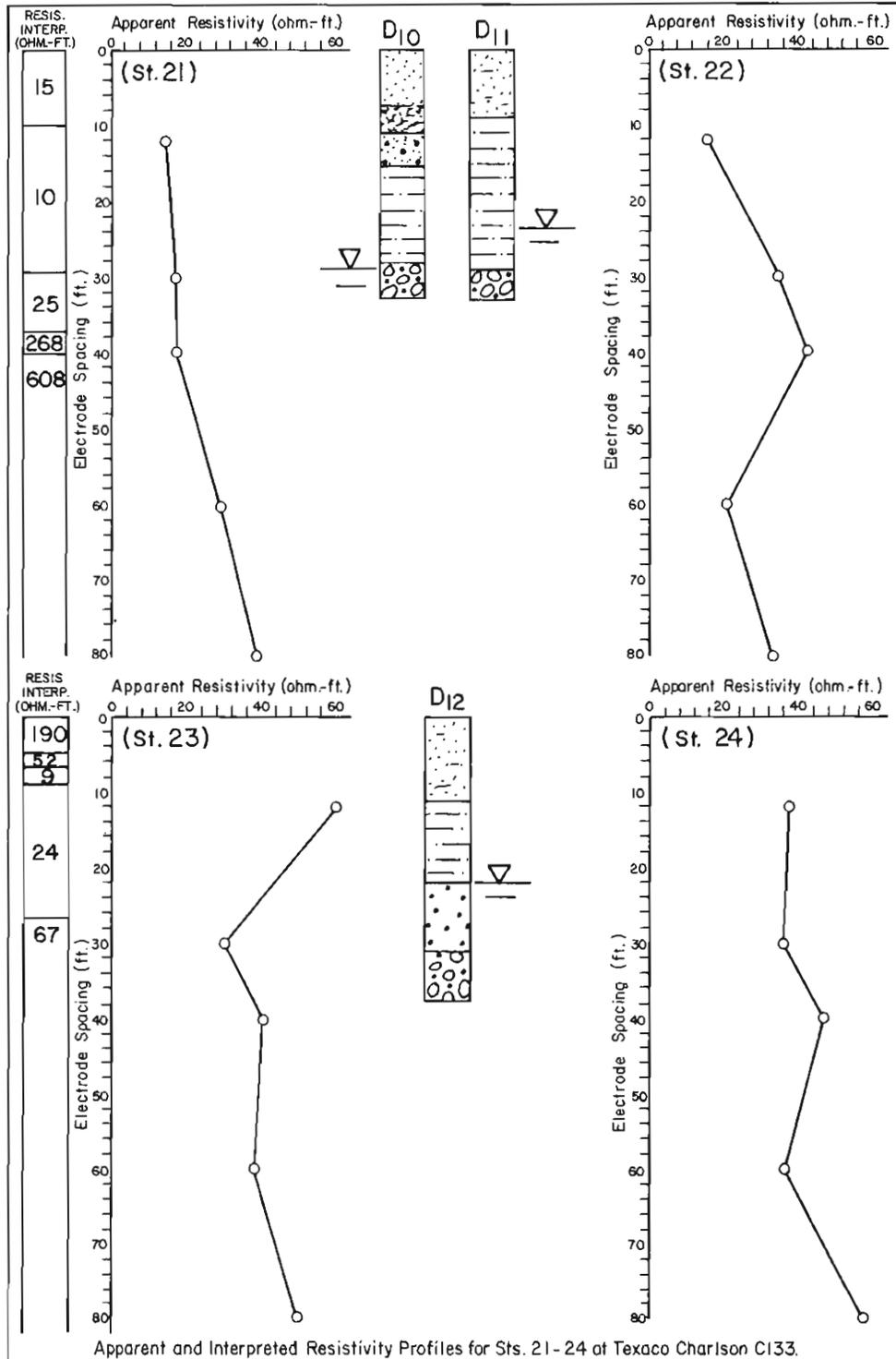


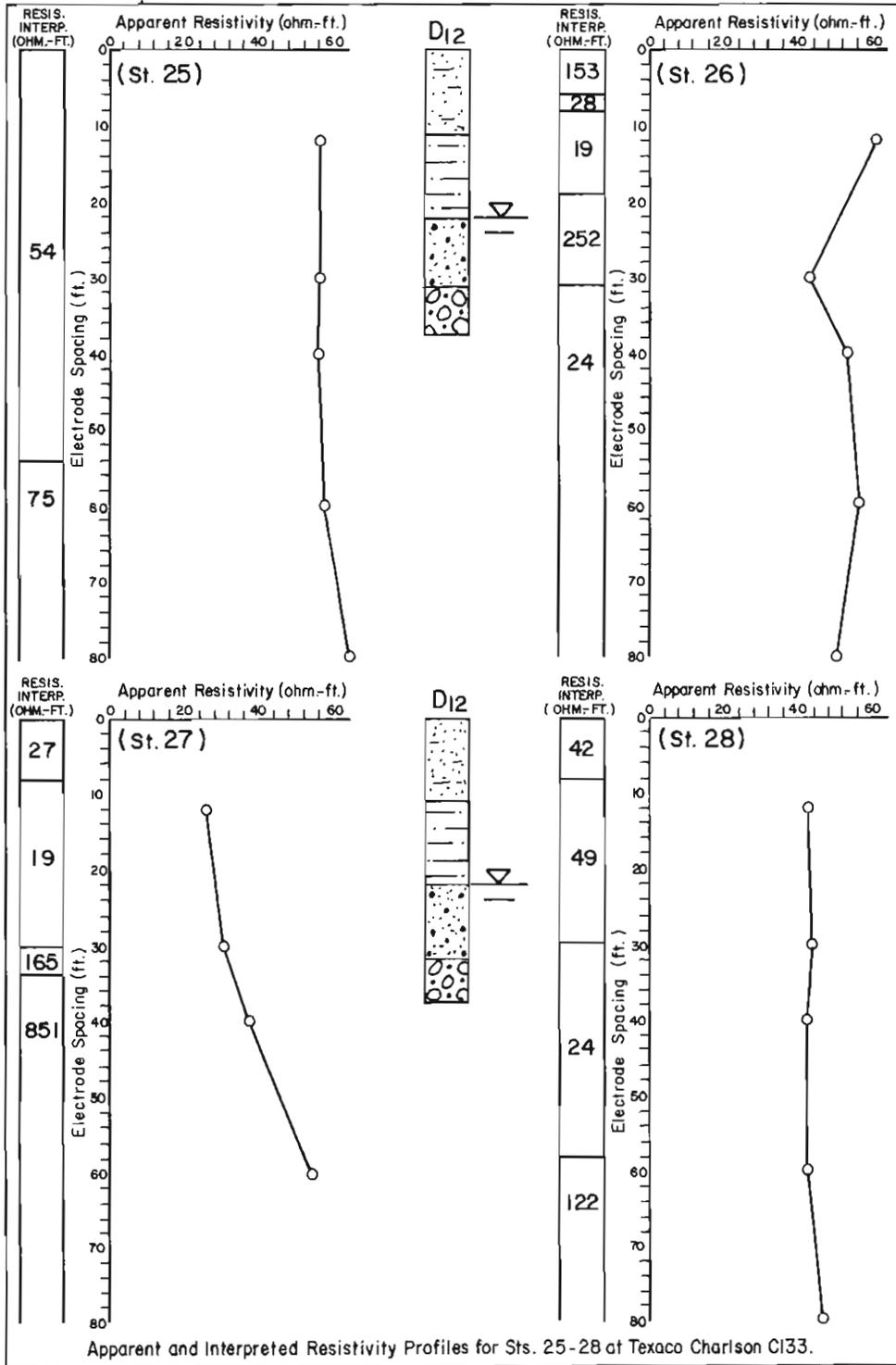
Apparent and Interpreted Resistivity Profiles for Sts. 9 - 12 at Texaco Charlson C133.

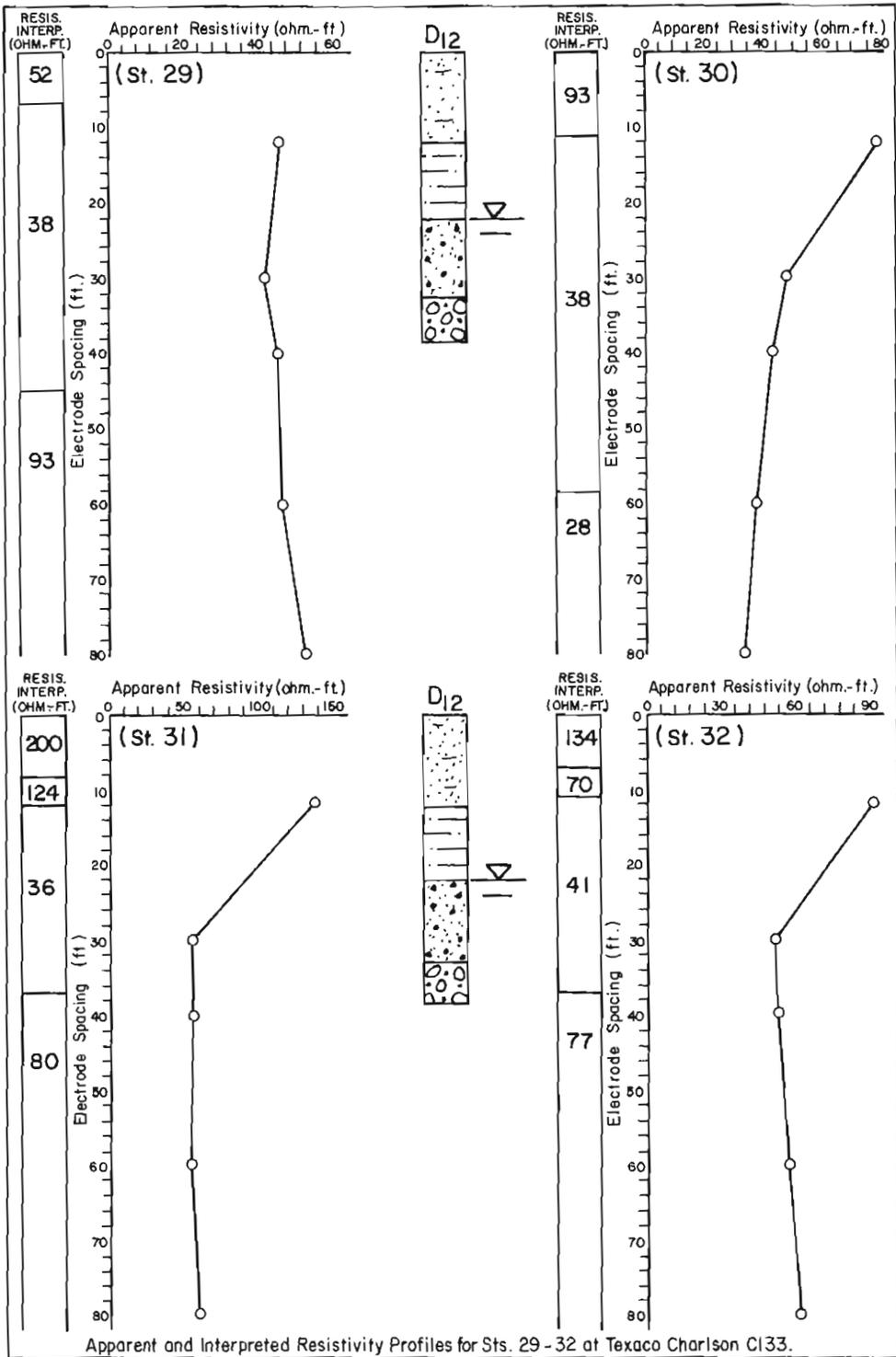




Apparent and Interpreted Resistivity Profiles for Sts. 17 - 20 at Texaco Charlson CI33.







APPENDIX G

DRILLING FLUID ADDITIVES USED AT THE BELCO PETROLEUM
SHEEP CREEK BN #1-11 AND APACHE FEDERAL #1-5 SITES

APPENDIX G-I

DRILLING FLUID ADDITIVES USED AT THE BELCO
PETROLEUM SHEEP CREEK BN #1-11 SITE

APPENDIX G-II

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

APPENDIX G-III

DRILLING FLUID ADDITIVES USED AT THE APACHE FEDERAL #1-5 REENTRY

APPENDIX G-I

DRILLING FLUID ADDITIVES USED AT THE BELCO
PETROLEUM SHEEP CREEK BN #1-11 SITE

Drilling Fluid Additives
Belco Petroleum Sheep Creek BN #1-11
Drilling Dates: 3/27/77 through 4/18/77

<u>Quantity</u>	<u>Product Name</u>	<u>Physical or Chemical Composition</u>
385 sacks	Geogel	Sepiolite (chain lattice clay)
305 sacks	My-Lo-Jel	Corn starch
227 sacks	Salt Gel	Attapulgate 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 naphtha 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.)

APPENDIX G-II

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

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

<u>Quantity</u>	<u>Product Name</u>	<u>Physical or Chemical Composition</u>
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	$\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$
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.)

APPENDIX G-III

DRILLING FLUID ADDITIVES USED AT THE APACHE FEDERAL #1-5 REENTRY

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

<u>Quantity</u>	<u>Product Name</u>	<u>Physical or Chemical Composition</u>
397 sacks	My-Lo-Jel	Corn starch
124 sacks	Sea Mud	Sepiolite
122 sacks	Salt Gel	Attapulgate clay, Fuller's Earth
21 sacks	TDF-Gel	* *
10 sacks	Preservative	Paraformaldehyde
9 sacks	Desco	Sulfomethylated tannin-sodium dichromate mixture
6 sacks	Sodium Dichromate	$\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$
4 sacks	HME	* *
4 cans	Magco-Poly- Defoamer	Polyalkylene glycols

(sacks are commonly 100 lbs.)

* * Composition unknown