

**A SYSTEMATIC APPROACH TO LANDFILL SITE
CHARACTERIZATION WITH EMPHASIS ON GEOPHYSICS
AND MODELING**

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1.0 INTRODUCTION

1.1 Background

Until recently, waste materials were disposed of with only limited regard to the environment. Much of the blame for this was a lack of understanding of the role of waste disposal practices in ground-water contamination. Ignorance of, or unwillingness to adhere to, sound hydrologic principles has resulted in the degradation of the ground-water resources in many areas. More recently, however, considerable attention has been given to the various problems related to waste disposal. To effectively regulate waste disposal the various states have passed legislation to control the disposal of wastes. These rules and regulations, although varying somewhat from state to state, govern the management and disposal of wastes, requiring that prospective landfill operators acquire permits for their landfills and adhere to appropriate standards of design and operation. Procedures for development and submittal of permit applications have been established in each state, and review procedures have been implemented.

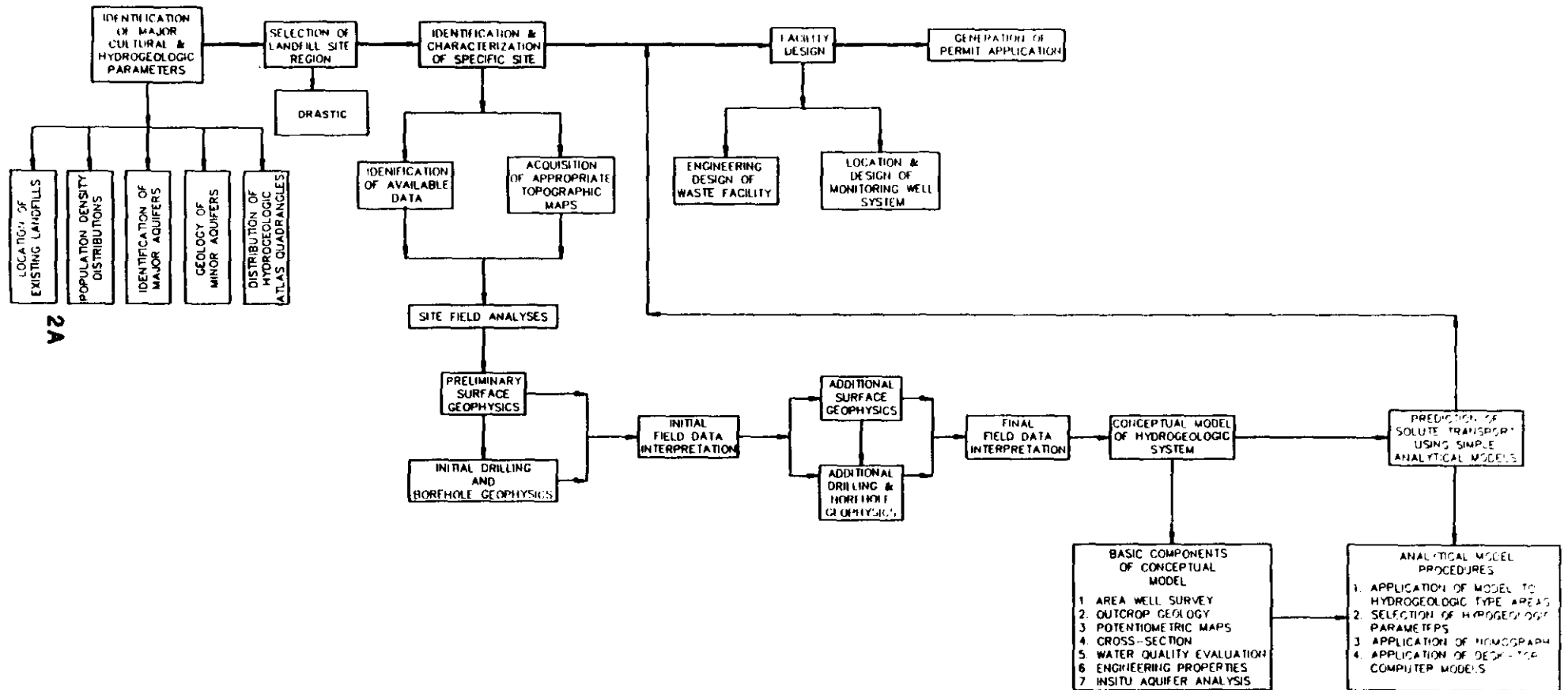
A primary component of these application requirements is a demonstrable understanding of the hydrogeologic regime by the applicant. These procedures are explicit and often expensive to

implement using traditional approaches to data gathering. To facilitate future characterization and final selection of waste disposal sites, the Oklahoma State University Department of Geology under the direction of Douglas C. Kent began a two year study funded by the U. S. Geological Survey under a grant through the Oklahoma Water Resources Research Institute Program. The objective was to describe a systematic approach using geophysical and modeling applications to characterize potential and existing landfill sites. Such a systematic approach may be visualized in the form of a flow chart as is shown in Figure 1. This chart constitutes an expert conceptual system by which a potential landfill site may be characterized and included in a permit application to a state or federal agency. This approach is designed to be utilized by both regulatory agencies and the private sector. Specific methods are cited in the extensive bibliography included in this document.

Ground-water availability and quality must be assessed in an area targeted for a waste disposal facility. In addition, an assessment of the impact of these activities upon local ground-water resources is required. Traditional methods for this characterization include the collection of borehole cuttings and cores, local well inventories, measurement and analysis of local outcrops and an analysis of published information regarding the site and/or immediate area. The production of borehole cuttings and cores in sufficient quantities and qualities to be characteristic of the site is especially expensive. As many as fifty borings may be required to acquire data adequate to

FIGURE 1

SYSTEMATIC APPROACH TO LANDFILL SITE CHARACTERIZATION



characterize even a ten acre site. A primary reason for this large number of borings and the resulting high cost of this analysis is the trade-off between the very high cost of core extraction and the subjectivity of the interpretation of cuttings. Other techniques, not formerly used for evaluation of ground-water resources, are now available and cost effective when used and interpreted properly. These methods include surface and borehole geophysical techniques and ground-water modeling. When used properly and in conjunction with traditional techniques, the total cost of evaluation may be substantially reduced without a loss of accuracy. Indeed, the degree of accuracy should substantially increase by the application of these methods.

1.2 Objectives

The primary concern of this study is to produce a document that could be utilized by state government agencies and private firms alike to more effectively characterize potential solid waste disposal sites. At present, the techniques utilized for this characterization are both time consuming and expensive. The result is that either excessive costs are incurred or inadequate characterizations are produced. The latter is especially undesirable in that the waste facility, if permitted, runs the risk of contaminating ground-water.

A systematic method does exist, as will be demonstrated in this report, that can be used to implement site characterization analyses for landfill siting. This method consists of following a step-wise path that will lead the applicant through the

necessary data accumulation and interpretations and result in the generation of a final permit application. This step-by-step approach includes the identification of major cultural and hydrogeologic parameters, selection of a landfill site region, the identification and characterization of a specific site, the prediction of solute transport using simple analytical models, the facility design and finally the generation of the permit application. Each of these components is identified in Figure 1 along with supporting concerns that must be addressed.

The flow chart as presented here is composed of basic data gathering and interpretation techniques that should be familiar to the ground water scientist. These techniques are well documented but often are not incorporated into general landfill site selection processes. Very little has been published regarding landfill site selection. The major exception to this is Johnson and Luza (1978). They analyzed rock units and outcrop belts throughout the state of Oklahoma that might be used effectively as host rocks for disposal of industrial wastes. Their intent was to produce a document and associated graphics that could be utilized by industry and government to screen large regions of the State and identify those areas that appear most favorable, geologically, for disposal of hazardous wastes. Even with the availability of their document, the geophysical properties of formations exposed in Oklahoma have gone virtually unstudied, particularly in areas where the formations are near the surface.

There is a moderate amount of literature on the use of geophysical surface and borehole methods and modeling to study ground-water problems. The majority of these publications are concerned with exploration for usable groundwater or with detection and/or evaluation of existing contamination; however, a large amount of the information that these publications contain may be applied to site selection. Four bodies of literature are discussed here: general landfill site selection processes, borehole geophysics, surface geophysics and modeling.

1.2.1 General Landfill Site Selection Process.

The literature devoted to landfill site selection has focused largely on hazardous wastes and their appropriate disposals. This obviously both Federal and State legislations oriented to the clean up and safe disposal of toxic substances.

This literature may largely be viewed as either process oriented or specific methods oriented. Several authors have attempted to design analytical processes by which appropriate landfill sites could be ultimately identified (Reed and Henningson, 1982; Landon, 1983; Knowles, Lee and Adamowski, 1982). There is a great deal of similarity among these processes, with only details of the number of steps involved in the process varying significantly. Reed and Henningson (1982), for example, proposed a series of overlays, each mapping a specific parameter. Once all overlays were in place, appropriate regions that might be studied in detail would appear. Landon (1983) and Knowles, Lee and Adamowski (1982) proposed multi-phased approaches to identify

appropriate sites. Each began with a broad, regional analysis and concluded with specific site characterizations entailing in-depth physical, cultural and economic analyses.

Several authors have focused on the specific methods to be used in landfill site characterizations. This literature is broad in scope, and much of it will be discussed in later portions of this review. Specific methods encountered in the literature include; the use of aerial photographs in managing hazardous waste facilities (Lyon, 1982); use of geophysics as a method to reduce both time and cost of site characterization (Glaccum, Benson and Noel, 1982); and, overview of hydrogeologic considerations in hazardous waste site selection (Farmer, Bryson and Evans, 1982). These methods are all appropriate for data collection and all have specific merits that make them attractive tools in site selection.

1.2.2 Borehole Geophysics

The literature devoted to borehole geophysics is large but not very diverse. The majority of this literature discusses either the use of specific borehole tools at specific locations or the use of borehole geophysical tools in general.

Some of this body of literature has been devoted specifically to ground-water hydrology. Several authors have focused on ground-water applications almost entirely (Dobecki and Romig, 1985; Guyod, 1972; Dyck, et. al., 1972; Keys, 1968; Keys and Sullivan, 1979; MacCary, 1983; Wheatcraft, et. al.). Keys (1968) and Keys

and Sullivan (1979) focus on nuclear borehole logging. Baldwin and Miller (1979) are even more specific, concerned solely with gamma ray logs to delineate stratigraphy in glacial outwash. Likewise, some authors are concerned with identifying appropriate borehole tools for specific problems. For example, Kwader (1984a) was concerned only with porosity identification and in a second article that same year (1984b) with water quality determinations.

Several authors have realized that most often a single borehole technique is inadequate for either the resolution of a particular problem or for the full characterization of a particular site. Harris and McCammon (1971) discussed synergistic uses of several logs to determine porosity and lithology. They used a combination of neutron, density and acoustic logs and a computer based processing system. Reed (1985), on the other hand, compared natural gamma logs and surface resistivity surveys in glacial drift and alluvium, concluding that resistivity values decreased as gamma counts increased. Others utilizing multiple logs to solve specific problems included: DeLuca and Buckley's (1985) investigation of fractures in metamorphic rocks and the identification of water bearing fractures by means of caliper, resistivity and spontaneous potentials; and Mickam, Levy and Lee's (1984) use of natural gamma and caliper logs in karst terrain to identify solution cavities and aquitard formations.

1.2.3 Surface Geophysical Methods.

The use of surface resistivity measurements to detect fractures has been studied by several authors. Taylor (1984), using Wenner array apparent resistivity measurements to detect joints in dolomite concealed by glacial overburden, measured joint strike and the resulting porosity of the dolomite. Leonard-Mayer (1984) found that the same method worked in both carbonates and clastic rock.

The use of surface resistivity to delineate stratigraphy, locate bedrock, and find fractures is common. A report by Tucci (1984) is typical in finding that low resistivity corresponded with fine-grained deposits; this by itself is not particularly meaningful, but must be correlated with borehole information and other geologic data to be significant. Water table levels were also found by the survey, appearing as a decrease in resistivity values. Ogden and Eddy (1984), working in northwest Arkansas, used tri-potential surface resistivity surveys to distinguish water-filled fractures from air-filled fractures. Caves could also be found in this manner, but have been found to be a more complicated matter.

Surface D.C. resistivity surveys were also used by Stewart and others (1985) to delineate stratigraphic zones in a sequence of siliceous and carbonate sediments. They found that aquifer permeability was directly related to resistivity. The most permeable layer, three to fifteen meters below the surface, was capable of being delineated by this method. Pennington (1985) also investigated surface resistivity techniques. His objective

was to locate contamination, but his conclusions are applicable to site selection assessment as are Benson's (1983) analyses of geophysical techniques to identify buried wastes and waste migration. Pennington found the Schlumberger array to be much superior to the Wenner array in sensitivity, resistance to interference, and field time required. The results are more complicated to interpret with the Schlumberger array, both felt the benefits outweigh the problems of complexity.

Wrege and others (1985) found that fissures as small as one inch in width in alluvium could be detected by seismic methods that used horizontal shear waves. A hammer and an embedded steel rod were used as the energy source, and geophone terminals connected to a 12-channel signal-enhancement engineering seismograph picked up and recorded the signals. Results were processed on a desktop computer and excellent results were obtained in detecting both exposed and concealed fissures. Levine and others (1984) used 3-dimensional vertical seismic profiling to locate fractures in crystalline rock. Seismic crosshole techniques were used, and indicated fracture continuity between two boreholes. The seismic velocity of the rock and the borehole dimensions were used to determine the hydraulic conductivity.

1.2.4 Ground-Water Modeling

The prediction of ground-water movements and especially contaminant plumes within ground-waters is a highly complex undertaking. The simultaneous presence of numerous interactive

mechanisms (physical, chemical and biological) make it very difficult to obtain a clear picture of the dynamics of the hydrogeologic environment. Models have been extensively used to predict these dynamic situations for both contaminated and uncontaminated ground-water movements.

A wide range of models is available for use by today's hydrogeologist. These models include descriptive, physical, analog and mathematical. Mathematical models appear to be the most useful for site characterization purposes. These models, however, are complex and demand greater expertise in computer modeling and require greater cost outlay for equipment in order to be of use.

Many mathematical models are presently available. The differences between these models are mostly in the number of simplifications made during derivation of the governing equations and their method of solution. Once the governing equations and the initial and boundary conditions are defined, solutions for the concentration can be generated by fairly straightforward, but tedious, mathematical manipulations. There are two methods by which this may be accomplished: analytical and numerical.

In order to obtain an analytical solution of the transport equation, it is generally necessary to assume a constant fluid velocity, a constant dispersion coefficient, constant physical parameters and a simplified geometry for the simulated system. Explicit mathematical expressions for the concentration can be used in the analytical model. More advanced implicit mathematic

expressions are used in the numeric model. Analytical solutions are easily applied and are very cost effective when compared to many of the numerical models available. The disadvantage, however, is the need to make various simplifying assumptions. In spite of this restriction, it appears that the available two- and three-dimensional analytic solutions (Wilson and Miller, 1978; Kent, Pettyjohn, and Prickett 1985) could be applied to many hydrogeologic situations, especially those that are well-defined hydrogeologically.

Many field problems lend themselves more readily to the use of numerical than to analytical models. This is especially the case when the problem involves complex physical and chemical characteristics which are distributed spatially through time. When numerical techniques are used, the partial differential equations are generally reduced to a set of approximating algebraic equations, which subsequently are solved using methods of linear algebra. The most commonly used numerical methods are finite differences and finite elements. When the finite difference techniques are used, the partial derivatives in the governing equations are approximated by appropriate finite difference equations. When the finite elements methods are used the dependent variables (such as pressure head and concentration) are approximated by a finite series of basic (or shape) functions and associated time-dependent coefficients. Each of these methods have been applied successfully to ground-water problems. Although variations and improvements have been made, the two primary examples of these models are Trescott, and others (1976)

and Konikow and Bredehoeft (1978). Trescott developed a finite difference model that simulates ground water flow in 2-dimensions. Konikow and Bredehoeft developed a finite difference model capable of predicting the migration of solute transport in 2-dimensions. Most other finite difference numerical models are variations of these two forms.

1.3 Objectives and Report Structure

Since this report is designed to be utilized by both State government agency staff and private firms for evaluation of hydrogeologic situations, typical settings are presented to amplify the results. The report focuses on the systematic approach defined in the flow chart presented in Figure 1. **Methods are briefly described but the reader is directed to the bibliography and encouraged to refer to these references when applying the method of approach used here.** The delineation of hydrogeologic type areas and the processes involved in adequately identifying and characterizing a site for landfill development are developed following this format. Hydrogeologic type areas are used as examples in delineating the process of site identification and characterizations. Numerous examples are given of typical characterization responses that a prospective applicant might encounter. Data generated for the State of Oklahoma will be used for these examples.

2.0 APPLICATION OF THE SYSTEMATIC APPROACH TO LANDFILL SITE IDENTIFICATION AND CHARACTERIZATION

2.1 Introduction

Each state has now enacted regulations that are designed to guide the prospective landfill applicant. These regulations may be obtained by contacting the regulating agency in the state within which the proposed landfill will be located. The State of Oklahoma for example has developed an extensive set of guidelines designed to aid the prospective applicant and assure that all environmental concerns are addressed. Guidelines for items to be included in the engineering plans and specifications for a Type II through Type VII solid waste disposal site are included as Appendix A of this document. Also included is a printout of a computer assisted program developed by the authors of this document to assist in the preparation of solid waste disposal applications. Following this outline will assure that all necessary site characterization components are included in the landfill application.

A primary reference for the process of landfill site selection is **Surface Disposal of Controlled Industrial Wastes in Oklahoma** (Johnson and Luza, 1978). The Johnson and Luza study is designed to be used in conjunction with the regional geologic reconnaissance studies that were begun in 1977 by the Oklahoma Geological Survey, in cooperation with the Oklahoma Department of Economic and Community Affairs. Johnson and Luza classified the geologic formations in Oklahoma into three categories, or zones,

based on their interpreted suitabilities to the disposal of controlled industrial wastes. This approach to site selection, as acknowledged by Johnson and Luza, will not replace the necessity of in-depth analysis to evaluate the suitability of a particular site. The purpose of the Johnson Luza study is, rather, to provide a greater understanding of the geologic variations in the State of Oklahoma and the relationship of geology to the general siting of controlled industrial waste landfills.

A second program that is related to the process of landfill site selection is the EPA standardized system for evaluating groundwater pollution potential using hydrogeologic settings. This program is termed DRASTIC. This system helps the user evaluate the relative ground-water pollution potential of any hydrogeologic setting and may be employed nationwide. This scheme is a relative ranking using a combination of weights and ratings to produce a numerical value, called DRASTIC INDEX, which helps prioritize areas with respect to ground-water contamination vulnerability. This system is based entirely on available data. Again, this system is only a beginning for the prospective landfill permit applicant. More detailed analysis of any particular site must be performed prior to the submission of an application for a landfill.

The remainder of this section is devoted to discussing the specific processes involved in landfill site selection. The final component of this site selection process is the generation of a state landfill permit application. Each step is discussed

in detail and where possible examples of data generation techniques are included. The process of landfill site selection is quite involved, but each step should be familiar to those who have already been involved in similar site selections. Figure 1, depicts the major categories and data generation requirements necessary for successful permit application submission. This flow diagram will be used as a basic outline for the following discussion.

2.2 Identification of Major Cultural and Hydrogeologic Parameters

2.2.1 Identification of Hydrogeologic Parameters

The initial steps at landfill siting involve the determination of regional suitabilities. The State of Oklahoma, like most other states, is highly variable in terms of geologic, hydraulic, demographic and other cultural features. Many of these features are very important to the landfill site decision making process. Specific guidelines have been established by which the prospective applicant must present to the Oklahoma State Department of Health general information, technical information and the proposed site plan for the landfill (Oklahoma State Health Department, 1987).

2.2.1.1 Major and Minor Aquifers

In 1983 the Oklahoma State Department of Health (1983) published maps of principle bedrock, alluvial and terrace aquifers along

with their recharge areas for the State of Oklahoma. These maps were compiled mainly from a series of hydrologic atlases prepared cooperatively by the Oklahoma Geological Survey (Marcher, 1969; Marcher and Bingham, 1971; Hart, 1974; Bingham and Moore, 1975; Carr and Bergman, 1976; Havens, 1977; Bingham and Bergman, 1980; Morton, 1980; Marcher and Bergman, 1983) and the U. S. Geological Survey (Wood and Hart, 1967; Sapik and Goemaat, 1973; Morton and Goemaat, 1973). The boundaries of the aquifers include the areas shown as being favorable or moderately favorable for development of ground-water resources on the hydrologic atlases.

The major aquifers as delineated by the Oklahoma State Department of Health are widely distributed across the State. They range in lithology from sands of recent age to limestones and conglomerates. There even exist predominantly shale and evaporitic deposits that constitute principle aquifers.

Recharge areas for the principle aquifers are also delimited on the Health Department's maps, based upon the surface geology of Oklahoma and the relationship of outcropping rocks to ground-water aquifers. Recharge areas include outcrops of the aquifers and outcrops of overlying porous and permeable rocks that are hydraulically connected with the aquifers. In addition, a four mile safety zone is incorporated beyond the known limits of an aquifer. Recharge areas, where distinct from the aquifers, are as important as the aquifers themselves since water that moves through the recharge areas reaches the aquifers. These recharge areas, then, must be characterized along with the actual aquifers.

Since all areas of the State are underlain by geologic formations containing some ground-water in some quantity and/or form, those areas not designated by the Oklahoma State Department of Health (1983) as principal ground-water resources are here delimited as minor ground-water resources. As in the case of the principal ground-water resources, all geologic types are well represented in this category. There exist, as will be shown later, sandstone, shale, carbonate and interbedded lithologies as well as evaporites and igneous formations that are described as minor ground-water resources.

Although the care to be taken with minor ground-water resource areas may not be as stringent as for the principal areas discussed earlier, it is still vitally important to the welfare of the State and its citizens that these resources be protected. It is necessary, then, not only to describe these resource areas in a like manner to the principal aquifers, but that the hydrogeologist actively engaged with solid waste disposal facilities be aware of techniques that will ensure an accurate and complete characterization of these areas. For these reasons only cursory separation of the principal and minor ground-water resources are made here. It is assumed that the ground-water resources of the State of Oklahoma are important regardless of the quantity of water available for use. Delineation, where necessary, may be made for individual site analyses by the hydrogeologist and the Health Department for application purposes.

2.2.1.2 Hydrogeologic Parameters

Using data generated by the Oklahoma Geological Survey and U.S. Geological Survey four major categories of hydrogeologic parameters for known geologic formations in Oklahoma were identified and incorporated into a matrix for easy access (Appendix B). These parameters include predominant lithology of the formation involved, formation bed thickness, predominant grain sizes in the case of sandstones and whether the formation has been included into the Oklahoma State Health Departments principal ground-water resource category. These parameters are used in this document to represent permeability and associated characteristics of the formations under analysis.

Each of the groupings discussed above is further subdivided into a number of descriptive units to more definitively identify each formation. The predominant lithology of a formation (denoted by P in the matrix) may be defined as carbonate, sandstone, shale, interbedded carbonate-sandstone-shale, igneous, evaporites or conglomerate. Bed thicknesses are denoted as thin (less than 50 feet thick), thick (greater than 100 feet) or medium (between 50 and 100 feet in thickness) with the correct response marked with an X on the matrix. The hydrologic atlas' delineation of fine, medium or coarse grained sandstones is here used for lack of other data sources and is likewise marked with an X on the matrix. The delineation of principal or minor ground-water resources are as discussed earlier with the principal ground-water resources denoted by PM on the matrix.

A total of one-hundred and eighty different formations or groupings of formations are included in the matrix. Oklahoma and U.S. Geological Survey data were analyzed to determine the hydrogeologic characteristics of each formation for those parameters discussed above. In the cases where several or all possible categories for a parameter are denoted, the available data for several portions of the State do not agree due to changes in the hydrogeologic environments across the State. Where this has occurred each is included within the matrix and no attempt is made to discern the spatial variations further.

2.2.1.3 Hydrogeologic Type Areas

Johnson and Luza (1978) classified the various geologic formations of Oklahoma into three zones for the purpose of analyzing sites for surface disposal of controlled industrial wastes. These three zones were delimited by the formations' permeability and associated favorability for disposal of contaminants. Generally, their results were that those formations that were predominantly shales or clays were most favorable (Zone 1) for disposal sites due to their very low permeabilities. Likewise, formations predominantly of sandstones or other highly permeable lithologies were deemed least favorable (Zone 3). Zone 2 constitutes a less favorable category than Zone 1.

Based on the results of the hydrogeologic parameter matrix presented above, four hydrogeologic type areas are identified within Oklahoma (see Appendix B). Again, these parameters are

indicative of permeability and associated variables and should be considered as appropriate inclusions into solid waste disposal site characterizations. Each of the four groups will respond differently to geophysical investigations. It is, then, important that the investigator be aware of the specific type associations with which he is dealing and the responses that would be expected.

The four hydrogeologic type areas are most easily recognized on the basis of predominant lithologies present. However, each of the other parameters discussed above is equally important. The four type areas are; semiconsolidated to unconsolidated clastic formations, interbedded sandstone-shale-limestone formations, shale and clay formations and carbonate formations. Due to their often high permeabilities the evaporitic, conglomerate and igneous formations are included in the semiconsolidated to unconsolidated clastic type areas. The igneous formations are included because of their association with fracture flow of ground-waters.

It should be pointed out that the formations described in both the matrix and the four hydrogeologic type areas are not homogenous throughout the State. Each will vary spatially, sometimes significantly. For this reason, an attempt was made to utilize the most common characterization of each formation especially within the hydrogeologic type area designations. In other areas of the State the reader may expect to see somewhat different characteristics for a particular formation.

2.2.1.4 Delineation of Geophysical Study Sites

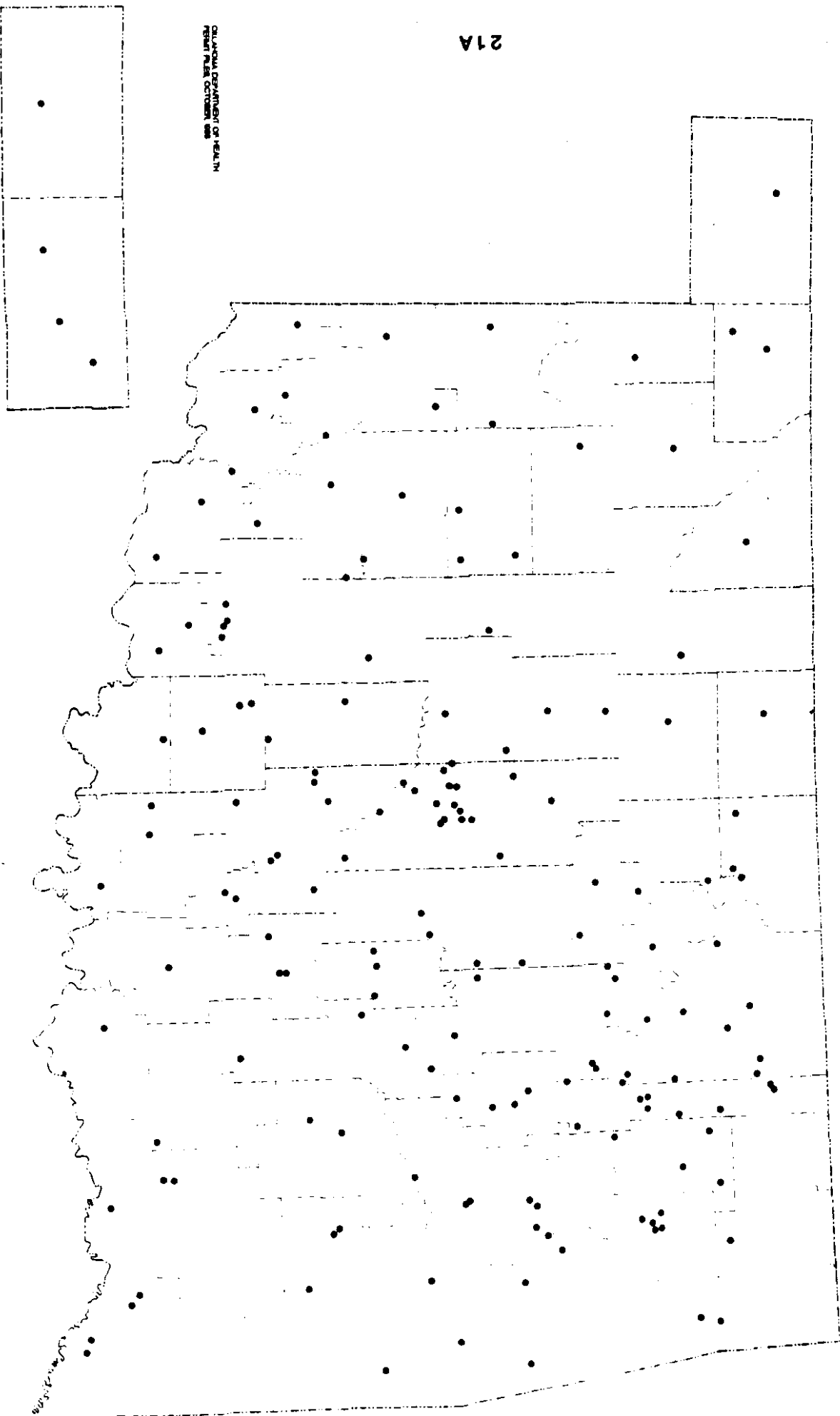
A major objective of this document is the identification of specific responses to surface and borehole geophysical techniques. In order to accomplish this task within an area with a wide ranging lithology, as Oklahoma surely does, specific study sites within the major hydrogeologic type areas are necessary. A minimum of four major study sites, one within each type area, were chosen to gather geophysical responses for specific lithologies. In addition, numerous other sites are included where necessary to represent major variations within a particular type area.

The four study sites, along with typical data responses, are used as the basis for modeling each of the type areas. This will be further discussed later in this document.

2.2.2 Major Cultural Parameters

Two cultural features that must be quickly addressed are the location of existing landfills and the distribution of existing populations. Figure 2 depicts the location of existing solid waste landfills within the State of Oklahoma, as of 1986. Figure 3 shows the distribution of population within the State. This figure presents the areas of population density greater than ten per square mile. As would be expected, the areas with a higher population density are the areas with the larger number of existing landfills. A linear zone from the northeast part of Oklahoma to the southwest part of the State is easily seen on

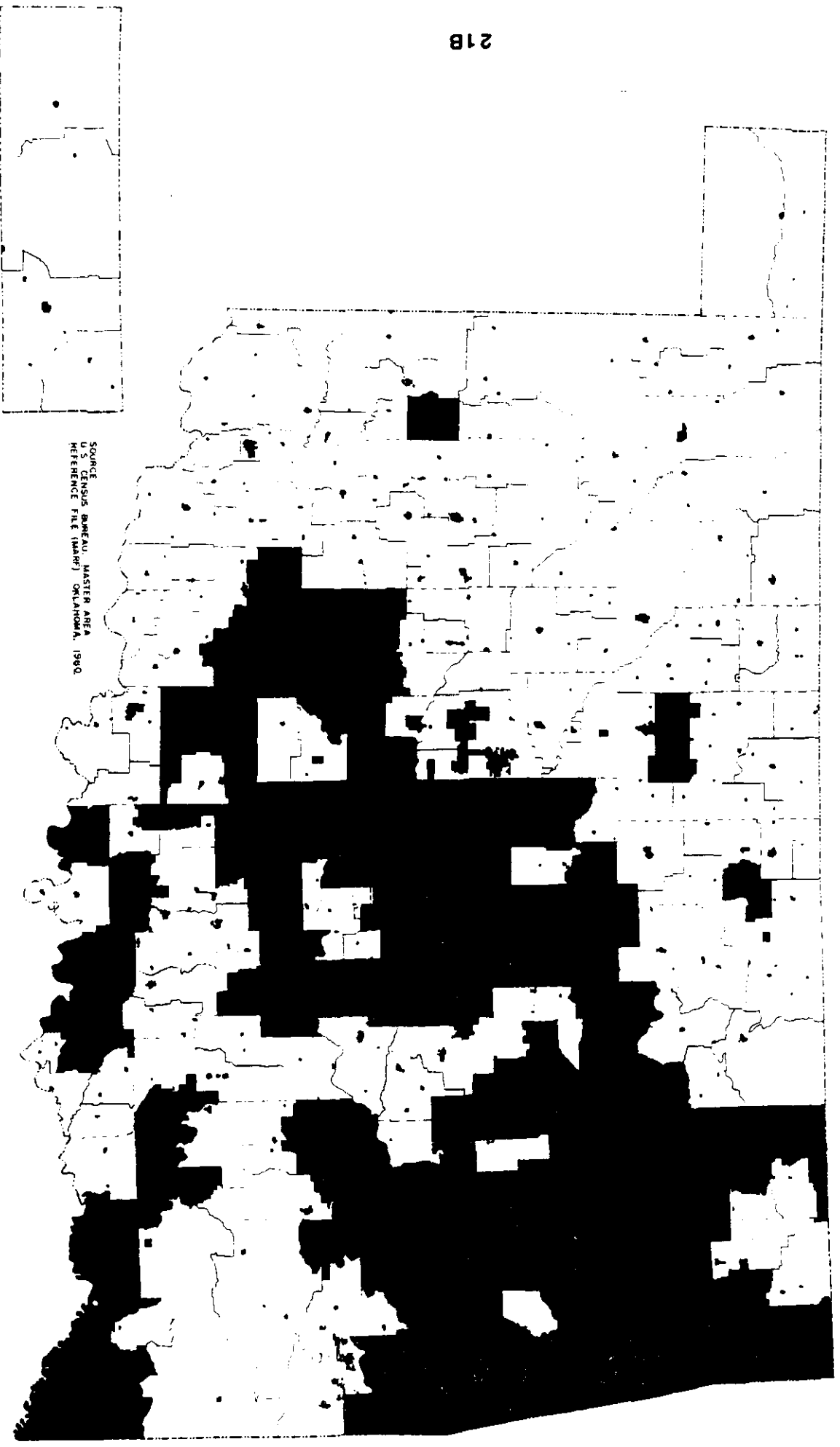
QUADRA DEPARTMENT OF HEALTH
HEALTH PLAN, OCTOBER 1988



LOCATION OF SOLID WASTE LANDFILLS, 1988

FIGURE 2

POPULATION DENSITIES OF 10 PER SQUARE MILE OR GREATER BY CENSUS DISTRICT



SOURCE:
U.S. CENSUS BUREAU, MASTER AREA
REFERENCE FILE (MAREF) OKLAHOMA, 1980

FIGURE 3

both of these figures. It would be prudent, where feasible, for the potential future landfill permit applicant to seek sites remote from this high density zone, although it is likely that within this zone suitable locations may still be found.

Also on a regional basis, the potential applicant should be aware of the variability of major aquifer systems that exist within the State. It is not likely that the governing State agencies would allow a major landfill to be constructed in areas that are underlain by a major aquifer or recharge zone to a major aquifer system. Figure 4 represents the distribution of major aquifer systems within the State and the general geologic relationships of these systems. It should be pointed out that the alluvial systems are shown on Figure 5, Surface Geology of Major and Minor Aquifers. This presentation of the major aquifers is intended to clarify the geologic relationships involved.

Areas remote from the major aquifers are not without ground-water resources. Often these areas are characterized as having ground-water in low quantities or of poor quality. Generally speaking, ground-water exists everywhere within the State of Oklahoma, although it is not always economically available.

Figures 4 and 5 are derived primarily from the Hydrologic Atlas series of the Oklahoma Geological Survey. These atlases were prepared in cooperation with the United States Geological Survey. Nine atlases were prepared for the State exclusive of the panhandle. One atlas was prepared for each of the three counties in the panhandle of the State. A total of twelve

MAJOR BEDROCK AQUIFERS

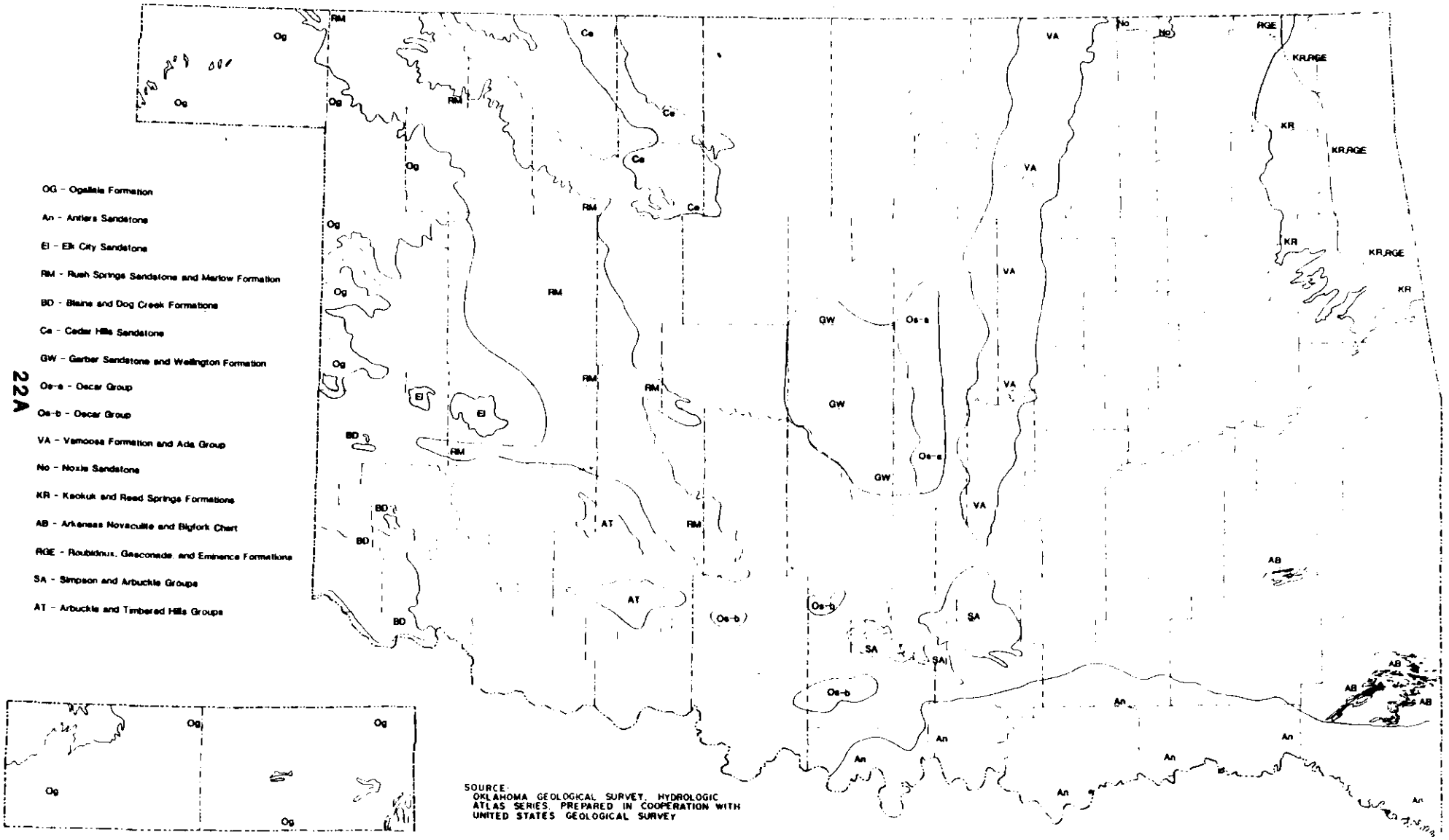


FIGURE 4

atlases have been prepared (see Figure 6). These atlases are readily available from the Oklahoma Geological Survey. Each atlas contains valuable information for the prospective landfill permit applicant including: geology of the quadrangle, surface water characteristics, precipitation, water quality, and availability of ground-water resources.

2.3 Selection of Landfill Site Region

Based on a review of the above regional data bases it should be possible for the prospective permit applicant to select a specific region or area of the State to be further analyzed for potential landfill siting. Likewise, it is equally possible for a landowner to quickly evaluate his holdings and determine a general suitability for landfill siting. Based on this general evaluation, the prospective permit applicant may now determine whether a more detailed site characterization is warranted. If the applicant feels that such actions are justified, the next step is the identification and characterization of a specific site or series of sites.

2.4 DRASTIC

The National Water Well Association under the sponsorship of the EPA's Robert S. Kerr Environmental Research Laboratory has developed a methodology known as DRASTIC that will allow the pollution potential of any hydrogeologic setting to be systematically evaluated anywhere in the United States (Aller, et.al., 1987). This methodology should be applied as an early

DISTRIBUTION OF WATER ATLAS QUADRANGLES

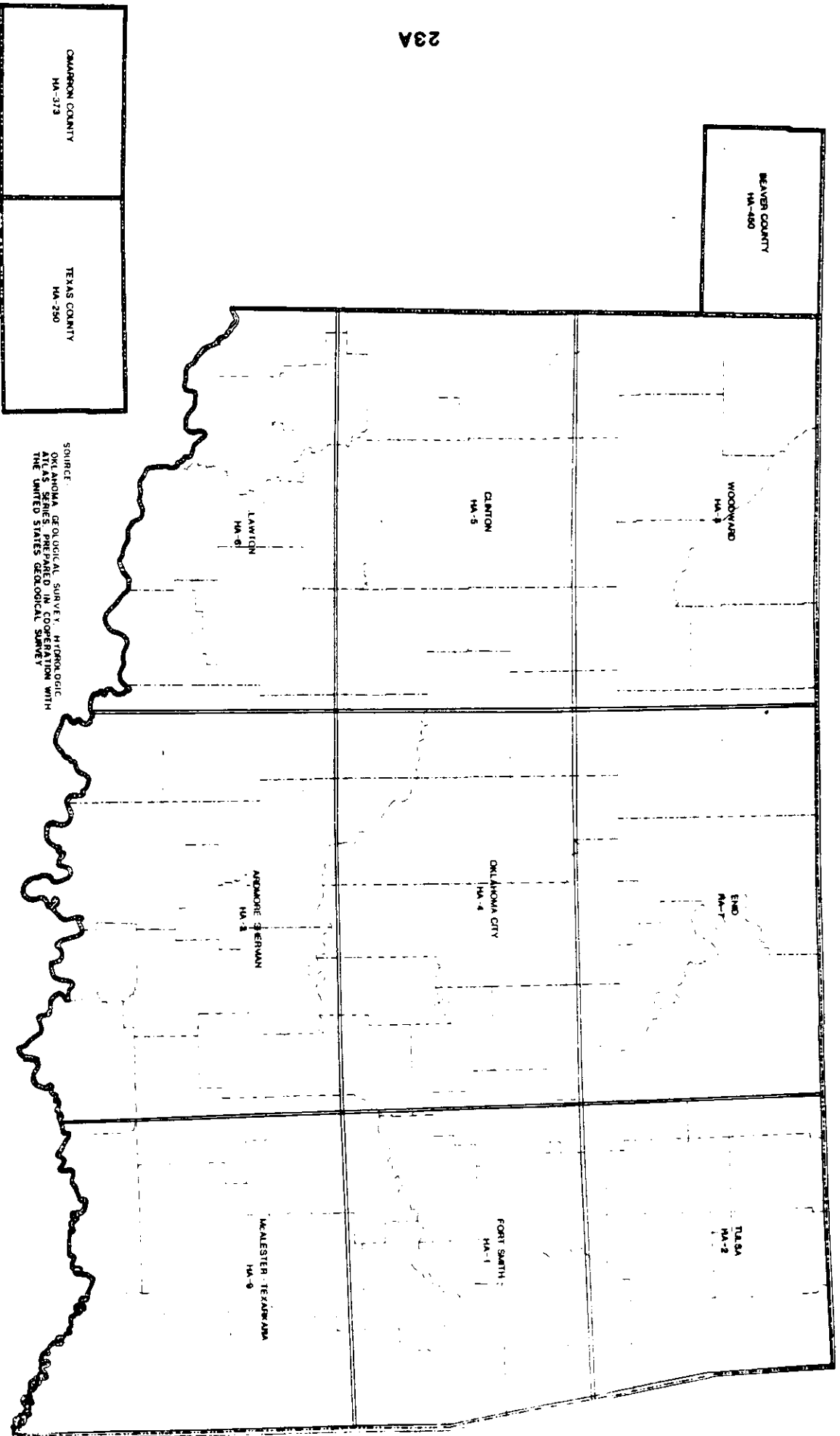


FIGURE 6

analysis of any region within which a waste facility might be proposed. The system has been designed to produce a numerical rating, which may be used to evaluate the relative suitability of any region for a waste disposal facility. For demonstration purposes page 223 of the DRASTIC manual is included in Appendix C. This example depicts the Ogallala aquifer and its resulting Drastic Index.

2.5 Identification and Characterization of Specific Site

2.5.1 Identification of Available Data

Once a prospective applicant determines that a particular site is appropriate for detailed analysis a series of data generation steps are required. Often a significant amount of geologic and ground-water related data is available from a number of State and Federal agencies. The Oklahoma Water Resources Board, for example, maintains data banks such as Storet, Watstore, well driller's logs and flood prone maps. The United States Geological Survey (USGS) and the Oklahoma Geological Survey (OGS) are repositories of geologic reports, surface water, and ground-water information banks such as Storet and Watstor. Numerous geological log libraries are available for use by the prospective applicant. Appendix D presents a more complete listing of data sources. The prospective applicant is encouraged to take advantage of these data sources. Both time and cost will be saved through their utilization.

2.5.2 Acquisition of Appropriate Topographic Maps

The state geological surveys are also a source for topographic maps; which are of paramount importance. These maps should be used in virtually every stage of the data gathering and reduction process.

2.5.3 Site Field Analyses

Numerous analyses must be accomplished at the site of the proposed landfill. These analyses provide the prospective permit applicant with data that will be reduced and used in the actual permit application. It is important that this data collection be undertaken with care and that all aspects of scientific methodologies be followed. A mistake at this stage may mean the difference between permit issuance or rejection. Site field analyses will comprise many operations. Initial activities to be carried out at least in part by the geologist/hydrogeologist, include an outcrop analysis of the site and surrounding area and a well survey of the vicinity.

The outcrop analysis, should be undertaken after the geologist has become thoroughly familiar with all existing literature concerning the site and region. This stage, outcrop analysis, involves the location and field logging of all available outcrops in the vicinity. These should be recorded on outcrop logging forms with all required information recorded. At a later time these logs will be utilized in conjunction with additional logs taken at the time of borehole logging to determine site geologic

characteristics. The position of any streams or other water courses should be noted and the water levels determined.

The vicinity well survey should include all identifiable wells within a minimum one mile radius of the outer edge of the proposed landfill site. This survey should incorporate abandoned and operating wells, drilled and hand dug wells and visible surface water sources that are recognizable. Of particular importance is the location of any surface seeps or springs. These constitute surface exposures of the uppermost aquifer. This will necessitate a door to door canvassing of the affected area and the questioning of the local population regarding both wells and surface water resources. Remember to inquire about abandoned wells, which are often forgotten by the residents until mentioned by the well survey crew.

Although it is not always critical, it is nevertheless good policy to have both pH and conductivity meters available for quick water quality sampling purposes. This information will provide a handy reference in ground-water interpretations and may prove useful in providing arguments regarding potential water deterioration if this point is later contended. It is also good policy to obtain a water sample from each inventoried well, where possible. It is important to follow all correct sampling methods for obtaining water samples to assure that cross-contamination or accidental contamination of the samples does not occur. It is also important to transport these samples to a reputable laboratory for analysis as soon as is possible.

2.5.4 Preliminary Surface Geophysics

In addition to the above noted field activities, three types of analysis are available to produce necessary data for permit generation. Of these three analyses only one is required in the State of Oklahoma for permit application. All proposed landfill sites must be investigated with a borehole drilling program to characterize the geology and ground-water resources at the site. An initial decision, then, is the location of these required boreholes. A common approach is to simply distribute these boreholes somewhat evenly across the proposed site. This, however, is not the most cost-effective or optimum data gathering approach. The use of preliminary surface geophysics will both save money and increase the quality of data generated.

Several methods of surface geophysics are available for field analysis. The most commonly employed methods are Direct Current (D.C.) resistivity, electro-magnetic (EM) conductivity and seismic refraction. Each of these tools are designed and utilized differently and each will provide somewhat different information regarding the hydrogeologic environments. Accurate interpretations are of vital importance and should not be undertaken without adequate background. In a subsequent section interpretations of surface geophysics will be discussed in conjunction with borehole geophysics and drill sample logging.

The use of surface geophysics can significantly reduce the cost of site characterization by minimizing the number of drill holes needed to interpret various aspects of a specific site. Such

information as the expected locations of specific lithologies and the location of the saturated surface may be obtained with practice and a background in hydrogeology.

2.5.5 Initial Drilling and Borehole Geophysics

Once the initial surface geophysical analysis has been completed the hydrogeologist will then be able to advance boreholes in sites chosen to provide optimum information. Fewer boreholes will then be necessary to gain the required data. As the boreholes are advanced, the hydrogeologist should be present to sample log each hole. A field book should be maintained to record not only the sample interpretations but other information that might be utilized at a later date for permit generation. Such information as date, time drilling began and ceased, difficulties in the drilling operation, weather conditions, methods of drilling and the type of drilling rig utilized and completion and development information if the boreholes are cased as piezometers. The hydrogeologist must be able to identify all lithologies and hydrologic conditions penetrated and be able to chose with confidence the correct zones to be screened and developed as piezometers.

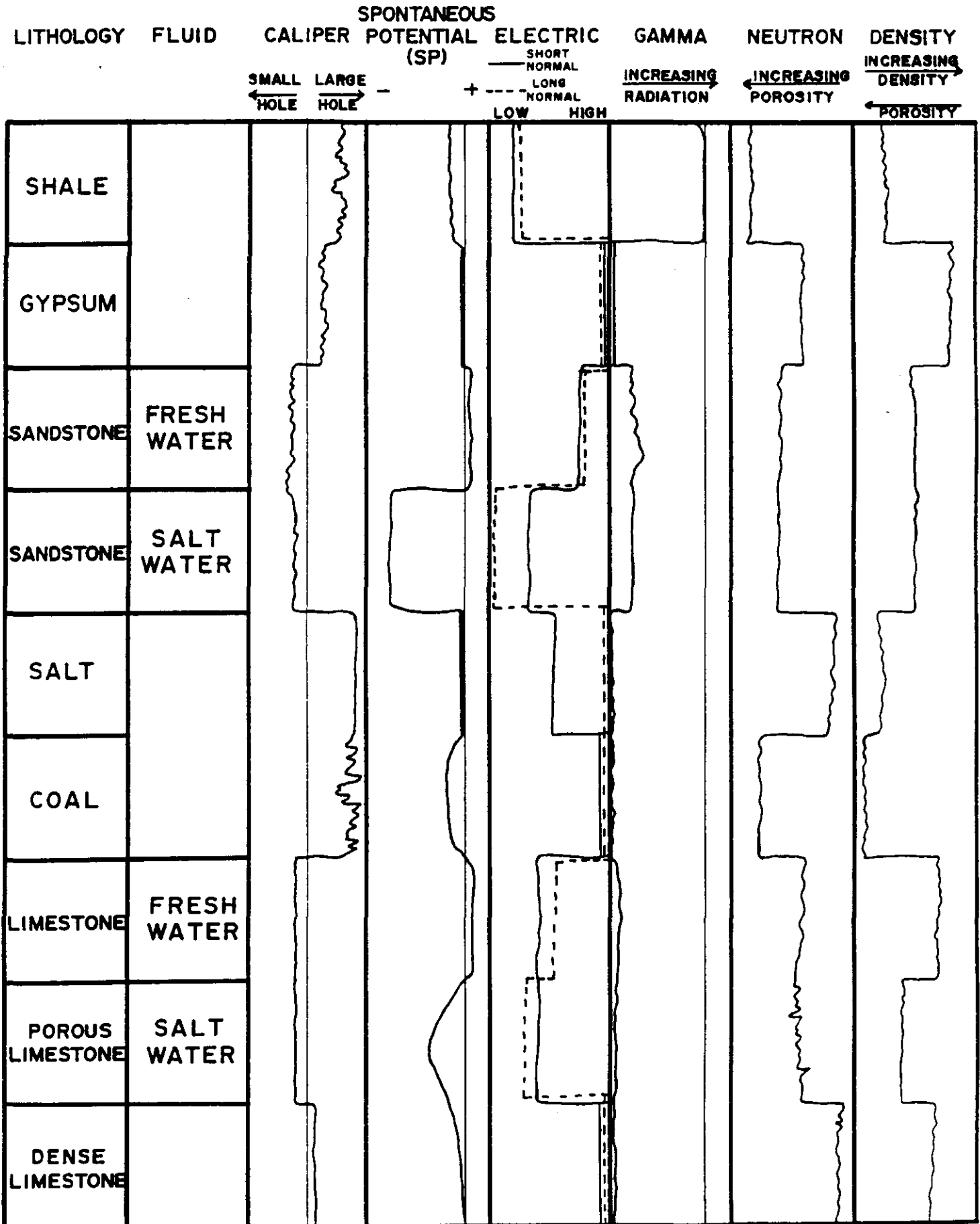
During the drilling operation the hydrogeologist should collect samples of the materials penetrated for laboratory analysis. This analysis should include the basic engineering properties of the materials, such as Atterberg limits, proctor density, and soils classification. These analyses should be performed by a reputable engineering laboratory. The specific analytical

techniques are to be documented and included in the permit application.

Upon reaching the desired depths of each hole, borehole geophysics can be utilized to again increase the amount and precision of data from the site. Borehole geophysics interpretations will allow the hydrogeologist to correct his sample logs and extend the data base with confidence. There exist a wide variety of borehole geophysical logs but only a few are commonly utilized for ground-water and shallow geologic purposes. These are identified under two categories; nuclear and electrical. The nuclear logging techniques commonly employed include natural gamma, gamma-gamma (density) and neutron. Often these three are employed as a composite to facilitate interpretation, as such, the logs are mechanically corrected. The electrical logs constitute a broader grouping. They commonly include several resistivity logs, spontaneous potential and caliper. Typical geophysical log responses for particular lithologic and fluid situations are shown in Figure 7.

The State of Oklahoma requires that static water levels be determined in enough boreholes that an accurate potentiometric map may be produced. This will entail the completion and development of boreholes across the proposed site. This is necessary in most instances due to the rather slow recovery of water levels especially in shale sequences, the primary lithology targeted for landfill construction. Appropriate and approved techniques for completion and development must be

FIGURE 7
TYPICAL GEOPHYSICAL LOG RESPONSES
FOR FLUID AND ROCK TYPES



followed and these techniques must be discussed and otherwise documented in the permit application. Once well development has been accomplished, a scheduled water level measurement program should be instituted. Generally it is desirable to measure water levels at least semi-weekly through a rainy and dry season prior to permit application submission. It is important for the landfill engineering and architectural team to be aware of the maximum and minimum water levels at the particular site for adequate design of the landfill cells. This will ensure that the bottom of the cells will always be a minimum of five feet above the highest water level (a requirement of State regulations).

2.5.6 Initial Field Data Interpretation

The interpretation of the collected information is as important as the data collection itself. It is important to be aware of the interpretation methods for each form of borehole and surface geophysical method and the user must be able to compare these data with drill sample logging for a precise interpretation of the hydrogeologic environment. As discussed earlier, four hydrogeologic type areas were identified. Within these type areas examples of surface and borehole geophysics and drill sample logs were generated. These are here discussed as examples of typical interpretations.

2.6 Typical Interpretations of Geophysical Data in Type Areas

2.6.1 Introduction

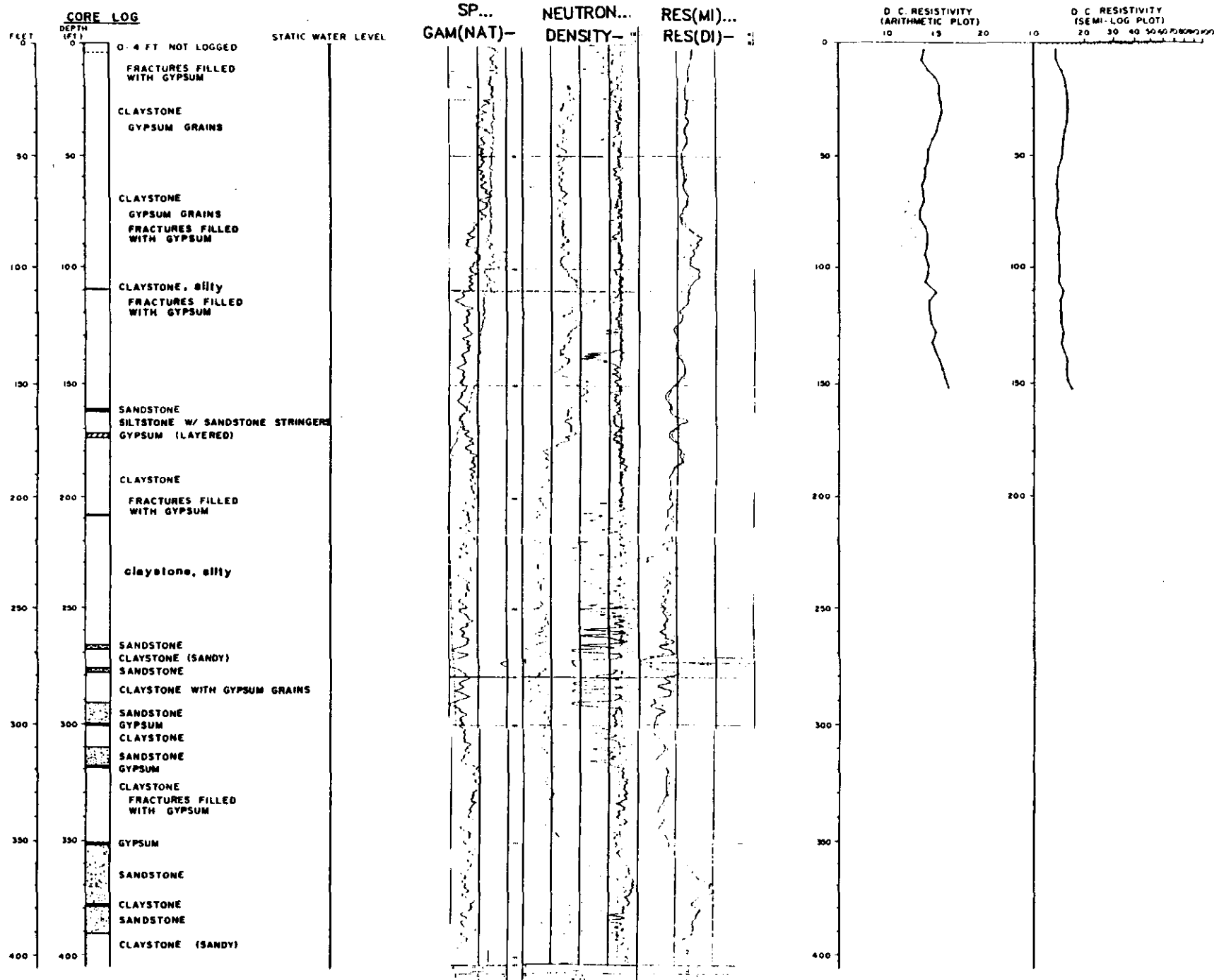
Each of the type areas introduced earlier will respond differently to geophysical investigations, therefore it is imperative that geophysical investigations be carried out by a professional hydrogeologist or an engineering geologist. It is equally important that this individual be aware of the specific type associations with which he is dealing and the responses that would be expected from geophysical techniques.

The following discussion is devoted to examples of geophysical results from the four hydrogeologic type areas defined earlier. It should be noted that these resulting interpretations are only examples and that variations of these responses are likely to be encountered where examples of slightly different type area lithologies than those depicted are encountered.

2.6.2 Type Area I

Type Area I depicts a typical situation in which the predominant lithology is shale. Figure 8 is an example of how a core log, borehole geophysics and D. C. resistivity survey might be compared. Although the lithology at this site is predominantly shale, the shale is not homogeneous in character and fractures filled with gypsum are common. In addition, several beds of sandstone are also to be found in this sequence. By comparing the gamma ray, neutron and spontaneous potential curves supplemented with the core log, these subsurface features may be

GEOPHYSICAL LOG RESPONSE IN TYPE AREA I



31A

identified. Figure 9 also depicts a seismic refraction plot taken near the borehole shown in Figure 8. This plot also depicts the typical shale response. This can be especially noted by comparing the zones of sandstone that were identified from the core log with the picks across the borehole geophysical logs.

A specialized borehole geophysical log may be utilized where a major constituent of the lithology is shale or clay in nature. Figure 10 is a comparison of a KUT plot depicting potassium (percent), uranium (ppm) and thorium (ppm) with natural gamma and neutron logs for the same borehole. As may be seen, a strong correlation between potassium and the gamma and neutron logs is evident.

2.6.3 Type Area II

Type Area II constitutes an unconsolidated terrace deposit. Figure 11 shows two typical responses for an unconsolidated sand material. In this figure the driller's log is compared to D.C. resistivity and a gamma log. The water level reading was not taken on the same day of the borehole log or the surface geophysical log and is not exactly correlated, however, it is close to that indicated from these logs. Figure 12 is a seismic plot of the same general area and may be compared to the data presented in Figure 11. Both the gamma log and the D.C. resistivity log suggest that the lithology is of an increasingly cleaner sand with depth. This is substantiated by the driller's log.

FIGURE 9
 RESPONSE IN TYPE AREA I
 SEISMIC REFRACTION

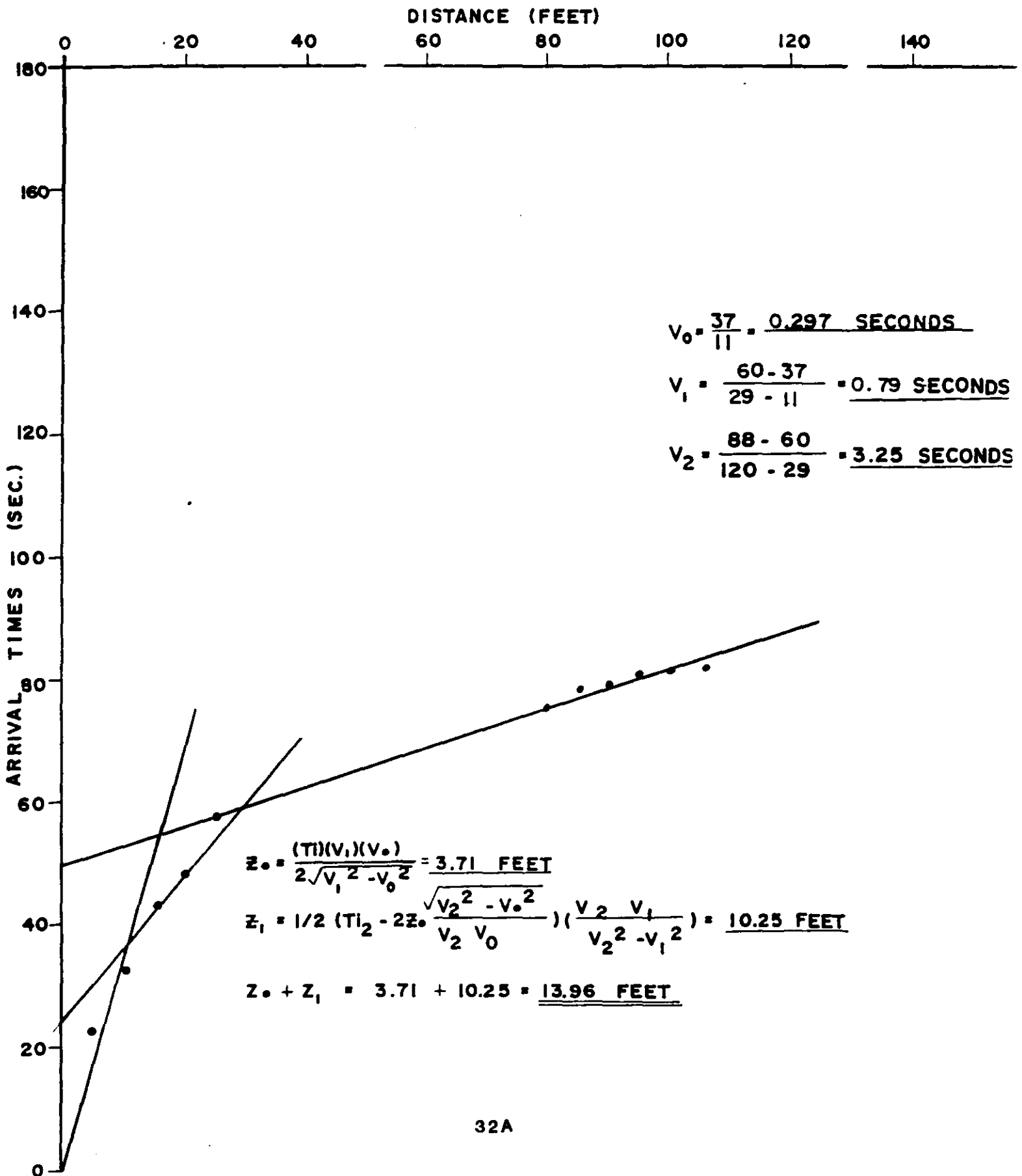


FIGURE 10

GEOPHYSICAL LOGS USED FOR CLAY IDENTIFICATION

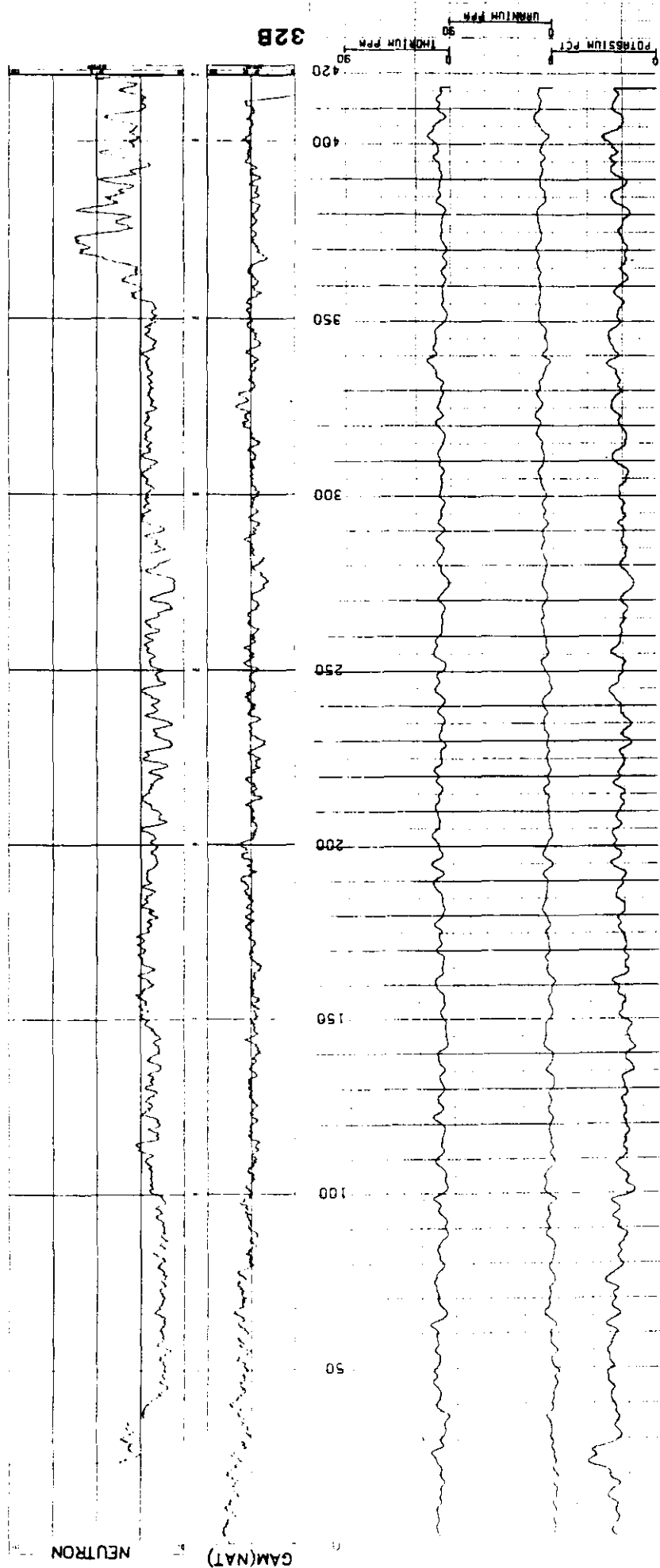
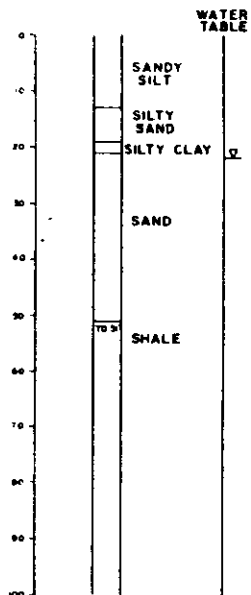


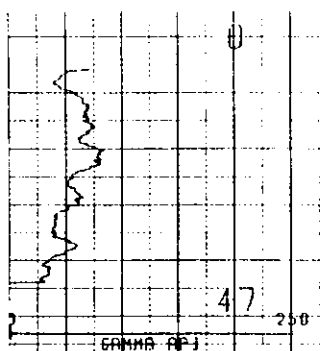
FIGURE 11

GEOPHYSICAL LOG AND D.C. RESISTIVITY RESPONSE IN TYPE AREA II

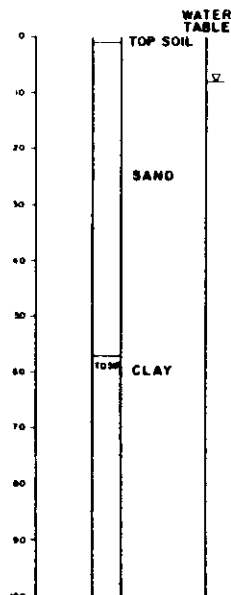
DRILLER'S LOG



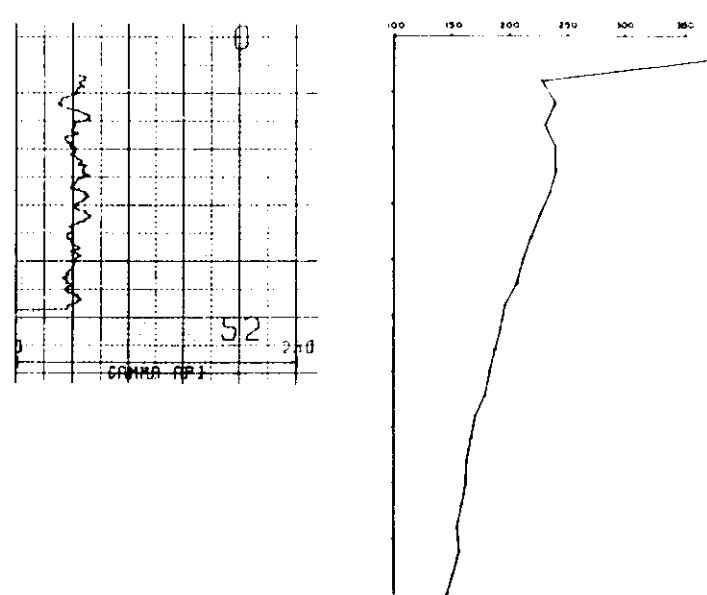
D. C. RESISTIVITY



DRILLER'S LOG



D. C. RESISTIVITY



27C

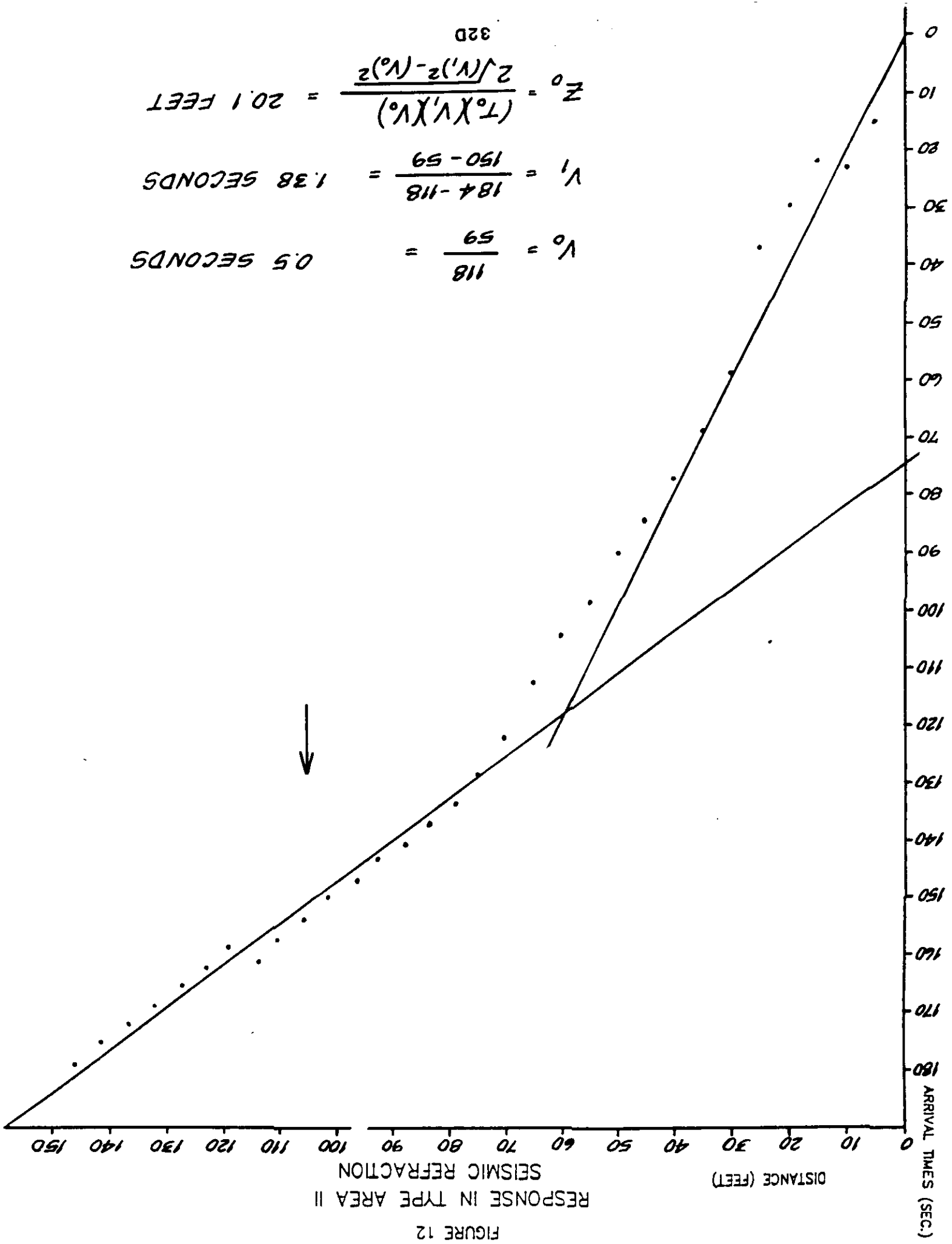


FIGURE 12

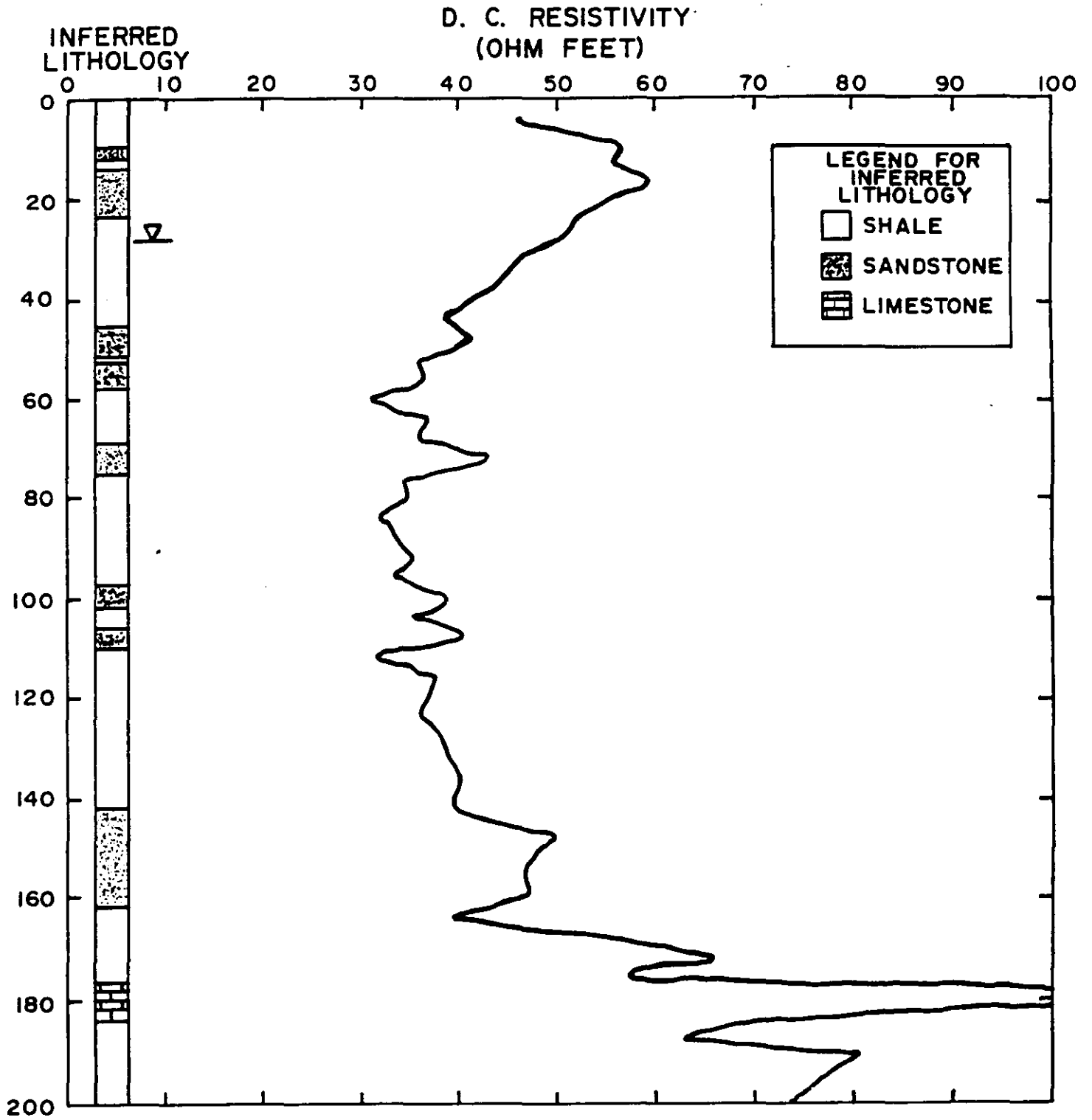
2.6.4 Type Area III

Type Area III is typical of interbedded sandstone and shale sequences. Figure 13 presents a comparison of driller's logs, gamma and neutron logs and D. C. resistivity survey. The upper portion of this sequence is characteristic of the interbedded sandstone and shale lithologies. Both the nuclear logs and the D.C. resistivity survey respond well to this lithological variation. The wide right fluctuation in the D.C. resistivity is indicative of the increased sandstone lithology. The neutron log is especially useful to pick the water table. For the example shown in Figure 13 the borehole was filled with water in order to illustrate the ability of this technique to determine the formation water table. In this case the water level was not measured the same day that the nuclear logs were run thus a slight variation does exist due to a fluctuating water levels.

Figure 13 is also a good example of both limestone and coal responses with nuclear logging devices. One can note the extreme increase in gamma counts associated with the coal deposit. One can also note that this lithology was not found by the drill sample logging. The limestone was recognized during the drill sample logging and is easily identified on both the gamma and neutron logs. This same response is depicted by D. C. resistivity surveys as shown in Figure 14. This figure also represents a typical sandstone/shale interbedded sequence, however, a limestone is near enough the surface to be identified by this technique.

FIGURE 14

D.C. RESISTIVITY RESPONSE FOR INTERBEDDED
SANDSTONE AND SHALE

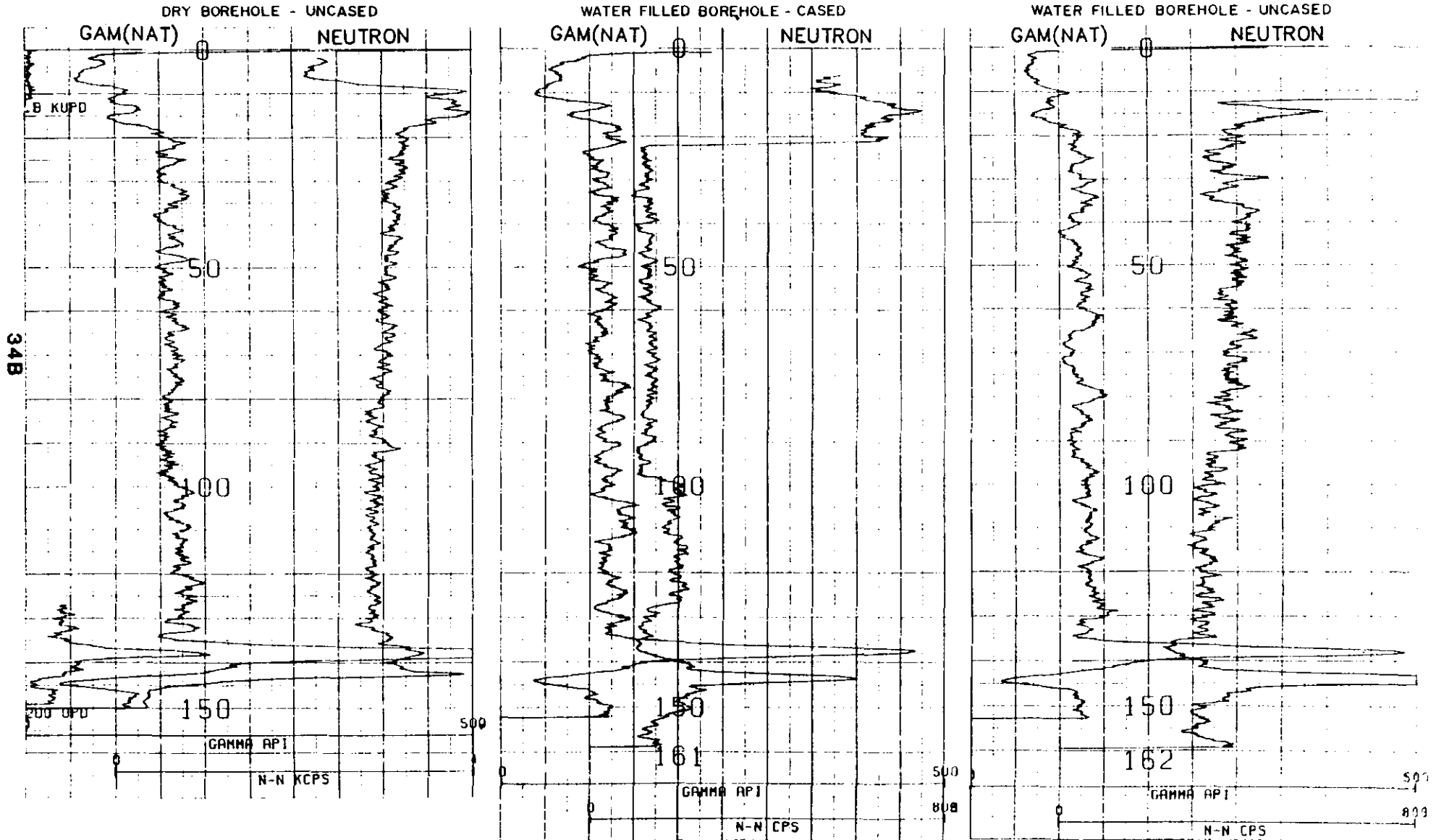


An important consideration of borehole geophysics is whether a borehole may be logged in the uncased or cased state. Figure 15 depicts a predominately shale sequence, indicative of Type Area I, that compares open and cased boreholes. As would be expected, each of the tools utilized in the open borehole were successful in producing usable data. Note, however, that Caliper, when run in the cased borehole produces only a straight line representing the inside of the casing. The gamma, neutron, density and electrical responses obtained by cased boreholes varies somewhat from the open hole responses. This is principally due to the dampening effect of casing and especially of filter pack and grout used to complete the cased borehole. As may be seen from Figure 15 the cased and uncased boreholes vary in that the cased signatures are more subdued than the uncased. From this characterization, it is obvious that open borehole logging is the more desirable. This, however, is not always possible due either to severe time constraints during drilling or to the potential for borehole collapse if completion is delayed.

To take this comparison a step further the cased and uncased boreholes may be logged either filled with a fluid or completely devoid of fluids. Figure 16 presents several logs of cased and uncased, fluid filled and dry boreholes. Although, again, the casing of the borehole does result in some dampening of the responses, for the nuclear logs there does not seem to be too great a variation in responses. The major variations come with the electrical logs. Resistivity and spontaneous potential logs are of no use when conducted in dry boreholes.

FIGURE 16

GEOPHYSICAL LOG RESPONSE TO CASED VS.
UNCASED AND DRY VS. WATERFILLED BOREHOLES



A situation of significance and often the basis of many problems for the landfill applicant is the perched water table. This is an important feature due to the often unexpected existence of ground-water above the regional water table elevation. In addition it is often difficult to identify this feature from borehole logs taken during drilling operations, especially if wash rotary drilling techniques are practiced. Geophysical analyses of these boreholes, however, will usually produce correct interpretations. Figure 17 depicts a typical geophysical response to perched conditions in the interbedded sandstone and shale sequence.

2.6.5 Type Area IV

Type Area IV is indicative of a predominantly limestone lithology. Figure 18 represents a shale/limestone contact. Notice the abrupt swing to the left of the nuclear logs at this contact point. D. C. resistivity, however, displays only a gradual migration of the curve in the direction of increasing ohms beginning at the soil/clay contact point and continuing through the limestone. This survey indicates that the limestone is not a "clean" deposit, but probably includes some shale lenses or clay nodules. This was not identified by the drill sample log and may also be seen in the gamma log plot and to a lesser extent by the neutron plot. A somewhat similar response is seen in Figure 19 in which a limestone is overlain by a chert and a chert residuum and is underlain by a shale.

LOG RESPONSE TO PERCHED WATER TABLE

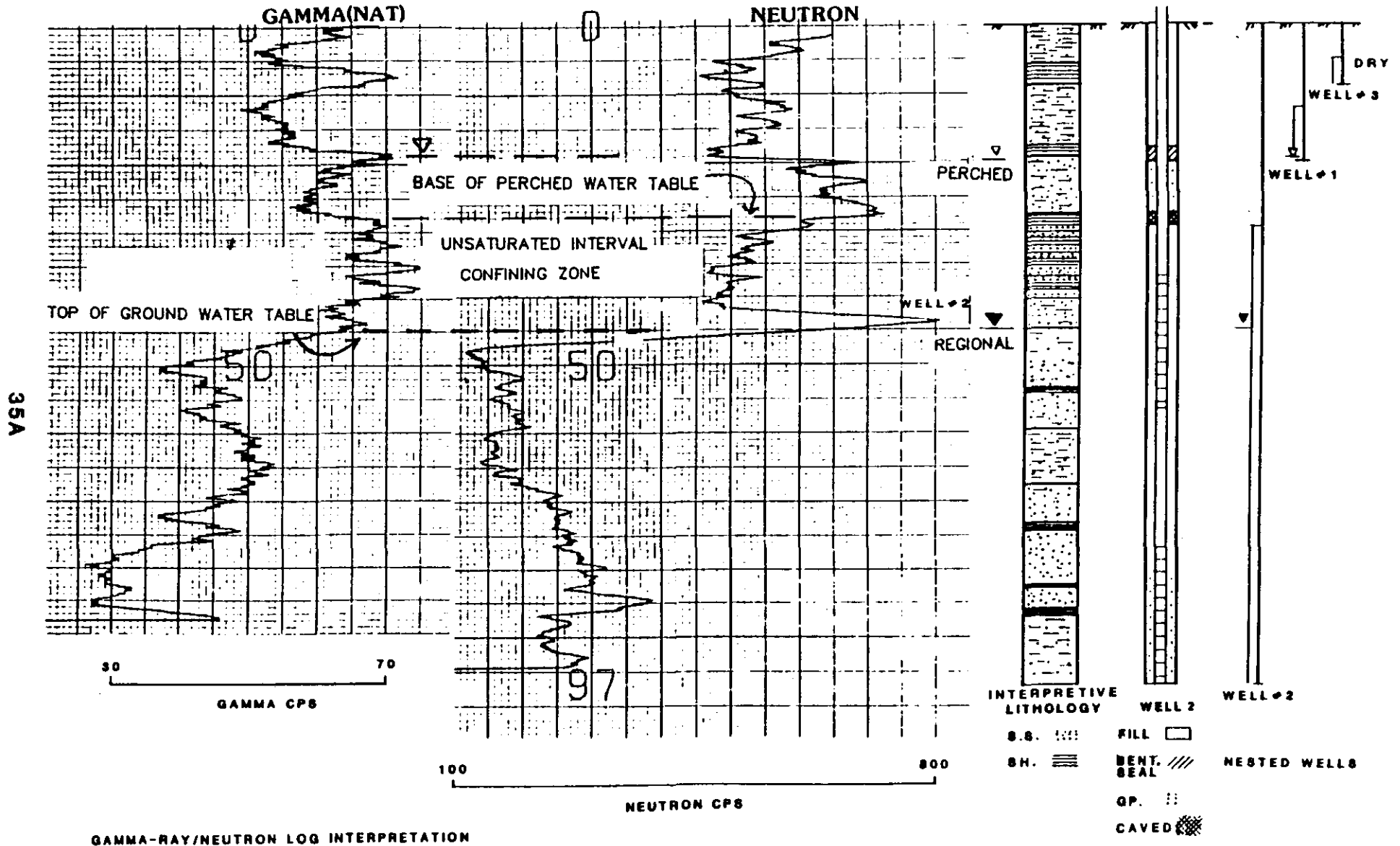


FIGURE 17

FIGURE 18

GEOPHYSICAL LOG RESPONSES TO TYPE AREA IV

TRI-STATE
DRILLER'S LOG

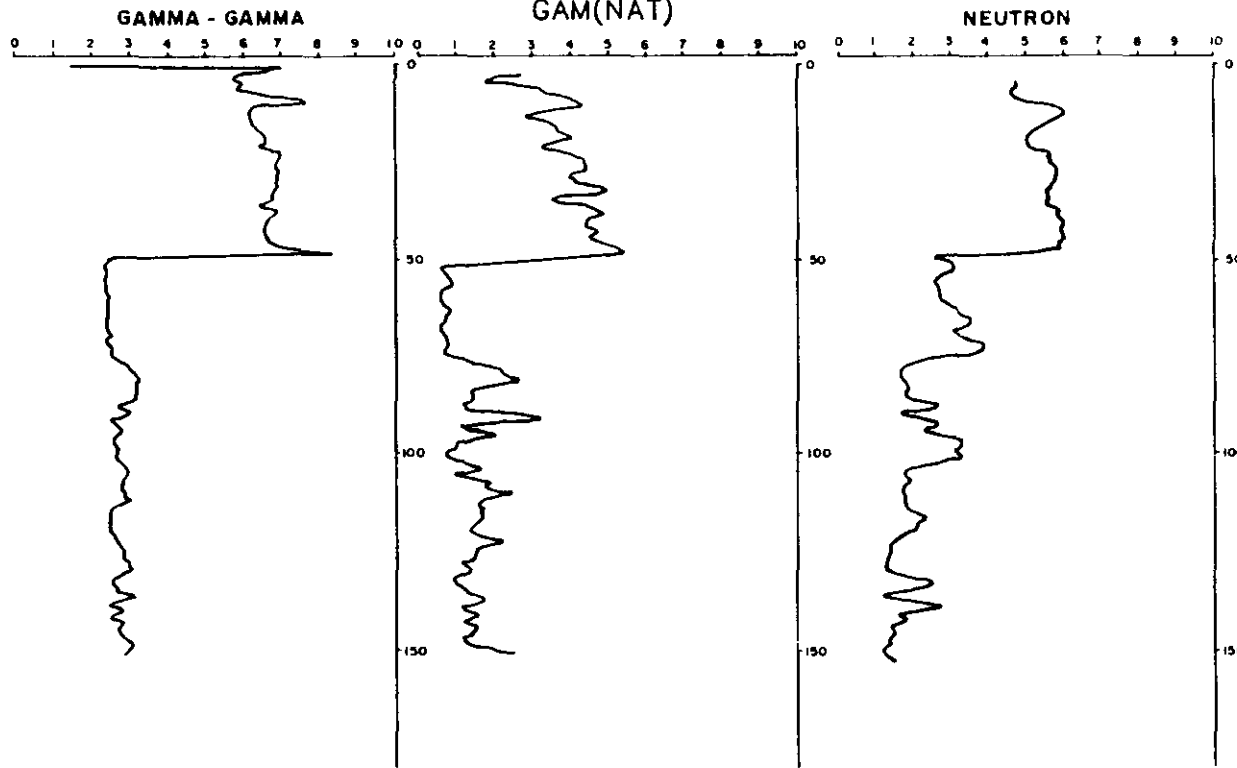
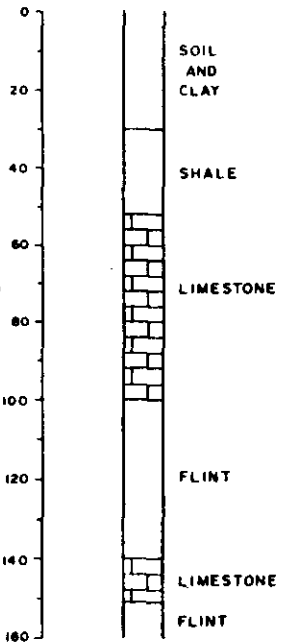
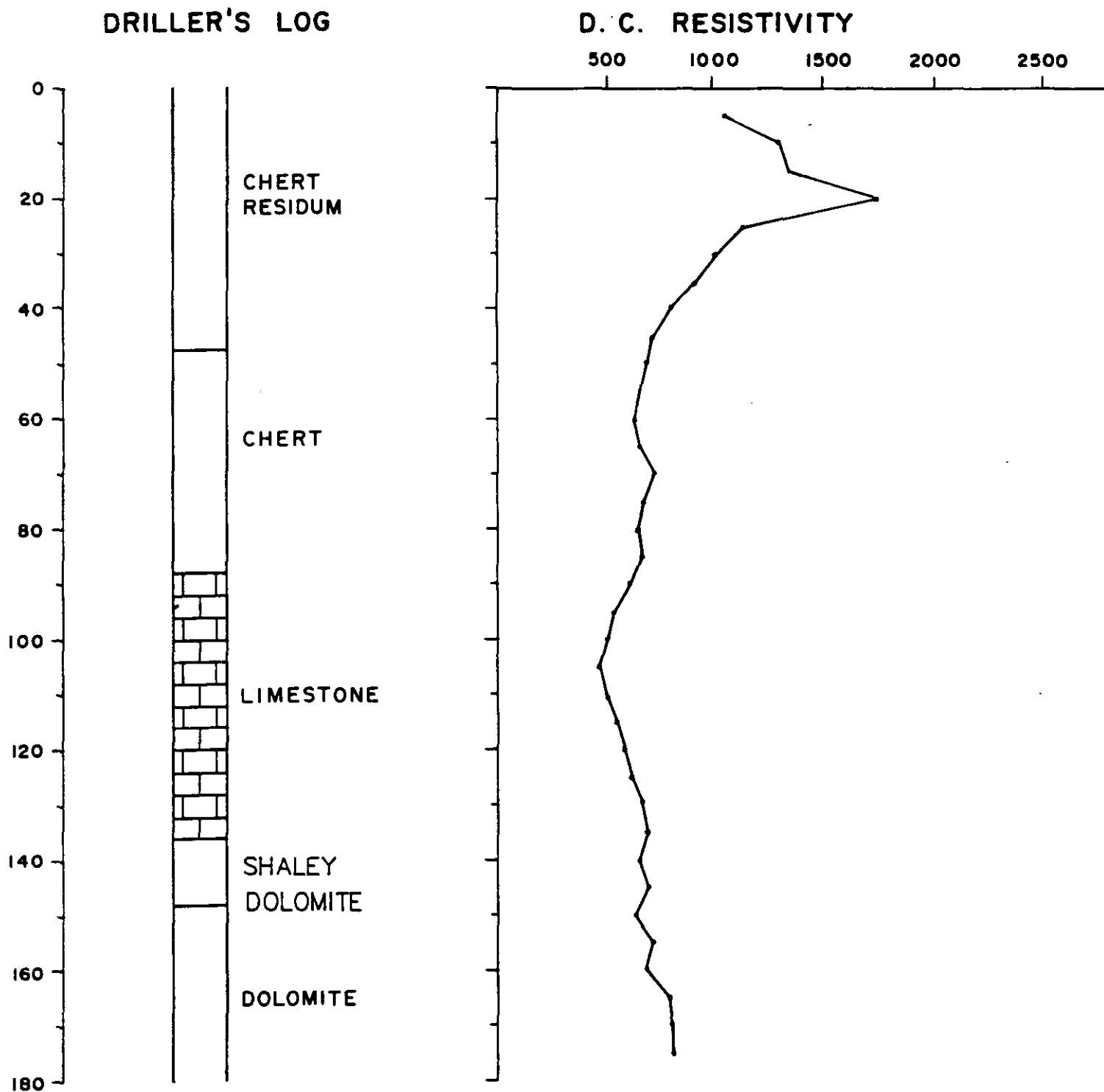


FIGURE 19

D.C. RESISTIVITY RESPONSE IN LIMESTONE LITHOLOGY



Several types of surface and borehole geophysical logging techniques have been discussed thus far. These have not included electromagnetic (EM) conductivity. The reason for this is that this technique is less useful than those discussed for preliminary landfill site characterizations. This does not mean, however, that EM conductivity is not without its usefulness. One major use for this technique is in the identification of contamination plume patterns. Figures 20-21 depict two different methods by which EM conductivity might be successfully employed. Figures 20 and 21 represent 10 meter spacings of horizontal dipole orientation. Figure 20 shows a planar, contour map representation of a EM conductivity survey above an abandoned municipal landfill. Notice the higher conductivity readings in the landfill portion of the map and the indication that a leachate plume is migrating in the direction of the pond. Vertical profiling of this same data (see Figure 21) shows a similar situation on a modified three-dimensional basis.

2.7 Additional Data Needs

2.7.1 Geophysics and Test Drilling

Upon completion of the initial field data interpretation phase of the site characterization decisions may be made regarding the need for additional data upon which to base the permit application. Additional surface geophysics or drilling and borehole geophysics, or perhaps both might be desired. The initial analyses, including surface and borehole geophysics and borehole advancement, provided enough information for a basic

FIGURE 20

ELECTROMAGNETIC CONDUCTIVITY
10 METER HORIZONTAL DIPOLE
SURVEY DEPTH 7.5 METERS
(MILLI - Mhos/METER)

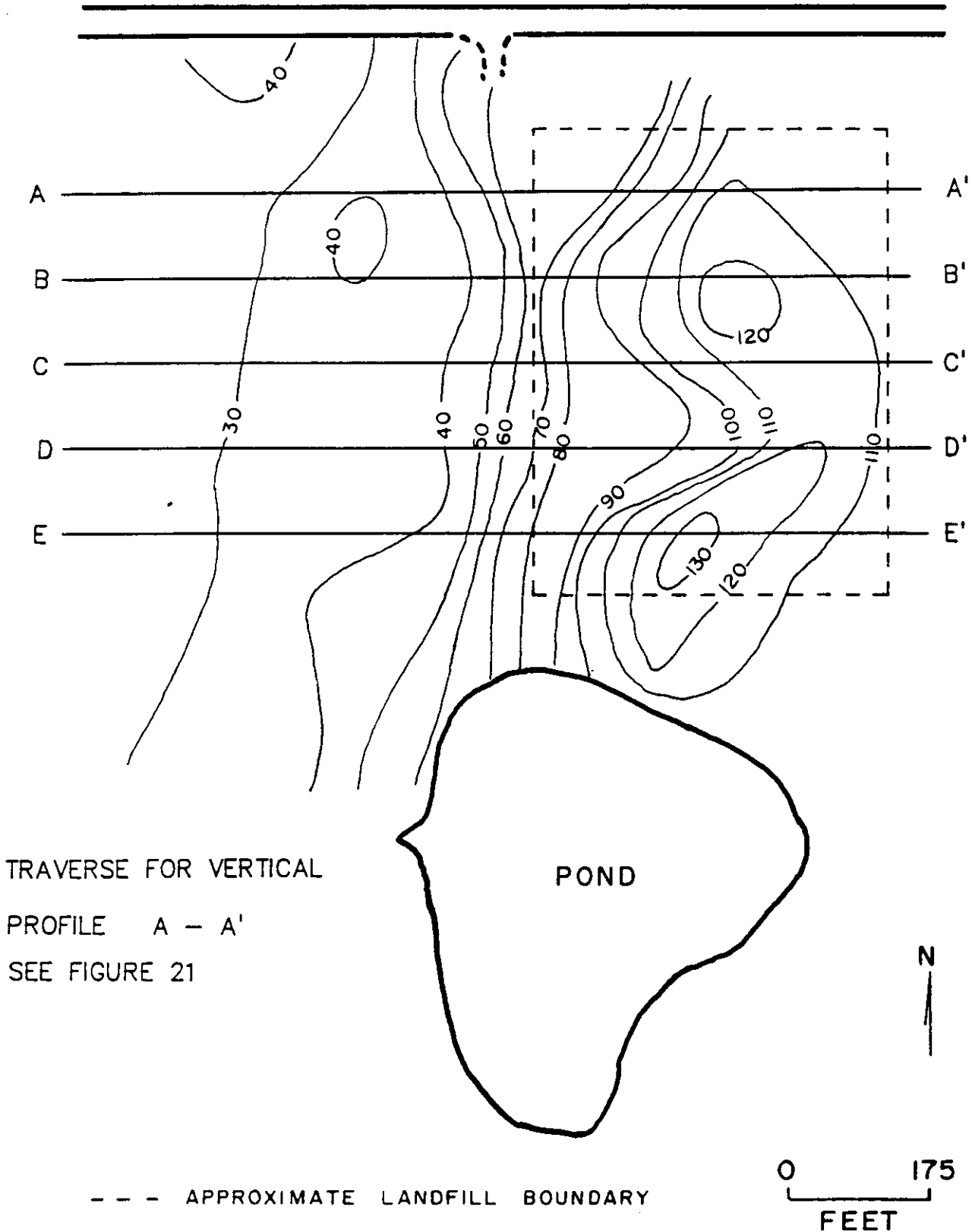
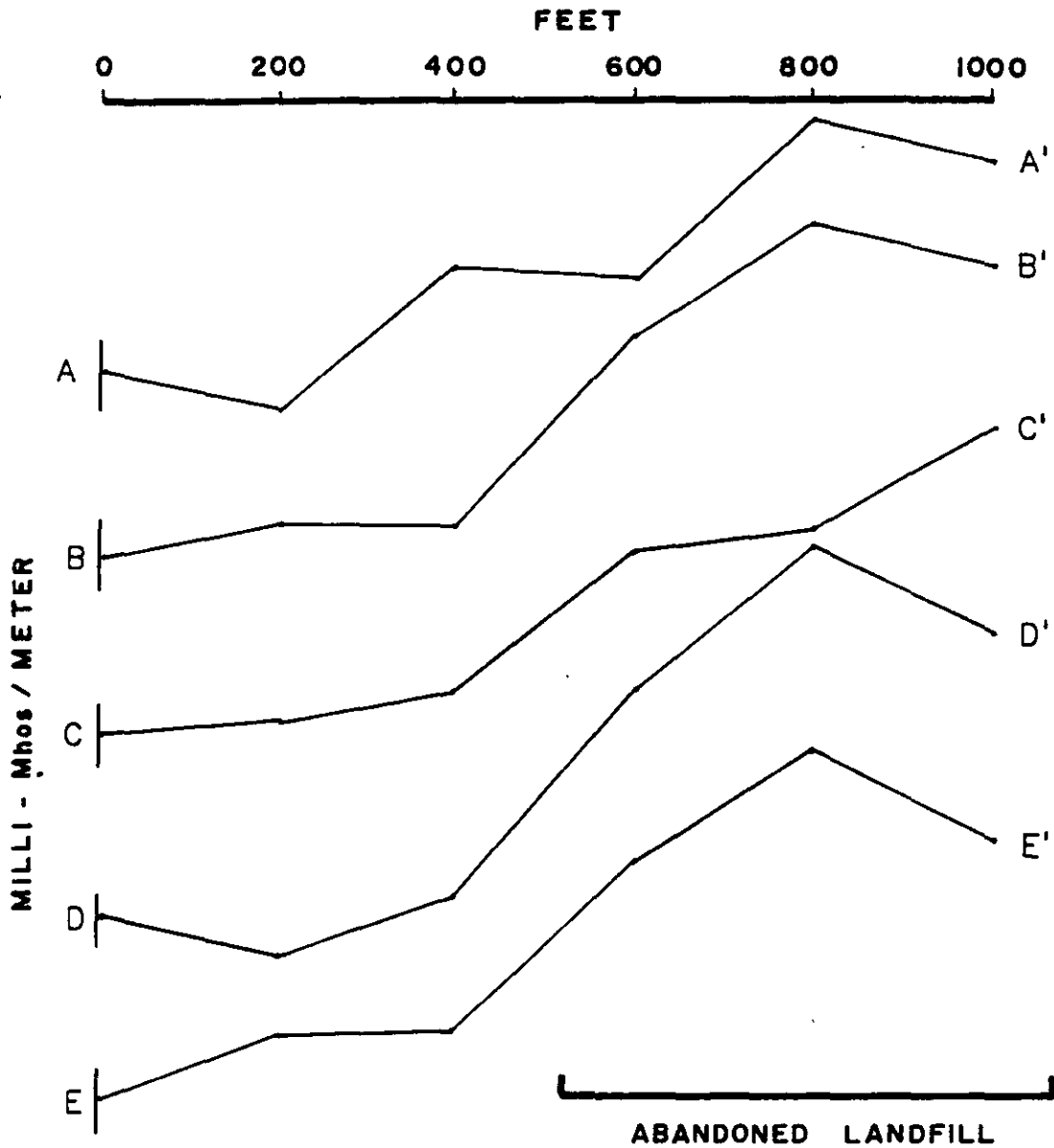


FIGURE 20
36A

FIGURE 21
ELECTROMAGNETIC CONDUCTIVITY
VERTICAL PROFILE



ABANDONED LANDFILL SITE
10 METER HORIZONTAL DIPOLE
SURVEY DEPTH = 7.5 METERS (24 FEET)
HORIZONTAL SCALE: 1 INCH = 200 FEET
CONDUCTIVITY VALUES: 1 INCH = 50 MILLI-Mhos/METER

understanding of the geology and hydrogeology of the site, but often little more than this is gained. This data should be adequate to direct the hydrogeologist in the location of any additional surface geophysical surveys and boreholes that might be deemed necessary for full characterization of the site. If additional boreholes are advanced, and usually this will be necessary, it is often a good idea to employ borehole logging on at least a part of these new boreholes. This will assure the most complete data base possible. Also, these additional boreholes should be completed and developed to gain additional information for potentiometric map generation and/or revision and will assure that the most appropriate landfill design will be developed.

2.7.2 Water Level Data

In addition to surface and borehole geophysics and the data generated from drilling sample logs, in situ aquifer analyses should be performed to obtain hydrogeologic characteristics. There are two primary categories of aquifer analyses that may be performed. The simplest is the slug test in which a slug of water is either added to or removed from a developed well. The rates of recovery are then monitored until the well again reaches a state of equilibrium, usually within a 24 hour period. This technique will provide a good measure of the aquifers permeability. The second method of aquifer analysis requires the pumping, or stressing, of a well and the monitoring of adjacent wells for water level responses. In addition to normal

hydrogeologic parameters, this technique will provide information about vertical interactions among aquifers if more than one aquifer is monitored.

2.7.3 Final Field Data Interpretation

After any additional data is collected, including static water levels for a satisfactory period of time, a final interpretation of field data may be undertaken. All data collected to this point should be considered in this interpretation. Where conflicting data are found to occur, the site characterization team must be in a position to make appropriate interpretations of the data, and to provide reasonable support for the final interpretation.

2.7.4 Conceptual Model of Hydrogeologic System

The result of the final data interpretation is the development of a conceptual model to describe the hydrogeologic system at the proposed site. This model will incorporate the total data set evolved to this point. This conceptual model will comprise a large portion of the permit application and proposal to the State health department.

2.8 Prediction of Solute Transport Using Simple Analytical Models

2.8.1 Introduction

Although not a requirement of the Oklahoma State Department of Health at this time, the prediction of solute transport from the proposed landfill if leakage should occur is a highly desirable component of any landfill permit application. This analysis can predict the direction and rate of movement of any leachate plume that might escape from the facility. This will facilitate the location of monitoring wells to detect such plumes at their earliest possible occurrence.

Because of the need to analyze contamination of ground-water resources many mathematical models have been developed to simulate ground-water flow and solute transports. These models serve a dual purpose: first, to simulate and predict the development of ground-water contamination plumes; and second, to solve the problems of ground-water reclamation. Three types of mathematical models have been developed to meet these objectives. These methods are the nomograph, the analytical model and the numerical model. The first two of these methods are most suitable for the groundwater scientist working without a substantial background in modeling techniques. Both the nomograph and the analytical model are straightforward and relatively simple to use, and they provide the scientist with significant information. For these reasons only the first two will be discussed here.

2.8.2 Analytical Model - - - The Nomograph

The nomograph is a diagrammatic representation of the contaminant plume. The solution may be found for various locations, times and concentrations. The primary result of the nomograph for the groundwater scientist is a feel for the nature of the contaminant plume rather than a map or cross-section view of the plume. This is often used to develop data for either analytical or numerical models that would follow, or it may be used as a quick check of modeled results.

Nomograph results have been calculated for each of the Type Areas discussed above. For each Type Area an expected concentration solution for a point 750 feet from the source and at an elapsed time of 3,650 days or steady state was developed. The distances and times shown are the same used for the analytical solutions to be discussed below. The results of these nomograph calculations are presented in Appendix E.

2.8.3 Analytical Computer Model

An analytical model usually produces a map or cross-section representation of the contamination plume. The model can calculate and display the concentration at a single point or as a grid map of concentrations. Four parameters are initially required for input in order to utilize the analytical model; the concentration of leachate at a specific time and distance, a down gradient distance from the source where concentration of leachate is computed, the transverse distance measured from the center-

line of ground-water flow, and the sample time from beginning of leachate source flow. In addition to these parameters dispersivity, porosity, retardation, decay and source terms are usually required.

Eight assumptions and limitations are generally used in preparing analytical models.

1. The ground-water flow regime is saturated.
2. The aquifer is infinite in aerial extent (x and y directions).
3. All aquifer properties are constant throughout the aquifer.
4. The ground-water flow is continuous and uniform in direction and velocity.
5. There is no dilution of the plume from recharge outside the source area.
6. The leachate source is a point in plain view.
7. The leachate is evenly distributed over the vertical dimension of the saturated zone.
8. The leachate source supplies a constant mass flow rate.

To demonstrate the effectiveness of analytical models, the model developed by Wilson and Miller (1978) will be used. This model employs an analytical mass transport differential equation. Computer programs based on this model were written by Kent, et. al. in 1985. For each of the Type Areas discussed earlier a solution is computed for a concentration at a specified time (3,650 days is used in this example) since hypothetical or actual contamination has entered the ground-water (saturated zone) (see

Appendix E). The most significant result of these calculations is that the variations in concentrations over time and distance are directly related to the specific type of lithology present. For shales, characterized by a low permeability, travel times and distances are low. For unconsolidated sands, however, the travel times and resulting plume migration is more rapid.

It is not difficult to realize that by varying the input parameters a specific site may be easily modeled with a moderate degree of accuracy. This type of information will allow the hydrogeologist to more accurately locate monitoring wells such that the earliest detection of any leachate leaks may be realized.

2.9 Facility Design

2.9.1 Introduction

Once the site characterization is completed the prospective landfill permit applicant is now ready to design the specific landfill. Facility design involves primarily two forms of design; engineering design of the waste facility and the location and design of the monitoring well system that will serve the facility.

2.9.2 Engineering Design

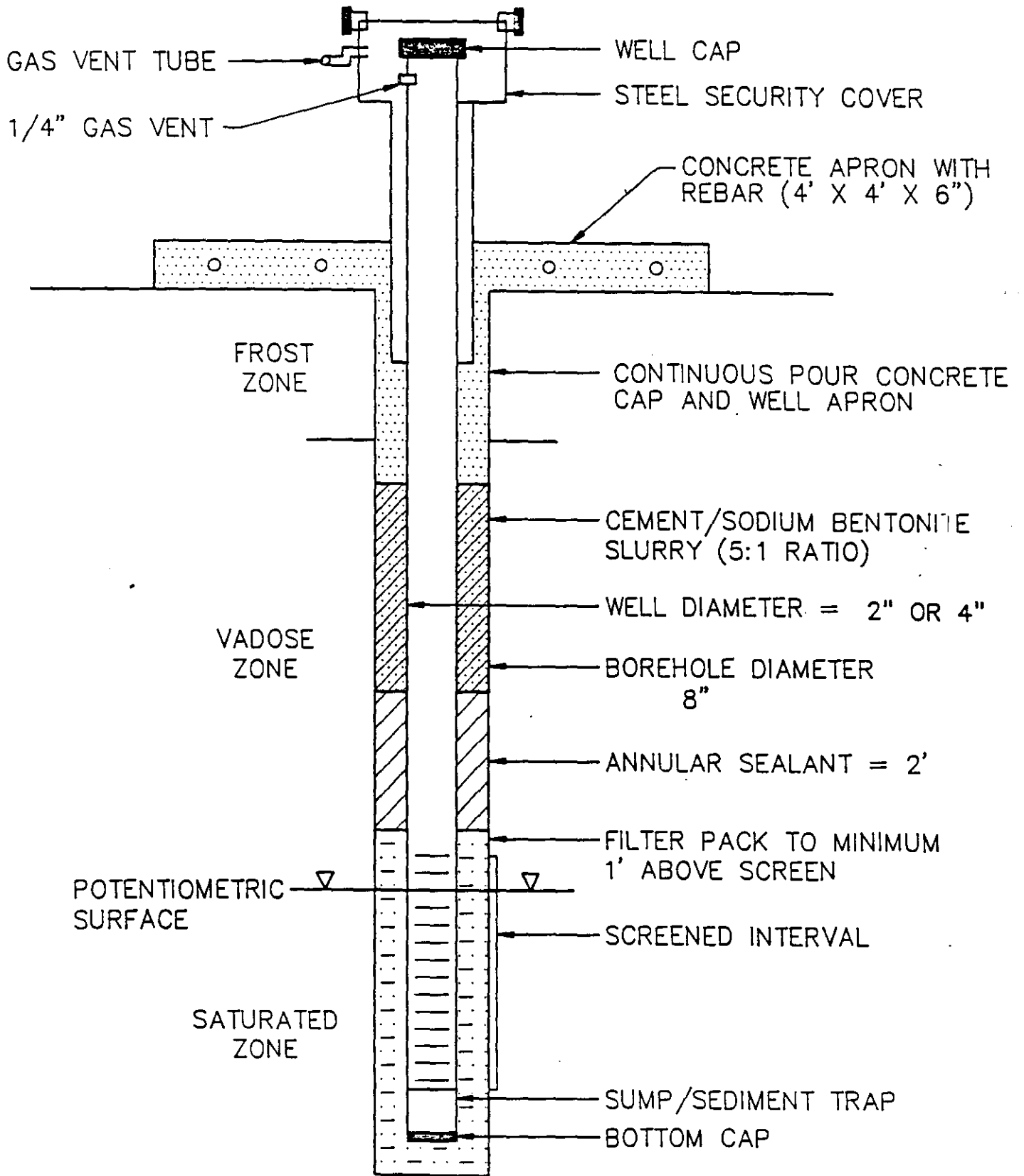
A registered engineer must be involved in the design of all aspects of the landfill facility. This will include disposal cells, borrow material, drainage, etc. The engineer must have available the site characterization results to adequately plan the facility. It is an Oklahoma State Department of Health (OSDH) requirement that the bottom of the cells maintain a minimum five foot separation from the water table. The site characterization data will also provide information regarding the types of liners and need for site borrow materials. It is often the case that borrow materials must be obtained off site in order to meet minimum permeability requirements (less than or equal to $1E-7$ cm/s).

2.9.3 Location and Design of the Monitoring Well System

The data collected during the site characterization period will be vitally important in the determination of the number, location of monitoring wells and depths of screen. The primary objective of well location is that the affected aquifer(s) are being monitored in such a manner that, if the landfill were to leak, the monitoring well system would identify that leak at the earliest possible time. Figure 22 is an example of a monitoring well design that has been approved for both state and EPA groundwater monitoring projects.

The minimum number of up- and down- gradient monitoring wells required by regulations (one up and three down gradient) are

FIGURE 22



TYPICAL MONITORING WELL

inadequate in most situations. In order to determine the number and locations of monitoring wells the hydrogeologist must have a clear understanding of the ground-water system at the site. This will include each of the required analyses and resulting maps or cross-sections, but will usually require additional information such as surface and borehole logging, flow net analysis and leachate plume models. Only with these techniques can the hydrogeologist be relatively assured of an adequate understanding the ground-water situation at the site.

2.10 Generation of Permit Application

The actual landfill permit application will incorporate all the data collected through the site characterization process, and the final engineering and monitoring well designs derived from that data. It is vially important that this application be prepared using the guidelines established by the state agency under whose jurisdiction the application will be reviewed. Again, as an example, Appendix A presents guidelines established by the State Of Oklahoma for the preparation of solid waste disposal site applications. Also included in this appendix is a computer print out of a program to assist the potential applicant or his consultants in the preparation of the application package. This application should be put together by the hydrogeologist and engineer. It should be in the form of a professional document that is concise, yet complete. All required (OSDH) components and any additional data that is pertinent to the argument should be included. This document will be reviewed by the professional

staff at OSDH and be made available for public review. A public meeting will be held in which the community at large will be given a chance to comment on the proposed facility. The OSDH will then make a decision to permit the landfill or to return the application with specific comments regarding needed revision. The applicant then has the option to revise the application for a second review. This revision process may take place a number of times if the OSDH is not satisfied with any portion of the application. The suggested revisions may take the form of simple rewriting of the document, or a request for additional information, some of which may have to be collected in the field by the hydrogeologist and/or the engineering staff and may even take the form of additional boreholes and static water levels. Until the OSDH's professional staff is satisfied that the proposed landfill is safe and meets all State requirements, the landfill cannot be permitted. When a permit is issued the operator may then begin construction on the landfill.

2.11 Summary

The procedure for landfill permitting as discussed above must be carried out in detail, and will require several months to over a year for completion. Most of the data to be collected requires a significant amount of time and capital. These may be reduced, however, if the suggested geophysical and modeling components are included. Conducting surface geophysical surveys prior to borehole development will allow more accurate location of the boreholes to gain the greatest amount of data with the minimum

number of boreholes. Likewise, once holes are drilled the use of borehole geophysics greatly reduces the error in lithologic and hydrogeologic interpretation. Especially if borehole geophysics are interpreted as each borehole is completed, the necessity of a second phase of drilling may be limited. These savings may be translated into both capital and time, each of which are important considerations for the prospective applicant.

3.0 SUMMARY AND CONCLUSIONS

Four hydrogeological type areas were identified to characterize much of the State of Oklahoma. These were: 1) predominantly shale; 2) semi-consolidated to unconsolidated clastics; 3) interbedded shale, sandstone and limestone; and 4) carbonate. These four areas were identified on the basis of outcrop geology and associated hydrogeologic characteristics. Each is assumed to be affected somewhat differently by the siting of solid waste landfills.

Two forms of geophysical techniques were analyzed for characterizing landfill sites in Oklahoma. These were surface geophysical (including direct current resistivity, electromagnetic conductivity and seismic refraction) and borehole geophysical (including electrical logs and nuclear logs) techniques. Each of these techniques were applied to the four identified hydrogeologic type areas. The results of these applications were used as examples in a description of the process for landfill permit application.

Each geophysical technique performed differently for the type areas considered here. The neutron techniques were exceptionally well suited for all four type areas and were very useful in picking out the water table in all cases. The combination of gamma ray, neutron and spontaneous potential probes was well

suiting in delineating subsurface lithologies. In addition, important data regarding the ground-water hydraulics (hydraulic conductivity, porosity and formation fluid type) were characterized.

The Direct Current (D.C.) resistivity technique proved to be well suited in identifying specific lithologies and water table depth when used in conjunction with borehole control. The seismic refraction technique is also applicable for that purpose. Electro-magnetic conductivity was less effective than the other surface geophysical techniques.

Results indicate that surface and borehole techniques should be utilized in a hierarchy of activities for site suitability characterization. Drilling of monitoring and observation wells should be based on geophysical interpretations used in conjunction with other supplemental data. The most important application of surface and borehole techniques is the delineation of potential zones of contaminant migration with more accuracy. Modeling may then be used to characterize fate and transport of contaminants along these conductive zones. These techniques will not only produce a higher degree of accuracy but are also cost effective in comparison with large numbers of trenches and boreholes otherwise needed for the same level of characterization.

BIBLIOGRAPHY

All bibliographic references are coded for the readers easy identification of subject categories. In the left-hand margin the code letter (A through N) refers to a major subject category of interest as identified below. Note that some references may be placed into more than one subject category.

- A - General
- B - Borehole Geophysics
- C - Surface Geophysics
- D - Site Characteristic Strategy
- E - Modeling
- F - Hydraulic Testing Methods
- G - Ground Water Quality
- H - Remote Sensing
- I - Hydrogeologic Investigations
- J - Data
- K - Ground Water Monitoring
- L - Contaminant Hydrogeology
- M - Landfills
- N - Textbooks and Government Documents

Code Reference

- N "A Compendium of Superfund Field Operation Methods", U.S. Environmental Protection Agency, EPA Document No. EPA/540/P-87/001, December, 1987.

- C Ali, Hamid O., "Gravity and Seismic Refraction Measurements For Deep Groundwater Search in Southern Darfur Region, Sudan," in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition, NWWA, 1985, pp.106-120

- B Baldwin, A. Dwight, Jr., and Miller, James, 1979, "The Use of a Gamma Logger to Delineate Glacial and Bedrock Stratigraphy in Southwestern Ohio" GROUND WATER, Vol. 17(4), p. 385-389.

- G Barcelona, M.J., J.A. Helfrich, E.E. Garske and J.P. Gibb. "A Laboratory Evaluation of Groundwater Sampling Mechanisms," GROUND WATER MONITORING REVIEW, Spring 1984, pp.32-41.

- B Bennett, Gordon D. and Eugene P Patten, Jr. "Borehole Geophysical Methods for Analyzing Specific Capacity of Multi-Aquifer Wells". U.S. Department of the Interior, Geological Survey, 25 pages.

- B,C, Benson, Richard C., et.al., "Geophysical Techniques for Sensing Buried Wastes and Waste Migration", Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Las Vegas, Nevada.
- C,D Benson, R.C., and R.A. Glaccum, " Site Assessment: Improving Confidence Levels with Surface Remote Sensing", EPA National Conference on Management of Uncontrolled Hazardous Wastes, October 15-17, 1980, pp.59-65.
- N Bingham, Roy and Bergman, DeRoy L., "Hydrologic Atlas 7: Reconnaissance of the Water Resources of the Enid Quadrangle, North-Central Oklahoma", Oklahoma Geological Survey, 1980.
- N Bingham, Roy and Moore, Robert L., "Hydrologic Atlas 4: Reconnaissance of the Water Resources of the Oklahoma City Quadrangle, Central Oklahoma", Oklahoma Geological Survey, 1975.
- N Birkeland, Peter W., "Soils and Geomorphology", Oxford University Press, 1984.
- I Bredehoeft, John D., "Variation of Permeability in the Ten Sleep Sandstone in the Bighorn Basin, Wyoming, as Interpreted from Core Analysis and Geophysical Logs," U.S. Geological Survey Professional Paper 501-D, 1964, pp. D166-D170.
- D,F Broadhead, R. "The Development of Methods for Determining Aquifer Characteristics. GROUNDWATER 19 (2) pp. 230-232, 1981.
- I Bunker, Carl M. and Wendell A. Bradley, "Measurement of Bulk Density of Drill Core By Gamma-Ray Absorption," U.S. Geological Survey Professional Paper, 1961, B-310 to B-313.
- B Bunker, C.M. and C.A. Bush, "A Comparison of Potassium Analyses by Gamma-Ray Spectrometry and Other techniques," U.S. Geological Survey Professional Paper 575-B, 1967, pp. B-164- B-169.
- B Butler, Dwain K. and Joseph R. Curro, Jr., "Crosshole Seismic Testing--Procedures and Pitfalls," GEOPHYSICS, Vol. 46, #1 (January 1981), p.23-29.
- D Butler, Dwain K. and Jose L. Llopis, "Military Requirements for Geophysical Groundwater Detection and Exploration", in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition, NWWA, 1985, pp 228 - 248.

- C Carmichael, Robert S. and George Henry Jr., "Gravity Exploration for Groundwater and Bedrock topography in Glaciated areas" *GEOPHYSICS* Vol 42 #4 (June 1977), pp. 850-859.
- N Carr, Jerry E., and Bergman, DeRoy L., "Hydrologic Atlas 5: Reconnaissance of the Water Resources of the Clinton Quadrangle, West-Central Oklahoma", Oklahoma Geological Survey, 1976.
- D Cartwright, K., R.W. Gilkeson, and T.M. Johnson, "Geological Considerations in Hazardous-Waste Disposal". *JOURNAL OF HYDROLOGY* 54 (1-3) pp. 357 - 368, December 1981.
- N Chen, Philip S., *INORGANIC, ORGANIC, AND BIOLOGICAL CHEMISTRY*, Harper and Row.
- I Chitsazan, Manouchehr, "Hydrogeologic Evaluation of the Boone- St.Joe Carbonate Aquifer. Masters, University of Arkansas, 1980.
- A,B, C Cordes, Edwin H., "Groundwater Instrumentation Program of the United States Geological Survey," *GROUND WATER MONITORING REVIEW*, Fall 1984, pp. 103-114.
- B,I Croft, M.G., "A Method of Calculating Permeability From Electric Logs, " United States Geological Survey, Professional Paper 750-B, 1971, pp. B-265-B-269.
- B Crosby, James W. and Paul Davis, " Geotechnical Applications of Borehole Geophysics," *JOURNAL OF GEOTECHNICAL ENGINEERING DIVISION* , Proceedings of the American Society of Civil Engineers, Vol. 107, # GT 10, October 1981, pp. 1255-1267.
- B Crosby, James W. and John D. Scott, "Borehole Geophysics in Nuclear Power Plant Siting," Geological Society of America, *Reviews in Engineering Geology*, Vol. IV, 1979, pp.215-225.
- C Daniels, Jeffrey J., " Three-Dimensional Resistivity and Induced-Polarization Modeling Using Buried Electrodes", *GEOPHYSICS*, Volume 42 #5, (August 1977), pp.1006-1019
- C Daniels, Jeffrey J., "Interpretation of Buried Electrode Resistivity Data Using a Layered Earth Model," *GEOPHYSICS*, Vol 43, #5 (August 1978) pp. 988-1001.
- B Daniels, Jeffrey, "Hole-To-Surface Resistivity Measurements", *GEOPHYSICS* , Volume 48, # 1, (January 1983) pp. 87-97.

- B DeLuca, Richard J., and Buckley, Barbara K., 1985, "Borehole Logging to Delineate Fractures in a Contaminated Bedrock Aquifer," in Second National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington, Ohio, NWWA.
- C Dix, C. Hewitt, "Seismic Velocities From Surface Measurements", GEOPHYSICS, Volume 20, #1 (January 1955) pp. 68-86.
- B,C Dobecki, T. L., and Romig, P. R., 1985 "Geotechnical and Groundwater Geophysics": GEOPHYSICS, vol. 50 (12), pp. 2621 - 2636.
- N DRASTIC: A STANDARDIZED SYSTEM FOR EVALUATING GROUND-WATER POLLUTION POTENTIAL USING HYDROGEOLOGIC SETTINGS, U.S. Environmental Protection Agency, EPA Document No. EPA/600/2-87/035.
- N Driscoll, Fletcher M., GROUND WATER AND WELLS, Second Edition, Johnson Division, St. Paul, Mn., 1986.
- G Dunbar, D., H. Tuchfeld, R. Siegel and R. Sterbentz, "Ground Water quality Anomalies Encountered During Well Construction, Sampling and Analysis in the Environs of a Hazardous Waste Management Facility," GROUND WATER MONITORING REVIEW. Summer, 1985. pp.70-74.
- C Dutta, N.P., "Seismic Refraction Method to Study the Foundation Rock of A Dam". GEOPHYSICAL PROSPECTING, Vo. 32, (1984). pp. 1103-1110.
- B Dyck, J. H., Keys, W. Scott and Meneley, W. A., 1972, "Application of Geophysical Logging to Groundwater Studies in Southeastern Saskatchewan" CANADIAN JOURNAL OF EARTH SCIENCES, vol. 9, pp. 78-94.
- I Farmer, G. Thomas, Bryson, Hal Jr., and Evans, Mark L., 1982, "Hydrogeologic Considerations in Hazardous Waste Facility Siting", In A Northeast Conference; The Impact of Waste Storage and Disposal on Ground-Water to Sources, pp. 7.2.1- 7.2.18 Ithaca, New York: Cornell University Center of Environmental Resources.
- A,I Ferguson, D.L., "Access to Water-related Data in Texas". JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT DIV. PROC. ASCE Vol. 107 # WR2, pp. 375-383, October 1981.
- N Fetter, C.W., APPLIED HYDROGEOLOGY, Second Edition, Charles Merrill Publishing Co., 1987.

- C Flathe, H., "Five-Layer Master Curves for the Hydrogeological Interpretation of Geoelectrical Resistivity Measurements Above a Two-Story Aquifer," GEOPHYSICAL PROSPECTING. Vol.XI. pp. 471- 508. (1963).
- N Freeze, Allan, R. and Cherry, John A., GROUNDWATER, Prentice-Hall, Inc., 1979.
- B,C Frohlich, Reinhard K. "Combined Geoelectrical and Drill-Hole Investigations for Detecting Freshwater Aquifers in Northwestern Missouri". GEOPHYSICS. Vol. 39, # 3 (June 1979) pp. 340-352.
- C Gagne, R.M., S.E. Pullan and J.A. Hunter. "A Shallow Seismic Reflection Method for use in Mapping Overburden Stratigraphy," in Surface and Borehole Geophysical methods in Groundwater Investigations Second National Conference and Exposition. NWWA. 1985. pp 132-145.
- C Gelchinsky, B. and V. Shtivelman. "Automatic Picking of First Arrivals and parameterization of Travel Time Curves," GEOPHYSICAL PROSPECTING. Vol.31, 1983. pp.915-928.
- N "Geogydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties", U.S. Geological Survey, Water Resources sInvestigation 25-75.
- D,I Geraghts, J.J., "Evaluations of Hydrogeologic Conditions". EPA National Conference on Management of Uncontrolled Hazardous Wastes. 1980. pp. 49-52.
- C,K Gilkeson, Robert H. and Keros Cartwright, " The Application of Surface Electrical and Shallow Geothermic Methods in Monitoring Network Design". GWMR. Summer 1983. pp.30-42.
- B,C Glaccum, Robert, Benson, Richard and Noel, Michael, 1981, D,I "Using Geophysics to Reduce Cost and Risk in Hazardous Waste Site Investigations" in Studies of Hydrogeology of the Southeastern United States; Americus, Georgia: Southwestern College, pp. 59-64.
- B,C, D Glaccum, Robert A., Richard C. Benson and Michael R. Noel, "Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations". GWMR. Summer 1982, pp. 36-40.
- B,C, K Greenhouse, J.P., L.A. Faulkner, P.E. Pehme and J. Wong. "Geophysical Monitoring of an "Injected Contaminant Plume: Experiments with a Disposable E-Log". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA, 1985, pp. 64-82.

- I,L Greenhouse, J.P. and R.D. Harris, "Migration of Contaminants in Groundwater at a Landfill: a Case Study." JOURNAL OF HYDROLOGY. 63(1983), pp.177-197.
- C Greenhouse, John P. and David Slaine. "The Use of Reconnaissance Electromagnetic Methods to Map Contaminant Migration". GWMR. Spring 1983, p.47-59.
- N GROUNDWATER, U.S. EPA Publication EPA/625/6-87/016, March, 1987.
- N "Ground Water Resources of the Rush Springs Sandstone of Southwestern Oklahoma", Oklahoma Water Resources Board, Hydrologic Investigations Publication 72, 1976.
- B Guyod, Hubert, "Interpretation of Electric and Gamma Ray Logs in Water Wells", THE LOG ANALYST, vol. 6(5), pp. 30-44.
- B Guyod, Hubert, "Application of Borehole Geophysics to the Investigation and Development of Groundwater Resources". WATER RESOURCES BULLETIN. Vol.8 #1. (Feb. 1972). pp. 161-174.
- C Hagedoorn, J.G., "The Plus-Minus Method of Interpreting Seismic Refraction Sections," GEOPHYSICAL PROSPECTING. Vol. 7, pp.158-182.
- C Hales, F.W. "An Accurate Graphical Method For Interpreting Seismic Refraction Lines". GEOPHYSICAL PROSPECTING. Vol. VI. pp.285-294. (1958).
- B,C Harris, Martin H., and McCammon, R. B., 1971, "A Computer Oriented Generalized Porosity - Lithology Interpretation of Neutron, Density, and Sonic Logs", JOURNAL OF PETROLEUM TECHNOLOGY, vol. 23, pp. 239-248.
- N Hart, Donald L., Jr., "Base of Fresh Ground Water in Southern Oklahoma", U.S. Geological Survey, Hydrologic Investigations Atlas Ha-223, 1966.
- N Hart, Donald L., Jr., "Reconnaissance of the Water Resources of the Ardmore and Sherman Quadrangles, Southern Oklahoma" Oklahoma Geological Survey, Hydrologic Atlas 3.
- D,I Hart, D.L., Jr., R.E. Davis. "Geohydrogeology of the Antleis Aquifer (Cretaceous) Southeastern Oklahoma. Oklahoma Geological Survey. Cir-81, 1981. # 21. p.5.
- N Havens, John S., "Reconnaissance of the Water Resources of the Lawton Quadrangle, Southwestern Oklahoma", Oklahoma Geological Survey, Hydrologic Atlas 6, 1977.

- D,I Hawkins, David B. and Daniel B. Stephens. "Ground-Water modeling in a Southwestern Alluvial Basin," GROUNDWATER, Vol.21, #6, Nov.-Dec. 1983, pp733-739.
- C Hawkins, L.V. " The Reciprocal Method of Routine Shallow Seismic Refraction Investigations" GEOPHYSICS, Vol. XXVI, # 6 (Nov.1961) pp.806-819.
- N Heath, R. C., BASIC GROUND-WATER HYDROLOGY, U.S. Geological Survey, Water Supply Paper 2220, 1984.
- B,C D Heely, Richard W. and Bruce A. Marshall, " The Use of Geophysical Techniques in an Accelerated Search for Groundwater in the Connecticut River Valley, Massachusetts" in Surface and Borehole Geophysical Methods in Groundwater investigations, Second National Conference and Exposition, NWWA. 1985. pp.249-264.
- N Hem, John D., STUDY AND INTERPRETATION OF THE CHEMICAL CHARACTERISTICS OF NATURAL WATER, Third Edition, U.S. Geological Survey, Water-Supply Paper 2254.
- C Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne and R.L. Good. "Shallow Seismic Reflection Mapping of the Overburden-Bedrock Interface with the Engineering Seismograph--Some simple Techniques". GEOPHYSICS. Vol. 49, # 8 (Aug.1984). pp.1381-1385.
- C Inman, Joseph Robert. "Resistivity Inversion with Ridge Regression". GEOPHYSICS. Vol; 40, # 5 (Oct. 1975). pp. 798-817.
- N Johnson, Kenneth S., "Maps Showing Principal Ground-Water Resources and Recharge Areas in Oklahoma", Oklahoma State Department of Health, 1983.
- K,L Johnson, Thomas M., Keros Cartwright and Rudolph M. Schuller. "Monitoring of Leachate Migration in the Unsaturated Zone in the Vicinity of Sanitary Landfills". GWMR. Fall, 1981, pp.55-63.
- I Jorgensen, Donald G., Tony Gogel and Donald C. Signor. "Determination of Flow in aquifers Containing Variable-Density Water". GWMR. Spring 1982. pp. 40-45.
- D,I, K Kaugmann, Robert F., T. Alan Gleason, R. Brian Ellwood and Gerald P. Lindsey, "Ground-Water Monitoring Techniques For Arid Zone Hazardous Waste Disposal Sites". GWMR. Fall, 1981. pp.47-54.
- C Keck, William G, George Henry, Jr. and Robert C. Minning. "The Keck Method of Computing Apparent Resistivity". GWMR. Fall 1981. pp.64-68.

- E Kent, Douglas C., Pettyjohn, Wayne A. and Prickett, Thomas A., "Analytical Methods for the Prediction of Leachate Plume Migration", GWMR, Spring 1985, pp. 46-58.
- B Keys, W. Scott, 1968, "Well Logging in Ground-Water Hydrology" GROUND WATER, vol. 6(1), pp. 10-18.
- B Keys, W.S. and R.F. Brown, "The Use of Well Logging in Recharge Studies of the Ogallala Formation in West Texas". U.S. Geological Survey. Professional Paper 750-B. pp. B270-B277.
- B,D Keys, W. Scott and L.M. MacCary, "Application of Geophysics to Water-Resources Investigations" Chapter E1. Techniques of Water Resources Investigations of the U.S. Geological Survey, Book 2. U.S. GEOLOGICAL SURVEY. 1981.
- B,D, I Keys, W. Scott, and James K. Sullivan, 1979, "Role of Borehole Geophysics in Defining the Physical Characteristics of the Raft River Geothermal Reservoir, Idaho" GEOPHYSICS, vol, 44 (6), pp. 1116-1141.
- D Knowles, G. David, Lee, George W., and Scott J., 1983, "Hazardous Waste Site Field Investigations; Geophysical Techniques Utilized For Cost Effectiveness" in Proceedings of the second Ohio Environmental Engineering Conference on Hazardous Waste Management For The 80's, pp. 183-198, Ann Arbor, Michigan: Ann Arbor Science.
- I Kwader, Thomas, 1984, "Estimating Aquifer Permeability From Formation Resistivity ; Factors" in First National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations: pp. 713, Worthington, Ohio, NWWA.
- B Kwader, Thomas , 1984, "The Use of Geophysical Logs for Determining Formation Water Quality:, in First National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, pp. 833-841, Worthington, Ohio, NWWA.
- B Kwader, Thomas, "Resistivity-Porosity Cross Plots for Determining In-Situ Formation Water Quality-Case examples". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition, NWWA. 1985. pp. 415-424.
- C,K, L Ladwig, Kenneth J., "Electromagnetic Induction Methods for Monitoring Acid Mine Drainage" GWMR. Winter 1983. pp.46-51.

- B,C Laine, Daren L., Jorge O. Parra and Thomas E. Owen. "Application of an Automatic Earth Resistivity System for Detecting Groundwater Migration Under a Municipal Landfill". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA, 1985. pp. 34-50
- D Landon, Ronald A., 1983, "A Multi-Level Screening Process for Siting Hazardous Waste Management Facilities", in A Northeast Conference; The Impact of Waste Storage and Disposal on Ground-Water Resources, pp. 7.1.1 - 7.1.18, Ithaca, New York; Cornell Univ. Center for Environmental Research.
- C Lankston, Robert W., Marian M. Lankston and Lawrence M. West. "Seismic Reflection Profiling in the Cedar River Basin, Western Washington". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp.146-164.
- C Leonard-Mager, Patricia J., 1984, "Development and Use of Azimuthal Resistivity Surveys for Jointed Formations", in First National Conference on Surface and Borehole Geophysical Methods in Ground-water Investigations, pp.853 - 876, Worthington, Ohio: NWWA.
- B,C Linck, C.J., "Geophysics as an Aid to the Small Water Well Contractor". GROUNDWATER. Vol 1, #1. Jan 1963. pp. 33-37.
- B Lindsey, Gerald P., 1985, "Dry Hole Resistivity Logging" in second National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington, Ohio: NWWA. pp.371-376.
- H Lyon, John Grisom, 1982, "Use of Aerial Photographs and Remote Sensing in the Management of Hazardous Wastes." , pp. 163-171 in Proceedings of the second Ohio Environmental Engineering Conference on Hazardous Waste Management in the 80's Ann Arbor Michigan: Ann Arbor Science.
- B MacCary, L.M. "Resistivity and Neutron Logging in Silurian Dolomite of Northwest Ohio". U.S. Geological Survey, Professional Paper 750-D. 1971. pp. D190-D197.
- B MacCary, L.M. "Geophysical Logging in Carbonate Aquifers". GROUNDWATER. Vol.21, #3. May-June 1983. pp. 334-342.
- B MacCary, L.M. "Use of Geophysical Logs to Estimate Water-Quality Trends in Carbonate Aquifers". NTIS PB 80-224124. USGS WRI 80-57.

- K,L MacFarlane, D.S., J.A. Cherry, R.W. Gillham and E.A. Sudicky. "Migration of Contaminants in Groundwater at a Landfill: Case Study 1. Groundwater Flow and Plume Delineation". JOURNAL OF HYDROLOGY. Vol.13 1983. pp.1-29.
- N Marcher, Melvin V., "Reconnaissance of the Water Resources of the Fort Smith Quadrangle, East-Central Oklahoma" Oklahoma Geological Survey, Hydrologic Atlas 1, 1969.
- N Marcher, Melvin V., and Bergman, DeRoy L., "Reconnaissance of the Water Resources of the McAlester and Texarkana Quadrangles, Southeastern Oklahoma", Oklahoma Geological Survey, Hydrologic Atlas 9.
- N Marcher, Melvin V., and Bingham, Roy H., "Reconnaissance of the Water Resources of the Tulsa Quadrangle, Northeastern Oklahoma", Oklahoma Geological Survey, Hydrologic Atlas 2, 1971.
- G,K, Mast, Vernon. "The Use of Ionic Mixing Curves in L Differentiating Oil Field Brine From Natural Brine in a Fresh Water Aquifer" GROUNDWATER MONITORING REVIEW. Summer 1985. pp.65-69.
- B Matthews, W.R. "Typical Log-Curve Shapes Indicate Formation Characteristics". THE OIL AND GAS JOURNAL. Dec.6, 1971. pp. 66-72.
- B McConnell, Cary Lewis. "Groundwater Salinity and Resource Evaluation by Spontaneous Potential Measurements, Eastern Jefferson and Carter Counties, Oklahoma". PhD. Dissertation. University of Oklahoma. 1981.
- B,C Mickam, James T., Levy, Benjamin S., and Lee, George W. Jr., 1984- Surface and Borehole Geophysical Methods in Ground Water Investigations". GROUND WATER MONITORING REVIEW, Vol. 4(4), pp. 167-171.
- D,I Minasian, R.S., "Prospecting for Subsurface Water in the Central Volcanic Highland of Armenia By Geophysical Methods". GEOPHYSICAL PROSPECTING. Vol.27, pp.868-814.
- B,M Montgomery, Robert J., Robert W. Taylor and Henry A. Koch. "Use of Downhole Geophysical Methods in Determining the Internal Structure of a Large Landfill". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp. 377-386.
- B,K Moraham, Thomas and Richard C. Dorrier. "The Application of Television Borehole Logging to Ground Water Monitoring Problems" . GWMR. Fall 1984. pp. 172 - 175.

- D,M Moran, S.R., B.M. Arndt. "Geologic Criteria in Waste-Management Site Selection in Northeastern North Dakota". NTIS: PB 83-108423. OWRT A-040-N.DAK (1).
- N Morton, Robert B., "Preliminary Investigations of the Hydrogeology of the Permian to Tertiary Rocks of the Oklahoma Panhandle" U.S. Geological Survey, Miscellaneous Geologic Investigations, Map I-738, 1975.
- N Morton, Robert B., "Reconnaissance of the Water Resources of the Woodward Quadrangle, Northwestern Oklahoma", Oklahoma Geological Survey, Hydrologic Atlas 8, 1980.
- N Morton, R.B., and Goemaat, R.L., "Reconnaissance of the Water Resources of Beaver County, Oklahoma", U.S. Geological Survey, Hydrologic Investigations Atlas HA-450, 1973.
- B,C, D Murphy, V.J., T.F. Sexton and E.N. Levine. "Geophysics as Related to Siting of Nuclear Power Plants". Geological Society of America. REVIEWS IN ENGINEERING GEOLOGY. Vol. IV. 1979. pp. 197-199.
- B,M Nelson, P.H., K.A. Magnusson and R. Rachiele. "Application of Borehole Geophysics At an Experimental Waste Storage Site". GEOPHYSICAL PROSPECTING. Vol.30. 19823. pp.910-934.
- B,K Norris, Stanley E., 1972, " The Use of Gamma Logs in Determining the Character of Unconsolidated Sediments and Well Construction Features ": GROUND WATER, Vol. 10(6), pp. 14-21.
- A,B, C O'Brien, Keith M. and William J. Stone. "Role of Geological and Geophysical Data in Modeling an Alluvial Basin, Southwest New Mexico". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp. 198 - 214.
- C Ogden, A. E., and Eddy, P. S. Jr., 1984, "The Use of Tri-Potential Resistivity to Locate Fractures and Caves for Siting High Yield Water Wells", pp. 130-149 in First National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations. Worthington, Ohio: NWWA.
- C van Overmeeren, Ronald A. "A Combination of Electrical Resistivity, Seismic Refraction and Gravity Measurements For Groundwater Exploration in Sudan". GEOPHYSICS. Vol. 46. #9. Sept. 1981. pp. 1304-1313.

- B Patten, Eugene P. Jr., and Gordon D. Bennett. "Application of Electrical and Radioactive Well Logging To Ground-Water Hydrology". U.S. Geological Survey. Water-Supply Paper. 1544-D. 1963. pp. D1-D60.
- I Parker, R.A. L.E. Dunlap, and C.G. Saver. "Analysist Computer Simulation of Stream--Aquifer Hydrology Arkansas River Valley, Southwestern Kansas
- C,L Pennington, Dennis, 1985, "Selection of Proper Surface Resistivity Techniques and Equipment for Evaluation of Ground Water Contamination", in the Second National Conference on Surface and Borehole Geophysical Methods in Ground Investigations, Worthington, Ohio: 1985.
- B Pickett, G.R. "The Use of Acoustic Logs in the Evaluation of Sandstone Reservoirs". GEOPHYSICS. Vol.XXV. #1 Feb. 1960. pp. 250-274.
- G,K Popkin, Barney. "Guidelines for Ground-Water Quality Assessment: For Hazardous Waste Facilities". GROUNDWATER MONITORING REVIEW. Spring. 1987. pp.65-70.
- N PROTECTION OF PUBLIC WATER SUPPLIES FROM GROUND-WATER CONTAMINATION, U.S. EPA Publication EPA/625/4-85/016, April 1985.
- C Pullan, S.E., and J. A. Hunter. "Seismic Model Studies of The Overburden-Bedrock Reflection". GEOPHYSICS. Vol.50, #11. Nov. 1985. pp.1684-1688.
- G,K Quince, J.R. and G.L. Gardner. "Recovery and Treatment of Contaminated Ground Water: Part II". GROUNDWATER MONITORING REVIEW. Fall, 1982. pp. 18-25.
- B,I Rabe, C. L. " A Relation Between Gamma Radiation and Permeability, Denver-Julesburg Basin". JOURNAL OF PETROLEUM TECHNOLOGY. Feb. 1957. pp. 65-67.
- B Rabson, W.R. "Chlorine Detection By the Spectral Log". THE PETROLEUM ENGINEER. March, 1959. pp B102 - B106 and B111.
- N RCRA GROUND-WATER MONITORING TECHNICAL ENFORCEMENT GUIDANCE DOCUMENT, National Water Well Association, Columbus, Ohio, September, 1986.
- A,L Reed, J. S., and Henningson, J. C., 1982, " Determination of Disposal Sites for PCB Contaminated Material Dredged From the Hudson River Bed:, pp. 81-93, in Hazardous Waste Management for the 80's, ed. by Thomas L. Sweeney et. al., Ann Arbor, Michigan: Ann Arbor Science.

- B,C Reed, Phillip, 1985, " Comparative Analysis of Surface Resistivity Surveys and Natural-Gamma Radiation Borehole Logs in Illinois", in the Second National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington, Ohio: NWWA.
- L,M Reinhard, Martin, Naomi L. Goodman and James F. Barker. "Occurrence and Distribution of Organic Chemicals in Two Landfill Leachate Plumes". ENVIRONMENTAL SCIENCE TECHNOLOGY. Vol. 18, 1984. pp.953-961.
- B Rhodes, D.F. and W.E. Mott. "Quantitative Interpretation of Gamma-Ray Spectral Logs". GEOPHYSICS. Vol. 31. 1966. pp. 410-418.
- C,K Ringstad, Clyde and Dale C. Bugenig. "Electrical Resistivity Studies to Delimit Zones of Acceptable Groundwater Quality". GWMR. Fall 1984. pp.66-69.
- I Ritchy, Joseph D. and Mark A. Collins. "An Overview of Computer Technology Used in Groundwater Field Studies: Part I: Basics". GWMR. Winter 1984. pp.33-38.
- B,C, K,L Rogers, R.B., and W.F. Kean. "Monitoring Ground-Water Contamination at a Fly Ash Disposal Site Using Surface Electrical Resistivity Methods. GROUNDWATER. 18 (5) Sept.- Oct. 1980. pp.472 -478.
- C,M Rudy, Richard J. and John A Caoile. "Utilization of the Shallow Geophysical Sensing At Two Abandoned Municipal/Industrial Waste Landfills on the Missouri River Floodplain". GWMR. Fall 1984. pp.57-64.
- N Sapik, D.B., and Goemaat, R.L., "Reconnaissance of the Ground-Water Resources of Cimarron County, Oklahoma" U.S. Geological Survey, Hydrologic Investigations Atlas HA-373, 1973.
- D,I Satpathy, B.N. and D.N. Kanungo. "Groundwater Exploration in Hard-Rock Terrain- A Case History" GEOPHYSICAL PROSPECTING. Vol.24, 1976. pp.725-736.
- B Scott, J.H., P.H. Dodd, R.F. Drouillard, and P.J. Mudra. "Quantitative Interpretation of Gamma-Ray Logs". GEOPHYSICS. Vol.26, #2. APRIL, 1961. PP.182-191.
- C,K Sendlein, Lyle V.A. and Hasen Yazicigil. "Surface Geophysical Methods for Groundwater Monitoring: Part I". GWMR. Fall 1981, pp.42-46.
- B,I Senger, James A. "Defining Glacial Stratigraphy With the Neutron Log" in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA, 1985. pp. 355-368.

- C Slotnick, M.M. "A Graphical Method for the Interpretation of Refraction Profile Data" . GEOPHYSICS, Vol.XV, #2. April 1950, pp.163-180.
- C Smith, Nariida C. and Keeva Vozoff. "Two-Dimensional D.C. Resistivity Inversion For Dipole-Dipole Data". I EEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, Vol. GE-22, #1, Jan. 1984. pp.21-28.
- B Snelgrove, Frank B. and J.D. McNeill. "Theory and Design Considerations of a Borehole Electromagnetic Conductivity Probe". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp.339-354.
- C,I Spangler, Daniel P. and Fred J. Libby. "Application of the Gravity Survey Method to Watershed Hydrology". GROUNDWATER, Vol.6, 1968. pp.21-26.
- B,I Spencer, Steven M. "Stratigraphic Determinations and Correlations Based on Borehole Geophysics". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition, NWWA. 1985. pp.326-338.
- C Stewart, M., A. Stodghill and P. Putzier. "An Automated D.C. Resistivity System" in Surface and Borehole Geophysical Methods in Groundwater Investigations: Second National Conference and Exposition, NWWA, 1985, pp.1-11.
- C,I Stewart, Mark; Stodghill, Allan; and Putzier, Paul, 1985, "Goelectric Delineation of Coastal Ride Aquifer", in the second National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington, Ohio: NWWA.
- C,L Stollar, Robert L and Paul Roux. "Earth Resistivity Surveys-A Method for Defining Ground-Water Contamination". GROUNDWATER. Vol.13, #2. March-April, 1975. pp.145-150.
- C,M Sweeney, Jerry J. "Comparison of Electrical Resistivity Methods for Investigation of Groundwater Conditions at a Landfill Site". GWMR, Winter,1984. pp.52-54.
- E,K, M Sykes, J.B., et.al., "Numerical Simulation of Flow and Contaminant Migration at an Extensively Monitored Landfill". WATER RESOURCES RESEARCH 18 (6) pp.1687-1704, Dec.1982.

- B,D Taylor, Kendrick C. and Leslie G. McMillion. "A Strategy for the Hydrologic Interpretation of Well Logs". in Surface and Borehole Geophysical Methods in Groundwater investigations, Second National Conference and Exposition. NWWA, 1985. pp.314-323.
- C Taylor, Robert. "An Automated D.C. Resistivity System" in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA, 1985. pp.12-22.
- C Taylor, Robert W. and Douglas S. Cherkauer. "The Application of combined Seismic and Electrical Measurements to the Determination of the Hydraulic Conductivity of a Lake Bed". GWMR. Fall 1984. pp.78-85.
- C Taylor, Roby W., 1986 "The determination of Joint Orientation and Porosity from Azimuthal Resistivity Measurements", pp. 37-51 in First National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington Ohio: NWWA.
- C,I Tucci, Patrick, 1984 "Surface Resistivity Studies for Water Resources Investigations, Near Tucson, Arizona", pp.92-106 in First National Conference on Surface and Borehole Geophysical Methods in Water Resources Investigations, Worthington, Ohio; NWWA.
- B Tittman, J. and J.S. Wahl. "The Physical Foundations of Formation Density Logging (Gamma-Gamma)". GEOPHYSICS. Vol.30,1965. pp.284-294.
- C Tripp, A.C., W.W. Hohmann and C.M. Swift, Jr., "Two-Dimensional Resistivity Inversion". GEOPHYSICS. VOL.49, #10 (OCT. 1984). PP.1708-1717.
- B Turlan, A.N. Jr. "Estimating Water Quality From Electrical Logs" U.S. Geological Survey, Professional Papers, 1962, pp.C135-C136.
- C Underwood, Joan E., Katherine J. Laudon and Thomas S. Laudon. "Seismic and Resistivity Investigations Near Norway, Michigan" GWMR, Fall 1984. pp.86-91.
- B Urban, T.C. and W.H. Diment. "Convection in Boreholes: Limits on Interpretation of Temperature Logs and Methods for Determining Anomalous Fluid-Flow" in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition, NWWA, 1985, pp.399-413.

- C,L Urish, Daniel W. "The Practical Application of Surface Electrical Resistivity to Detection of Ground-Water Pollution". GROUND-WATER. Vol. 21, #2. March-April, 1983. pp.144-152.
- C,L Valentine, Robert N. and Thomas Kwader. "Terrain Conductivity as a Tool for Delineating Hydrocarbon Plumes in a Shallow Aquifer- A Case Study". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp. 52-63.
- C Vandenberghe, J. "Combined Refraction Seismic and Gravimetric Investigations in a Paleogeographical and Geological Research Program". GEOPHYSICAL PROSPECTING. Vol. 24. 1976. pp.371-379.
- B,G Vonhof, J.A. "Water Quality Determination From Spontaneous-Potential Electriclog Curves". JOURNAL OF HYDROLOGY. Vol.4. 1966. pp.341-347.
- C,I Wallace, D.E. "Some Limitations of Seismic Refraction Methods in Geohydrological Surveys of Deep Alluvial Basins". GROUNDWATER. Vol. 8, 1970. pp.8-13.
- B Walter, F. "Recent Developments of Physical Investigations in Boreholes and Wells". GEOLOGIE EN MIJNBOUW. Vol. 51 (1). pp.121-130. 172.
- N WATER RESOURCES OF ENID QUADRANGLE, OKLAHOMA HYDROLOGIC ATLAS HA7, Oklahoma Geological Survey.
- C,L Weber, Dennis D., James F. Scholl, Douglas J. LaBrecque, Eric G. Walther and Roy B Evans. "Spatial Mapping of Conductive Groundwater Contamination With Electromagnetic Induction". GWMR. Fall 1984. pp.70-77.
- B,D, Wheatcraft, Stephen W., Kendrick C. Taylor, John W. Hess L and Thomas Morris, "Borehole Sensing Methods for Ground-Water Investigations at Hazardous Waste Sites", EPA, Environmental Monitoring Systems Laboratory, August 1983.
- B,C, Wilt, M.J. and C.F. Tsang. "Monitoring of Subsurface Contaminants With Borehole/Surface Resistivity Measurements". in Surface and Borehole Geophysical Methods in Groundwater Investigations, Second National Conference and Exposition. NWWA. 1985. pp.167-177.
- N Wood, P.R., and Hart, D.L., Jr., Availability of Ground Water in Texas County, Oklahoma" U.S. Geological Survey, Hydrologic Investigations, Atlas HA-250, 1967.

- C Wrege, Beth M. Hasbrouck, Wilfred P.; and Schumann, Herbert H., 1985, "Seismic Surface-Wave Attenuation Across Earth Fissures in the Alluvium, South-Central Arizona, in Second National Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Worthington, Ohio: NWWA. pp. 121-130.
- B,C, Yazicigil, Hasen and Lyle V.A. Sendlein. "Surface Geophysical Techniques in Groundwater Monitoring: Part II". GWMR. Winter, 1982. pp.56-62.
- K

SOLID WASTE DISPOSAL SITE APPLICATION GUIDELINES
(STATE OF OKLAHOMA EXAMPLE)

APPENDIX A

5.1 General Information Requirements

- a) Name of site --
- b) Type of site --
- c) Description of proposed operation --
- d) Name and address of applicant --
- e) Location of proposed site --
- f) Distance to nearest residences --
- g) Distance to nearest airport --
- h) Distance to nearest flood prone area --
- i) Type, condition, and maintenance of access road to the site --
- j) Land use of adjacent property within 2 miles --
- k) Official legal description of facility --
- l) Proof of ownership of interest --
- m) Hours of operation --
- n) Equipment to be used --
- o) Type of wastes to be accepted --
- p) Sources of wastes to be accepted --
- q) Estimated tons or cubic yards of wastes to be received daily--
- r) Population or population equivalent to be served --
- s) Estimated life of the site --

5.2 -- Technical Information Requirements, Type I-V and Type VII Facilities

5.2.1 -- Flood plain --

5.2.2 -- Geology

5.2.2.1 -- Describe the following:

- a) Rock formations and lithology of the site --

- b) Structural features (such as folds, faults, fractures, etc.)--
- c) Geologic cross-section across site --
- d) Specific descriptions of rock strata at and near the site --

5.2.3. Soils

- 5.2.3.1. -- Borings plan (see specific requirements p. 48 OSHD Bulletin 0524) --
- 5.2.3.2 -- Logs of each borehole and site map with location and elevation of each borehole --
- 5.2.3.3. -- Water levels - must attain the static water level and report on borehole logs --
- 5.2.3.4. -- Plugging with 10 feet of cement grout beginning 3 ft. below ground level --
- 5.2.3.5. -- Testing report: laboratory report of soil and rock characteristics (see specifics p. 49) --
- 5.2.3.6. -- Permeability (see p.49-50 specific requirements) --
- 5.2.3.6.1. -- Laboratory permeability tests (see p.50 requirement)
- 5.2.3.6.2. -- In-situ permeability tests (for requirements p.50) -
- 5.2.3.7. -- Cover materials: suitability and availability of onsite materials --

5.2.4.-- Surface water hydrology

- a) Description of drainage network --
- b) USGS topographic map with all receiving waters indicated --
- c) Description of water use --
- d) Description of general water quality for impoundments within one mile of site --

5.2.5. -- Ground water hydrology

- 5.2.5.1. -- Highest seasonal potentiometric water surface elevations, hydraulic gradients, directions of flow, and supportive potentiometric maps ---
- 5.2.5.2. -- Estimated rate of flow --
- 5.2.5.3. -- Nature and extent of ground water --

5.2.5.4. -- Recharge or discharge areas --

5.2.5.5. -- Information on the existence of potential ground water sources or ground water use in the area that could be affected by the proposed site; specifically the location, total depth, and depth to water of:

- a) All domestic or private water supply wells within one-half mile of the site --
- b) All municipal or public water supply wells within one mile of the proposed site --
- c) General description of the quality of the groundwater in the area --

5.2.6. -- Maps required

5.2.6.1. -- General location map --

5.2.6.2. -- Topographic map --

5.2.6.3. -- Flood plain map --

5.3. -- Technical Information Requirements -- Type VI facilities --

5.4 -- Technical Information Requirements - Type VII Facilities -

5.5 -- Technical Information Requirements - Type IX and X Facilities --

5.6 -- Plans and Specifications for site Development

5.6.1. -- Site design:

5.6.1.1. -- Equipment list --

5.6.1.2.-- Roads (type of construction and materials) --

5.6.1.3. -- Surface drainage (see p. 53 for requirements) --

5.6.1.4. -- Ground water protection --

5.6.1.5. -- Surface water -- must provide:

a) Location of all surface water monitoring points on the topographic map, preliminary contour map, general layout map and completion map --

b) A sampling and analysis plan --

5.6.1.5.2. -- Ground water: provide the following:

- a) Ground water contour map (show the location, number, and surface elevation of monitor wells) --
 - b) A detailed drawing of a typical monitor well --
 - c) A sampling and analysis plan --
- 5.6.1.5.3. -- Gas: provide the following:
- a) Detail drawing of typical gas monitor well --
 - b) Sampling and analysis plan --
- 5.6.1.6. -- Closure; Detailed informatin on the following:
- 5.6.1.6.1. -- Schedule for closure --
- 5.6.1.6.2. -- Calculation of amount of cover material needed --
- 5.6.1.6.3. -- Procedures for placing, grading, leveling, stabilizing and vegetating the final cover --
- 5.6.1.6.4. -- Construction of drainage system --
- 5.6.1.6.5. -- Details of final grading and final contours shall be shown on construction plans --
- 5.6.2. -- Site Construction: The following maps and plans shall be provided:
- 5.6.2.2. -- General plan view: A constructed map showing the following:
- a) Dimensions of permit boundary and facilities --
 - b) Locations of borings, core holes, monitor wells, test wells, monitoring sites, test pits, sampling sites --
 - c) Original contours at five foot intervals --
 - d) Sequence of excavations, filling and final cover --
 - e) Surface drainage --
 - f) Fencing and gates, utility lines, and easements --
 - g) Access roads into and on the site --
 - h) Proposed trenches and fill face areas, pits, lagoons, disposal areas, etc., and general sequence of filling operations --
 - i) Cover material borrow areas --
 - j) Employee and equipment shelters --

- 5.6.2.3. -- Typical fill cross sections --
 - a) Permeability --
 - b) Results --
- 5.6.2.5. -- Completion map --
- 5.6.3. --Site operation --
- 5.6.4. -- Site maintenance:
 - 5.6.4.1. -- post-closure care --
 - 5.6.4.2. -- post-closure maintenance --
 - 5.6.4.3. -- Post-closure monitoring --
- 5.6.5. -- Liner installation and testing plan:
 - 5.6.5.1. -- General --
 - 5.6.5.2. --Natural liner: must include the following:
 - 5.6.5.2.1. -- Preliminary design test:
 - a) Classification --
 - b) Permeability --
 - c) Results --
 - 5.6.5.2.2. -- Post excavation/pre-disposal tests:
 - a) Visual inspection --
 - b) Thickness/integrity --
 - c) Natural or in-place moisture and density --
 - d) Laboratory or in-situ permeability tests --
 - 5.6.5.2.3. -- Failure (see p.57) --
 - 5.6.5.3. -- Reconstructed liner --
 - 5.6.5.3.1. --Internal side slopes no more than 3:1 --
 - 5.6.5.3.2. -- preliminary design tests --
 - 5.6.5.3.3. -- Pre-construction design test (following shall be conducted)
 - a) Atterberg limits --

b) moisture-density relationship --

c) Permeability --

5.6.5.3.4. -- Installation tests (following tests shall be performed)

a) moisture-density relationship --

b) visual inspection --

5.6.5.3.5. -- Construction verification tests: (following shall be performed)

a) Thickness of liner be verified --

b) visual inspection by soil scientist, engineer or geologist --

c) Permeability -- two tests per acre performed on the finished liner --

5.6.5.4. -- Artificial liner (see p. 58) --

NOV 28 1988

**REGULATIONS GOVERNING
SOLID WASTE AND SLUDGE MANAGEMENT
(OSDH Bulletin 0524)**

Recommended by the
Solid Waste Management Advisory Council
July 25, 1985

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Oklahoma State Board of Health
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**Waste Management Service
Environmental Health Services
OKLAHOMA STATE DEPARTMENT OF HEALTH**

**REGULATIONS GOVERNING
SOLID WASTE AND SLUDGE MANAGEMENT**

(As Amended April 2, 1987 by the Oklahoma State Board of Health)

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other supporting data, that is procedurally and/or technically incomplete, or deficient in detail.

4.4.7.3. If the application is denied, applicant may submit a new application on the same site, which will require a new public notice. Alternatively, applicant may submit a new application on a new site, or terminate his participation in the permit process.

4.4.7.3.1 Basis for denial shall be an application, with supporting data, which:

- a) contains false, misleading, misrepresented, or substantially incorrect or inaccurate information, or
- b) fails to demonstrate compliance with the Act or the Regulations, or
- c) fails to provide sufficient information to enable the Department to determine the applicant's compliance with the Act and Regulations.

CHAPTER FIVE

APPLICATION INFORMATION REQUIREMENTS

5.0 GENERAL PROVISIONS

5.0.1 Content. The application for permit shall consist of the application form, general information, technical information and site plan.

5.0.2 Forms. The applicant shall use forms supplied by the Department.

5.0.3 Format. The applicant shall prepare the application in accordance with the format set out in the Guidelines for Submission of an Application.

5.1 GENERAL INFORMATION REQUIREMENTS

The following information is required in all applications.

- Name of site.
- Type of site.
- A brief description of the proposed operation.
- Name of applicant and applicant's address.
- Location of proposed site.
- Distance to nearest: residences, airport, flood prone area.
- Type, condition, and maintenance of access road to the site.
- Land use of adjacent property and general area within two miles.
- An official legal description of the site comprising only that acreage to be encompassed in the development of the facility. Said description may be by metes and bounds, section, township, and range (and parts thereof), or book and page number of plat records (for platted property).
- Proof of ownership of interest.

- Hours of operation.
- Equipment to be used.
- Type of wastes to be accepted.
- Source(s) of wastes to be accepted.
- Estimated tons or cubic yards of wastes to be received daily.
- Population or population equivalent to be served.
- Estimated life of the site.

5.2 TECHNICAL INFORMATION REQUIREMENTS, TYPE I - V AND TYPE VII FACILITIES

The following information is required in all applications for Type I through Type V and Type VII facility permits, except see **R** 5.2.8 for requirements for Type III-B permit applications.

- 5.2.1 Flood plain. A determination of the 100 year floodplain on or adjacent to the site. See **R** 1.1.5.
- 5.2.2 Geology. Information on geology and hydrogeology shall include the formation underlying the deepest formation penetrated by the bore holes and/or monitor wells, and all formations exposed in outcrop on or near the site.
- 5.2.2.1 Describe the geology in terms of:
- a) rock formations in the area and at the site, and the lithology of the formations. Use accepted stratigraphic and lithologic nomenclature, and provide sources or references for information not observed first hand by applicant or applicant's engineer.
 - b) structural features such as folds, faults, fractures, etc.
 - c) characteristics and engineering properties or references for the soil and rock materials at the site.
 - d) a geologic cross section of the area, including the site, showing formations and, if applicable, structural features.
 - e) specific descriptions of the rock strata observed on the surface of the site and near the site (in drainages, road cuts, and other surface outcrops), including orientation (strike and dip) of the strata. Orientation should be measured accurately, or carefully estimated if conditions do not permit accurate measurements.
- 5.2.3 Soils. A report of the onsite soil and rock materials including the following:
- 5.2.3.1 Borings plan: Sufficient borings are required to provide a representative sampling of the types of soil and rock materials onsite. Dry methods of subsurface exploration (i.e. auger, air rotary) are preferred over wet (water rotary or mud). The minimum number, locations, and depths of borings required to present a representative profile can only be determined by careful analysis of the general characteristics, geology, field tests and proposed operation of the site. The following table is provided as a guide

for planning. More may be required if the preliminary data is inconclusive. The borings should be located to give coverage of the entire site with particular attention to the disposal areas. The minimum depth of borings under optimum soil/rock conditions (that is, relatively impermeable soils) shall be at least ten (10) feet below the deepest proposed excavation (lowest elevation at which wastes will be deposited). With less favorable conditions, the depth should be at least twenty (20) feet below the deepest proposed excavation.*

<u>Size of Site In Acres</u>	<u>Number of Borings 10' below</u>	<u>*Minimum No. of Borings 20 Ft. Below Deepest Excavation</u>
less than 5	2-4	2
5 to 9	4-6	3
10 to 19	6-10	5
20 to 49	10-15	7
50 to 100	15-20	7-12

For sites larger than 100 acres, a preliminary boring plan must be filed with the Department.

- 5.2.3.2 **Logs:** A log of each borehole shall be submitted, together with a site map showing the location and elevation of each boring. Each borehole log shall report the surface elevation of the borehole and the soil and rock layers present, describing said layers: constituents, color, texture, degree of compaction or consolidation and amount of moisture present; and any additional information necessary for a complete and adequate description. The thickness of each layer shall be shown on the borehole log, and enough information obtained to classify each soil stratum based on the Unified Soil Classification System, and each rock stratum according to accepted geological classification systems.
- 5.2.3.3 **Water levels:** If subsurface water is encountered, the test hole shall be bailed of all drilling fluids for its entire depth, and the initial depth that water was encountered should be noted on the boring log. The static water level shall be obtained by measuring the depth to the water level daily until it has remained stable for a period of 24 hours or longer, and noted on the borehole log, indicating the time required for the water level to stabilize. If water is encountered while drilling in the vicinity of an existing disposal site, the hole shall be bailed of all drilling fluids and a sample of the subsurface water shall be taken after the water level has stabilized and the sample analyzed to determine the existence of any contaminants. Applicant should consider converting test bore holes into piezometers to determine ground water gradients.
- 5.2.3.4 **Plugging:** All holes drilled in conjunction with soil testing and evaluation shall be bailed and, once ground water data is obtained, adequately plugged to preclude surface contamination from entering, and to prevent contamination of aquifers. The plugging shall consist of ten (10) feet of cement grout placed from a depth of three (3) feet below ground level to thirteen (13) feet below ground level. The top three feet shall be

backfilled with on-site soils displaced during drilling. All test holes which penetrate any buried waste shall be plugged from three (3) feet below ground level to their total depth. This plug shall be a bentonite drilling mud with at least one sack of cement grout per fifteen feet of test hole depth. In all holes where water bearing formations are encountered during drilling, holes shall be plugged with grout from their termination depth to a depth three (3) feet below ground level.

- 5.2.3.5 Testing report: A laboratory report of soil and rock characteristics shall be submitted consisting of at least one sample from each layer that will form the bottom and sides of the proposed disposal area. The design engineer shall make or have made as many additional tests as necessary to provide a typical profile of the soil and rock stratification within the site. No laboratory work need be performed on highly permeable layers which obviously will require lining. The soil samples shall be tested by a soils laboratory under the direction of a Registered Professional Engineer. The primary concern should be to obtain data on field (in-situ) conditions by collecting undisturbed samples, and conducting field tests when appropriate. The soil tests shall consist of the following:

Sieve analysis and hydrometer analysis: #4, #10, #40, #200,-200, and a hydrometer analysis on -200 fraction - ASTM D422.
Atterberg Limits - ASTM D423 and D424.
Moisture Content - ASTM D2216.

- 5.2.3.6 Permeability: All soils that are to be used as a natural or reconstructed liner, and that are within the following range of values, shall be tested either in a soils laboratory or in-situ for the coefficient of permeability. Normally, all soils below the range of values stated below are sandy and are not suitable for liners, unless additional test data support a deviation. Soils which exceed the range of values stated are high in clay content and do not require additional testing to prove their adequacy for sanitary landfill purposes. The physical parameters stated are to be considered as guidelines for soil sample testing. Engineering judgment must be used on those samples which exhibit some but not all of the boundary limits stated:

Plasticity Index	15 to 25
Liquid Limit	30 to 50
Percent Passing 200 Mesh Sieve (-200)	30 to 50

- 5.2.3.6.1 Laboratory permeability (hydraulic conductivity) tests are to be performed according to one of the following standards on undisturbed soil samples. Where excavations already exist on the site that are to be used for waste disposal, undisturbed samples shall be taken from the sidewalls of those excavations and permeability tests made on the horizontal axis. Permeability tests should include one on the horizontal axis since most sedimentary rocks are more permeable laterally than vertically. All test results shall indicate the type of test used, the method and the condition, preparation and orientation of each sample.

- (a) Falling head permeability test - ASTM Special Technical Publication 479.

- (b) Constant head permeability test - ASTM D2434 - for materials for reconstructed and recompacted liners only.
- (c) Any new methods approved by ASTM or the Department prior to use.

An analysis of the soils or rock data and a recommendation as to the adequacy of in-situ materials for ground water protection, or the type and thickness of constructed liner (when necessary - see R's 2.1.3 and 5.6.5), shall be provided by a professional engineer experienced in geotechnical engineering, or a hydrogeologist or geologist having at least a university-granted four-year degree in geology and no less than four years of experience in engineering geology.

Methods of investigation, sampling, and analysis plus certification thereof shall be provided.

Adequate geologic and soil and rock investigations shall be conducted to provide the data for groundwater hydrology (R 5.2.5).

5.2.3.6.2 In-situ permeability tests shall be conducted in accordance with one of the following methods.

- (a) ASTM Special Technical Publication 746
- (b) pump test or slug injection test of the target intervals)
- (c) see R 5.2.3.6.1(c).

5.2.3.6.3 Regardless of plasticity index, liquid limit, and percentage fine particles (passing #200 sieve), any material designed to be used as natural liner must be tested for permeability prior to disposal of wastes thereon (see R 5.6.5.2).

5.2.3.7 **Cover material:** Provide information on the suitability and availability of onsite soil for use as daily, intermediate, and final cover, and for use as topsoil. Discuss soil characteristics and quantities.

5.2.4 Surface water hydrology. The following information shall be submitted on all streams, lakes, and ponds within one-half mile of the proposed site boundary.

- A description of the drainage network.

- A U.S.G.S. 7.5 minute series topographic quadrangle map (15 minute series if a 7.5 is not published), or comparable map with all receiving waters indicated.

- A description of the water use.

- A description of the general water quality for impoundments within one half mile of any receiving streams.

5.2.5 Ground water hydrology. The following information on ground water at the site shall be submitted:

- 5.2.5.1 Highest seasonal potentiometric water surface elevations, hydraulic gradient(s) and direction(s) of flow, and supportive potentiometric maps.
- 5.2.5.2 Estimated rate of flow.
- 5.2.5.3 Nature and extent of ground water.
- 5.2.5.4 Recharge or discharge areas.
- 5.2.5.5 Information on the existence of potential ground water sources or ground water use in the area that could be affected by the proposed site; specifically the location, total depth, and depth to water of:
- All domestic or private water supply wells within one-half mile of the proposed site boundary.
 - All municipal or public water supply wells within one mile of the proposed site boundary.
 - A general description of the quality of the ground water in the area.
- 5.2.6 Maps required. The following maps shall be provided in legible form, complete with legend, scale, and north directional arrow.
- 5.2.6.1 General location map: This map should be all or part of a one-inch-to-two-miles scale county highway map as published by the Oklahoma Department of Transportation. The location of the proposed site shall be clearly identified on said map. If a site is located within a municipality and a municipal map with better information is available, then it shall be used for this purpose.
- 5.2.6.2 Topographic map: This map shall be a United States Geological Survey 7.5 minute series topographic quadrangle map (15 minute series may be used where 7.5 minute series maps have not been printed) or equivalent, encompassing the area of the site. The map shall clearly identify the location of the following: site boundaries; access routes; airports within two miles of the site; all homes, buildings, water wells (including private and municipal, potable and irrigation water, etc.), water and wastewater collection, treatment and distribution facilities, rivers, streams, canyons, ravines, lakes, ponds, marshes, and any other items of interest within one-half mile of the proposed site. This map may be supplemented by a constructed land use map or an aerial photograph, the scale of which should be within the range one-quarter mile to one-half mile per inch, that depicts the location of the homes, buildings, wells, ponds, lakes, etc within one-half mile of the site boundary.
- 5.2.6.3 Flood plain map: This map shall be: a Flood Insurance Rate Map prepared by the Federal Emergency Management Agency; or a Flood Prone Area Map prepared by the United States Geological Survey; or an equivalent constructed map based on determinations, from sources approved by the Department, that depicts the limits and elevations of any one-hundred (100) year flood plain on or adjacent to the proposed site (see § 1.1.5).
- 5.2.7 Water balance base data. The following information shall be provided so that the Department can perform water balance calculations in cases

where in situ materials do not meet minimum ground water protection standards. The applicant should furnish this information to the Department early in the site evaluation/facility design process, so that the Department's water balance calculations can be completed and made available to the applicant for use in the facility design:

- U. S. Department of Agriculture Soil Conservation Service information and advice regarding soil fertility, soil types, appropriate plant types, recommended reclamation strategy, and similar factors. Include information on both surface and subsurface soils, and on materials to be used for daily (or initial), intermediate, and final covers and for topsoil. See also **R's** 5.2.3 for soil information requirements.
- Information on wilting points and field capacities of the soils to be used as topsoils and as daily (or initial), intermediate, and final covers.
- Depth to ground water, including seasonal variations in the ground water table (see **R** 5.2.5.1).
- Distance to streams, floodplains, and surface water impoundments (lakes, ponds, and marshes, for example) in the area around the site. (see **R's** 5.2.1 and 5.2.4).
- A discussion of predicted vegetative cover on areas brought to final grade for closure, including density and types of vegetation anticipated at the stages of activity immediately after placement of final cover, and at six month intervals for a period of three years following such placement. Take into account soil fertility, seeding and fertilizing plans, effect of the wastes and soil types on plant growth, and past performance of landfill reclamation efforts.
- The Department will use mean precipitation and temperature values from Haug, J.A.H., 1985, "CLIMOCS - A climatological summary of 267 Oklahoma cooperative stations, 1954 - 1983", Climate Summary 1985-1, published by the Oklahoma Climatological Survey, Norman, Oklahoma, to calculate water balance. The applicant may provide additional data for precipitation and temperature from recognized sources such as the U.S. Weather Service.
- Maximum areal extent, at any point prior to final closure, of fill areas covered with: a) daily (or initial) cover; b) intermediate cover; and c) unvegetated final cover during the operational life of the facility.
- Proposed slope and frequency of application of intermediate cover (see **R** 3.0.12 for frequency requirements).
- Proposed slope of final cover (see **R** 3.0.30 for requirements).
- Slope and vegetation data for the site and the area immediately surrounding the site, including consideration of any area that will contribute run-off to the site proper.

- Proposed operational procedures and design features to provide assurance that the intrusion of surface and ground waters into the disposal excavations will be prevented (see R's 2.0, 2.1, 3.0.11-13, 3.0.15, 3.0.29 and 30, and 5.6).

5.2.8 The following information is required for Type III-B permit applications.

5.2.8.1 Flood plain. See R 5.2.1.

5.2.8.2 Soils. Soils information from published or unpublished reports of the U. S. Soil Conservation Service, U. S. Geological Survey, U. S. Army Corps of Engineers, or other appropriate agencies. Include information on types and quantities of soil available for use as weekly or monthly cover and for final cover. If soils available on the proposed site are inadequate in quality or quantity to meet the needs of the facility for its lifetime, the applicant may plan to supplement said soils with materials obtained from sources offsite. In such cases, the applicant shall supply information about the location, quantity, and quality of the soils to be borrowed from offsite. If a soil borrow area is adjacent to the proposed facility, the applicant shall plan the borrow activity in such a manner that neither surface nor ground water systems are adversely affected.

5.2.8.2.1 Three (3) test pits or trenches shall be excavated in the proposed disposal area to a depth at least five (5) feet below the deepest level proposed for excavation in the facility design. Provide descriptions of the soils and rocks exposed in said trenches. Provide a berm around the trenches and cover the trenches with plastic or canvas to restrict entry of surface water and precipitation into them. Observe and measure water levels (if any) in the trenches for at least one (1) week to determine ground water levels. See R 2.1.3.3.2 for ground water protection standards, See R 5.2.8.4 for ground water information required.

5.2.8.3 Surface water hydrology. See R 5.2.4.

5.2.8.4 Ground water. Provide the following information on ground water at and near the proposed site.

a) reports of any water encountered in the test trenches, including measurements of depth below ground surface of any flows of ground water or accumulations of standing water from seeps, springs, or other ground water sources.

b) See R 5.2.5.5.

5.2.8.5 Maps required

a) see R 5.2.6 and its subparts.

b) a constructed map at a scale no smaller than one (1) inch to two hundred (200) feet, showing: permit boundary; original contours at five (5) foot intervals; direction and sequence of excavations; fencing and gates, utility lines, and easements; access roads; and employee and equipment shelters.

5.2.8.6 Sites considered for Type III-B facilities should be evaluated for suitability by comparing site characteristics with the following criteria:

- location outside bedrock aquifers and their recharge areas, as identified on sheet 2 ("Bedrock aquifers and recharge areas") in Johnson, K.S., compiler, 1983, "Maps showing principal ground-water resources and recharge areas in Oklahoma", published by the Oklahoma Geological Survey, Norman, Oklahoma.
- location outside alluvial aquifers and their recharge areas, as identified in sheet 1 ("Unconsolidated alluvium and terrace deposits") in the publication cited above.
- soils and earthen materials are clays, silty clays, or weathered shales, or unfractured shales, mudstones, claystones, or siltstones that can be excavated by available equipment. (Unconsolidated sands, silty sands, and gravels, and sandstones, limestones, cherts, and fractured and jointed shales and siltstones will not provide adequate protection for ground water resources).
- ground water is highly mineralized, or is deeper than two hundred (200) feet, or is of low yield and unused for domestic or stock water within one mile.
- no public water supply wells are within two miles, or no private water supply wells within one mile that use water from a potentially affected aquifer.
- no surface water flowing from the proposed site is used, or flows into a body of surface water that is used, for public or private water supply within two miles of the site.
- existing ground surface is flat or only gently sloping, at or near the divides of small drainages on low hills or ridges, readily accessible by good roads, possessing deep soil profiles, and free of major erosional features such as ravines. Surface run-on from adjacent areas should be minimal and readily controllable.

Sites that do not meet the criteria listed above may require more stringent ground water protection measures, surface water control measures, and/or more engineering design work than sites that do meet the criteria.

5.3 TECHNICAL INFORMATION REQUIREMENTS - TYPE VI FACILITIES

Refer to Guidelines issued by The Department for information required in permits for solid waste processing facilities.

5.4 TECHNICAL INFORMATION REQUIREMENTS - TYPE VIII FACILITIES

Refer to Chapter 6 and Guidelines issued by the Department for information required in permits for beneficial use of sludges.

5.5 TECHNICAL INFORMATION REQUIREMENTS - TYPE IX AND X FACILITIES

The Department shall be consulted on a case by case basis to determine

technical information requirements for experimental or innovative disposal/treatment facilities and for landfill reclamation sites. The Department may publish Guidelines for such facilities should the need for said Guidelines arise.

5.6 PLANS AND SPECIFICATIONS FOR SITE DEVELOPMENT

5.6.1 Site design: The following items are required for all Type I through Type V and Type VII facilities, except as specified in § 5.6.6 for Type III-B facility requirements.

5.6.1.1 Equipment: Provide a list of equipment to be used in the construction and operation of the proposed site, including the following information on each piece of equipment: type, size, weight, and use intended.

5.6.1.2 Roads: Information shall be provided on the types of road construction and materials to ensure that all access roads to the active disposal areas shall be passable during inclement weather by normal vehicular traffic.

5.6.1.3 Surface drainage: Surface drainage shall be designed, insofar as practicable, to sheet flow and to minimize surface water runoff onto the working areas by effectively diverting or routing runoff around or through the site away from the disposal areas. All dikes, terraces, embankments, drainage structures, or diversion channels shall be of adequate size and grade to effectively handle the design flow with adequate freeboard and minimal erosion.

Drainage calculations shall be based upon the 25-year rainfall intensity for temporary structures, and the 50-year rainfall intensity for permanent structures where there is no potential for erosion of refuse or cover, nor for increased flooding, erosion, or sedimentation of adjacent property. Where these potentials exist, the drainage structures shall be designed for the 100 year rainfall intensity.

In order to design an appropriate drainage structure for a given watershed, the peak discharge from the watershed caused by a design frequency flood must be calculated. The peak discharge depends on several factors, such as:

- area of the watershed.
- type of soils and vegetative.
- slope of the watershed.
- climatic condition of the watershed.
- duration of the design frequency rainstorm.
- time of concentration of the flow through the watershed.
- rainfall intensity.

Peak discharge rates to be used in designing drainage structures shall be calculated in accordance with the following. The modified rational methods and the USGS method can be found in the drainage design manual in current usage at the Oklahoma Department of Transportation.

1. If the drainage area is smaller than one square mile (640 acres), use one of the modified rational methods as developed by the Oklahoma

Department of Transportation.

2. If the drainage area is larger than one square mile but smaller than two square miles (1280 acres), use any two of the following methods to calculate peak discharge: a) One of the modified rational methods; b) the USGS methods; c) the HEC-1 and HEC-2 computer programs developed through the Hydrologic Engineering Center of the U.S. Army Corps of Engineers; d) an equivalent or better method approved by the Department. Then compare the results of these two methods, and also compare the results with information obtained from survey books and from gaging stations if such data are available. Apply engineering judgement to determine which is the most reasonable peak discharge, keeping in mind that conservative estimates (larger peak discharges) are favored over liberal estimates because the Department's aim is to help ensure disposal sites are not subject to problems created by surface waters.
3. If the drainage area is larger than two square miles (1280 acres), but smaller than twenty-five hundred (2500) square miles, use the USGS Method, HEC-1 and HEC-2 computer programs, or an equivalent or better method approved by the Department.

Designs shall include such features as typical cross-sectional areas, ditch grades, and flowline elevations through each particular reach of the structure. Sample calculations shall be provided to verify that natural drainage patterns offsite will not be significantly altered by any changes to onsite drainage patterns. Natural and designed drainage patterns and structures shall be shown on construction plan maps.

- 5.6.1.4 Ground water protection: The site shall be designed to protect ground water. See **R's** 2.1.
- 5.6.1.5 Monitoring: A plan shall be provided for the monitoring of ground water, surface water, and gas at the site in accordance with Regulations and Guidelines. See **R's** 2.2.
 - 5.6.1.5.1 Surface water: The following shall be provided:
 - The location of all surface water monitoring points on the topographic map, and on the preliminary contour map, general layout map and completion map when possible.
 - A sampling and analysis plan in accordance with **R** 2.3.1.4.
 - 5.6.1.5.2 Ground water: The following shall be provided:
 - A ground water contour map, based on data from previous sections, that shows the location, number, and surface elevation of all monitor wells. See **R** 2.3.2.
 - A detailed drawing of a typical monitor well that shows all dimensions, materials, locations and well construction procedures.
 - A sampling and analysis plan in accordance with **R** 2.3.2.9.

- 5.6.1.5.3 Gas: The following shall be provided where gas monitoring is required:
- A detailed drawing of a typical gas monitor well showing all dimensions, materials, locations and well construction procedures when necessary.
 - A sampling and analysis plan.
- 5.6.1.6 Closure: Detailed information shall be provided on the following:
- 5.6.1.6.1 A schedule for closure. See Chapter Three - Operational Regulations.
- 5.6.1.6.2 The calculation of the amount of cover material needed for closure in accordance with the schedule for closure.
- 5.6.1.6.3 The procedures for placing, grading, leveling, stabilizing and vegetating the final cover.
- 5.6.1.6.4 The construction of drainage systems.
- 5.6.1.6.5 Details on the final grading and final contours shall be shown on construction plans.
- 5.6.2 Site construction: The following maps or plans shall be provided:
- 5.6.2.1 Preliminary contour map: A constructed map showing the topographic contours prior to any operations on the site. The contour intervals shall not be greater than five feet. The map shall be constructed at a scale no smaller than one (1) inch to two hundred (200) feet. This map should show the location and quantities of surface drainage entering, exiting or internal to the site and any area subject to flooding by the one hundred (100) year flood.
- 5.6.2.2 General plan view: A constructed map, or if more practical a series of sector maps, on a scale no smaller than one (1) inch to two hundred (200) feet that shows the following minimum amount of information:
- a) Dimensions of permit boundary (should coincide with legal boundary on application) and facilities.
 - b) Locations of borings, core holes, monitor wells, test wells, monitoring sites, test pits, sampling sites.
 - c) Original contours at five foot intervals.
 - d) Sequence of excavations, filling and final cover.
 - e) Surface drainage - location of diversion ditches, dikes, dams, pits, ponds, lagoons, berms, terraces, etc.
 - f) Fencing and gate(s), utility lines, and easements.
 - g) Access roads into and on the site.

- h) Proposed trenches and fill face areas, pits, lagoons, disposal areas, etc., and general sequence of filling operations.
 - i) Cover material borrow areas.
 - j) Employee and equipment shelters.
- 5.6.2.3 Typical fill cross sections: Constructed plan profiles that transect the site through or very near the soil borings in order that the borehole logs can also be shown on the profile. A large or irregularly shaped site may require several of these cross sections, both laterally and longitudinally, to depict the following information: the elevation(s) of the top of any dikes or levees; the final cover; wastes; ground surface; the bottom of excavations; the side slopes of trenches and fill areas; ground water monitor wells; gas wells or vents; recorded initial and static water levels.
- Detailed cross sections of typical cell operation and development can be shown on an inset somewhere on the map, as can certain construction and design details.
- 5.6.2.4 Ground and surface water protective measures: Constructed drawings depicting the locations and typical sections of levees, dikes, drainage channels, culverts, holding ponds, liners, or any other facilities relating to protection. Details of monitor well construction shall be placed here.
- 5.6.2.5 Completion map: A constructed map showing the final contours of the entire site when completed at closure.
- 5.6.3 Site operation. This section shall provide guidance from the design engineer to site management and operating personnel in sufficient detail to ensure that daily operations are in accordance with site design and construction criteria throughout the life of the site, and are in accordance with the Regulations. As a minimum, this section shall provide specific guidance or instructions on operational standards (see R's 3.0).
- 5.6.4 Site maintenance:
- 5.6.4.1 Post-closure care: Provisions shall be made for the inspection of the site on a routine basis and for protection of the site from improper or conflicting use that is not compatible with the intended use of the site.
 - 5.6.4.2 Post-closure maintenance: Provisions shall be made for the following: mowing (when applicable); repair of settlement and erosion of final cover; repair of erosion or sedimentation of drainage structures; revegetation of final cover; repair of any other structures or facilities.
 - 5.6.4.3 Post-closure monitoring: This section shall provide for the continuance of all the environmental monitoring programs for a minimum of eight (8) years after proper closure.
- 5.6.5 Liner installation and testing plan:

5.6.5.1 General: A Liner Installation and Testing (LIT) Plan shall be submitted for those sites requiring containment and separation of wastes from groundwater by a natural, reconstructed, or artificial liner or the equivalent thereof (see **R** 2.1.3). The plan shall include all the information and provide all of the guidance necessary for liner design, placement and testing to assure continuous compliance with ground water protection regulations. The following Regulations, 5.6.5.2 through 5.6.5.4, provide the minimum data required in each LIT plan for a particular type of liner.

5.6.5.2 Natural liner: sufficient types and numbers of borings, excavations and tests shall be conducted and the results submitted to the Department to assure that the natural in-place (in-situ) materials will meet the groundwater protection standards established in **R** 2.1.3. The following tests and frequencies are an established minimum based on uniform and ideal conditions (most sites will have variable conditions and therefore require additional tests):

5.6.5.2.1 Preliminary design tests:

- a) Classification: the classification tests in **R** 5.2.3.5 at a rate of one testing effort (set of tests) per layer per borehole.
- b) Permeability: hydraulic conductivity tests at a minimum rate of three (3) per each classified soil/rock layer that will form the sides and bottom of the proposed disposal area in accordance with **R** 5.2.3.6.

Results: the results of the above tests will establish the design excavation depth(s) for the landfill. Said excavation depths shall be depicted on the cross-sections. **R** 5.6.2.3.

5.6.5.2.2 Post excavation/pre-disposal tests:

- a) Visual inspection: a visual inspection of disposal area floor performed and reported by a competent soils scientist, engineer or geologist. The visual inspection shall locate any cracks, joints, fractures, roots, exposures or other physical phenomena that might indicate areas more permeable than the requirements allow and to assist in locating the areas for the post excavation tests that follow.
- b) Thickness/integrity: a minimum of five (5) probes per acre to a depth of 3 feet below the excavated disposal area floor (top of natural liner) to ensure the thickness and integrity of the liner and assist in locating the areas for the moisture, density and permeability tests.
- c) Natural or in-place moisture and density: at a minimum rate of five (5) tests per acre.
- d) Laboratory or in-situ permeability tests: minimum of three tests per acre shall be performed on the liner (sides and bottom) in accordance with ASTM Special Technical Publication 746, or ASTM Special Technical Publication 479, upon approval by the Department.

- 5.6.5.2.3 **Failure:** Any and all areas failing to meet the permeability requirements in a natural state must comply with **R** 5.6.5.3 or **R** 5.6.5.4 for reconstructed or artificial liners, respectively. Should any of the preliminary design tests fail to indicate the required permeability, a LIT Plan for a reconstructed liner shall be submitted. In the case of a failure of any post-excavation tests, a LIT Plan for a reconstructed liner shall be submitted to the Department, as an addendum to the Site Plan. See **R** 2.1.3.6.
- 5.6.5.3 **Reconstructed liner:** Sufficient information shall be submitted on the methods of liner placement and testing to ensure that the liner is properly installed and maintained, and that continuous compliance with **R** 2.1.3 is maintained. The following tests and methods are minimum requirements:
- 5.6.5.3.1 **Internal side slopes of disposal areas where liner will be constructed shall be no steeper than 3:1 (run:rise).**
- 5.6.5.3.2 **Preliminary design tests:** See **R** 5.6.5.2.1.(a) and (b).
- 5.6.5.3.3 **Pre-construction design tests:** The following tests shall be conducted on samples of materials selected for possible use in liner construction, at a minimum rate of one sample per 10,000 cubic yards:
- a) Atterberg limits - ASTM D423 and D424;
 - b) moisture-density relationship - ASTM D698;
 - c) permeability - ASTM D2434.
- 5.6.5.3.4 **Installation tests:** The following tests shall be performed at a rate of at least three (3) per acre per lift:
- a) determination of moisture and density values of each lift emplaced by the nuclear density method (ASTM D2922), or the drive-cylinder method (ASTM D2937), or the rubber balloon method (ASTM D2167), or the sand-cone method (ASTM D1556).
 - b) visual inspection: for rocks, cobbles, roots or other foreign objects over three inches in diameter, and for any flaws, cracks, or other defects in the emplaced liner.
- 5.6.5.3.5 **Construction verification tests:** The following quality control tests shall be performed to verify that the liner is installed as designed, in accordance with **R** 2.1.3.6:
- a) thickness: the thickness of the liner shall be verified by means of a control survey;
 - b) visual inspection: the finished liner shall be visually inspected by a competent soils scientist, engineer, or geologist to detect any flaws in construction;

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
OKLAHOMA WATER RESOURCES BOARD

RECONNAISSANCE OF THE WATER RESOURCES
OF BEAVER COUNTY, OKLAHOMA

By

R. B. Morton and R. L. Goemaat

HYDROLOGIC INVESTIGATIONS
ATLAS HA-450



DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
OKLAHOMA WATER RESOURCES BOARD

AVAILABILITY OF GROUND WATER IN
TEXAS COUNTY, OKLAHOMA

By
P. R. Wood and D. L. Hart, Jr.

HYDROLOGIC INVESTIGATIONS
ATLAS HA-250



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ATLAS HA-250

- c) permeability: two tests per acre shall be performed on the finished liner (sides and bottom) in accordance with ASTM Special Technical Publication 746, or ASTM Special Technical Publication 479 upon approval by the Department.

- 5.6.5.4 Artificial liner: A constructed lining other than compacted clay soils, such as polymeric membranes, or bentonite or other approved admixtures, may be used upon approval by the Department. All such liners shall be designed, installed, tested and maintained in strict accordance with an approved liner installation and testing plan that incorporates the specifications and recommendations of the manufacturer, ASTM, EPA and of the Department.
- 5.6.5.5 Testhole plugging: All test holes shall be plugged in accordance with **§** 5.2.3.4. All shallow holes (three feet or less in depth) shall be plugged by placing soil (or a bentonite grout) back in the test holes in three inch layers and manually tamping said soil at least twenty times per square inch with a heavy bar. The soil shall be placed in the hole at optimum moisture content and tamped evenly into the hole.
- 5.6.6 The following information shall be provided for Type III-B facilities.
 - 5.6.6.1 A narrative describing the design and intended development and operational plans for the facility, stating the planned excavation depths, development style, and design features. Include information, supported by such drawings as are necessary, on methods to control run-off water.
 - 5.6.6.2 Site operation. A guidance manual in narrative form, itemized to agree with operational standards in **§** 3.0, which will provide the facility's management and operating personnel with sufficient detailed information to ensure that normal operations at the facility are performed in accordance with the Regulations and with the facility's design and operating criteria.
 - 5.6.6.3 Closure. See **§** 5.6.1.6.
 - 5.6.6.4 Site maintenance. See **§** 5.6.4.1 and 5.6.4.2.
- 5.6.7 Type VI facilities. Plans and specifications for solid waste processing facilities shall be in accordance with Guidelines issued by the Department.
- 5.6.8 Type VIII facilities or sites. Plans and specifications for beneficial use of sludge shall be in accordance with provisions of Chapter Six, and with Guidelines issued by the Department.
- 5.6.9 Type IX and X facilities. Plans and specifications for Type IX and X facilities shall be in accordance with guidance provided by the Department on a case-by-case basis. See **§** 5.5

5.7 **REQUEST FOR VARIANCE**

Any request for variance shall be included in the narrative portion of the application, and shall state explicitly the Regulation from which a variance

is sought. The nature of the variance shall be clearly stated, and all pertinent information shall be included to support the request, including:

- a) technical design information and calculations where required; and
- b) evaluation of the effects resulting from the variance, as compared with the effects of following the Regulations; and
- c) justification of the variance based on evaluation of adverse impacts on public health and the environment that might result from the variance.

CHAPTER SIX

BENEFICIAL USE OF TREATMENT PLANT SLUDGES BY LAND APPLICATION

- 6.0 **GENERAL:** The following regulations provide minimum standards for the application of water and wastewater treatment plant sludges to land at agronomic rates beneficial as a soil enrichment. It is the intent of these Regulations to restrict such land application to that which will benefit the soil and enhance it for crop production and other vegetative growth.
- 6.1 Sludge management plans required. Sewage and water treatment sludge generators or applicators shall submit sludge management plans to reduce the amount of site specific information needed for approval of individual land application sites.
- 6.2 Sludge generators with approved sludge management plans may distribute or sell Level II and III sludges provided the user completes and signs an information sheet and an agreement to utilize the sludge in accordance with these Regulations.
- 6.3 The sludge generator must keep a record of sludge handled for at least five (5) years after the expiration date of the permit. The sludge records must include:
- A. Date of shipment and application
 - B. Weather conditions, when delivered
 - C. Location of sludge application site
 - D. Amount of sludge applied or delivered
 - E. Quality of sludge
 - F. Sludge use agreements
 - G. Area of land applied

GEOLOGIC FORMATION PARAMETERS

APPENDIX B

GEOLOGIC FORMATION PARAMETERS

p = Primary lithology
s = Secondary lithology
pm = Associated with major aquifer

Thin bedded = < 50 feet
Thick bedded = > 100 feet

Formation	Predominant Lithologies/ Aquifer Association							Bed Thickness			SS Grain Size		
	LS	SS	Sh	Inbd	Ign	Evp	Cong	Thin	Med	Thck	F	M	C
Ada Fm.	s	s	s	pm			s		x	x	x		
Admire Fm.			p						x				
Altamont Fm.	p		s										
Antlers SS		pm					s			x	x	x	x
Americus LS	p							x					
Arbuckle GP	pm						s			x			
Arkansas Novaculite		s	s	pm			s			x			
Atoka Fm	p	s	s	s			s			x	x	x	x
Auburn Sh			p						x				
Bandera Fm		s	p										
Barnsdale Fm	s	p	s	s					x	x	x		
Batesville Fm		p					s						
Belle City Fm	s	s	s	p				x					
Bennington LS	p							x					
Bigfork Chert	pm	s	s							x			
Bird Creek LS	p							x					
Bison Shale		s	s	p					x	x	x		
Blackgum FM	p												
Blaine Fm			s			pm			x	x			
Blakely SS		p								x	x	x	x
Blaylock SS		s	s	p				x			x		
Boyd FM	p		s										
Boggy Fm	s	s	s	p						x	x	x	x
Bokchito Fm	s	s	p							x			
Brownstown Mrl	s	s	p						x				
Brownville LS	p							x					
Burgen SS	s	p	s			s							
Butterfly Dol	p									x			
Caddo Fm	p		s							x			
Calvin SS		s	s	p					x	x		x	
Carlton Rhyl						p				x			
Cedar Hills SS		s	s	pm						x	x		
Chanute Fm		p	s	s				x	x	x	x	x	x
Chattanooga Sh		s	p										
Checkerboard LS	p		s					x					
Chickachoc Cher	p	s	s							x			
Chickasha Fm		s	s	p			s	x	x	x	x		
Cloud Chief Fm		s	s	p		s		x	x	x	x		
Coffeyville Fm	s	s	s	p			s			x	x	x	x
Colbert Porph						p				x			

Collier Sh	s		p		s				x			
Colorado Gp	s		s	p				x	x		x	
Cool Creek Fm	p	s									x	
Cotter Dol.	p				s							
Cottonwood LS	p							x				
Crystal Mte SS	s	p			s						x	x
Dakota Gp		p									x	x
Delaware Ck Sh	s		p								x	
Denton Clay	s		p						x			
Dewey Limestone	s	s	s	p				x	x			
Dockum Group		s	s	p				x	x		x	x
Dog Creek Shale		s	s	pm	s				x		x	x
Dornick Hlls Gp	p	s									x	
Doxy Shale			p					x	x		x	
Duncan SS		p	s	s	s						x	x
Eagle Ford FM			p						x			
Elk City SS	s	pm	s		s						x	
Elk Fork Member			p		s				x		x	
Elmont LS	p							x				
ElReno Group		s	s	p	s						x	
Exeter(Entrada)												
Sandstone		p						x				x
Fairmont Shale		s	p		s			x	x		x	
Fayetteville FM	p		s									
Fernvale Lmstne	p										x	
Fite Limestone	p											
Flowerpot Shale		s	p	s	s			x	x		x	x
Ft. Riley LS	p							x				
Ft. Scott LS	s	s	s	p								
Ft. Sill LS	p										x	
Frisco Fm	p											
Garber SS		s	s	pm	s						x	x x x
Goddard Shale	s	s	p								x	
Goodland LS	p							x	x			
Grayhorse LS	p							x				
Grayson Marl	p		s					x				
Hale Formation	p	s	s									
Hart Limestone	p							x				
Hartshorne SS		s	s	p								x x
Hennessey Group		s	s	p							x	
Herington LS	p											
Hilltop Fm	s	p	s					x	x			
Hindsville Fm	p		s									
Hogshooter LS	s	s	s	p				x	x		x	x
Holdenville Fm	s	s	s	p	s						x	
Honey Creek LS	pm										x	x
Hughes Creek Sh			p								x	
Hunton Group	p		s								x	
Iola Limestone	p	s	s					x	x		x	
Jackfork Group		p	s								x	x x
Johnson Shale			p								x	
Johns Valley Fm	s	s	s	p	s						x	
Keokuk Fm			s		pm							
Kiamichi Fm	s		p					x	x			
Kingman Slst		s	s	p							x	x x

Kiowa Formation	s	s	p		s	x	x	x			
LaBette Fm	s	s	s	p							
Lecompton Lmstn	p					x					
Lenapah Fm	p		s								
Limestone Gap	p	s	s					x	x	x	x
Lung Creek Lmst	p					x					
Lynne Mte.Fm		s	s	p				x	x	x	x
McAlester Fm		s	s	p				x			
McNutt Lmstn	p								x		
Marlow Fm	s	pm			s	x	x	x			
Mazarn Shale			p					x			
Missouri Mtn Sh	s	s	s	p	s		x	x			
Moorefield Fm	p		s								
Morrison Fm		s	s	p	s					x	
Morrowan-											
Atoka Fm		s	s	p				x	x	x	x
Nellie Bly Fm	s	s	p		s		x	x	x	x	
Neva Limestone	p					x					
Nowata Fm	s	s	s	p							
Ogallala Fm	s	s	s		pm	x	x	x	x		
Oil Creek and											
Jones Fm	p	s	s					x			
Oologah Fm	s	s	s	p							
Oscar Group	s	s	s	pm	s		x	x			
Ozan Formation	s	s	p				x				
Pawnee Fm	p		s								
Pawpaw SS		p					x			x	
Pitikin Fm	p										
Polk Creek Sh	s	s	s	p	s		x	x			
Poney Creek Sh			p				x				
Post Oak Congl		s	s	pm	s			x			
Purgatoire Fm		s	s	p				x			
Purcell SS		s	s	p	s		x	x	x	x	x
Quarry Mtn.Fm	p										
Raggedy Mtn											
Gabbro					p				x		
Reading Lmstn	p					x					
Reagan SS		pm					x	x			x
Red Eagle Lmstn	p					x					
Reeds Spring Fm	pm				s						
Roca Shale			p			x					
Royer Dolomite	p							x			
Rush Springs Fm	pm	s			s		x	x			
St. Joe Grp	p		s								
Sallisaw Fm	p	s			s						
Salt Plains Fm		s	s	p				x		x	
San Angelo SS		s	s	p	s		x				
Savanna Fm	s	s	s	p				x	x	x	x
Seminole Fm		s	s	p	s			x			
Senora Fm	s	s	s	p				x		x	
Severy-Aarde SS			p			x					
Signal Mtn Lmst	p							x			
Soper Lmstne	p					x					
Spavinaw Granite					p						
Stanley Shale		s	p		s			x			

Stonebreaker Sh			p					x				
Stuart Shale		s	s	p				x	x		x	x
Sycamore and Weldon Shale	s		p				x	x	x			
Sylvan Shale			p					x	x			
Tallant Fm	s	p	s	s				x	x		x	x
Tenkiller Fm	p											
Thurman SS		s	s	p		s		x	x	x	x	x
Timbered Hills Group	pm	s	s			s				x		
Tishomingo and Troy												
Tokio Fm	s	p	s							x		
Torpedo Fm					p				x			x
Turkey Run LS	p							x				
Tyner Fm	p	s	s			s						
Union Valley Fm	p	s								x		x
Vamoosa Fm	s	s	s	pm		s				x	x	x
Vanoss Group	s	s	s	p		s				x	x	
Viola Lmstne and Bromide Fm	s	s	s	p						x		
Wakarusa Lmstne	p							x				
Walnut Clay			p					x				
Wann Fm	s	p	s	s					x	x	x	x
Wapanucka Fm	p		s							x		
Weatherford Gyp						p				x		
Wellington Fm		s	s	pm		s				x		x
Weno Clay		s	p			s				x		
West Spring Creek & Kinblade Fm	p	s	s								x	x
Wetumka Shale	s	s	s	p						x		
Wewoka Fm	s	s	s	p		s		x	x	x		
Whitehorse Grp		s	s	p						x		x
Wichita Granite Grp						p					x	
Winfield Lmstne	p									x		
Womble Shale	s	s	s	p						x		x
Woodbine Fm		p	s			s					x	x
Woodford Shale			p							x		
Wreford Lmstne	p							x				

FORMATIONS BY GEOLOGIC TYPE AREAS

SHALE

Marlo Formation (Major Aquifer)
Elm Fork Member
Flowerpot Shale
Eagle Ford Formation
Bokchito Formation
Kiamichi Formation
Walnut Clay
Woodford Shale
Sylvan Shale
Ozan Formation
Brownstown Marl
Weno Clay
Denton Clay
Nelly Bly Formation
Goddard Shale
Delaware Creek Shale
Sycamore Shale
Welden Shale
Stanley Shale
Mazarn Shale
Collier Shale
Kiowa Formation
Doxey Shale
Chattanooga Shale
Fairmont Shale
Bandera Formation
Roca Shale
Johnson Shale
Hughes Creek Shale
Admire Shale
Pony Creek Shale
Stonebreaker Shale
Auburn Shale
Severy-Aarde Shale

SEMI-CONSOLIDATED TO UNCONSOLIDATED CLASTICS

Rush Springs Formations (Major Aquifer)
Duncan Sandstone
Woodbine Formation
Antlers Sandstone (Major Aquifer)
Reagan Sandstone (major Aquifer)
Tokio Formation
Pawpaw Sandstone
Hilltop Formation
Jack Fork Group
Blakely Sandstone
Crystal Mountain Sandstone
Dakota Group
Elk City Sandstone (Major Aquifer)
Burgin Sandstone
Tallant Formation
Barnsdale Formation
Wann Formation
Chanute Formation
Batesville Formation
Exeter (Entrada) Sandstone

INTERBEDDED SANDSTONE/SHALE

Cloudchief Formation
Whitehorse Group
ElReno Group
Dog Creek Shale (Major Aquifer)
San Angelo Sandstone
Post Oak Conglomerate (Major Aquifer)
Hennessey Group
Garber Sandstone (Major Aquifer)
Wellington Formation (Major Aquifer)
Oscar Group (Major Aquifer)
Viola Limestone-Bromide Formation
Arkansas Novaculite (Major Aquifer)
Missouri Mountain Shale
Blaylock Sandstone
Polk Creek Shale
Womble Shale
Lynne Mountain Formation
Chickasha Formation
Bison Shale
Purcell Sandstone
Vanoss Group
Ada Formation (major Aquifer)
Vamossa Formation (Major Aquifer)
Belle City Formation
Coffeeville (Francise) Formation
Seminole Formation
Holdenville Formation
Wewoka Formation
Wetumka Shale Calvin Sandstone
Senora Formation
Stuart Shale
Thurman Sandstone
Boggy Formation
Savanna Formation
McAlester Formation
Hartshorne Sandstone
Morrowan-Atokan Formation
Johns Valley Formation
Salt Plains Formation
Cedar Hills Sandstone (Major Aquifer)
Kingman Siltstone
Dewey Limestone
Hogshooter Limestone
Torpedo Formation
Nowata Formation
Oologah Formation
LaBette Formation
Ft. Scott Formation
Colorado Group
Purgatoire Formation
Morrison Formation
Dockum Group

CARBONATE

Arbuckle Group (Major Aquifer)	Ft. Riley Limestone
Timbered Hills Group (Major Aquifer)	Wreford Limestone
Graysn Marl	Cottonwood Limestone
Bennington Limestone	Red Eagle Limestone
Caddo Formation	Long Creek Limestone
Goodland Limestone	Americul Limestone
Hunton Group	Brownville Limestone
Fernvale Limestone	Gray Horse Limestone
Bigfork Chert (Major Aquifer)	Elmont Limestone
Oil Creek Formation	Reading Limestone
Jones Formation	Wakarusea Limestone
West Spring Creek Formation	Bird Creek Limestone
Kinblade Formation	Turkey Run Limestone
Cool Creek Formation	Lecompton Limestone
McKinzie Hill Formation	
Butterfly Dolomite	
Royer Dolomite	
Ft. Sill Limestone	
Signal Mountain Limestone	
Honey Creek Limestone (Major Aquifer)	
McNutt Limestone	
Soper Limestone	
Atoka Formation	
Wapanucka Formation	
Union Valley Formation	
Dornick Hills Group	
Chickachoc Chert	
Limeston Gap	
Bloyd Formation	
Hale Formation	
Pitikin Formation	
Fayetteville Formation	
Hindsville Formation	
Moorefield Formation	
Reeds Spring Formation (Major Aquifer)	
St. Joe Group	
Sallisaw Formation	
Frisco Formation	
Quarry Mountain Formation	
Tenkiller Formation	
Blackgum Formation	
Cotter Dolomite	
Fite Limestone	
Tyner Formation	
Iola Limestone	
Checkerboard Limestone	
Lenapah Formation	
Altamont Formation	
Pawnee Formation	
Herington Limestone	
Neva Limestone	
Hart Limestone	
Winfield Limestone	

EVAPORITES

Weatherford Gypsum Formation
Blaine Formation (Major Aquifer)

IGNEOUS

Carlton Phylite
Wichita Mountain Granite Group
Raggedy Mountain Gabbro
Colbert Porphyry
Tishomingo Granite
Troy Granite
Spavinaw Granite

CONGLOMERATE

Ogallala Formation (Major Aquifer)
Keokuk Formation (Major Aquifer)

MAJOR_AQUIFER_FORMATION

Alluvium
Dune Sands
Terrace Deposits
Ogallala Formation
Antlers Sandstone
Elk City Sandstone
Rush Springs Sandstone
Marlow Formation
Blain Formation
Dog Creek Formation
Cedar Hills Sandstone
Garber Sandstone
Wellington Pormation
Oscar Group
Vamossa Formation
Ada Group
Noxie Sandstone
Keokuk Formation
Reeds Spring Formation
Arkansas Movaculite
Big Fork Chert
Roubidoux Formation
Gasconsde Formation
Eminence Formation
Simpson Group
Arbuckle Group
Timbered Hills Group
Post Oak Conglomerate

APPENDIX C
DRASTIC

5. HIGH PLAINS

(Thick alluvial deposits over fractured sedimentary rocks)

The High Plains region occupies an area of 450,000 km² extending from South Dakota to Texas. The plains are a remnant of a great alluvial plain built in Miocene time by streams that flowed east from the Rocky Mountains. The plain originally extended from the foot of the mountains to a terminus some hundreds of kilometers east of its present edge. Erosion by streams has removed a large part of the once extensive plain, including all of the part adjacent to the mountains, except in a small area in southeastern Wyoming.

The original depositional surface of the alluvial plain is still almost unmodified in large areas, especially in Texas and New Mexico, and forms a flat, imperceptibly eastward-sloping tableland that ranges in altitude from about 2,000 m near the Rocky Mountains to about 500 m along its eastern edge. The surface of the southern High Plains contains numerous shallow circular depressions, called playas, that intermittently contain water following heavy rains. Some geologists believe these depressions are due to solution of soluble materials by percolating water and accompanying compaction of the alluvium. Other significant topographic features include sand dunes, which are especially prevalent in central and northern Nebraska, and wide, downcut valleys of streams that flow eastward across the area from the Rocky Mountains.

The High Plains region is underlain by one of the most productive and most intensively developed aquifers in the United States. The alluvial materials derived from the Rocky Mountains, which are referred to as the Ogallala Formation, are the dominant geologic unit of the High Plains aquifer. The Ogallala ranges in thickness from a few meters to more than 200 m and consists of poorly sorted and generally unconsolidated clay, silt, sand, and gravel.

Younger alluvial materials of Quaternary age overlie the Ogallala Formation of late Tertiary age in most parts of the High Plains. Where these deposits are saturated, they form a part of the High Plains aquifer; in parts of south-central Nebraska and central Kansas, where the Ogallala is absent, they comprise the entire aquifer. The Quaternary deposits are composed largely of material derived from the Ogallala and consist of alluvial deposits of gravel, sand, silt, and clay and extensive areas of sand dunes. The most extensive area of dune sand occurs in the Sand Hills area north of the Platte River in Nebraska.

Other, older geologic units that are hydrologically connected to the Ogallala thus form a part of the High Plains aquifer include the Arikaree Group of Miocene age and a small part of the underlying Brule Formation. The

Arikaree Group underlies the Ogallala in parts of western Nebraska, southwestern South Dakota, southeastern Wyoming, and northeastern Colorado. It is predominantly a massive, very fine to fine-grained sandstone that locally contains beds of volcanic ash, silty sand, and sandy clay. The maximum thickness of the Arikaree is about 300 m, in western Nebraska. The Brule Formation of Oligocene age underlies the Arikaree. In most of the area in which it occurs, the Brule forms the base of the High Plains aquifer. However, in the southeastern corner of Wyoming and the adjacent parts of Colorado and Nebraska, the Brule contains fractured sandstones hydraulically interconnected to the overlying Arikaree Group; in this area the Brule is considered to be a part of the High Plains aquifer.

In the remainder of the region, the High Plains aquifer is underlain by several formations, ranging in age from Cretaceous to Permian and composed principally of shale, limestone, and sandstone. The oldest of these, of Permian age, underlies parts of northeastern Texas, western Oklahoma, and central Kansas and contains layers of relatively soluble minerals including gypsum, anhydrite, and halite (common salt) which are dissolved by circulating ground water. Thus, water from the rocks of Permian age is relatively highly mineralized and not usable for irrigation and other purposes that require freshwater. The older formations in the remainder of the area contain fractured sandstones and limestones interconnected in parts of the area with the High Plains aquifer. Although these formations yield freshwater, they are not widely used as water sources.

Prior to the erosion that removed most of the western part of the Ogallala, the High Plains aquifer was recharged by the streams that flowed onto the plain from the mountains to the west as well as by local precipitation. The only source of recharge now is local precipitation, which ranges from about 400 mm along the western boundary of the region to about 600 mm along the eastern boundary. Precipitation and ground-water recharge on the High Plains vary in an east-west direction, but recharge to the High Plains also varies in a north-south direction. The average annual rate of recharge has been determined to range from about 5 mm in Texas and New Mexico to about 100 mm in the Sand Hills in Nebraska. This large difference is explained by differences in evaporation and transpiration and by differences in the permeability of the surficial materials.

In some parts of the High Plains, especially in the southern part, the near-surface layers of the Ogallala have been cemented with lime (calcium carbonate) to form a material of relatively low permeability called caliche. Precipitation on areas underlain by caliche soaks slowly into the ground. Much of this precipitation collects in playas that are underlain by silt and clay, which hamper infiltration, with the result that most of the water is lost to evaporation. During years of average or below average precipitation, all or nearly all of the precipitation is returned to the atmosphere by evapotranspiration. Thus, it is only during years of excessive precipitation that significant recharge occurs and this, as noted above, averages only about 5 mm per year in the southern part of the High Plains.

In the Sand Hills area of Nebraska, the lower evaporation and transpiration and the permeable sandy soil results in about 20 percent of the precipitation (or about 100 mm annually) reaching the water table as recharge.

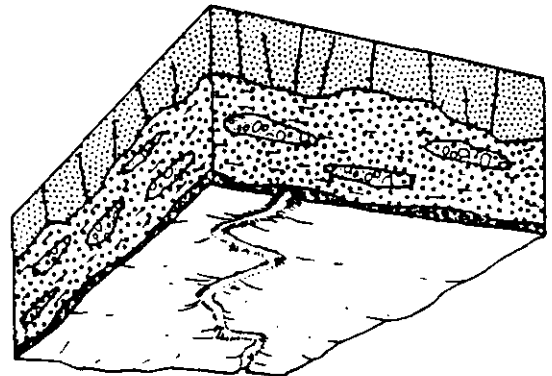
The water table of the High Plains aquifer has a general slope toward the southeast of about 2 to 3 m per km (10 to 15 ft per mile). Gutentag and Weeks (1980) estimate, on the basis of the average hydraulic gradient and aquifer characteristics, that water moves through the aquifer at a rate of about 0.3 m (1 ft) per day.

Natural discharge from the aquifer occurs to streams, springs, saline lakes and seeps along the eastern boundary of the plains, and by evaporation and transpiration in areas where the water table is within a few meters of the land surface. However, at present the largest discharge is probably through wells. The widespread occurrence of permeable layers of sand and gravel, which permit the construction of large-yield wells almost any place in the region, has led to the development of an extensive agricultural economy largely dependent on irrigation. Gutentag and Weeks (1980) estimate that in 1977 about $3.7 \times 10^{10} \text{m}^3$ (30,000,000 acre-ft) of water was pumped from more than 168,000 wells to irrigate about 65,600 km² (16,210,000 acres). Most of this water is derived from ground-water storage, resulting in a long-term continuing decline in ground-water levels in parts of the region of as much as 1 m per year. The lowering of the water table has resulted in a 10 to 50 percent reduction in the saturated thickness of the High Plains aquifer in an area of 130,000 km² (12,000 mi²). The largest reductions have occurred in the Texas panhandle and in parts of Kansas and New Mexico.

The depletion of ground-water storage in the High Plains, as reflected in the decline in the water table and the reduction in the saturated thickness, is a matter of increasing concern in the region. However, from the standpoint of the region as a whole, the depletion does not yet represent a large part of the storage that is available for use. Weeks and Gutentag (1981) estimate, on the basis of a specific yield of 15 percent of the total volume of saturated material, that the available (usable) storage in 1980 was about $4 \times 10^{12} \text{m}^3$ (3.3 billion acre-ft). Luckey, Gutentag, and Weeks (1981) estimate that this is only about 5 percent less than the storage that was available at the start of withdrawals. However, in areas where intense irrigation has long been practiced, depletion of storage is severe.

HIGH PLAINS
(5A) Ogallala

This hydrogeologic setting is characterized by moderately flat topography and thick deposits of poorly-sorted, semi-consolidated, clay, silt, sand and gravel that may be underlain by fractured sedimentary rock which is in hydraulic connection with overlying deposits. In some parts of the High Plains, especially in the southern part, shallow zones of the unconsolidated deposits have been cemented with calcium carbonate. The permeability of this caliche layer varies with the degree of cementation, fracturing and clay mineral content. Precipitation averages less than 20 inches per year and recharge is very low throughout most of this water-deficient area. The bedrock and the overlying semi-consolidated deposits both serve as extensive sources of ground water. Water levels are typically deep, but extremely variable. The Ogallala is underlain by bedded, unconsolidated deposits of fractured sandstone, limestone, volcanic ash, silty sand, sandy clay and shales. These formations are hydraulically connected to the Ogallala and the overlying alluvium, from which they derive their recharge.

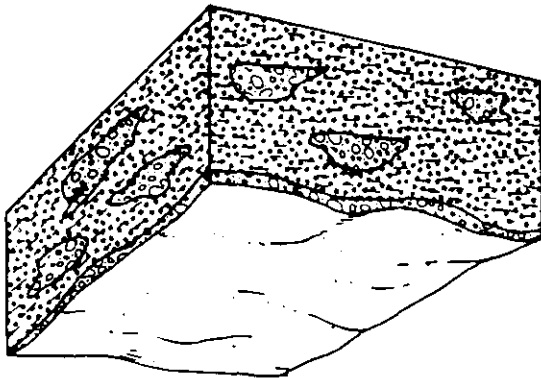


SETTING 5 A Ogallala		GENERAL	
FEATURE	RANGE	WEIGHT	RATING NUMBER
Depth to Water	75-100	5	2
Net Recharge	0-2	4	1
Aquifer Media	Sand and Gravel	3	8
Soil Media	Shrink/Agg. Clay	2	7
Topography	2-68	1	9
Impact Vadose Zone	S & G w/ silt, clay	5	6
Hydraulic Conductivity	700-1000	3	6
Pesticide Index 109			

SETTING 5 A Ogallala		GENERAL	
FEATURE	RANGE	WEIGHT	RATING NUMBER
Depth to Water	75-100	5	2
Net Recharge	0-2	4	1
Aquifer Media	Sand and Gravel	3	8
Soil Media	Shrink/Agg. Clay	5	7
Topography	2-68	3	9
Impact Vadose Zone	S & G w/ silt, clay	4	6
Hydraulic Conductivity	700-1000	2	6
Pesticide Index 136			

HIGH PLAINS
(5B) Alluvium

This hydrogeologic setting is characterized by low to moderate relief, and is comprised of gravel, sand, silt and clay alluvial sediments. These deposits are variable in thickness. They form, where saturated, a portion of the High Plains aquifer, and locally all of it where the Ogallala is missing. Water levels are variable, but recharge is limited throughout most of the area by low precipitation. The shallow caliche layer of cemented, unconsolidated deposits also develops in the alluvium in some localities. Similar to the Ogallala, recharge to the deeper sandstones is through the alluvial deposits.



SETTING 5 B Alluvium		GENERAL	
FEATURE	RANGE	WEIGHT	RATING NUMBER
Depth to Water	50-75	5	3
Net Recharge	0-2	4	1
Aquifer Media	Sand and Gravel	3	8
Soil Media	Sandy Loam	2	6
Topography	0-28	1	10
Impact Vadose Zone	S & G w/ silt, clay	5	6
Hydraulic Conductivity	300-700	3	4
Pesticide Index 107			

SETTING 5 B Alluvium		GENERAL	
FEATURE	RANGE	WEIGHT	RATING NUMBER
Depth to Water	50-75	5	3
Net Recharge	0-2	4	1
Aquifer Media	Sand and Gravel	3	8
Soil Media	Sandy Loam	5	6
Topography	0-28	3	10
Impact Vadose Zone	S & G w/ silt, clay	4	6
Hydraulic Conductivity	300-700	2	4
Pesticide Index 135			

HYDROGEOLOGIC DATA SOURCES

APPENDIX D

HYDROGEOLOGIC DATA SOURCES

National Sources of Data:

Storet
Watstore
Nawdex
National Water Well Association (NWWA)
U.S. Geological Survey (U.S.G.S.)
U.S. Environmental Protection Agency (EPA)

State of Oklahoma Sources of Data

Oklahoma Water Resources Board (OWRB)
Oklahoma State Department of Health (OSDH)
Oklahoma State Geological Survey (OSGS)
Oklahoma Center for Water Research (OCWR)
Riley's Log Library

Others:

Thesis
University of Oklahoma
Oklahoma State University
Tulsa University

OKLAHOMA GEOLOGICAL SURVEY

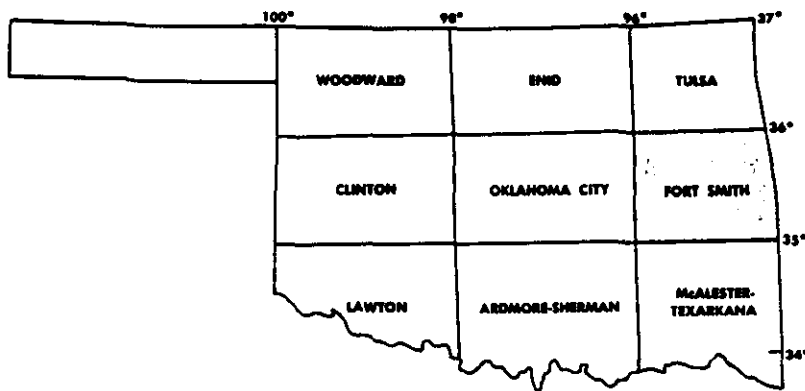
CHARLES J. MANKIN, *Director*

HYDROLOGIC ATLAS 1

**RECONNAISSANCE OF THE WATER RESOURCES OF THE FORT SMITH QUADRANGLE
EAST-CENTRAL OKLAHOMA**

by
MELVIN V. MARCHER

Prepared in cooperation with
United States Geological Survey



Scale
1:250,000

University of Oklahoma
Norman
1969

OKLAHOMA GEOLOGICAL SURVEY

CHARLES J. MANKIN, *Director*

HYDROLOGIC ATLAS 2

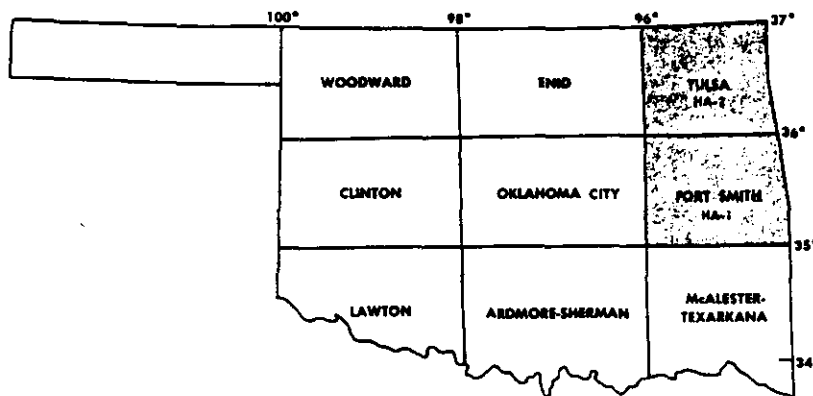
RECONNAISSANCE OF THE WATER RESOURCES OF THE TULSA QUADRANGLE

NORTHEASTERN OKLAHOMA

by

MELVIN V. MARCHER AND ROY H. BINGHAM

Prepared in cooperation with
United States Geological Survey



Scale
1:250,000

University of Oklahoma
Norman
1971

OKLAHOMA GEOLOGICAL SURVEY

CHARLES J. MANKIN, Director



Hydrologic Atlas 3

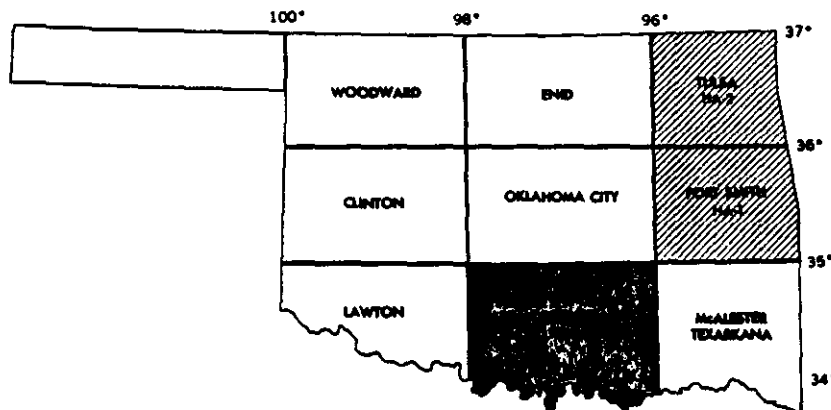
**RECONNAISSANCE OF THE WATER RESOURCES OF THE ARDMORE
AND SHERMAN QUADRANGLES, SOUTHERN OKLAHOMA**

By

DONALD L. HART, JR.
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY

Scale 1:250,000



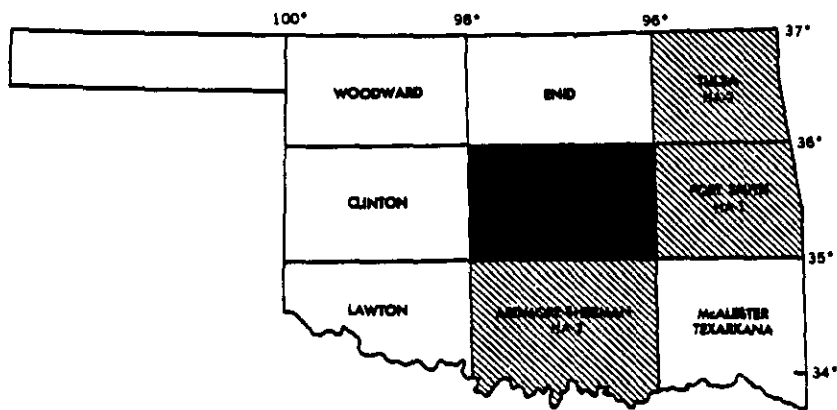
OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

HYDROLOGIC ATLAS 4

RECONNAISSANCE OF THE WATER RESOURCES OF THE OKLAHOMA CITY QUADRANGLE
CENTRAL OKLAHOMA

By
ROY H. BINGHAM and ROBERT L. MOORE
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY



Scale 1:250,000

OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

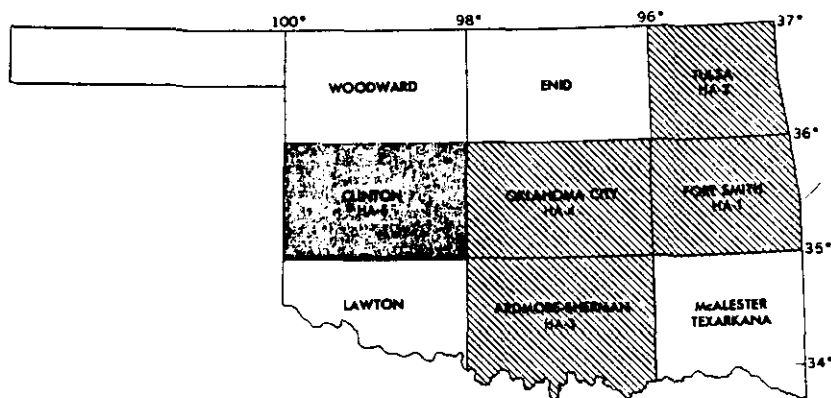
HYDROLOGIC ATLAS 5

RECONNAISSANCE OF THE WATER RESOURCES OF THE CLINTON QUADRANGLE
WEST-CENTRAL OKLAHOMA

By

JERRY E. CARR and DEROY L. BERGMAN
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY



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OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

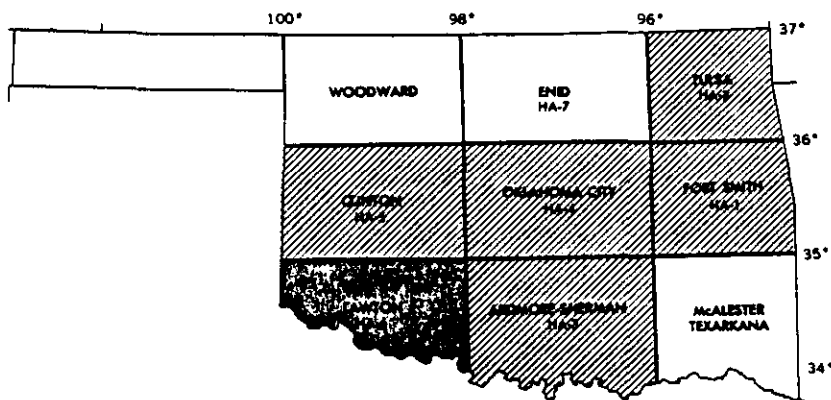
HYDROLOGIC ATLAS 6

RECONNAISSANCE OF THE WATER RESOURCES OF THE LAWTON QUADRANGLE
SOUTHWESTERN OKLAHOMA

By

JOHN S. HAVENS
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY



Scale 1:250,000



OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

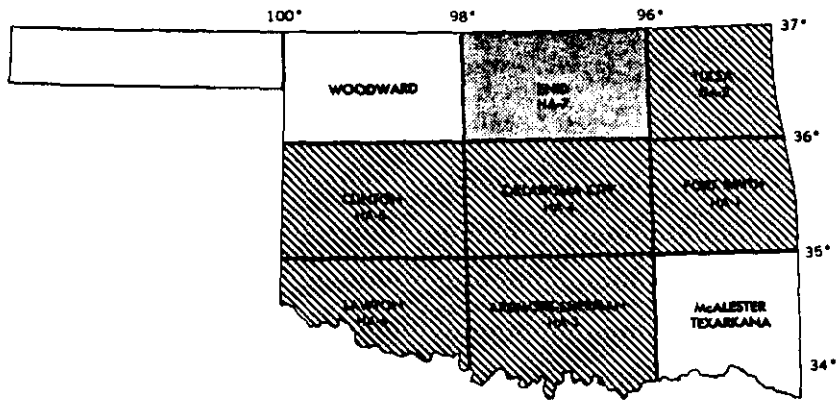
HYDROLOGIC ATLAS 7

RECONNAISSANCE OF THE WATER RESOURCES OF THE ENID QUADRANGLE
NORTH-CENTRAL OKLAHOMA

By

ROY H. BINGHAM AND DEROY L. BERGMAN
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY



Scale 1:250,000



OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

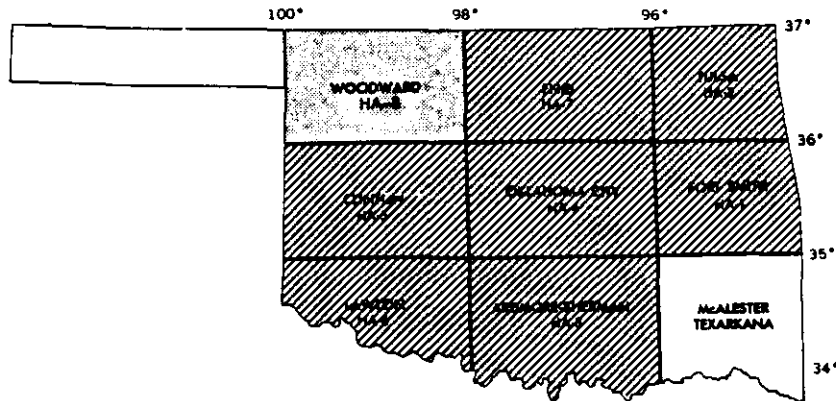
HYDROLOGIC ATLAS 8

RECONNAISSANCE OF THE WATER RESOURCES OF THE WOODWARD QUADRANGLE
NORTHWESTERN OKLAHOMA

By

ROBERT B. MORTON
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY



Scale 1:250,000

OKLAHOMA GEOLOGICAL SURVEY
CHARLES J. MANKIN, *Director*



Hydrologic Atlas 9

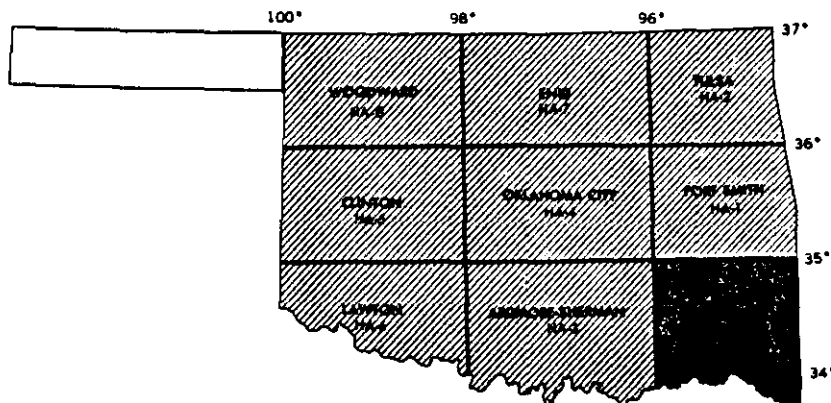
**RECONNAISSANCE OF THE WATER RESOURCES OF THE MCALESTER
AND TEXARKANA QUADRANGLES, SOUTHEASTERN OKLAHOMA**

By

MELVIN V. MARCHER AND DEROY L. BERGMAN
U.S. Geological Survey

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY

Scale 1:250,000



DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
OKLAHOMA WATER RESOURCES BOARD

RECONNAISSANCE OF THE GROUND-WATER RESOURCES
OF CIMARRON COUNTY, OKLAHOMA

By
D. B. Sapik, and R. L. Goemaat

HYDROLOGIC INVESTIGATIONS
ATLAS HA-373



PUBLISHED BY THE U. S. GEOLOGICAL SURVEY
WASHINGTON, D. C. 20242

1973

SAPIK AND GOEMAAT—RECONNAISSANCE OF WATER RESOURCES, CIMARRON CO., OKLA.

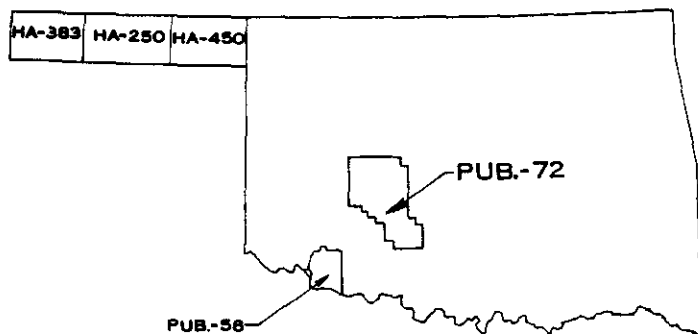
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MAP HA-373

GROUND WATER RESOURCES OF THE RUSH SPRINGS SANDSTONE OF SOUTHWESTERN OKLAHOMA

HYDROLOGIC INVESTIGATIONS
PUBLICATION 72
1976

Required by: 82 O.S. Supplement 1972, § 1020.4



Published by
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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
OKLAHOMA WATER RESOURCES BOARD

PRELIMINARY INVESTIGATIONS OF THE HYDROGEOLOGY
OF THE PERMIAN TO TERTIARY ROCKS OF THE
OKLAHOMA PANHANDLE

By
Robert B. Morton

MISCELLANEOUS GEOLOGIC INVESTIGATIONS
MAP I-738



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WASHINGTON D.C. 20242

MORTON-HYDROGEOLOGY OF PERMIAN TO TERTIARY ROCKS, OKLAHOMA PANHANDLE, MAP I-738

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH
THE OKLAHOMA CORPORATION COMMISSION
AND OKLAHOMA WATER RESOURCES BOARD

**BASE OF FRESH GROUND WATER
IN SOUTHERN OKLAHOMA**

By
Donald L. Hart, Jr.

HYDROLOGIC INVESTIGATIONS
ATLAS HA-223



PUBLISHED BY THE U. S. GEOLOGICAL SURVEY
WASHINGTON, D. C.
1966

ATLAS HA-223

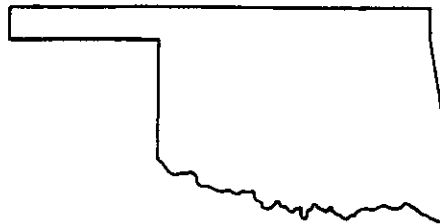
OKLAHOMA STATE DEPARTMENT OF HEALTH

Joan K. Leavitt, M.D., *Commissioner of Health*

MAPS SHOWING PRINCIPAL GROUND-WATER RESOURCES AND RECHARGE AREAS IN OKLAHOMA:

Sheet 1 – Unconsolidated Alluvium and Terrace Deposits
and
Sheet 2 – Bedrock Aquifers and Recharge Areas

Compiled by
Kenneth S. Johnson
Oklahoma Geological Survey



Scale, 1:500,000
1983

NOMOGRAPH AND ANALYTICAL MODEL RESULTS

APPENDIX E

SHALE

Thickness (m) = 28 Ft.
Porosity (n) = 0.2
Velocity (v) = .03 Ft/day

Dispersion:

$$D_x = 10 \text{ Ft}^2/\text{day}$$

$$D_y = 2 \text{ Ft}^2/\text{day}$$

Retardation (Rd) = 1

Volume Flow Rate = 225 Ft³/day

Source Concentration (Co) = 100 mg/l

Mass Flow Rate (Q_{Co}) = (22,500 Ft³/day) (100 mg/l)
or 6.23 x 10⁻⁵ Lb/day

X_D = 333.3 Ft Where X_D = D_x/V = 10/.03 = 333.3 Ft

T_D = 1.11 x 10⁴ days Where T_D = RdD_x/V² = (1)(10)/(.03)² =

Q_d = 1.25 Ft³/day Where Q_d = nm D_x D_y =
(0.2)(28) (10)(2) = 1.25

Application 1: Solve for concentration when distance (X) = 750 Ft
and time = infinity (steady state)

Plot the following on the nomograph:

A: X/X_D = 750 Ft/333.3 Ft = 2.25

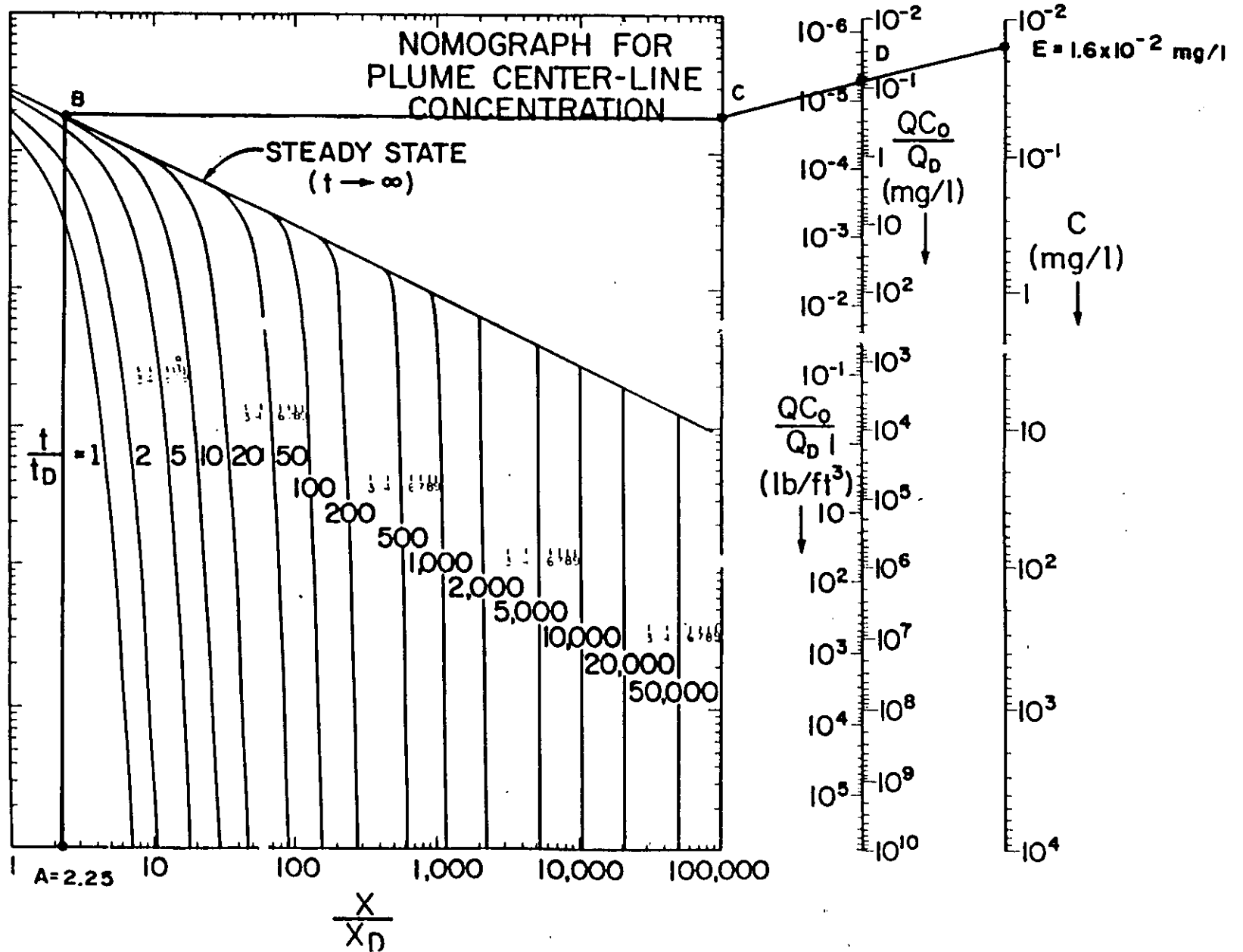
B: t/T_D = Steady state (use steady state line)

C: Intersection of line with vertical scale on right side of
nomograph

D: Q_{Co}/Q_d = 6.23 x 10⁻⁵ LB/day/1.25 Ft³/day =
4.98 x 10⁻⁵ Lb/ft³

E: Read concentration directly from vertical scale for
concentration (mg/l).

SHALE
APPLICATION 1: CONCENTRATION
AT 750 FEET AND STEADY STATE



THICKNESS = 28.0000 FT
 POROSITY = .200000
 VELOCITY = .300000E-01 FT/D

 X DISPERSION = 10.0000 FT2/D
 Y DISPERSION = 2.00000 FT2/D

 RETARDATION = 1.00000
 DECAY GAMMA = 1.00000

X LOCATION (FT) .000000
 Y LOCATION (FT) .000000
 AREA (FT2) 250000.
 START TIME (DAYS) .000000
 VOLUME FLOW RATE (FT3/D) 225.000
 SOURCE CONCENTR. (MG/L) 100.000

 SAMPLE TIME = 3650.00 DAYS
 X SCALE (1.00000 FT)
 Y SCALE (1.00000 FT)
 CONCENTRATION (1.00000 MG/L)

	X	75	150	225	300	375	450	525	600	675	750
Y 0	0	0	0	0	0	0	0	0	0	0	0
375	1	1	1	1	1	1	0	0	0	0	0
300	7	7	7	6	5	3	2	1	1	0	0
225	31	32	30	24	18	12	8	5	3	1	1
150	115	113	92	67	45	29	17	10	5	3	1
75	-1	295	166	103	64	39	23	13	7	3	1
0	115	113	92	67	45	29	17	10	5	3	1
-75	31	32	30	24	18	12	8	5	3	1	1
-150	7	7	7	6	5	3	2	1	1	0	0
-225	1	1	1	1	1	1	0	0	0	0	0
-300	0	0	0	0	0	0	0	0	0	0	0
-375											

WORST APPROXIMATION = +- 209. %
 1 SOURCE(S) SHOWN AS "-1".

COMMAND?

SANDSTONE

Thickness (m) = 28 Ft.
Porosity (n) = .25
Velocity (v) = 28 Ft/day

Dispersion:

$$D_x = 75 \text{ Ft}^2/\text{day}$$

$$D_y = 15 \text{ Ft}^2/\text{day}$$

Retardation (Rd) = 1

Volume Flow Rate = 225 Ft³/day

Source Concentration (Co) = 100 mg/l

Mass Flow Rate (Q_{Co}) = (22,500 Ft³/day)(100mg/l)

$$\text{OR } 6.23 \times 10^{-5} \text{ Lb/day}$$

X_D = 2.67 FT Where X_D = D_x/v = 75 Ft²/day/28 FT/day = 2.67 Ft

T_D = 8.3 x 10⁻⁴ Where T_D = Rd D_x/v² = (1)(75)/(2.67)² = 7.17 days

Q_D = 234.8 Ft³/day Where Q_D = nm D_x D_y =

$$(.25)(28)(75)(15) = 234.8 \text{ Ft}^3/\text{day}$$

Application 1: Solve for concentration when distance (X) = 750 Ft
and time equals infinity (steady state).

Plot the following on the nomograph:

A: X/X_D = 750Ft/2.67 Ft = 280.9

B: t/T_D = Steady state (use steady state line)

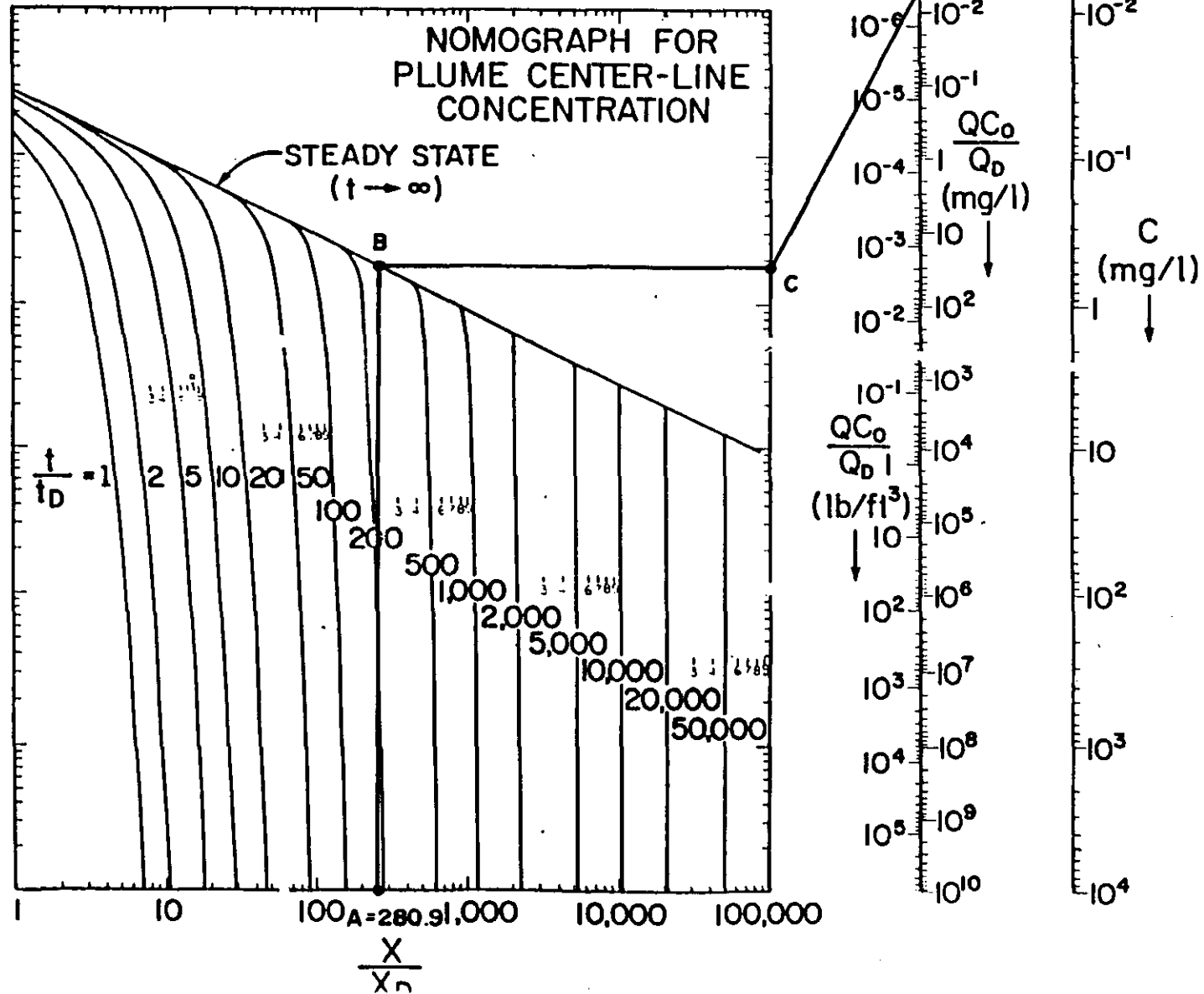
C: Intersection of line with vertical scale on right side of nomograph.

D: Q_{Co}/Q_d = 6.23 x 10⁻⁵ Lb/day/234.8 Ft³/day =

$$2.65 \times 10^{-7} \text{ Lb/Ft}^3$$

E: Read concentration directly from vertical scale for concentration (mg/l).

SANDSTONE
 APPLICATION 1: CONCENTRATION
 AT 750 FEET AND 3650 DAYS



THICKNESS = 28.0000 FT
 POROSITY = .250000
 VELOCITY = .280000 FT/D

 X DISPERSION = 75.0000 FT2/D
 Y DISPERSION = 15.0000 FT2/D

 RETARDATION = 1.00000
 DECAY GAMMA = 1.00000

X LOCATION (FT) .000000
 Y LOCATION (FT) .000000
 AREA (FT2) 250000.
 START TIME (DAYS) .000000
 VOLUME FLOW RATE (FT3/D) 225.000
 SOURCE CONCENTR. (MG/L) 100.000

 SAMPLE TIME = 3650.00 DAYS
 X SCALE (1.00000 FT)
 Y SCALE (1.00000 FT)
 CONCENTRATION (1.00000 MG/L)

Y	X	0	150	300	450	600	750	900	1050	1200	1350	1500
750	0	0	0	0	0	0	0	0	0	0	0	0
600	0	0	1	1	1	1	1	1	1	0	0	0
450	1	1	2	2	2	2	2	2	2	1	1	1
300	3	4	5	5	5	4	4	3	3	3	2	2
150	11	12	12	11	10	8	7	6	6	4	3	3
0	-1	32	21	16	13	10	8	7	7	5	4	3
-150	11	12	12	11	10	8	7	6	6	4	3	3
-300	3	4	5	5	5	4	4	3	3	3	2	2
-450	1	1	2	2	2	2	2	2	2	1	1	1
-600	0	0	1	1	1	1	1	1	1	0	0	0
-750	0	0	0	0	0	0	0	0	0	0	0	0

WORST APPROXIMATION = +- 110. %
 1 SOURCE(S) SHOWN AS "-1".

COMMAND?

T

-1 FOR STEADY STATE,
 SAMPLE TIME (DAYS) :

?

-1

COMMAND?

.IG
 SANDSTONES

FRACTURED CARBONATE

Thickness (m) = 28 Ft.
Porosity (n) = .4
Velocity (v) = 28 Ft/day

Dispersion

$$D_x = 80 \text{ Ft}^2/\text{day}$$

$$D_y = 10 \text{ Ft}^2/\text{day}$$

Retardation (Rd) = 1

Volume Flow Rate = 225 Ft³/day

Source Concentration (Co) = 100 mg/l

Mass Flow Rate (Q_{Co}) = (22,500 Ft³/day) (100mg/l)

$$\text{OR } 6.23 \times 10^{-5} \text{ Lb. day.}$$

X_D = 2.86 Ft. Where X_D = D_x/V = 80 Ft²/day/28 Ft/day =
2.86 Ft.

T_D = 1.02 x 10⁻¹ Days Where T_D = Rd D_x/V² =
(1)(80)/(28)² = 1.02 x 10⁻¹

Q_D = 316.8 Ft³/day Where Q_D = nm D_x D_y =
(.4)(28) (80)(10) = 316.8

Application 1: Solve for concentration when distance (X) = 750 Ft.
and time equals infinity (steady state).

Plot the following on the nomograph:

A: $X/X_D = 750\text{Ft}/2.86\text{Ft} = 262.2$

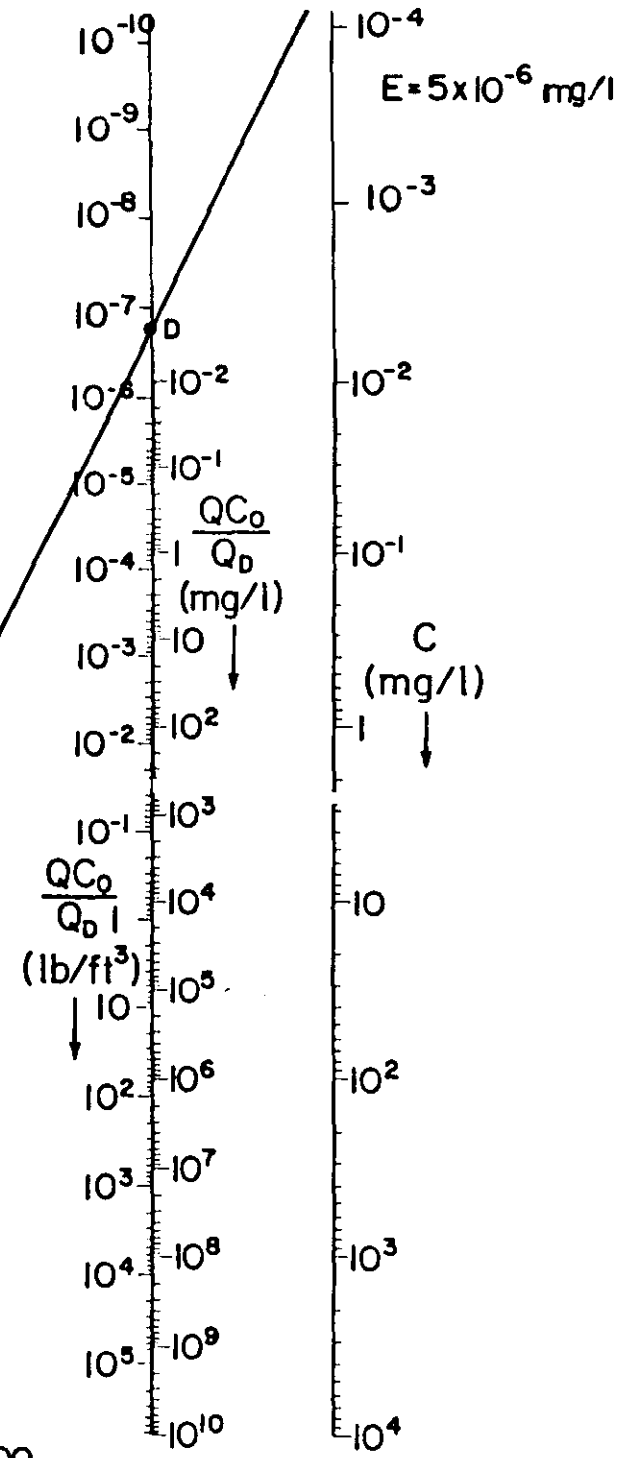
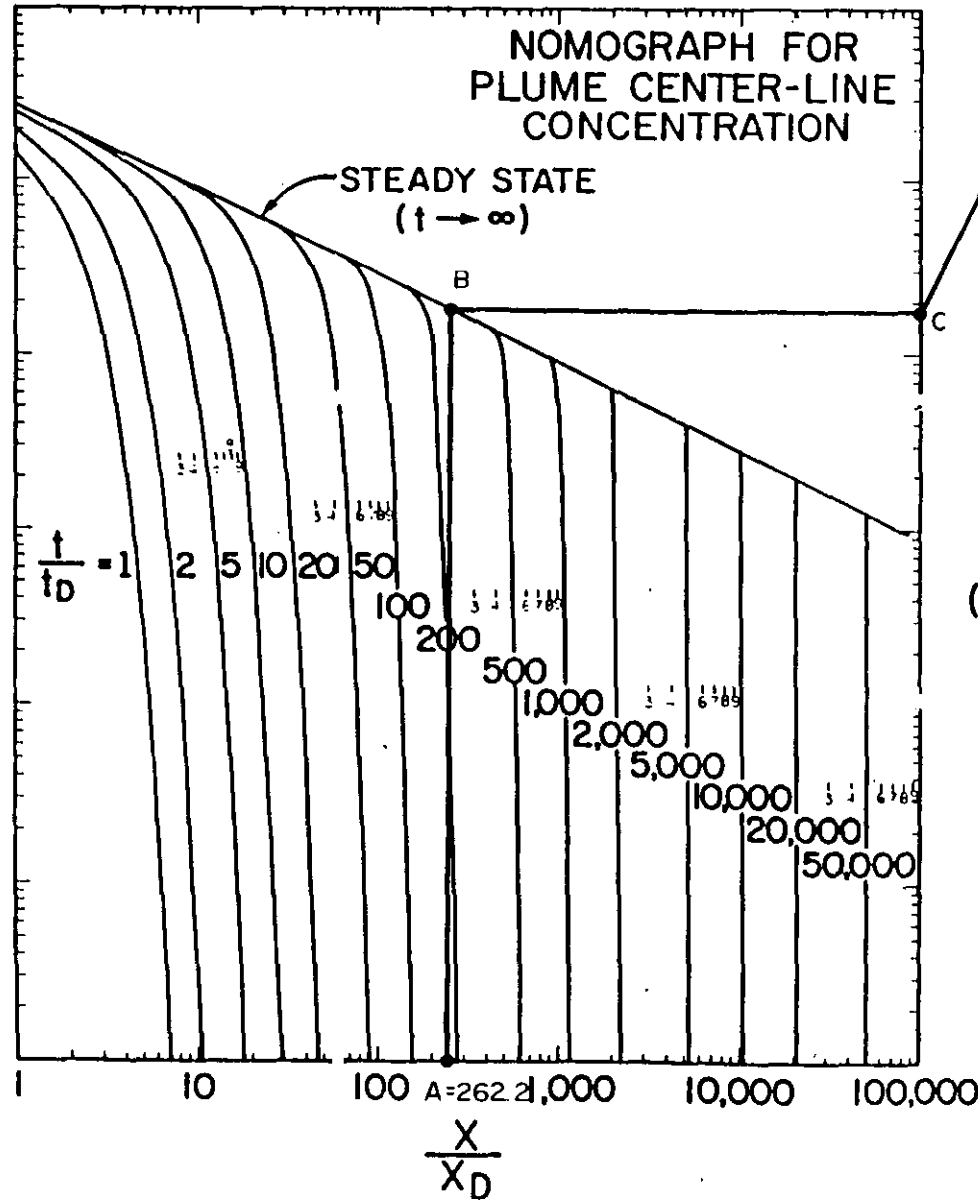
B: $t/T_D = \text{Steady State}$ (use Steady State line)

C: Intersection of line with vertical scale on right side of nomograph.

D: $Q_{Co}/Q_d = 6.23 \times 10^{-5} \text{ Lb/day} / 316.8 \text{ Ft}^3/\text{day} =$
 $1.97 \times 10^{-7} \text{ Lb./ft}^3$

E: Read concentration directly from vertical scale for concentration (mg/l).

FRACTURED CARBONATE
 APPLICATION 1: CONCENTRATION
 AT 750 FEET AND 3650 DAYS



. 16
 FRACTURED CARBONATE
 PERPENDICULAR TO GRADIENT

THICKNESS = 28.0000 FT
 POROSITY = .400000
 VELOCITY = 28.0000 FT/D
 X DISPERSION = 80.0000 FT2/D
 Y DISPERSION = 10.0000 FT2/D
 RETARDATION = 1.00000
 DECAY GAMMA = 1.00000

X	Y	AREA	START	VOLUME	SOURCE
LOCATION	LOCATION	(FT2)	TIME	FLOW RATE	CONCENTR.
(FT)	(FT)		(DAYS)	(FT3/D)	(MG/L)
.000000	.000000	250000.	.000000	225.000	100.000

SAMPLE TIME = 3650.00 DAYS
 X SCALE (1.00000 FT)
 Y SCALE (1.00000 FT)
 CONCENTRATION (1.00000 MG/L)

Y	X	75	150	225	300	375	450	525	600	675	750
375	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0
0	-1	4	3	2	2	2	2	1	1	1	1
-75	0	0	0	0	0	0	0	0	0	0	0
-150	0	0	0	0	0	0	0	0	0	0	0
-225	0	0	0	0	0	0	0	0	0	0	0
-300	0	0	0	0	0	0	0	0	0	0	0
-375	0	0	0	0	0	0	0	0	0	0	0

WORST APPROXIMATION = +- .210E+05%.
 1 SOURCE(S) SHOWN AS "-1".

COMMAND?

UNCONSOLIDATED SAND

Thickness (m) = 28 Ft.
Porosity (n) = .4
Velocity (v) = 2.8 Ft/day

Dispersion:

$$D_x = 75 \text{ Ft/day}$$

$$D_y = 15 \text{ Ft/day}$$

$$\text{Retardation (Rd)} = 1$$

$$\text{Volume Flow Rate} = 225 \text{ Ft}^3/\text{day}$$

$$\text{Source Concentration (Co)} = 100 \text{ mg/l}$$

$$\text{Mass Flow Rate (Q}_{CO}) = (22,500 \text{ Ft}^3/\text{day})(100 \text{ mg/l}) \text{ OR}$$
$$6.23 \times 10^{-5} \text{ Lb/day}$$

$$X_D = 26.8 \text{ Ft} \quad \text{Where } D_x/V = 75/2.8 = 26.8 \text{ Ft}$$

$$T_D = 9.6 \text{ Days} \quad \text{Where } T_D = (Rd)(D_x)/V^2 = (1)(75)/(2.8)^2 =$$
$$9.6 \text{ Days}$$

$$Q_D = 375.7 \text{ Ft}^3/\text{day} \quad \text{Where } Q_D = nm \ D_x \ D_y =$$
$$(.4)(28) \ (75)(15) = 375.7 \text{ Ft}^3/\text{day}$$

Application 1: Solve for concentration when distance (X) = 750 Ft.
and time equals infinity (steady state).

Plot the following on the nomograph:

A: $X/X_D = 750 \text{ Ft}/ 26.8 \text{ Ft} = 27.99$

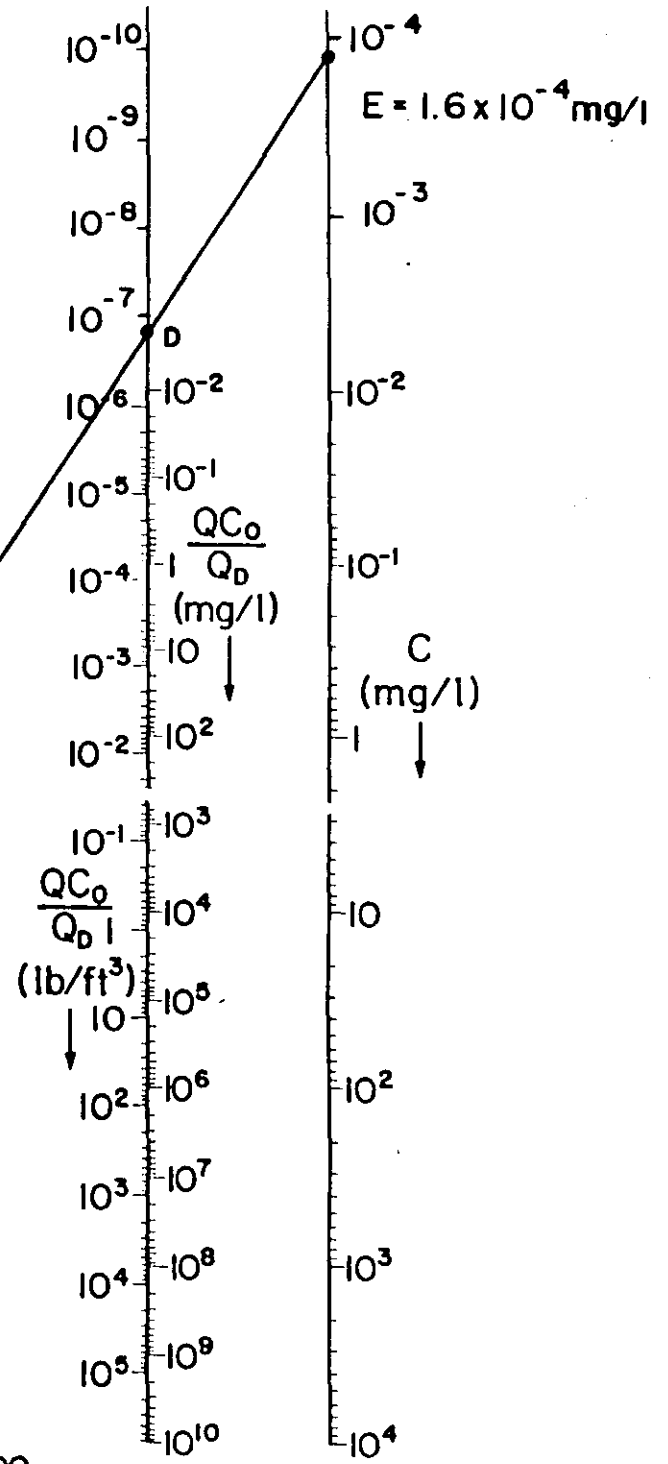
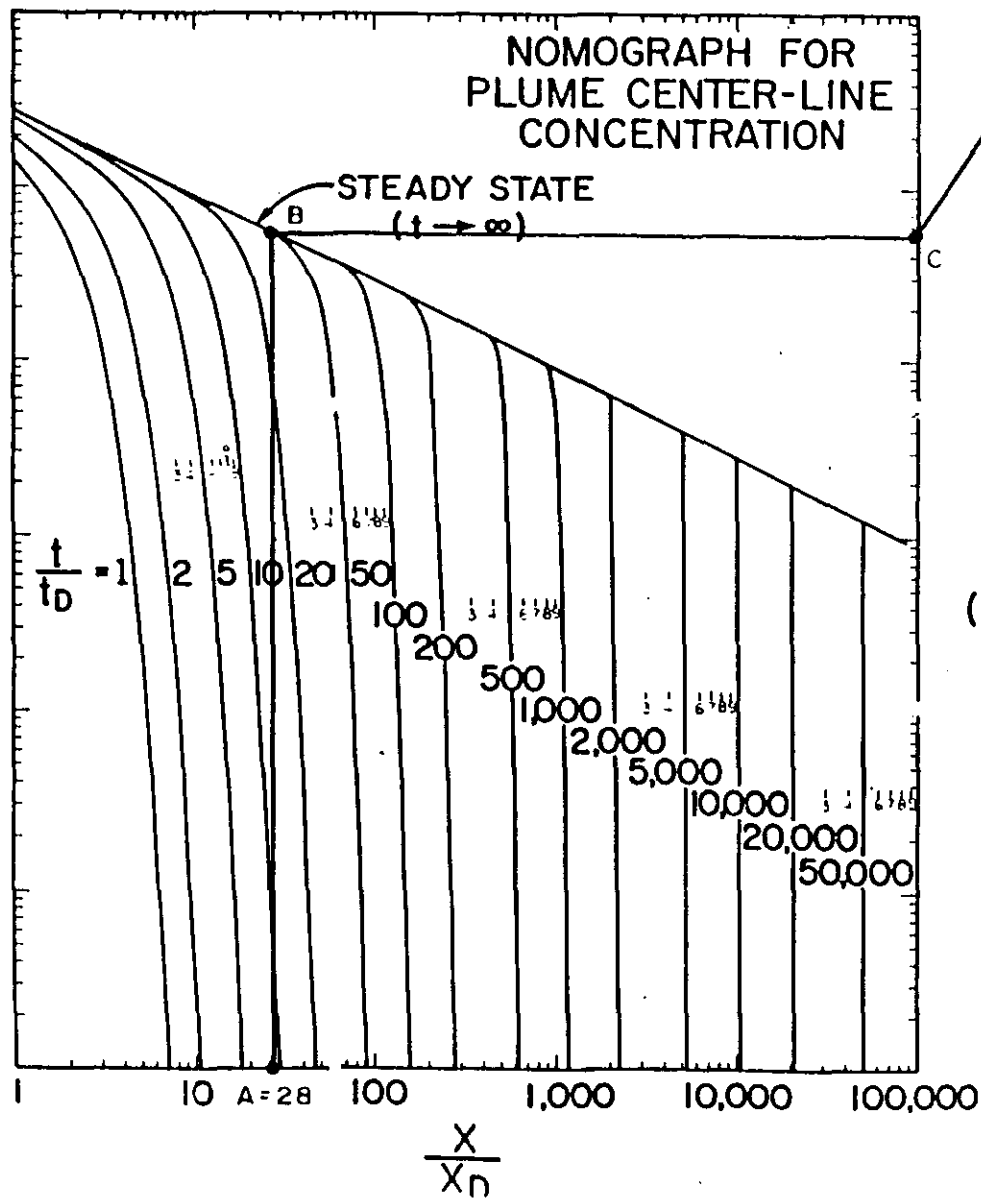
B: $t/T_D = \text{Steady state (use steady state line)}$

C: Intersection of line with vertical scale on right side of nomograph.

D: $Q_{CO} / Q_D = 6.23 \times 10^{-5} \text{ Lb/day}/ 375.7 \text{ Ft}^3/\text{day} =$
$$1.66 \times 10^{-7} \text{ Lb/ft}^3$$

E: Read concentration directly from vertical scale for concentration (mg/l).

UNCONSOLIDATED SAND
 APPLICATION 1: CONCENTRATION
 AT 750 FEET AND 3650 DAYS



.IG
UNCONSOLIDATED SAND

THICKNESS = 28.0000 FT
 POROSITY = .400000
 VELOCITY = 2.80000 FT/D
 X DISPERSION = 75.0000 FT2/D
 Y DISPERSION = 15.0000 FT2/D
 RETARDATION = 1.00000
 DECAY GAMMA = 1.00000

X LOCATION (FT) .000000
 Y LOCATION (FT) .000000
 AREA (FT2) 250000.
 START TIME (DAYS) .000000
 VOLUME FLOW RATE (FT3/D) 225.000
 SOURCE CONCENTR. (MG/L) 100.000
 SAMPLE TIME = 3650.00 DAYS
 X SCALE (1.00000 FT)
 Y SCALE (1.00000 FT)
 CONCENTRATION (1.00000 MG/L)

Y	X	75	150	225	300	375	450	525	600	675	750
375	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	1	1	1	1
75	0	1	1	2	2	2	2	2	2	2	2
0	-1	10	7	6	5	5	4	4	4	3	3
-75	0	1	1	2	2	2	2	2	2	2	2
-150	0	0	0	0	0	0	0	1	1	1	1
-225	0	0	0	0	0	0	0	0	0	0	0
-300	0	0	0	0	0	0	0	0	0	0	0
-375	0	0	0	0	0	0	0	0	0	0	0

WORST APPROXIMATION = +- .150E+04%.
 1 SOURCE(S) SHOWN AS "-1".

COMMAND?

BOREHOLE GEOPHYSICAL COMPANIES

APPENDIX F

BOREHOLE GEOPHYSICAL COMPANIES

I. Century Geophysical Company

**Tulsa, Ok. 74115
Telephone (918) 838-9811**

**Natural Gamma
Resistance (Single Point)
Spontaneous Potential
Temperature
Fluid Resistivity
Focused Gamma-Gamma Density
Caliper (Single and 3 Arm)
Neutron-Neutron Porosity
Deviation
KUT (Potassium, Uranium and Thorium)
Sonic**

II. Dresser Atlas, Inc. P.O. Box 6504 Houston, Tx. 77265

**Resistivity Tools
Induction Electrolog
Dual Induction-Focused
Dual Laterlog
Minilog
Micro Laterolog
Proximity Minilog
Dielectric Log**

**Radioactivity Tools
Compensated Neutron Log
Compensated Densilog
Sidewall Epithermal Neutron Log
Gamma Ray-Neutron Log
Spectralog
Dual Detector Neutron Lifetime Log
PDK-100
Carbon/Oxygen Log
Multiparameter Spectroscopy Instrument
Perforating-Formation-Collar Log**

**Acoustic Tools
Borehole Compensated Acoustilog
Long Spaced BHC Acoustilog
Circumferential Acoustilog
Acoustic Cement Bond Log
Borehole Televiewer**

**Borehole Seismic Services
Synthetic Seismogram
Velocity Survey
Vertical Seismic Profile**

**III. Gearhart Industries, Inc.
P.O. Box 1258
Ft. Worth, Tx. 76101
Telephone: (817) 293-1300**

Resistivity Tools

**Induction Electric Log (IEL)
Dual Induction Log (DIL)
Big Hole Induction (BH)
Dual Laterolog (DLL)
Micro-Spherically Focussed Log (MSFL)
Microlog (MEL)
Micro-Laterolog (MLL)
Dielectric Constant Log (DCL)
Slim Hole Induction-Short Normal**

Porosity Tools

**Spectral Litho Density (SLD)
Compensated Density Log (CDL)
Compensated Neutron Log (CNS)
Sidewall Epithermal Neutron (SNL)
Borehole Compensated Sonic Log (BCS)
Long Space Sonic Log (LSS)
Slim Hole Compensated Density-Gamma Ray**

Gamma Ray Tools

**Gamma Ray Tool (GR)
Spectral Gamma Ray Tool (SGR)**

Specialty Tools

**Selective Formation Tester (SFT)
Six Arm Dipmeter
Four Electrode Dipmeter (FED)
Hard Rock Coring Tool (HRCT)
Sidewall Coring Tool (SWC)**

Logging Tools

**Gamma Ray-Neutron-OCL
Cement Bond Log/GR-N (CBL)
Pulse Echo Tool (PET)
Pulsed Neutron Log
Multi-Arm Caliper
X-Y Caliper
Radial Differential Temperature (RDT)
Temperature Log
Borehole Audio Tracer (BATS)
Freepint Indicator and Backoff System**

IV. Mineral Logging Systems, Inc.
P.O. Box 40498
Ft. Worth, Tx. 76140
Telephone: (817) 293-1777

Gamma Ray/CCL
Neutron/CCL
Gamma Ray/Neutron
Gamma Ray/Tracer
Shooting Gamma Ray
Gamma Ray/Density
Bulk Density
Compensated Density
High Resolution Density
Fluid Density
Ore Logging
Motorized Injector
Temperature
Flow Meter
Sonic Bond
Compensated Sonic
X-Y Caliper
Caliper
Fluid Resistivity
Fluid Sampler
Guard
Micro-Log
E-Log
Free Point

V. Schlumberger Well Services
5000 Gulf Freeway
P.O. Box 2175
Houston, Tx. 77001
Telephone (713) 928-4000

Resistivity Logging
Dual Induction Log
Dual Laterolog
Microspherically Focused Log
Proximity Microresistivity Logs

Porosity Analysis and Lithology Identification
Litho-Density Log
Compensated Neutron Log
Borehole-Compensated Sonic Log
Electromagnetic Propagation Log
Natural Gamma Ray Spectrometry Log
Nuclear Magnetism Log

Combination Logs and Formation Evaluations

- Dual Induction/Sonic Log
- Compensated Neutron/Litho-Density Log
- Triple Combo Log
- Cyberlook Log
- Litho-Density Quicklook Log
- Litho-Analysis Log
- Volan Log
- Global Processing
- Global Rig Log
- Global Dual Water Log
- Producibility Log
- Logs for Drilling Engineers
- Compaction Log
- Borehole Profile-Cement Volume Log
- Directional Log
- True Vertical Depth Log
- Mechanical Properties Log
- Sand Strength Analysis Log
- Frachite Log

Geology and Geophisics Logging

- Dipmeter Processing
- Dual Dipmeter Log
- Dual Dipmeter DUALDIP Processing
- Dual Dipmeter Pad-to-Pad Processing
- Cyberdip Log
- CLUSTER Processing
- GEODIP Processing
- Directional Survey
- Fracture Identificaiton Log
- Faciolog Computation
- Geocolumn Display
- Well Seismic Recording
- Vertical Seismic Profiles

Auxiliary Services

- Gamma Ray Log
- Caliper Log
- Borehole Geometry Log
- Temperature Log
- Audio Log
- Ultra-Long-Spaced Electrical Log

BOREHOLE GEOPHYSICAL TOOLS

APPENDIX G

Borehole Geophysical Logging Equipment

The range of borehole logging equipment seems very large and, as a result, very complex. This, though, need not be the case. There are relatively few general categories of borehole logging equipment with which the hydrogeologist need become aware, each of the tools will then fall into one of these general categories. Even beyond these general categories, the hydrogeologist will most often use relatively few tools. The remaining tools are for specialized uses and may not be used but a few times within the career of the hydrogeologist.

This Appendix is designed to give the reader a very general understanding of the most commonly used borehole geophysical tools. It is not designed to be exhaustive of the borehole geophysical tools at the hydrogeologist's disposal from those companies, or others, mentioned in Appendix D. The six tools to be discussed here are those found on Figure 7 of the text.

Spontaneous Potential

The Spontaneous Potential (SP) log is a record of the naturally occurring potentials in the well bore as a function of depth. This tool is used chiefly for geologic correlation, determination of bed thickness, and separating nonporous from porous rocks in shale-sandstone and shale-carbonate sequences. The recording is a relative measurement of the DC voltage in the borehole without a zero being recorded. It can be run only in open (uncased) holes that are filled with a conducting fluid, such as mud or water.

Caliper

The caliper log is a continuous profile of the borehole wall. This log illustrates the variations in borehole diameter over the length of the borehole. Calipers may be designed as one-, two-, three- or four-armed models. Each of these models has specific uses and the hydrogeologist should consult the borehole logging firm prior to ordering the specific tool to assure the most appropriate tool is provided.

Gamma Ray

Natural-gamma logs are records of the amount of natural-gamma radiation that is emitted by all rocks. The chief use of natural-gamma logs is for the identification of lithology and stratigraphic correlation in open or cased, liquid- or air-filled holes. The gamma ray log is most often used to identify the shale content of sedimentary formations. Clean sandstones and carbonates normally exhibit a low level of natural radioactivity, while the clay minerals and fine particles in shales show higher levels of radioactivity due to adsorption of the heavy radioactive elements.

Neutron

The use of the neutron log requires the arrangement of a neutron source and a detector within a borehole probe. The resulting output is generally a function of the hydrogen content of the borehole environment. These logs are used primarily for the measurement of moisture content above the water table and of

total porosity below the water table. These logs, then, are used for delineation of porous formations and determination of their porosity. They respond primarily to the amount of hydrogen present in the formation.

Gamma-Gamma (Density) Log

Gamma-gamma logs are records of the intensity of gamma radiation from a source in the probe after it is backscattered and attenuated within the borehole and surrounding rocks. Most of the photons scattered in the formation are rescattered and lost, but some are scattered back to the tool detector. Therefore, the more electrons there are available to scatter gamma photons, the less the number of photons that get back to the detector. The density of electrons in a material is very nearly proportional to the bulk or mass density of the materials, and thus, the counting rate is a function of the mass density of the formation.

Resistivity

Electrical resistance is the ratio of the voltage drop, or potential gradient, produced by a flow of current to that current. In other words, it is the resistance to the flow of electrical current through a medium. In geophysics it is the resistance to the flow of current through the pore spaces in the rock of a formation. Since the pore spaces are typically filled with water solution, the resistance can be used to determine the amount of pore space in a rock.