HYDROGEOLOGIC CHARACTERIZATION AND EVALUATION OF VARIOUS GEOPHYSICAL TECHNIQUES AT AN ABANDONED REFINERY SITE IN PAWNEE COUNTY, OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Nature of the Problem

While working as an intern hydrogeologist for a local energy company, I sought a nearby site which would be suitable for a Master's thesis project. The site I chose was attractive due to the large amount of subsurface data which had been collected. The study area of my thesis is within Pawnee County, Oklahoma (Figure 1). The study area is the location of a former oil refinery which occupies approximately 170 acres in an area of differential erosion and gentle westerly dipping beds.

A hydrogeologic investigation was carried out at the site by the property owner in several phases of drilling to obtain information on the geologic conditions that would likely effect fluid migration. Plate 1 is a topographic contour map of the study area which identifies monitor well and core hole locations, certain site features and the location of generalized hydrogeologic geologic cross-sections. Over 160 soil borings and rock cores were retrieved and 50 monitor wells were constructed.   Topographic relief on the site ranges from 730 feet above mean sea level at Cedar Creek to 830 feet above mean sea level along the western edge of the property.

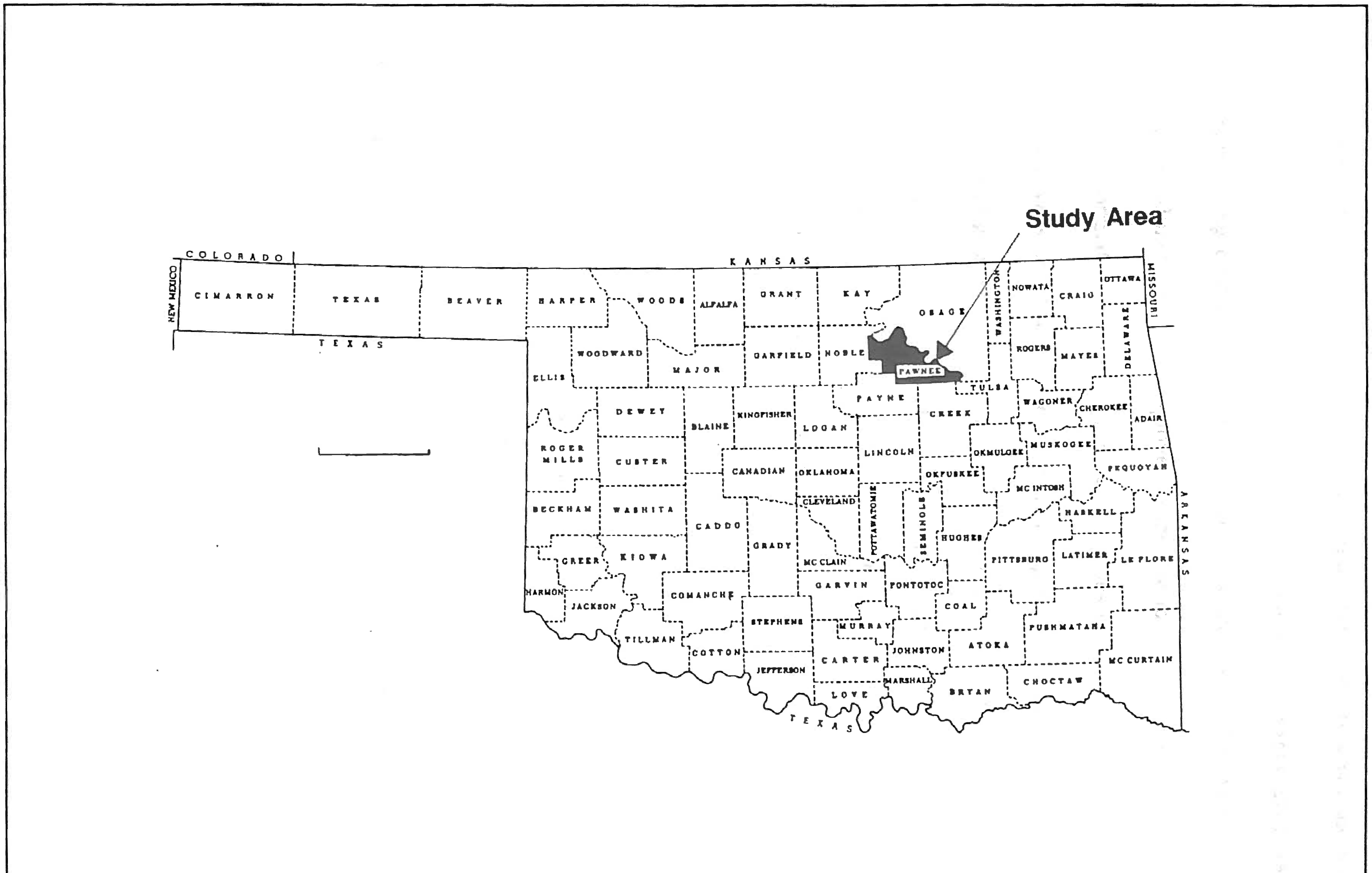

Figure 1. General Location of Study Area

Because of the extensive amount of subsurface data, the site was considered to be ideal for determining potential applications and limitations of several geophysical tools frequently being used to characterize hazardous waste sites. Subsurface and surface geophysical methods were employed at the site in order to demonstrate their ability to aid in correlating and defining rock conditions in the shallow subsurface. Several monitor wells cased with a steel outter casing and PVC innner casing were logged with natural gamma and neutron tools for lithologic and stratigraphic correlation purposes. The geophysical borehole logging program was conducted in monitor wells across the site in order to verify data from drillers logs and to assist in interpreting hydrogeologic cross-sections. Surface geophysical techniques were used to assist in mapping bedrock topography and shallow geologic features that might suggest the presence of faulting.

At the southern portion of the study area several seismic-reflection surveys utilizing different field parameters were conducted to evaluate the efficacy of the technique for mapping overburden thickness and bedrock surfaces. At the same location where the seismic reflection survey lines were conducted a Ground Penetrating Radar (GPR) survey was performed in order to compare and evaluate the two techniques side-by-side. The primary goals of the seismic program and the GPR survey were to determine the presence or absence of near-surface faulting and to map the bedrock-alluvium interface.

Objectives of Study

The primary objectives of the study are as follows:

1) To identify, with satellite imagery and aerial photography, surface features that might indicate the presence of faulting at or near the study area.

2) To use rock, soil and water level data in characterizing the hydrogeology at the study area.

3) To apply gamma and neutron borehole logging techniques in order to delineate lithologic, stratigraphic and possible structural heterogeneity across the study area.

4) To apply surface geophysical techniques in order to define and correlate rock conditions in the shallow subsurface at the southern extent of the study area.

Overview of Experimental Approach

1) An extensive review of all published literature on the Virgilian Series of the Pennsylvanian System, of northeastern Oklahoma, was undertaken.

2) Satellite images and aerial photographs were examined in order to determine whether or not lineaments could be detected at or near the study area.

3) Rock cores and lithology logs from soil borings and monitor wells at the study area were examined in detail.

4) Hydrogeologic cross-sections A - A', & B - B' (Plates 3a & 4a) were constructed using only core and sample data to show lateral and vertical facies

relationships and to identify potential pathways for contaminant migration.

5) Potentiometric maps of known water bearing units were constructed to identify groundwater flow paths.

6) A borehole geophysical logging program was conducted in monitor wells across the site utilizing natural gamma and neutron tools in order to verify lithologic continuity in near surface rocks.

7) Over one-hundred feet of rock core from monitor well LMW12 was scanned with a natural gamma detector.

8) Hydrogeologic cross-sections A - A', & B - B' (Plates 3b & 4b) were reconstructed by integrating borehole geophysical data with core data.

9) A series of shallow seismic-reflection survey lines were conducted in an attempt to map the bedrock/alluvium interface and to identify structural and/or stratigraphic features that might affect fluid migration.

10) A 50 MHz Ground Penetrating Radar survey (A - E) was conducted at the same location the shallow seismic-reflection surveys were conducted.

11) Hydrogeologic cross-section A - A" (Plate 5) was constructed using information from surface and subsurface geophysical techniques as well as core data.

CHAPTER II

LITERATURE REVIEW

Overview of Geophysical Techniques and Applications

In recent years, prediction of contaminant migration in hydrogeological systems has become very important when characterizing hazardous waste sites. The need to develop a more accurate picture of flow-controlling geologic features has enhanced the development of specific geophysical tools and methods. Often a first approach is to examine remotely sensed data, such as satellite imagery or aerial photography in order to evaluate pollution suseptibility of rocks through fractures at or near the ground surface. Some geophysical methods actually offer a direct means of detecting contaminant plumes and flow directions in both the saturated and unsaturated zones. Other techniques offer ways of obtaining detailed information about soil and rock properties in the subsurface which can be used to evaluate migration pathways (Benson et al., 1988).

With the increasing recognition of problems associated with hazardous waste disposal and groundwater remediation, new potential applications of borehole geophysical logging to hydrogeological investigations have been developed (Keys, 1989). Most available literature on borehole geophysics has been directed toward petroleum applications, which can be quite different from groundwater applications. Surface geophysical methods such as shallow seismic-reflection and ground penetrating radar are also becoming increasingly important in conducting hydrogeological investigations with recent advances occurring in the development of instrumentation and new field techniques. Several investigators (Hunter et al., 1982; Davis and Annan, 1985; Kent and Overton, 1987; Miller et al., 1989; Steeples and Knapp, 1982) have demonstrated the usefulness of these newer instruments and techniques in mapping bedrock surfaces and identifying structural and stratigraphic features that affect fluid migration.

Frequently the design and placement of monitor wells at a hazardous waste site is based on interpretations arising from the increase of geologic information coming from boring and monitor wells. This type of sample and drill method is often based upon some rather speculative assumptions and can prove to be quite expensive when a large tract of land must be assessed. An alternative to this type approach would be to integrate ground truth from existing sample and well data with information from a well planned geophysical survey or combination of surveys. By adopting an integrated approach to site characterization, expenses and man hours as well as safety risks can be reduced by improving the accuracy with which future monitor wells are located. With recent advances in equipment and techniques, the following geophysical methods are increasingly being relied upon when characterizing geologic features at hazardous waste sites.

Remote Sensing

Remote sensing involves feeling, measuring, or imaging sensations without actually being in direct contact with the object. Aerial photography, satellite imagery, and even surface geophysical tools such as seismic and ground penetrating radar profiling qualify as remote sensing tehniques. The first practical use of aerial photography dates back to World War I and the developement of aeronautics, when an aerial camera was used to photograph parts of Germany for military reconnaissance (Pandey, 1987).

Over the past 30 years, aerial photogeology has been developing at an increasing rate, particularly in the wider part of the electromagnetic spectrum, namely color, infra-red, multiband photography, radar, and thermal infra-red imagery. With the advent of orbital satellites, a tremendous amount of geological data is available. The Landsat Multispectral Scanner (MSS) sensor is a line scanning device which simultaneously scans the terrain passing beneath an orbiting spacecraft. The multispectral scanner measures and records natural energy reflections in four electromagnetic spectral bands from the surface of the earth. Data is then converted to digital format on-board the satellite and rescaled in subsequent ground processing depending upon the application (Jensen, 1986).

Data which has been remotely sensed with either satellite imagery or aerial photography is often useful in conducting groundwater resource studies. Geologic structures such as fractures and joints affect the occurrence of groundwater and its susceptibility to pollution. Detection and analysis of lineaments from remotely sensed data can lead to the discovery of bedrock fractures which may influence the recharge and preferential flow of groundwater.

Some of the most prominent features on air photos and satellite images are the straight or gently curved alignments (lineaments) of topography, vegatation, and stream courses which mark the trace of rock fractures at the earth's surface. Azimi (1978) used multispectral scanned (MSS) satellite imagery to descriminate lineaments and evaluate pollution susceptibility and recharge in an unconfined chert-limestone aquifer. Lattman and Nickelsen (1958) used aerial photographs to show the close similarity between lineaments on photos with joint sets mapped on the ground.

Geophysical Borehole Logging

Geophysical borehole logging is simply a technique which measures some physical rock property from and surrounding a borehole. The measurements can be made from a variety of electrical, nuclear, acoustic or similar tools depending upon the particular type of information desired. The equipment consists of a downhole sensor or sensors that make the actual measurements and then relay the information inside electrical wiring, which is inside the transport cable to the surface. At the surface, signals from downhole are converted to standard units and stored digitally or plotted on paper in the case of an analog system.

Credit is given to the Schlumberger brothers for developing the first borehole geophysical logs, in France in 1927 (Schlumberger & Schlumberger, 1929). Though the existence of natural electrical potentials caused by differences in a boreholes lithologic section was known as early as 1830, it wasn't until 1931 that Schlumberger engineers recorded and plotted these spontaneous potentials (Keyes and MacCary, 1971). In 1918, C.E. Van Orstrand of the United States Geological Survey worked with down-hole temperature logging equipment to plot "depth-temperature curves." This logging equipment was the first to be used by the U.S.G.S. and probably was the first to be used anywhere (Johnston and Adams, 1916).

Historically, environmental investigations involving groundwater have assumed that subsurface geologic conditions are simple and homogeneous. To the contrary, the opposite is normally true. Investigators at hazardous waste sites usually have some general ideas concerning on-site conditions but in-situ testing is usually approached with educated guesswork utilizing soil borings and monitor wells. This approach to site characterization is costly in terms of time, money, and safety risks. This sometimes requires the additional placement of wells to correctly characterize the site and the effects of contamination on the environment.

The role of borehole geophysics in hazardous waste site investigations is to assist in solving complex problems related to geology and hydrogeology. Geophysical borehole logs provide information which can be used to quickly assess the construction of wells and the character of fluids and rocks as well as data which can be analyzed in more detail at a future date (Crowder & Irons, 1989). The data obtained may include information on lithology, thickness and continuity of aquifers and confining beds, relative porosity, fractures, groundwater flow and groundwater chemistry. The amount and benefit of information depends upon the logging suite, geologic variables, borehole conditions, and interpreter experience as well as knowledge of the present technology.

A U.S. Environmental Protection Agency (EPA) study of 22 R.C.R.A. sites concluded that incorrect screening was used in 50% of the monitor wells tested, that 30% of the wells were incorrectly placed, and that in 10% of the sites, wells were placed prior to determining the direction of groundwater flow (Wheatcraft et al., 1986). Complex geologic conditions and the collection of tremendous amounts of data make evaluation of these sites difficult. Because site characterizations are conducted within rigorous time constraints, a common complaint is that while a great deal of time is expended collecting data, sufficient time for interpretation is rarely allowed.

The most important objective of borehole geophysics is to obtain more information from a well than can be obtained from drilling, sampling, and testing. Geophysical logs provide a continuous record which is objective, repeatable and comparable even though the logs may have been gathered with different equipment at different times. This ability to repeat and compare measurements makes it possible to see changes in the groundwater system over time. An additional benefit is that many logs measure properties of rock volumes that are many times larger than the core or cuttings from a well (Keyes, 1989).

The following is a brief discussion of nuclear logging applications and limitations:

Nuclear logs simply measure the natural radiation in the borehole wall or measure the response of the rock in the borehole wall to bombardment from a radioactive source. The chief advantages in using nuclear logs are that they can be operated through either steel or PVC casing and since the energy source is actually inside the tool rather than at the surface, stray electronic currents and magnetization of the winch cable do not create anomalous readings.

Of the three types of radiation - alpha particles, beta particles, and gamma photons - only gamma photons are measured by well logging equipment. Neutrons are also capable of penetrating materials like casing, drilling mud, and rock but they tend to be slowed down and captured by materials with a high hydrogen content such as water. Neutrons or gamma photons are produced by a source inside the logging sonde and then measured after they are bombarded against the borehole wall. The most common naturally occurring radioactive isotopes tend to be concentrated in clay minerals. In most sedimentary rocks the number of gamma counts is directly proportional to the percent of clay minerals present in the rock (Clemmens, 1989).

The most widely used nuclear logs for groundwater applications are *natural gamma* logs. No radioactive source is needed to make natural gamma logs because the tool simply detects the naturally occurring, gamma emitting radioisotopes present in the borehole wall. The depth of influence investigated by the natural gamma tool is a function of the radioactive energy present in the borehole, the density of the material through which the radiation passes, and the design of the probe. The amplitude of the natural gamma deflection is diminished when materials like heavy drilling mud or cement and casing are placed between the probe and the borehole wall.

Natural gamma logs are used primarily for lithologic correlation, however errors are likely if the log response in the study area is not well understood. As with the other types of logs previously discussed, background information on the local geology from core and sample data should be used to aid in log interpretation. Lateral heterogeneity in grain size and distribution or percent of arkosic material in a sandstone may have a dramatic effect on the gamma log response from well to well (Keys, 1989). Granitic basement rocks are more radioactive than most geologic materials followed by shales, clays, arkosic sands, and quartz sands. Materials like coal, gypsum, limestone, and anhydrite tend to have diminished gamma intensity.

Identifying exactly which radioisotopes have contributed to the gamma log through quantitative analysis is not possible using the natural gamma tool but rather requires a highly specialized type of natural gamma log called a *spectral gamma* log. The spectral gamma tool counts the gamma rays and measures the energy level of the individual rays which makes it possible to determine the source of the isotope. Spectral gamma data provides much more diagnostic information about lithology than natural gamma data because concentrations of uranium, thorium and potassium, can be determined quantitatively (Keys, 1989). Its ability to identify individual radioisotopes also makes spectral gamma logging an excellent tool for the selection and monitoring of sites used for the disposal of radioactive waste.

The gamma-gamma density log detects radiation the same way that the natural gamma log does except that it measures radiation backscattered from bombardment by a sealed gamma source located on the logging sonde (Clemmens, 1989). Gamma-gamma logging is based on the premise that the attenuation of gamma radiation as it passes through the rocks surrounding the borehole is proportional to the bulk density of those particular rocks (Keys, 1989). For this reason, when properly calibrated the gamma-gamma density log is capable of measuring bulk density, porosity, and moisture content. This information can be used to evaluate well construction by locating unfilled annular space and the top of cement through casing. By varying the source strength and spacing, very thin beds and fractures at a shallow radius from the tool can be detected or information deeper in the formation can be extracted. If gamma-gamma density logs are run before and after drawdown during a pumping test they can be used to calculate specific yield (Davis, 1967).

The *neutron* logging sonde is similar in tool configuration to gamma-gamma density logging sonde except that the probe contains a source of neutrons, commonly Americium-Beryllium. Neutron logs can be run in liquid or air-filled, cased or uncased holes and are capable of seeing through steel, PVC, or teflon. High energy neutrons leave the source at a particular velocity and retain their velocity unless they collide with particles of similar mass such as hydrogen atoms. Hydrogen atoms present near the borehole absorb high energy neutrons exiting the logging probe. The presence of hydrogen is an indicator of water content in the rocks penetrated since most natural hydrogen in the ground is in the form of water.

Above the water table the neutron log indicates water saturation and below the water table it may indicate porosity (Clemmens, 1989). This ability to identify moisture in the unsaturated zone has been used in ground water applications for finding perched water tables (Darr et al., 1990). Direct measurement of porosity with neutron logs is not possible but they can be calibrated for these specific variables and corrected for extraneous effects. Shales and clays can introduce errors into the measurement of porosity with neutron logging because the tool is not capable of distinguishing between hydrogen in bound water and hydrogen in free water. In general, neutron logging is affected by many of the same borehole parameters that affect gamma-gamma logging, but usually to a lesser degree.

Darr et al., (1990), determined that responses of the neutron log to well construction materials made it possible to evaluate the water saturation state of bentonite placed as a seal above a sand pack in the annulus between casing and the borehole wall. Where the bentonite seal was known from well construction information anomalously higher counts on the cased hole neutron log were interpreted as the result of partially saturated bentonite. The same study demonstrated that the neutron log was uniform in attenuation throughout a single well which was logged in both an open hole through drilling mud and in an air-filled PVC cased hole. Therefore, even though the neutron response is attenuated by well construction materials, the response maintains a consistent character making interpretation less speculative.

Shallow Seismic-Reflection

Both seismic refraction and reflection surveys rely on sound waves generated at the ground surface by a mechanical impact or an explosive source. The seismic *refraction* method is simple and inexpensive but tends to be rather low-resolution and requires that each geologic layer increase in seismic velocity as you move deeper into the subsurface. Ideally the interfaces studied in a small refraction survey should be shallow, planar and should have dips less than 15 degrees . Seismic *reflection,* on the other hand, can map reflecting boundaries with spatial resolution 5 to 10 times better than refraction mapping, does not require increasing velocity with depth, and because of shorter geometry requirements between the source and geophones, a smaller source is practical. Some disadvantages associated with seismic reflection are that high quality data are dependent upon site conditions and that aquisition and processing costs are higher than those for refraction surveys (Steeples and Miller, 1989).

Unlike seismic refraction, seismic reflection methods involve no prior assumptions about layering or seismic velocity. The simplest case of seismic reflection occurs at a velocity boundary where a single layer overlies an infinitely thick material, as shown in Figure 2. An impulsive source emits acoustic energy into the ground and records the time it takes for that energy to pass from the surface to the subsurface layer and back. The path of least time will be from a reflecting point half-way between the source and the receiver with the angle of incidence on the reflecting layer equal to the angle of reflection from the reflecting layer.

In reality, several layers of rock generally contribute to a seismogram, thus making the data quite complex. The presence of seismic energy that has bounced one or more times between layers (multiple reflections), near-surface velocity variations, and lateral heterogeneity of rocks all combine to make interpretation difficult. Nevertheless, seismic reflection techniques overcome many of the problems associated with seismic refraction surveys. Reflections tend to have large relative amplitude (as

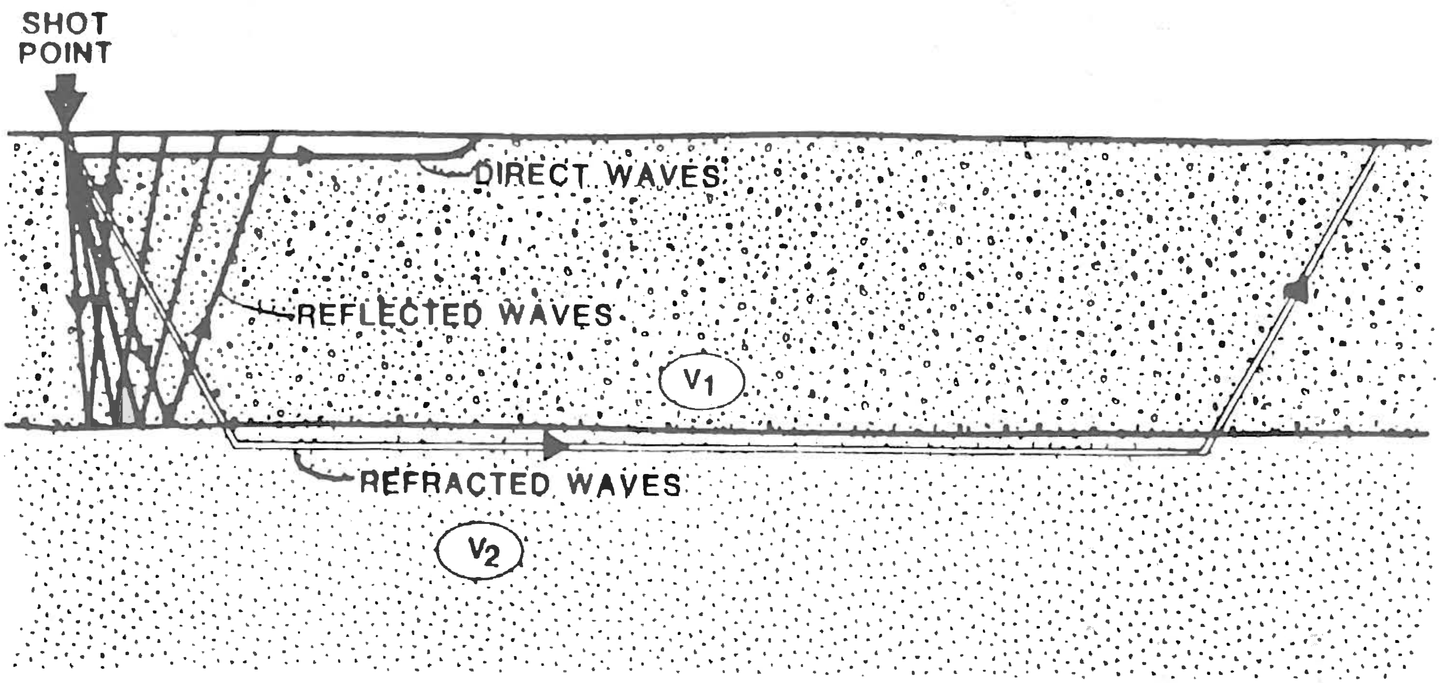

Figure 2. Geometry of Seismic Ray Paths

much as an order of magnitude) in comparison with refractions from the same horizon and may potentially provide considerable detail about overburden structure and bedrock topography.

Optimum conditions for the successful application of seismic reflection methods are generally found at sites where surface materials are made up of fine-grained clays and are saturated. In this type of setting, the ground more easily transmits high-frequency seismic energy (300-500 Hz). In surface materials that are coarse-grained and where the water table is several meters below the source and receivers, dominant frequencies of reflection data may be below 100 Hz and resolution of the data will likely be low (Hunter et al., 1980).

Seismic reflection has been used as an exploration tool in the petroleum industry for over sixty-years (Dobrin,1976) and more recently as a tool for water exploration and hydrogeological studies in the near surface (Geissler, 1989; Miller, Steeples, Brannan, 1989). So called "high resolution" reflection methods were intiated in the oil industry in the 1970's when there arose a need to identify shallow stratigraphic oil and gas traps more efficiently (Farr, 1977). The need to see high frequency reflections from shallow horizons led to the development of improved digital recording equipment and seismic detectors which have helped to make aquisition and processing of seismic data easier. The equipment and many of the techniques which were developed for use in shallow mineral exploration are commonly used today for near-surface reflection and refraction studies by engineers and environmental geoscientists.

The seismic reflection technique in the past few years has been used to map bedrock beneath alluvium near hazardous waste sites, detect abandoned coal mines, and to map intra-alluvial stratigraphy and shallow faults (Steeples and Miller, 1989). Steeples and Knapp (1982) have experimented extensively with rifle sources for high resolution seismic reflection work and have had considerable success in obtaining shallow reflections under a variety of geologic conditions. K. Helbig at the University of Utrecht used an engineering seismograph to collect high frequency data from tidal flats in the Netherlands. Excellent high frequency reflections as shallow as 5 meters were produced by the group at the University of Utrecht because the tidal flat sediments were completely saturated and no attenuating low-velocity layer existed at the surface (Helbig et al., 1985).

In planning well locations for a groundwater monitoring program it is extremely helpful to have detailed knowledge of bedrock topography and to know where coarse grained aquifer deposits may be located. Mapping the bedrock surface beneath alluvium is a classic problem which has traditionally involved interpolating contour lines between widely spaced drill holes or carrying out extensive drilling projects which are costly and environmentally undesirable. Structural anomalies on the order of several meters may go uncompensated for in a hydrogeologic flow model which is based upon nominally spaced drill data. At a site in Texas, detailed maps created with a combination of seismic and drill data revealed major paleodrainages and bedrock lows where contaminants were suspected to have migrated (Miller et al., 1989). The continuous subsurface profiles created using seismic reflection at this site allowed for the rationale placement of groundwater quality monitor wells.

Bedrock-overburden contacts have been mapped with success using seismic reflection at depths greater than 20 meters (Hunter et al., 1984) and at depths as shallow as 4 meters (Miller et al., 1989). In addition to resolving bedrock interfaces at shallow depths, seismic reflection has also been used to map intra-alluvial features thought to play a role in the preferential flow of groundwater. In the future, as techniques are improved upon and resolution increases even further, it should become possible to readily identify clay layers and interbedded structures within alluvial materials. Though it is certainly not practical to expect this degree of resolution from seismic reflection in all alluvial environments, where applicable it will be a very useful tool for engineering and environmental purposes.

Defining the exact locations of near-surface faults is another problem which seismic reflection can be useful at solving. Detailed earthquake hazard research is frequently guided by first locating shallow faults where reactivation is likely. Treadway et al., (1988) discusses the use of the shallow seismic-reflection method to successfully map faults to depths of 50 meters in the vicinity of a fault scarp which was produced by the 1983 Borah Peak earthquake in Idaho. Faulted or fractured areas near the surface also may act as conduits for fluid migration in or around hazardous waste sites. Waste site migration problems due to shallow faulting are not uncommon but little is available in the way of published case histories.

Both seismic refraction and reflection techniques are viable tools for shallow geotechnical and environmental investigations. Several of the case histories mentioned here illustrate where seismic methods can provide cost effective, high resolution, continuous subsurface information which can only be duplicated by extensive drilling projects. The success of a survey hinges on the experience and expertise of the person designing, implementing and interpreting the survey. Selection of optimum technique and field parameters will ensure that the objectives of a survey are being met and that the interpretation is simplified as much as possible.

Ground Penetrating Radar

Ground penetrating radar (GPR) is a geophysical technique that offers the potential for high-resolution mapping of shallow soil and rock conditions (Davis and Annan, 1989). The need to better understand overburden conditions for activities such as geochemical sampling, environmental assessments, geotechnical investigations, archeological studies and the factors which control the flow of groundwater has increased the demand for methods which can image the subsurface with a high degree of resolution. The radar offers an economic method of extending the effective horizontal extent of borehole information, which is especially important to geotechnical engineers, geologists and hydrogeologists.

Recent developements in GPR technology have increased the depth penetrating capabilities of the system in geological materials. The newer systems allow digitization of the signal at the receiver and then store the data onto an internal or external disk drive. Once the data is stored it can then be processed using a variety of techniques similar to those used in the processing of seismic reflection data. The newer GPR instrumentation is easy-to-use, is relatively portable and lends itself well to carrying out controlled surveys in difficult operating conditions.

GPR technique is very similar in principle to reflection seismic and sonar techniques. Seismic techniques can map to much greater depths than GPR, but the radar generally provides higher resolution soundings more economically in the near surface environment. With GPR, a short pulse of high frequency electromagnetic energy is transmitted into the ground. The propagation of the radar signal is dependent upon the high frequency electrical properties present. Changes in soil electrical properties are generally associated with changes in volumetric water content which in turn gives rise to radar reflections. In rock, the radar signal is sensitive to changes in lithology and water filled or dry fractures (Topp et al., 1980).

Velocity and attenuation are factors used to describe the propagation of radio frequency waves in the ground and are dependent upon the dielectric and conductive properties present at the site being surveyed. As electromagnetic waves propagate downward into the ground, changes in electrical impedance generate reflections. Electrical impedance is controlled by changes in the relative permittivity or dielectric constant of the ground. The dielectric constant or relative permittivity are terms used to describe the high frequency (10–1000 MHz) electrical properties of many geological materials (Davis and Annan, 1989). Table I provides the dielectric constants and electrical conductivities observed in common geological materials. The depth to which a radar signal can penetrate is most influenced by the attenuation in the ground and the reflection properties at a boundary where the electrical properties vary. Davis

TABLE I

TYPICAL DIELECTRIC CONSTANT, ELECTRICAL CONDUCTIVITY,VELOCITY AND ATTENUATION OBSERVED IN COMMON GEOLOGIC MATERIALS

MATERIAL	**K** dielec.constant	**σ (mS/m)** elec. conduct.	**V (m/ns)** velocity	**ά (dB/m)** attenuation
Air	1	0	0.30	0
Distilled Water	80	0.01	0.033	0.002
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	3×10^3	.01	10^3
Dry Sand	3-5	0.01	0.15	0.01
Saturated Sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry Salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

(after Annan, 1992).

mS/m = milli-Siemens per meter
m/ns = meters per nano-second
dB/m = decibels per meter

and Annan (1989) discuss an equation which can be used to calculate the radar signals range where such variables as antenna efficiency, attenuation and backscatter gain of the target are known. In most situations, however, there are too many unknowns to effectively calculate the radar's ability to penetrate a particular material. It is usually best to test the radar on the site to determine the applicability of the system for solving the objective.

Applications of GPR range from identifying waste pits (Merlin, 1990) to mapping shallow geological structure and stratigraphy and detecting the water table. Annan et al., (1991) discuss the use of GPR to detect the interface between the unsaturated and saturated zones in various types of shallow geologic settings. Work by Killey and Annan (1985), describes the use of GPR to map intra-alluvial stratigraphy and an underlying bedrock surface while Davis and Annan (1989) demonstrate the GPR's potential for the high-resolution mapping of rock stratigraphy. The use of GPR in mapping sedimentary features is recent, first pioneered by Ulriksen (1982), then advanced by Moorman (1990), Jol and Smith (1991,1992), and Smith and Jol (1992). Numerous other published and unpublished studies discuss the use of GPR to locate metallic objects, monitor conductive plumes, and to investigate potential collapse areas near old mine workings (Annan, 1992).

CHAPTER III

HYDROGEOLOGIC SETTING

Regional Geology

In a July, 1980 LANDSAT multispectral scanning (MSS) image of eastern Pawnee County, the study area and several lineaments are identified immediately south of the Arkansas River and west of Keystone Reservoir (Figure 3). Greig's (1959) thesis provides a detailed geologic map of Pawnee County which shows the Vamoosa formation present in the study area immediately southwest of Cleveland, Oklahoma (Figure 4). While conducting field studies throughout Pawnee County, Greig (1959) located several surface faults near the study area with aerial photographs. Figure 5 is a 1940 aerial photograph showing the the surface trace of a fault approximately one-mile south of the study area.

Structural Features

Structurally, the Vamoosa formation in Oklahoma lies on the Northeast Oklahoma Platform and the west sloping Prairie Plains homocline at a dip of 30 to 65 feet per mile. The platform is bounded by the Cherokee Basin to the north, the Nemaha Ridge to the west, the Arkoma Basin to the south, and the Ozark Uplift to the

Figure 3. 1980 LANDSAT Image of Eastern Pawnee County, Oklahoma.

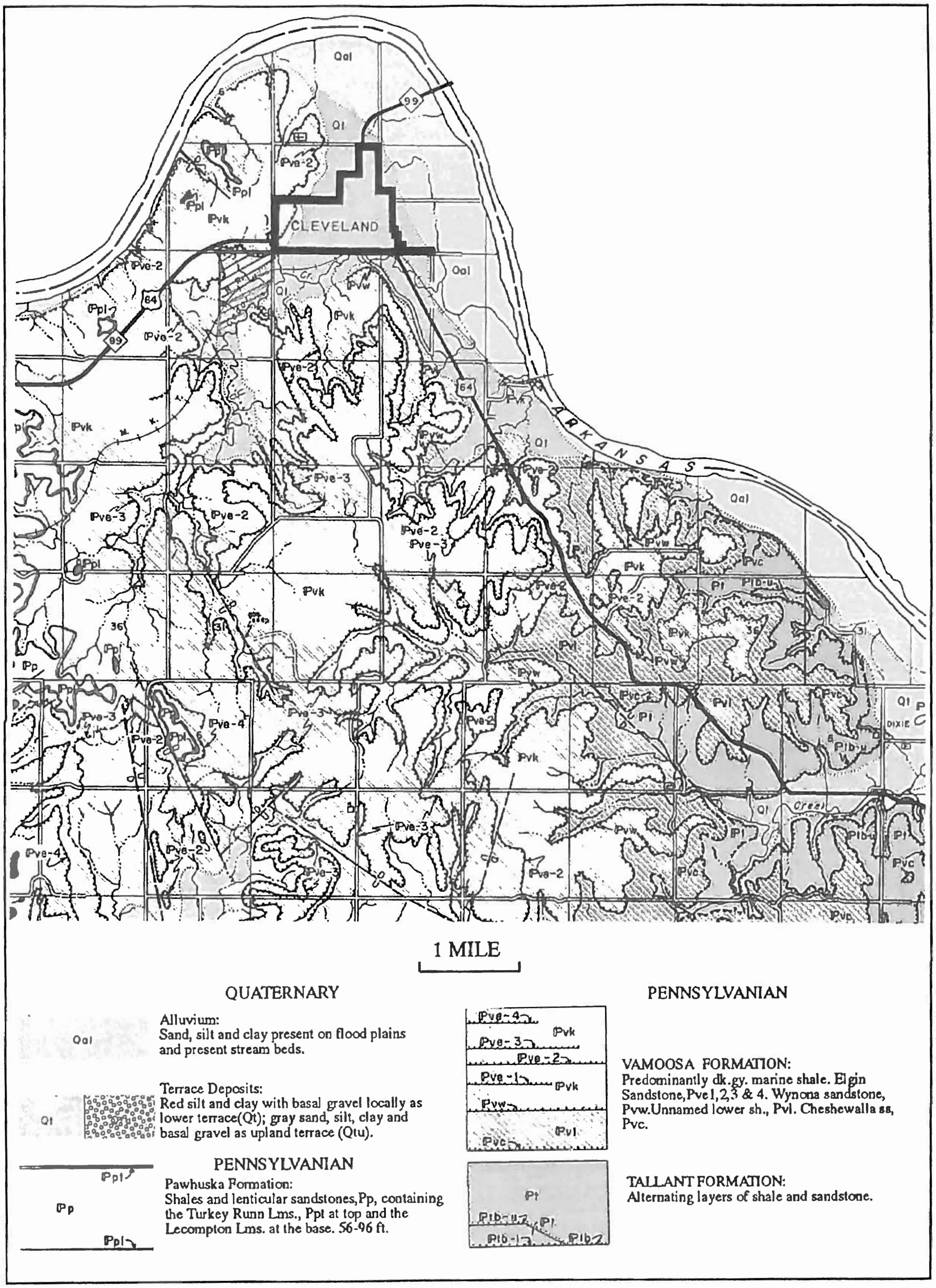

Figure 4. Detailed Geologic Map of Eastern Pawnee County Showing Elgin Sandstone Outcrop and Fault Traces (after Greig, 1959).

Figure 5. Aerial Photograph of Land Surface Surrounding Study Area.

east. Superimposed on the homocline and running in a north-south belt from approximately 50 miles south of the study area to the Kansas state line are a series of en echelon faults. The faults occur in parallel bands trending northwest or northeast across the eastern third of Pawnee County. Figure 6 illustrates the distribution of the en echelon faults and their relation to the Ozark-Arbuckle uplift and the Nemaha Ridge. They generally do not exceed 3 miles in length and vertical displacement across the faults is usually less than 100 feet. Though subsurface data is sparse, it is believed that the subsurface displacement diminishes with depth and the faults probably do not extend below Pennsylvanian age rocks (Levorsen, 1928). The nearest surface evidence of faulting occurs approximately one mile south of the study area.

Stratigraphy

The Vamoosa formation consists of interbedded sandstones and shales which strike approximately north-south and dip gently to the west. Throughout deposition of the Kanwaka shale periodic uplift in the south caused the development of a series of lenticular, multilateral and multistoried deltaic distributary and alluvial channel deposits known as the Elgin sandstone. The Elgin Sandstone interval within the Vamoosa formation in Pawnee County represents a transgressive-regressive couplet. The Elgin is made up of a series of thin-bedded and lenticular sandstone bodies that make up a laterally complex aquifer which is extremely heterogeneous (Terrell, 1972).

Greig (1959) places the Kanwaka shale and the Elgin sandstone beds within the Shawnee Group of the upper Virgilian Series. He describes the Kanwaka and Elgin

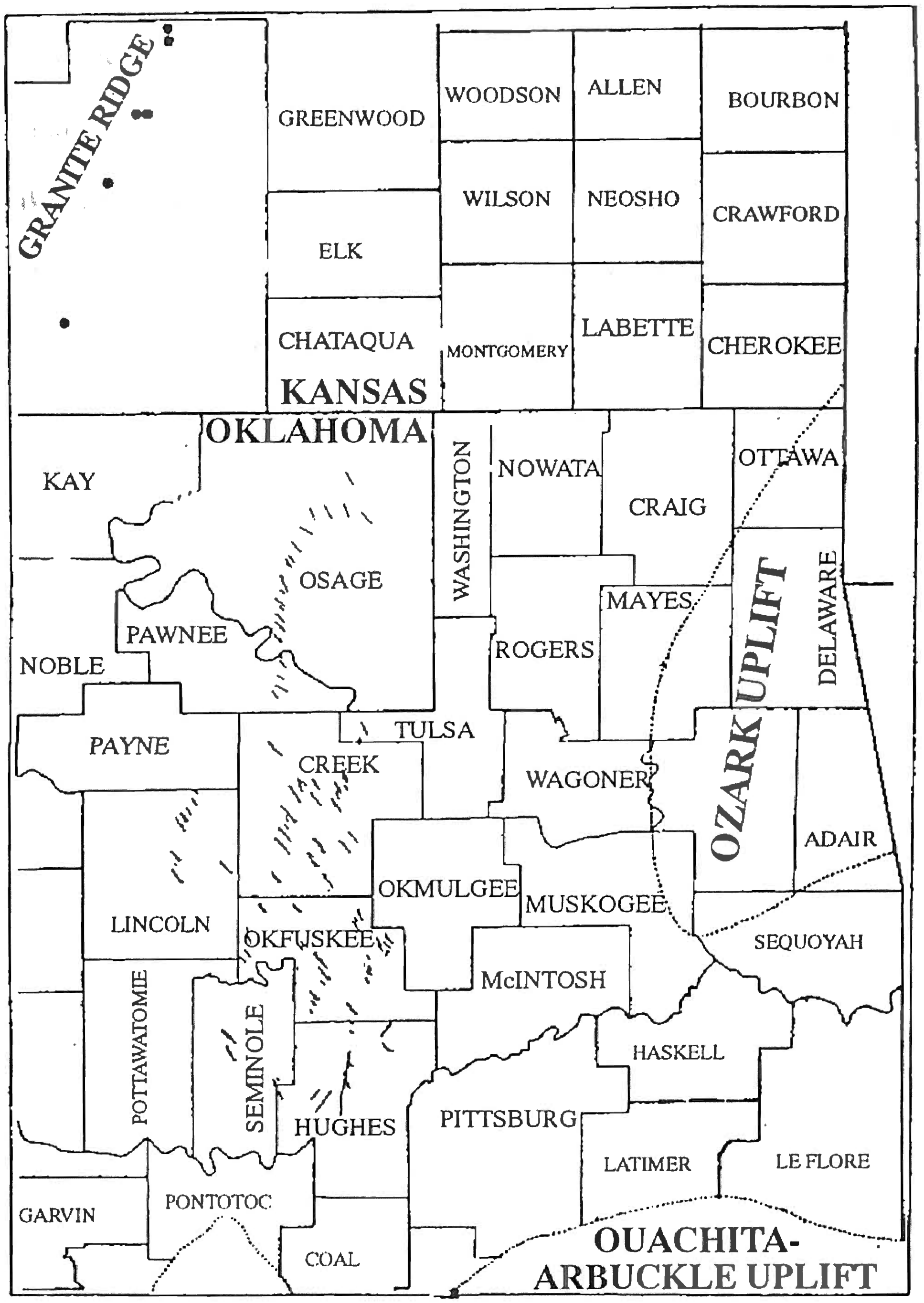

Figure 6. Distribution of En Echelon Faults and Their Relationship to Tectonic Features in the Region (after Foley, 1924).

sequence in Pawnee County as having an aggregate thickness of about 265 feet consisting primarily of dark marine shale with interbedded sandstones (Figure 7). At the study area the only units encountered during drilling were the Kanwaka shale,Elgin sandstone and Quaternary age Terrace Deposits. This study focuses on those rocks of the Kanwaka shale, the Elgin sandstone and Quaternary Terrace Deposits.

In Pawnee County the Elgin is made up of four sandstone beds (Pve1 through Pve4) and numerous sandstone lenses within the Kanwaka shale, Pve1 being the oldest sandstone and Pve4 being the youngest (Figure 7). The Kanwaka shale is best developed in Pawnee County in the vicinity of the study area but only one of the Elgin sandstone beds (Pve2) is believed to be present there. In the vicinity of the study area the second Elgin sandstone (Pve2) actually consists of several sandstones interbedded with shale (Greig, 1959). The second Elgin sandstone (Pve2) should probably be considered as a zone of lenticular sand bodies rather than as a single continuous bed because it is doubtful that any one of them is continuous over a wide area. Greig (1959) concluded from aerial photographs of southeastern Pawnee County, that the second Elgin (Pve2) sandstone and the third Elgin (Pve3) sandstone are distinct units separated by as much as 20 feet of shale. Near the study area however, the third Elgin sandstone (Pve3) likely is no more than the top member of the second Elgin sandstone (Pve2) zone of lenticular sand bodies (Greig, 1959).

Because the sands are all medium-to-fine grained, massive to cross bedded and are all in some cases jointed, it is virtually impossible to distinguish them from one another over a wide distance. Distribution of the thickest sandstone units are confined

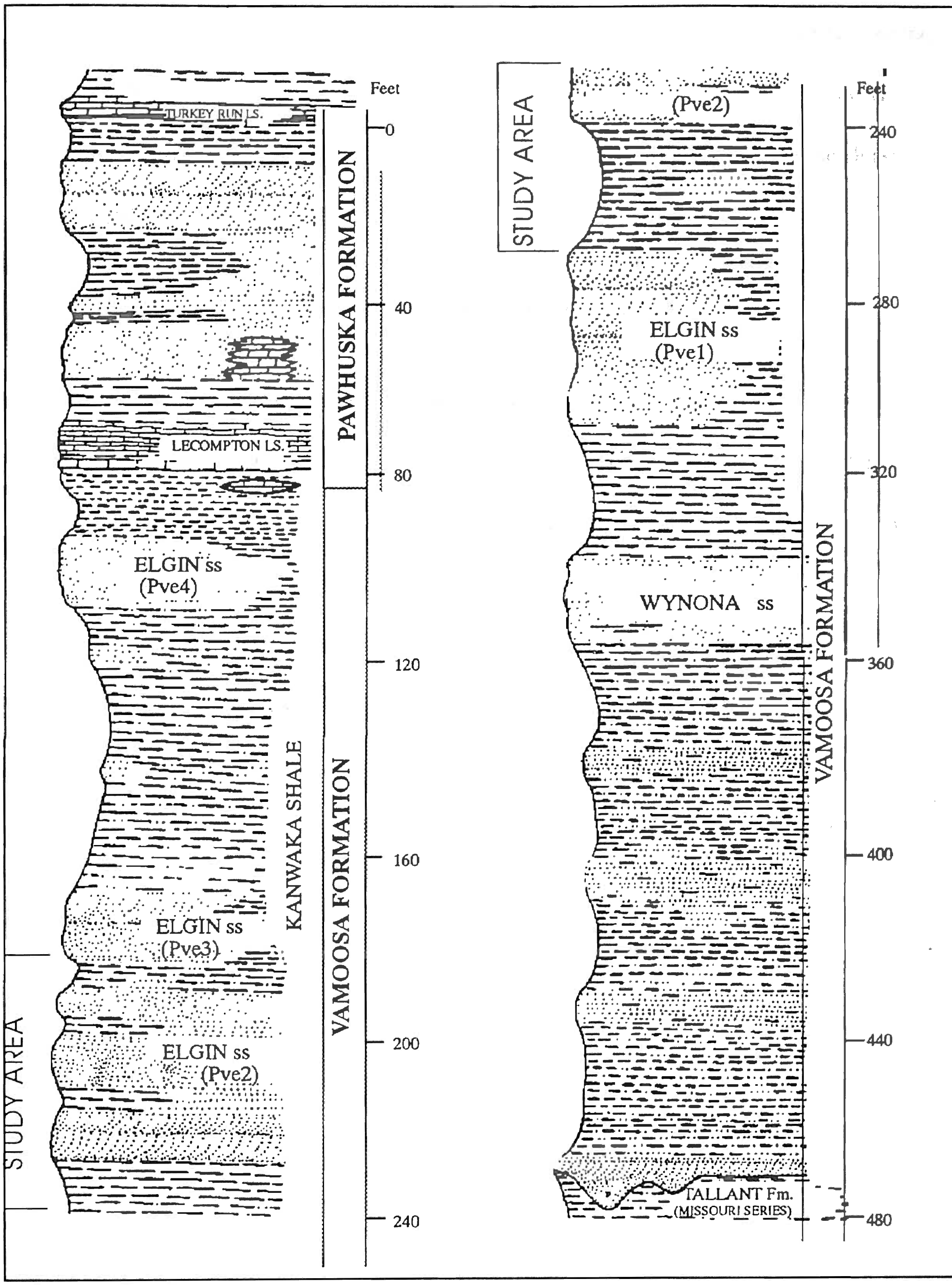

Figure 7. Generalized Composite Section of the Vamoosa Formation in Pawnee County (after Greig, 1959).

to areas south of the study area where deposition is representative of sand-rich deltaic sequences. Near the study area, the sandstone sequence at and near the surface is probably representative of both lenticular and the thinner delta-fringe marine deposits (Terrell, 1972).

Physiography of Pawnee County

Pawnee County is part of the Osage Plains section of the Central Lowlands province of the United States. Snider (1917) described the eastern portion of Pawnee County as the Sandstone Hills and the western portion of the county as the Red Bed Plains. The Sandstone Hills portion of the county is made up of rocks which are predominantly gray shales interbedded with resistant escarp forming sandstone and limestone beds. The Red Bed Plains are predominantly made up of red shales and soft sandstones.

Pennsylvanian and Permian rocks in eastern Pawnee County lie on the gentle westward tilt of a post-Permian structure known as the Prairie Plains homocline. Tilting and differential erosion of the sedimentary rocks in eastern Pawnee County formed the series of parallel north-south trending ridges previously alluded to as the Sandstone Hills. The ridges are capped by massive sandstones while the valleys are underlain by softer shale deposits. These sandstone ridges tend to be covered with thick timber and give rise to very rugged terrain. In contrast, the Red Bed Plains of the western portion of the county tend to be occupied by gently rolling grasslands (Snider, 1917). Elevations in the county range from approximately 1000 feet above mean sea level to approximately 730 feet above mean sea level on Keystone reservoir at the eastern edge of the county. Local relief is not extreme and rarely exceeds 150 feet.

Pawnee County is drained by two major rivers, the Arkansas, which forms the northern border of the county and the Cimarron River in the south part of the county. The present pattern of streams was formed following formation of the peneplain surface during a single erosion cycle which is still active today. Thick beds of alluvium in the stream valleys are still accumulating today. Secondary streams are diverted to the northern and southern halves of the county by an east-west divide, with the area north of the divide flowing into the Arkansas river and the area south of the divide flowing into the Cimarron river. Most of the secondary streams throughout the county are intermittent and even the largest, Black Bear Creek, is dry during periods of drought (Greig, 1959).

Soils

Soils at the study area are classified in the Cleora, Darnell, Dennis, and Port soil associations. All of these soils formed under tall prairie grasses in material that weathered from shale and sandstone (Soil Conservation Survey, 1966). The Cleora fine sandy loam is an 18-60 inch thick, noncalcareous, friable soil that occurs along the narrow dissected bottomlands in the eastern portion of the Pawnee County. At the study area, the Cleora soil varies from a light sandy loam to a loam with interstratified yellowish-red clays. Darnell soils are very friable, rapidly drained, range in thickness at the study area between 4 and 16 inches, and cover approximately 50% of the site. The Dennis loam covers approximately 10% of the study area and is made up of 20-50 inch thick, dark, granular, soils that have weathered from siltstone, sandstone, and interbedded clay shale of Pennsylvanian age. The Dennis loam is found at the northeast corner of the study area north of the railroad right-of-way. The Port silt loam ranges in thickness between 10 and 60 inches and can be found on the flood plain of Cedar Creek covering approximately 20% of the study area. The Port silt loam typically has a clayey substratum that causes the soil to drain fairly slowly. A typical profile of the Port silt loam has about 12 inches of dark silt loam which grades into very dark brown granular clay loam. Beneath 24 inches, the soils become lighter in color and may contain layers of silty clay (Soil Conservation Survey, 1966).

Climate

Pawnee County has a continental climate marked by fairly low humidity and pronounced changes in temperature and precipitation. In winter months it is common for this area to receive a combination of warm moist air from the Gulf of Mexico and cold dry air from the north. The alternate flows of cold and warm air bring significant variations of temperature, precipitation, cloudiness and wind velocity. A maximum temperature of 114 degrees F has been recorded in both July and August and a minimum temperature of -24 degrees F has been recorded in January. In summer though, clear days average around 80 degrees F and in winter daytime temperatures average around 40 degrees F. Average yearly rainfall ranges from 35 inches in the western portions of the county to 38 inches in the east (Soil Conservation Survey, 1966).

Ground Water

The principal source of potable ground water in eastern Pawnee County comes from the Vamoosa formation. Movement of ground water in the Vamoosa aquifer is controlled primarily by the lateral and vertical distribution of sandstone and shale units. Where sandstone thickness is greatest, the zone of potable water is also thick; where sandstone grades into less permeable shale, the base of potable water rises in elevation (D'Lugosz and McClaflin , 1986). The aggregate thickness of water-bearing sandstones is greatest south of the Cimmaron River, where it reaches a maximum of 550 feet near Seminole, Oklahoma. North of the Cimmaron River, the average thickness of the sandstones is about 100 feet. Work done by D'Lugosz and McClaflin (1986) shows that an overall decrease in transmissivity occurs from south to north corresponding with decreasing saturated thickness and sand thickness. In accordance with the regional dip of the aquifer, regional movement of ground water is presumed to be toward the west (D'Lugosz and McClaflin , 1986).

CHAPTER IV

SITE CHARACTERIZATION

Site Geology

Interpretation of the site geology was determined primarily by examination of continuous soil and rock cores extracted at the study area. Rapid changes in the vertical and areal extent of lithologic facies made attempts at detailed correlation very tenuous. Very small scale changes in lithology were incorporated into gross lithologic packages in order to make correlations across the study area easier. Plate 1 shows the locations of southwest-northeast and west-east generalized geologic cross-sections at the study area. Plate 2 is a generalized surface geology map of the study area showing the outcrop of hydrogeologic units. Plates 3, 4 and 5, are generalized hydrogeologic cross-sections of the study area. Plates 3a and 4a were constructed solely from boring and core hole data while Plates 3b and 4b were constructed by integrating core and boring data with information from the natural gamma geophysical borehole logs.

In Pawnee County, the Kanwaka shale includes four members of the Elgin Sandstone interbedded with the massive shales that make up the bulk of the Kanwaka shale. Greig (1959) designates the Pennsylvanian age Elgin sandstones as the Pve1, being the oldest and Pve4 the youngest (Figure 7). Depending upon location, all of the four Elgin sandstone units actually contain multiple layers of sandstone and shale that are laterally heterogeneous. According to Greig, only the second Elgin sandstone (Pve2) is continuously mappable across the county. Greig extends only the second Elgin sandstone (Pve2) onto the study area but identifies the third Elgin sandstone (Pve3) capping ridges immediately to the southeast.

Outcropping on the northwest half of the study area are interbedded Pennsylvanian age units of Elgin sandstone and Kanwaka shale (Plate 2). The southeastern part of the study area at the surface is made up of Quaternary Terrace Deposits which are underlain by the massive Kanwaka shale, seen in the quarried exposure immediately south of Cedar Creek. An upper member of the second Elgin sandstone (Pve2) can be seen capping the ridge above the Kanwaka shale quarry.

At the northwest corner of the study area (Plate 2), what is designated as the A sandstone may actually be a basal portion of the third Elgin sandstone (Pve3). However, for purposes of this thesis, only the second Elgin sandstone is believed to be present at the study area. Laterally continuous sandstone and shale beds across the study area were labeled A, B, C, and D (Plate 2). The A sandstone and shale being the youngest and the D sandstone and shale being the oldest. Stratigraphic units presented on Plate 2 are described in more detail in the following discussion.

Quaternary Terrace Deposits

The Terrace Deposits consist of red silts and clays and some basal gravel. Thickness ranges from 0 feet in the channel of Cedar Creek, where erosion has downcut into the underlying Kanwaka shale, to over 40 feet along the western contact with the Pennsylvanian sandstone and shale units.

A Sandstone

The A Sandstone outcrops along the northwestern boundary of the study area. This sandstone unit ranges in thickness from about 0 to 20 feet. It is commonly fine to medium-grained, tan to light brown and moderately friable.

A Shale

This unit underlies the A Sandstone in the western portion of the study area. The A shale is dark-reddish brown to blue-gray at the base and attains a maximum thickness of 20 feet at the study area.

B Sandstone

This sandstone unit ranges in thickness from 0 to over 30 feet . It has been truncated by erosion along its eastern edge, and dips gently to the west-northwest. The B sandstone is fine to medium-grained grading to a coarser texture with depth. It is white to tan and commonly contains green to gray silty shale partings.

B Shale/C Sandstone/C Shale

These units, though apparently lenticular in nature, seem to be fairly continuous across the north half of the study area. The B Shale is dark gray, slightly fissile and is approximately 5 feet thick. The C Sandstone is light gray and ranges in thickness from 2 to 10 feet. The C Shale is also dark gray and appears to range between 2 and 10 feet in thickness. These units as a whole represent a discreet zone of separation between the B (upper) and D (lower) Sandstone units.

D Sandstone

The D (Lower) Sandstone is exposed in only one small area north of Cedar Creek. Soil borings and core holes indicate that the C and D sandstone units extend along the southwest portion of the property, but have been eroded in the rest of the area occupied by the Terrace Deposit. The D sandstone is characteristically a fine-grained, gray sandstone containing occasional shale laminae and reaching a maximum thickness of 53 feet at the study area.

Kanwaka Shale

The Kanwaka shale is a blue-gray marine shale which averages in excess of 100 feet in thickness beneath the D sandstone and Terrace Deposit. Greig (1959) notes that the Kanwaka shale in Pawnee County is best developed in the vicinity of the study area, particularly at the quarry shown at the southeastern portion of the study area immediately south of Cedar Creek. The quarry was excavated to supply materials to a brick plant which was operated for a period of 15 to 20 years in the early part of the century. The shale contains numerous small ironstone concretions and locally abundant molluscan fauna (Greig, 1959).

Hydrogeologic Characterization

Davis and Dewiest (1966) discuss confined, unconfined and perched groundwater conditions and offer a simple stratigraphic example of a sequence of alternating sandstones and shales (Figure 8) that closely resembles the hydrogeologic sequence present at the study area. At the study area, perched water tables are thought to be present in the shallow unconfined sandstones while a shift toward semi-confined conditions are believed to be present in the deeper hydrogeologic units. At the study area four primary hydrologic zones of interest were identified by the property owner (Kerr-McGee Corporation, 1992). The A, B and D sandstone units as well as the Terrace deposits were identified as having distinct water tables (Plates 3,4 & 5). Groundwater levels were measured in all monitoring wells on September 24, 1992 and are presented with other monitor well information in Appendix C. Plates 6, 7 & 8 are potentiometric surface maps of the B Sandstone (upper sandstone), D Sandstone (lower sandstone) and the Quaternary Terrace Deposits. Water tables for the three units evaluated are also depicted on Plates 3, 4 & 5 in cross-sections of the study area.

The water table in the Terrace Deposit ranges in depth from 15 to 20 feet below grade. Groundwater flows to the southeast with an average gradient of 0.016 feet per foot and discharges into Cedar Creek (Plate 6). Evaluation of the hydrologic data indicates that the water table in the D Sandstone (lower sandstone) may discharge directly into the Terrace Deposit along the erosional subcrop (Plates 4 & 8). The gradient in the D Sandstone ranges from 0.0025 feet per foot in the northwest portion

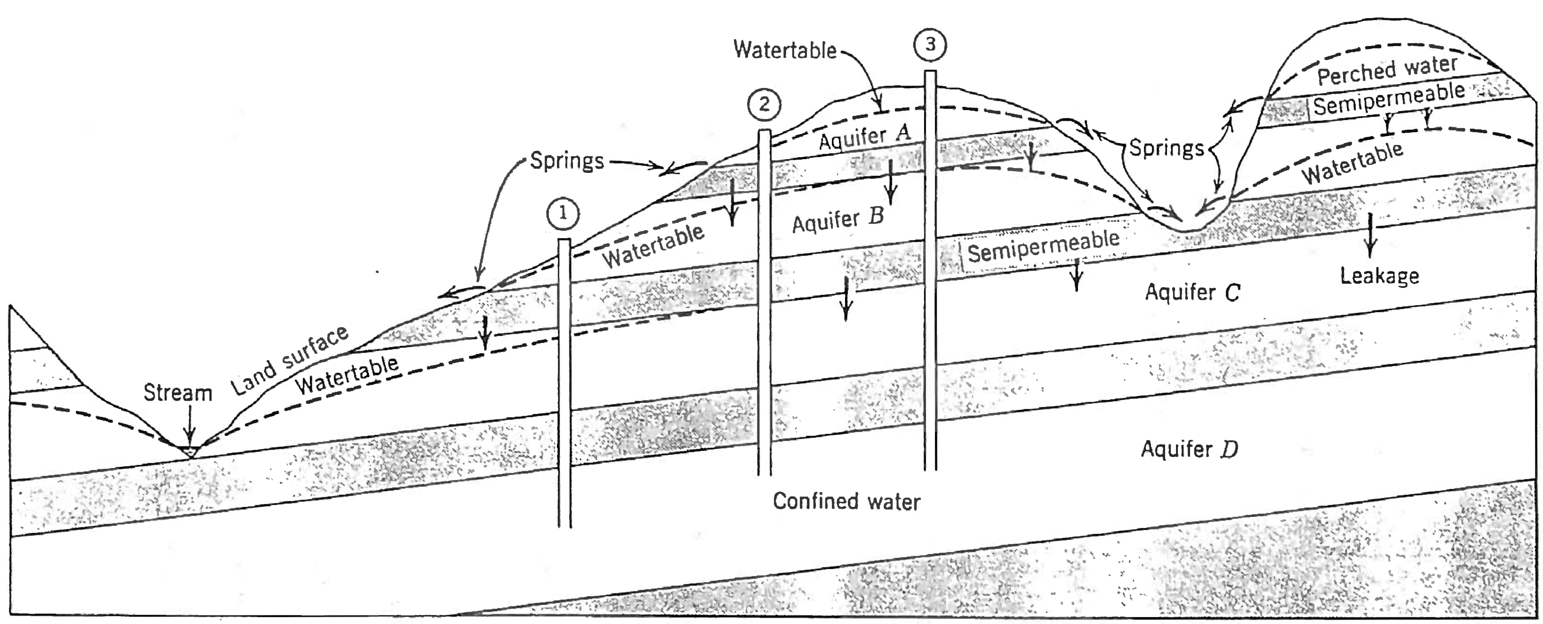

Figure 8. Stratigraphic Sequence of Alternating Rock Units with Confined, Unconfined, and Perched Water Tables (after Davis and Dewiest, 1966).

of the study area to 0.050 feet per foot into the Terrace Deposit along the erosional subcrop (Kerr-McGee Corp., 1992). Depths to groundwater range from 3 feet below grade near the erosional subcrop discharge area to 60 feet below grade along the western boundary of the property. The D Sandstone water table probably is confined in the northern and western portions of the property due to the low permeability of the overlying B and C Shale units. In the central portion of the property, recharge is probably occurring where the C and D Sandstones have been subjected to erosion. The relationships of these units and the overlying shale units are shown on cross-sections A - A' and B - B' (Plates 3 & 4).

The B Sandstone (upper sandstone) potentiometric surface map is presented on Plate 7. The B Sandstone water table is perched and discharges at the outcrop along the erosional edge. The water table is mounded within a local zone of recharge located around UMW1 (Plates 2 and 7). Plate 4 shows the groundwater flow to have a westward component within the B Sandstone. Depth to water in the B Sandstone ranges from 3 feet below grade near the discharge area to 43 feet below grade at the western edge of the property.

The A Sandstone (Plate 2) is limited in outcrop to an exposure along the western edge of the property. One monitor well (UAMW1) is screened in this zone from 807 feet to 817 feet. Depth to water at UAMW1 is approximately 10 feet below grade and, as in the B Sandstone, the water table in the A Sandstone may be perched. The A Sandstone is hydraulically separated from the B Sandstone by the A Shale which is 10 feet thick at UAMW1. Recharge is likely to occur along the erosional outcrop.

Aquifer Properties

The property owner installed three pumping wells in each of the hydrologic units to be used for aquifer tests. The wells, designated QPW-1 (Terrace Deposit), UPW-1 (Upper Sandstone), and LPW-1 (Lower Sandstone), are located on Plate 1. All pumping wells were constructed of 4-inch diameter PVC with flush threaded joints. 72-hour drawdown and 24-hour recovery aquifer tests were performed in each pumping well. Water levels were recorded throughout drawdown and recovery in the pumping wells and all observation wells (existing ground water monitor wells) within reasonable distance.

During pumping of the Upper (B) and Lower (D) Sandstones, monitor wells installed in both units were monitored. Results from the 24-hour recovery test in the Lower (D) Sandstone did not indicate that the Upper (B) Sandstone water table was affected by drawdown in the Lower (D) Sandstone. However, approximately two days after recovery test measurements on the Lower (D) Sandstone were completed, it was noted that water levels in the upper monitor well (UMW1) or Upper (B) Sandstone were significantly lower than when the test began. This delayed drainage effect may indicate that communication does exist between the Upper (B) and Lower (D) Sandstone. Table II (Kerr-McGee Corp., 1992) contains results of the three pumping tests along with estimated ground water velocities calculated from average or minimum/maximum gradients.

The three water tables within the sandstones are separated by shale layers which act as barriers to flow. It is likely that these sandstone intervals are not completely separate and distinct units but rather are likely part of a large sandstone body which contains several impermeable but discontinuous shale intervals. Permeability studies by Terrell (1972) show that lenticular sandstones have a preferred direction of grain orientation and that the Elgin sandstones in Oklahoma have a maximum horizontal permeability which is 18 percent greater than the vertical permeability. Locally, faulting may also be hydrologically important by either retarding ground water flow or creating preferential flow paths for recharge of the aquifers.

TABLE II

AQUIFER TEST DATA AND ESTIMATED
GROUND WATER VELOCITIES

UNIT	Ave T (GPD/FT)	Saturated Thickness	Ave K (GPD/FT²)	GRADIENT MIN	GRADIENT MAX	GRADIENT AVE	EST. Porosity	VELOCITY MIN	VELOCITY MAX	VELOCITY AVE
Terrace Deposit	1387 [1]	8	185			.016	20%			2
Upper Sand	62 [2]	10	6.2	.017	0.1		10%	.014	.83	
Lower Sand	660 [3]	35	19	.0025	.02		10%	.006	.51	

(modified after Kerr-McGee Corporation, 1992).

[1] Formation fully penetrated by well
[2] Formation fully penetrated by well screen
[3] Formation partially penetrated by well screen (56%)

Groundwater velocity calculated as:

$$\text{Minimum } V = \frac{K \; i^{min}}{7.48} ; \qquad \text{Maximum } V = \frac{K \; i^{max}}{7.48 \, n}$$

where:

Minimum V = groundwater velocity in feet/day (Darcian Velocity)
Maximum V = groundwater velocity in feet/day (Seepage Velocity)
K = hydraulic conductivity in gallons/day/ft^2
i^{min} = minimum gradient in feet/feet
i^{max} = maximum gradient in feet/feet (Seepage Velocity)
n = estimated formation porosity

CHAPTER V

EXPERIMENTAL METHODOLOGIES

Remote Sensing

A 1980 LANDSAT multispectral scanning (MSS) image (Figure 3) of the region surrounding the study area was examined in an effort to identify surface features that might suggest the presence of faulting. The MSS image has a spatial resolution of 57 by 79 meters per pixel and recorded four bands of visible and near-infared spectrum. The red color indicated on the image represents healthy vegatation and is useful for descriminating vegatation types, soil boundaries, and cultural features. The light blue color represents silty waters of the Arkansas River and Keystone Reservoir. The steel grey color is representative of inert materials (roads and highways). A few very subtle linear alignments of topography and vegatation were noted and marked on the satellite image to indicate the possible expression of a fault or fracture zone.

Stereopairs of aerial photographs shot by the Army Corp. of Engineers in 1940 were also examined and compared to the satellite data in order to evaluate possible surface faults at or near the study area. In 1959, Greig used aerial photo stereopairs to assist in mapping lithologic units and the series of en echelon faults that traverse the eastern third of Pawnee County. Figure 5 is a 1940 aerial photo which clearly shows the trace of a fault approximately 1 mile south of the study area.

Borehole Geophysics

Gross count natural gamma logging is undeniably the most common logging measurement made. It can be made in open and cased holes, with or without fluid, and continues to be one of the best correlation devices available. At the study area monitor wells logged were completed in competent Pennsylvanian age rocks with only a thin weathered zone at the surface.

An investigation was undertaken at the study area to characterize lithology and to correlate well data across the site. When monitor wells were drilled, an on-site geologist described and recorded lithology from rock cores, soil boring samples and drill cuttings. At a later date, a borehole geophysical logging program was conducted at the study area inside eleven monitor wells. The monitor wells were divided into three groups based upon the particular rock unit in which the wells were completed. Upper monitor wells are designated UMW, lower monitor wells, LMW, and Quaternary monitor wells, QMW. Appendix D contains well construction information on each series of monitor wells. Natural gamma and neutron logs were recorded in analog format in ten monitor wells which were completed with six-inch diameter steel outer casing and 2-inch diameter PVC inner casing. The steel casingwas set through the upper sandstone intervals where present in order to prevent the near surface aquifer from possibly transmitting fluids during drilling to any deeper formations. The lower monitor wells were screened with 2-inch diameter slotted PVC pipe at varying depths beneath the steel casing point (see Appendix D). One well, lower monitor well 12 (LMW12), was logged with the gamma and neutron tools before and after completing the hole with 6-inch diameter steel casing.

The natural gamma detector was positioned at the top of the logging sonde and the neutron source and detector were positioned at the bottom of the sonde. The logging sonde was 1 5/8" in diameter and was approximately 8 feet long. The natural gamma detector was located 6-inches below the top of the logging tool and the neutron source was located approximately 6-inches from the bottom of the logging tool. The neutron detector was positioned approximately 15 inches above the neutron source. The neutron probe utilized an americium-beryllium source with a strength of 1.5 curies.

The ten cased hole logs were run in both air and water filled casing (see Appendix D). Immediately following retrieval of 120 feet of rock core, lower monitor well 12 (LMW12) was stemmed with drilling fluid and logged open hole using both the natural gamma and neutron tool. Lower monitor well 12 (LMW12) was the only well logged in an uncased borehole. After coring the first 70 feet of LMW12, a natural gamma and neutron log was conducted. After completion of the geophysical log, 6-inch steel casing was set to a depth of 70 feet in order to protect any deeper formations from possible near surface contamination. The hole was then drilled out to a final depth of 130 feet. Before PVC casing and screen were set to the bottom of the well, the natural gamma and neutron suite of geophysical tools were run once again. This geophysical log recorded measurements from behind steel casing down to 70 feet and then from the open borehole to the final depth of 130 feet. These two logs are compared side by side along with a gamma scan of the cored interval and a lithology log in Plate 9.

The results of the well logging program were plotted in analog format in the field, converted to digital format and then imported into a computer-aided drafting program (AutoCAD) where they were manipulated into presentation format (see Appendix A). Well log plots include natural gamma and neutron curves, lithologic and core descriptions, well elevations and depths.

Shallow Seismic Reflection

The shallow seismic-reflection method has been used increasingly since 1980 in applications shallower than 30 meters as a tool for providing continuity in subsurface information and interpretation between drill holes (Steeples and Knapp, 1982). The shallow-reflection technique has recently been used in mapping bedrock beneath alluvium in the vicinity of hazardous waste sites, detecting abandoned coal mines, following the top of the saturated zone during an aquifer test in an alluvial aquifer, and in mapping shallow faults (Steeples and Miller, 1989). Detection of these shallow reflection events requires closely spaced source-receiver geometries, severe low-cut analog filtering, a suitable high-frequency seismic source, and a seismograph with quiet amplifiers and analog/digital (A/D) conversion into a large digital word (Knapp and Steeples, 1986).

The objective of the shallow seismic reflection survey at the study area was to map shallow structural and stratigraphic features such as possible bedrock faults, bedrock topography and alluvium thickness between two monitor wells. Steeples and Miller (1989) give a detailed discussion regarding equipment and techniques commonly used to perform shallow seismic reflection surveys.

At the study area, a series of 12-fold common-depth point (CDP) seismic reflection surveys were conducted with split-spread source/receiver geometry. The surveys were conducted using a 24-channel (EG&G Geometrics ES-2401) seismograph between KCH12 and QMW6 along cross section line A - A" (Plate 1). Field files were stored on floppy disks in SEG-2 format for processing in the field on the portable seismograph and back in the office on a desk top computer. Seismic energy was generated by striking a 16 lb. sledgehammer against an aluminum strike plate and was recorded with arrays of 40 Hz geophones as well as single 40 Hz geophones. A triggering mechanism taped to the handle of the sledgehammer provided a time-break signal at the moment the sledgehammer hit the strike plate.

Based on information from core hole KCH12 and monitor well QMW6 (Plate 5) it was suspected that a 40-foot thick sandstone interval was either faulted or eroded out along cross-section line A- A". Figure 9 is a graphical plot of seismic reflection Line # 1a, which was performed split-spread using 40-foot receiver arrays, 20-foot receiver intervals and a far offset of 250 feet. Seismic reflection survey Line # 1a was conducted in order to try and identify fault indicators along a major lithologic boundary several hundred feet deep. A dramatic change in first arrival times midwaythrough the line suggested that weathered surface materials varied locally in

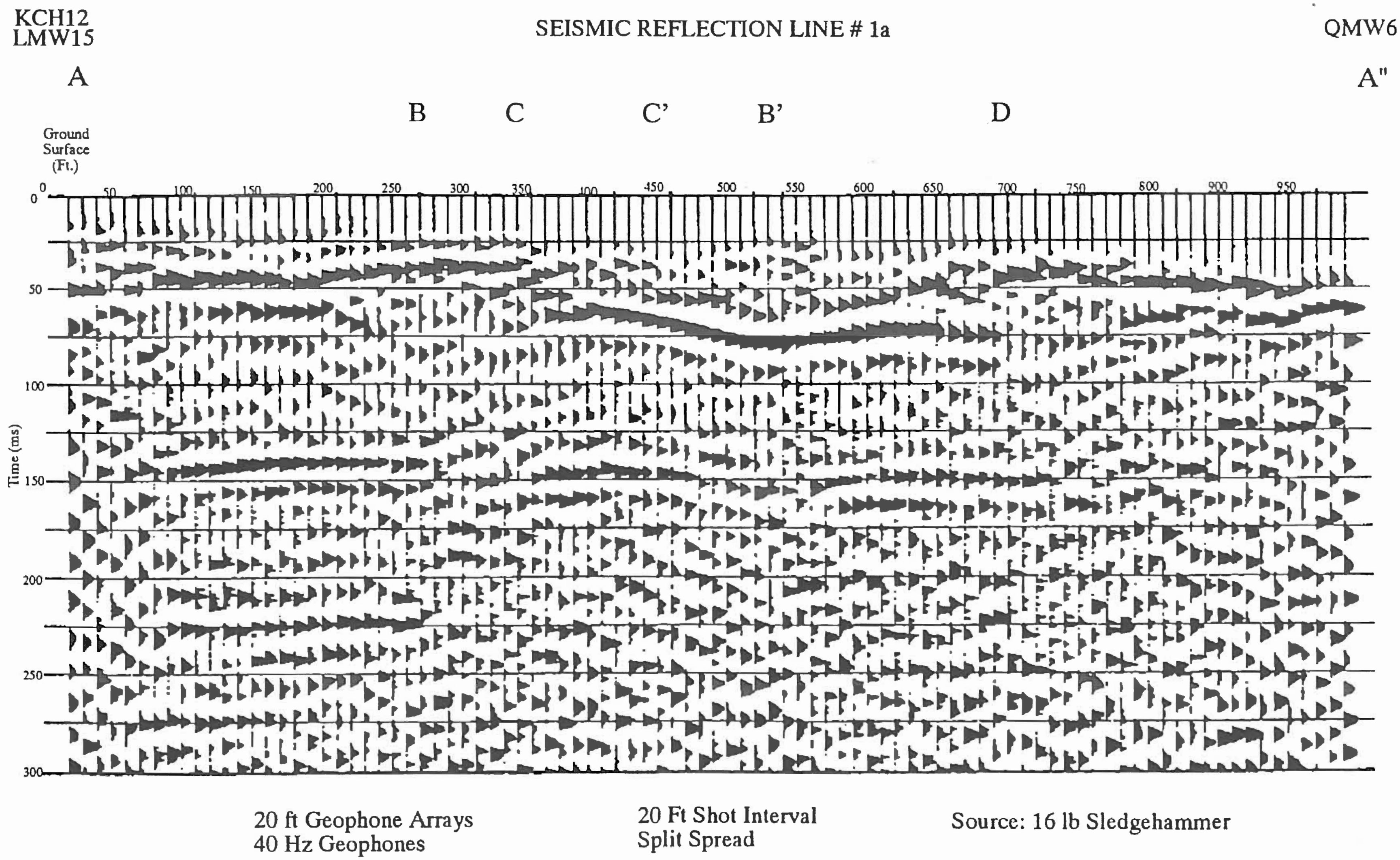

Figure 9. Seismic Reflection Survey Line # 1a (A - A").

thickness. At 150 ms a strong reflection event can be traced across the seismogram with some consistency but is disrupted in several areas. This disruption is probably due to near-surface refraction static shifts which have resulted because of change in the thickness of weathered or alluvial materials in the near surface. Figure 10 (Line #1b) is a graphical plot of Line # 1a after being processed with refraction statics software from Green Mountain Geophysics. After correcting for refraction statics shifts, the reflector seen at 150 ms in Line # 1a can easily be correlated across the seismogram with little or no disruption in Line # 1b.

Seismic reflection Line # 2 was conducted immediately parallel to Line # 1 using different field parameters in an attempt to increase resolution and define the local bedrock topography. Figure 11 is a graphical plot of Line # 2 (C - C'), beginning at footage maker 260 and ending at footage marker 450 . This line was recorded using a split-spread source/receiver geometry but utilized 6 foot overlapping 40 Hz geophone arrays with a three foot source interval. A strong sloping reflector appears in Line # 2 to a maximum depth of approximately 60 ms. It is believed that this sloping reflector may represent the interface between the Terrace Deposit and the bedrock.

Figure 12 is a graphical plot of Line # 3 (D -D') which begins at footage marker 340 and ends at footage marker 440 along A - A". Seismic reflection Line # 3 (D - D') was conducted in an effort to see if the same results achieved in Line # 2 could be acquired with a less cumbersome set of field parameters. As in seismic Lines # 1 & # 2, seismic Line # 3 was shot with a split/spread source-receiver geometry but Line # 3 employed the use of single 40 Hz geophones rather than arrays

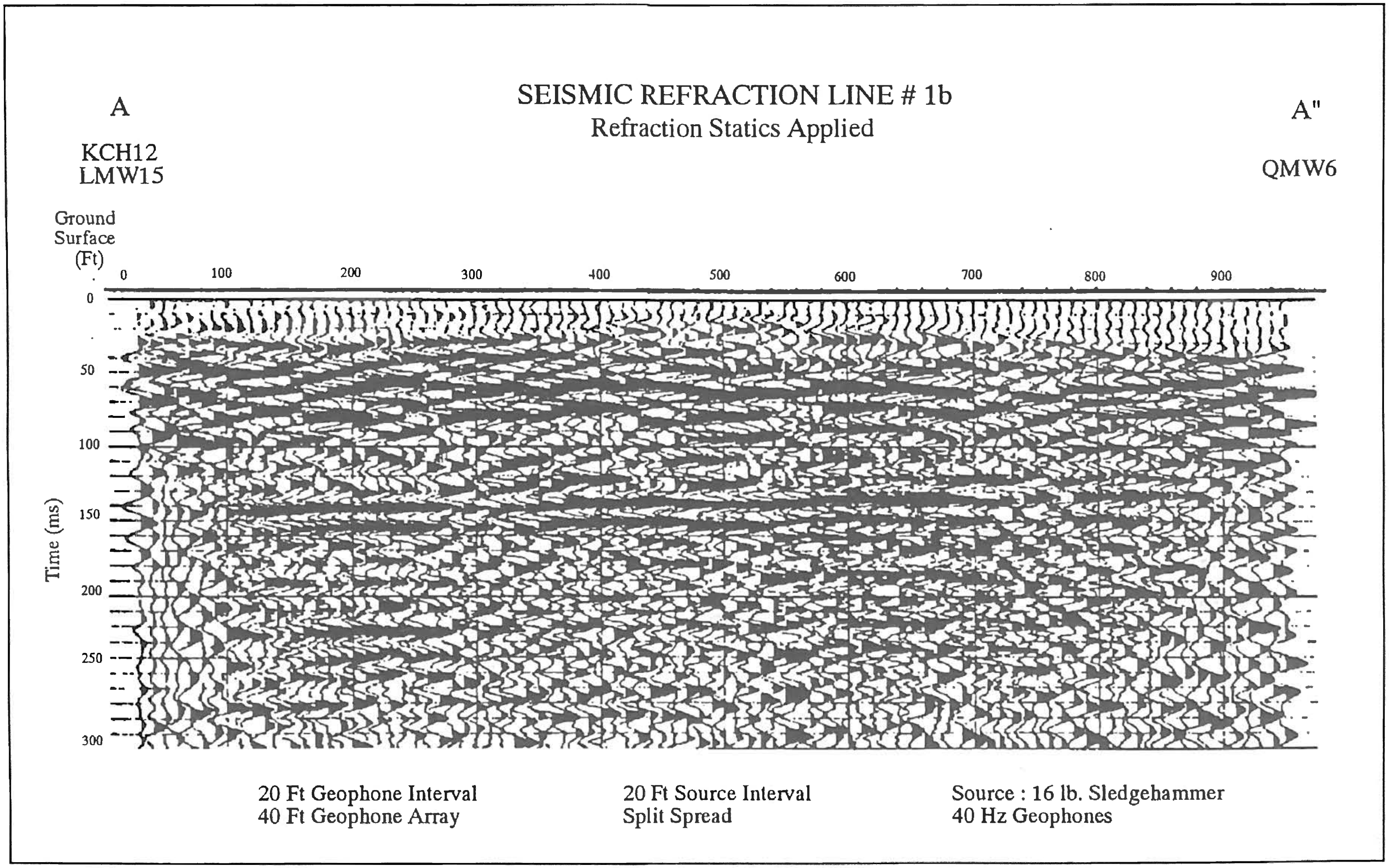

Figure 10. Seismic Reflection Survey Line # 1b (A - A").

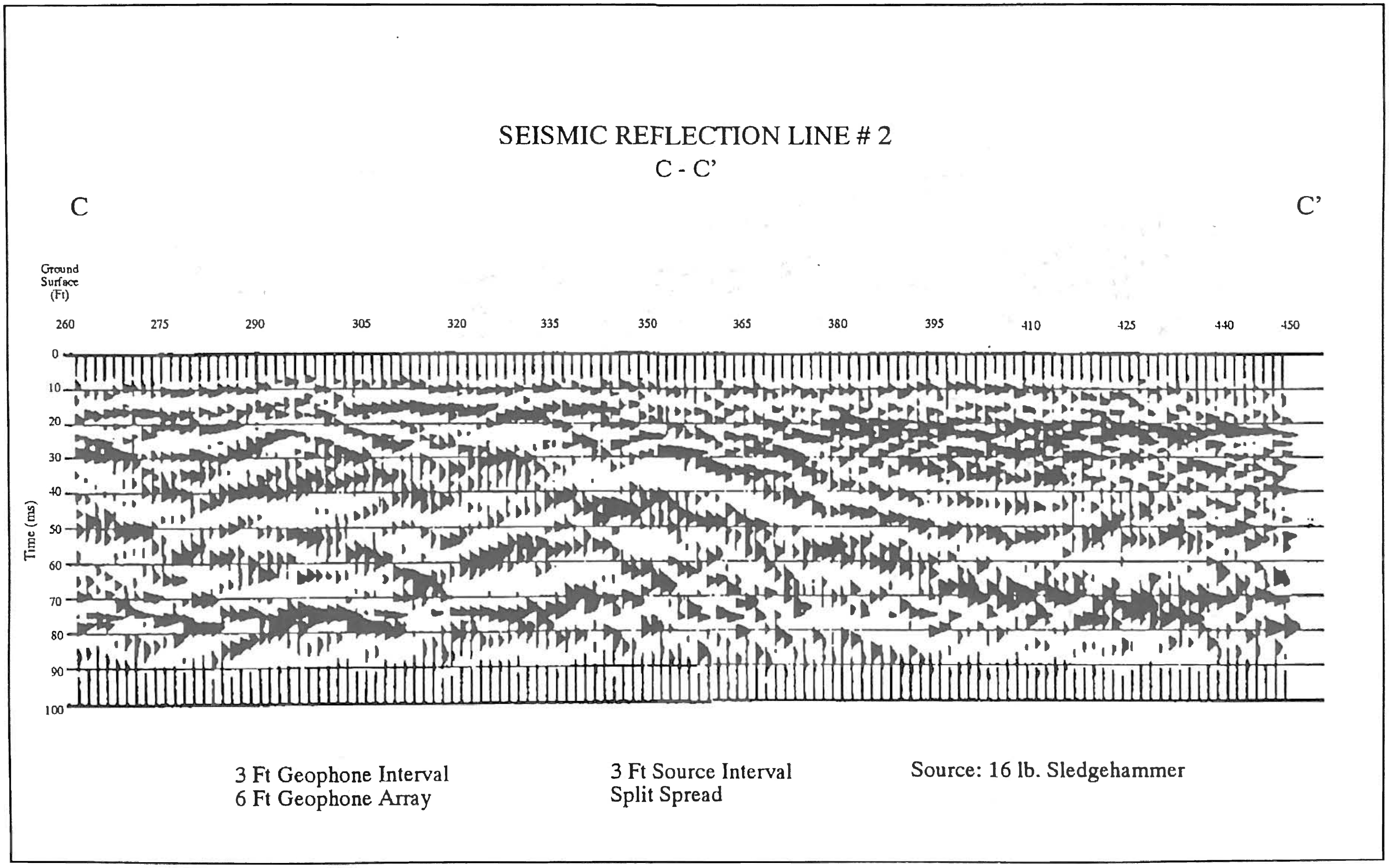

Figure 11. Seismic Reflection Survey Line # 2 (C - C').

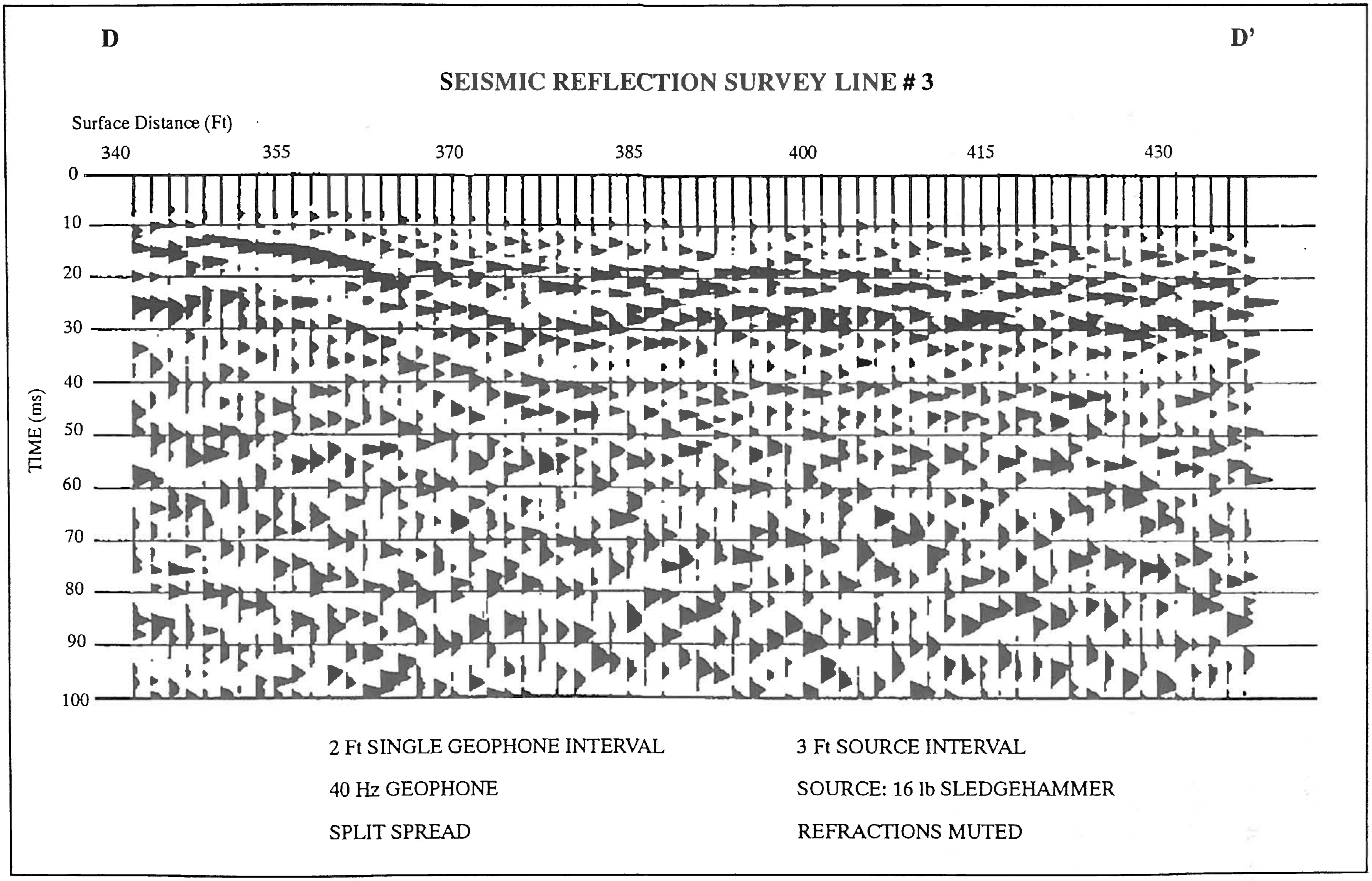

Figure 12. Seismic Reflection Survey Line # 3 (D - D').

of 40 Hz geophones. To diminish any interferences from wind noise, a 4-inch diameter auger was used to drill shallow holes for placement of the single geophones. In addition to diminishing the effects of wind noise it was believed that a better coupling between the geophone and the soil was obtained.The geophone interval in Line #3 was two feet and the source interval was 3 feet. Once again, a 16 lb. sledge hammer and aluminum strike plate were used for an energy source.

Processing of all seismic data was carried out on a desk top personal computer using software produced by Lookout Geophysical. The following processing flow was carried out on all three seismic reflection lines:

1) Data was resampled from the SEG-2 format to a format that the processing software would accept.

2) Surface elevations from a 2 foot contour interval map were entered into Lookout Geophysical's software to make a rough statics correction.

3) All traces were sorted and filtered with a spectral balancing filter in order to locate the optimal frequencies needed to see reflection events.

4) The traces were windowed and any dead traces were removed.

5) Gathered individual shot records and brought them into one file.

6) Normal moveout was applied.

7) Traces were summed together into a final stack.

Ground Penetrating Radar

The ground penetrating radar (GPR) system used in this study was manufactured by Sensors & Software Inc.. Figure 13 illustrates the complete system used in this investigation. Equipment necessary to conduct the ground penetrating radar survey included a transmitting and receiving antenna, a control unit or console and a display device (notebook computer). The heart of the system is the timing unit which controls the generation of the radar signal and then the detection of returned signals as a function of time. The transmitter and receiver components consist of separate electronics packages plus lightweight fiberglass antennae. Power from a 12 volt DC power source is used to generate a very short duration high voltage pulse which is radiated from the transmitter antenna into the ground. When the transmitted energy reaches an interface between two materials with differing dielectric properties, part of the energy is reflected back to the receiver antenna and the remainder continues into the subsurface. At this point the digitized signal is fed from the receiver antenna to the receiver electronics where it is detected and passed on to a notebook computer for storage and display.

Selection of the optimal operating frequency for a radar survey is not simple. There is a trade off between spatial resolution, depth of penetration and system portability. Low frequency antennae generally provide greater depth penetration but in turn provide less resolution. Higher frequency antennae tend to provide greater resolution but achieve relatively shallow results. As a rule, it is better to trade off resolution for penetration.

In the reflection mode, the radar transmitter and receiver antennas are deployed in a fixed configuration and are moved over the ground surface along a measured

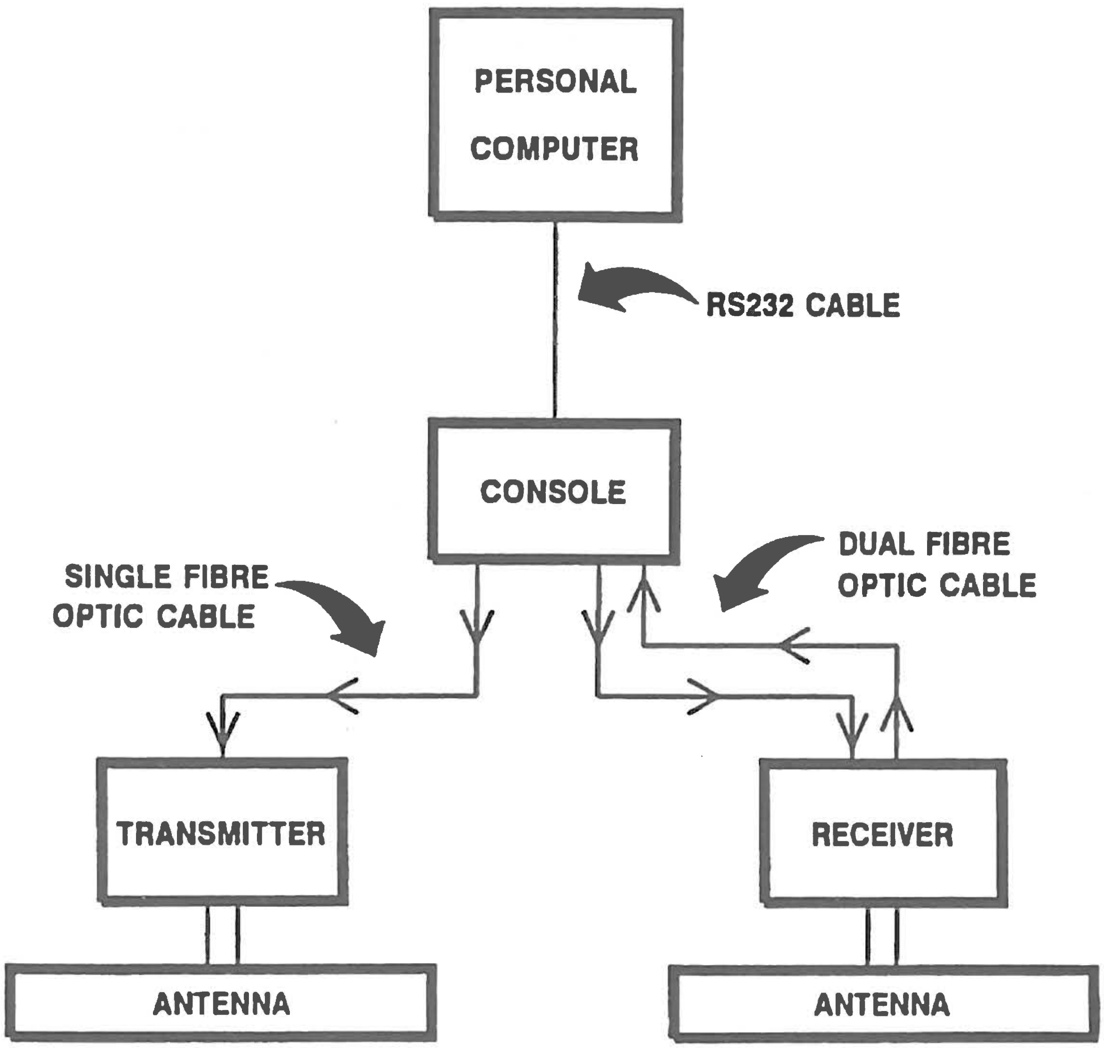

Figure 13. Block Diagram of the PulseEKKO IV Ground Penetrating RadarSystem (after Annan, 1992).

survey line. The reflection mode yields a cross-sectional view, similar to a seismic reflection line, which shows the travel time to reflectors versus position. The GPR software was set up to run in a continuous operating mode which automatically signals the operator to move the antennae to the next sample station when the current station has been completely sampled. The advantage of operating in a continuous mode is that the time spent collecting data is minimized and the flexibility in allowing an entire survey to be conducted by one person if necessary.

At the study area three attempts were made using 200 MHz, 100 MHz, and 50 MHZ transmitter and receiver antennae to collect a subsurface profile. Several short test profiles indicated that the best depth penetration was accomplished using the 50 MHz antennae. As a result of the preliminary test information, a single GPR survey line was conducted in reflection mode using the 50 MHz transmitter and receiver antennae. The survey was carried out along the same survey line as were the seismic reflection profiles, starting at LMW15 (A) and ending approximately 200 feet west of QMW6 (A"). Figure 14 is a graphical plot of the survey showing travel time versus ground surface position.

The transmitter and receiver antennae were deployed oriented parallel with one another, but six-feet apart. The six-foot separation between antennae was required in order to prevent the transmitted signal from overpowering the receiver electronics. The step size or fixed distance that the two antennae were moved before collecting data was two-feet. The two-foot step size was deemed an adequate sampling of data considering the total length of the survey. The total time window was 650 ns and the

A
WEST

GROUND PENETRATING RADAR SURVEY

E
EAST

Number of Traces = 365
Total Time Window = 650
Starting Position = 0.0
Final Position = 728
Step Size Used = 2 Ft.

Nominal Frequency = 50 MHz
Antenna Separation = 6 Ft.
Pulser Voltage (V) = 400
Number of Stacks = 32
Survey Mode = Reflection

KCH12
LMW15

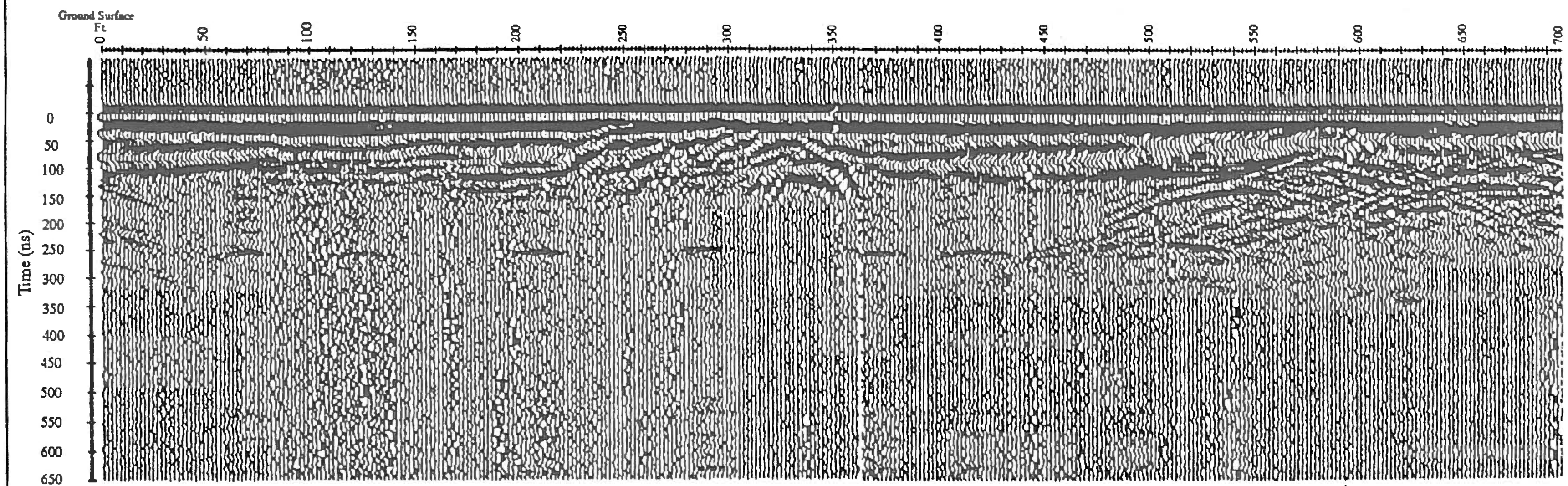

Figure 14. 50 MHz Ground Penetrating Radar Survey Line (A - E).

number of stacks used was 32.

Processing of the GPR data in most cases is virtually non-existent with the exception of applying AGC (automatic gain control) during and after data acquisition. The software package supplied with the GPR is designed to automatically line up the first arrival events so that post-collection processing is minimized or eliminated. However, after the survey has been recorded, it is possible to enhance the plot by changing the AGC and the plot layout parameters. The factors which are critical to the survey but which must be decided upon during acquisition are antenna frequency, antenna separation, step size, number of stacks, time window, and survey mode. These parameters cannot be manipulated with the software once a survey has been completed.

CHAPTER VI

EXPERIMENTAL RESULTS AND INTERPRETATIONS

Remote Sensing

The July, 1980 LANDSAT MSS image of the region surrounding the study area was evaluated in an effort to identify surface faulting. The technique was utilized with the understanding that low spatial resolution of the image made it difficult to interpret minor structural features. The high degree of vegatative cover present during the month of July was also likely to have covered possible structural features. Ideally, when interpreting geologic structure from satellite imagery, an image should be shot during winter months with low vegatative cover on a clear day with low sun angles. For some of the reasons mentioned, the satellite data was of limited success in helping to identify geological structures in the subsurface using physiographic and structural indicators. Lineaments that were identified are noted in Figure 3. One lineament appears to correspond with a surface fault mapped previously by Greig (1959).

Aerial photographs of the study area were examined alongside the satellite imagery in an effort to discern the presence of surface faulting. The increased resolution of the aerial photograph stereopairs made it possible to distinguish rock units which were exposed at the surface and to locate at least one fault (Figure 4) which had been mapped previously by Greig (1959). The aerial photographs also provided a historical look at the study area and made it possible to identify the location of manmade structures and process areas present at the refinery in 1940.

Borehole Geophysics

A borehole geophysical survey was conducted in several monitor wells across the study area during a three day period from March 24 through March 27, 1992. A total of eleven monitor wells were logged with natural gamma and neutron logging tools. The eleven wells were logged inside PVC and steel casing with the exception of LMW 3 which was cased with only PVC casing. One well, LMW 12,was logged both inside an open wellbore and after completion, inside a wellbore cased with steel casing. Logging LMW12 before and after completion made it possible to analyze the attenuating effects of casing and other annular materials on the gamma and neutron logging tools. The goals of the geophysical logging survey were to aid in characterization of the site and to assist in the identification of the site's structure, stratigraphy, and prinicipal ground water migration pathways.

Plate 9 shows a comparison of the natural gamma log from lower monitor well 12 (LMW12) which was conducted in both an uncased and cased hole. In addition to the borehole geophysical logs, over 120 feet of continuous rock core was retrieved from LMW12 and taken to a laboratory where it was scanned with a natural gamma ray detector. The core description and the results of the gamma core scan are also plotted alongside the two natural gamma logs in Plate 9.

Because of deviation from the typical response of gamma logs to lithology, some background information on a new study area is needed in order to decrease the possibility of error in interpretation. The tests run on LMW 12 afforded the luxury of seeing a direct comparison between the response of the natural gamma log signature from both cased and uncased holes alongside a continuous core of the entire logged interval. Abrupt changes in lithology and some gradational changes in clay and shale content can be noticed when observing the core description and the logs side by side. Results of the tests show agreement between each of the methods with slight variations probably occurring because of the presence of casing. Slight shifts in the gamma record from the core scan are likely caused by missing core.

The chief advantages of using natural gamma and neutron logs are that they can be operated through either steel or PVC casing and that they pose no risk of radiation exposure due to the fact that they contain no source of radioactivity. The ability to conduct a geophysical logging survey through PVC and steel casing was paramount at the study area since all but one of the monitoring wells had been installed prior to the planning of this thesis. Analyzing the effects of attenuation on cased hole logs from LMW 12 increased the level of confidence with which interpretation of gamma and neutron logs were carried out on the pre-existing monitor wells at the study area. The ten pre-existing monitor wells at the study were logged with the natural gamma and neutron tool through steel and PVC casing.

Plates 3a and 4a are hydrogeologic cross-sections (A - A' & B - B') of the study area which were constructed solely from core information and the site geologist's logging records. Plates 3b and 4b are the same cross-sections which have been reinterpreted with the aid of natural gamma logs. The most significant differences that are observed between the stratigraphic positioning of rock units occurs with the B Shale and C Shale. In both cross-sections the intermediate depth shale or clay units (B Shale/C Sandstone/C Shale) are shifted when identified with the natural gamma curve. It is possible that gradational changes in clay content, which are not immediately apparent when observed in drill or core samples, are being detected with the gamma tool. It is also possible that missing samples within the core barrel or sampler may have led to a shift in the true stratigraphic position of clay or sand units.

The geophysical well logs and core information appear to confirm the heterogeneity suspected in the various sandstone and shale bodies across the study area. In some cases, where alternating sand and shale layers were very thin, multiple layers were incorporated into gross lithologic packages for ease of correlation across the study area. Location of the shale or clay layers was considered to be very important in characterizing the site because of their ability to alter or impede the flow of fluids in the subsurface. The existence of separate water tables in each of the sandstones tested indicates that vertical communication between the sandstone bodies is probably controlled by the thickness and lateral extent of the shale layers.

Shallow Seismic Reflection

Testing of several different frequency seismic sources and geophones was carried out at the study area from April, 1992 through January, 1993. Early attempts to record high frequency shallow seismic events were carried out using equipment originally designed for recording low frequency seismic reflection events commonly used in the oil and gas industry. Problems associated with low frequency interference and difficulty in recording frequencies above 100 Hz led to the acquisition of higher frequency geophones and experimentation with a high frequency seismic source which was economical and safe. The most successful shallow seismic-reflection lines carried out at the study area were conducted with 40 Hz vertical geophones and a 16 lb. sledgehammer for a seismic energy source.

Cross section A - A" (Plate 5) is a generalized hydrogeologic interpretation between core hole 12 (KCH12) and Quaternary monitor well (QMW6) based on core information and data from shallow seismic reflection and ground penetrating radar (GPR) surveys. At the surface along A - A", it was noted that weathered sandstone was seen in outcrop between footage markers 250 and 350. The first seismic reflection survey line (Figures 11 & 12) was conducted along a straight line beginning at KCH12 and ending at QMW6. The purpose of Line #1 was to gather information regarding possible bedrock faulting. Source/receiver geometries were fairly large in order to focus on reflection events that were likely to occur at depths greater than 100 feet. As discussed in Chapter VI, results from Line #1a were spurious because of interference caused by a thickening of weathered (alluvial) materials over the local bedrock. However, it was clear from Line #1a that a strong reflection event was taking place at approximately 150 ms in time. Line #1b shows lateral continuity of the 150 ms reflector after statics corrections were made to Line #1a.

In an effort to substantiate the presence of an erosional contact between LMW15 and QMW6, seismic reflection Line #2 (Figure 11) was conducted between B - B' focusing on reflection events taking place within the first 100 feet of the surface. Closer source and receiver geometries increased resolution and made it possible to see what appears to be a sloping reflection event starting at approximately 20 ms and continuing with increasing dip across the survey line. It is possible that this curved event represents the surface of the bedrock. Whether the bedrock immediately underlying the terrace deposit here is sandstone or shale cannot be determined without drilling information.

The final seismic reflection line (Line # 3) was conducted along an even shorter interval of the original seismic line between KCH12 and QMW6. Figure 12 is a graphical plot of seismic reflection Line #3 (C - C') which shows some type of dipping reflection event though it is not as pronounced as the reflection event shown in Line #2 (Figure 11). The purpose for conducting Line #3 was to attempt to duplicate the results of Line #2 with less cumbersome field parameters. In fact, Line #3 was easier to conduct in the field but offered much less desirable results.

Due to the site dependent nature of seismic reflection surveying, preliminary field tests like those performed at the study area are usually necessary. Handicapping the series of seismic surveys performed at the study area was the fact that, though individual gathers could be viewed in the field, a final stacked section could not be viewed until data was collected and taken into the office to be processed. This meant that a test using a predetermined set of field parameters had to be carried out in the field and processed before one could evaluate the results of the surveys design. The search for appropriate field parameters likely would have been sped up considerably if a portable computer with processing software had been available to take into the field.

The results of the shallow seismic reflection survey were not as conclusive as had been originally hoped but important insight to equipment needs were gained. Improvement in signal would likely be accomplished with higher frequency geophones (100 Hz) and a more repeatable seismic energy source. At the study area, problems associated with collecting high resolution seismic reflection data at depths shallower than 100 feet, centered primarily around the inability to record very high frequency acoustic. Most of the problems encountered at the study area early on, with regard to low frequency interference, were overcome by using arrays of geophones rather than single geophones.

Ground Penetrating Radar

On January 21, 1993, a ground penetrating radar (GPR) survey using the PulseEKKO ground penetrating radar was conducted at the study area between core hole KCH 12 and monitor well QMW 6 (see Plate1). The GPR profile started at KCH 12 and paralleled seismic reflection Line#1 for 690 feet but was terminated before reaching QMW 6 because of standing water and mud. Figure 14 shows the results of GPR survey with travel time displayed in the vertical direction and ground surface position displayed along the horizontal axis. The GPR profile is essentially the same as a seismic reflection profile except that the electromagnetic frequencies measured by the GPR are much higher than the acoustic energy levels measured with shallow seismic techniques.

Initially, 200 and 100 MHz transmitter and receiver antennae were experimented with in an attempt to profile the bedrock surface beneath alluvial deposits along the southern border of the study area. These early attempts at profiling were unsuccessful because of the presence of silty clay layers near the surface. The final GPR survey (Fihure 14) was conducted using 50 MHz antennae with a six-foot antenna separation. Results of the survey are clearly not optimal but do indicate the existence of at least one anomalous feature in the subsurface.

The GPR profile presented in Figure 14 shows reflections down to about 150 ns. In the area between footage markers 240 and 360, curving reflectors appear to come to the surface. Along this portion of the survey line, what is believed to be in situ sandstone can be seen in outcrop. The strong reflection event that occurs between 50 and 75 ns across the profile probably represents an intra alluvial reflector from within the terrace deposit. The series of small hyperbolas at 250 ns spaced every 60 feet are probably a result of the interference from the computer and console coming too close to the transmitter and receiver. The events seen between 500 and 700 feet all seem to have a fairly high frequency and are therefore probably coming from reflections in the air. If, in fact, the strong hyperbolic reflections seen occurring at 240 and 350 feet are representing the sandstone seen in outcrop, this may be the erosional edge of the D Sandstone. The information collected from the GPR survey was interpreted alongside the seismic reflection data in order to assist in constructing hydrogeologic cross-section A - A" (see Plate 5).

As with the information from the seismic reflection survey, results from the GPR survey were not as promising as initially anticipated. Limited success was achieved in locating the alluvial\bedrock interface where depth to bedrock with the 50 MHz antennae though it appears that some intra-alluvial features appear withyin the Terrace Deposits. Because of the high electrical conductivity found in the Terrace Deposits, it is doubtful that depth penetration greater than 10 feet was achieved using the 50 MHz antennae. The next lowest frequency antennae available was a 25 MHz transmitter and receiver but it was not rented because of time constraints and the added expense involved in shipping. The 50 MHz antennae are both approximately 6 feet long while the 25 MHz antennae are approximately 12 feet in length. Nevertheless, it is questionable whether even the 25 MHz antennae would achieve the desired penetration because of the highly conductive nature of the surface materials found at the southern portion of the study area within the Terrace Deposits.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The goals of this research were to characterize the hydrogeology at an abandoned refinery site using core, drill, and water level data and to demonstrate the potential application of specific surface and subsurface geophysical tools to hazardous waste site investigations. Information from satellite imagery, aerial photography, core hole, drilling, and water level data, aquifer tests, along with data from geophysical borehole, shallow-seismic reflection, and ground penetrating radar surveys were collected and interpreted to characterize the hydrogeology at the study area. The study area was chosen because of the large number of groundwater monitor wells at the site, which provided an unusually dense hydrogeologic data base to utilize in interpreting observations.

In order to better characterize the hydrogeologic conditions present at the study area, a series of objectives were established and followed. The following summary and discussion describes the approach used to characterize the hydrogeology and evaluate specific geophysical tools at the study area.

1) LANDSAT multispectral scanning (MSS) satellite imagery (Figure 3) and aerial photography (Figure 5) was examined in order to establish the existence of

surficial lineaments or fracture patterns at or near the study area which might play a role in the preferrential flow of groundwater. The satellite image was of limited value in interpreting structural features in the vicinity of the study area due to low spatial resolution and heavy vegatative cover though it did appear to identify one previously identified fault trace. Stereoscopic pairs of vertical aerial photographs of the study area offered a greater degree of resolution than the MSS image, allowing the interpreter to distinguish some rock units and minor structural features

2) Several hundred feet of rock core (Appendix B) was examined in detail along with lithology logs from ground water monitor wells in order to characterize aquifers and confining layers present at the study area. Hydrogeologic cross-sections of the study area (Plates 3a & 4a) were constructed using only core, drilling, and water level data from across the study area. Water level data recorded on 9-24-92, in groundwater monitor wells across the study area was used to construct potentiometric surface maps the three known hydrogeologic units (Plates 6,7, & 8). Potentiometric surfaces shown all hydrogeologic cross-sections reflect the potentiometric surface maps of the three known water bearing hydrogeologic units (Plates 6,7 & 8).

3) A geophysical borehole logging program was carried out inside eleven groundwater monitor wells at the study area. The shallow hydrogeologic boundaries which influence the flow of ground water at the study area were evaluated with natural gamma borehole logging tools in order to verify information collected from core and sample data. Based on comparisons of natural gamma logs conducted in lower monitor well 12 (LMW12) before and after casing was set (Plate 9), it is believed that

the gamma tool was successful at identifying shales and clays in existing groundwater monitor wells cased with both steel and PVC. The geophysical logs from LMW12 were also compared with over 120 feet of continuous rock core which was retrieved from the well. Neutron logs were conducted along with the natural gamma logs as a secondary means of measuring moisture content. Results from the borehole geophysical logging program were used to re-interpret hydrogeologic cross-sections (Plates 3b & 4b) constructed solely from core and sample data (Plates 3a & 4a). In some cases, where the clay content of sandstone increased without being easily noticeable in the cored sections, the gamma log detected the increased radiation found in the clay or shale. The ability of the natural gamma log to pick boundaries of the sandstone aquifers make it particularly valuable for determining where to locate ground water monitor well screens or to evaluate previously constructed groundwater monitor wells.

4) Several shallow seismic reflection surveys were conducted in an attempt to profile the shale and sandstone bedrock surface covered by Quaternary terrace deposits at the southern portion of the study area (Plate 5) between LMW15 and QMW6 (A - A"). Several different field parameters were employed at the study area in an effort to improve the signal-to-noise ratio when recording high frequency seismic reflection events. No evidence of bedrock faulting was identified at the study area where the seismic survey was carried but what appears to be the edge of a bedrock\alluvial boundary is discernible on seismic Line # 2 (Figure 11). The sloping reflection event on Line #2 is interpreted to be the erosional subcrop of Lower (D) Sandstone.

Because of the extremely site-dependent nature of shallow seismic reflection surveying, some preliminary testing is critical to assessing resolution limits. At most locations, it is extremely difficult to map geologic boundaries with seismic reflection at depths shallower than 50 feet although published case studies do exist. An objective of this thesis was to profile the bedrock/alluvium interface at the study area and to determine whether or not bedrock faulting could be detected. Seismic reflection did help prove that no major fault displacement at the southern portion of the study area but it did not show whether or not fracturing may exist. A technique which appeared successful for mapping the reflecting boundary of the bedrock/alluvium interface was resolved, but because of the physically cumbersome receiver arrays necessary, the technique would probably not be economically feasible at the study area. Further experimentation with higher frequency sources, filters, receivers, and detailed velocity analyses would undoubtedly lead to an increase in resolution of data at the study area. It can be expected that as micro-electronic technology continues to advance and newer, less cumbersome techniques are developed, variations on the method will see increased acceptance where detailed identification of geologic boundaries are the objective.

5) A ground penetrating radar survey (Figure 14) was carried out at the same location that the seismic profiles were conducted (A - E) in order to evaluate the two techniques effectiveness at profiling shallow geologic features side-by-side. The ground penetrating radar offered a rapid means of collecting data with relative ease and seems to have been effective at profiling reflection events within the first ten feet

of the surface. However, highly conductive soils at the southern portion of the study area prevented most of the 50 MHz signal from penetrating to depths that would have been useful in mapping the entire bedrock surface. Though it was not possible to map the entire bedrock surface with the 50 MHz antennae, the GPR was successful at defining the probable lateral extent of the sandstone bedrock shown in Plate 5.

The greatest restriction on the use of the GPR is imposed by the rapid attenuation of the radar signal in high electrical conductivity materials, such as clays or in aquifers with highly mineralized groundwater. Moving to an even lower frequency antenna (25 MHz) likely would have increased penetration but also would have probably resulted in a decreased resolution of reflector locations.

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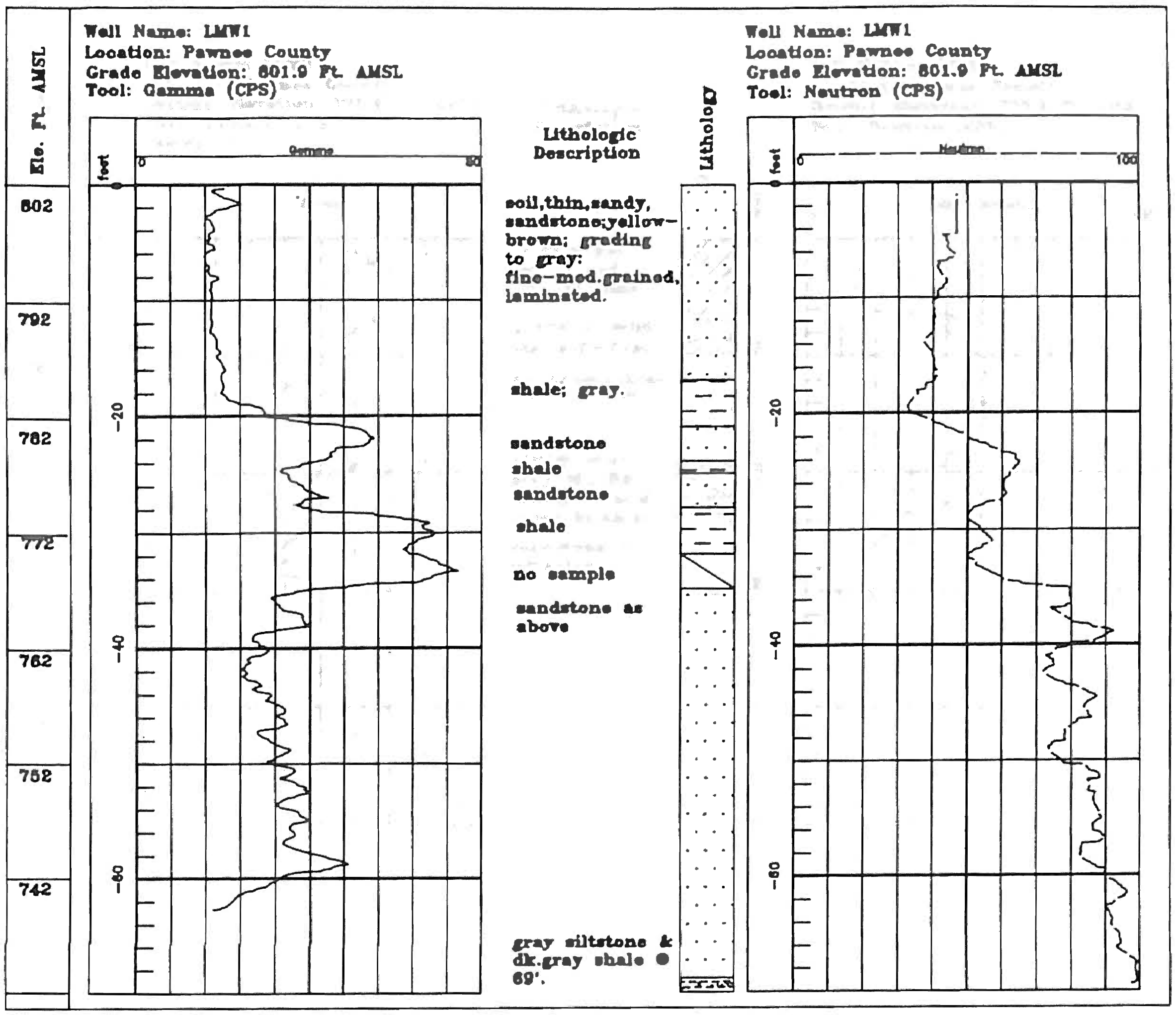
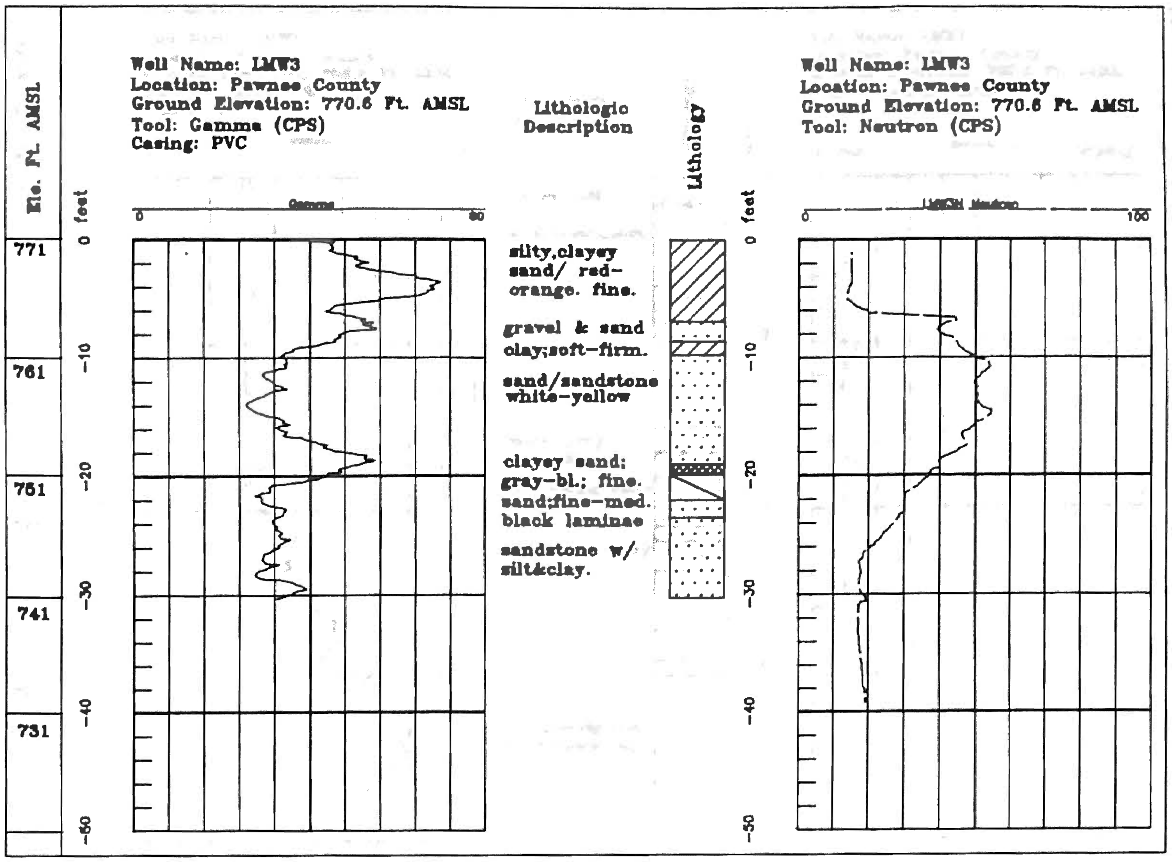
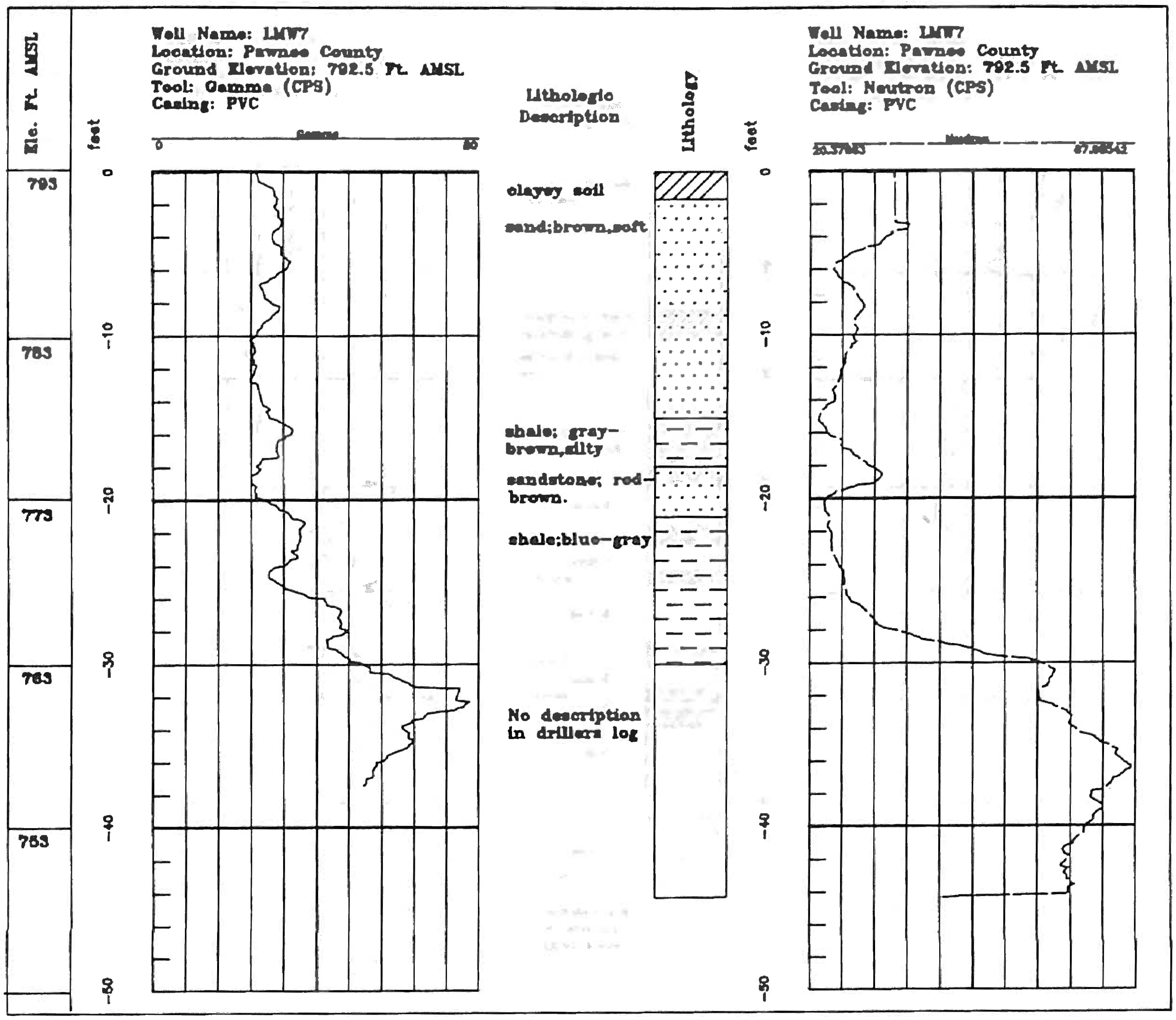
APPENDIX A

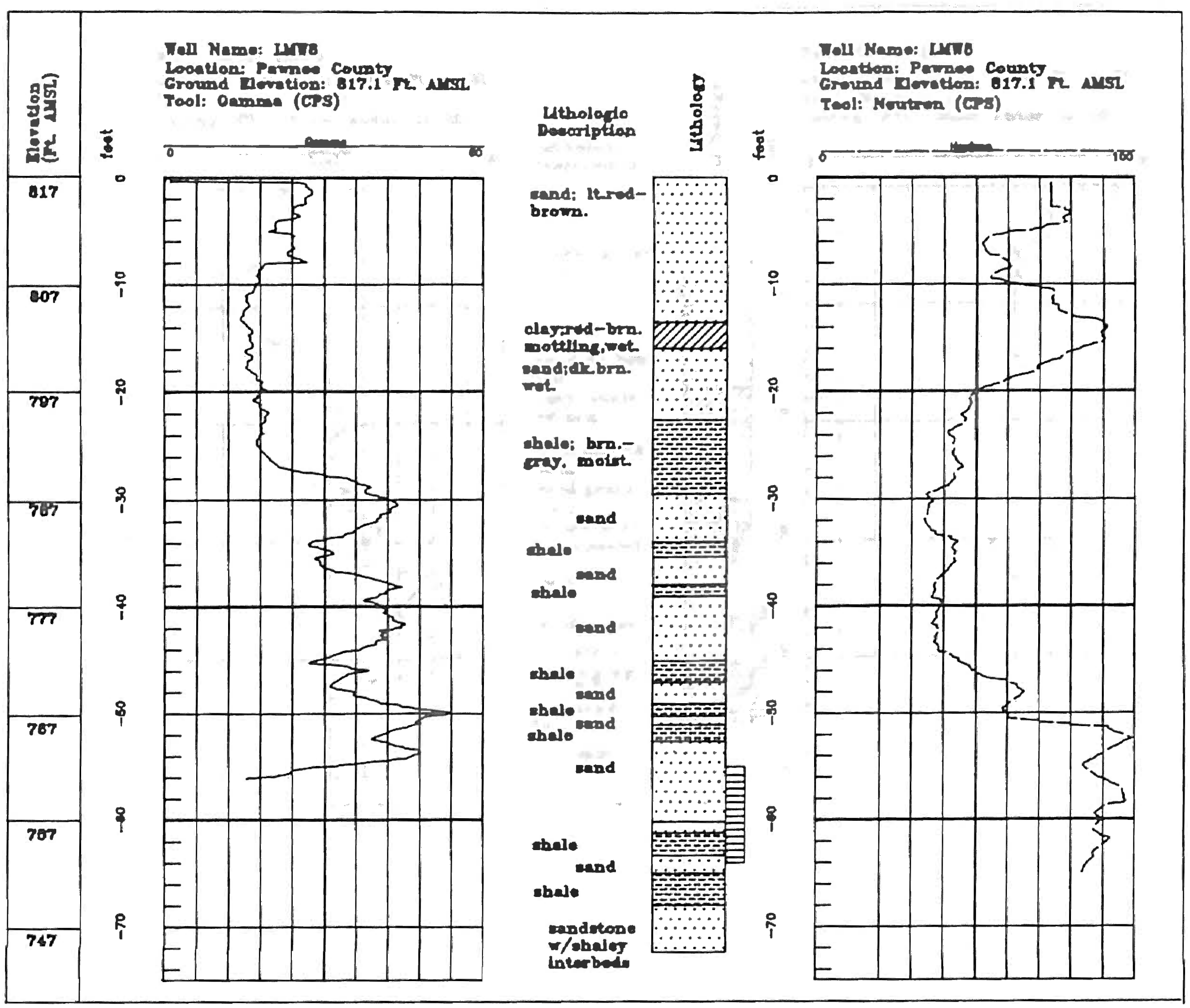
GEOPHYSICAL WELL LOGS FOR MONITOR WELLS AT THE STUDY AREA

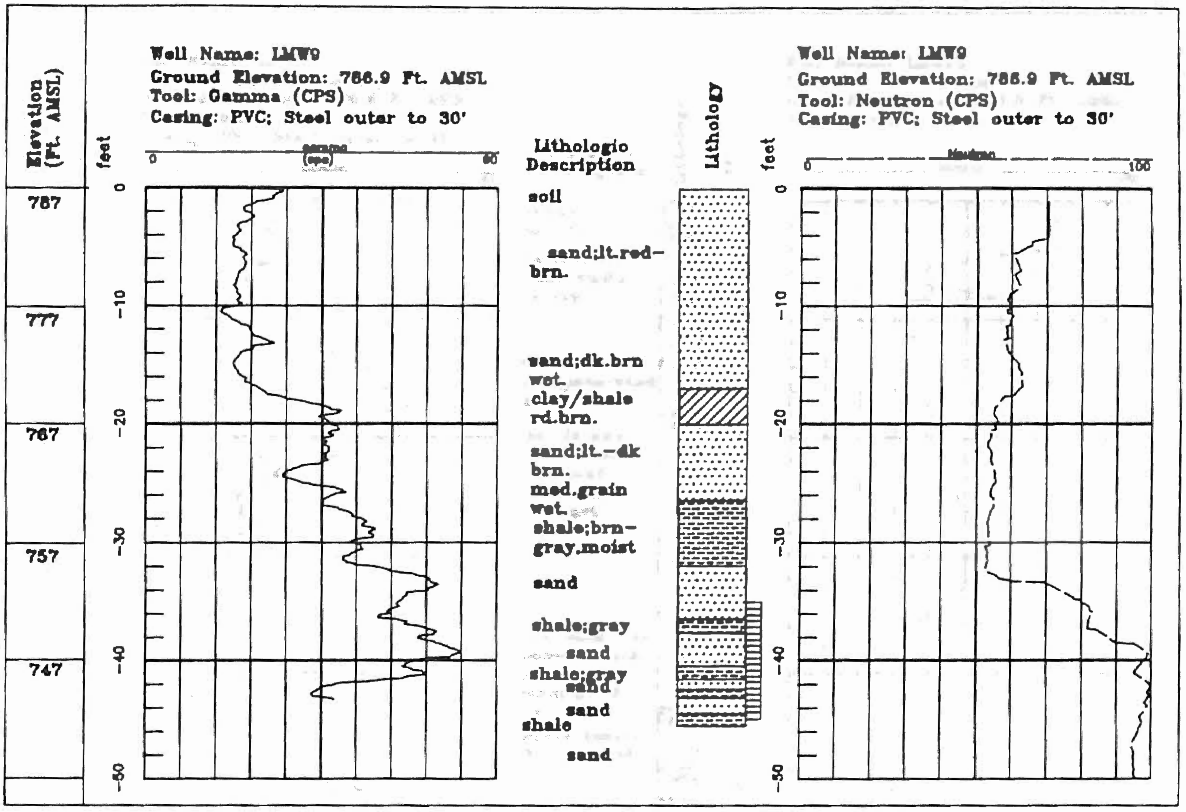


Ele. Ft. AMSL
Well Name: LMW1
Location: Pawnee County
Grade Elevation: 801.9 Ft. AMSL
Tool: Gamma (CPS)
feet
Gamma
802
792
782
772
762
752
742
-20
-40
-60
Lithologic Description
Lithology
soil,thin,sandy, sandstone;yellow-brown; grading to gray: fine-med.grained, laminated.
shale; gray.
sandstone
shale
sandstone
shale
no sample
sandstone as above
gray siltstone & dk.gray shale @ 69'.
Well Name: LMW1
Location: Pawnee County
Grade Elevation: 801.9 Ft. AMSL
Tool: Neutron (CPS)
Neutron
0
100

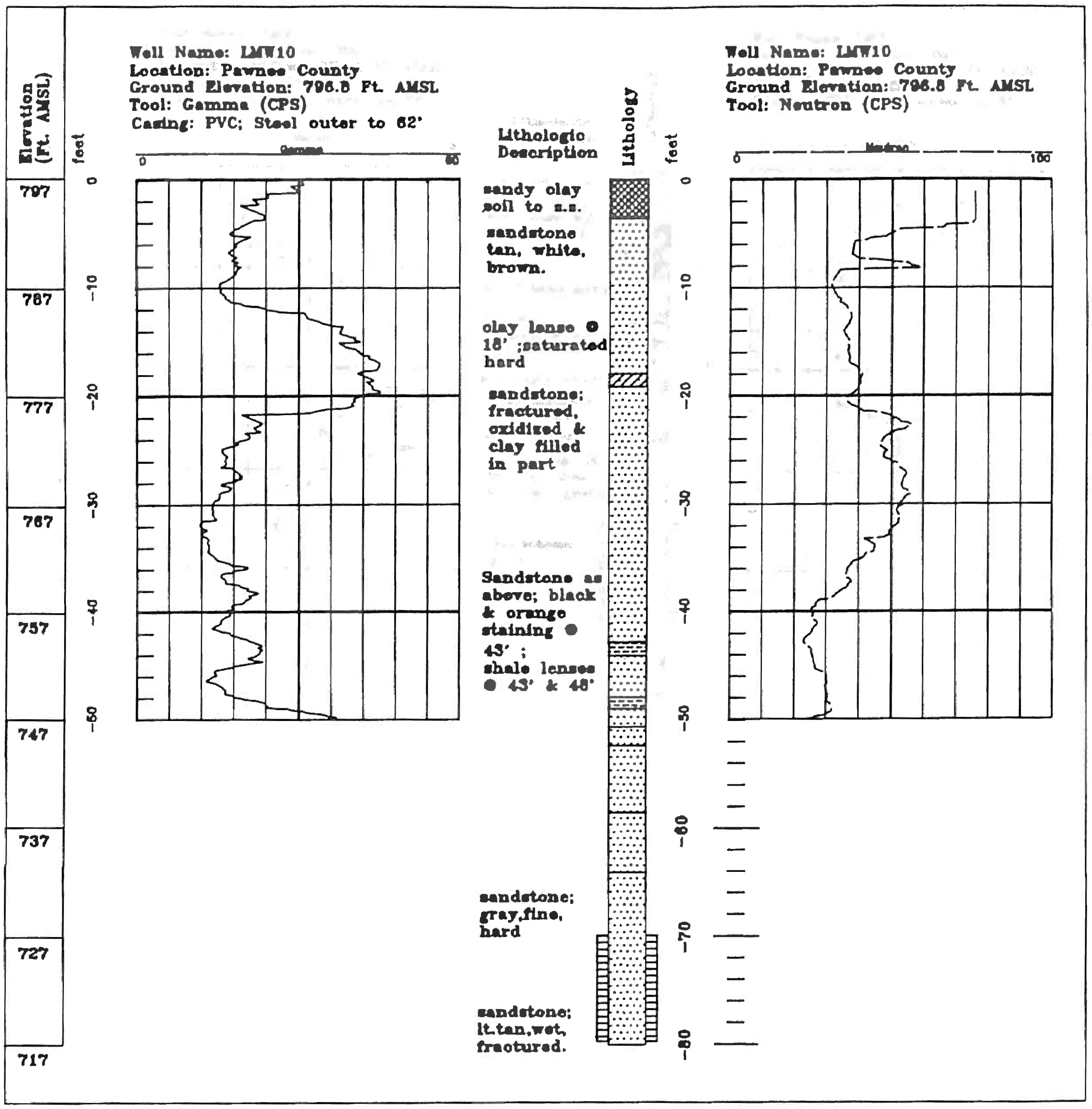

Ele. Ft. AMSL
771
761
751
741
731
0 feet
-10
-20
-30
-40
-50
Well Name: LMW3
Location: Pawnee County
Ground Elevation: 770.6 Ft. AMSL
Tool: Gamma (CPS)
Casing: PVC
0
80
Lithologic Description
silty,clayey sand/ red-orange. fine.
gravel & sand
clay;soft-firm.
sand/sandstone white-yellow
clayey sand; gray-bl.; fine.
sand;fine-med. black laminae
sandstone w/ silt&clay.
Lithology
Well Name: LMW3
Location: Pawnee County
Ground Elevation: 770.6 Ft. AMSL
Tool: Neutron (CPS)
0
100


Well Name: LMW7
Location: Pawnee County
Ground Elevation: 792.5 Ft. AMSL
Tool: Gamma (CPS)
Casing: PVC
Ele. Ft. AMSL
feet
Lithologic Description
Lithology
clayey soil
sand;brown,soft
shale; gray-brown,silty
sandstone; red-brown.
shale;blue-gray
No description in drillers log
Well Name: LMW7
Location: Pawnee County
Ground Elevation: 792.5 Ft. AMSL
Tool: Neutron (CPS)
Casing: PVC
793
783
773
763
753
0
-10
-20
-30
-40
-50

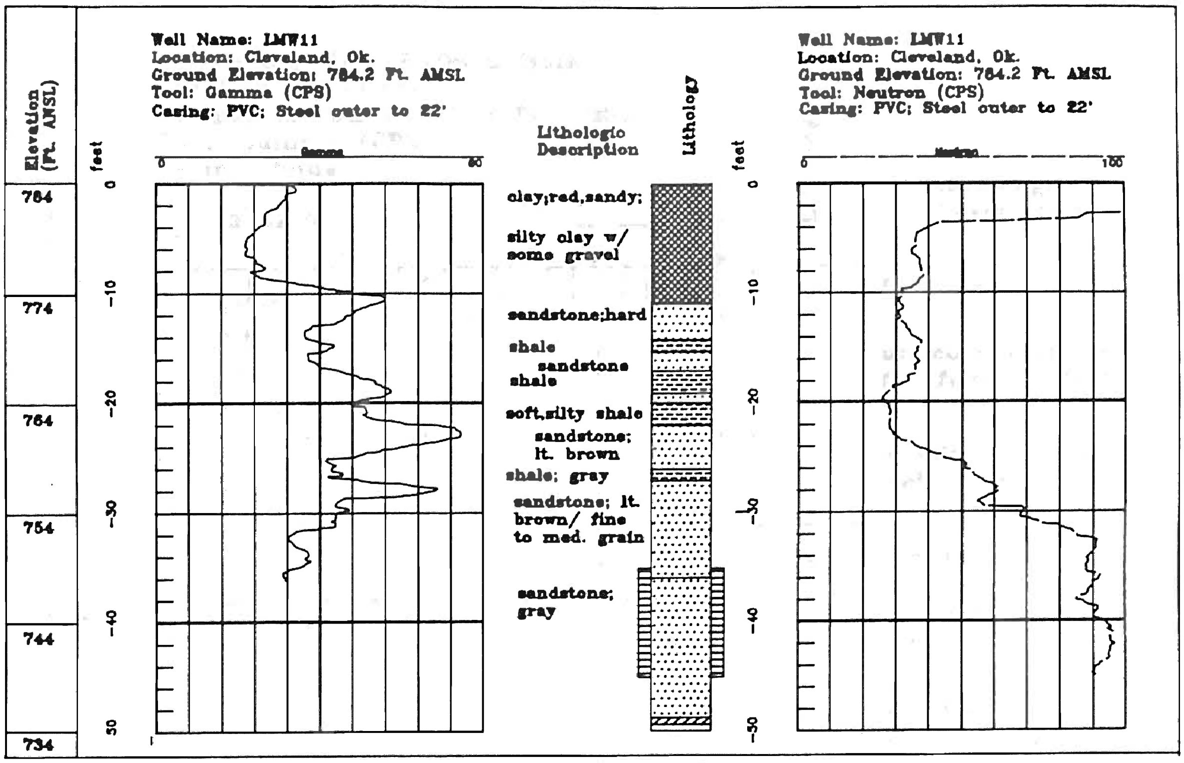

Elevation (Ft. AMSL)
817
807
797
787
777
767
757
747
feet
0
-10
-20
-30
-40
-50
-60
-70
Well Name: LMW8
Location: Pawnee County
Ground Elevation: 817.1 Ft. AMSL
Tool: Gamma (CPS)
0
80
Lithologic Description
Lithology
sand; lt.red-brown.
clay;red-brn. mottling,wet.
sand;dk.brn. wet.
shale; brn.-gray. moist.
sand
shale
sand
shale
sand
shale
sand
shale
sand
shale
sand
shale
sand
shale
sandstone w/shaley interbeds
Well Name: LMW8
Location: Pawnee County
Ground Elevation: 817.1 Ft. AMSL
Tool: Neutron (CPS)
0
100

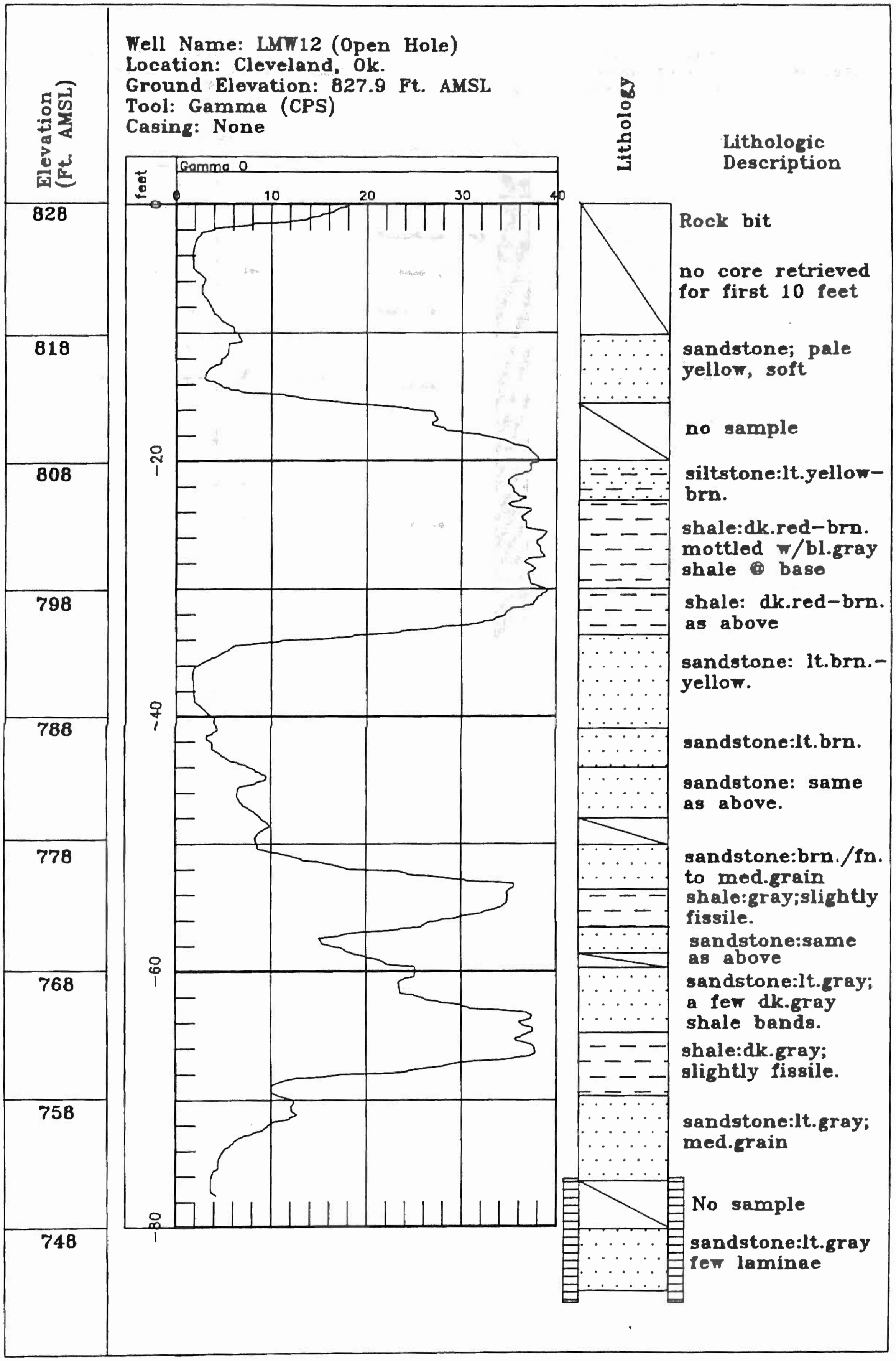


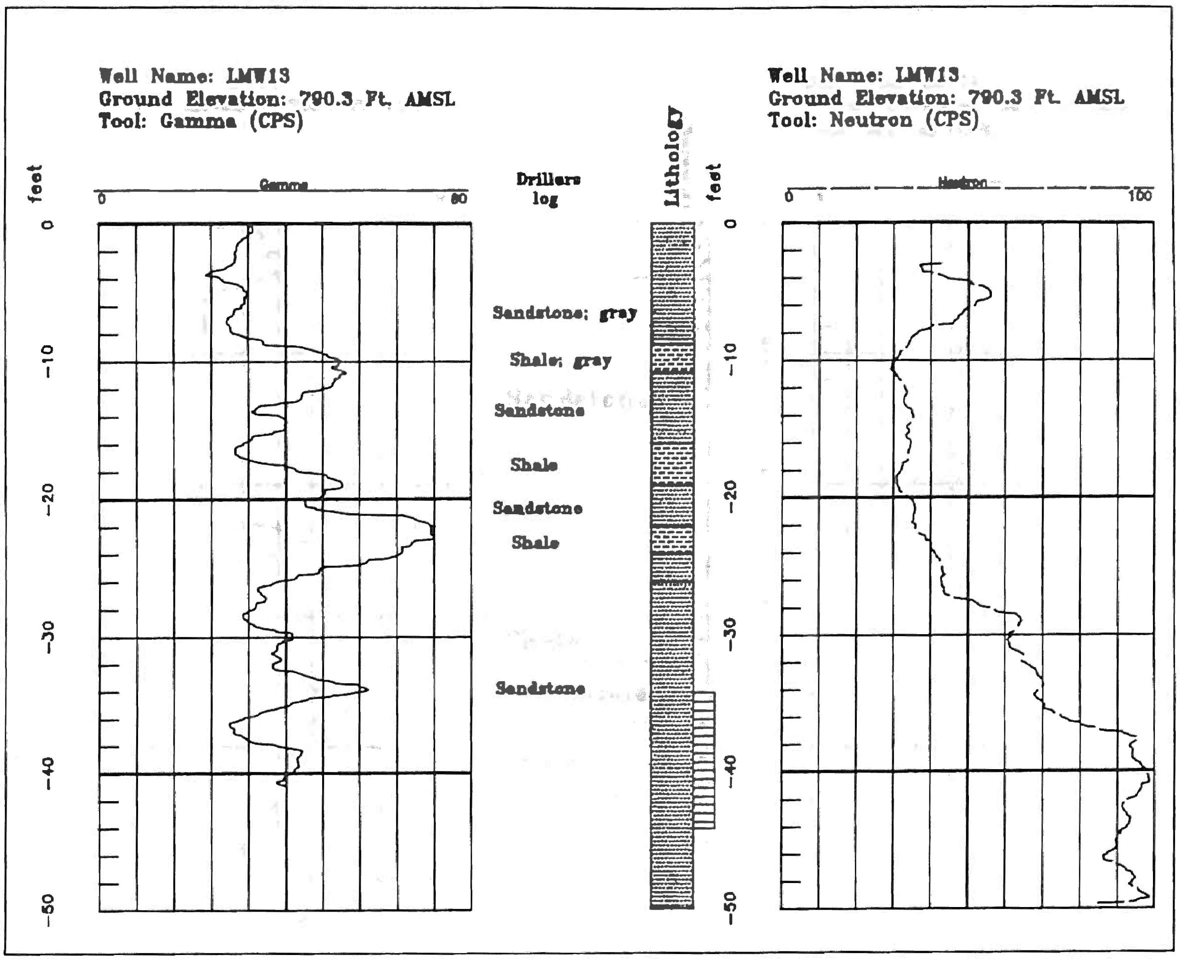
Elevation (Ft. AMSL)
feet
Well Name: LMW9
Ground Elevation: 786.9 Ft. AMSL
Tool: Gamma (CPS)
Casing: PVC; Steel outer to 30'
0
80
Lithologic Description
soil
sand;lt.red-brn.
sand;dk.brn wet.
clay/shale rd.brn.
sand;lt.-dk brn. med.grain wet.
shale;brn-gray,moist
sand
shale;gray
sand
shale;gray
sand
sand
shale
sand
Lithology
Well Name: LMW9
Ground Elevation: 786.9 Ft. AMSL
Tool: Neutron (CPS)
Casing: PVC; Steel outer to 30'
0
100
787
777
767
757
747
0
-10
-20
-30
-40
-50

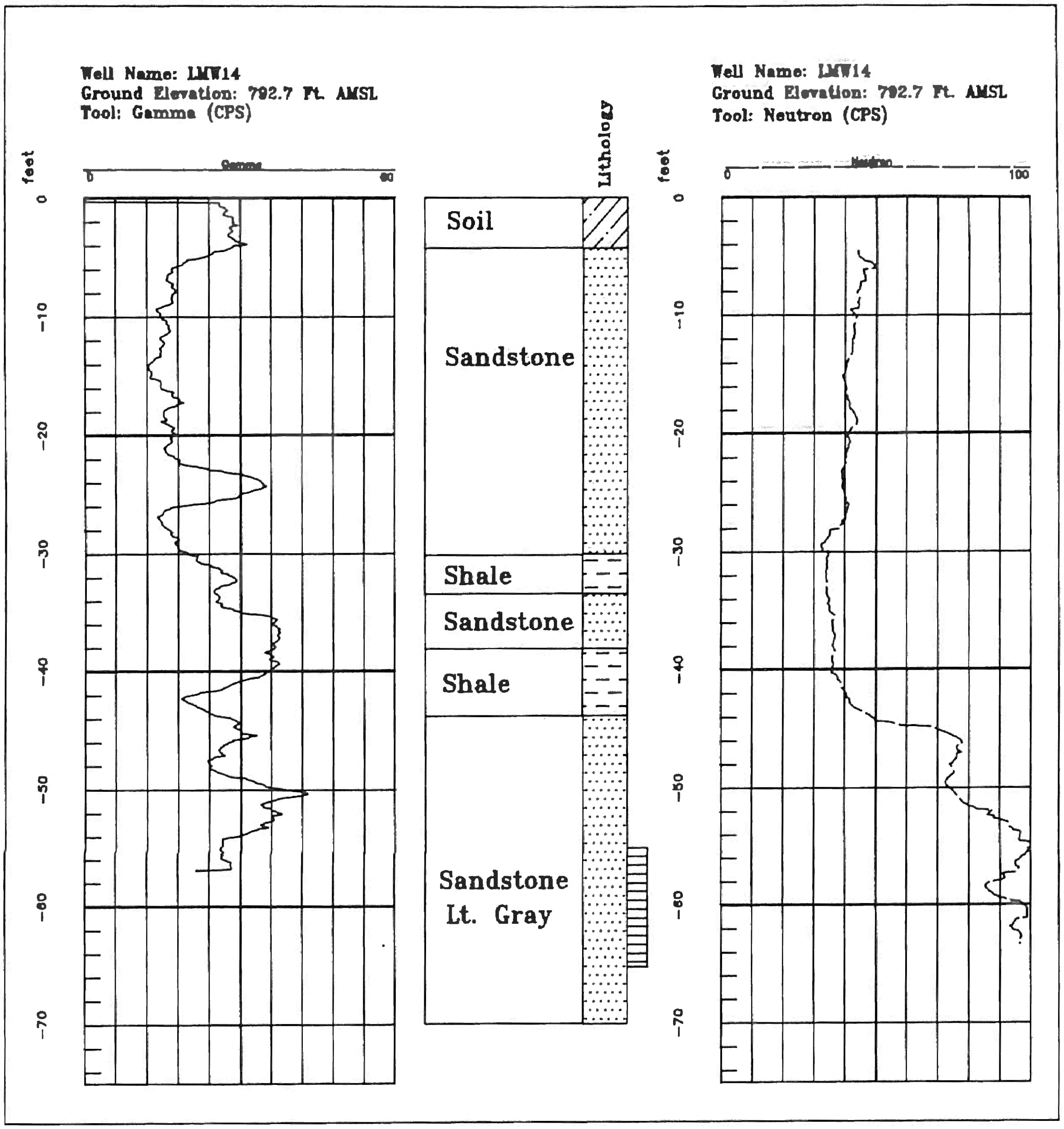


Elevation (Ft. AMSL)
797
787
777
767
757
747
737
727
717
feet
0
-10
-20
-30
-40
-50
-60
-70
-80
Well Name: LMW10
Location: Pawnee County
Ground Elevation: 796.8 Ft. AMSL
Tool: Gamma (CPS)
Casing: PVC; Steel outer to 62'
Gamma
0
60
Lithologic Description
sandy clay soil to s.s.
sandstone tan, white, brown.
clay lense @ 18' ;saturated hard
sandstone; fractured, oxidized & clay filled in part
Sandstone as above; black & orange staining @ 43' ; shale lenses @ 43' & 48'
sandstone; gray,fine, hard
sandstone; lt.tan,wet, fractured.
Lithology
Well Name: LMW10
Location: Pawnee County
Ground Elevation: 796.8 Ft. AMSL
Tool: Neutron (CPS)
Neutron
0
100

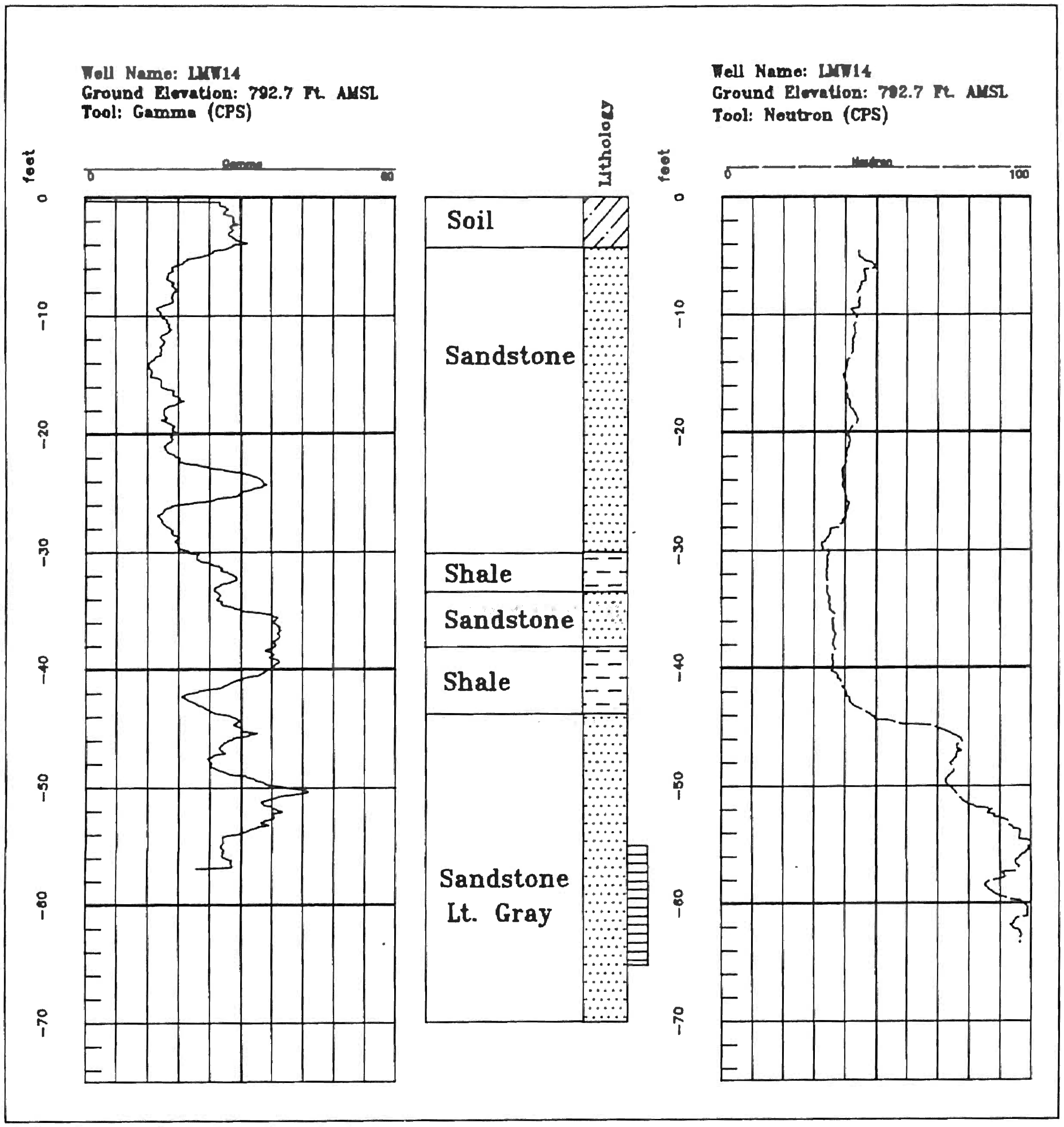

Well Name: LMW11
Location: Cleveland, Ok.
Ground Elevation: 784.2 Ft. AMSL
Tool: Gamma (CPS)
Casing: PVC; Steel outer to 22'
Lithologic Description
Lithology
Well Name: LMW11
Location: Cleveland, Ok.
Ground Elevation: 784.2 Ft. AMSL
Tool: Neutron (CPS)
Casing: PVC; Steel outer to 22'
Elevation (Ft. AMSL)
feet
784
774
764
754
744
734
clay;red,sandy;
silty clay w/ some gravel
sandstone;hard
shale
sandstone
shale
soft,silty shale
sandstone; lt. brown
shale; gray
sandstone; lt. brown/ fine to med. grain
sandstone; gray


Well Name: LMW12 (Open Hole)
Location: Cleveland, Ok.
Ground Elevation: 827.9 Ft. AMSL
Tool: Gamma (CPS)
Casing: None
Elevation (Ft. AMSL)
Lithology
Lithologic Description
Gamma 0
feet
0
10
20
30
40
-20
-40
-60
-80
828
818
808
798
788
778
768
758
748
Rock bit
no core retrieved for first 10 feet
sandstone; pale yellow, soft
no sample
siltstone:lt.yellow-brn.
shale:dk.red-brn. mottled w/bl.gray shale @ base
shale: dk.red-brn. as above
sandstone: lt.brn.-yellow.
sandstone:lt.brn.
sandstone: same as above.
sandstone:brn./fn. to med.grain
shale:gray;slightly fissile.
sandstone:same as above
sandstone:lt.gray; a few dk.gray shale bands.
shale:dk.gray; slightly fissile.
sandstone:lt.gray; med.grain
No sample
sandstone:lt.gray few laminae


Well Name: LMW13
Ground Elevation: 790.3 Ft. AMSL
Tool: Gamma (CPS)
feet
Gamma
0
80
Drillers log
Lithology
feet
Well Name: LMW13
Ground Elevation: 790.3 Ft. AMSL
Tool: Neutron (CPS)
Neutron
0
100
Sandstone; gray
Shale; gray
Sandstone
Shale
Sandstone
Shale
Sandstone
0
-10
-20
-30
-40
-50



Well Name: LMW14
Ground Elevation: 792.7 Ft. AMSL
Tool: Gamma (CPS)
Gamma
0
60
feet
0
-10
-20
-30
-40
-50
-60
-70
Lithology
Soil
Sandstone
Shale
Sandstone
Shale
Sandstone
Lt. Gray
Well Name: LMW14
Ground Elevation: 792.7 Ft. AMSL
Tool: Neutron (CPS)
Neutron
0
100


Well Name: LMW14
Ground Elevation: 792.7 Ft. AMSL
Tool: Gamma (CPS)
feet
Gamma
0
60
0
-10
-20
-30
-40
-50
-60
-70
Lithology
Soil
Sandstone
Shale
Sandstone
Shale
Sandstone
Lt. Gray
Well Name: LMW14
Ground Elevation: 792.7 Ft. AMSL
Tool: Neutron (CPS)
feet
Neutron
0
100
0
-10
-20
-30
-40
-50
-60
-70

APPENDIX B

CORE DESCRIPTIONS

KCH-1

Depth (ft.)	
0-10	No sample collected.
10-17	Sandstone: white to lt. brown, green in places, fine-med. grained, hard, fractured, brown iron spots toward bottom.
17-24	Sandstone and clayey sand; fine black laminae in places.
24-35	Sandstone: silty/clayey with fractures at 26 feet, black laminae in places, and some lt.brown cross lamination.
35-42	Sandstone: hard, fine, black laminae, a few fractures.
42-55	Shale: dark, bl.-gray, soft-firm; sandstone at 42.7', 43', 46.5'-47', 50.5-51', and 53.5-54'.

KCH-2

Depth (ft.)

0-35 Alluvial sands and clays.

35-83 Shale: dark blue-gray, firm, sandstone clasts at 36.5' and 37.5' (fn. grained and gray, few fractures).

KCH-3

Depth (ft.)	
0-16	Soft clay: brown and gray.
16-23.5	Gray shale: clayey, hard, laminated, some mottling.
23.5-34	Sandstone: yellowish-brown, well sorted, fine grained.
34-37	Shale: gray, clayey, some sandstone interbeds.
37-47	Sandstone: wavy, inclined laminae present.
47-48	Shale: dk. gray, clayey, crumbled.
48-52.5	Sandstone: gray, hard with shaley laminae.
52.5-55	No sample
55-57	Sandstone: lt. gray, fine grained, well sorted.
57-59.5	Silty-gray clayey shale.
59.5-61	Sandstone: gray, wavey laminae.
61-75	Shale: gray, even textured.
75-105	Shale: dk. gray, fine grained, hard.
105-117	NO SAMPLE
117-138	Shale: dark gray, fine grained.
138-144	Sandstone: lt. gray, very hard.
144-150	NO SAMPLE
150-155	Shale: dark gray, clayey.
155-157	Sandstone: gray, dense, hard.

KCH-4

Depth (ft.)	
0-2	Soil.
2-12	Sandstone:reddish-brown, medium grained, friable.
12-13	NO SAMPLE
13-18	Sandstone: lt. brown to reddish brown.
18-21	Clay: red-brown, laminated
21-24	Clay: gray.
24-28	NO SAMPLE
28-31	Sandstone.
31-32.5	Shale: dark gray clayey
32.5-50	Sandstone: fine to med., brown; inclined, clay-filled fractures at 33 feet, horizontal laminations at 45' to 47'.
50-60	Sandstone: gray-massive; shale breaks at 56' and 58'.
60-74	Sandstone: light gray, some laminae, highly distorted laminae at 72 feet.
74-80	Sandstone and shale interbeds.
80-88	Siltstone and v. fine grained sandstone: even textured.
88-100	Shale: dark-gray, horizontal laminations; siltstone beds at 90', 93' and 98'.
100-110	NO SAMPLE
110-115	Shale: dark gray, even textured.

KCH-5

Depth (ft.)	
0-16	Soil and alluvial materials.
16-30	Shale: dark-gray, even textured.
30-35	NO SAMPLE
35-54	Shale: dark-gray as above.
54-61	Siltstone: gray; gray shale layers at 53' and 56'.
61-96	Shale: dark gray.
96-98	NO SAMPLE
98-108	Shale: gray to reddish brown.
108-116	Shale: red with gray mottling.
116-118	Shale:gray-black, red mottling.

KCH-6

Depth (ft.)	
0-24	Alluvial materials.
24-57.5	Shale: dark gray, even texture.
57.5-58.5	Siltstone.
58.5-67	Shale: as above
67-72	Siltstone: hard, siliceous.
72-83	Shale: dark gray, fissile.
83-86	Siltstone: hard, siliceous.
86-99	Shale: dark-gray, fissile, clayey.
99-100	Siltstone with sandstone.
100-38	Shale: dark-gray, fissile, clayey.
138-153	Sandstone: well sorted,very fine grained at top, coarser toward bottom.
153-165	Shale: dark-reddish brown, clayey.
165-172	Sandstone: hard, some siltstone present.
172-180	Interbedded sandstone to 174' grading to red shale from 174 to 180.

KCH-7

Depth (ft.)	
0-2	Surface material; reworked.
2-10	Sandstone: yellow-brown.
10-13	Sandstone:
13-18	Shale: gray and yellow; brown, fissile.
18-23	Sandstone: olive-brown;fine-grained, well sorted.
23-25	NO SAMPLE
25-52.5	Sandstone: As above; horizontal laminations in places; shale lenses at 35', 38' and 41'.
52.5-54	Shale: dark gray, clayey.
54-58	Siltstone and v. fine grain sandstone; dark-gray.
58-63	Sandstone: light gray, slumped and distorted laminae.
63-64.5	Shale: dark-gray, clayey.
64.5-124	Shale: dark gray, clayey.
124-129	Siltstone: very hard.
124-180	Shale: dark gray, fissile; thin beds of siltstone at 137', 139' and 156'.
180-189	Shale: red, clayey, fissile.
189-195	Siltstone: light greenish-gray.
195-201	Shale: red, clayey, fissile.

KCH-12

Depth (ft.)	
0-10	Sandy-clay; fine-medium grained; brown-orange.
10-20	Sandstone: tan-white, fine-medium, clayey at 12', laminated in places.
20-26	Shale: blue-gray, blocky, dry, firm.
26-57	Sandstone: gray, fine, shaley laminae at 30'.
57-60	Sandstone and shale mixed.
60-63	Shale with siltstone.
63-66	NO SAMPLE
66-155	Shale: gray to dark gray, hard; sandstone interbeds at 68', 71', 73'.
155-163	Sandstone: gray, fine, some shaley laminae & partings.
163-167	NO SAMPLE
167-171	Shale: dark-gray, firm.
171-174	Shale/sandstone mixture.
174-193	Shale: dark-gray, soft-firm.
193-200	Shale: dark gray, fissile; some siltstone in places.
200-204	Siltstone: red-brown and gray, mottled, interlaminated.
205-217	Shale: dark gray, red mottling.
217-224	Siltstone: dark-reddish gray.
224-230	Siltstone: shaley, red.

KCH-13

Depth (ft.)	
0-5	Soil, clayey-sand, yellowish tan, grades to sandstone.
5-12	Sandstone: lt. yellowish-brown, weathered, friable, med. to fine grained.
12-27	Sandstone: as above.
27-34	Shale: lt. reddish-brown to dark gray.
34-37	Sandstone:
37-45	Shale: dark gray, fissile, clayey.
45-49	Sandstone: some horizontal laminae.
49-68	Interbedded sandstone and shale.
68-76	Sandstone: massive to laminated with shaley interbeds.
76-80	Shale: dark gray.
80-88	Shale with sandstone interbeds

APPENDIX C

GROUNDWATER MONITOR WELL DATA

QUATERNARY TERRACE DEPOSIT MONITOR WELL DATA

MONITOR WELL #	TOP OF CASING ELEVATION	STICK UP (ft)	DEPTH TO WATER (ft)*	WATER ELEVATION (9-24-92)	SCREENED INTERVAL (ft)*
LMW1	754.17	2.78	22.03	729	16-26
QMW2	756.43	2.09	22.77	732	18-28
QMW3	749.39	2.42	NA	NA	9-19
QMW4	759.18	2.36	16.21	741	9-34
QMW5	750.98	2.55	14.11	734	7-17
QMW6	749.52	3.51	10.42	736	NA
QMW7	766.02	2.98	16.96	746	8-28
QMW8	758.17	1.14	17.70	739	8-28
QMW9	760.97	2.41	20.76	738	12-27
QMW10	763.78	1.66	20.32	742	18-27
QMW11	764.11	1.47	6.49	756	8-18
QMW12	753.29	2.75	NA	NA	13-22
QMW13	759.27	2.49	20.91	736	17-26
QMW14	772.35	3.09	16.80	753	5-15
QMW15	772.31	2.87	23.62	746	6-21

* Footage based on elevation from ground level

A & B SANDSTONE (UPPER SANDSTONE) MONITOR WELL DATA

MONITOR WELL #	TOP OF CASING ELEVATION	STICK UP (ft)	DEPTH TO WATER (ft)*	WATER ELEVATION (9-24-92)	SCREENED INTERVAL (ft)*
UAMW1	830.64	2.96	11.75	816	NA
UMW1	805.05	1.80	5.20	798	7-17
UMW2	804.96	1.66	4.73	798.6	3.6-8.1
UMW3	815.06	2.84	18.06	794.16	13-23
UMW4	820.29	2.93	27.26	790.10	16-26
UMW5	788.73	2.94	8.54	777.25	4-14
UMW6	799.69	2.92	9.06	787.71	9-19
UMW7	794.3	3.83	NA	NA	1-21
UMW8	830.81	2.02	45.02	783.77	32-42
UMW9	813.23	2.99	DRY	DRY	13-23
UMW10	781.44	3.29	20.94	757.21	17-27
UMW11	806.31	2.21	NA	NA	10-20
UMW12	806.30	2.29	9.25	794.76	8-17
UMW13	795.39	2.24	12.38	780.77	11-20
UMW14	792.78	2.52	10.99	779.27	8-17
CMW7	786.91	2.47	10.66	773.78	NA
CMW9	799.70	2.15	12.02	785.53	NA

* Footage based on elevation from ground level

D SANDSTONE (LOWER SANDSTONE) MONITOR WELL DATA

MONITOR WELL #	TOP OF CASING ELEVATION	STICK UP (ft.)	DEPTH TO WATER (ft.)*	WATER ELEVATION (9-24-92)	SCREENED INTERVAL (ft.)*
*** LMW1	804.21	2.25	35.60	766	55-70
LMW2	805.18	2.24	36.27	767	35-50
** LMW3	772.47	1.81	23.93	747	8-38
LMW4	770.71	3.17	6.26	761	4-14
LMW5	781.08	2.47	12.26	766	10-19
LMW6	NA	NA	NA	NA	6-16
*** LMW7	794.62	2.08	44.90	748	34-44
*** LMW8	819.13	2.01	49.84	767	55-65
*** LMW9	788.62	1.72	19.32	768	35-44
*** LMW10	797.97	1.15	28.71	768	70-80
*** LMW11	786.01	1.82	16.83	767	35-45
† LMW12	829.32	1.45	53.53	774	76-86
*** LMW13	792.41	2.15	27.21	763	39-49
*** LMW14	794.61	1.96	26.42	766	55-65
*** LMW15	779.30	1.95	27.03	750	35-45

* Footage based on elevation from ground level

** Natural gamma and neutron logs conducted inside PVC Casing

*** Natural gamma and neutron logs conducted inside PVC and Steel Casing

† Natural gamma and neutron logs conducted inside Open Hole and Steel Cased Hole

APPENDIX D

GROUNDWATER MONITOR WELL

CONSTRUCTION DATA

QUATERNARY TERRACE DEPOSIT MONITOR
WELL CONSTRUCTION DATA

MONITOR WELL #	* DEPTH OF OUTTER STEEL CASING (FT)	DIAMETER OF STEEL CASING	* DEPTH OF INNER PVC CASING (FT)	DIAMETER OF PVC CASING	* SCREENED INTERVAL (FEET)
QMW1	NONE	-	28.7	2"	16-26
QMW2	NONE	-	30.6	2"	18-28
QMW3	NONE	-	21.7	2"	9-19
QMW4	NONE	-	36.7	2"	9-34
QMW5	NONE	-	19.3	2"	7-17
QMW6	NONE	-	NA	NA	NA
QMW7	NONE	-	30.8	2"	8-28
QMW8	NONE	-	29.5	2"	8-28
QMW9	NONE	-	28.5	2"	12-27
QMW10	NONE	-	27	2"	18-27
QMW11	NONE	-	19.7	2"	8-18
QMW12	NONE	-	22	2"	13-22
QMW13	NONE	-	26	2"	17-26
QMW14	NONE	-	16.6	2"	5-15
QMW15	NONE	-	21.7	2"	6-21

* Footage based on elevation from ground level

A & B SANDSTONE (UPPER SANDSTONE) MONITOR WELL CONSTRUCTION DATA

MONITOR WELL #	* DEPTH OF OUTTER STEEL CASING (FT)	DIAMETER OF STEEL CASING	* DEPTH OF INNER PVC CASING (FT)	DIAMETER OF PVC CASING	* SCREENED INTERVAL (FEET)
UAMW1	NA	NA	NA	NA	NA
UMW1	NONE	-	18.5	2"	7-17
UMW2	NONE	-	8.6	2"	3.6-8.1
UMW3	NONE	-	23	2"	13-23
UMW4	NONE	-	26	2"	16-26
UMW5	NONE	-	14	2"	4-14
UMW6	NONE	-	19	2"	9-19
UMW7	NONE	-	21	2"	1-21
UMW8	28	12"	42	2"	32-42
UMW9	NONE	-	23	2"	13-23
UMW10	NONE	-	27	2"	17-27
UMW11	NONE	-	21	2"	10-20
UMW12	NONE	-	17	2"	8-17
UMW13	NONE	-	21	2"	11-20
UMW14	NONE	-	17	2"	8-17
CMW7	NONE	NA	NA	NA	NA
CMW9	NONE	NA	NA	NA	NA

* Footage based on elevation from ground level

D SANDSTONE (LOWER SANDSTONE) MONITOR WELL CONSTRUCTION DATA

MONITOR WELL #	* DEPTH OF OUTTER STEEL CASING (FT)	DIAMETER OF STEEL CASING	* DEPTH OF INNER PVC CASING (FT)	DIAMETER OF PVC CASING	* SCREENED INTERVAL (FT)
*** LMW1	18	6"	71.7	2"	55-70
LMW2	NA	NA	54.3	2"	35-50
** LMW3	NONE	NONE	39.7	2"	8-38
LMW4	NONE	NONE	14.6	2"	4-14
LMW5	NONE	NONE	19	2"	10-19
LMW6	NONE	NONE	17	2"	6-16
*** LMW7	25.6	6"	45	2"	34-44
*** LMW8	46	6"	65	2"	55-65
*** LMW9	31	6"	45	2"	35-44
*** LMW10	62	6"	80	2"	70-80
*** LMW11	22	6"	45	2"	35-45
† LMW12	70	6"	86	2"	76-86
*** LMW13	22	6"	50	2"	39-49
*** LMW14	43	6"	66	2"	55-65
*** LMW15	27.5	6"	45	2"	35-45

* Footage based on elevation from ground level

** Natural gamma and neutron logs conducted inside PVC Casing

*** Natural gamma and neutron logs conducted inside PVC and Steel Casing

† Natural gamma and neutron logs conducted inside Open Hole and Steel Cased Hole

VITA

Brian W. Burgess

Candidate for the degree of

Master of Science

Thesis: HYDROGEOLOGIC CHARACTERIZATION AND EVALUATION OF VARIOUS GEOPHYSICAL TECHNIQUES AT AN ABANDONED REFINERY SITE IN PAWNEE COUNTY, OKLAHOMA

Major Field: Geology

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Personal Data: Born in Houston, Texas, January 19, 1962, the son of Ruth Naomi Dees and Curtis William Burgess Jr.

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