#24

THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCE

INTERPRETATION OF BOREHOLE GEOPHYSICAL LOGS IN SHALLOW CARBONATE ENVIRONMENTS AND THEIR APPLICATION TO GROUND WATER RESOURCES INVESTIGATIONS

by

THOMAS KWADER

A Dissertation submitted to the
Department of Geology
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Approved:

Professor Directing Dissertation

December, 1982

INTERPRETATION OF BOREHOLE GEOPHYSICAL LOGS IN SHALLOW CARBONATE ENVIRONMENTS AND THEIR APPLICATION TO GROUND WATER RESOURCES INVESTIGATIONS

(Publication No. _____)

Thomas Kwader
The Florida State University, 1982

Major Professor: James Bryant Cowart, Ph.D.

Borehole geophysical logs were run in numerous core test holes from a wide variety of near-surface, freshwater, Tertiary-carbonate environments in order to determine their application to hydrogeologic investigations. Log interpretation principles traditionally applied to saline-granular systems, were applicable, in almost all cases to the logs run in freshwater-carbonate environments. Porosity and resistivity logs were effectively used to determine lithology, water quality and water transmitting properties of freshwater carbonate and granular (quartz sand) aquifer systems. Lithologic and porosity determinations for limestones, dolomites and quartz sands were obtained by cross plotting data obtained from neutron and density logs. Formation pore water resistivity (R_W) was accurately determined by cross plotting porosity and saturated formation resistivity (R_O) over a wide range of values. Once R_W was determined, water quality, with respect to various ion concentrations, could be reasonably inferred for a particular water mass. Major ion concentrations are highly correlative to R_W in both granular and carbonate aquifers. Resistivity-porosity cross plots (RPCP) were also used to delineate water masses and water quality changes in

small diameter test holes.

In freshwater environments formation permeability appeared to be related to formation resistivity (F, $F = R_o/R_w$). Electrical current, in freshwater environments, is conducted primarily along the grain-matrix interface (surface conductance) rather than directly through the saturating fluid (electrolylic conductance) as is usually the case in petroleum exploration procedures. Formations of high resistivity, characteristically, are composed of well sorted, large, uniform grain diameters (i.e., low surface contact to pore volume ratios). Factors decreasing formation resistivity (small grain diameters, poor sorting, flatter grain shapes, increased clay content, etc.) also decrease formation permeability. This relationship has important hydrologic implications regarding the estimation of formation permeability, for the first time, without actually pumping the well tapping the aquifer.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Dr. J. B. Cowart for his guidance and patience through many long hours during the course of this study. I also wish to thank the other members of my committee, Dr. J. K. Osmond, Dr. W. F. Tanner, Dr. W. C. Parker, and Dr. W. C. Burnett for their helpful suggestions and review of the manuscript. Appreciation is also extended to J. William McCartney and James A. Stidham of the Northwest Florida Water Management District for their patience and assistance throughout this study. I am also indebted to Walt Schmidt of the Florida Bureau of Geology for many hours of discussions concerning the lithostratigraphy of Florida, Jon Arthur for providing many hours of laboratory analyses and the South and Southwest Florida Water Management Districts for contributing many geophysical logs, cores and lithologic descriptions from their Districts. A special thanks is also extended to Matilde Munoz for drafting the figures, Leslie Bell for proofreading and Linda Rowan for typing the manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES - (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - (continued)

LIST OF ILLUSTRATIONS - (continued)

LIST OF ILLUSTRATIONS - (continued)

INTRODUCTION

The purpose of this research is to develop a better understanding of information available from borehole geophysical logs commonly run in shallow wells and test holes. A more comprehensive approach to log interpretation is urgently needed by hydrogeologists charged with the responsibility of evaluating, developing and protecting the ground-water resources.

In recent years, there has been a great deal of attention focused on the environmental sciences, particularly, ground-water resources. Ground-water related topics gaining recent attention have included sink-hole developments, ground-water pollution from industrial waste sites, "mining" of ground water for irrigation in the western states, and ground-water declines associated with long-term droughts. Accompanying this attention has been the growing need for information regarding "the flow of fluids through porous media" or ground-water hydrology. Ignorance or the unwillingness to adhere to sound hydrologic principles has resulted in the degradation and/or near depletion of the ground-water resources in many areas.

The hydrogeologist, a relatively new breed of scientist, is often responsible for evaluating ground-water availability in a particular area or assessing the impact of a certain activity upon local ground-water resources. In addition to collecting cuttings and cores from water wells and shallow test holes, borehole geophysical logging has become one of the most valuable tools of the hydrogeologist for obtaining and evaluating information as related to the subsurface environment. Modern geophysical logging equipment can be used to obtain a continuous record of various

parameters within the borehole related to lithology, water quality within formations and water-transmitting characteristics of hydrogeologic units.

Geophysical logging has been extensively used in the petroleum industry for more than fifty years. Petroleum logging principles and interpretations have been documented in many volumes. However, logging of small diameter shallow water wells and test holes for the purpose of collecting hydrogeologic information is a relatively new field. Logging of shallow holes advanced in the early 1970's when the "age of micro-electronics" made it technically practical and economically feasible to develop small, lightweight, probes and equipment. It was soon realized that many of the principles and interpretations of deep well logs, as used in the petroleum industry, were not applicable to shallow near-surface environments. Many shallow logs are difficult to interpret and in some cases responded differently than expected. These deviations are attributed to the shallow sediments being less compact, having a greater degree of secondary porosity, lower temperatures, and higher pore fluid resistivities.

In many areas, such as gently rolling to flat lying topographies, geophysical logs provide the only method of obtaining information on subsurface formations. Although cores and well cuttings are valuable for discerning lithology, a complete suite of logs complement this data by providing information on pore water quality, permeability, porosity, bulk density, formation resistivity, cementation and clay content. Well cuttings provide useful lithologic information but have limitations since they represent only point samples and are subject to contamination due to density setting during circulation in the borehole. Clays for example,

if present, are usually poorly preserved in most sets of well cuttings. Cuttings seldom reveal the degree of secondary porosity which is extremely valuable information to the hydrogeologist. Geophysical logs, on the other hand, provide a continuous record of borehole parameters relating to facies changes, vertical gradations and the nature of contacts at exact depths. Geophysical logs also provide the most reliable method of lithostratigraphic correlation over wide areas.

This research is the first attempt to evaluate the usefulness of geophysical logs collected over a wide range of Tertiary sediments, and presents the data in a semi-quantitative manner based upon known lithologies determined from cores and complete sets of well cuttings. This research is centered around the three key areas of concern to hydrogeologists: 1) determining the type of lithology in the subsurface; 2) evaluating the water quality residing in the pore spaces of the producing zones; and 3) assessing water transmitting properties of formations in small diameter test holes.

Although many types of geophysical logs are available, measuring a wide variety of parameters, none of the probes are able to directly determine any of the hydrogeologic characteristics mentioned above. In many instances, the information of interest can be strongly inferred by cross plotting geophysical data obtained (such as formation resistivity, porosity, bulk density, acoustic velocity, natural gamma radiation, etc.) in such a manner that the characteristics of the desired parameter can be determined. Another way of describing the cross plotting technique is to imagine the information desired occupies a specific area inside a three-dimensional polygon. Each of the corners represents a physical characteristic of the parameter desired. If a value can be obtained for each end

point, the desired parameter will be located where all of the lines intersect at a unique point inside of the polygon.

Geophysical logging involves the recording and interpretation of a wide variety of physical parameters and it is assumed that the reader has some knowledge of geophysical logging. Basic concepts are only briefly discussed in this text. The reader will be referred to numerous articles discussing widely accepted principles, logging theory, radiation statistics, instrumentation, and applications throughout the course of the text.

Many of the results and conclusions from this research were empirically derived by observing numerous log patterns over large areas involving various types of logs in order to infer hydrogeologic relationships. In addition to this being a study of geophysical logs in near-surface environments this is the first time the study of log responses in various types of Tertiary carbonates has been documented. Most log interpretation principles in the literature deal with clean, uniform granular type materials in thick sections. Carbonates, on the other hand, (especially Tertiary carbonates) often exhibit an extremely wide range of porosity, permeability and cementation commonly observed over extremely short vertical sections. Several observations, from the shallow test holes logged, are inconsistent with those documented in the petroleum literature and have merely been identified and need further attention.

The study area for this research is not rigorously defined in an areal sense, but includes a wide range of carbonate and unconsolidated quartz sands and gravels deposited on the Floridan Platform and adjacent

shelf areas. This research began by studying a number of cores supplemented by a fairly comprehensive suite of logs available in, a relatively small geographic area, the Apalachicola Embayment of Northwest Florida, (Figure 1). These cores penetrate a wide range of lithologic types. After a working hypotheses of the log signatures, correlative to the cores were developed, these hypotheses were tested in other locations of Tertiary sedimentary environments where cores and complete sets of cuttings were also available. Hypotheses concerning the determination of pore water quality, using geophysical logs, were also tested in both granular and carbonate aquifers (Figure 2). Well locations and descriptions are available in Appendix P.

Whenever possible, log measurements were compared to laboratory tests (porosity, permeability and bulk density) obtained from cores on the same test hole. Other analyses of core material were performed using x-ray diffraction, gamma spectrometry and observations under a low powered binocular microscope. Aquifer and flowmeter tests were run in a number of wells in an attempt to correlate water transmitting characteristics of hydrologic zones to permeability as inferred from the logs.

Figure 1.--Location map of wells and test holes where cuttings and cores were obtained for use in this study. See Appendix P for well location and complete well data.

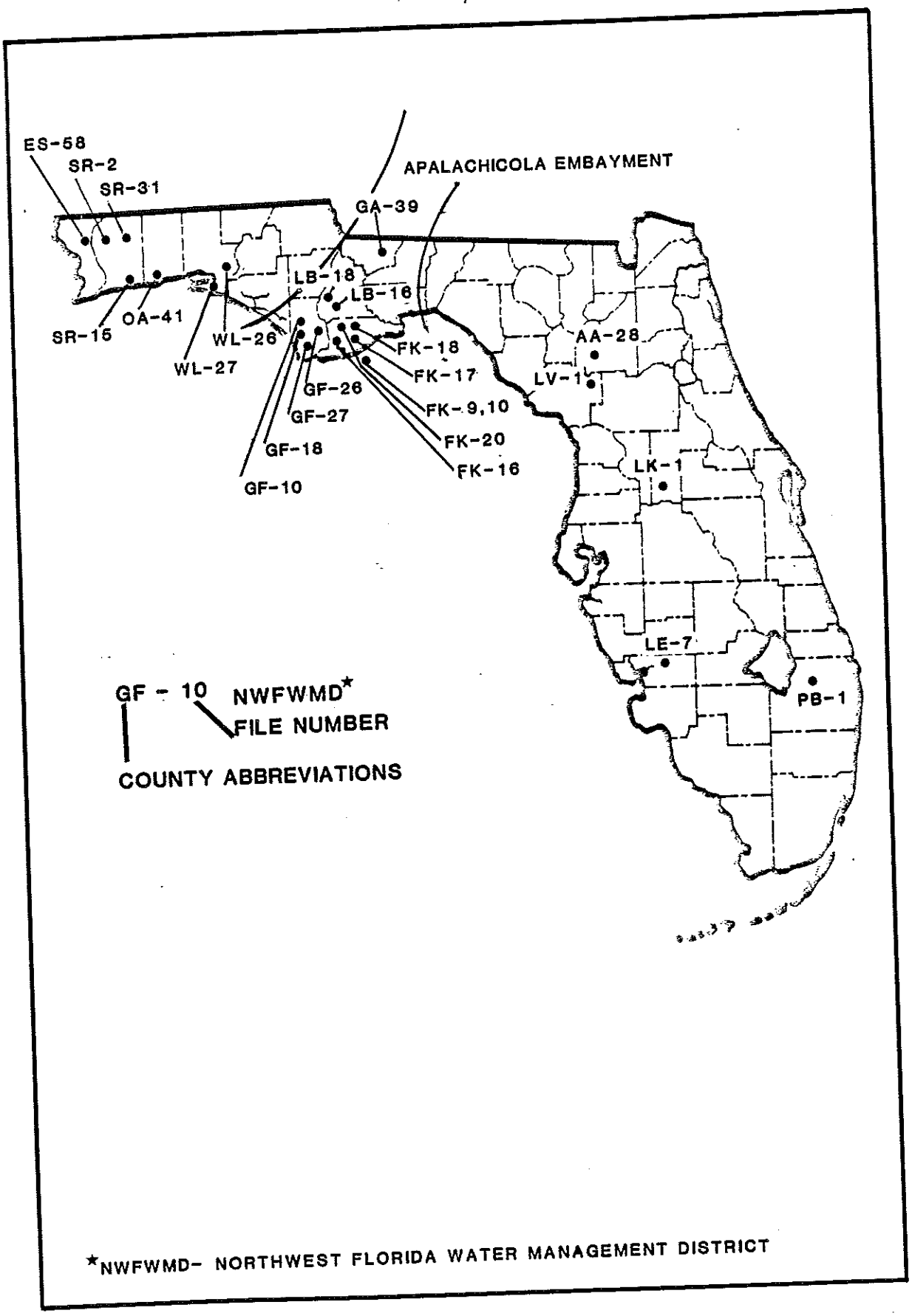
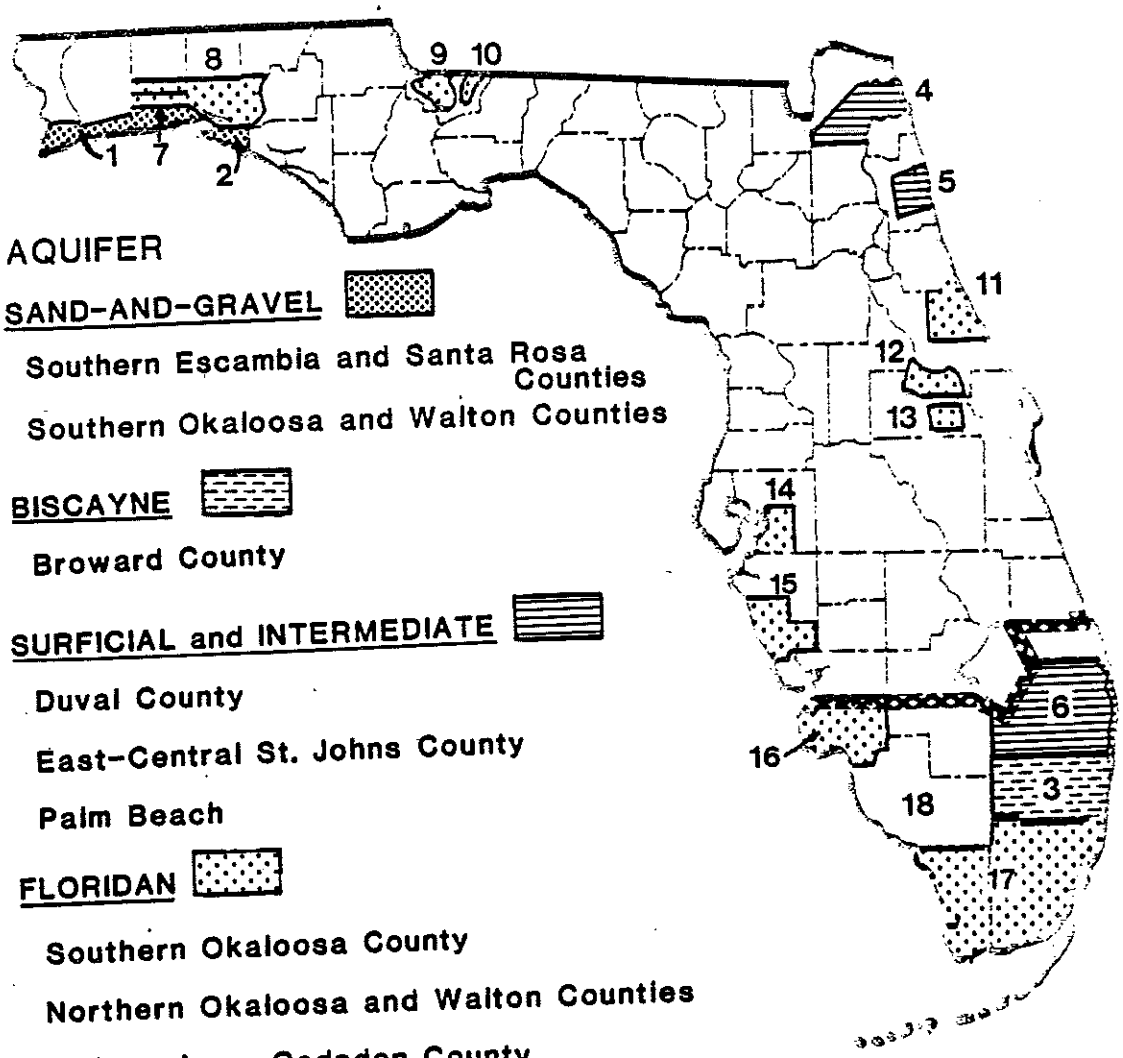

ES-58
SR-2
SR-31
APALACHICOLA EMBAYMENT
GA-39
LB-18
LB-16
SR-15
OA-41
WL-26
WL-27
FK-18
FK-17
FK-9,10
FK-20
FK-16
GF-26
GF-27
GF-18
GF-10
AA-28
LV-1
LK-1
LE-7
PB-1
GF - 10 NWFWMD*
FILE NUMBER
COUNTY ABBREVIATIONS
*NWFWMD- NORTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Figure 2.--Location map of wells used in this study for water quality determinations from logs.



MAP No. AQUIFER

SAND-AND-GRAVEL

1 Southern Escambia and Santa Rosa Counties

2 Southern Okaloosa and Walton Counties

BISCAYNE

3 Broward County

SURFICIAL and INTERMEDIATE

4 Duval County

5 East-Central St. Johns County

6 Palm Beach

FLORIDAN

7 Southern Okaloosa County

8 Northern Okaloosa and Walton Counties

9 Quincy Area, Gadsden County

10 Havana Area, Gadsden County

11 Northeastern Volusia County

12 Seminole County

13 Southeastern Orange County

14 Southwestern Hillsborough County

15 Sarasota County

16 Lee County

17 Monroe County and Dade Counties

DEEP CARBONATES

18 St. Lucie, Martin, Palm Beach, Broward, Dade, Monroe, Hendry and Lee Counties

PREVIOUS STUDIES UTILIZING GEOPHYSICAL LOGS AS AN AID TO GROUND-WATER INVESTIGATIONS

The first papers addressing the interpretation of geophysical logs in water wells were published in the early 1950's and primarily discussed water quality as determined from electric logs in unconsolidated sands (Jones and Buford, 1951; Pryor, 1956). In the early to mid-1960's, geophysical logging of wells was still a cumbersome and very expensive way of obtaining information from water wells. A few articles alluded to the advent of geophysics to the water well industry and how logs could aid the water well contractor. In addition to electric logs, natural gamma logs were being run for the first time in water wells to aid in determining lithology in cased boreholes. Most articles were very short and generalized.

In 1966, Alger and Turcan independently published two of the first papers addressing water quality using electric logs. Although the principles they applied were simply an extension of relationships used in the petroleum industry for many decades these applications provided a method for approximating pore water quality without actually pumping producing zones penetrated by test holes.

Since the early 1970's, about the time when modern water well logging equipment generally became available, the density, porosity, acoustic velocity and normal electric logs were added to the more sophisticated hydrogeologic geophysical programs. The addition of these probes greatly enhanced the information available from boreholes, but little was known on the response of these probes in freshwater aquifer

systems. Articles pertaining to water wells and shallow test holes since the mid 1970's have generally been site specific discussing complete suites of logs usually from a single borehole. These articles are generally more technical and most commonly appear in the U. S. Geological Survey Professional or Water Supply Papers.

Croft's classic paper (1971) reported that the normal electric log, in freshwater environments, may be partially influenced by the geometry of the packing of granular materials. Croft also recognized that resistivity may be used to infer permeability if porosity and pore water resistivity are known. MacCary published two papers during the last decade (1978, 1980) which began to demonstrate the usefulness of geophysical logs in a semi-quantitative manner as an aid in hydrogeologic investigations. The earlier paper discussed, for the first time, interpretation of geophysical logs in a carbonate aquifer system rather than unconsolidated formations. The latter paper discussed the use of electric logs to map water quality trends in areas with good well control.

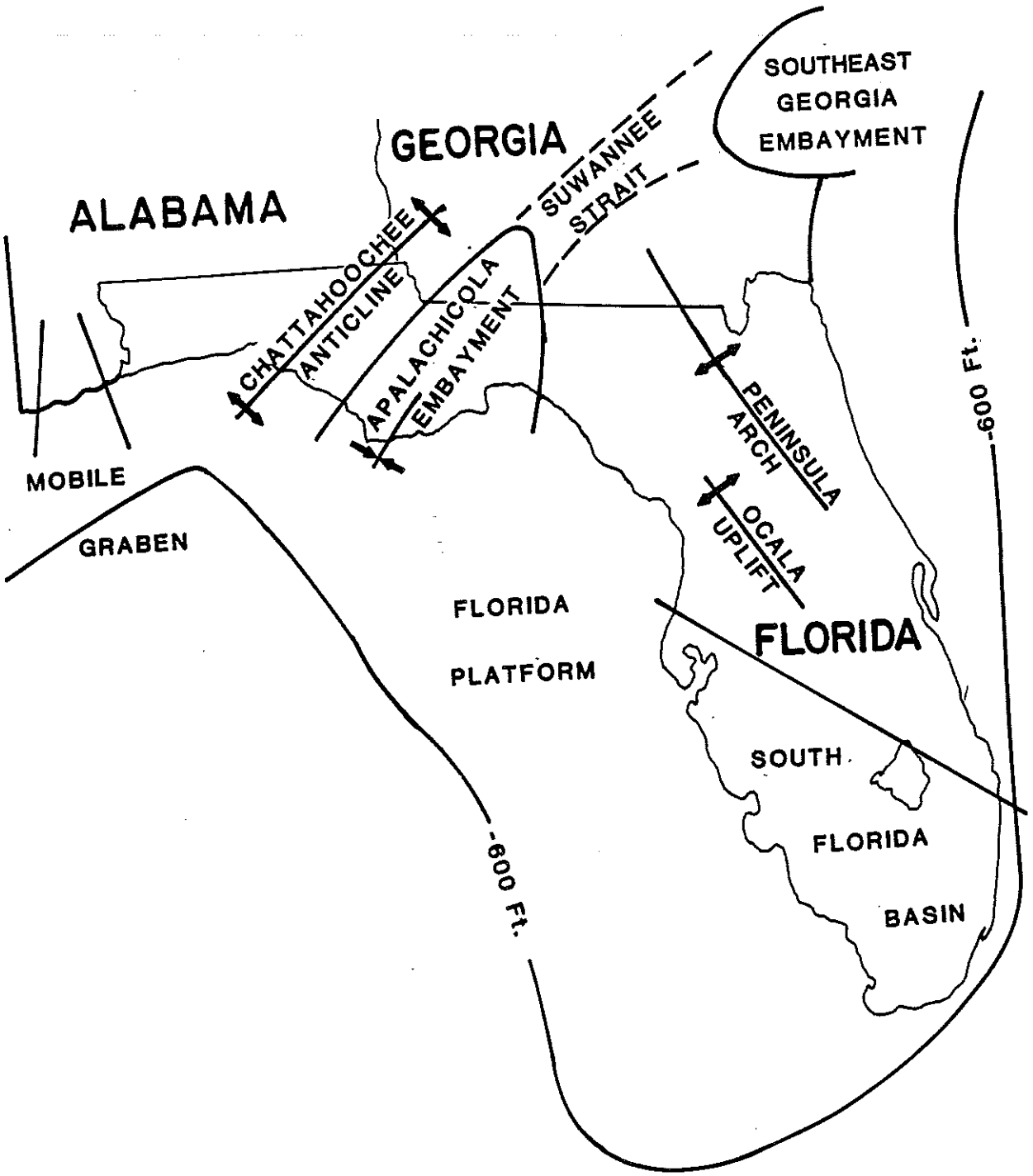
At the present time, only one text has addressed the application of borehole geophysics to water resources investigations (Keys and MacCary, 1971). Although an outstanding publication, this text is mainly concerned with logging fundamentals and the physical principles affecting the probes' response and contains a minimal amount of information on determining lithology from geophysical logs.

DEPOSITIONAL HISTORY OF HYDROGEOLOGICAL UNITS IN STUDY AREA

The oldest carbonate units of hydrogeologic importance within the study area were deposited on the Florida Platform (Figure 3) during Paleocene time. This platform, which is approximately twice the width of the current peninsula of Florida, was separated from the mainland by the Suwannee Straits at least through Oligocene time. Carbonates deposited on the platform are similar to the carbonates forming today on other quite warm water restricted platforms such as the Florida Bahamas. Seawater, saturated with respect to calcium carbonate was uplifted onto the platform where gentle heating of the waters drove off carbon dioxide and caused the precipitation of relatively pure calcium-carbonate units. This environment favored the existence of numerous types of marine fauna which influenced the texture of the carbonates ultimately deposited on the platform. In some of the shallower areas of the platform, where circulation was restricted and evaporation exceptionally high, the waters became supersaturated causing many evaporates and sulfates to be deposited. In these restricted basins very few fauna could tolerate the high salinities which may account for the scarcity of fossils in these zones (Sweeney and Windham, 1979).

On the west and northwestern margin of the Suwannee Straits calcareous units were also being deposited during Paleocene and Eocene time. These formations were dominated by a greater clastic fraction and characteristically contain more argillaceous and silty material than their southern counterparts.

Figure 3.--Major structural features affecting the regional hydrogeology of the Southeastern Coastal Plain.

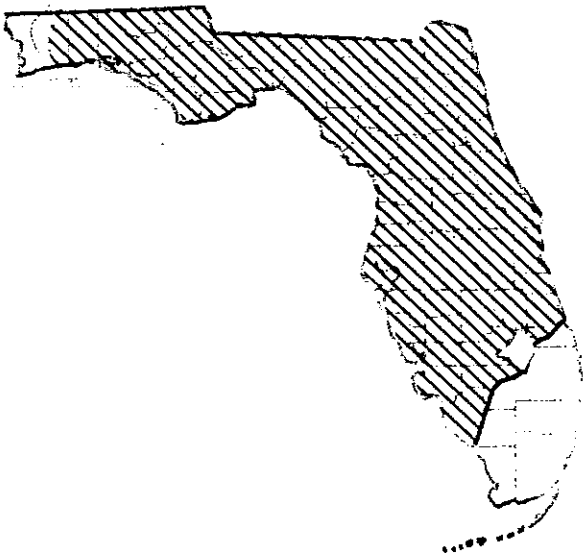

SOUTHEAST
GEORGIA
EMBAYMENT
GEORGIA
SUWANNEE
STRAIT
ALABAMA
CHATTAHOOCHEE
ANTICLINE
APALACHICOLA
EMBAYMENT
PENINSULA
ARCH
-600 Ft.
MOBILE
GRABEN
OCALA
UPLIFT
FLORIDA
PLATFORM
FLORIDA
SOUTH
FLORIDA
BASIN
-600 Ft.

During the closing of the Suwannee Straits, longshore currents transported fine quartz sand southward along the Gulf coast which interfingered and mixed with the deposition of the carbonate units. Closing of the Straits enabled a much more diverse assemblage of material to be transported on to the relatively "pure" carbonate platform. In addition to the new source areas constant sea level fluctuations created complex lithologic interfingering and facies changes involving numerous mineral types. Dominant lithologies deposited adjacent to the platform include quartz sands, silts, marls, clays (montmorillonite, palygorskite and kaolinite), phosphates, limestones, and dolomites. Many of the later formations are believed to have been reworked and redeposited during Upper Miocene time. The Hawthorn Formation exemplifies this assemblage and has often been referred to as a dumping ground for alluvial terrestrial, marine, deltaic and prodeltaic beds of diverse lithology (Scott and MacGill, 1981).

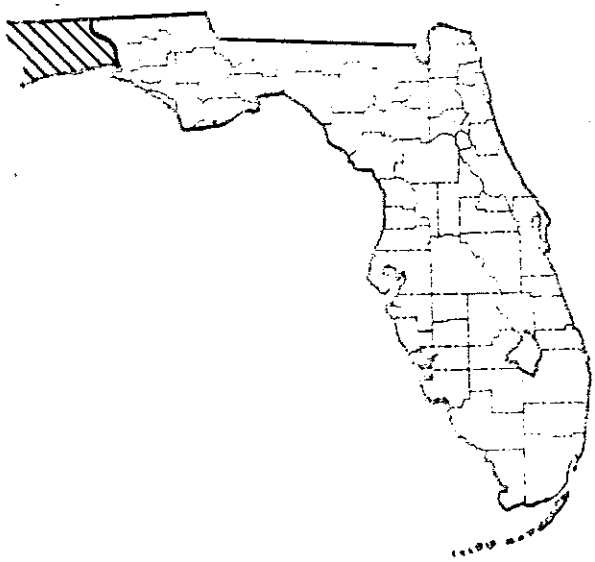
Major Aquifers In The Study Area

Florida is highly dependent upon ground water as a source for potable drinking supplies. Currently, over 95 percent of Florida's population derives their drinking water from four major aquifer systems. These four aquifer systems are composed primarily of carbonates and quartz sands ranging in age from Upper Paleocene to Pleistocene (Figure 4). Of the four major aquifers, the Floridan aquifer is by far the most extensive and underlies most of the southeastern coastal plain of the United States. The Floridan aquifer includes carbonates ranging in age from Paleocene to approximately Middle Miocene. The other three important aquifer systems (sand-and-gravel, Biscayne and Surficial

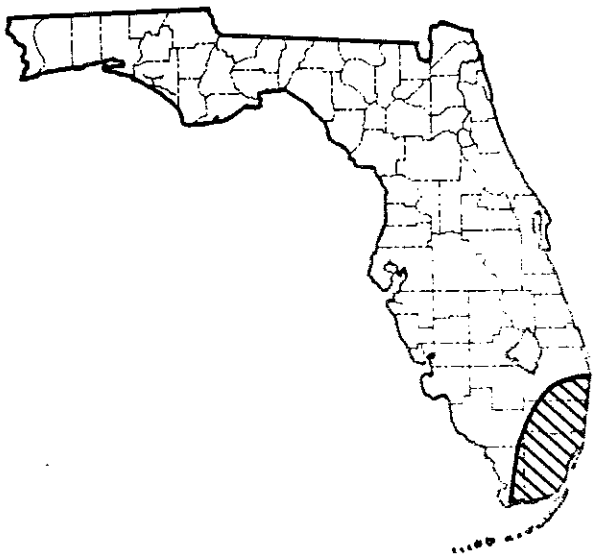
Figure 4.--Location of the four main hydrologic units containing potable water in the study area.



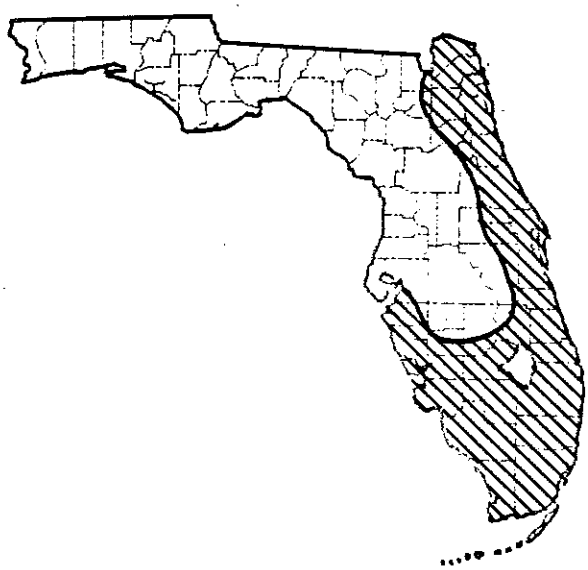
FLORIDAN AQUIFER
(LIMESTONE)



SAND AND GRAVEL AQUIFER
(QUARTZ SANDS AND GRAVELS)



BISCAYNE AQUIFER
(LIMESTONE,SAND)



SURFICIAL AND INTERMEDIATE AQUIFERS
(SAND,SHELL,LIMESTONE)

Aquifers) are comprised of deposits of quartz sands and discontinuous carbonate units ranging in age from Lower Miocene to Recent, often overlying but not hydrologically connected to the Floridan aquifer.

Floridan Aquifer

The Floridan aquifer is comprised of a thick carbonate sequence ranging in age from Upper Paleocene to Upper Miocene (Figures 4 and 5). The thickness of the Floridan aquifer ranges from less than 100 feet in the panhandle to more than 3,500 feet in southwest Florida. The elevation of the top of the aquifer ranges from 150 feet above mean sea level (in Jackson County) to more than 1,500 feet below mean sea level in the extreme western portion of the panhandle (Kwader and Schmidt, 1978).

Carbonate formations comprising important water-bearing units within the Floridan aquifer include, in ascending order, the Cedar Key, Oldsmar, Lake City, Avon Park, Ocala, Suwannee and Tampa formations. More often than not, these carbonate units are overlain by Miocene clays which inhibit direct recharge to the Floridan aquifer. In areas where these clays are absent, recharge takes place through surficial permeable sands in direct hydraulic contact with the underlying carbonate sequence. Permeability within the Floridan, both horizontal and vertical, often varies several orders of magnitude over very short distances.

Although the Floridan is the primary source of potable ground water within the State of Florida, in the extreme western panhandle and in the general area southeast of Lake Okeechobee, the dissolved mineral content of water within the Floridan exceeds the recommended safe drinking water limits and is not utilized as a potable supply (Figure 6). Water

Figure 5.--Generalized stratigraphic column and corresponding principal aquifer units in the study area. (Modified from Franks, 1982).

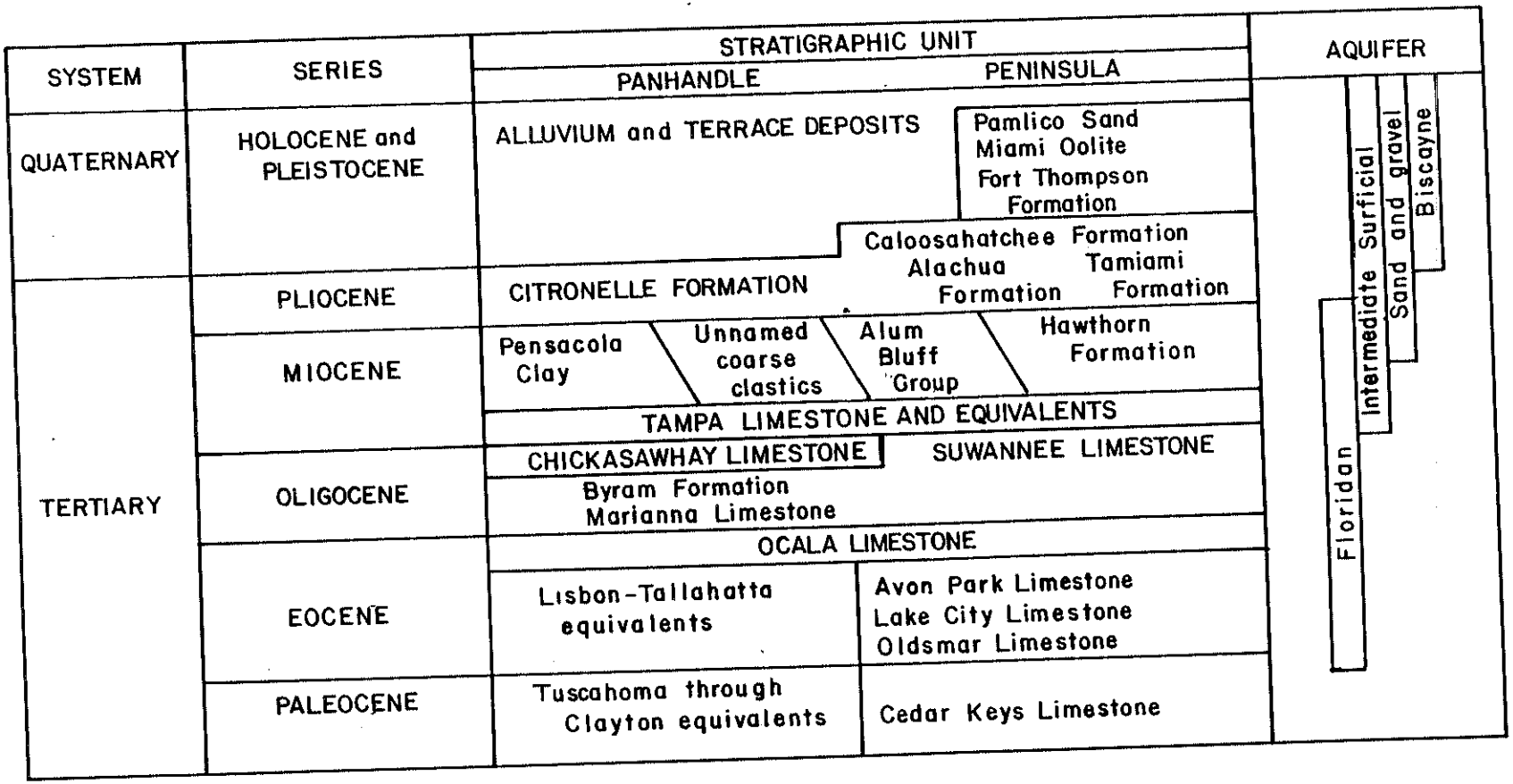
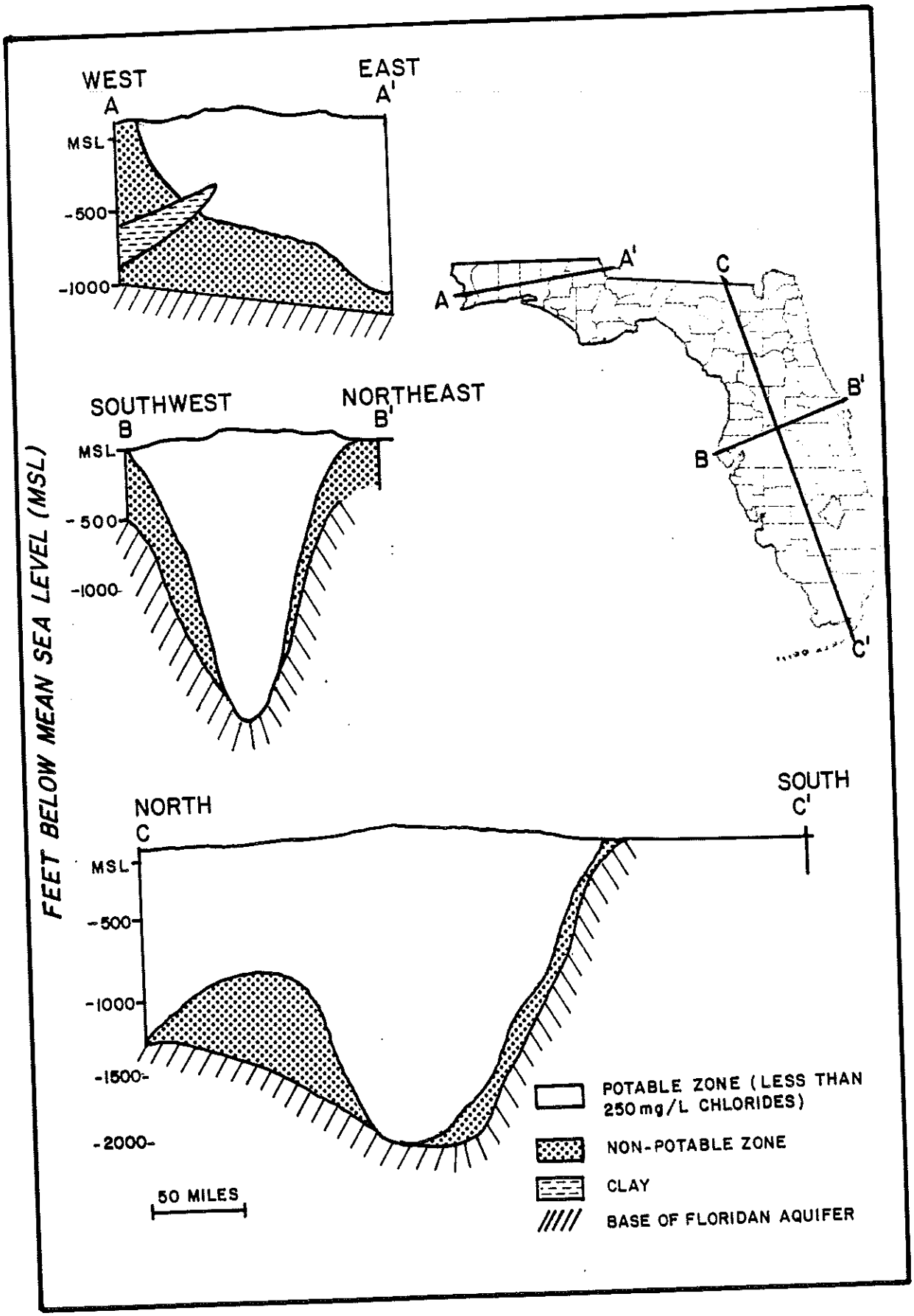

SYSTEM
SERIES
STRATIGRAPHIC UNIT
PANHANDLE
PENINSULA
AQUIFER
QUATERNARY
HOLOCENE and PLEISTOCENE
ALLUVIUM and TERRACE DEPOSITS
Pamlico Sand
Miami Oolite
Fort Thompson Formation
Caloosahatchee Formation
Alachua Formation
Tamiami Formation
TERTIARY
PLIOCENE
CITRONELLE FORMATION
MIOCENE
Pensacola Clay
Unnamed coarse clastics
Alum Bluff Group
Hawthorn Formation
TAMPA LIMESTONE AND EQUIVALENTS
CHICKASAWHAY LIMESTONE
SUWANNEE LIMESTONE
OLIGOCENE
Byram Formation
Marianna Limestone
OCALA LIMESTONE
EOCENE
Lisbon-Tallahatta equivalents
Avon Park Limestone
Lake City Limestone
Oldsmar Limestone
PALEOCENE
Tuscahoma through Clayton equivalents
Cedar Keys Limestone
Floridan
Intermediate
Surficial
Sand and gravel
Biscayne

Figure 6.--Thickness of fresh water in the Floridan aquifer through various cross sections of Florida. (Modified from Franks, 1982).


WEST
A
EAST
A'
MSL
-500
-1000
A
A'
C
B
B'
SOUTHWEST
B
NORTHEAST
B'
MSL
-500
-1000
C'
NORTH
C
SOUTH
C'
MSL
-500
-1000
-1500
-2000
50 MILES
FEET BELOW MEAN SEA LEVEL (MSL)
POTABLE ZONE (LESS THAN 250 mg/L CHLORIDES)
NON-POTABLE ZONE
CLAY
BASE OF FLORIDAN AQUIFER

quality within the Floridan is generally of a calcium-magnesium bicarbonate type, but occasionally in the coastal areas, the ground water contains a considerable amount of sodium chloride from connate or modern day sea-water intrusion. Calcium sulfate type waters are encountered in deep wells penetrating formations containing anhydrite or gypsum.

Sand-and-Gravel Aquifer

In the extreme western portion of the Florida panhandle the strata dip gently toward the southwest and ground water within the Floridan aquifer becomes more mineralized with depth (Figure 6) . Overlying the Floridan, in this area, is a thick wedge shaped deposit of coarse sands and gravels (Upper Miocene to Holocene) comprising the sand-and-gravel aquifer which provide the primary source of ground water (Figures 4 and 5). Extensive interbedding and interfingering of kaolin and illite clays render it difficult to correlate permeable units even over short distances. Stratigraphic correlation is also severely hindered by the scarcity of fossils in both the clays and coarse clastics. Thickness of the sand-and-gravel aquifer ranges from a feather edge in central Walton County to more than 800 feet in northern Escambia County. Clay content generally increases toward the southwest where clay becomes the dominant lithology with fewer and thinner interbedded sand lenses.

Water quality within the sand-and-gravel aquifer is generally excellent due to the relative insolubility of the quartz sands. In this area iron (Fe^{+2},Fe^{+3}), more often than chloride, renders the water unfit for human consumption.

Biscayne Aquifer

In the highly populated area of southeast Florida, the sole source of potable ground water is from the shallow Biscayne aquifer (Figures 4 and 5). The Biscayne aquifer ranges in thickness from land surface to 240 feet in the coastal area and thins to a feather edge toward the western interior of the peninsula. Lithologically, the Biscayne is comprised of limestone (and oolite) in the south and grades to a sandstone and unconsolidated sand, north and eastward. Recharge is directly from local rainfall which dissolves the upper portion of the aquifer and greatly enhances the permeability. Some wells are reported to yield 7,000 gallons per minute with very little drawdown.

Water quality is generally very good, but deteriorates with depth and toward the coastal area since the aquifer is under water table conditions and occasionally intruded by saltwater.

Surficial and Intermediate Aquifers

All of the unconsolidated water-bearing units at land surface not included in the Floridan, sand-and-gravel, or Biscayne aquifers, have been categorized together and jointly named the Surficial and Intermediate aquifers (Figures 4 and 5). These aquifers are generally composed of sands, shells, limestones and dolomites not hydrologically connected to the underlying Floridan aquifer.

The Surficial aquifers are generally comprised of sands, oolites and poorly consolidated limestones under water-table conditions. Underlying the Surficial aquifers in many areas is another water-bearing unit, the "Intermediate aquifer", which is not in hydrologic connection with the overlying Surficial aquifer or underlying Floridan aquifer. Occasionally, this unit is referred to as the "secondary

artesian" or "semi-artesian unit". These two aquifers, the Surficial and Intermediate aquifers, are important producing aquifers along the east coast and south Florida. Thickness is generally greatest in the coast area (up to 400 feet in east-central Florida) and pinches out against the central peninsula highlands.

Since these aquifers are usually under water-table conditions, water quality generally deteriorates along the coastal areas and with increasing depth. Hardness (due to calcium and magnesium) increases in portions of the aquifer where limestones, oolites and dolomites are dissolved by the percolating waters.

RELATIONSHIP OF GEOLOGIC FORMATIONS TO HYDROGEOLOGIC UNITS

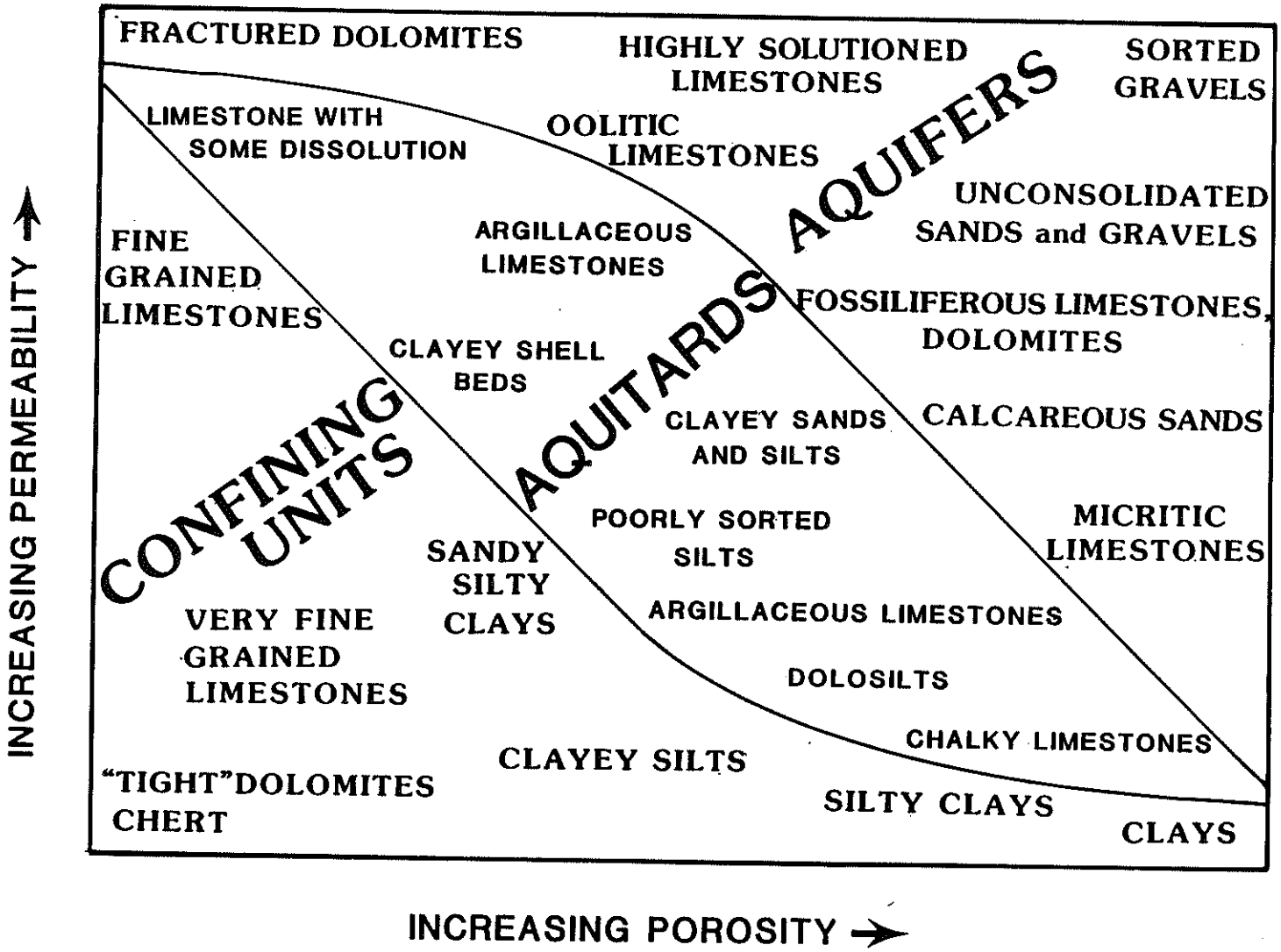
Geologically, formations are generally classified as one of two types; 1) lithostratigraphic units - which exhibit a similar lithology and texture over a large geographic area; or 2) biostratigraphic (time-stratigraphic) units - which are based upon a particular type index fossil or fossil assemblage contained in the rock unit. Since these fauna may have a wide areal distribution these fossils are frequently found in many types of environments (especially planktonic type foraminifera) and are relatively independent of the lithology. Most of the formation names in Florida are based upon biostratigraphic zonations. Although this scheme has as aided statigraphers to correlate units throughout the state, the hydrogeologic (equivalent to hydrostratigraphic) units more closely parallel lithostratigraphic units and thus are often independent of formational identity.

A hydrogeologist sub-divides a geologic column based upon the water transmitting characteristics of a particular unit (aquifers, aquicludes and confining beds). Thickness of the hydrogeologic unit is determined by the degree of hydrologic connection and variation between the units. A carbonate may act hydrologically, as an aquifer, aquiclude or confining bed depending upon the texture of the original matrix and degree of secondary porosity development. A tight crystalline dolomite may act as a confining bed or as a highly productive aquifer depending upon the presence of fracture porosity. "Pure" calcium-carbonate limestones may be excellent aquifers (as in vuggy and cavernous material) or transmit water

very slowly (chalky limestones) depending upon the degree of secondary porosity. Figure 7 is an illustration showing the relationship between hydrogeologic units and various lithologic materials.

The origin of dolomite, as to whether or not most dolomite is primary or a secondary alteration product of original limestone units, is still a subject of great debate. Recent studies conducted on dolomites in Florida seem to strongly suggest that most dolomite results from the alteration of original limestone units. Limestones may be altered at a freshwater-saltwater interface migrating in accordance with sea level fluctuations and freshwater head changes in the aquifer (Fanning et. al 1981, Hanshaw, et. al, 1971, Bloom, 1982).

Figure 7.--Permeability vs. porosity for different types of hydrogeologic units and lithologies.


FRACTURED DOLOMITES
HIGHLY SOLUTIONED LIMESTONES
SORTED GRAVELS
LIMESTONE WITH SOME DISSOLUTION
OOLITIC LIMESTONES
AQUIFERS
UNCONSOLIDATED SANDS and GRAVELS
FINE GRAINED LIMESTONES
ARGILLACEOUS LIMESTONES
FOSSILIFEROUS LIMESTONES, DOLOMITES
CLAYEY SHELL BEDS
AQUITARDS
CONFINING UNITS
CLAYEY SANDS AND SILTS
CALCAREOUS SANDS
POORLY SORTED SILTS
MICRITIC LIMESTONES
SANDY SILTY CLAYS
ARGILLACEOUS LIMESTONES
VERY FINE GRAINED LIMESTONES
DOLOSILTS
CHALKY LIMESTONES
CLAYEY SILTS
"TIGHT"DOLOMITES CHERT
SILTY CLAYS
CLAYS
INCREASING PERMEABILITY
INCREASING POROSITY

CARBONATE POROSITY AND PERMEABILITY RELATIONSHIPS AND THEIR EFFECT ON GEOPHYSICAL LOG RESPONSES

Carbonate Porosity and Permeability

In clastic depositional environments primary porosity is directly related to the texture and fabric which in turn influenced by the size, sorting and shape of the grains at the time of deposition. Each depositional environment is characterized by a distinct suite of processes active at the sediment-water interface unique to that particular environment. Each sedimentary environment can then be characterized by a unique vertical sequence of sedimentary structures, fabrics and textures. This suite of characteristics can be used to predict the location and distribution of the most porous (well sorted, coarse grained, etc.) and permeable zones.

Some carbonate sediments behave and have similar depositional histories, textures, etc. as their clastic quartzose counterparts. Carbonate particles having rounded shapes include foraminifera, pellets, pelloids and oolites. These particles often form areally extensive, marine sand belts, tidal bar belts, spillover lobes and other clastic-carbonate deposits.

For the most part, porosity and permeability prediction in carbonate rocks, especially those deposited in shallow waters, is very complex. Primary depositional patterns, fossil types, water chemistry, volumes of migrating pore fluids, regional deformational events, eustatic fluctuations in sea level, burial rates and depths all have important effects on the development of carbonate porosity and

permeability.

Porosity may be divided into two types, primary and secondary. Unconsolidated sediments such as quartz, silts, sands, gravels, etc., predominantly exhibit primary (or intergranular) porosity. Primary porosity may be modified or decreased by compaction and/or cementation. Secondary porosity is formed after deposition and is often less homogeneously distributed than primary porosity. Secondary porosity may further be divided into: 1) solution porosity - enlargement of openings due to dissolution of matrix by percolating ground waters; or 2) fracture porosity - which often occurs in dolomites and siliceous limestones.

Carbonate primary porosity is rarely preserved after burial and is usually highly altered by chemical diagenetic processes. The relative solubility of original carbonate minerals (mainly aragonite and high magnesium calcite) render carbonate rock sequences particularly susceptible to alteration. In many instances, early diagenesis causes complete cementation of the primary pore space. Secondary porosity, as a result, often is forced to develop along the least porous sections of the original matrix by the leaching of less soluable material. This process often produces effective intercrystalline porosity in limestones.

Porosity in quartzose-clastic materials is primarily of the interparticle type and fluid flow is around the grains rather than through pore spaces as a result of dissolving less soluble matrix material. These unconsolidated materials normally do not develop as high a degree of secondary porosity as carbonate rock sequences (Table 1).

Table 1. Comparison of Porosity in Sandstone and Carbonate Rocks (Choquette and Pray, 1970).

Aspect	Sandstone	Carbonate
Amount of primary porosity in sediments	Commonly 25-40%	Commonly 40-70%
Amount of ultimate porosity in rocks	Commonly half or more of initial porosity; 15-30% common	Commonly none or only small fraction of initial porosity; 5-15% common in reservoir facies
Type(s) of primary porosity	Almost exclusively interparticle	Interparticle commonly predominates, but intraparticle and other types are important
Type(s) of ultimate porosity	Almost exclusively primary interparticle	Widely varied because of postdepositional modifications
Sizes of pores	Diameter and throat sizes closely related to sedimentary particle size and sorting	Diameter and throat sizes commonly show little relation to sedimentary particle size or sorting
Shape of pores	Strong dependence on particle shape- a "negative" of particles	Greatly varied, ranges from strongly dependent "positive" or "negative" of particles to form completely independent of shapes of depositional or diagenetic components
Uniformity of size, shape, and distribution	Commonly fairly uniform within homogeneous body	Variable, ranging from fairly uniform to extremely heterogeneous, even within body made up of single rock type
Influence of diagenesis	Minor; usually minor reduction of primary porosity by compaction and cementation	Major; can create, obliterate, or completely modify porosity; cementation and solution important

Table 1. Comparison of Porosity in Sandstone and Carbonate Rocks (Choquette and Pray, 1970). - (continued)

Aspect	Sandstone	Carbonate
Influence of fracturing	Generally not of major importance in reservoir properties	Of major importance in reservoir properties if present
Visual evaluation of porosity and permeability	Semiquantitative visual estimates commonly relatively easy	Variable; semiquantitative visual estimates range from easy to virtually impossible; instrument measurements of porosity, permeability and capillary pressure commonly needed
Adequacy of core analysis for reservoir evaluation	Core plugs of 1-in. diameter commonly adequate for "matrix" porosity	Core plugs commonly inadequate; even whole cores (3-in. diameter) may be inadequate for large pores
Permeability-porosity interrelations	Relatively consistent; commonly dependent on particle size and sorting	Greatly varied; commonly independent of particle size and sorting

Carbonate porosity manifests itself in many forms, such as moldic, fracture, or interparticle as discussed by Choquette and Pray (1970). Dolomitization can greatly alter primary porosity and enhance permeability of carbonate rocks originally deposited as limestones. After a limestone has been dolomitized, the matrix material becomes more dense and porosity is increased by a corresponding amount (approximately 12% provided compaction does not take place). The formation of sucrosic dolomitic rhombs also increases permeability since the newly formed dolomite will act, for hydrologic purposes, as a granular material having interparticle type of porosity. More importantly dolomitization greatly reduces the ductility of the rocks causing them to be highly susceptible to fracturing even in tectonically "quiet" areas. Fracture porosity is by far the most effective type of porosity for increasing a formations' permeability. Although fracture porosity, by volume is relatively low, the interconnectedness of the pore space is much greater per unit volume than any other type of porosity.

Carbonate Porosity and Permeability Effects on Geophysical Logs

Four types of geophysical logs are directly influenced by the type and volume of porosity present in carbonate formations (a more detailed explanation to log response in various types of lithologies is discussed later in the text).

Log - Porosity Related Response

Neutron - measures water saturation contained in the pore spaces;

Density - measures the saturated bulk density (fluid and matrix) of the formation;

Acoustic Velocity - measures the interval transit time through the formation which is directly related by the degree of porosity;

Electric Logs - influenced, in part, by the void volume ratio to grain contact area;

Lithologic types and textures often have a pronounced affect on various types of geophysical logs.

Type Lithology (Relative-Porosity, Permeability) - Log Response

Sucrosic Dolomites - (moderate porosity, moderate permeability) act like well cemented sandstones and may be treated as granular material on all logs, if the zone measured is not highly fractured;

Fractured Crystalline Dolomites - (very low porosity, high permeability) are often very productive zones, but are the most difficult to detect on all four types of logs. The electric log may measure resistivity through the matrix (very high resistivity) or along fractures parallel to the borehole (low resistivity);

Dolomites of Moldic Porosity - (high porosity - moderate to high permeability) since these units have very high porosities (up to 65% including vug and intercrystalline porosity), they are easily detected on all four logs.

Vuggy to Cavernous Limestones - (moderate porosity - high permeability) often responds similar to clays (porous, low resistivity) on all four logs depending upon the size, volume, and distribution of the vugs;

Argillaceous Limestones - (moderate porosity - low to moderate permeability) are easy to detect on most log suites, especially electric logs which are often recorded as having a higher resistivity than clay; and

Chalk and Very Fine Grained Limestones - (high porosity - low permeability) since chalk is comprised of clay size particles, all of the logs will respond similarly to clay. For hydrologic purposes, clays and chalks behave similarly, and it is not important to distinguish between these two lithologies.

In many cases the porosity of a given formation may have a greater influence on a particular log than the lithology. Also, the porosity of a formation is commonly inversely related to permeability.

GEOPHYSICAL LOGS APPLICABLE TO WATER RESOURCES INVESTIGATIONS

Types of Information Available from Various Log Suites

Currently, more than one hundred logging units are being utilized for the purpose of obtaining information pertaining to water resources investigations in the United States. These units range in size from small portable hand operated units to multi-axle trucks with capabilities approaching the state-of-the-art in petroleum geophysical logging. The type of probes selected for hydrogeologic research in this study was based upon their: 1) application to hydrogeology; 2) current availability; and 3) initial and maintenance cost. Summarized in Table 2 are the most common types of probes currently in use for hydrogeologic investigations by various governmental and private corporations. The types of probes listed in the Table have been divided into three categories based upon the level of information obtained: 1) basic - equipment easy to operate (single conductor cable) and relatively low initial investment; 2) intermediate - requiring a multi-conductor cable for deep penetrating electric and radioactive probes; and 3) advanced - includes all of the above, probes generally not available to the water well industry (still in the experimental stage), and probes having a limited application to water resources investigations. Also, there are many probes having an application to hydrogeology, but are generally cost prohibitive to users outside of the petroleum industry.

This research is based upon probes in the intermediate category which provide a considerable amount of information to the hydrogeologist, at least in a semi-quantitative manner, and are of a reasonable cost.

TABLE 2 Primary Application of Geophysical Logs Used in Water Resource Investigations

Level of Logging Program	Probe	Symbol used in Text	Measures	Stratigraphic Correlation	Lithology	Formation Density	Porosity	Permeability	Fracturing & Sol. Cav.	Producing Zones	Grain Size	Clay Content	Specific Yield (Water Table)	Ground Water Flow (Lateral)	Water Level	Water Quality	Resistivity of Formation	Location of Casing	Condition of Casing	Location of Screens	Bonding of Cement	Casing Leaks	Useful Logs in Casing	Comments
BASIC	Natural Gamma	G	Natural radiation from U, Th, K	A	A		C	B	C	B		B										B	C	X	Most commonly used probe
	Point Resistance	Rp	Resistance of borehole	B	B		C		B	C					C	C	B	C						Severely affected by borehole rugosity
	Spontaneous Potential	Sp	Electrochemical activity of fluids	B	B		B	C		B	C	B		B	C	C		C		C				Rarely applicable in thick freshwater carbonates
	Caliper	C	Borehole diameter	B	B	C	C	C	B	C								A	B			B	C	Used to correct other logs
	Temperature-gradient	T_{g1}	Borehole temperature		C			C		C		C		B	A			C			B	B	X	Many diverse uses
	-differential	T_{d1}	Slight temperature changes					B		B				B	A			B			B	A	X	0.01°C sensitive
	Casing Collar Locator	CCL	Locates bottom of casing, collars															A	B			B	X	Not for P.V.C.
	Fluid Sampler	S	Fluid point sampler													A						C	X	Used with fluid res.
	Flowmeter	V_f	Vertical fluid velocity					A		A			A					C				C	X	1 mpm (4 fpm) minimum fluid velocity required
INTERMEDIATE	Neutron	N	Hydrogen ion concentration	A	A	B	A	B	B	B		B	A			A	C		B			B		X	Good logs in carbonates
	Density	D	Formation/fluid density	A	A	A	B	C	B	B	C	C	B			A	C		B			B		X	Confirms porosity
	Normal Res. - 16"	E_{16}	Resistivity of pore water and lithology	A	A	C	B	B	B	B	B	B				C	B	B	B	C	B				Wide application
	Normal Res. - 64"	E_{64}	Resistivity of pore water and lithology	A	A	C	B	B	B	B	B	B				C	B	A	B	C	B				3m (10') minimum thickness on beds
	Acostic Velocity	V_a	Velocity of induced signal	A	B	A	A	C		B		B				C			B			A		X	Borehole sensitive
	Fluid Resistivity	R_f	Resistivity of borehole fluid					B						B	A	A							B	X	Requires smooth borehole
	Lateral	R_a	Resistivity of pore water and lithology	A	A	C	B	C	B	B		B				C	B	B	B	C					Spacing generally too long for carbonates
	Induction	C	Conductivity of pore water and lithology	A	A	C	B	C	B	B		B				C	B	A	B						Measures conductivity
	Laterolog	R_o	Deep resistivity of pore water and lithology	A	A	C	B	C	B	B		B				C	B	A	B		B				Potential not fully developed in carbonates
ADVANCED	Microfocused	R_{mx}	Resistivity of borehole wall	C	C		C	B		C	C							C							Limited use in carbonates
	Gamma Spectrometry	G_s	Distinguishes between different gamma energies	C	B							B												X	Used to distinguish clays
	Tracer Injection	I_t	Injects fluid to be traced vertically	C	C		C	B	C														B	X	Saline or radioactive tracers
	Borehole Televiewer	V_{te}	Sonic signal is attenuated by pores and fractures	C	B	B	A	C	A	B	C							B							Very useful in carbonates
	Borehole Television	B_{ti}	Video record of borehole	C	C		C	C	A	B					A			A					A	X	Requires coaxial cable

BASIC -- Easy to operate (single conductor cable), relatively low cost initial investment.

INTERMEDIATE -- Requires multiconductor cable, radiation license, and considerable initial investment.

ADVANCED -- These tools are seldom used in hydrogeologic investigations due to their cost, availability, or limited application.

A Most direct application. Additional information may be required for optimum interpretation.

B Requires the use of other logs or information for a proper interpretation.

C Requires considerable additional information to confirm any interpretation.

Probes having a potential use to hydrogeologic investigations, which are in limited use at this time, are briefly summarized at the end of this section.

Although most geophysical logging programs operate at the basic level the type and amount of information available from these logs are limited to stratigraphic correlation, water-level measurements, estimates of water quality and lithologic determinations, and some types of well inspection.

Intermediate level logging suites greatly enhance the quality and type of information obtained for parameters of hydrogeologic interest such as lithology, hydrostratigraphic correlation, formation porosity, permeability (indirect), matrix density, formation resistivity, clay content (%), water saturation, secondary porosity, grain cementation and pore water quality (Table 3).

The following section provides a brief overview of the geophysical logging equipment and the probes used in this study. A more detailed description is included in Appendix H. The reader is referred to the following references for a more detailed discussion on geophysical logging theory, principles, and instrumentation - Patten and Bennett, 1966; International Atomic Energy Agency, 1971; Keys and MacCary, 1971; Schlumberger, 1972; Lehr and Campbell, 1973; Dresser Atlas, 1975; Gearhart-Owens, 1975; and Hilchie, 1982.

Overview of Geophysical Equipment

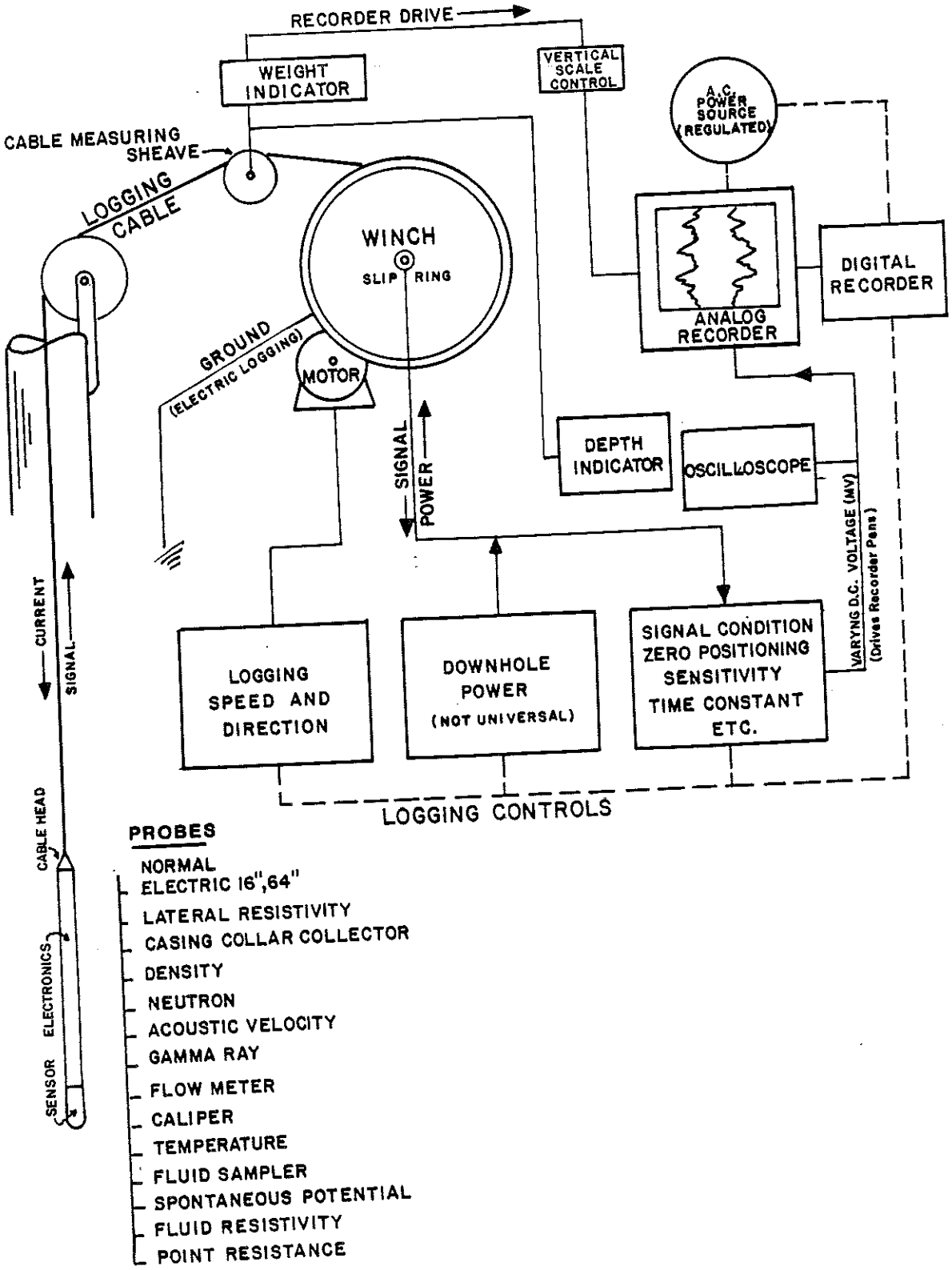
Most logging units are powered by a 110-volt, gasoline driven A/C generator. The A/C current is transformed into D/C current (usually 12 to 24 volts) and transmitted down the logging cable to the probe (Figure 8).

Table 3.--Hydrogeologic Application and Probe Cross Reference.

HYDROGEOLOGIC APPLICATION	PROBES
Lithology	Natural Gamma, Neutron, Density, Acoustic Velocity, Electric*, Temperature
Formation Porosity (ϕ)	Neutron, Density, Acoustic Velocity
Permeability (k) (Indirect)	Natural Gamma, Neutron, Electric, Flow Meter
Matrix Density (ρ_{ma})	Density, Acoustic Velocity
Formation Resistivity R_o	Electric
Clay Content (%)	Natural Gamma, Neutron, Density, Electric
Water Saturation (S_w%)	Electric, Neutron
Secondary Porosity	Acoustic Velocity, Neutron, Caliper, Televiewer
Cementation Factor (m)	Neutron, Density, Electric
Water Movement	Tracer Injection, Temperature
Water Quality (R_w)	Electric, Fluid Resistivity
Fracture Identification	Borehole Televiewer, Acoustic Velocity
Hydrostratigraphic Correlation	Natural Gamma, Neutron, Density, Electric
Specific Yield	Calibrated Neutron Logs
Grain Size (Indirect)	Electric Logs, Neutron
Water Level and Saturated Zones	Temperature, Neutron, Density, Electric
Well Inspection	Caliper, Density, Borehole Television, SP
Cement Location	Temperature, Density, Acoustic Velocity

*Electric may include any or all of the following: long and short normal, lateral, spontaneous potential, point resistance, induction guard and focused (micro or deep).

Figure 8.--Portable logging system block diagram. (Modified from Keys and MacCary, 1971).


RECORDER DRIVE
WEIGHT INDICATOR
VERTICAL SCALE CONTROL
A.C. POWER SOURCE (REGULATED)
CABLE MEASURING SHEAVE
LOGGING CABLE
WINCH
SLIP RING
GROUND (ELECTRIC LOGGING)
MOTOR
ANALOG RECORDER
DIGITAL RECORDER
SIGNAL
POWER
DEPTH INDICATOR
OSCILLOSCOPE
VARYING D.C. VOLTAGE (MV) (Drives Recorder Pens)
CURRENT
SIGNAL
LOGGING SPEED AND DIRECTION
DOWNHOLE POWER (NOT UNIVERSAL)
SIGNAL CONDITION
ZERO POSITIONING
SENSITIVITY
TIME CONSTANT
ETC.
LOGGING CONTROLS
CABLE HEAD
ELECTRONICS
SENSOR
PROBES
NORMAL
ELECTRIC 16",64"
LATERAL RESISTIVITY
CASING COLLAR COLLECTOR
DENSITY
NEUTRON
ACOUSTIC VELOCITY
GAMMA RAY
FLOW METER
CALIPER
TEMPERATURE
FLUID SAMPLER
SPONTANEOUS POTENTIAL
FLUID RESISTIVITY
POINT RESISTANCE

The "signal" relayed back to the surface electronics is either a pulse type (most common type of signal - converted at a ratemeter) or a direct current. These pulses, or current readings, are calibrated and recorded in analog form on strip chart paper. In some of the more sophisticated units, the data are also stored in digital form on magnetic tape for processing at a later time. Asquith, 1978, provides an excellent discussion on using computer programs for interpreting geophysical logs.

Calibrating Logging Equipment

Every geophysical probe is influenced to various degrees by extraneous borehole geometric factors which contribute to the log recorded. Many of the adverse factors can be accounted for and corrected by using other logs, such as; temperature logs to correct resistivity measurements, caliper logs to correct variations in borehole diameter, etc. At this time only two logs, the natural gamma and neutron, have calibrated test holes available to operators of geophysical equipment. These test holes, located in Houston, Texas, are used for calibrating logs to accepted industry standards (American Petroleum Institute, A.P.I., 1974). Essentially, every borehole is unique and has a wide range of physical properties affecting each log run. Logs run in shallow boreholes are mainly used in a semi-quantitative manner and the values derived for a particular zone are normally used only as a relative comparison between zones within the same well. Many of the more advanced petroleum industry probes have internal circuitry which automatically compensate for extraneous factors before actually printing the log in analog form. Although the probes and surface electronics are generally not as sophisticated in water well logging programs, good results can be obtained for porosity, bulk density, formation resistivity, natural

gamma activity, etc., if the interpreter is aware of the factors affecting each log response. Table 4 summarizes some of the factors affecting geophysical logs.

Table 4.--Factors Affecting Quantitative Interpretation of Geophysical logs.

Natural Gamma, Density, Neutron and Acoustic Velocity Logs

1. Density of the borehole fluid;
2. Borehole diameter;
3. Thickness of the casing and cement;
4. Position of the detector in the borehole;
5. Spectrum and sensitivity of the detector;
6. Density of the formation;
7. Logging speed, time constant, sampling length; and
8. Bed thickness.

Factors Affecting Radius of Investigation

Log	Used in Casing	Typical Depth of Investigation	Response Decreased By
Gamma	Yes	12" - 18"	Cement, casing, dense fm.
Neutron	Limited	6" - 12"	Cement, casing, porous mat.
Density	Limited	4" - 12"	Cement, casing, dense fm.
Acoustic Velocity	No	12" - 36"	Less consolidated material
Short Normal (16")	No	8" - 20"	Low resistivity fms.
Long Normal (64")	No	36" - 120"	Low resistivity fms.
Point Resistance	No	2" - 6"	Water quality, clays
Spontaneous Potential	No	---------	Low mud-formation water contrast

Many operators of geophysical logging equipment are unable to routinely calibrate their probes in the A.P.I. test pits. As an alternative, many operators run a complete suite of logs in a small diameter observation well and compare log responses from time to time

in order to check for relative log consistency. Deviations from earlier runs alert the operator of a possible malfunction or change in electrical resistance in the logging lines.

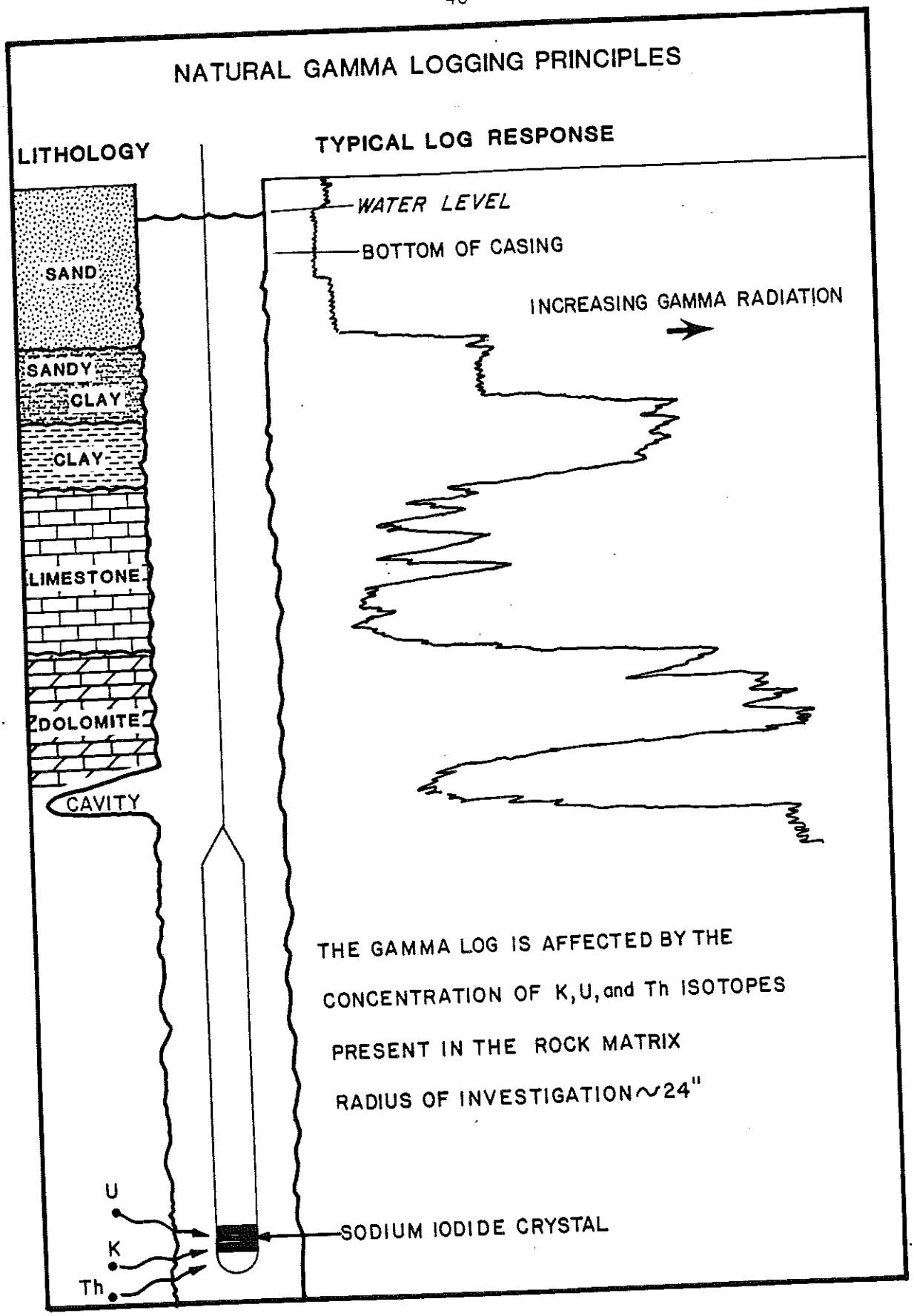
Probes Utilized for Hydrogeologic Data Collection

Natural Gamma

The natural gamma log was first introduced to the logging industry in 1939 and has since become the most widely used log in the water well industry. Although any attempt to quantify measurements from this log would be highly subjective, the gamma is an important probe for use in hydrostratigraphic correlations. The gamma log is often used to infer lithology, if the local geology is known.

The gamma log records natural gamma radiation emitted from formations adjacent to the borehole (Figure 9). The gamma radiation detected is primarily from the decay of three naturally occurring elements; potassium -40 (K^{40}) and from daughter isotopes in the uranium (U) and thorium (Th) decay series. Gamma rays received at the probe's detector range in energy from approximately 0.5 MeV to 3.0 MeV. Most of the gamma energy received at the detector is less than 1.0 MeV. Gamma rays are extremely penetrating and are effectively used in cased and cemented wells, although a small correction factor may be necessary (Appendix O). Approximately 90% of the gamma rays recorded originate from within 18 inches of the borehole. The most common type of detector used in natural gamma probes is the scintillation type utilizing a thallium activated, sodium iodide crystal. Gamma rays are not differentiated into discrete energy ranges; therefore, isotopes emitting the gamma rays (K, U, or Th) cannot be quantified or proportioned.

Figure 9.--Natural gamma logging principles and typical log response.


NATURAL GAMMA LOGGING PRINCIPLES
LITHOLOGY
TYPICAL LOG RESPONSE
WATER LEVEL
BOTTOM OF CASING
INCREASING GAMMA RADIATION
SAND
SANDY CLAY
CLAY
LIMESTONE
DOLOMITE
CAVITY
THE GAMMA LOG IS AFFECTED BY THE
CONCENTRATION OF K,U, and Th ISOTOPES
PRESENT IN THE ROCK MATRIX
RADIUS OF INVESTIGATION ~24"
U
K
Th
SODIUM IODIDE CRYSTAL

Another gamma sensitive tool, the gamma-spectrometer, is able to to differentiate isotopes by recording discrete energy ranges and will be discussed later in this section.

Formations of high gamma activity include minerals incorporating high percentages of potassium, uranium and/or thorium in their lattice structure. Some of the more common potassium rich gamma active formations include potassium feldspars, micas, volcanic ashes and illitic clays. Uranium and thorium tend to concentrate in phosphorites, apatites, organic materials, uraniferous sands, and dolomites. Although gamma logs can be correlated in many instances over tens of miles, the probe is actually recording radioactive material in concentrations significantly less than one percent of the rock matrix volume. Slight changes in depositional environments or sediment source areas can greatly influence the activity recorded on gamma logs.

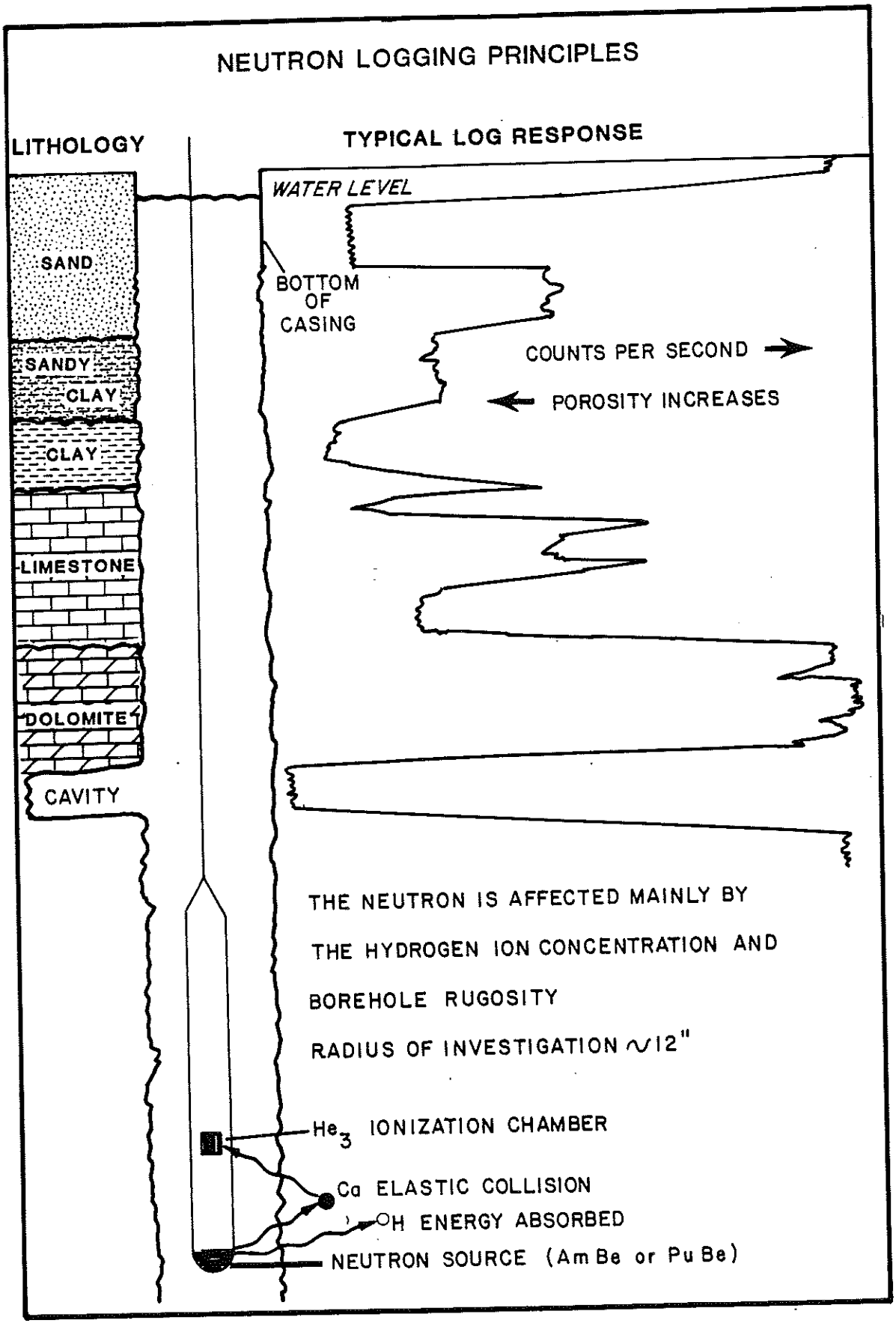
According to the petroleum literature, the gamma log has proven to be an effective "shale" indicator, but in near surface environments the gamma log has not proven to be an effective means for determining clay ("shale") content. Gamma logs are commonly used in a non-quantitative manner for mapping hydrostratigraphic units.

Neutron (Porosity)

The neutron probe directly measures hydrogen saturation within the formation pore spaces (Figure 10). Since this research is concerned in near-surface freshwater saturated formations, it is assumed that all of the hydrogen saturation is due to water rather than the presence of hydrocarbons.

The neutron probe is equipped with a radioactive source (usually Am^{241}-Be) which constantly bombards the adjacent formation with high

Figure 10.--Neutron logging principles and typical log response.


NEUTRON LOGGING PRINCIPLES
LITHOLOGY
TYPICAL LOG RESPONSE
WATER LEVEL
SAND
BOTTOM OF CASING
SANDY CLAY
CLAY
COUNTS PER SECOND
POROSITY INCREASES
LIMESTONE
DOLOMITE
CAVITY
THE NEUTRON IS AFFECTED MAINLY BY
THE HYDROGEN ION CONCENTRATION AND
BOREHOLE RUGOSITY
RADIUS OF INVESTIGATION ~12"
He3 IONIZATION CHAMBER
Ca ELASTIC COLLISION
H ENERGY ABSORBED
NEUTRON SOURCE (Am Be or Pu Be)

energy neutrons. These neutrons are constantly undergoing a de-energizing process as they collide with atoms comprising the formation and saturating fluids. The amount of energy lost during each collision is a function of the collision angle with the other atoms and the relative difference in mass. Since hydrogen atoms are relatively abundant and similar in mass to the neutron, the hydrogen ions are primarily responsible for the energy reduction, or decrease in the number of neutrons counted at the detector.

Since many phenomena take place during the collision of a neutron with a hydrogen ion, such as lowering of thermal energy levels, emission of gamma rays from hydrogen atoms, etc., there are many types of neutron probes in use. The type of neutron probe most applicable to water resources investigations, and the type used in this study, is the neutron-epithermal neutron (N-E-N). This type of probe records the neutrons arriving at the detector (13" from the source) which have been thermalized to a lower energy state (0.1 to 100 eV) as a result of collisions with hydrogen atoms (Brown and Anderson, 1979). The number of neutrons detected are exponentially related to the formations' porosity and are scaled accordingly on log paper. Neutron probes have a relatively shallow radii of investigation (6"-12", decreasing with increased hydrogen content) and are greatly affected by the rugosity of the borehole. A caliper log is necessary to correct for borehole diameter changes and to eliminate zones with excessively large cavities. Well casing and cement affect the neutron log, but interpretations can be made in some small diameter wells drilled by the cable tool method.

Density (gamma-gamma)

Density logging also employs an artifical radioactive source attached to the logging probe (Figure 11). The source is commonly a medium energy gamma emitter (normally Cs^{137} or Co^{60}) capable of penetrating 6 to 12 inches into the formation. Density logs are also a porosity type log measuring the electron density of the formation. As gamma rays collide with electrons, the frequency of Compton scattering collisions is directly related to the number of electrons within the formation and, in turn, is related to the bulk density (ρ_b -expressed in gm/cc). In order to calculate porosity from a density log, both the fluid density (in fresh waters $\rho_f = 1.0$) and matrix density must be known. Porosity, or formation bulk density (ρ_b), can be derived from the density log using the following equation:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad (1)$$

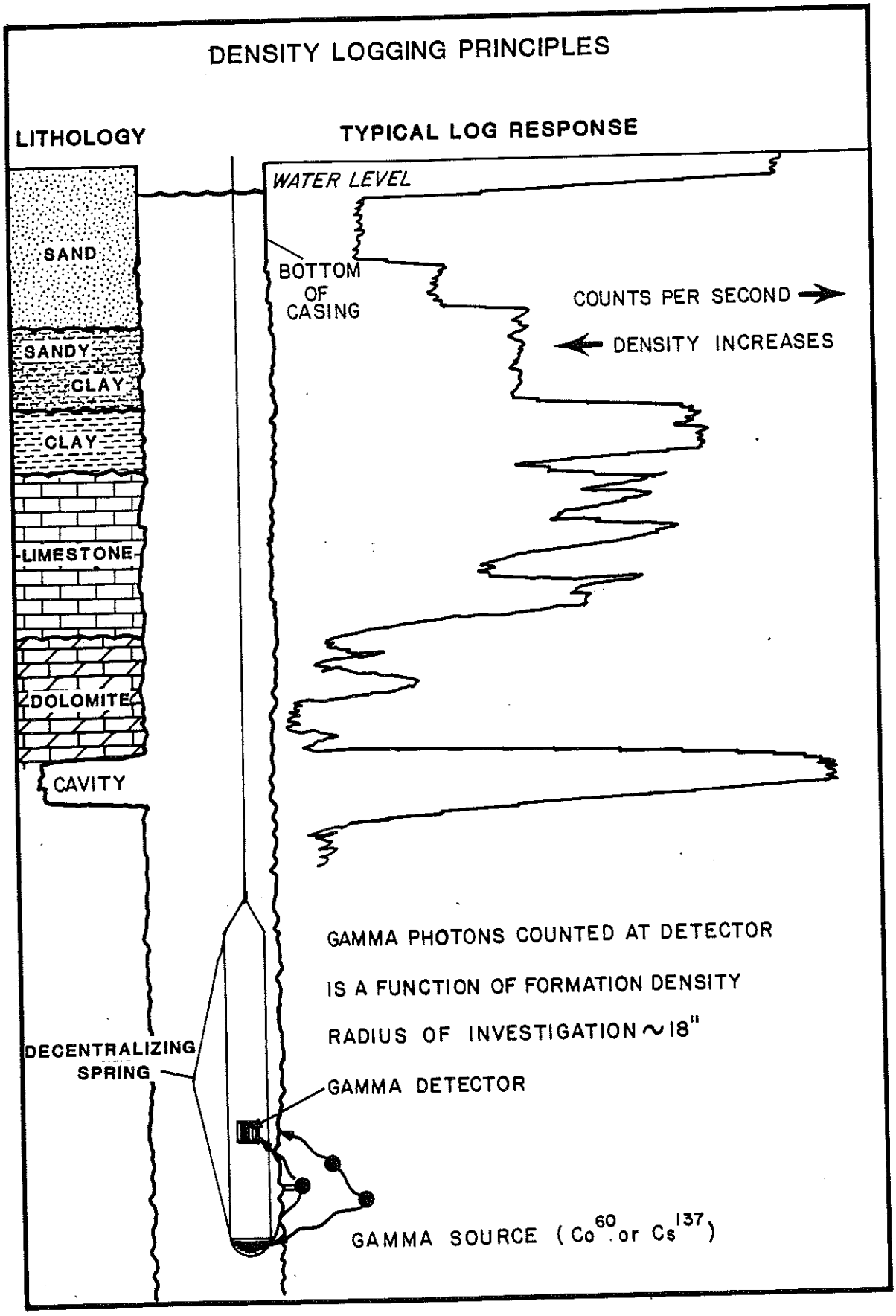
$$\text{or:} \quad \rho_b = \phi . \rho_f + (1-\phi)\rho_f \qquad (2)$$

where: ϕ = porosity in percent
ρ_{ma} = bulk density of matrix
ρ_b = bulk density from log
ρ_f = bulk density of pore fluid

For the purpose of this research, the following matrix densities are used for analyzing the Tertiary sediments:

Lithology	Density (g/cc)
Quartz Sand	2.65
Clay: kaolinite	2.60-2.63
montmorillonite	2.2-2.7
illite	2.76-3.00
Limestone	2.71
Dolomite	2.85
Anhydrite	2.95

Figure 11.--Density logging principles and typical log response.


DENSITY LOGGING PRINCIPLES
LITHOLOGY
TYPICAL LOG RESPONSE
WATER LEVEL
SAND
SANDY CLAY
CLAY
LIMESTONE
DOLOMITE
CAVITY
BOTTOM OF CASING
COUNTS PER SECOND
DENSITY INCREASES
GAMMA PHOTONS COUNTED AT DETECTOR
IS A FUNCTION OF FORMATION DENSITY
RADIUS OF INVESTIGATION ~18"
DECENTRALIZING SPRING
GAMMA DETECTOR
GAMMA SOURCE (Co60 or Cs137)

The type of density log most commonly used in water resources investigations is the decentralized probe with a side collimating detector window in contact with the borehole wall. Orienting the window toward the formation aids in eliminating the effects of borehole rugosity. Advanced types of density probes utilize two detectors, at different spacings, in order to compensate for changes in borehole diameter. These compensated probes are primarily limited to use in the petroleum industry.

Density logs are greatly affected by multiple thicknesses of casing and/or cement. Increasing the distance between the source and detector increases the depth of investigation, provided the strength of the source is sufficient to penetrate this greater distance. Relative density comparisons for various formations, can be made in small diameter wells drilled by the cable tool method.

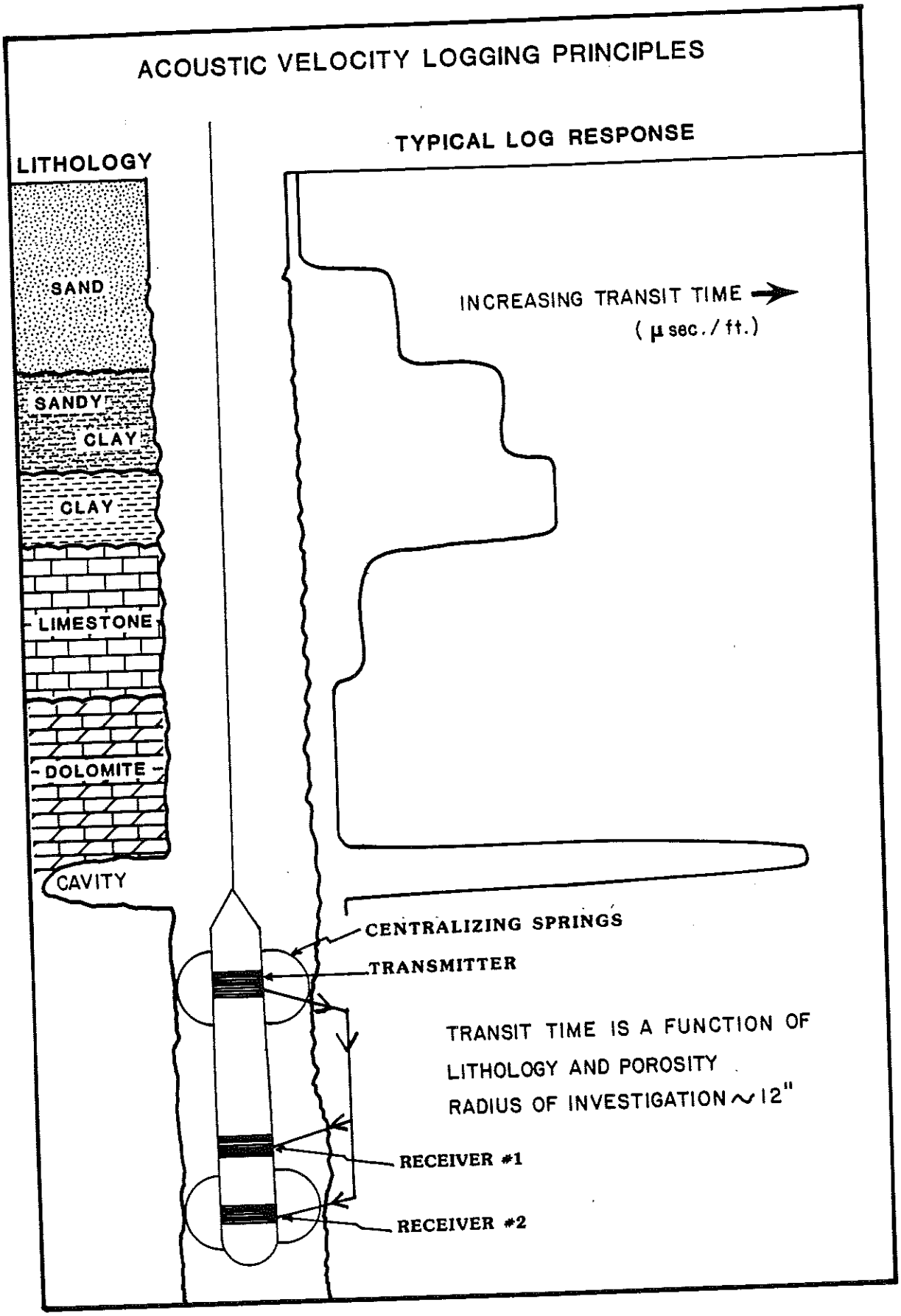
Acoustic Velocity (Sonic)

The acoustic velocity probe measures the travel time of an artificially generated compressional wave transmitted through 12 inches of formation matrix (Figure 12). The transit time is influenced by the lithology, density and porosity of the formation. If the lithology is known, the porosity can be derived from the Wyllie equation (porosity is assumed to be homogeneous):

$$\phi = \frac{\Delta t_{ma} - \Delta t}{\Delta t_{ma} - \Delta t_f} \qquad (3)$$

where: ϕ = porosity in percent from the acoustic velocity log
Δt_{ma} = travel time of the rock matrix
Δt = travel time from the acoustic velocity log
Δt_f = travel time of the pore fluid (= 189 μsec in freshwater)

Figure 12.--Acoustic velocity logging principles and typical log response.


ACOUSTIC VELOCITY LOGGING PRINCIPLES
LITHOLOGY
TYPICAL LOG RESPONSE
SAND
SANDY CLAY
CLAY
LIMESTONE
DOLOMITE
CAVITY
INCREASING TRANSIT TIME →
(μ sec. / ft.)
CENTRALIZING SPRINGS
TRANSMITTER
TRANSIT TIME IS A FUNCTION OF
LITHOLOGY AND POROSITY
RADIUS OF INVESTIGATION ~ 12"
RECEIVER #1
RECEIVER #2

Matrix travel times of Tertiary sediments, as used in this study, are assumed to have the following values:

Lithology	Travel Time (μsec/ft)
Quartz Sand (unconsolidated)	59
Clays	70-167
Limestone	48
Dolomite	43
Anhydrite	50

Formations containing an appreciable clay content tend to have acoustic velocities less than "clean" matrix travel times (assuming similar porosities). Vuggy carbonates, on the other hand, record acoustic travel times greater than "true" (for a given porosity). The acoustic velocity log records only the fastest compressional waves and may "bypass" vugs and cavities not homogeneously distributed.

Acoustic velocity logs may be used to evaluate the volume of secondary porosity in carbonate formations. The results may then be compared to porosity values derived from neutron or density logs measuring gross (bulk) porosity. The difference in porosity is an approximation of secondary or fracture porosity (Brown et al, 1981).

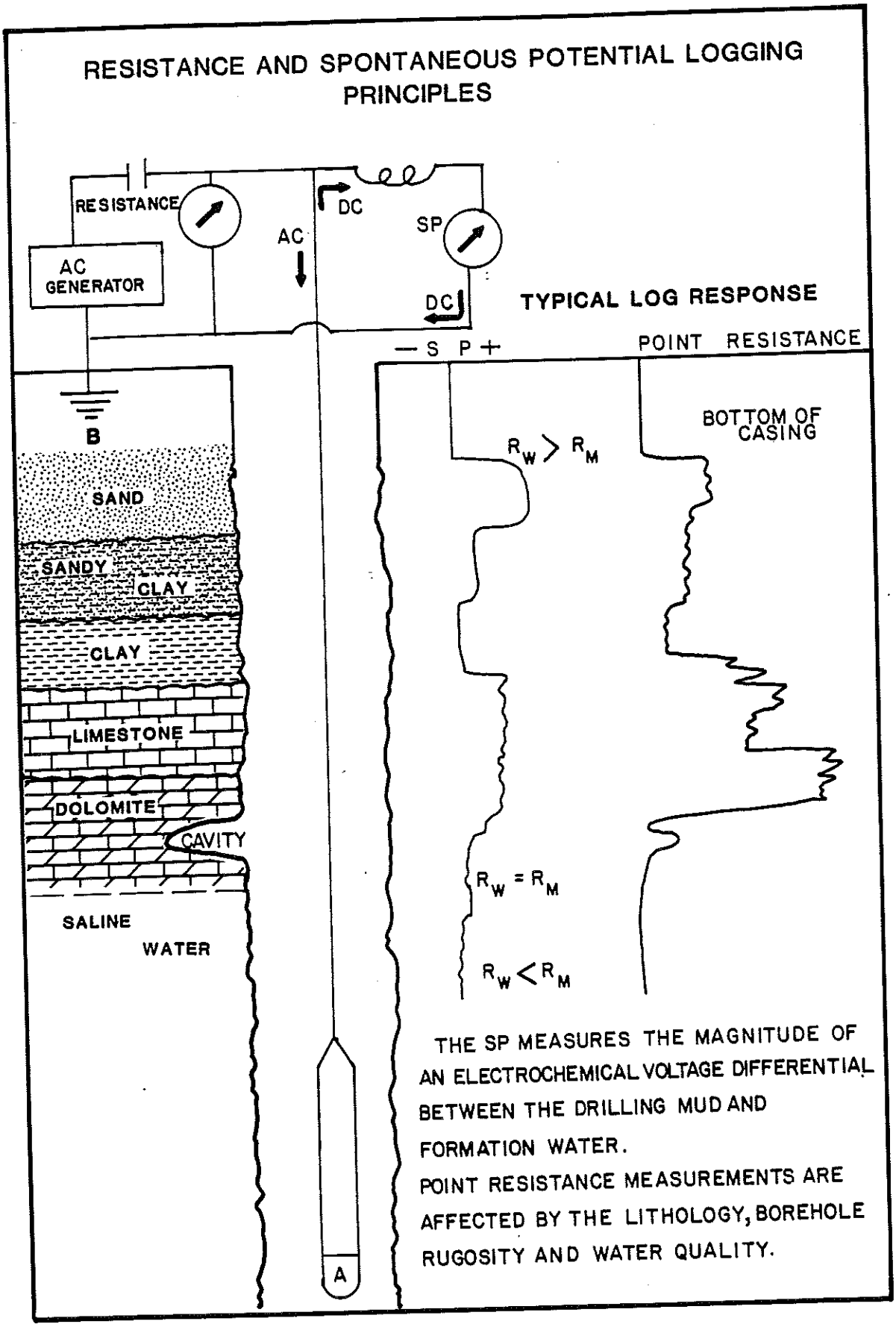
Point Resistance Electric Logs - (also known as resistance or single point logs)

One of the oldest and simplest of probes is the point resistance probe (Figure 13). Resistance logs record point contact resistance (in ohms) of the formation. The resistance measured is related by Ohms Law:

$$r = \frac{V}{I} \quad (4)$$

V = volts (kept constant by internal electronics)
I = current (in amperes)
r = resistance (measured in ohms)

Figure 13.--Resistance and spontaneous potential logging principles and typical log response.


RESISTANCE AND SPONTANEOUS POTENTIAL LOGGING PRINCIPLES
RESISTANCE
AC GENERATOR
AC
DC
SP
DC
B
SAND
SANDY CLAY
CLAY
LIMESTONE
DOLOMITE
CAVITY
SALINE WATER
A
TYPICAL LOG RESPONSE
— S P +
POINT RESISTANCE
BOTTOM OF CASING
$R_W > R_M$
$R_W = R_M$
$R_W < R_M$
THE SP MEASURES THE MAGNITUDE OF AN ELECTROCHEMICAL VOLTAGE DIFFERENTIAL BETWEEN THE DRILLING MUD AND FORMATION WATER.
POINT RESISTANCE MEASUREMENTS ARE AFFECTED BY THE LITHOLOGY, BOREHOLE RUGOSITY AND WATER QUALITY.

Advantages of this log include its ability to be run on a single conductor cable and its relatively shallow radius of investigation (which enables precise recording of formation contacts). The shallow radius of investigation, considered to be about two to three times the electrode diameter (about 3" to 5", depending upon the formation resistance), also has numerous disadvantages. Even the smallest cavities (or washouts), where contact with the formation is temporarily broken during logging, greatly affect the log response. Caliper logs are necessary, for proper log interpretation, in order to eliminate zones of extraordinary diameter.

Spontaneous Potential Logs

Spontaneous potential (SP) logs essentially use the same circuitry as the point resistance logs except slight changes in the natural electrochemical potential between the borehole fluid and pore fluid is recorded (in millivolts, mv). SP logs are commonly used in the petroleum industry to calculate pore water resistivity (R_w) as related by the following equation:

$$SP = -K \log \frac{R_{mf}}{R_w} \qquad (5)$$

where: SP = the log deflection in millivolts
K = a constant, approximately equal to 60 + 0.133T (T is temperature in °F)
R_{mf} = the resistivity of the mud filtrate (rarely measured in water well construction practices)
R_w = the resistivity of the formation pore water

The above equation indicates that a considerable contrast must exist between the resistivities of the borehole fluid and the formation pore water to obtain a measurable SP deflection. Many water wells are drilled with fresh water drilling muds or in many cases with no mud at

all, therefore, water resistivity measurements obtained using SP logs are very subjective from formations saturated with freshwater. Fresh water (and freshwater muds) are unable to create a sufficient contrast in resistivity to produce a measurable SP deflection. If an SP log is obtained in freshwater zones, the response will probably be opposite of logs run in saline formations. In freshwater zones, the borehole fluid resistivity is usually less than the formation fluid ($R_m < R_w$).

Normal Electric Logs

Normal electric logs (Figure 14) have essentially been replaced by induction logs (discussed later) in the petroleum industry during the last two decades. Proper interpretation of normal electric logs depends highly upon the accurate determination of porosity. Since neutron, density and acoustic velocity logs have been introduced, porosity values are more easily obtained, and normal electric logs have once again become an important probe for use in water resources investigations. Short (16") and long (64") electrode spacings measure electrical current potential changes through a given formation volume, as related by Ohm's Law:

$$R = \frac{V}{I} \cdot \frac{A}{L} \qquad (6)$$

where: R = resistivity in ohm m^2/m (ohm-meters)
V = potential difference across the formation in volts
I = electrical current in amperes
A = cross sectional area of formation in meters squared (m^2)
L = length of formation in meters (m)

The saturated formation resistivity (R_o) measured is directly influenced by (Figure 15):

1) The formation lithology;

Figure 14.--Normal electric logging principles and typical log response.

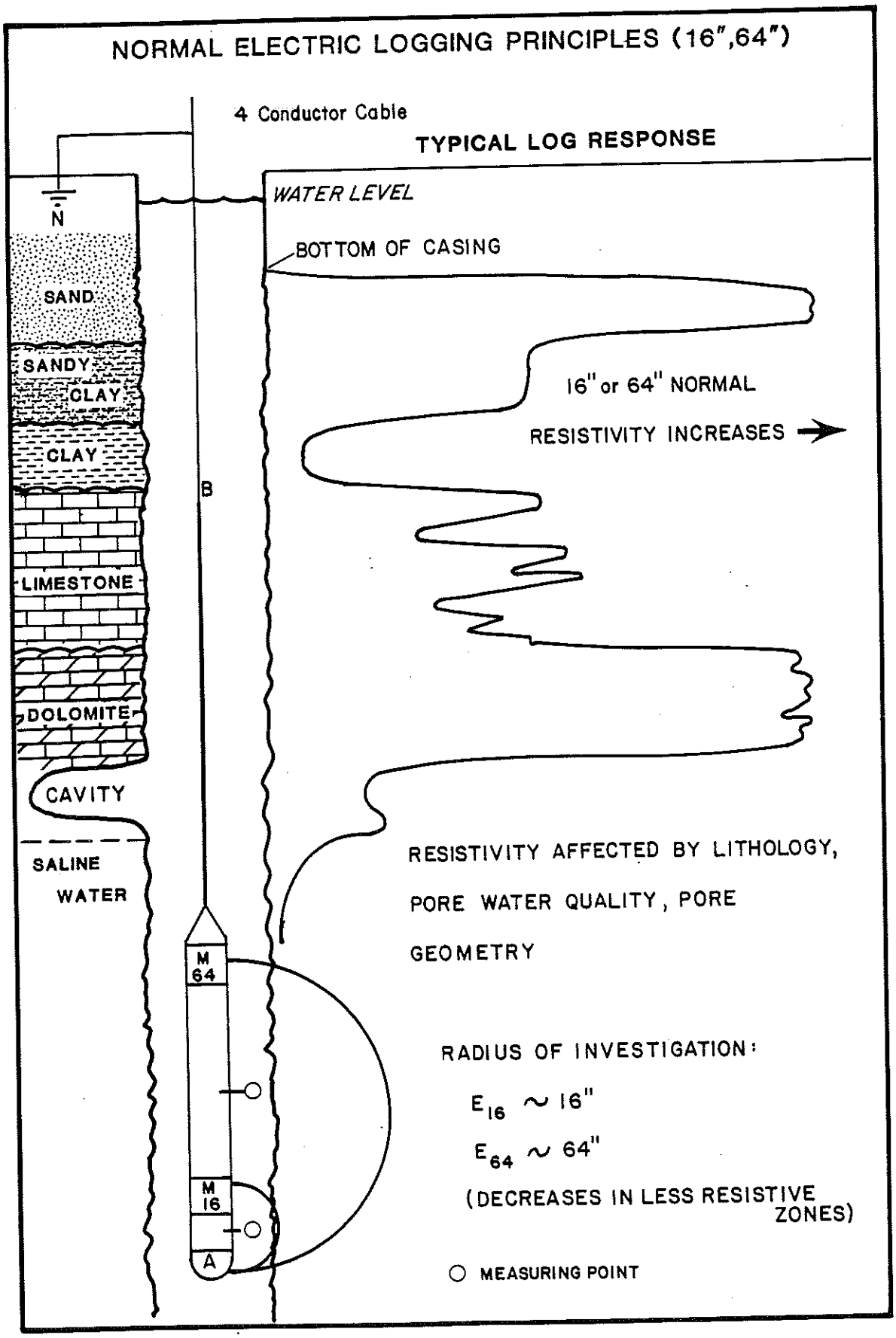
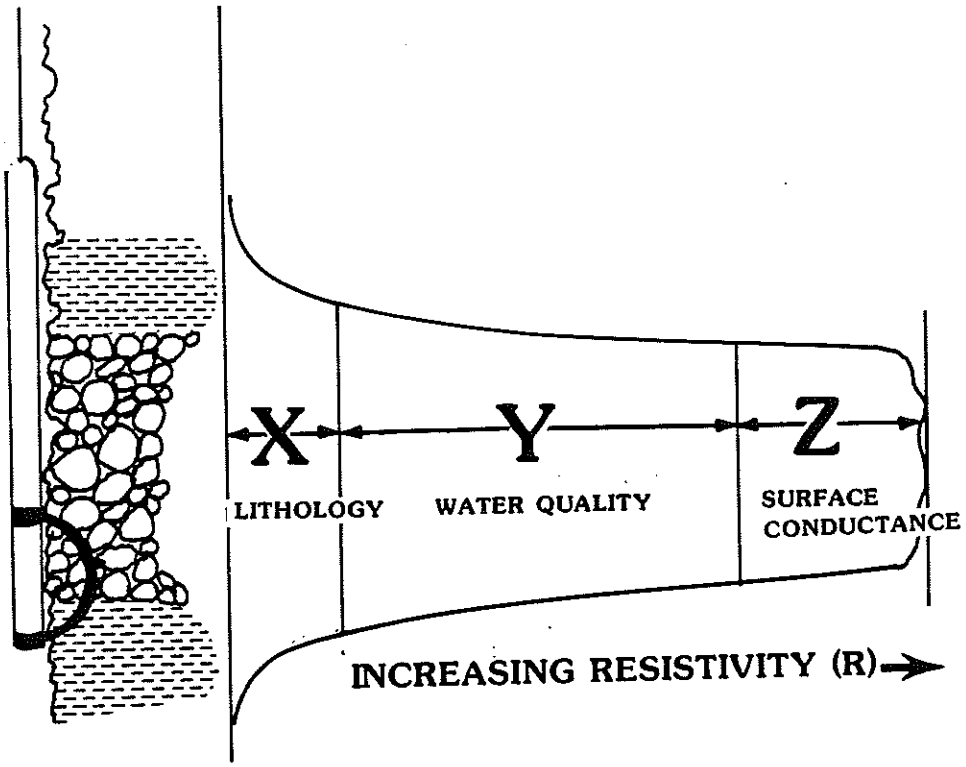

NORMAL ELECTRIC LOGGING PRINCIPLES (16",64")
4 Conductor Cable
TYPICAL LOG RESPONSE
WATER LEVEL
BOTTOM OF CASING
N
SAND
SANDY CLAY
CLAY
LIMESTONE
DOLOMITE
CAVITY
SALINE WATER
B
M 64
M 16
A
16" or 64" NORMAL RESISTIVITY INCREASES
RESISTIVITY AFFECTED BY LITHOLOGY, PORE WATER QUALITY, PORE GEOMETRY
RADIUS OF INVESTIGATION:
$E_{16} \sim 16"$
$E_{64} \sim 64"$
(DECREASES IN LESS RESISTIVE ZONES)
MEASURING POINT

Figure 15.--Factors influencing the resistivity measured by electric logs. The resistivity measured is greatly affected by the type lithology, water quality contained in the pore spaces of the formation and the geometry of the packing of the grains.



$$R_{LITHOLOGY\ (X)}\ \text{(quartz sand, clay, etc.)}$$

$$R_{WATER\ QUALITY\ (Y)}\ \text{(conductivity of pore water)}$$

$$+\ R_{SURFACE\ CONDUCTANCE\ (Z)}$$

$$\text{(GRAIN SIZE FACTOR)} \times \frac{\text{POROSITY}}{\text{GRAIN CONTACT AREA}}$$

$$= R_{TOTAL}$$

2) The ionic conductivity of the saturating formation water (R_w); and

3) A surface conductance factor which is related to grain size and pore geometry (ratio of porosity to grain contact area).

Except to aid in confirming zones with an appreciable volume of clay, electric logs are rarely used to determine lithology. Clays have low matrix resistivity, due to their extremely fine grain size and high cation exchange capacities . Other common types of sedimentary minerals such as sand size quartz grains, limestones and dolomites have infinitely high matrix resistivities. Since formation resistivity (R_o) is largely a function of pore water resistivity (R_w) and surface conductance it is almost impossible to distinguish sands from carbonates based solely on electric logs.

Symbols are often used to denote resistivity of the various borehole zones (Figure 16). These zones radiate outward from the mud in the borehole (R_m) through the mud flushed zones (R_{xo}) and finally out into the true resistivity saturated with formation containing its native water (R_o or R_t).

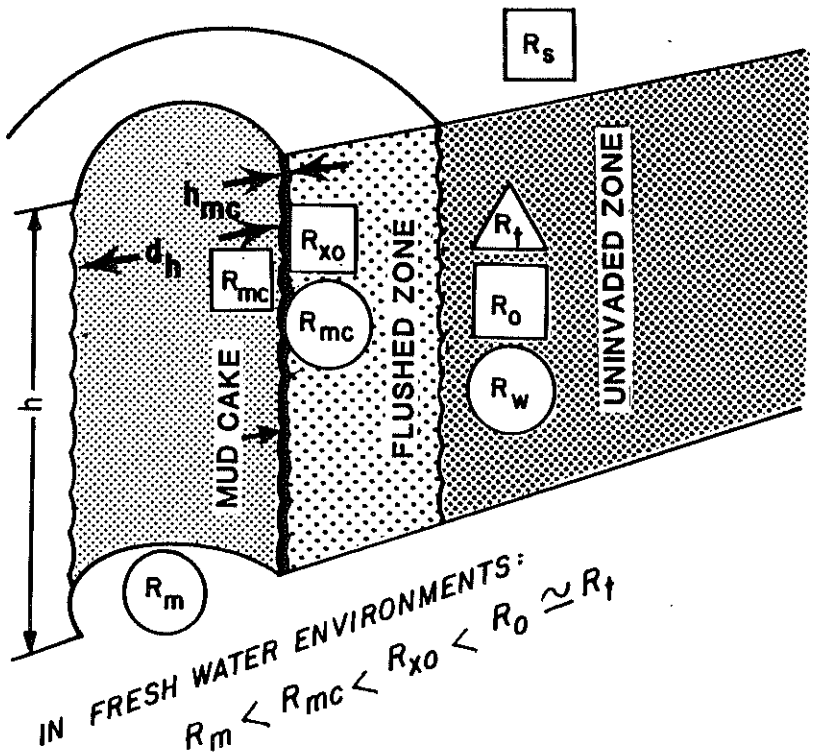
Any type of electric log may be used to determine R_o (actually R_t is used in the petroleum industry but R_o tends to R_t in freshwater wells) according to the equation:

$$R_o = \frac{R_t}{(S_w)^2} \qquad (7)$$

where: S_w is water saturation, in percent

If the formation is 100 percent saturated with water, usually the same water used to mix the drilling mud, then R_o tends to equal R_t.

Figure 16.--Symbols used to denote fluid resistivities and flushed zones. (Modified from Schlumberger, 1972).



IN FRESH WATER ENVIRONMENTS:

$R_m < R_{mc} < R_{xo} < R_o \simeq R_t$

R_m	MUD RESISTIVITY
R_{mc}	MUD CAKE RESISTIVITY
R_o	RESISTIVITY OF FORMATION SATURATED WITH WATER
R_{xo}	RESISTIVITY OF FLUSHED ZONE
R_s	RESISTIVITY OF ADJACENT BED
R_t	TRUE RESISTIVITY OF FORMATION
d	DIAMETER
h	THICKNESS

○ RESISTIVITY OF THE FLUID

□ RESISTIVITY OF THE ZONE

△ RESISTIVITY OF THE FORMATION

One of the main differences between water well drilling and petroleum exploratory drilling is control of the drilling mud. In petroleum exploration, mud resistivity, viscosity and density are carefully controlled since these factors have an important influence on the quantitative analyses of electric logs. In water well drilling, the mixing of the drilling mud is more of an art and rarely are these factors controlled.

Electric logs are only run in the uncased portion of the well where the formations are saturated. Log response in freshwater environments is particularly sensitive to large borehole diameters and formations saturated with highly resistive fluids. These factors coupled together often force most of the current to travel along the borehole yielding apparently low formation resistivity.

Lateral Electric Logs

This type probe is very similar to the normal electric except for a change in electrode configuration (normally a 6' $\overline{AO}$ spacing in water resources investigations). This rearrangement of electrodes enables a deeper penetration into the formation which yields a better approximation of the true formation resistivity (R_0). True lateral logs commonly have an electrode spacing in excess of 18 feet and require exceptionally thick uniform formations for proper interpretation. Unfortunately this deeper reading is at the expense of averaging the resistivity of all the beds within the radius of investigation. Ideally, hydrogeologic units should be relatively uniform over a span of at least twice the radius of investigation in order to minimize adjacent bed boundary effects.

A summary of the Hydrogeologic Application of electric logs is listed in Table 5.

Caliper Logs

Caliper logs are primarily used to correct for changes in borehole diameter directly affect the response of neutron, density, acoustic velocity and short normal electric logs. Caliper logs are also used to approximate the induration of formations which is related to the type of lithology. The most common type of caliper log used in water resources investigations is the self-centering three-arm mechanical type, capable of recording diameters from 2 to 36 inches.

Temperature (gradient and differential) Logs

Temperature logs can be used to; infer lithology over thick uniform sections, inner borehole flow, static water levels, and to correct resistivity measurements to standard temperature (25°C, 77°F). Temperature logs are also used to locate cement behind casings by detecting increases in temperature due to the heat of hydration of fresh cement.

Fluid Resistivity Logs

Fluid resistivity logs record the resistivity of the borehole fluid directly as the borehole fluid is channeled between electrodes located inside the probe. Formation pore water resistivity (R_W) is measured directly, assuming no inner borehole flow.

Fluid Sampler

The fluid sampler is a simple probe capable of obtaining fluid samples anywhere in the borehole by activating a motor controlled valve inside the probe. These point samples are often compared with the fluid resistivity log for determining water quality.

Table 5.--Hydrogeologic Application of Electric Logs (From Keys and MacCary, 1971).

Property Investigated	Single Point	Short Normal	Long Normal	Lateral Device	Focused Guard and Laterolog	Micro-Focused	Induction	SP
Lithologic Correlation	X	X	---	---	X	---	X	X
Bed Thickness	X	X	---	---	X	X	X	X
Formation Resistivity (low R muds)	---	---	X	X	X	---	X	---
Formation Resistivity (fresh mud)	---	---	X	X	---	---	X	---
Invaded Zone Resistivity	---	X	---	---	---	---	---	---
Flushed Zone Resistivity	---	---	---	---	---	X	---	---
Formation Water Resistivity	---	---	X	X	X	---	---	---

Flowmeter (fluid velocity)

This probe measures the relative rate of vertical flow within the borehole. Assuming the borehole diameter is smooth, the slope of the line recorded on the log is directly related to the quantity of water contributed from each zone to the well bore. Although a simple probe, when used in conjunction with the caliper and fluid resistivity probe, parameters such as zone permeability and corresponding water quality can be obtained.

Specialized Probes Used in Hydrogeologic Investigations

Laterolog (focused or guard logs)

Laterologs are primarily used in the petroleum industry to overcome the high conductivity of saline drilling fluids. Electric current is induced into the formation by arranging the electrodes in a configuration in order to focus the current into the formation without appreciably averaging formation resistivity over long vertical spans. Guard logs achieve the same results by means of physically extending the length of the electrodes along the center of the probe. These two types of probes have proven to be extremely valuable for use in hydrogeologic investigations, especially in large diameter wells and in boreholes containing highly resistive pore waters.

Microfocused Electric (microguard) Logs

Microfocused logs have the same electrode arrangement as laterologs, but on a much smaller scale. This probe is primarily designed to measure the resistivity of the mud (R_m) and has a very shallow depth of investigation. It is doubtful that these probes will ever be widely utilized in water resources investigations since mud

characteristics are rarely controlled.

Induction Logs

Induction logs have virtually replaced the standard normal electric log in the petroleum industry. Essentially, this probe provides all of the information of which the normal probes are capable. The only limitation, which renders this log unsuitable for water resources investigations, is that the borehole fluid must have a resistivity at least 2.5 times the resistivity of the formation water. These conditions are usually reversed in freshwater environments which may severely limit the potential use of this probe in many hydrogeologic investigations.

Gamma Spectrometric Logs

These are very specialized logs capable of differentiating gamma rays into discrete energy ranges. The three natural gamma emitting isotopes (potassium, uranium and thorium) has a characteristic gamma spectrum associated with its respective decay series. The gamma spectrometric log records these spectra, which can be analyzed for the relative proportions of each isotope. In some instances, the gamma spectrometric tool can be used to distinguish between gamma "active" potassium and uranium enriched dolomites or phosphorites. This probe is currently used for evaluating uranium ore deposits and probably has little application to water resources investigations.

Tracer Injection Probe

This probe injects a highly saline or short-lived radioactive fluid at a desired depth in the borehole. This fluid is then monitored by detectors located above and below the point of injection. The vertical movement is then observed, with respect to time, and recorded.

Other factors must be known, such as aquifer head differentials, in order to calculate permeability of producing and receiving zones.

Borehole Televiewer

The borehole televiewer transmits a sonic "signal" from a rotating head located on the bottom of the probe. As the sonic signal is reflected back to the probe, a picture is produced representing the negative features (depressions) of the borehole wall. These black and white impressions are useful in observing secondary porosity features such as vugs and fractures. Although the information recorded by this log cannot be used in a quantitative manner, the shapes of the pores and degree of fracture porosity are strong indicators of the water transmitting characteristics of the formation. These probes are still in the experimental stage of development and are very costly.

Borehole Television

Within the last few years, microelectronics have made it feasible to reduce the size of television cameras to less than two inches in diameter. These continuous television surveys (also available in color) can be used in a non-quantitative manner to observe fracture porosity and solution cavities. At this time, television surveys are mainly used in tool recovery operations and well inspections.

LITHOLOGIC DETERMINATIONS FROM GEOPHYSICAL LOGS

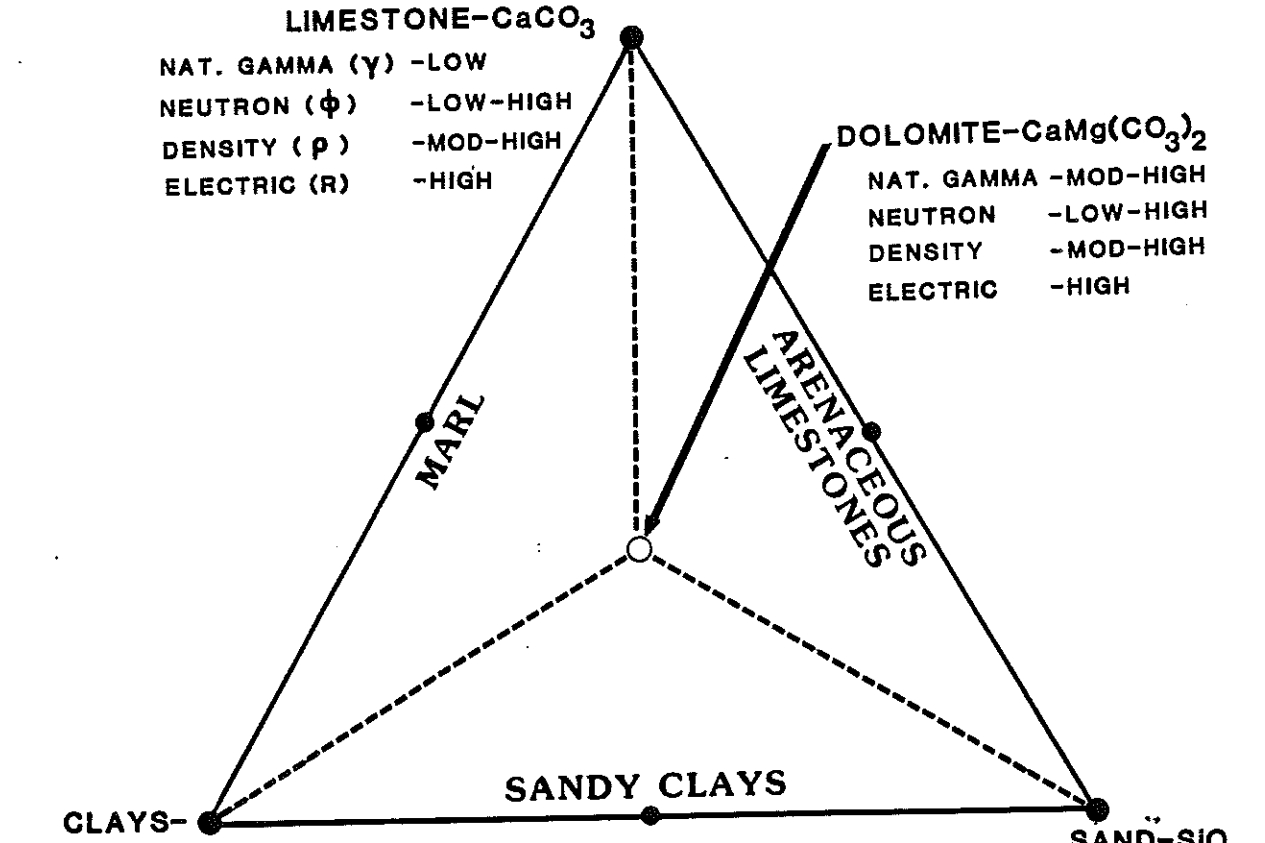
One of the most accurate methods of determining lithology is by cross plotting information obtained from the porosity suite of logs (neutron, density and acoustic velocity). Lithologic type, essentially, is determined by solving the formation matrix density by cancelling porosity obtained by different types of porosity logs. At the present time, lithologic determinations from geophysical logs are rarely performed in hydrogeologic studies. Only a limited number of shallow well logging units have the capability of running the probes needed to cross plot lithologic information.

The four main lithologies found in sedimentary environments include quartz sands, limestones, dolomites and clays (Figure 17). Other sedimentary minerals of minor significance include anhydrite and gypsum. These later minerals are highly soluble (releasing dissolved calcium and sulfate) and generally render ground water unpotable and will not be discussed in this research.

Methods and geophysical logs used for determining lithology, as discussed in this section include:

Method	Log
Lithology-Porosity cross plot	Neutron, Density and Acoustic Velocity
M and N plot	Neutron, Density and Acoustic Velocity
Thermal Conductivity	Gradient and Differential Temperature
Induration	Caliper
Natural Gamma and Gamma Spectrometry	Natural Gamma and Gamma Spectrometric

Figure 17.--Typical log responses to the dominant lithologies of the Tertiary sediments of the Southeastern Coastal Plain. The terms low, moderate (mod) and high refer to the relative magnitude of pen deflection from the log base line.


LIMESTONE-$CaCO_3$
NAT. GAMMA (γ) -LOW
NEUTRON (ϕ) -LOW-HIGH
DENSITY (ρ) -MOD-HIGH
ELECTRIC (R) -HIGH
DOLOMITE-$CaMg(CO_3)_2$
NAT. GAMMA -MOD-HIGH
NEUTRON -LOW-HIGH
DENSITY -MOD-HIGH
ELECTRIC -HIGH
MARL
ARENACEOUS LIMESTONES
SANDY CLAYS
CLAYS-
SAND-SiO_2
KAOLINITE $Al_4Si_4O_{10}(OH)_8$
MONTMORILLONITE $Al_2Si_4O_{10}(OH)_8 \times H_2O$
ILLITE $K_{1.5}Al_4(Si\ Al)_8O_{20}(OH)_4$
NAT.GAMMA -LOW-HIGH
NEUTRON -HIGH
DENSITY -LOW
ELECTRIC -LOW
NAT.GAMMA -LOW
NEUTRON -MODERATE
DENSITY -MODERATE
ELECTRIC -HIGH

Electric logs are rarely used for lithologic determinations since the resistivity of the three dominant producing lithologies (sands, limestones and dolomites) are very similar. Water resistivity, cementation and pore geometry also influence formation resistivity to a greater degree than lithology. Electric logs can be used to confirm the presence of clays and argillaceous materials when used in conjunction with other logs. Clays and clay in matrices significantly affect the response of many geophysical logs. The detection of clays also has hydrogeological importance. The last portion of this section addresses methods for determining clay content and clay type present.

Lithologic-Porosity Cross Plots

Differentiating various lithologic types is commonly performed by cross plotting geophysical logs responding to matrix density and porosity. Cross plotting, essentially, is a graphical method of solving for two unknowns (porosity and the composition ratio between two lithologic end-members), provided two of the parameters are directly related to the unknowns being solved. Since there are three unique types of porosity logs (neutron, density and acoustic velocity), three different cross plot combinations are possible (density-neutron, acoustic velocity-neutron and density-acoustic velocity). These three types of cross plots are termed lithologic-porosity cross plots and provide a considerable amount of information concerning lithology, porosity, clay content and secondary porosity. The main drawback of lithologic cross plots is the assumption that only two lithologies are present and the zone being evaluated is a mixture of only these two end-members (limestone-dolomite, limestone-quartz sand, or dolomite-quartz sand).

If this assumption is true, and the logs are properly calibrated, then all three cross plots will produce similar results for lithology and porosity.

If a third lithology (or mineral) is introduced into the system, the calculations become a bit more complex. Instead of solving a point on a straight line between two lithologic end-members the point lies in the interior of a triangle with each lithology at the corners. Fortunately, all three porosity logs respond uniquely to quartz sand, limesone and dolomite. Data from these three logs can then be used simultaneously in two equations to yield the coordinates of a point within the triangle. This triangular cross plot is commonly called an M and N plot (Burke et al, 1969). M and N are derived from the equations:

$$M = \frac{\Delta t_f - \Delta t}{\rho_b - \rho_f} \times 0.1 \qquad (8)$$

and

$$N = \frac{\phi_{nf} - \phi_n}{\rho_b - \rho_f} \times 10 \qquad (9)$$

where, in freshwater saturations:

Δt_f = 189 μsec/ft
Δt = transit time from log
ρ_b = bulk density from log
ρ_f = 1.0
ϕ_{nf} = 1.0
ϕ_n = porosity from neutron log

The M and N plot is a mineralogical plot independent of primary porosity. Once a point is plotted on the triangular M and N plot, the relative percentages of each mineral type (lithology) can be determined. These percentages can then be replotted on the lithology-porosity cross plots to solve porosity.

Data points plotting below the M and N triangle contain an additional component of clay in the matrix. Clay increases the acoustic velocity which has the effect of reducing the value of M. The neutron log also responds to clay by recording an "apparent" porosity greater than the true porosity. These two factors, both due to clay in the matrix, serve to push the data points in a south and westerly direction below the triangle. Since clays exhibit a wide range of acoustic velocities and densities, it is difficult to calculate clay content from the M and N plot without knowing the type of clay present. Clay content correction techniques will be discussed later in this section.

Secondary porosity also has a peculiar effect on the M and N plot. Secondary porosity often forms large voids in irregular patterns. Compressional waves from the acoustic velocity transmitter tends to bypass large voids yielding an "apparently" low porosity on the acoustic velocity log. As a consequence, the numerator of the M factor increases and data points shift upward (north) of the triangular plot. If the percentage of each lithologic type is known, this information can be replotted on the lithology-porosity cross plots and secondary porosity effects can be quantified. There is still some conjecture as to whether all the porosity not recorded on the acoustic velocity log is of a secondary nature.

The previous information may be summarized as follows; if:

$\phi_{\text{acoustic velocity}} = \phi_{\text{neutron-density}}$

then the two end-member lithology cross plot is correct (limestone-quartz sand, limestone-dolomite, or quartz sand-dolomite).

ϕ acoustic velocity $<$ ϕ neutron-density

then there are secondary porosity effects by-passed by the acoustic velocity probe.

ϕ acoustic velocity $>$ ϕ neutron-density

then the lithologic combination chosen was wrong and the M and N plot should be used as a starting point to determine the proper lithologic combination.

ϕ neutron-acoustic velocity $>$ ϕdensity

then there is probably an appreciable percentage of clay in the matrix that needs to be accounted for to obtain the correct lithology and porosity (Hilchie, 1982).

Examples of Lithology - Porosity Cross Plots

In order to minimize adverse extraneous factors affecting log response, the following methodology was used in selecting zones for analyses:

1) Smooth sections of the borehole where the zones were at or very near bit gauge;
2) Uniformly thick lithologic zones (as determined by the entire log suite). Transition zones were avoided whenever possible;
3) Zones exhibiting extreme values were used in order to plot data over a wide range of porosity, density, etc.;
4) Log measurements were averaged over approximately twice the probes radius of investigation in order to minimize adjacent bed effects; and
5) Clays and clayey zones were avoided.

Calibration methods for neutron, density and porosity logs are discussed in Appendix I. Algorithms for steps in utilizing lithologic-porosity cross plots follow the figure presented in the text.

Cross plot paper for different cementation factors is provided in Appendix N.

Neutron-Density Cross Plot for Well LV-1

The neutron-density cross plot is one of the most widely used lithology porosity cross plots used owing to its accuracy and to the wide use of neutron and density logs. The accuracy of this plot may be attributed to the wide separation between the lines representing the three main producing lithologies for the two parameters compared (porosity and density). The neutron porosity scale, along the X-axis, is calibrated in relative limestone porosity. A dolomite of the same porosity (or quartz sand) should be converted to the proper density. Table 6 may be used to convert neutron measurements to porosities or densities (in g/cc) for lithologies other than limestone.

Lithologic determinations were made for well LV-1, located in north-central Florida for the interval analyzed from 950 to 1,150 feet below land surface. Two distinct lithologies, pure dolomite and a limey-dolomite, appear to be interbedded throughout this interval. Porosity, as indicated from the cross plot (Figure 18), ranges from 4 to 31 percent Many of the zones analyzed suggest the dolomites are very compact and of low porosity. These inferences are in good agreement with the geologists' log, as described from the core obtained from this well (Appendix L). Very little or no clay is observed in the carbonate sequence is observed from the cross plot (points southeast of the dolomite line) or is noted in the geologists' log. The two points above the limestone line may be reflecting a small percentage of quartz sand that may have been washed during the drilling. Table 7 is an algorithm for outlining the steps for using lithologic-porosity cross plots.

Table 6.--Limestone, Dolomite and Sandstone Densities for Various Porosities in Saturated Freshwater Environments.

POROSITY	LIMESTONE	DOLOMITE	SANDSTONE
0	2.71	2.85	2.65
1	2.69	2.83	2.63
2	2.68	2.81	2.62
3	2.66	2.79	2.60
4	2.64	2.78	2.58
5	2.62	2.76	2.57
6	2.61	2.74	2.55
7	2.59	2.72	2.53
8	2.57	2.70	2.52
9	2.56	2.68	2.50
10	2.54	2.66	2.49
11	2.52	2.64	2.47
12	2.50	2.62	2.45
13	2.49	2.61	2.44
14	2.47	2.59	2.42
15	2.45	2.57	2.40
16	2.44	2.55	2.39
17	2.42	2.54	2.37
18	2.40	2.52	2.35
19	2.39	2.50	2.34
20	2.37	2.48	2.32
22	2.33	2.44	2.29
24	2.30	2.41	2.25
26	2.27	2.37	2.22
28	2.23	2.33	2.19
30	2.20	2.30	2.16
32	2.16	2.26	2.12
34	2.13	2.22	2.09
36	2.09	2.18	2.06
38	2.06	2.14	2.02
40	2.03	2.11	1.99
42	1.99	2.07	1.96
44	1.96	2.03	1.92
46	1.92	2.00	1.89
48	1.89	1.96	1.86
50	1.86	1.92	1.83
55	1.77	1.83	1.74
60	1.68	1.74	1.66
65	1.60	1.65	1.58
70	1.51	1.56	1.50
75	1.42	1.46	1.41
80	1.34	1.37	1.33
85	1.26	1.28	1.25
90	1.17	1.19	1.17
95	1.09	1.09	1.08
100	1.00	1.00	1.00

Figure 18.--Bulk density vs. neutron porosity - lithology cross plot for well LV-1 located in north central Florida. The geophysical logs are located in Appendix K and a geologic description of the core in Appendix L.

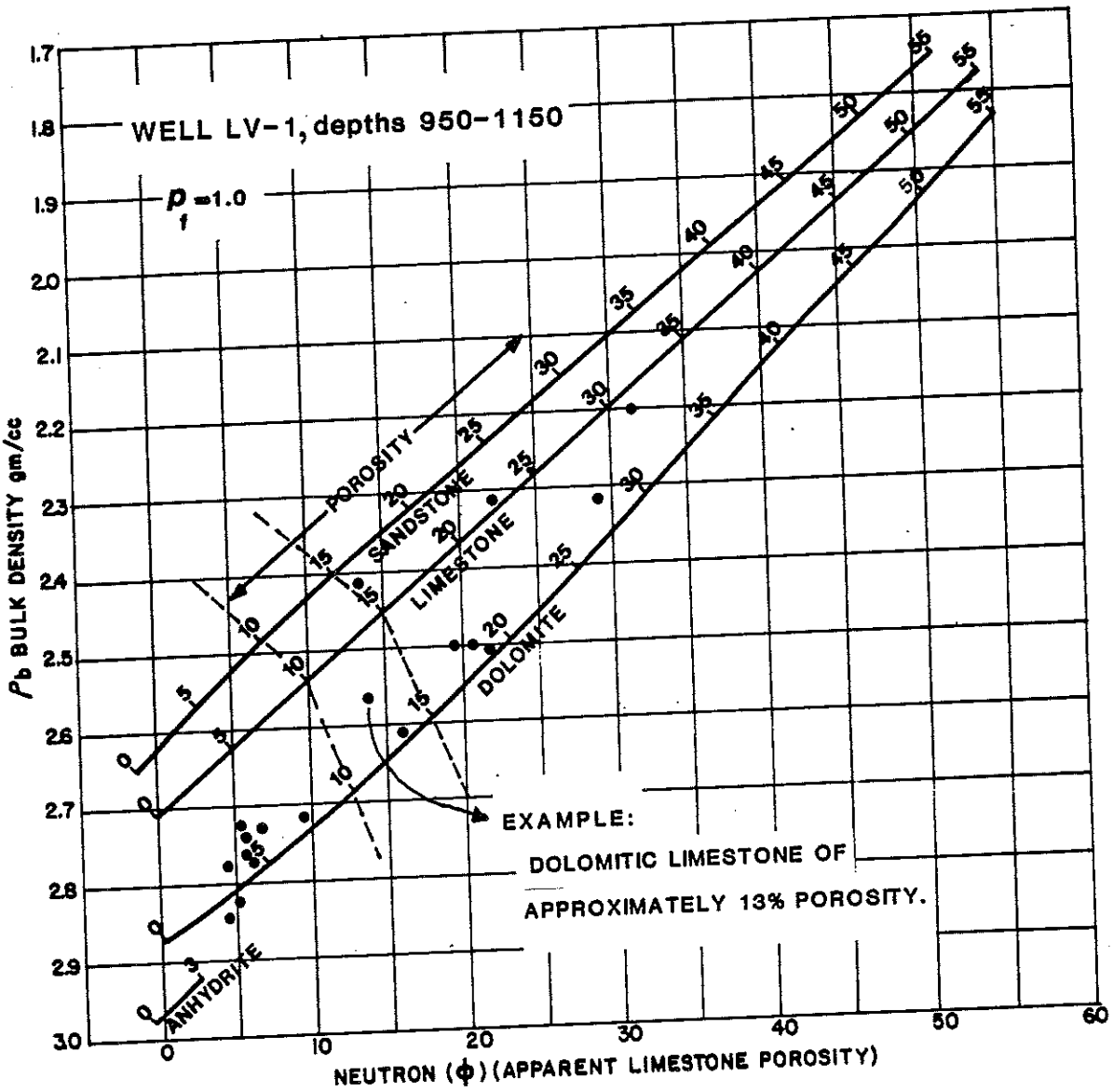

WELL LV-1, depths 950-1150
p_f =1.0
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ANHYDRITE
EXAMPLE:
DOLOMITIC LIMESTONE OF
APPROXIMATELY 13% POROSITY.
ρ_b BULK DENSITY gm/cc
NEUTRON (ϕ) (APPARENT LIMESTONE POROSITY)
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
0
10
20
30
40
50
60

Table 7.--Algorithm for Determining Lithology and Porosity from Density vs. Neutron, Acoustic Velocity vs. Neutron and Density vs. Acoustic Velocity Cross Plots.

1) Select zones near bit-gauge size from the caliper log which require no correction factor for borehole diameter.

2) Locate thick uniform lithologic zones (at least twice the thickness of the probe with the largest radius of investigation) from natural gamma and electric logs. Correction factors may be necessary for zones with thin sharp peaks, i.e., probe did not obtain maximum (or minimum) reading from zone.

3) Adjust neutron, density and acoustic velocity logs between minimum and maximum values. (See Appendix I for further discussion).

4) If the lithology scaled is not limestone, adjust porosity before aligning neutron, density and sonic transit time scales.

5) Compare porosity values of logs for agreement and compare with cutting (or cores) to determine if a clay content factor is necessary.

6) Readjust scales to clean lithologies and plot other points accordingly.

Logs required: neutron, density or acoustic velocity and caliper.

Assumptions:

A. Only saturated, clean zones (non-clays) are selected for analyses; and

B. Borehole diameters are at or near bit gauge.

C. Saturating fluid is fresh water.

Acoustic Velocity-Neutron Cross Plot For Well LE-7

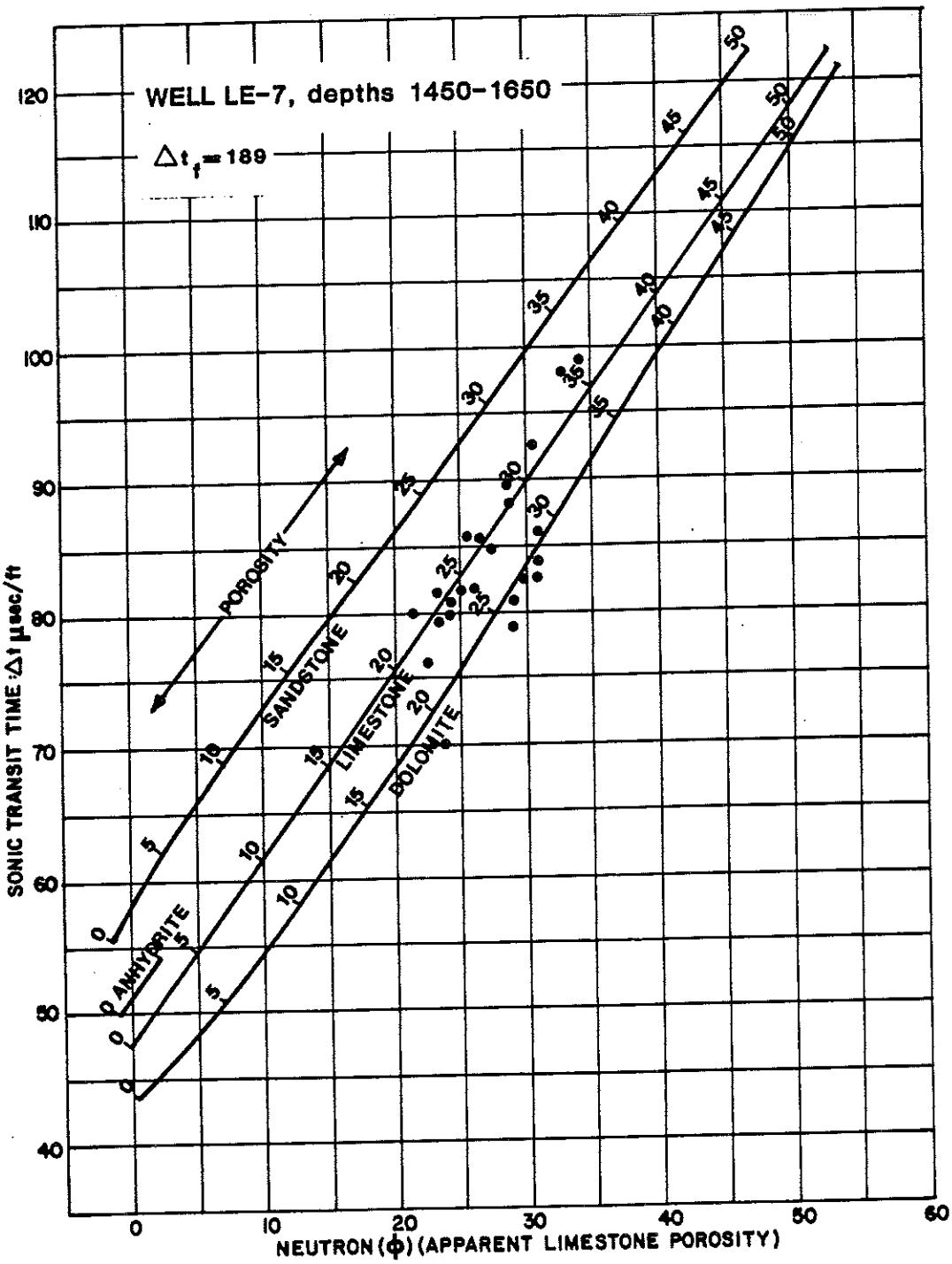
This type of lithology-porosity cross plot is restricted to formations containing little or no clay and formations with little secondary porosity. These two factors have opposing effects on the acoustic velocity log that may yield erroneous results. Clays tend to increase the acoustic velocity yielding an "apparently" high porosity value. Vugs and other types of secondary porosity, often record "faster" than true matrix velocities which tend to underestimate porosity.

The well chosen for this cross plot is located in the coastal area of Lee County, (Well LE-7) southwest Florida. From the depths analyzed, 1,450 to 1,600 feet below land surface, the cross plot (Figure 19) suggests a matrix comprised of both limestone and dolomite end-members. Porosity, from the 23 zones analyzed, ranged from 19 to 36 percent. Data points plotting slightly above the limestone line probably do not contain a sand component, but are probably reflect the presence of secondary porosity. Lithologic percentages of limestone and dolomite are in good agreement with the geologic log described from the well cuttings (geologic log, Appendix L, neutron and acoustic velocity logs, Appendix K).

Density-Acoustic Velocity Cross Plot of Well PB-1

This type of plot requires precise measurements from both the density and acoustic velocity logs. Borehole compensated probes and uniformly thick, porous lithologic sections are required for this type of plot. In order to obtain as precise measurements as possible, data for this cross plot were procured from a deep well run with borehole compensated probes by Schlumberger Well Surveys, Inc. The well is

Figure 19.-- Acoustic velocity vs. neutron porosity - lithology cross plot for well LE-7, southwest Florida. The geophysical logs are located in Appendix K and a geologic description of the core in Appendix L.


WELL LE-7, depths 1450-1650
Δt_f = 189
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ANHYDRITE
SONIC TRANSIT TIME: Δt μsec/ft
NEUTRON (Φ) (APPARENT LIMESTONE POROSITY)
120
110
100
90
80
70
60
50
40
0
10
20
30
40
50
60

located in southeast Florida (Well PB-1). The interval examined ranged from 4,000 to 4,150 feet below land surface. Unfortunately, the combination of compensated neutron and acoustic velocity logs with corresponding lithologic information was not available for any freshwater wells in the study area. Conclusions reached from the cross plot cannot be confirmed but are consistent with lithologic data collected from adjacent wells. According to the cross plot (Figure 20), about one-half of the zones analyzed are a dense, low porosity dolomite of six to eight percent porosity. The remaining zones contain a greater percent of limestone and appear to be more porous (up to 21 percent).

Density-acoustic velocity cross plots can be used to determine clay content (volume percent) of clayey-sands provided the density and acoustic velocity values of at least one zone analysed is known Since density values (obtained from density logs) are relatively unaffected by clay, clay percentages can be inferred linearly as a proportion of the distance between the sandstone line and the "known" clay point.

M and N Plot for Well PB-1

The M & N plot (Figure 21), has a variety of applications including determining mineral type, clay content and secondary porosity (independently of primary porosity). Data used for this plot were the same zones used in the density-acoustic velocity cross plot (Well PB-1), in addition to neutron porosity data. All of these probes were compensated for borehole rugosity.

Lithologic information from this plot also indicate a group of dense dolomites progressively grading to limestones also characterized by an appreciable increase in secondary porosity. Data points plotting below the dolomite-limestone line may contain an additional component of

Figure 20.--Bulk density vs. acoustic velocity cross plot for lithologic determinations for well PB-1, southwest Florida. The geophysical logs for this well are located in Appendix K.

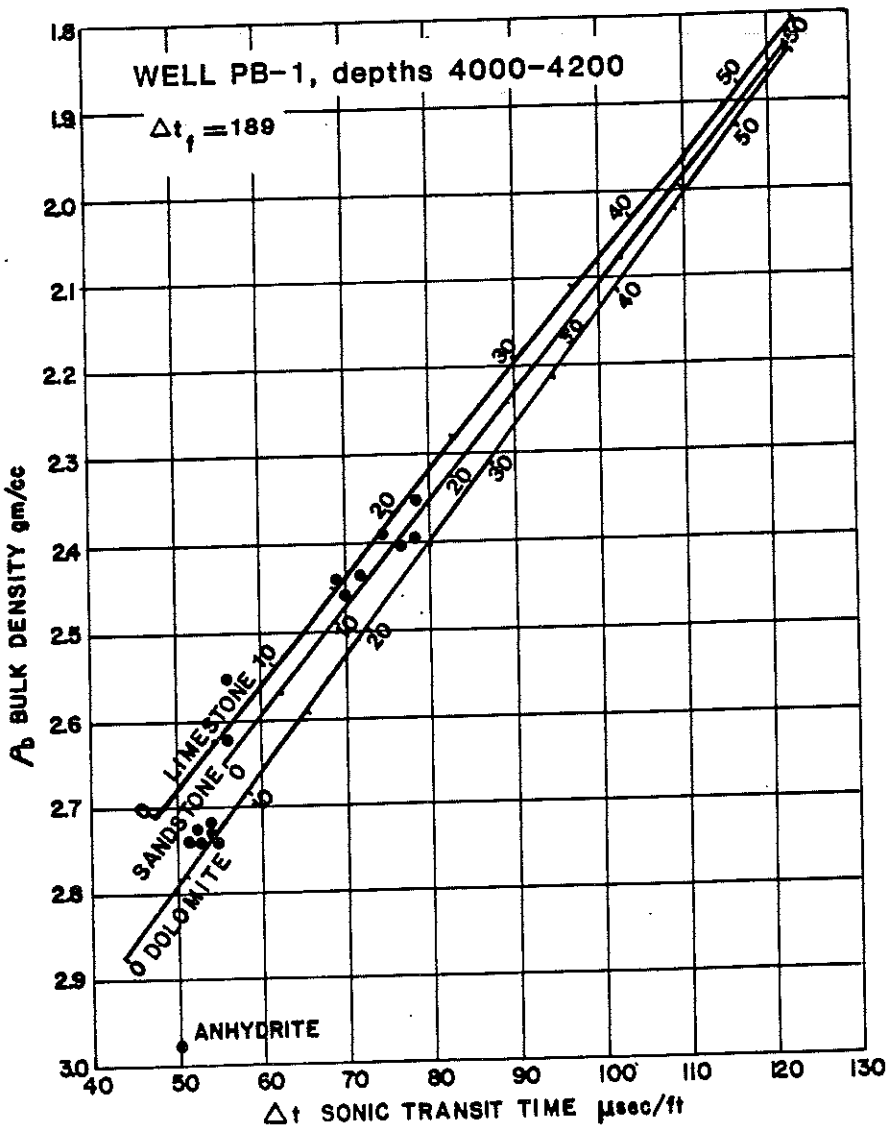
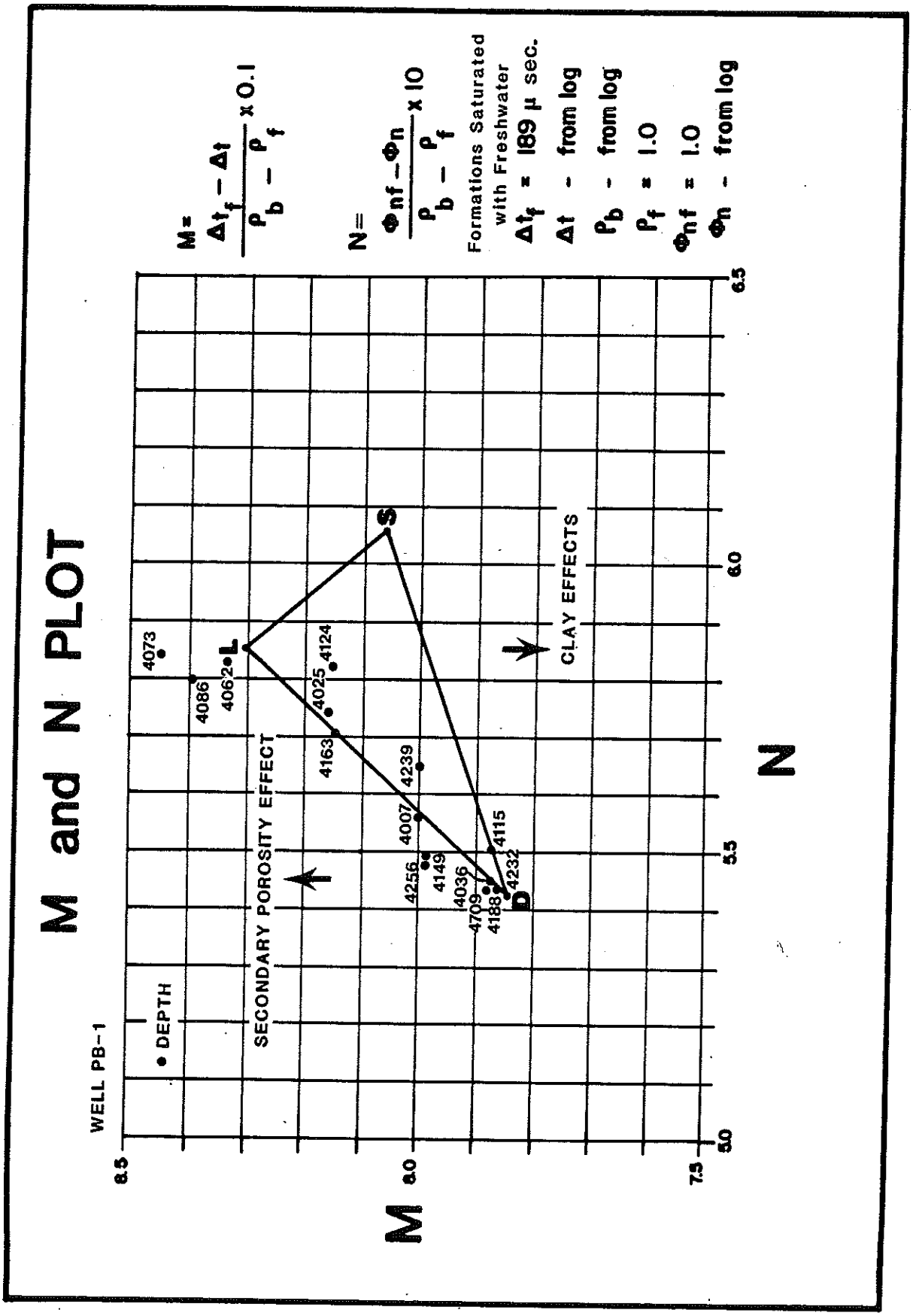

WELL PB-1, depths 4000-4200
$\Delta t_f = 189$
ρ_b BULK DENSITY gm/cc
Δt SONIC TRANSIT TIME μsec/ft
LIMESTONE
SANDSTONE
DOLOMITE
ANHYDRITE
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
40
50
60
70
80
90
100
110
120
130
0
10
20
30
40
50

Figure 21.--M & N plot for well PB-1, southeast Florida. This type of plot yields information on the mineralogical composition of the formation (D = dolomite, L = limestone and S = sandstone). Formations with an appreciable amount of clay and/or secondary porosity will plot slightly above or below the triangle in a north (secondary porosity) or south (clay) direction.


M and N PLOT
WELL PB-1
• DEPTH
SECONDARY POROSITY EFFECT
CLAY EFFECTS
M
N
8.5
8.0
7.5
6.5
6.0
5.5
5.0
4073
4086
4062
4124
4025
4163
4239
4007
4115
4256
4149
4036
4709
4188
4232
S
L
D
M= Δtf − Δt / ρb − ρf x 0.1
N= Φnf − Φn / ρb − ρf x 10
Formations Saturated with Freshwater
Δtf = 189 μ sec.
Δt - from log
ρb - from log
ρf = 1.0
Φnf = 1.0
Φn - from log

sand and/or clay. Other information would be required to confirm this departure from the carbonate line.

Comparison of Porosity and Density Log Values with Laboratory Core Analyses

Results of nine core samples from a test well (GA-39 located in eastern Gadsden County, northwest Florida) were analyzed for porosity by laboratory methods and compared to porosity measurements obtained from neutron and density logs. Each sample was split in the laboratory and analyzed for porosity. The core was obtained from an NX diamond bit core barrel (54 mm diameter). Laboratory and log measurements are summarized in Table 8. Geophysical logs and corresponding lab measurements of cored intervals are graphically represented in Figure 22.

Table 8.--Laboratory Core Analyses for Porosity as Compared to Porosity Derived from Neutron and Density Logs for Well GA-39.

Depth	Dominant Lithology	Lab Porosity (%)	Neutron Porosity (%)	Density Porosity (%)
75	Limestone	43.9	44	42
91	Limestone	48.5	51	43
101	Dolomite	44.2	45	46
206	Dolomite	32.2	33	41
227	Dolomite	71.4	52	40
268	Dolomite	40.0	42	36
276	Dolomite	47.7	55	38
335	Dolomite	43.3	34	36
358	Dolomite	43.9	40	36

The correlation coefficient (r), of the lab porosity compared to the neutron and density logs, for the nine zones analyzed (for

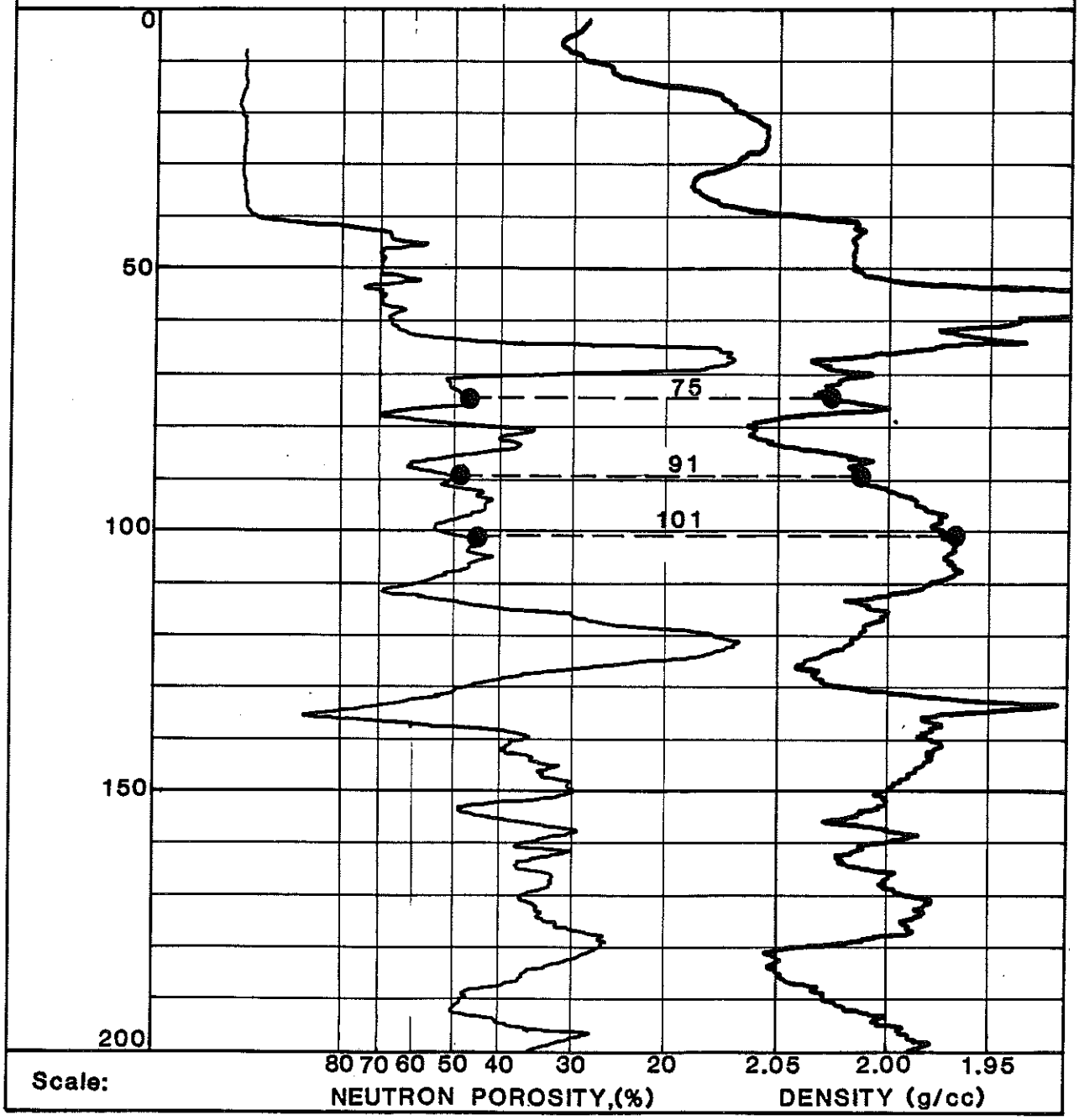
Figure 22.--Neutron and density logs from well GA-39 used in comparing porosity from laboratory core analyses. Data points (laboratory) plotting directly on the log curve are in good agreement with the log. Table 8 is a numerical comparison of the porosity values for the two methods.

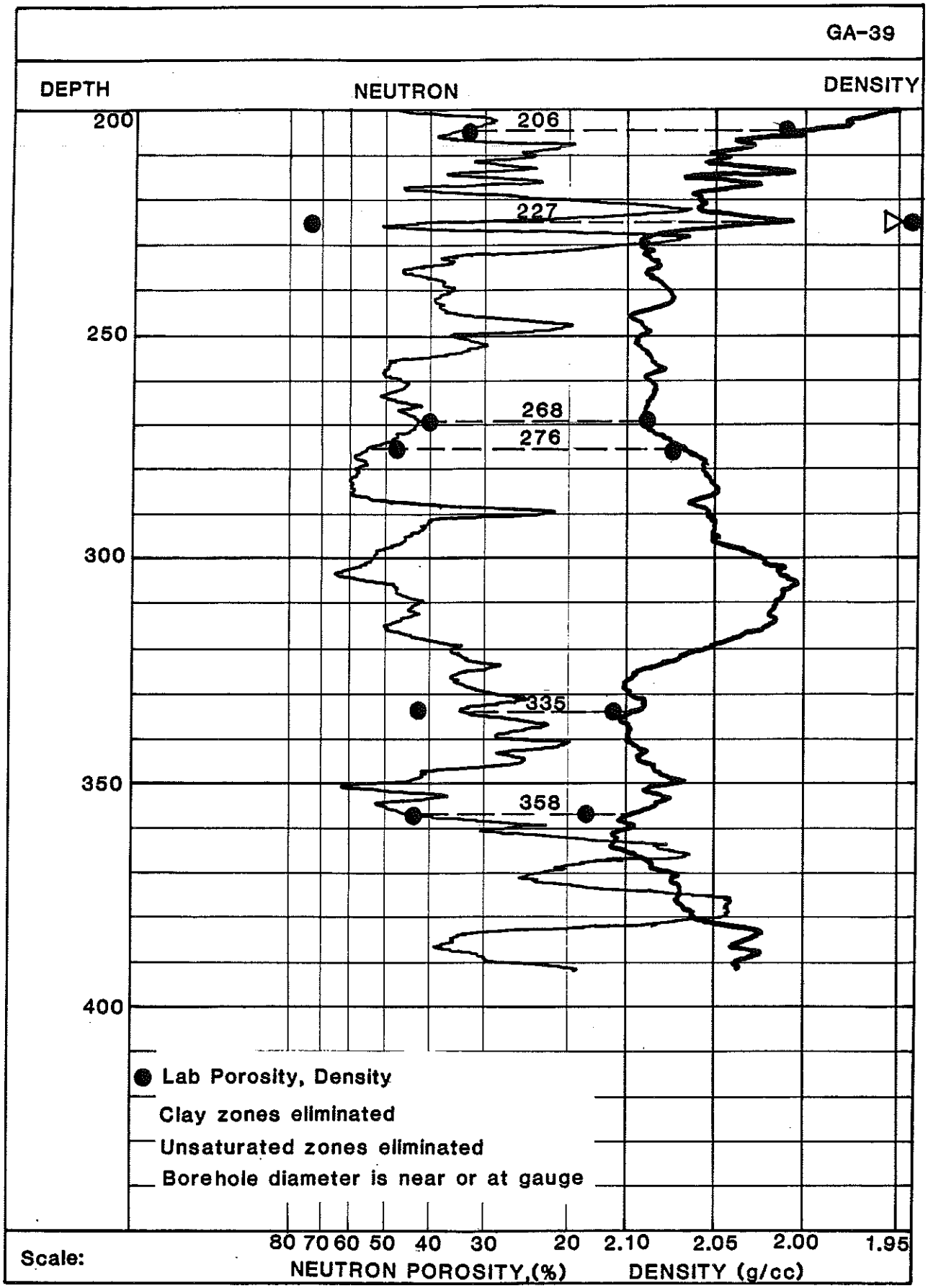
NAME NWFWMD-Core COUNTY Gadsden W- _____

LOCATION T 1N R 2W SEC. 06 1/4 _____ NWF- GA-39

DEPTH 470 CASING 42 DIA 4 AQUIFER Floridan

Notes:




GA-39
DEPTH
NEUTRON
DENSITY
200
250
300
350
400
206
227
268
276
335
358
Lab Porosity, Density
Clay zones eliminated
Unsaturated zones eliminated
Borehole diameter is near or at gauge
Scale:
80 70 60 50 40 30 20
NEUTRON POROSITY,(%)
2.10 2.05 2.00 1.95
DENSITY (g/cc)

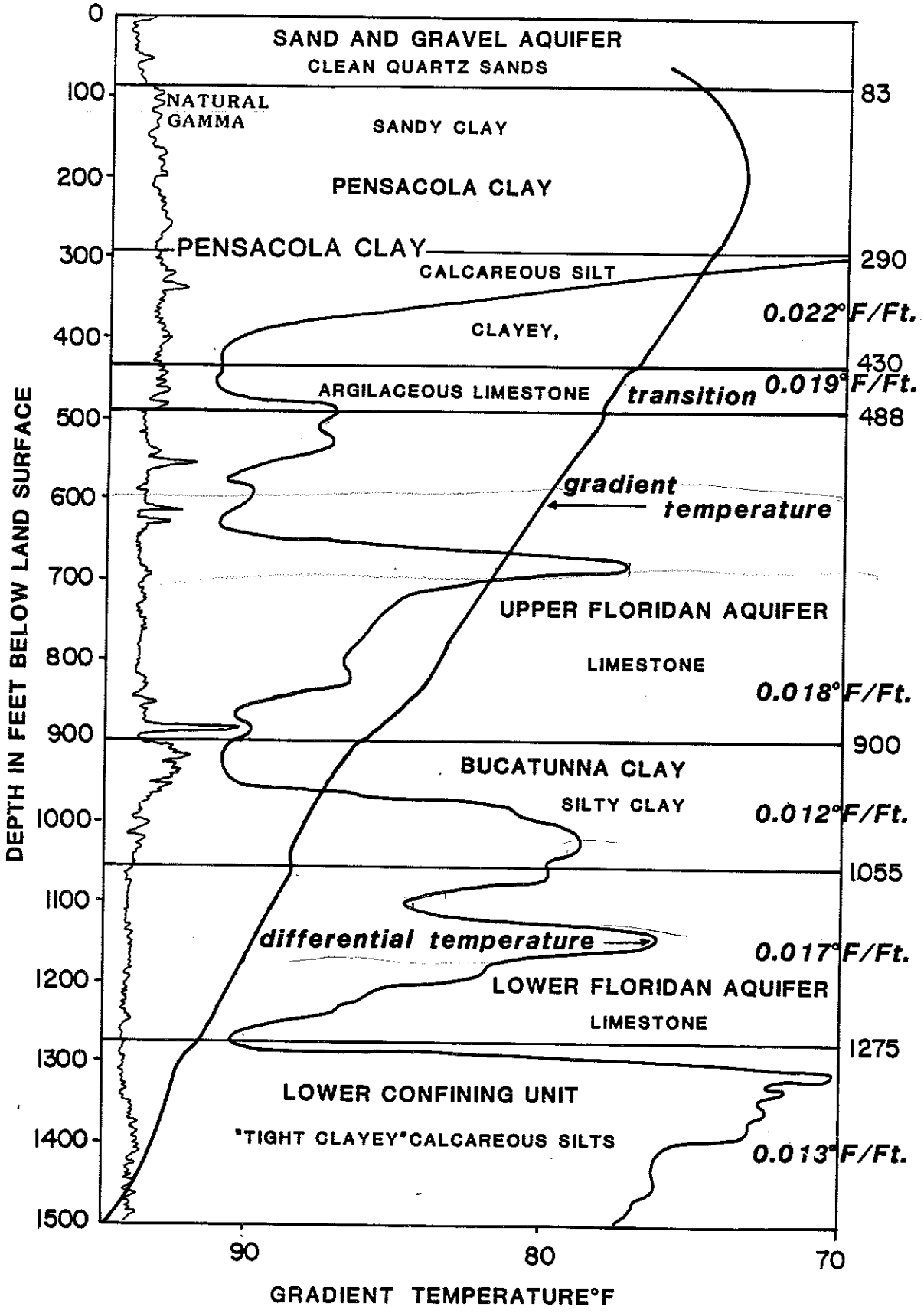
significance levels of Pearson Product - Moment correlation coefficients, Appendix G) is r = 0.67. The core from depth 227 is an extremely porous dolomite with moldic type porosity. If this sample were eliminated from the statistical analyses, the correlation coefficient would rise to about r = 0.92. A re-examination of volumetric and density analyses indicate that the porosity analyzed from this laboratory plug was too high. Observations from the core exhibit an extreme amount of variability in porosity with depth. Some of the porosity differences can be attributed to the geophysical logs "averaging" measurements over a greater vertical distance and actually may be more representative of the "true" formation values.

Lithologic Determination by Thermal Conductivity

Lithologically, thick homogeneous formations exhibit a distinct uniform thermal conductivity (Figure 23). The magnitude of conductivity is a function of the formation's mineralogy, porosity, pore geometry and volume of ground water circulated through the hydrologic system. An "average" geothermal gradient for the coastal plain may be on the order of 0.02/F° per foot of depth, but may vary significantly in different geographical areas depending upon the physical properties of the individual formations. The following thermal conductivity values represent some of the more common lithologies. (See Appendix F for a more detailed list of thermal conductivities.)

	Cal/Sec/Cm^2
Sandstone	3.0 -12.2
Limestone	2.4 - 8.1
Dolomite	9.3 -11.9
Clay	2.2 - 3.9
Water	1.43

Figure 23.--Gradient and differential temperature logs penetrating six hydrogeologic units, in southern Okaloosa County, Florida. Clays and argillaceous units tend to have a lower geothermal gradient than clean carbonates and quartz sands.


SAND AND GRAVEL AQUIFER
CLEAN QUARTZ SANDS
NATURAL GAMMA
SANDY CLAY
PENSACOLA CLAY
PENSACOLA CLAY
CALCAREOUS SILT
CLAYEY,
ARGILACEOUS LIMESTONE
transition
0.022°F/Ft.
0.019°F/Ft.
gradient temperature
UPPER FLORIDAN AQUIFER
LIMESTONE
0.018°F/Ft.
BUCATUNNA CLAY
SILTY CLAY
0.012°F/Ft.
differential temperature
0.017°F/Ft.
LOWER FLORIDAN AQUIFER
LIMESTONE
LOWER CONFINING UNIT
"TIGHT CLAYEY"CALCAREOUS SILTS
0.013°F/Ft.
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
83
290
430
488
900
1055
1275
90
80
70
DEPTH IN FEET BELOW LAND SURFACE
GRADIENT TEMPERATURE°F

Very sensitive temperature probes have been used in a few instances to determine the thickness of various hydrogeologic units in northwest Florida. The temperature log from (Figure 23) Well OA-41, distinctly defines six hydrogeologic zones based upon thermal conductivity. Clays appear to have a thermal gradient of about 0.012 °F/Ft. while thermal gradients of carbonate units are about 50 percent higher (about 0.018 °F/Ft.). The shape of the gradient temperature curve at the formation contact is characteristic of the relative thermal conductivity change. The slope of the gradient temperature curve increases upon entering more conductive units such as clays or argillaceous formations.

Lithology Inferred From Caliper Logs

The geometric shape of the borehole often can provide information concerning the type of lithology and induration of the formations penetrated by the drill bit (Figure 24). Although caliper logs do not reveal quantitative hydrogeologic information, the caliper can be used to confirm the presence of cavernous zones, clays, unconsolidated material and occasionally, highly fractured dolomites.

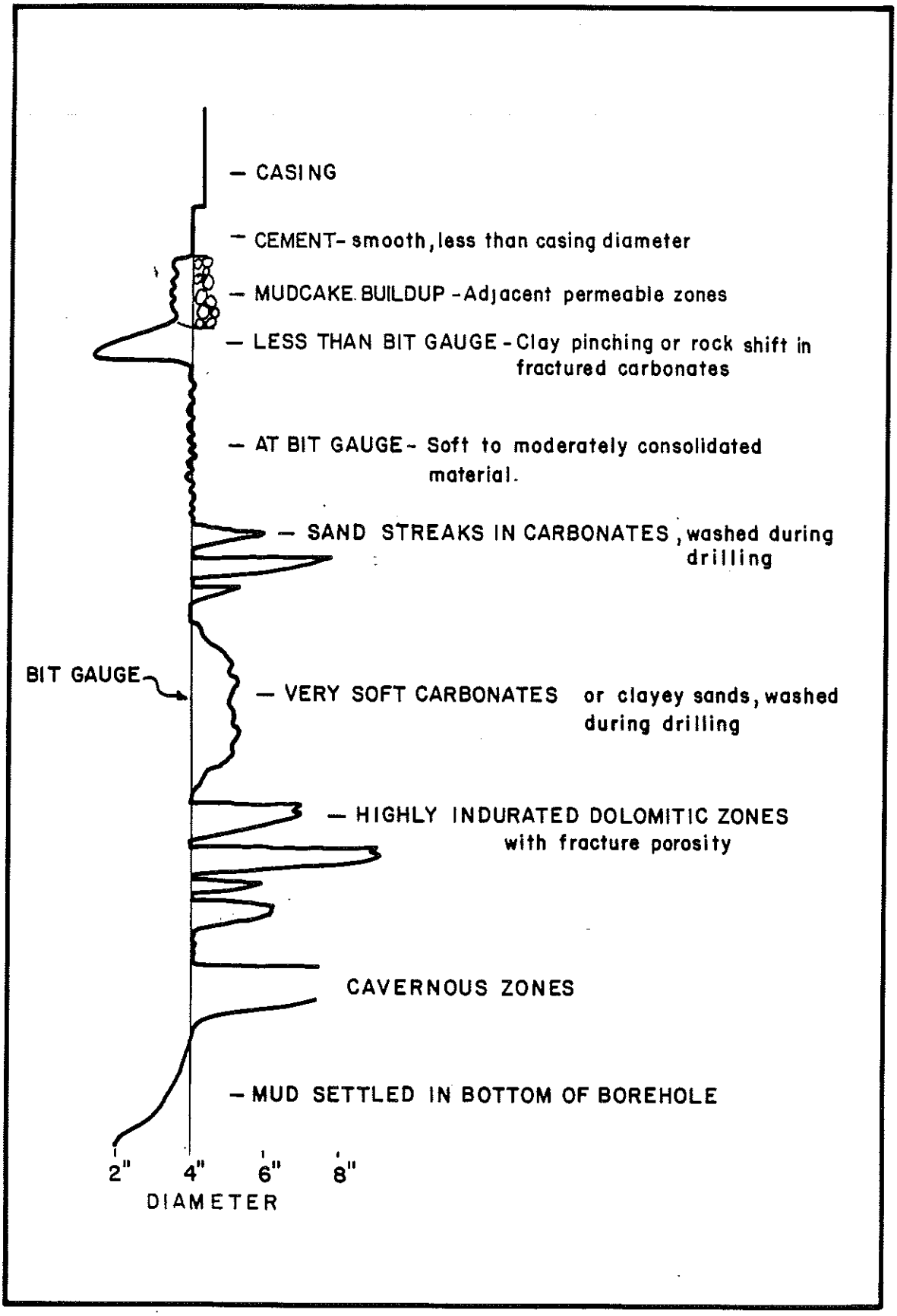
Most drill bits used in water well construction are designed to drill a smooth hole through moderately consolidated material. If the material is very soft, the shape of the hole will be fairly smooth, but exhibit an undulating surface characteristic of sands, clays, or poorly consolidated limestones. Thin "streaks" indicate a softer or less consolidated material has been washed from more consolidated zones, such as sand streaks bedded in a carbonate. Highly indurated dolomites have low ductility and often fracture into irregular shapes.

Figure 24.--Caliper log response to various types of lithologic units. The degree of induration and geometry of the borehole is often indicative of the lithology.

similar ionic characteristics) would tend to substitute for calcium in carbonate minerals.

If the above assumption is true, then it would appear that a gamma spectrometer probe (capable of separating gamma energies) would be capable of differentiating between gamma active dolomites and clays. Gamma spectrometric probes are available for borehole logging, but have been primarily restricted to locating sylvite or uranium deposits. In order to determine if gamma spectrometric probes would aid in water resources investigations, 90 core samples from 11 wells were chosen for gamma spectrometric and x-ray analyses based upon extreme high and low gamma activity as recorded on the natural gamma log. All major lithologic types, ranging in age from Eocene to Recent, were sampled. Methodology and laboratory procedures for determining the percent of total gamma activity emitted from each isotope is documented in Appendix J.

The results failed to conclusively prove that any of the isotopes preferred to concentrate in any particular type of lithology (Table 9 and Figure 26). The mean percent of total gamma activity from potassium was 8.5, 9.7, 8.4 and 9.6 for sand, clay, limestone and dolomite, respectively. Gamma activity uranium had means of 58.8, 56.5 65.3 and 63.6 percent for sand, clay, limestone and dolomite, respectively. Thorium had the greatest statistical deviation but was not convincingly incorporated in any particular type lithology. Thorium had percent gamma activities of 32.7, 33.8, 26.4 and 26.8 for sand, clay, limestone and dolomite respectively. The standard deviation for each of the samples was large enough to conclude that there is not an appreciable fractionation of these isotopes with respect to lithology. Figure 27 is


— CASING
— CEMENT- smooth, less than casing diameter
— MUDCAKE BUILDUP - Adjacent permeable zones
— LESS THAN BIT GAUGE - Clay pinching or rock shift in fractured carbonates
— AT BIT GAUGE - Soft to moderately consolidated material.
— SAND STREAKS IN CARBONATES, washed during drilling
BIT GAUGE
— VERY SOFT CARBONATES or clayey sands, washed during drilling
— HIGHLY INDURATED DOLOMITIC ZONES with fracture porosity
CAVERNOUS ZONES
— MUD SETTLED IN BOTTOM OF BOREHOLE
2"
4"
6"
8"
DIAMETER

Crystalline and sucrosic dolomites will often produce an extremely irregular borehole profile with only a few thin zones remaining at or near bit gauge. Cavernous zones will often span many feet vertically and extend beyond the maximum diameter measurable of most calipers (about 36 inches). Borehole diameters less than gauge may be the result of clays or clayey zones squeezing into the borehole, excessive mud cake buildup adjacent to permeable zones or fractured rocks shifting within the borehole. Comparing the caliper log with other logs may help to eliminate some of these possibilities.

Lithologic Determination From Natural Gamma and Gamma Spectrometry Logs

Natural gamma logs often display a wide range of gamma activity for various mixtures of quartz sand, clays, limestones and dolomites. Low gamma activity is normally associated with clean quartz sands, clays with low cation-exchange capacities, (kaolinite, discussed later in the clay content section), and clean platform type limestones (such as the Ocala Limestone). These types of lithologies often have gamma activity near background levels (10 to 20 A.P.I. Gamma ray units). High gamma activity is frequently associated with dolomites, high cation exchange capacity clays (illite), micaceous sands, feldspathic sands and clays, and phosphorites (Figure 25). Therefore, it is evident that the magnitude of gamma activity, as recorded on the gamma log, is not associated with any particular type of lithology. Most sediments are mixtures of two or more mineral end-members. Since virtually all gamma activity is from isotopes of three elements; potassium, uranium, and thorium, it would appear that potassium would preferentially fractionate in feldspathic sands and clay minerals, and uranium and thorium (having

Figure 25.--American Petroleum Institute (A.P.I.) gamma ray units for various types of Tertiary sediments.

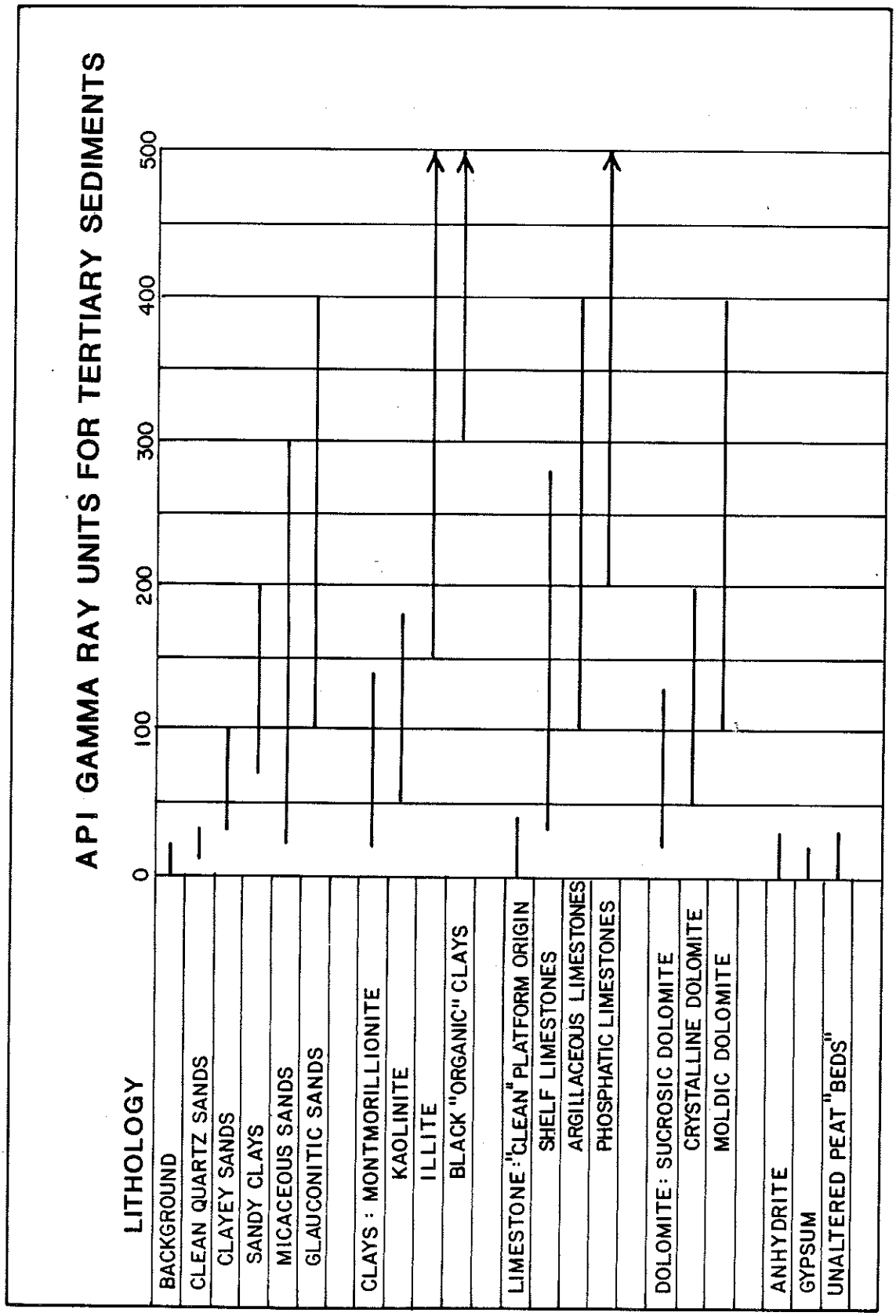

API GAMMA RAY UNITS FOR TERTIARY SEDIMENTS
LITHOLOGY
0
100
200
300
400
500
BACKGROUND
CLEAN QUARTZ SANDS
CLAYEY SANDS
SANDY CLAYS
MICACEOUS SANDS
GLAUCONITIC SANDS
CLAYS : MONTMORILLIONITE
KAOLINITE
ILLITE
BLACK "ORGANIC" CLAYS
LIMESTONE : "CLEAN" PLATFORM ORIGIN
SHELF LIMESTONES
ARGILLACEOUS LIMESTONES
PHOSPHATIC LIMESTONES
DOLOMITE : SUCROSIC DOLOMITE
CRYSTALLINE DOLOMITE
MOLDIC DOLOMITE
ANHYDRITE
GYPSUM
UNALTERED PEAT "BEDS"

Figure 26.--Trilinear plots of percent gamma-rays emitted from potassium (K), uranium (U), and thorium (Th) for sands, clays, limestones and dolomites. Each division represents five percent. None of the samples analyzed had gamma activity in excess of 15 percent.

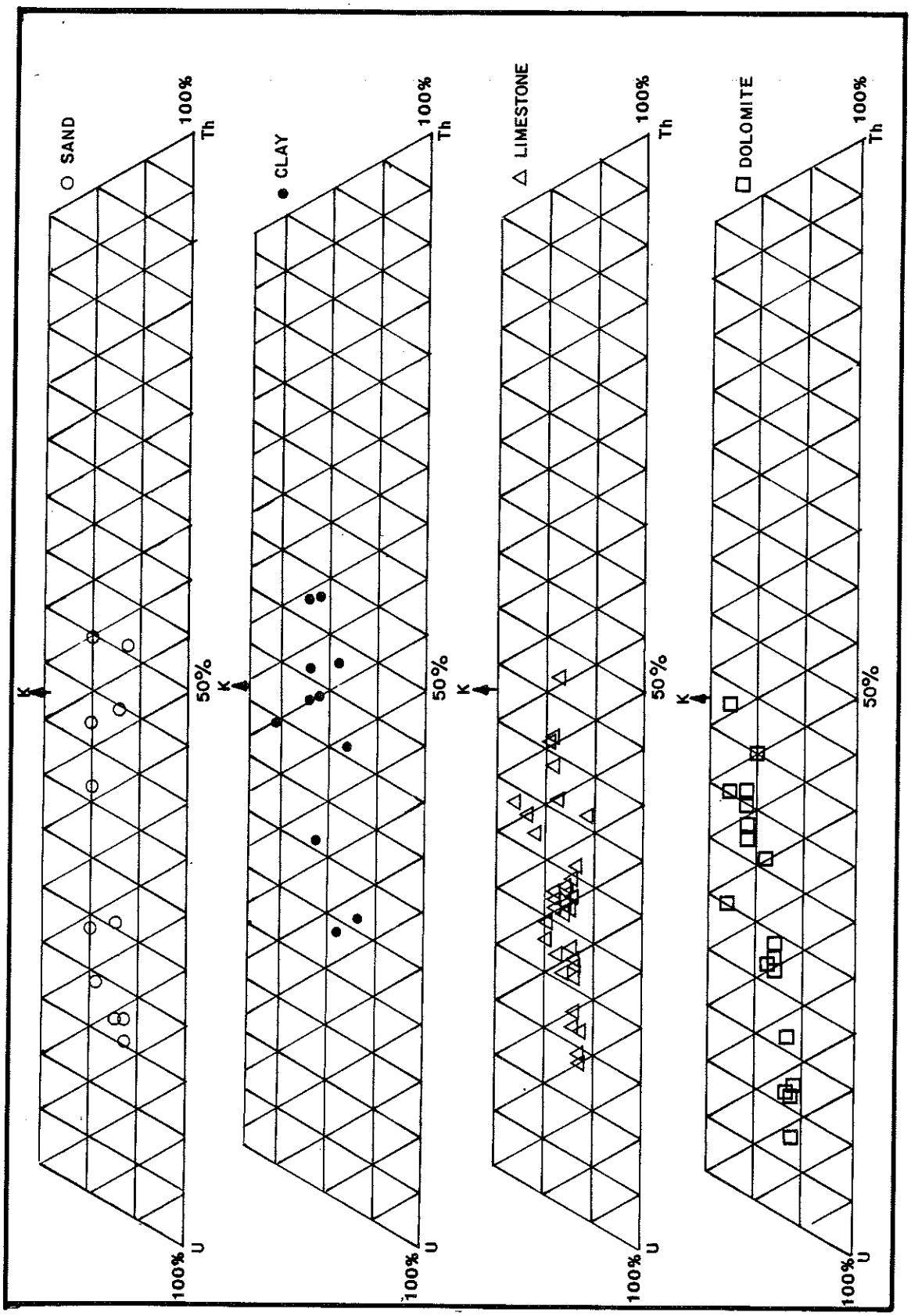

SAND
CLAY
LIMESTONE
DOLOMITE
100%
Th
50%
K
100%
U

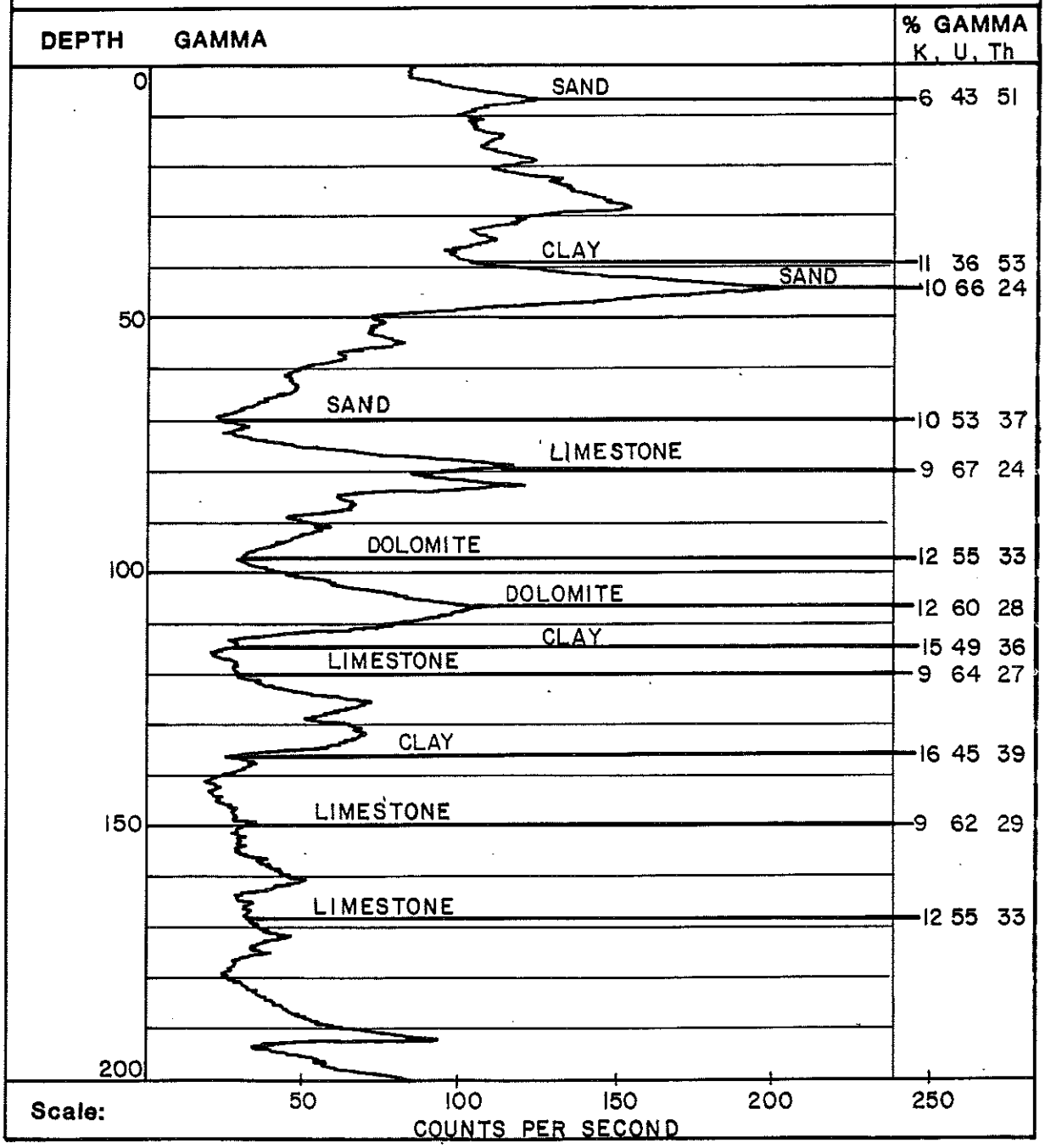
Figure 27.--Natural gamma log and relative gamma emissions (in percent) for various lithologies from uranium, thorium and potassium for well GA-39. The dominant lithology is noted beside the depth.

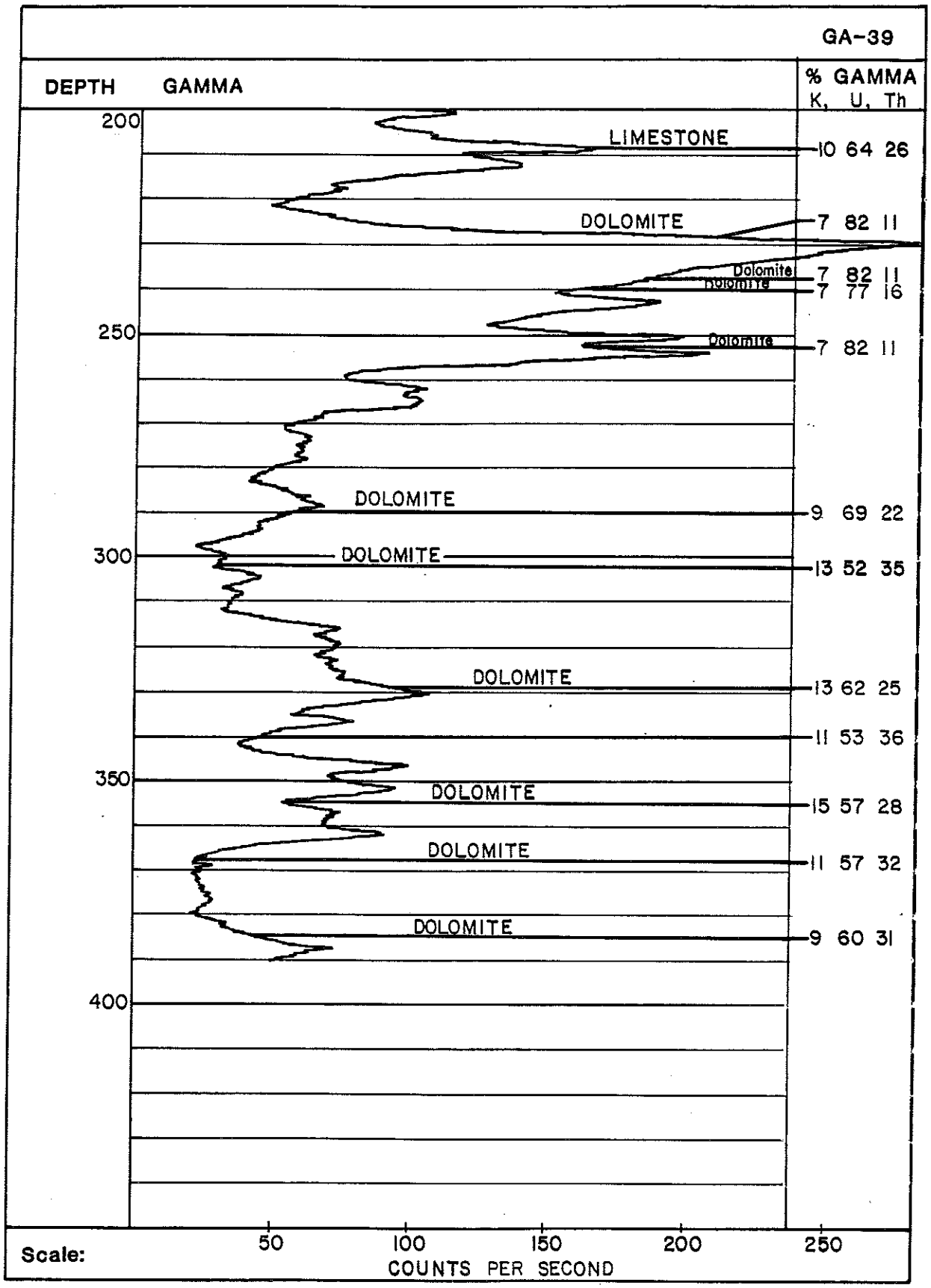
NAME NWFWMD-Core COUNTY Gadsden W- _____

LOCATION T 1N R 2W SEC. 06 1/4 _____ NWF-GA-39

DEPTH 470 CASING 42 DIA 4 AQUIFER Floridan

Notes:




GA-39
DEPTH
GAMMA
% GAMMA
K, U, Th
200
250
300
350
400
LIMESTONE
10 64 26
DOLOMITE
7 82 11
Dolomite
7 82 11
Dolomite
7 77 16
Dolomite
7 82 11
DOLOMITE
9 69 22
DOLOMITE
13 52 35
DOLOMITE
13 62 25
11 53 36
DOLOMITE
15 57 28
DOLOMITE
11 57 32
DOLOMITE
9 60 31
Scale:
50
100
150
200
250
COUNTS PER SECOND

a natural gamma log (Well GA-39) from a test hole penetrating quartz sands, clays, limestones and dolomites. The percent of gamma radiation (in counts per second) from each of the three gamma emitting isotopes is recorded to the right of the log.

In addition to the absence of any significant fractionation among these isotopes, only about 9% (9.26%) of the total number of gamma rays counted (from the 90 cores) were from potassium (K^{40}). Uranium accounted for the largest percent of gamma rays detected (61.12%) and thorium next, contributing 29.62 percent.

Table 9.--Percent of Total Gamma Rays Emitted from Potassium, Uranium and Thorium as Determined by Gamma Spectrometric Analyses for Various Types of Tertiary Sediments.

For all samples, including mixed lithologies (n = 90 from 11 wells).

	Potassium(K)	Uranium (U)	Thorium (Th)
n =	90	90	90
mean	9.26	61.12	29.62
std. dev.	2.26	12.05	12.41

Relatively "pure" lithologies (n = 72)

	SAND			CLAY			LIMESTONE			DOLOMITE		
	K	U	Th	K	U	Th	K	U	Th	K	U	Th
n =	11	11	11	11	11	11	32	32	32	18	18	18
mean	8.5	58.8	32.7	9.7	56.5	33.8	8.4	65.3	26.4	9.6	63.6	26.8
std. dev.	1.8	14.9	14.3	1.8	13.2	12.2	1.7	8.8	8.0	2.7	12.4	9.9

From this data, it appears that gamma spectrometry logs run in carbonate environments may not be a useful method for determining lithology.

A re-examination of the "clay material" analyzed indicated that many of the "clays" are actually weathered (or dissolved) carbonates of a clay size fraction. These calcareous clays have also incorporated a

minor amount of clay minerals (kaolinite, montmorillonite, etc.) which yield clay (mineral) peaks on x-ray diffractograms (See Dabous, 1981, for x-ray procedures).

Most of these calcareous "clays" have very high gamma activity. One explanation of the high gamma activity may be attributed to the "pure" calcium carbonate fraction, after being dissolved, leaves behind a more resistant residue fraction containing a high concentration of potassium, uranium and thorium. These clays often appear in unconformable, thin layers within thick carbonate sequences (of much lower gamma activity). Although these "clays" comprise only a small percentage of the total carbonate sequence, their presence is of great hydrologic importance. These clays often act as effective aquicludes greatly limiting the exchange of water between producing zones. These clays, although very thin but areally extensive, also are very distinct on natural gamma logs and can be used in subsurface mapping as strati-graphic marker horizons that can often be traced for tens of miles.

Estimating Clay Content From Clastic and Carbonate Formations

The single most important log interpretation problem is recognizing and determining the volume of clay present in producing zones. Clays can considerably affect the response of natural gamma, neutron acoustic velocity and electric logs. Only the density log appears to be "immune" to minor amounts of clay. Since most of the main logs are affected to some degree by clay, it can be assumed that lithologic determinations, water quality, and producing characteristics, as inferred from logs, may be in considerable error if the clay content

is not recognized.

The term "clay" has both mineralogical and grain size connotations (Table 10). Most geophysical logs respond similarly to clay minerals or sections comprised of "clay size" materials. The most notable exception is the natural gamma log, which varies considerably in response among various clay minerals.

Samples from a wide range of carbonate sequences indicate that true clay minerals are only present in significant quantities in Hawthorn (Middle Miocene) and younger formations. Clays directly overlying the Floridan aquifer and clays within the thick carbonate sequence are often clay size particles comprised of calcareous residium (by-products of the dissolution of the upper portion of the carbonate units). Incorporated in these calcareous clays (size term) are clay minerals deposited contemporaneously with the finer fraction of residium. In many instances, this small proportion of clay minerals (kaolinite, montmorillonite, etc.) will yield characteristic peaks on x-ray diffractograms. In many instances, the entire sample is erroneously assigned a clay (mineral) name although the bulk of the sample is calcareous.

It is also important, hydrologically, to recognize the type of clay distribution within the formation. Clays may appear in distinct thinly laminated streaks, alternating between very clean zones, or as interspersed particles homogeneously mixed with coarser granular material. Hydrogeologic units of the latter type distribution usually will be less productive than zones containing laminated clays.

Table 10.--Types of Clays Occurring in Tertiary Sediments Within the Study Area.

		LOG RESPONSE					
Clay-mineral	Formula	Gamma	Neutron*	Density	Acoustic**		Electric***
Kaolinite	$Al_4Si_4O_{10}(OH)_8$	Moderate	High H^+	2.69	Slows	t	Mod R
Montmorillonite	$Al_2Si_4O_{10}(OH)_8$	Low	High H^+	2.33	Slows	t	Low R
Illite	$K_{1.5}Al_4(Si, Al)_8O_{20}(OH)_4$	High	High H^+	2.76	Slows	t	Low R
Palygorskite	$Mg_5Si_8O_{20}(OH)_2(OH_2)4 \cdot 4H_2O$	Moderate	High H^+	2.4	Slows	t	Low R
Clay-size							
Chalk	$CaCO_3$	Low	Moderate H+	2.71	Slows	t	Mod R
Calcareous Residium	-----	High	High H+	----	Slows	t	Low R

*H = hydrogen concentration
**t = transit time
***R = resistivity

Clays in carbonates may appear as laminations but more commonly are homogeneously distributed throughout the carbonate unit (argillaceous limestones). Argillaceous limestones are very fine grained and rarely develop effective secondary porosity and are generally poor aquifers. Carbonate units, with areally continuous laminations, tend to respond as multiple aquifer systems since thinly laminated clays greatly impede the exchange of water between adjacent aquifers.

The type of clay distribution (interspersed or laminated) also affects acoustic velocity and electric logs. Formation with interspersed

type of plot appears to be applicable for both granular (Figure 29) and argillaceous formations (Figure 30). Both plots appear to yield reasonable results but should be further analyzed and compared with actual cores. The actual density and neutron logs for Figures 29 and 30 are included in Appendix K.

Another variation on clay content percentage for adjusting to true porosity, also utilized data from the density and neutron logs and can be estimated according to the equation (Schlumberger, 1975).

$$\phi_{\text{corrected}} \qquad \frac{(\phi_N)^2 + (\phi_D)^2}{\phi^2} \qquad (13)$$

The acoustic velocity log may be substituted for the density log in most clay content cross plots and equations, but is more sensitive to other factors and requires additional formation information.

clay do not seriously affect the acoustic velocity if the clay is entirely interstitial and not supporting the grains within the matrix. Laminated clays tend to slow acoustic waves, and record an "apparently" higher porosity. Interspersed clays, within a formation, will greatly reduce apparent resistivity to a greater degree than a formation with lamainated clays.

Effective clays, (clays with high ion exchange capacity) due to their ionic layering decrease resistivity below what would be expected from a reduction in grain size alone. Illite, especially, shows this effect of decreased resistivity while kaolinite, chlorite and dolosilts have "high" resistivity, similar to fine grained sands (Hilchie, 1982).

Clays and Natural Gamma Activity

In petroleum log interpretation, the natural gamma log, often called a "shale" log, is widely used to delineate shaly zones. Occasionally, the gamma log is also used as a quantitative indicator of shale content. Within the study area, the gamma log appears to be a rather poor indicator of clay (or "shale") for two reasons: 1) even the "very pure" clays (mineral) exhibit a wide range gamma activity from near background to greater than 500 A.P.I. counts per second; and 2) many other lithologies are known to have a wider range of gamma activity than clays.

"Pure" montmorillonite ($Al_2Si_4O_{10}(OH)_8$) does not readily incorporate any of the naturally occurring gamma active isotopes (K, U, or Th) and often appears as units of low activity on natural gamma logs. Many of the carbonates and phosphates freely substitute uranium and thorium ions in their lattice structure (up to 150 ppm uranium in pebble phosphates, (Sweeney and Windham, 1979)). Phosphatic limestones are

among the most gamma active formations encountered in carbonate environments due to the incorporation of uranium and thorium.

Methods for Determining Clay Content of Clastic and Carbonate Formations

Gamma Ray Index (GRI)

If the gamma active zones on a log are due to a particular type of clay (either as interspersed or laminations), the proportional amount of gamma activity of each zone can be measured by the Gamma Ray Index (GRI) Method. In addition to the above assumption, at least one sample point on the log must have its clay content (percentage) known in order to scale the remaining zones (Dresser Atlas, 1975).

$$\text{Gamma Ray Index (GRI)} = \frac{GR_{log} - GR_{clean\ sands}}{GR_{clay\ point} - GR_{clean\ sand}} \qquad (10)$$

or;

$$V_{clay} = 0.21 \times [2^{(2.9 \times GRI)} - 1]$$

where V = clay volume in percent

The plot of the clay-gamma relationship is semi-logarithmic where the clay has a proportionally larger effect on the gamma log in the low percentage range and a lesser contribution to total gamma activity in the higher range (Dresser Atlas, 1975). Figure 28 is an actual example using the GRI Method in a binary granular environment. The only two lithologies present (observed from a core) are coarse quartz sands and gravels, and an illitic-kaolinitic clay (determined by x-ray diffraction from all clay zones).

The GRI Method probably has less application in carbonates than in granular materials. Argillaceous limestones tend to incorporate a greater amount of "dirty", or gamma active carbonate material, that is

Figure 28.--Gamma log of well SR-2 used for clay content analyses of a clayey sand by the gamma-ray index method. The chart shown is for determining clay content by the gamma ray index method (From Dresser Atlas, 1975).

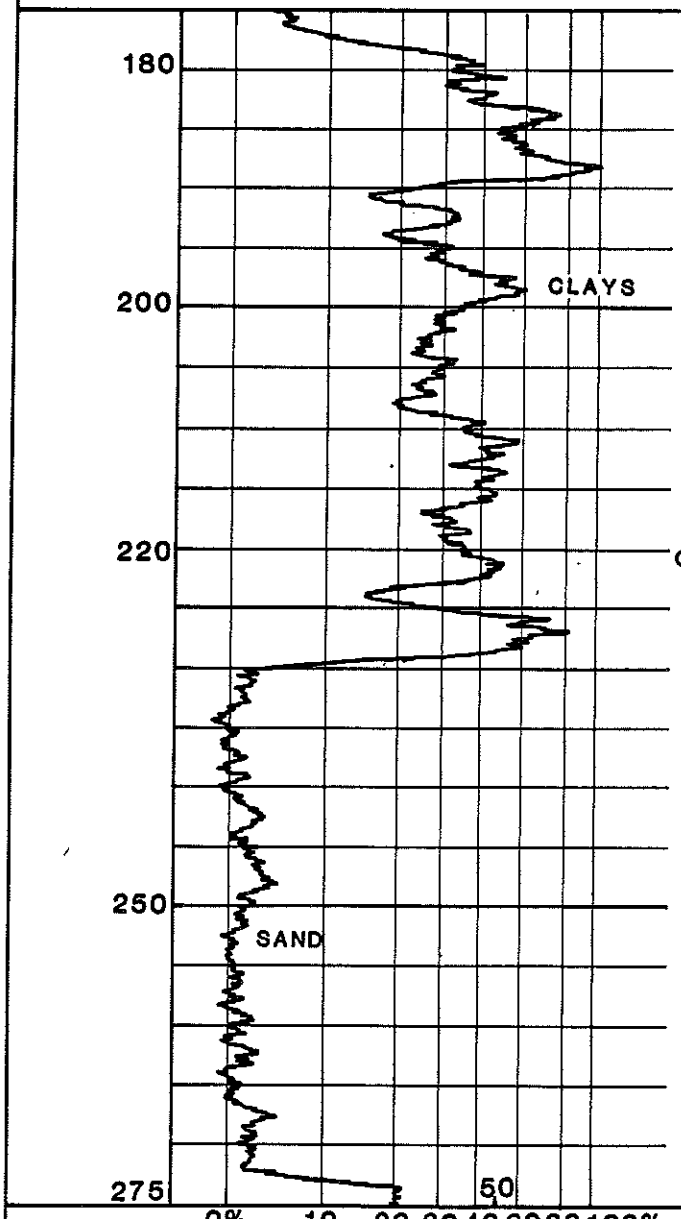
NAME Wilbur Weeks COUNTY Santa Rosa W- _____

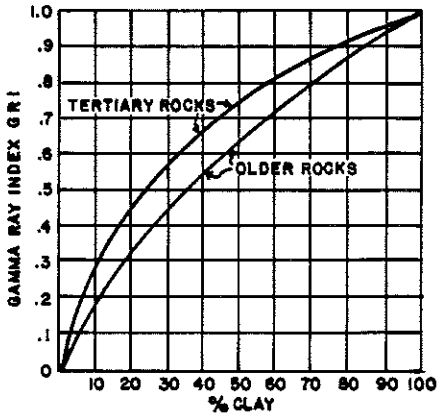
LOCATION T 4N R 29W SEC. 06 1/4 _____ NWF- SR-2

DEPTH 439 CASING 84 DIA 4 AQUIFER Surficial

Notes:

DEPTH GAMMA



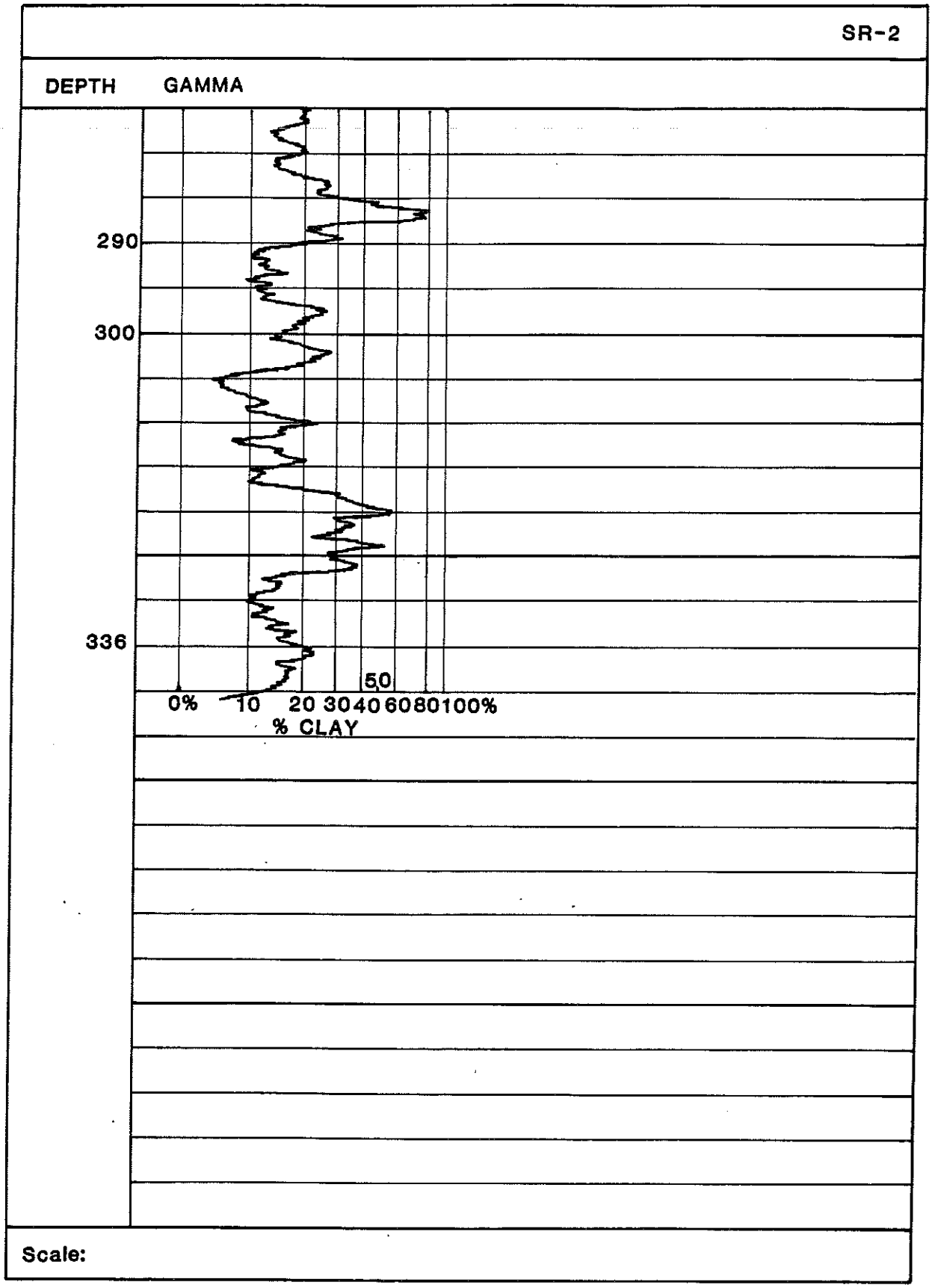


GAMMA RAY INDEX (GRI) =

$$\frac{GR_{log} - GR_{clean\ sand}}{GR_{clay} - GR_{clean\ sand}}$$

CPS	GRI	% CLAY
20	0	0
30	0.08	3
40	0.17	5
50	0.25	8
60	0.33	13
70	0.42	17
80	0.50	23
90	0.58	30
100	0.66	38
110	0.75	50
120	0.83	64
130	0.91	78
140	1.00	100

Scale:


SR-2
DEPTH
GAMMA
290
300
336
50
0%
10
20
30
40
60
80
100%
% CLAY
Scale:

not readily distinguished from gamma active "clayey" material.

q-Factor Method

The q Factor Method is used only in formations where the clay is interspersed in the formation. The q-Factor is related to (Gearhart-Owens, 1975);

$$q = \frac{\phi V_a - \phi_D}{\phi V_a} \qquad (12)$$

where: ϕV_a is porosity from the acoustic velocity log

ϕ_D is porosity from the density log

Although this equation assumes the density of the clay is similar to the matrix, which is rarely the case, q is used as a relative index for comparing the relative clay content between zones within the same well.

Density-Neutron Clay Content Cross Plot

Another method, independent of natural gamma activity, relies upon plotting matrix density from the density log against either the neutron or acoustic velocity log. Formation bulk density, as derived from the density log, is relatively unaffected by the presence of clay. If porosity from the neutron log (or acoustic velocity log) is plotted against the density log, the data points will lie on a 45-degree line if the zones analyzed are "clean" or "clay free". A departure from this slope of 45 degrees (due to an apparent increase in porosity from the neutron or acoustic velocity logs) is an indication of the presence of clay in the formation. At least one zone must have the clay percent known in order scale the other zones based upon a linear relationship between the clay free line and known "clay point" (Figure 29). This

Figure 29.--Density-sandstone porosity vs. neutron porosity cross plot for clay content determination of a clayey sand for well SR-15 and clay effect on resistivity log (From Guyod, 1966).

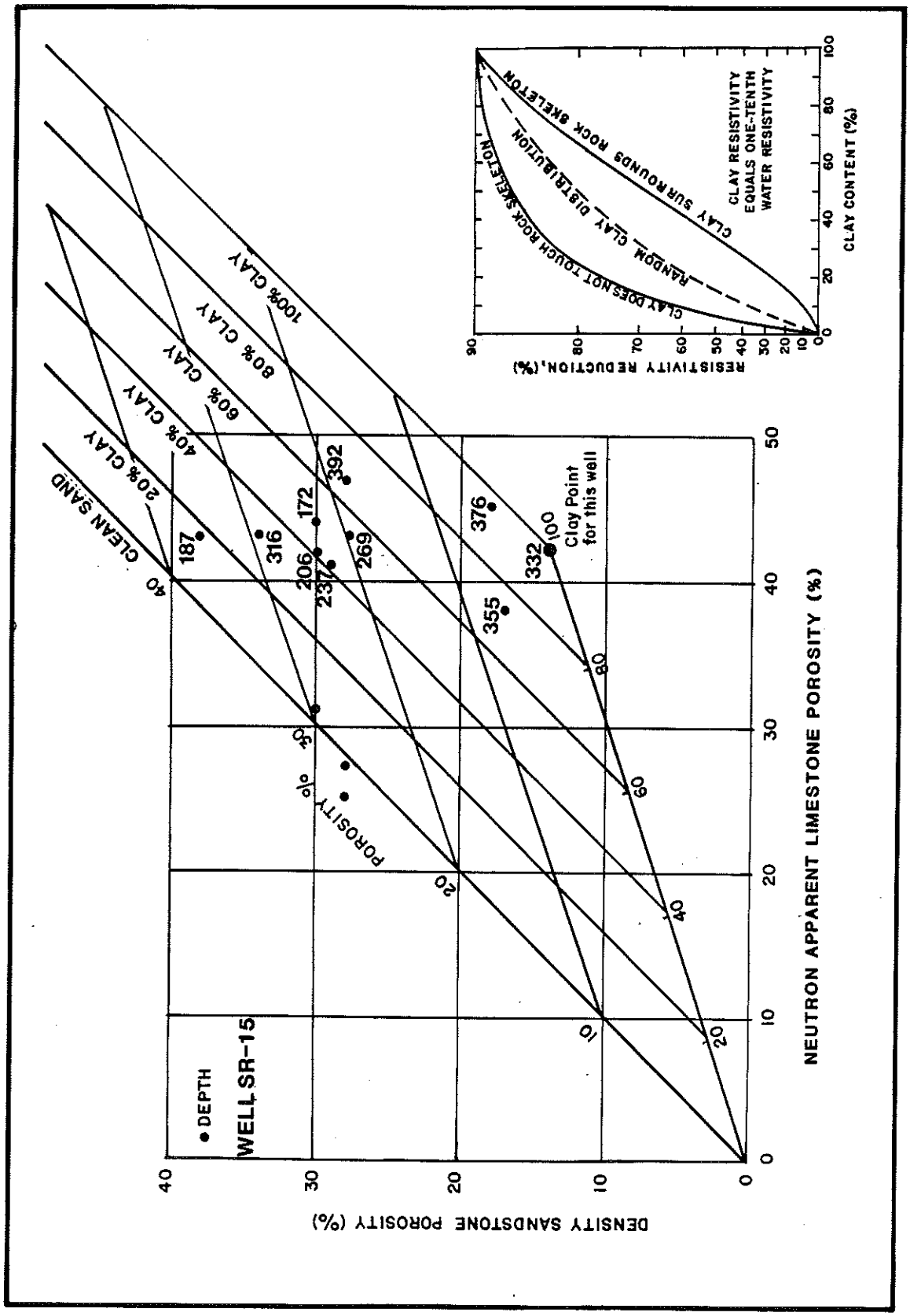

NEUTRON APPARENT LIMESTONE POROSITY (%)
DENSITY SANDSTONE POROSITY (%)
CLEAN SAND
20% CLAY
40% CLAY
60% CLAY
80% CLAY
100% CLAY
POROSITY %
Clay Point for this well
WELL SR-15
• DEPTH
187
316
206
172
237
392
269
376
332
355
100
CLAY SURROUNDS ROCK SKELETON
RANDOM CLAY DISTRIBUTION
CLAY DOES NOT TOUCH ROCK SKELETON
CLAY RESISTIVITY EQUALS ONE-TENTH WATER RESISTIVITY
RESISTIVITY REDUCTION, (%)
CLAY CONTENT (%)

Table 11.--Algorithm for Determining Clay Content of an Argillaceous Limestone or Clayey Sand by the Density vs. Neutron Cross Plot Method.

1) Select zones near bit-gauge size from the caliper log that require little or no correction factor for borehole diameter.

2) Locate thick uniform lithologic zones (at least four feet in thickness) from the natural gamma and electric logs.

3) Adjust the neutron and density logs between the minimum and maximum values (Appendix I for further discussion). At least one zone should be included where the clay content percent can reasonably be inferred from the logs and/or cuttings. This point will then be used as a pivot point for determining the clay content of the other zones (Figures 29 and 30).

4) Plot values from the neutron and density logs on arithmetic paper with the density scale on the y-axis. Density measurements for lithologies other than limestone should be corrected using Table 6.

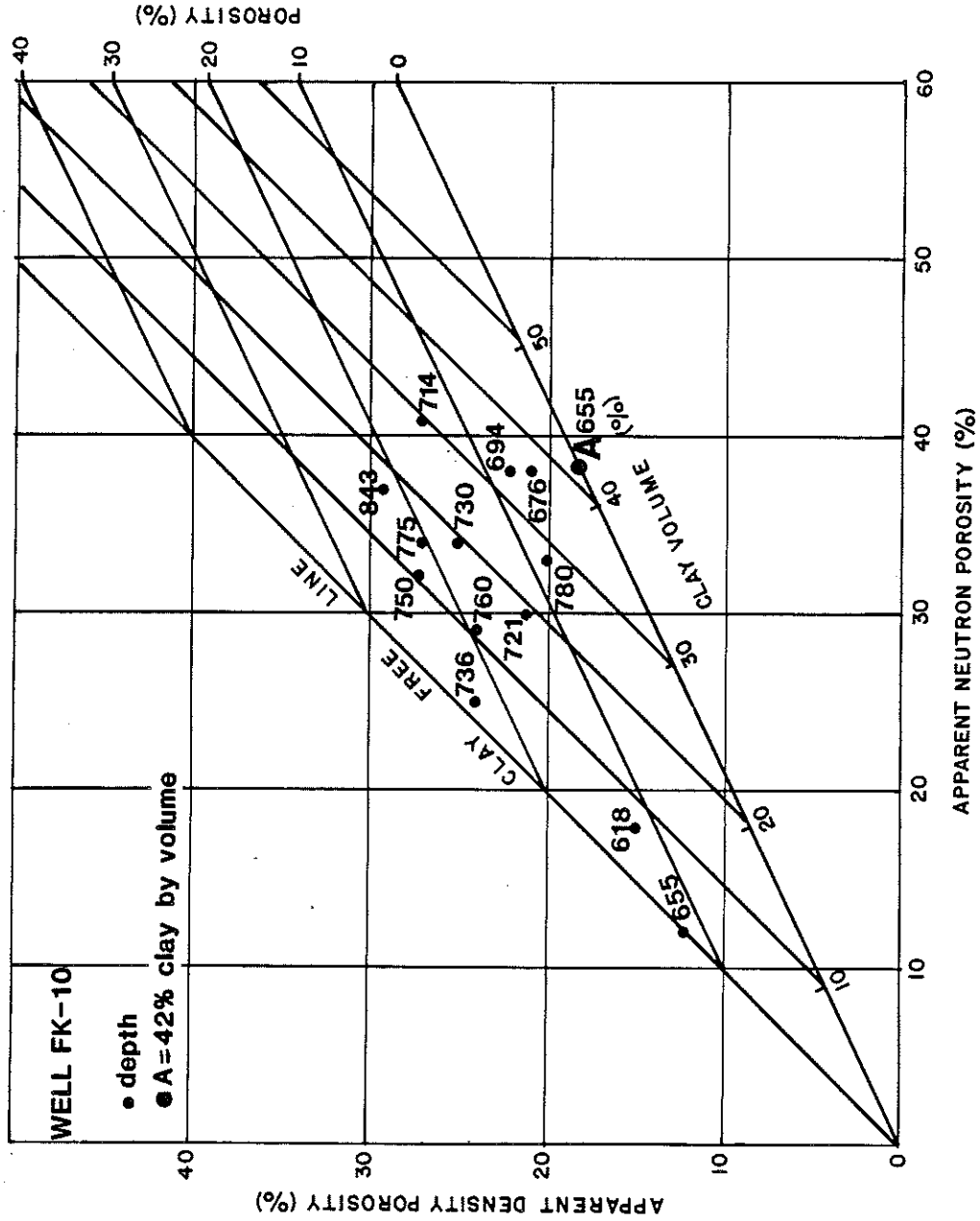
5) Draw the clay-free line (45 degrees, extending northeast from the 0.0 point). Draw another line through the point with the known clay percentage and scale proportionally back to zero. Extend the clay percentage lines parallel to the clay-free line through the graph.

Logs required: neutron, density, caliper, gamma and electric.

Assumptions:

A) Formations are 100% saturated with water; and
B) At least one zone has a known clay percentage (by volume).

Figure 30.--Density porosity vs. neutron porosity for determining clay content of an argillaceous limestone for well FK-10.


WELL FK-10
• depth
● A=42% clay by volume
APPARENT DENSITY POROSITY (%)
APPARENT NEUTRON POROSITY (%)
POROSITY (%)
CLAY VOLUME %
CLAY FREE LINE
A
655
714
694
676
730
843
775
750
760
721
780
736
618
655

DETERMINING FORMATION WATER QUALITY FROM GEOPHYSICAL LOGS

An important and often costly aspect of water resources investigations is the drilling of test wells for determining formation water quality. Ground-water quality generally decreases with depth, and as a function of time and distance traveled through the aquifer system. Water pumped from a well represents a composite sample of all the water-bearing zones transmitting water to the borehole. In order to determine the water quality of each particular zone, multiple test wells are often drilled to various depths to sample the different hydrogeologic units (a considerable savings in cost and time would be realized). If in situ formation pore water quality could be determined from a single, small diameter, deep test hole, without actually setting casing, developing, or pumping the well. Resistivity and porosity logs have been successfully used in the petroleum industry to determine R_w, which can in turn, be related to water quality for a particular chemical type water mass.

The suite of logs most sensitive to water quality changes are the various types of electric logs. Resistivity measurements recorded by electric logs are influenced by: 1) composition of the matrix material; 2) size, volume and geometry of the grains and pore spaces between the grains; and 3) resistivity of the fluid contained between the pore spaces of the grains. If the first two factors are known, then water resistivity, which is related to water quality, can be determined. Since matrix resistivities of the main water-bearing formations (sands, limestones and dolomites) are near infinity, the reduction in

resistivity recorded on electric logs is primarily the result of the grain size, pore volume and geometry (Formation Resistivity Factor - F) and the pore water resistivity (R_W).

This relationship is expressed by the equation:

$$R_W = \frac{R_O}{F} \quad (14)$$

where: R_W = resistivity of the formation pore water (in ohm-meters)
R_O = resistivity of the formation, 100% saturated with water
F = formation resistivity factor

The Formation Resistivity Factor (F) is the variable representing the size, pore volume and geometry of the grains and is equivalent to the following equations;

$$F = R_O/R_W \quad (14, \text{ rearranged})$$

or

$$F = \frac{a}{\phi^m} \quad (15, \text{ Archie Equation; Archie, 1942})$$

where: a = the pore geometry coefficient. a is often less than 1 for granular systems and greater than, or most often equal to 1 for carbonates and other consolidated formations

ϕ = porosity (in percent)

m = cementation factor

Rearranging the above equations, water resistivity (R_W) is expressed as:

$$R_W = R_O \phi^m \quad (16)$$

Values for the cementation factor (m) range from 1.4 for loosely sorted, unconsolidated quartz sands to greater than 5 for dense crystalline rocks of virtually zero porosity. Typical m values are given in Table 12 for various types of Tertiary sediments. Since m is

Table 12.--Typical Cementation Factor (m) and Formation Factor (F) Values for Tertiary Sediments.

m	Typical Ranges for Tertiary Formations	m
	Miocene-Pliocene Unconsolidated Surficial Sands	1.3-1.4
	Slightly Consolidated Sands	1.4-1.5
	Argillaceous Limestones	1.4-1.6
	"Shelf type" Poorly Solidated Limestones	1.5-1.7
	Clean "Platform type" Limestones	1.6-1.8
	Dolomitic Limestones	1.8-2.0
	Sucrosic Dolomites	2.0-2.2
	Crystalline Dolomites	2.2-2.4

m	Granular Material (from Hilchie, 1982)	
	Quartz Spheres	1.2
	Rounded Quartz Sand	1.4
	Platy Sand	1.6
	Spheres and Shells (1:1)	1.7
	Shell Fragments	1.8
	Kaolinite	1.87
	Illite	2.11
	Attapulgite	2.46
	Calcium Montmorillonite	2.70
	Sodium Montmorillonite	3.28

F, for: General Equation $\frac{a}{\phi^m}$ (15) a = pore geometry coefficient, a<1 for intergranular, a > 1 for fracture porosity.

Granular Systems $\frac{0.62}{\phi^{2.15}}$ (17) (Humble Formula)

Carbonate Rocks $\frac{1}{\phi^m}$ (18) (Archie Formula)

an exponent in the above R_w equations, it is critical to determine this value as accurately as possible. A value of m = 2 is commonly cited for carbonates encountered in petroleum test well drilling. This value appears to be too high for most Tertiary carbonates that have not been subjected to deep burial or high pressures compacting the original matrix. A range of m between 1.4 to 2.0 appears to be more reasonable for Tertiary carbonates used in this study. The lower value of 1.4 applies to argillaceous and poorly consolidated limestones. An increase in cementation has a pronounced effect in raising the value of m, such as in sucrosic and slightly crystalline dolomites (m = 1.8 to 2.0). Values for m also tend to increase as grain size decreases. The determination of m can only be derived by solving for all the other unknowns in the above equation (16) by cross plotting porosity and resistivity logs and not from laboratory measurements.

Pickett Porosity-Resistivity Cross Plot for Determining Cementation Factor (m) and Water Resistivity (R_w)

Water resistivity (R_w) and the cementation factor (m) may be determined by plotting porosity vs. saturated formation resistivity (R_o) on log-log paper (Pickett, 1973; MacCary, 1978; Figure 31 and Tables 13 and 14). If the resistivity of the water is constant throughout the zones analyzed, the slope of the line (fitted through the data points by a least-squares fit) will be equal to m by the following equation:

$$m = \frac{\log X_1 - \log X_2}{\log Y_1 - \log Y_2} \quad (19)$$

In a practical sense, m cannot remain constant in a given formation for extreme ranges in porosity, but may, for all practical purposes remain constant for porosity ranges of most aquifer systems.

Figure 31.--Porosity vs. resistivity (R_o) for finding m and R_w from well GF-12.

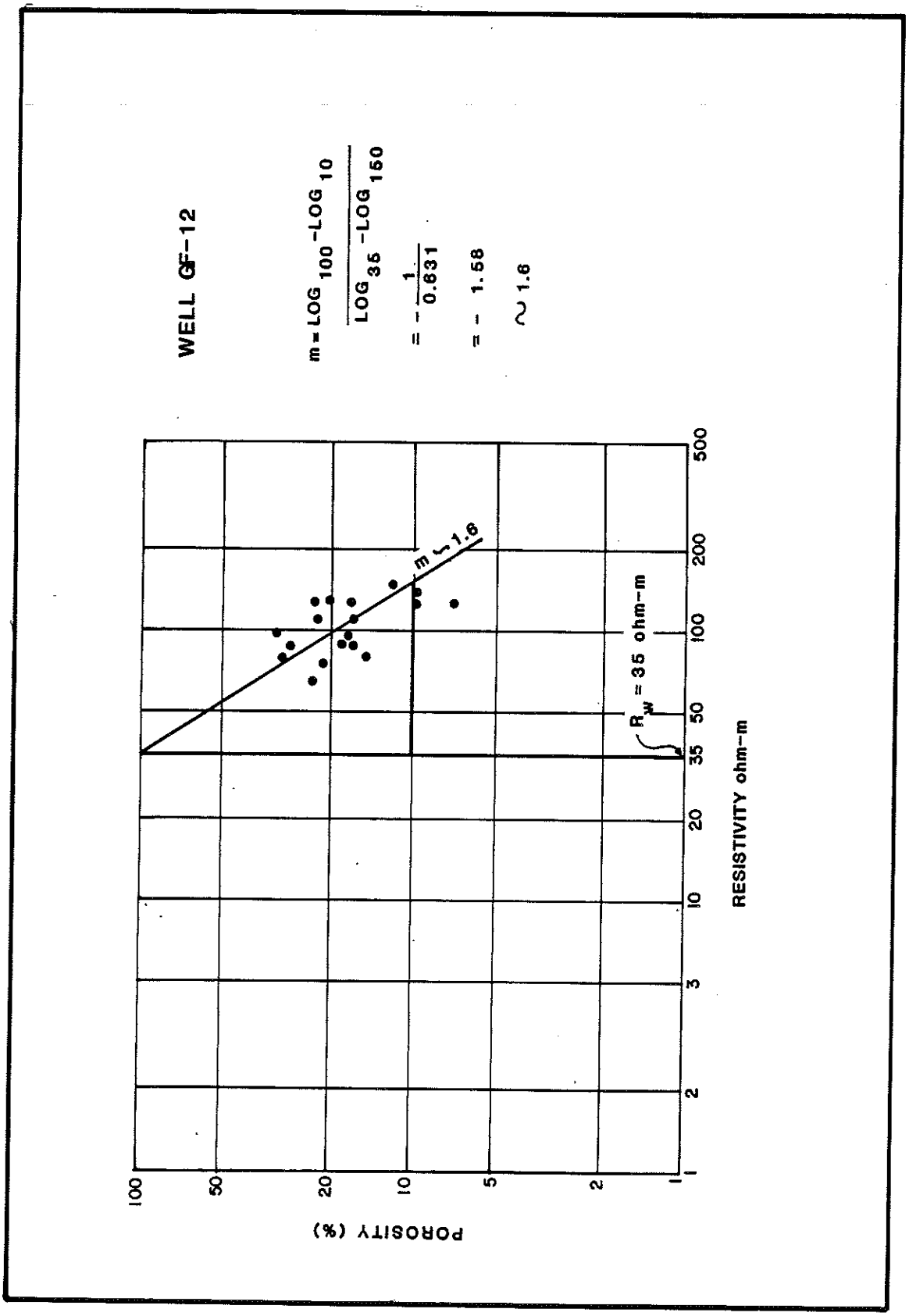

WELL GF-12
$m = \frac{LOG_{100} - LOG_{10}}{LOG_{35} - LOG_{150}}$
$= -\frac{1}{0.631}$
$= -1.58$
~ 1.6
m ~ 1.6
R_w = 35 ohm-m
RESISTIVITY ohm-m
500
200
100
50
35
20
10
3
2
1
POROSITY (%)
100
50
20
10
5
2
1

Table 13.--Algorithm for Determining Cementation Factor (m) by the Pickett Porosity vs. Resistivity Cross Plot Method.

1) Select zones near bit-gauge from the caliper log which require little or no correction factor for borehole diameter.

2) Locate thick zones of uniform lithology (at least twice the thickness of the longest radius of investigation) from the natural gamma and electric logs.

3) Plot porosity (from neutron, density and/or acoustic velocity logs) vs. R_0 (from electric logs 16", 64" lateral or induction logs) on log-log graph paper (Figure 31).

4) A wide range of porosities and R_0 values should be plotted to insure proper fit of a line through the data points.

5) The line should form a negative slope which will represent (m), the cementation factor. The slope (m) is derived from the equation:

$$(m) = \frac{\log X_1 - \log X_2}{\log Y_1 - \log Y_2} \quad (19)$$

Logs required: porosity (from neutron, density or acoustic velocity), short-normal electric, caliper and gamma.

Assumptions:

A. Pore water resistivity is constant throughout the zones analyzed;
B. Only saturated, clean zones (non-clays) are selected for analyses.

Table 14.--Algorithm for Determining R_W by the Pickett Porosity - Resistivity Cross Plot Method.

1) Select zones near bit-gauge size from the caliper requiring little or no correction factor for borehole diameter.

2) Locate thick zones of uniform lithology (at least twice the thickness of the deepest radius of investigation) from the natural gamma and electric logs.

3) Plot porosity (from neutron, density and/or acoustic velocity logs) vs. R_0 (from electric logs 16", 64" lateral or induction logs) on log-log graph paper (Figure 31).

4) A wide range of porosity and R_0 values should be plotted in order to properly fitting a line through the data points.

5) Fit line to data points by least squares regression and extrapolate line out to 100% porosity (Y-axis). Read R_W (X-axis) at that point. This value will be R_W with the matrix resistivity effects removed.

Logs required: porosity (from neutron, density or acoustic velocity) short-normal electric, gamma and caliper.

Assumptions:

A. Pore water resistivity is constant throughout the borehole; and
B. Only saturated, clean zones (non-clays) are analyzed.

If different sections of the aquifer were cemented to varying degrees (i.e., had less porosity due to increased cementation) then different values of m would be expected and should be assigned cementation values accordingly. Variations in m, with respect to porosity will be noted by changes in slope of the line fitted through the Pickett cross plot.

Similarly, the intercept of this line at 100 percent porosity will correspond to R_w. A particular value of R_w may be determined after m is obtained by substituting porosity and R_o into the equation:

$$\log R_w = \log R_o + m \log \phi \quad (20)$$

Formation Resistivity Factor (F)

The Formation Resistivity Factor (F) is related to m and changes logarithmically with formation porosity (Table 12 and Figure 32). For the purpose of this study, which includes unconsolidated granular aquifers and poor to moderately consolidated carbonate aquifer systems, the following equations are most often applicable:

Unconsolidated quartz sands;

$$F = \frac{0.62}{\phi^{2.15}} \quad \text{(Humble Formula)}$$

and for Tertiary carbonates:

$$F = \frac{1}{\phi^m} \qquad \text{where: } m = 1.6 \text{ to } 2.0$$

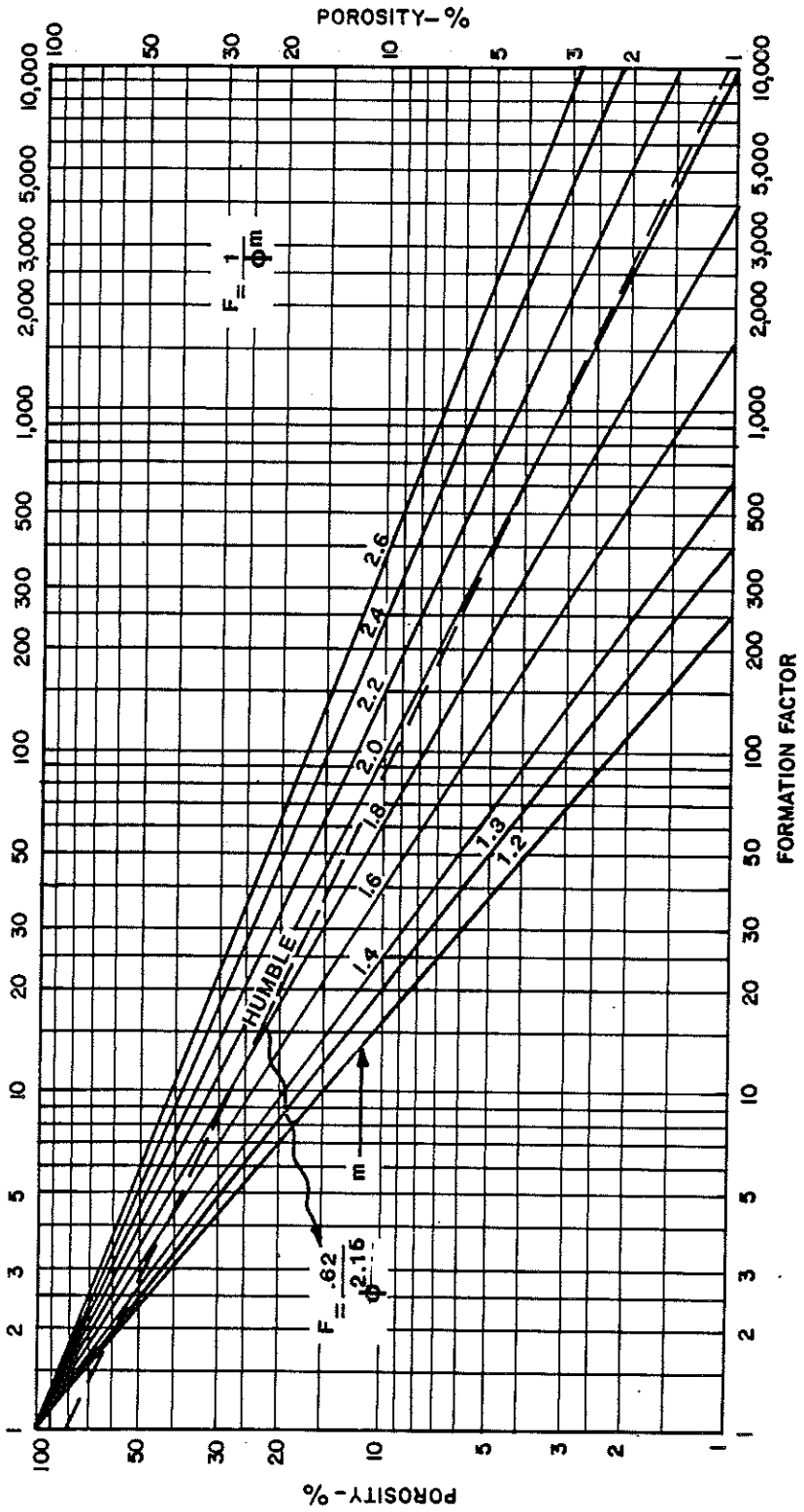
Geophysical Logs Used to Determine R_w

Since R_w is related to both porosity and F from the previous equation (16);

$$R_w = R_o \phi^m.$$

then; R_w can be determined by plotting saturated formation resistivity (R_o) versus porosity and reading R_o at the intercept of 100 percent porosity. This plot is referred to as the Pickett plot and

Figure 32.--Formation factor (F) vs. porosity for different cementation (m) factors. (From Gearhart-Owen, 1975).


POROSITY-%
FORMATION FACTOR
$F = \frac{1}{\phi^m}$
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.3
1.2
HUMBLE
m
$F = \frac{.62}{\phi^{2.15}}$

utilizes porosity from the neutron, density or acoustic velocity log, plotted along the Y-axis versus R_0 from the normal electric log. A line fitted through the data points will have the slope equal to the cementation factor (m).

Obtaining a valid R_0 measurement is normally not difficult since most producing zones of wells finished in carbonates are drilled without mud. Therefore, true saturated formation measurements (R_0) may be obtained very near the borehole wall. It is advisable to run at least a shallow and deep resistivity survey to observe the depth of mud invasion. Probes with shallow radii of investigation are preferred in order to avoid averaging resistivities over great thickness of vertical sections within the borehole. Occasionally it is necessary to increase the radius of investigation to obtain a deeper, more precise measurement of R_0 beyond the invaded zone. Measurements should be obtained from zones at least twice the probe's radius of investigation to minimize boundary effects. Clays and clayey zones should be avoided since many of the resistivity assumptions are violated due to the increased conductivity relating to the ionic structure of clays. Other factors adversely affecting electric log response include:

1) Formations containing highly resistive pore waters (greater than 100 ohm-meters) - which force the current to shunt along the borehole fluid;

2) rugged boreholes - generally with borehole deviations greater than half the radii of investigation;

3) highly fractured zones - allowing the current to follow along fractures, rather than through the matrix; and

4) unsaturated formations - which tend to have apparently high resistivity due to the high resistivity of air occupying the voids.

All resistivity measurements should be corrected to the standard temperature (25°C, 77°F) for proper comparisons and correction factors.

One of the primary differences in log interpretation between the petroleum industry and logs run in freshwater environments is the difference in saturated formation resistivity. In many cases, logs run in formations saturated with fresh water are at least two orders of magnitude greater in resistivity. Typical resistivity values are listed in Table 15.

Table 15.--Typical Resistivity Values for Common Formations and Fluids.

	Resistivity (ohm-meters)
Dry quartz sand, limestone or dolomite	Infinite
Clean limestone-saturated with fresh water	> 2,000
Clean dolomite-saturated with fresh water	> 1,000
Clean sand-saturated with fresh water	> 1,000
Marl	up to 600
Fresh water (in clean quartz sand)	up to 400
Fresh water (in carbonates)	up to 75
Borderline potable water	25
Clay	15
Drilling fluid (fresh water mixed)	2
Seawater	0.2

Hingle Resistivity Porosity Cross Plot (RPCP) for Determining Water Saturation and Water Resistivity.

The Hingle Resistivity Porosity Cross Plot Method yields additional information on water saturation (S_w, in percent), assuming a portion of the log analyzed is from the vadose zone and their is no change in R_w with depth. In order to obtain this additional information, it is assumed that m is constant in each of the producing zones analyzed. Normally m is first obtained from the Pickett Plot to determine the

correct RPCP paper with the corresponding m value (RPCP paper for m = 1.4, 1.6, 1.8, 2.0, and the Humble factor are in Appendix N).

Water Saturation by RPCP

Proper interpretation of all logs assumes the formation to be 100 percent saturated with fresh water. An algorithm for determining water saturation by the RPCP Method is summarized in Table 14. This plot requires that at least one point of known water saturation (usually chosen from a very deep zone) is necessary to scale other saturation percent lines (Figure 33). The Hingle RPCP Method assumes R_W remains constant over the zones analyzed since only one unknown resistivity can be solved for (S_W). Factors adversely affecting the validity of the data points include the addition of clays to the formation(s), which lower R_O, and chosing an improper m value value for the formation(s) analyzed.

Delineating Different Water Masses by RPCP

Probably the most useful purpose of the resistivity-porosity cross plot is to graphically show changes in water resistivity (R_W) versus depth. Individual water masses (hydrogeologic zones containing pore water of approximately the same resistivity and ion proportions) will tend to plot on a positive sloping line as R_O decreases with increasing porosity (Figure 34). Water resistivity generally decreases with depth within the same aquifer system. If the aquifer system is "layered" where distinct water masses are confined to discrete zones, each water mass will plot on a single straight line. Hydrogeologic zones of decreasing water resistivity (increased conductivity generally indicates poorer water quality) will plot on positive sloping lines, and increase in slope as R_W decreases. R_W may then be determined by

Figure 33.--Resistivity-porosity cross plot for determining water saturation percent in formations from well GA-39.

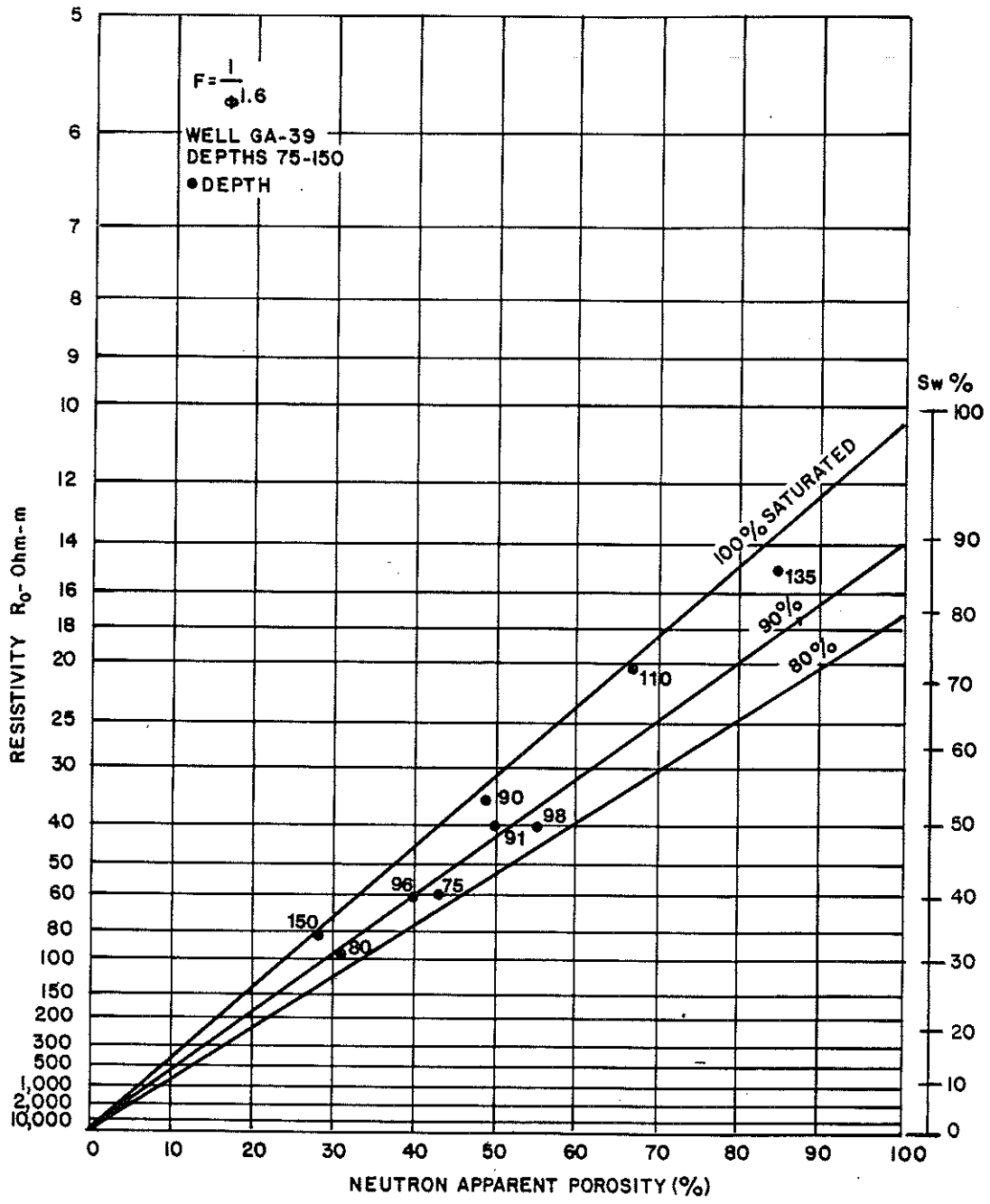

$F=\frac{1}{\phi^{1.6}}$
WELL GA-39
DEPTHS 75-150
●DEPTH
RESISTIVITY R_o- Ohm-m
NEUTRON APPARENT POROSITY (%)
Sw %
100% SATURATED
90%
80%
135
110
90
98
91
96
75
150
80

Table 16.--Algorithm for Determining Water Saturation (S_w) Percent In Unsaturated Zones by the Hingle Resistivity-Porosity Cross Plot Method.

1) Select zones at or near bit-gauge from the caliper log requiring little or no correction factor for borehole diameter.

2) Calibrate one of the porosity logs (neutron, acoustic velocity or density log) to the proper scale. (See Appendix I for further discussion of log calibrations).

3) Plot R_0 from the short-normal electric log vs. porosity on the proper resistivity-porosity cross plot paper (determined by m value) for the zones analyzed. Plot the depth next to each data point (Figure 34).

4) The uppermost data points should form a line sloping from northeast to southwest intersecting at the zero porosity point (and infinite resistivity).

5) A log scale in water saturation percent from zero to 100% porosity should intercept the line from step 4 at 100% and extend vertically downward to intercept the X-axis at zero porosity.

6) Other saturation lines (in percent) can be drawn from a log scale intercepting the zero porosity-infinite resistivity point.

Logs required: porosity (neutron, acoustic velocity or density) short-normal electric and caliper.

Assumptions:

A. Cementation factor (m) remains constant throughout the borehole; and
B. R_w is constant throughout zones analyzed.

Figure 34.--Resistivity-porosity cross plot for determining R_w and different water masses from well GF-12.

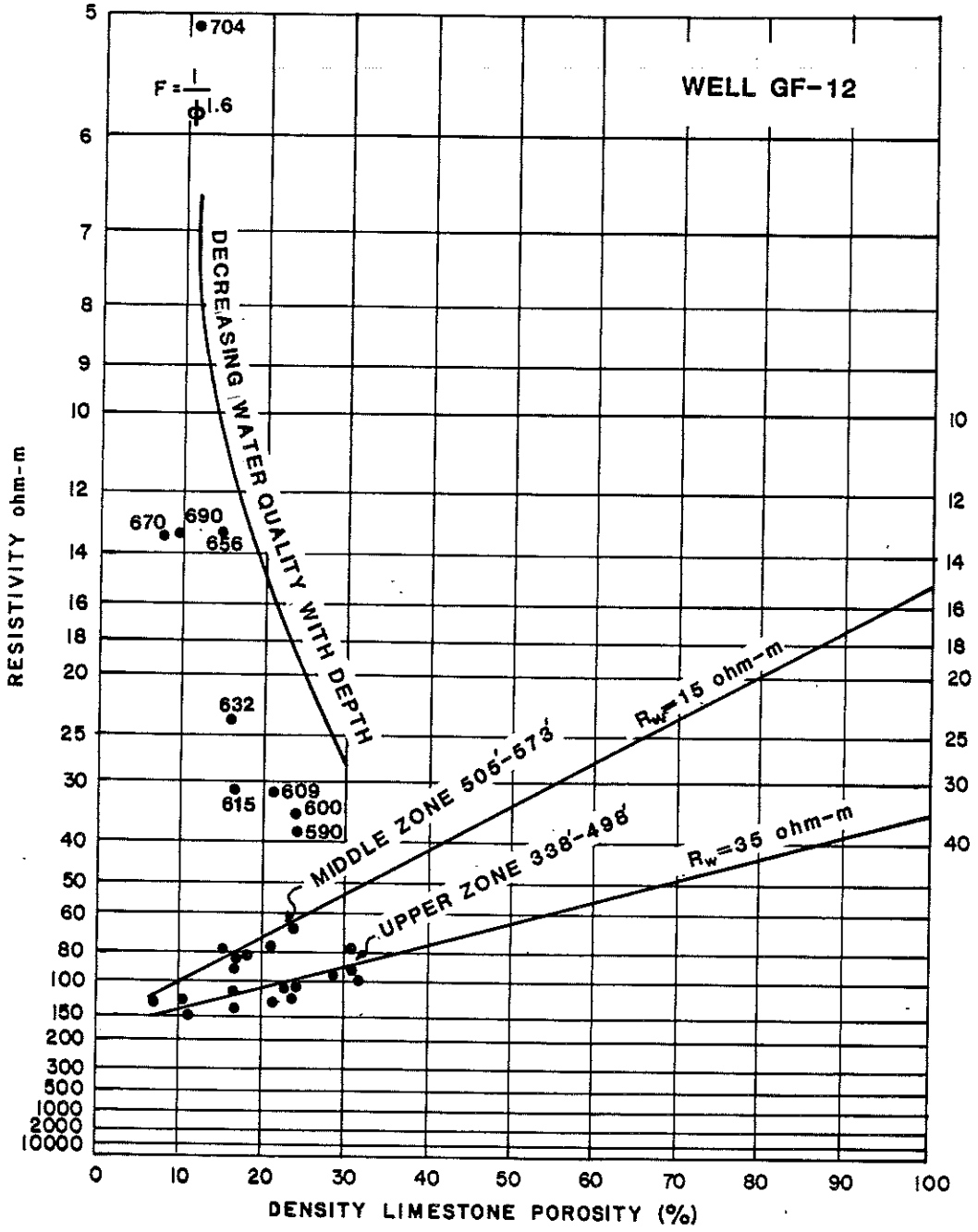

WELL GF-12
$F = \frac{1}{\phi^{1.6}}$
704
670
690
656
632
615
609
600
590
DECREASING WATER QUALITY WITH DEPTH
MIDDLE ZONE 505'-573'
UPPER ZONE 338'-498'
R_w=15 ohm-m
R_w=35 ohm-m
RESISTIVITY ohm-m
DENSITY LIMESTONE POROSITY (%)
5
6
7
8
9
10
12
14
16
18
20
25
30
40
50
60
80
100
150
200
300
500
1000
2000
10000
0
10
20
30
40
50
60
70
80
90
100

Table 17.--Algorithm for Determining R_w by the Hingle Resistivity-Porosity Cross Plot Method.

1) Select zones at or near bit-gauge from the caliper log that require little or no correction factor for borehole diameter.

2) Calibrate one of the porosity logs (neutron, acoustic velocity or density log) to the proper scale. (See Appendix I for further discussion of log calibrations).

3) Plot R_0 from the short-normal electric log vs. porosity on the proper resistivity-porosity cross plot paper (determined by m value) for the well analyzed. Plot the depth next to each data point to determine if the water resistivity decreases with depth linearly with depth or if distinct zones are present where the water resistivity remains relatively constant (Figure 34).

4) If water resistivity decreases continuously with depth, a single line cannot be fitted through the points to derive a R_w for that particular well (i. e., many water masses are present). If the data points appear to cluster in linear trend with a northeast-southwest slope and all the data points are contiguous with depth a line may be fitted through the data points to determine R_w at the 100% porosity - R_0 intercept.

Logs required: porosity (neutron or acoustic velocity or density), short-normal electric and caliper.

Assumptions:

A. Cementation factor (m) does not change appreciably through producing zones;
B. All formations are 100% saturated.

extending the line to 100 percent porosity and reading the resistivity at the intercept on the Y-axis. Hydrologic zones of relatively thick, uniform vertical permeability will exhibit a continuous degradation of water resistivity with increasing depth. Data analyzed from this type of aquifer system will plot with a negative slope, indicating there are numerous values for R_w. Attempting to fit a line through the data points will not yield a unique value for R_w (Figure 34, depths 590 to 704).

The "trade off" for this additional information requires a greater knowledge of the aquifer system and discretion in analyzing zones meeting the following conditions:

1) The zones analyzed are completely saturated ($S_w = 1.0$);
2) m is constant, or its variations are accounted for;
3) Clays and clayey zones are not analyzed;
4) Zones with fracture or extreme secondary porosity are not analyzed; and
5) Resistivity measurements are measuring R_o, beyond any mud invasion.

Zones analyzed should have a wide range of porosity and resistivity values to aid in fitting to the data. Temperature corrections should also be made for all resistivity measurements to obtain a more precise value of R_w. An algorithm using the RPCP Method for determining R_w is outlined in Table 16.

Example of Determining Water Resistivity Using RPCP, Well GF-12

The case history used for determining R_w by the RPCP Method is from a well (GF-12) drilled into the Floridan aquifer of central Gulf County, northwest Florida. Two distinct water masses are observed in

the upper portion of the well: 1) zone 1, depths 338'-498', with a R_w = 35 ohm-meters; and 2) zone 2, 505'-573', with a R_w = 15 ohm-meters. Water resistivity below zone 2 shows a continuous decrease in resistivity with depth until R_w at depth 704 is equal to about one ohm-meter. These analyses compare favorably with point samples obtained with the fluid sampler. The short normal electric (16") and density log, with corresponding data from zones analyzed, are located in Appendix K.

R_w from Fluid Resistivity Log Profiles

The most direct method for measuring R_w is with a fluid resistivity probe (Figure 35.) This probe should be run in the well only after it has been developed and has stabilized from all drilling and pumping activity. Fluid resistivity probes measure the resistivity of the borehole fluid passing between two or more electrodes located inside the probe. Optimum results have been obtained on wells meeting the following conditions:

1) Water Resistivity generally decreasing with depth;

2) The well has been sufficiently developed to remove all foreign water and mud from drilling activities; and

3) Inner borehole flow has not significantly altered the native formation water resistivity.

R_w from Spontaneous Potential Logs

Spontaneous potential (SP) logs are frequently used in the petroleum industry for determining formation water resistivity (R_w), but have little or no application in freshwater environments. Many of the assumptions are grossly violated in freshwater carbonate environments, such as the producing zone analyzed is: 1) often not of a granular material; 2) not bounded by ion sieving shales; or 3) contain pore

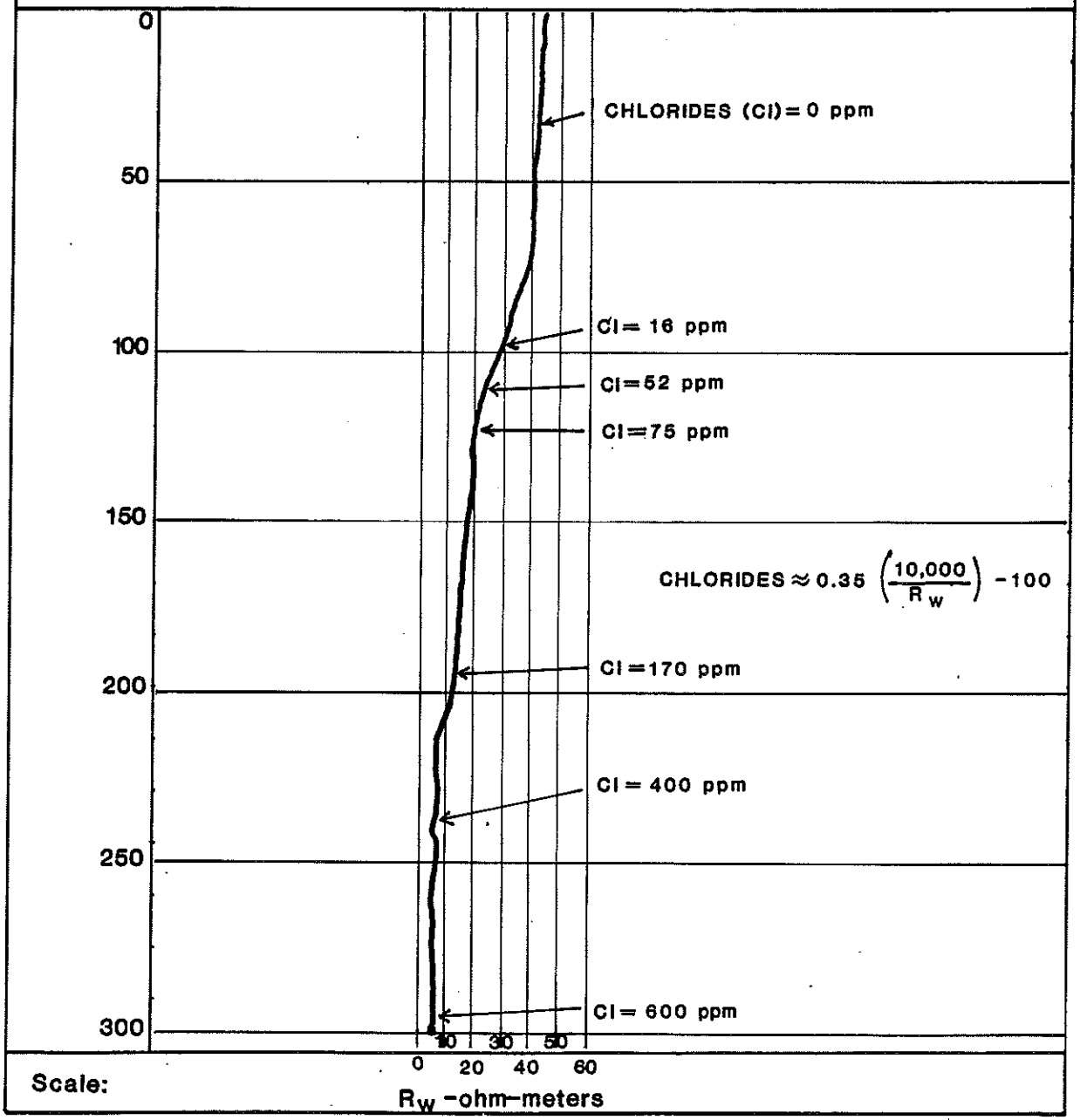
Figure 35.--Fluid resistivity log for determining R_w from well FK-10.

NAME St. George Is. COUNTY Franklin W- 7574

LOCATION T 9S R 6W SEC. 22 1/4 NWF-FK-10

DEPTH 918 CASING 93 DIA 8 AQUIFER Floridan

Notes:



Scale:

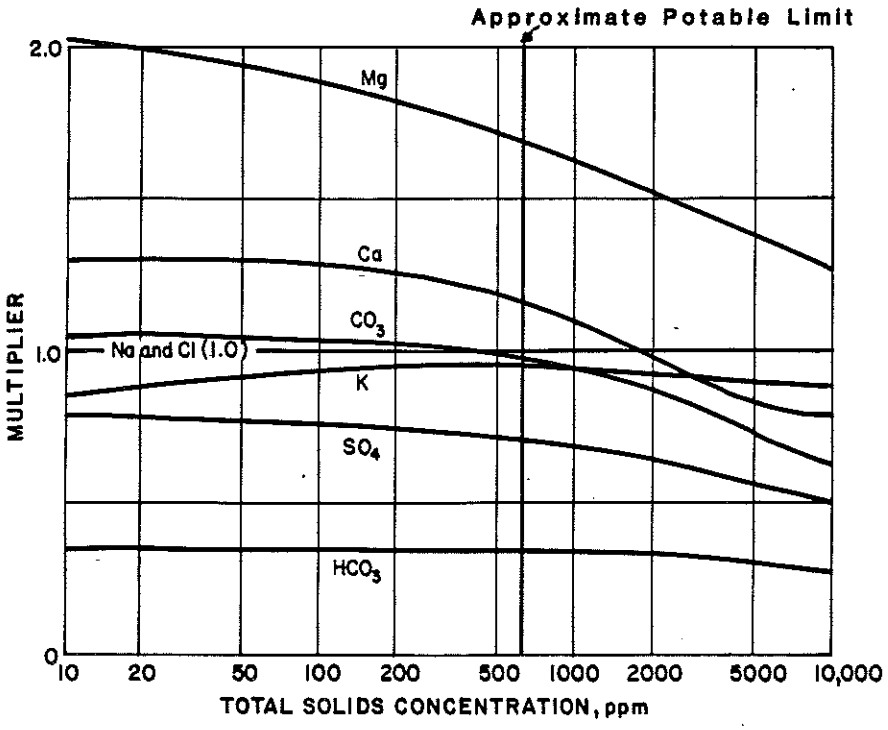
fluid in excess of 10,000 parts per million total dissolved solids. In addition, drilling mud resistivity or viscosity is not carefully monitored during the drilling of most shallow wells, and geophysical log suites rarely include shallow focused resistivity logs for determining the extent of mud flushing (R_m, R_{mf}, R_i or R_{we}) necessary for SP determinations.

Relationship Between Water Resistivity and Water Quality

Although formation pore water resistivity (R_w) is not a direct indicator of water quality, a strong correlation usually exists between R_w and the dominant ions comprising the ground water within the range of potable water (Figure 36). The dominant ions frequently have recommended concentration limits (usually expressed in parts per million-p.p.m.) and often have a definite linear relationship to R_w for a particular water mass. Chloride is usually the first ion to render ground water unpotable in granular aquifer systems, whereas, in carbonate aquifer systems, sulfate in addition to chloride most commonly govern the ground waters' potability (250 p.p.m. recommended limit for chloride and sulfate). In carbonate aquifer systems, other major ions such as calcium, magnesium and bicarbonate are present in relatively high concentrations, but are generally not considered harmful. Other obnoxious ions (such as iron) and toxic ions (arsenic, cadmium, etc.) are rarely present in concentrations great enough to affect the water resistivity.

The remainder of the water quality section addresses the relationship of R_w to specific ion concentrations. The chloride ion, which is the most common ion rendering water unpotable in granular and

Figure 36.--Total dissolved solids and various multiplier coefficients for different ions based upon sodium chloride. (Modified from Schlumberger, 1972).


Approximate Potable Limit
2.0
1.0
0
MULTIPLIER
Mg
Ca
CO_3
Na and Cl (1.0)
K
SO_4
HCO_3
10
20
50
100
200
500
1000
2000
5000
10,000
TOTAL SOLIDS CONCENTRATION, ppm

carbonate Tertiary aquifer systems, is plotted against R_W for 18 localities throughout the study area for all four major aquifer systems. Following this section are plots of other ions commonly present in granular and carbonate aquifer systems are plotted against R_W to determine the relationship (if any) to water resistivity.

Note: Water resistivity (R_W) is rarely measured in ohm-meters in hydrogeologic investigations. Specific conductance (conductivity in micromhos), is the reciprocal of resistivity and is related by the following equation;

$$\text{Specific conductance (in micromhos)} = \frac{10{,}000}{R_W} \quad (21)$$

Chloride concentrations and R_W measurements are influenced by changes in temperature and should be corrected to standard temperature using Figure 37.

Water Resistivity Versus Chloride Concentrations for Various Types of Aquifer Systems

Water resistivity versus chloride concentrations (in p.p.m.) were plotted for eighteen localities throughout the study area including water masses from all four major aquifer systems (location map, Figure 2; typical plot, Figure 38). The actual plots are included in Appendix M and results are tabulated in Table 18 for quick reference (numerical relationships and correlation coefficients).

Wells were selected in various localities based upon withdrawing water from the same aquifer system or water mass. Although a wide range of water resistivity and chloride values were plotted, it was assumed that the proportion of the ions remained relatively constant as dissolved mineral content of the water increased. This assumption

Figure 37.--Resistivity of saline solutions nomograph based upon temperature and chloride ion concentration. (Modified from Dresser Atlas, 1975).

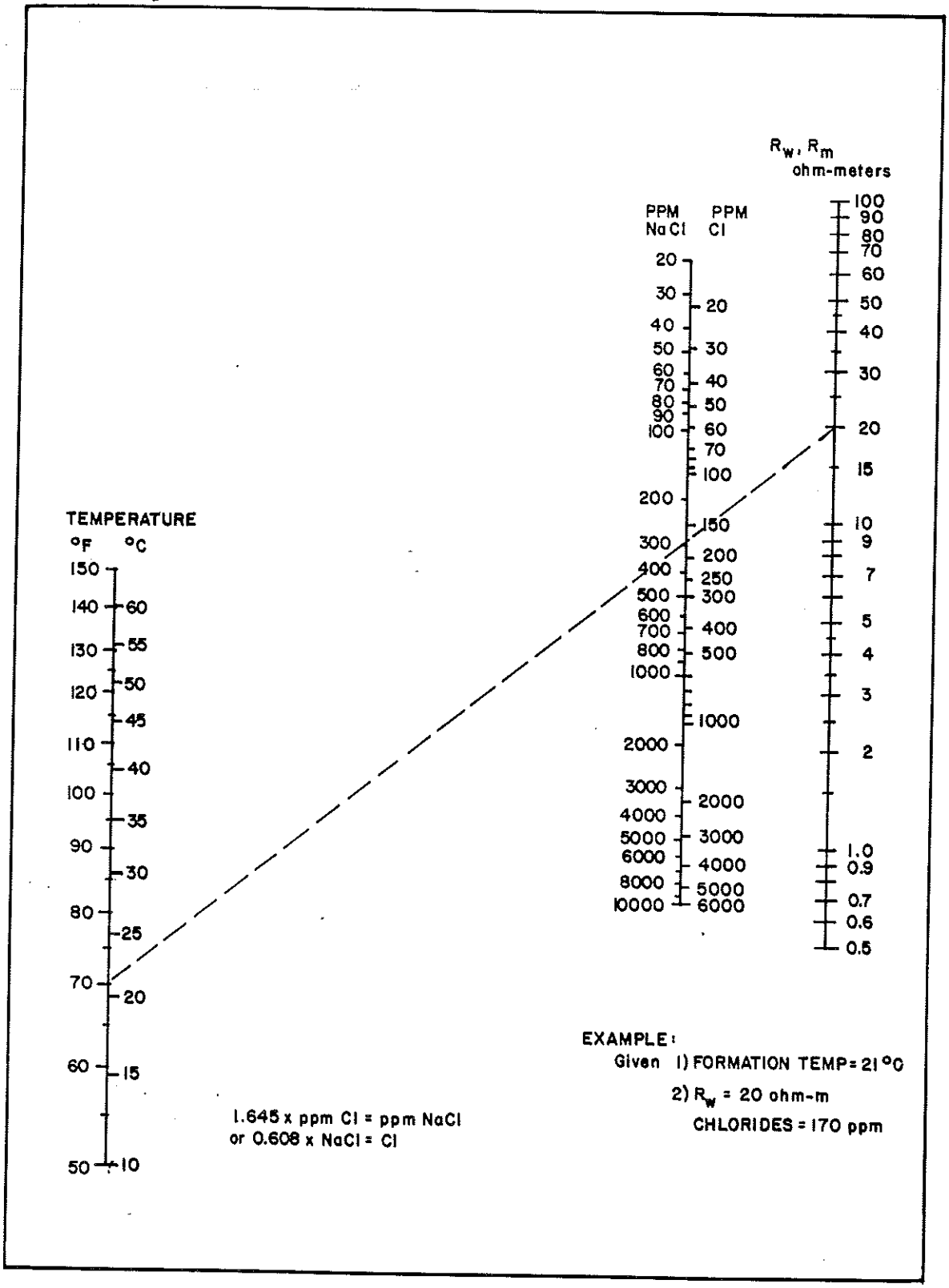

TEMPERATURE
°F °C
150 60
140 55
130 50
120 45
110 40
100 35
90 30
80 25
70 20
60 15
50 10
PPM NaCl
PPM Cl
20 20
30 30
40 40
50 50
60 60
70 70
80 100
90 150
100 200
200 250
300 300
400 400
500 500
600 1000
700 2000
800 3000
1000 4000
2000 5000
3000 6000
4000 8000
5000 10000
6000
R_w, R_m ohm-meters
100 90 80 70 60 50 40 30 20 15 10 9 7 5 4 3 2 1.0 0.9 0.7 0.6 0.5
1.645 x ppm Cl = ppm NaCl
or 0.608 x NaCl = Cl
EXAMPLE:
Given 1) FORMATION TEMP = 21 °C
2) R_w = 20 ohm-m
CHLORIDES = 170 ppm

Figure 38.--R_w vs. chloride concentration for the Floridan aquifer, Seminole County, Florida. Data from Barraclough, 1962.

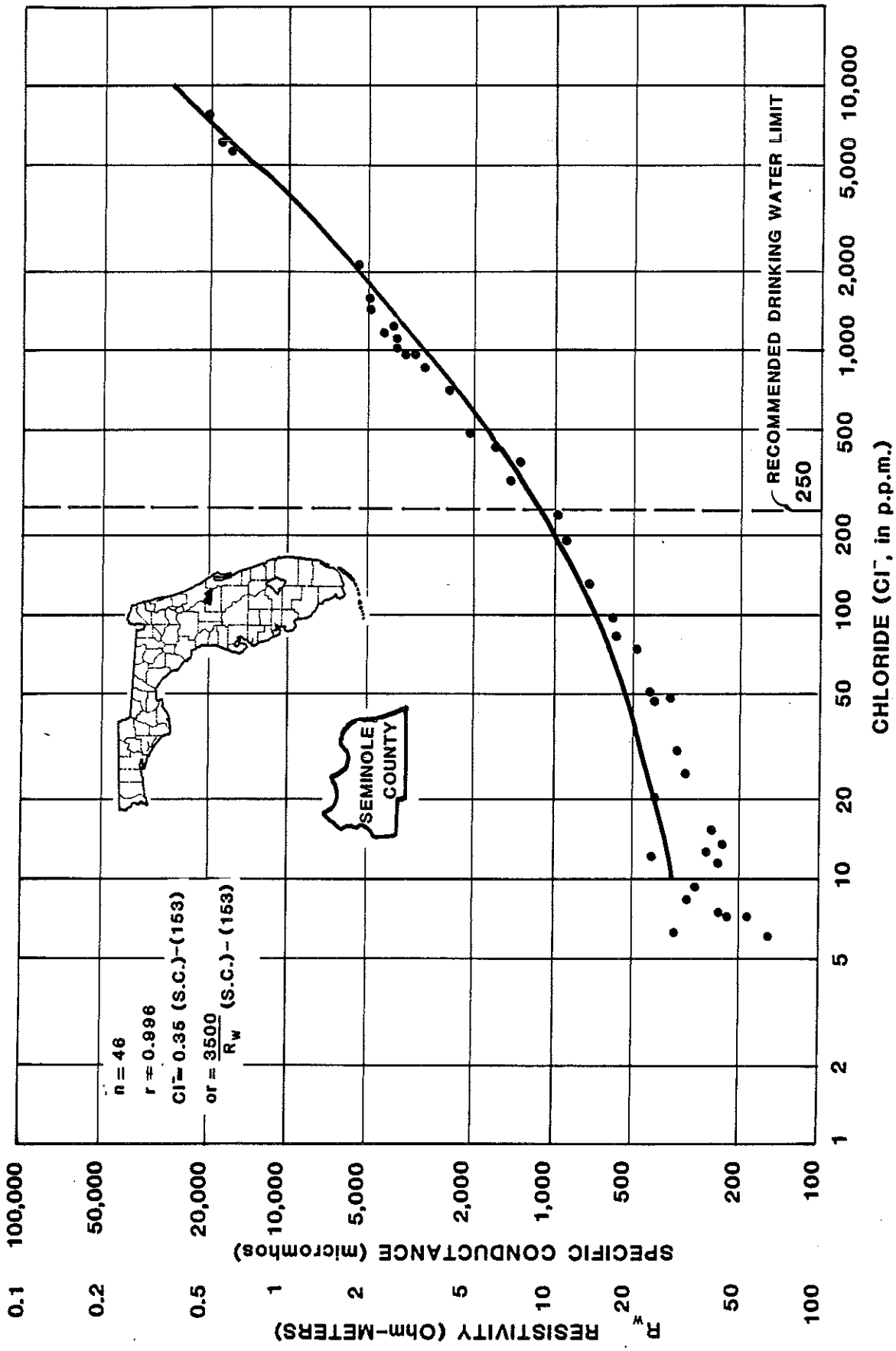

CHLORIDE (Cl⁻, in p.p.m.)
1
2
5
10
20
50
100
200
500
1,000
2,000
5,000
10,000
RECOMMENDED DRINKING WATER LIMIT
250
SEMINOLE COUNTY
n = 46
r = 0.996
Cl⁻ = 0.35 (S.C.)-(153)
or = 3500/R_w (S.C.)- (153)
SPECIFIC CONDUCTANCE (micromhos)
100,000
50,000
20,000
10,000
5,000
2,000
1,000
500
200
100
R_w RESISTIVITY (Ohm-METERS)
0.1
0.2
0.5
1
2
5
10
20
50
100

Table 18.--R_w vs. Various Ion Concentrations for the Four Major Aquifer Systems.

ION	R_w RELATIONSHIP	SPECIFIC CONDUCTANCE* (S.C.) RELATIONSHIP	n**	r***
Sand and Gravel Aquifer (sands, gravels, clays) - southern Escambia and Santa Rosa counties, Florida.				
Chloride (Cl^-)	$\frac{2,890}{R_w} - 11.46$	0.289(S.C.) - 11.46	137	0.995
Iron, total (Fe^{+2},Fe^{+3})	$\frac{5}{R_w} + 2.03$	0.0005(S.C.) + 2.03	120	0.019
Sand and Gravel Aquifer (quartz silts and sands) - southern Okaloosa and Walton counties, Florida.				
Chloride (Cl^-)	$\frac{1,010}{R_w} + 0.787$	0.101(S.C.) + 0.787	37	0.947
Biscayne Aquifer (sand) - Broward County, Florida.				
Chloride (Cl^-)	$\frac{2,800}{R_w} + 52$	0.28(S.C.) + 52	36	0.524
Surficial Aquifer (sand) - Duval County, Florida				
Chloride (Cl^-)	$\frac{350}{R_w} - 1$	0.035(S.C.) - 1	30	0.670
Surficial Aquifer (sands) - East-Central St. Johns County, Florida.				
Chloride (Cl^-)	$\frac{2,060}{R_w} - 109$	0.206(S.C.) - 109	38	0.917
Surficial Aquifer (sand) - Palm Beach County, Florida				
Chloride (Cl^-)	$\frac{2,320}{R_w} - 62$	0.232(S.C.) - 62	51	0.705
Floridan Aquifer (limestone) - southern Walton County, Florida.				
Chloride (Cl^-)	$\frac{3,220}{R_w} - 72.74$	0.322(S.C.) - 72.74	25	0.996
Floridan Aquifer (limestone and dolomite) - northern Okaloosa and Walton counties, Florida.				
Chloride (Cl^-)	$\frac{3,690}{R_w} - 107.9$	0.369(S.C.) - 107.9	91	0.999

Table 18.--R_w vs. Various Ion Concentrations for the Four Major Aquifer Systems. - (continued)

ION	R_w RELATIONSHIP	SPECIFIC CONDUCTANCE* (S.C.) RELATIONSHIP	n**	r***
Floridan Aquifer (limestones and dolomite) - Quincy area, Gadsden County, Florida.				
Chloride (Cl^-)	$\frac{3,070}{R_w}$ + 74.74	0.307(S.C.) + 74.74	32	0.992
Total Dissolved Solids	$\frac{5,900}{R_w}$ + 14.74	0.590(S.C.) + 14.74	27	0.986
Potassium (K^+)	$\frac{40}{R_w}$ + 1.55	0.004(S.C.) + 1.55	23	0.917
Magnesium (Mg^{+2})	$\frac{120}{R_w}$ + 9.35	0.012(S.C.) + 9.35	31	0.905
Hardness as (Ca^{+2}, Mg^{+2})	$\frac{723}{R_w}$ + 95.62	0.072(S.C.) + 95.62	32	0.851
Sulfate (SO_4^{-2})	$\frac{275}{R_w}$ + 3.607	0.0275(S.C.) + 3.607	32	0.774
Sodium (Na^+)	$\frac{1,677}{R_w}$ + 0.987	0.1677(S.C.) + 0.987	31	0.611
Fluoride (F^-)	$\frac{2}{R_w}$ +0.492	0.0002(S.C.) + 0.492	28	0.560
Calcium (Ca^{+2})	$\frac{10}{R_w}$ + 26.84	0.001(S.C.) + 26.84	31	0.101
Bicarbonate (HCO_3^-)	$\frac{37}{R_w}$ + 155.1	0.0037(S.C.) + 155.1	20	0.089
Dissolved Silica	$\frac{5}{R_w}$ + 16.14	0.0005(S.C.) + 16.14	25	0.070
Floridan Aquifer (limestones and dolomites) - Havana area, Gadsden County, Florida.				
Chloride (Cl^-)	$\frac{1,836}{R_w}$ - 60.57	0.1836(S.C.) - 60.57	25	0.995
Floridan Aquifer (limestone) - northeastern Volusia County, Florida.				
Chloride (Cl^-)	$\frac{3,260}{R_w}$ - 167	0.326(S.C.) - 167	43	0.998

Table 18.--R_w vs. Various Ion Concentrations for the Four Major Aquifer Systems. - (continued)

ION	R_w RELATIONSHIP	SPECIFIC CONDUCTANCE* (S.C.) RELATIONSHIP	n**	r***
Floridan Aquifer (limestone) - Seminole County, Florida.				
Chloride (Cl^-)	$\frac{3,500}{R_w} - 153$	0.35(S.C.) - 153	46	0.996
Floridan Aquifer (limestone) - southeastern Orange County, Florida.				
Chloride (Cl^-)	$\frac{2,780}{R_w} - 150$	0.278(S.C.) - 150	46	0.996
Floridan Aquifer (limestone) - southwestern Hillsborough County, Florida.				
Chloride (Cl^-)	$\frac{1,600}{R_w} - 88$	0.16(S.C.) - 88	33	0.930
Floridan Aquifer (limestone) - Sarasota County, Florida.				
Chloride (Cl^-)	$\frac{3,260}{R_w} - 191$	0.326(S.C.) - 191	28	0.941
Floridan Aquifer (limestone) - Lee County, Florida.				
Chloride (Cl^-)	$\frac{3,180}{R_w} - 182$	0.318(S.C.) - 182	40	0.912
Floridan Aquifer (limestone) - Dade and Monroe Counties, Florida.				
Chloride (Cl^-)	$\frac{3,720}{R_w} - 582$	0.372(S.C.) - 582	26	0.997
Deep Carbonates of nine-county area of south Florida.				
Chloride (Cl^-)	$\frac{4,170}{R_w} - 733$	0.417(S.C.) - 733	75	0.991

* Specific Conductance in Micromhos/cm^2.
** Number of Samples.
*** Correlation Coefficients.

appears to be valid throughout the potability range (Figure 38, 39, and 40).

Results

Eighteen plots utilizing over 800 comparisons (minimum of n = 25 for each plot) were used to determine the relationship between R_w vs. chloride ion concentrations (Figure 39). Sixteen of the eighteen plots had a Pearson Correlation Coefficient (r) of $r \geq 0.91$ and ten had a correlation coefficient ≥ 0.99 indicating a very strong relationship between R_w and chloride. The two localities utilizing the Biscayne and Surficial aquifers had an r of 0.51 and 0.67, respectively, and both appear to be sampling water from a mixture of different type waters. One water, in each case, is believed to be a calcium bicarbonate type and the second is of a sodium chloride type (from a intruding saline wedge). The mixing of two different type waters violates the linear proportion assumption involving ion concentrations, thus accounting for the lower correlations.

A general equation relating R_w for each of the four main aquifer systems (Table 19) may be expressed as;

Table 19.-- Approximate Relationship Between Chloride and R_w for the Four Major Aquifer Systems.

AQUIFER	RELATIONSHIP	
Sand-and-Gravel	$\text{Chlorides} = \frac{2,400}{R_w} - 5$	(22)
Biscayne	$\text{Chlorides} = \frac{2,800}{R_w} + 50$	(23)
Surficial and Intermediate	$\text{Chlorides} = \frac{1,600}{R_w} - 60$	(24)
Floridan	$\text{Chlorides} = \frac{3,100}{R_w} - 200$	(25)

Figure 39.--R_W vs. chloride concentration for various water masses throughout Florida.

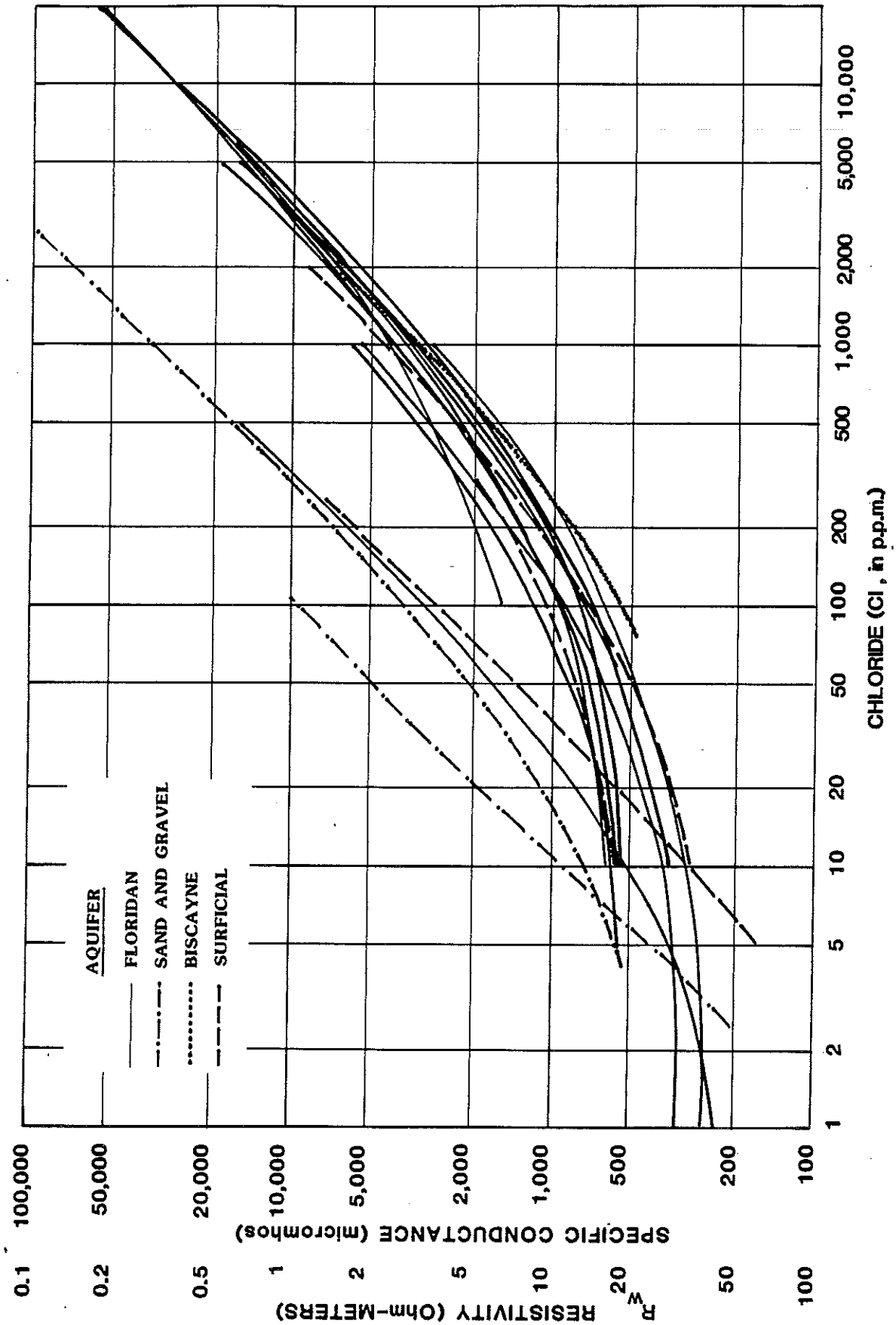

AQUIFER
FLORIDAN
SAND AND GRAVEL
BISCAYNE
SURFICIAL
CHLORIDE (Cl , in p.p.m.)
1
2
5
10
20
50
100
200
500
1,000
2,000
5,000
10,000
SPECIFIC CONDUCTANCE (micromhos)
100,000
50,000
20,000
10,000
5,000
2,000
1,000
500
200
100
RESISTIVITY (Ohm-METERS)
0.1
0.2
0.5
1
2
5
10
20
50
100

Figure 40.--R_w vs. various ion concentrations for the Floridan aquifer, Quincy area, Gadsden County, Florida. See Appendix M for individual plots and correlation coefficients.

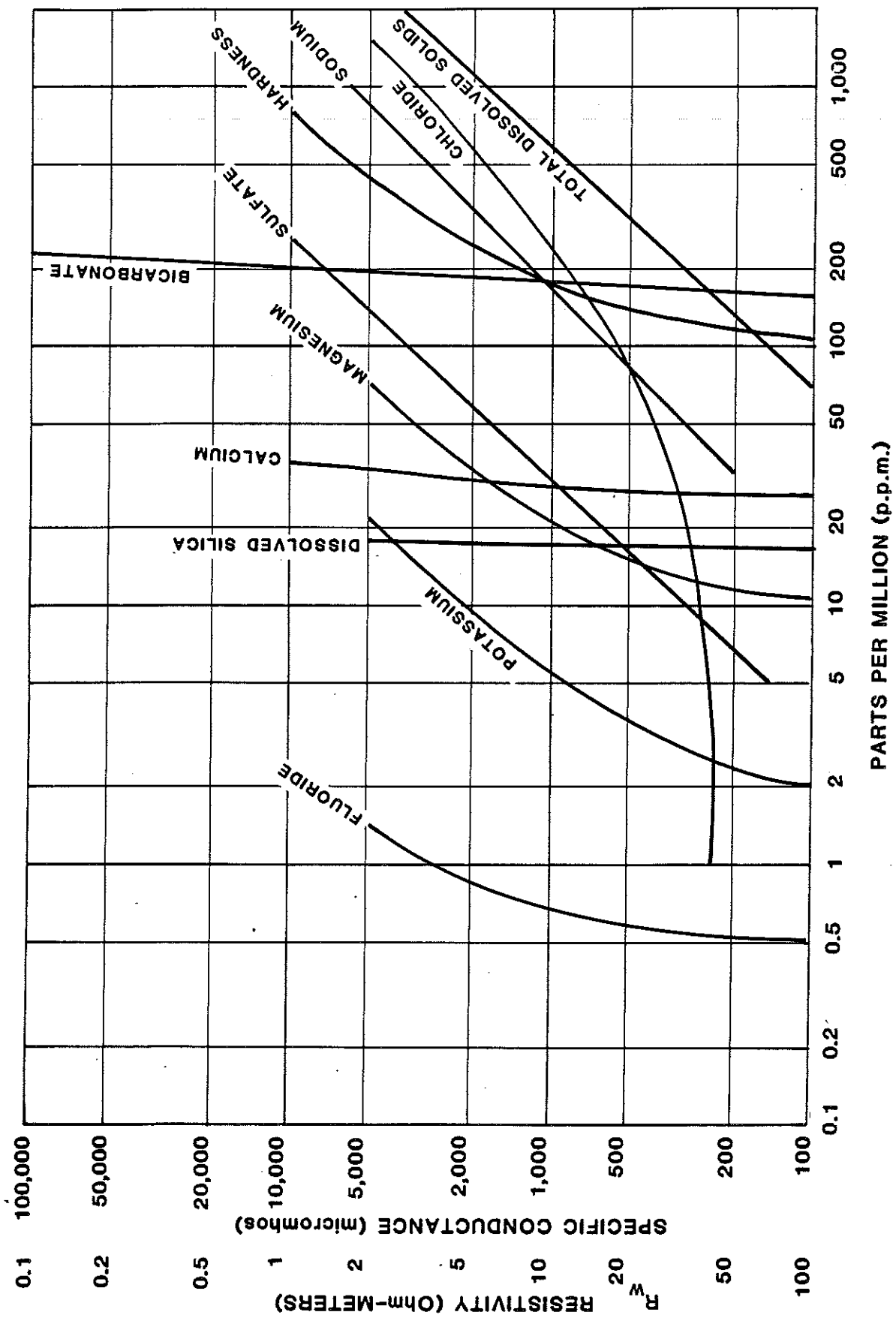

TOTAL DISSOLVED SOLIDS
CHLORIDE
SODIUM
HARDNESS
SULFATE
BICARBONATE
MAGNESIUM
CALCIUM
DISSOLVED SILICA
POTASSIUM
FLUORIDE
PARTS PER MILLION (p.p.m.)
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1,000
SPECIFIC CONDUCTANCE (micromhos)
100,000
50,000
20,000
10,000
5,000
2,000
1,000
500
200
100
R_W RESISTIVITY (Ohm-METERS)
0.1
0.2
0.5
1
2
5
10
20
50
100

Figure 39 is a composite overlay of all the least squares best fit lines for R_w vs. chloride. Although the relationship is not linear throughout the entire chloride range, the match of the lines is generally good. The above equations may be used as an approximation for the R_w-Chloride relationship for each of the major aquifer systems. For local analyses, it is advisable to plot the relationship from water samples taken from adjacent wells for the area under study.

Water Resistivity Versus Common Ion Concentrations In Carbonate Aquifers

In addition to plotting the relationship between R_w and the chloride ion concentration, ten other ions were compared to R_w in a carbonate aquifer to determine their significance and correlation. The ten water samples plotted from the Floridan aquifer in the Quincy area of Gadsden County, northwest Florida. At least 20 water quality samples ($n \geq 20$) were used for each R_w-ion plot. The numerical relationships are summarized in Table 20 and individual ion plots are located in Appendix M.

The individual ions and correlation coefficients are listed below:

Table 20.-- R_w vs. Correlation Coefficient (r) for Common Ions Present in the Ground Waters of the Floridan Aquifer System, Gadsden County, Florida.

Ion	n	Correlation Coefficient (r)
Chloride	32	0.992
Total dissolved solids	27	0.986
Potassium	23	0.917
Magnesium	31	0.905
Hardness (as Ca, Mg)	32	0.851
Sulfate	32	0.774
Sodium	31	0.611
Fluoride	28	0.560
Calcium	31	0.101
Bicarbonate	20	0.089
Silica (dissolved)	25	0.070

An overlay of least squares best fit lines for these ions vs. R_w reveal a positive relationship between most of these ions (Figure 40).

Chloride had the strongest correlation to R_w followed by total dissolved solids, potassium and magnesium.

Iron, in both soluble and insoluble forms (Fe^{+2}, Fe^{+3}), often exceed the recommended public health limit of 0.3 p.p.m. in granular aquifer systems (quartz sands and gravels). Unfortunately, there appears to be no correlation ($r = 0.019$) for 120 samples compared from the sand-and-gravel aquifer of extreme northwest Florida (Figure 41). The poor correlation may be attributed to the low conductivity of iron in the oxidized (insoluble state) and the relatively low concentrations of iron present (commonly less than one p.p.m.) in most ground waters.

Relationship of Saturated Formation Resistivity and Porosity to Potable Ground Water for the Major Aquifers in the Study Area

A quick estimation of water quality can be inferred from electric and porosity logs for each of the four aquifer systems in the study area. Figure 42 is a resistivity-porosity plot for the potable limit of each of the four aquifer systems. The potable limit lines (based on chlorides = 250 p.p.m.) were calculated from the following equation:

$$R_o = \frac{R_w}{\phi^m} \qquad (16)$$

where: ϕ = porosity in percent
R_o = resistivity of saturated formation, from normal or lateral log

and for each aquifer m and R_w* were assigned values of:

m	R_w	
1.6	7.21	Floridan
1.3	14.14	Biscayne
1.3	7.73	Sand-and-Gravel
1.3	5.15	Surficial and Intermediate

Figure 41.--R_w vs. iron concentrations for the sand-and-gravel aquifer, southern Escambia and Santa Rosa counties.

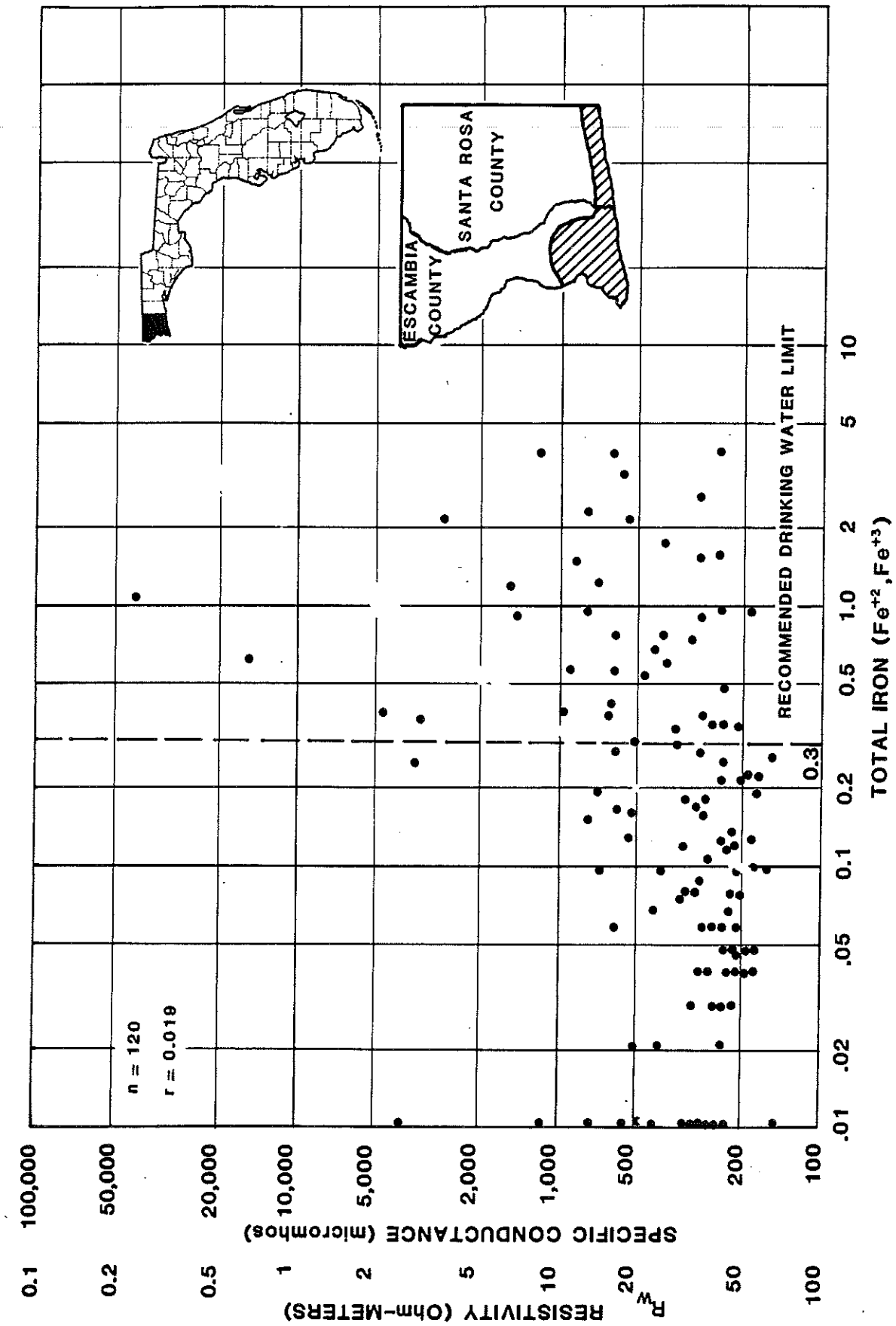
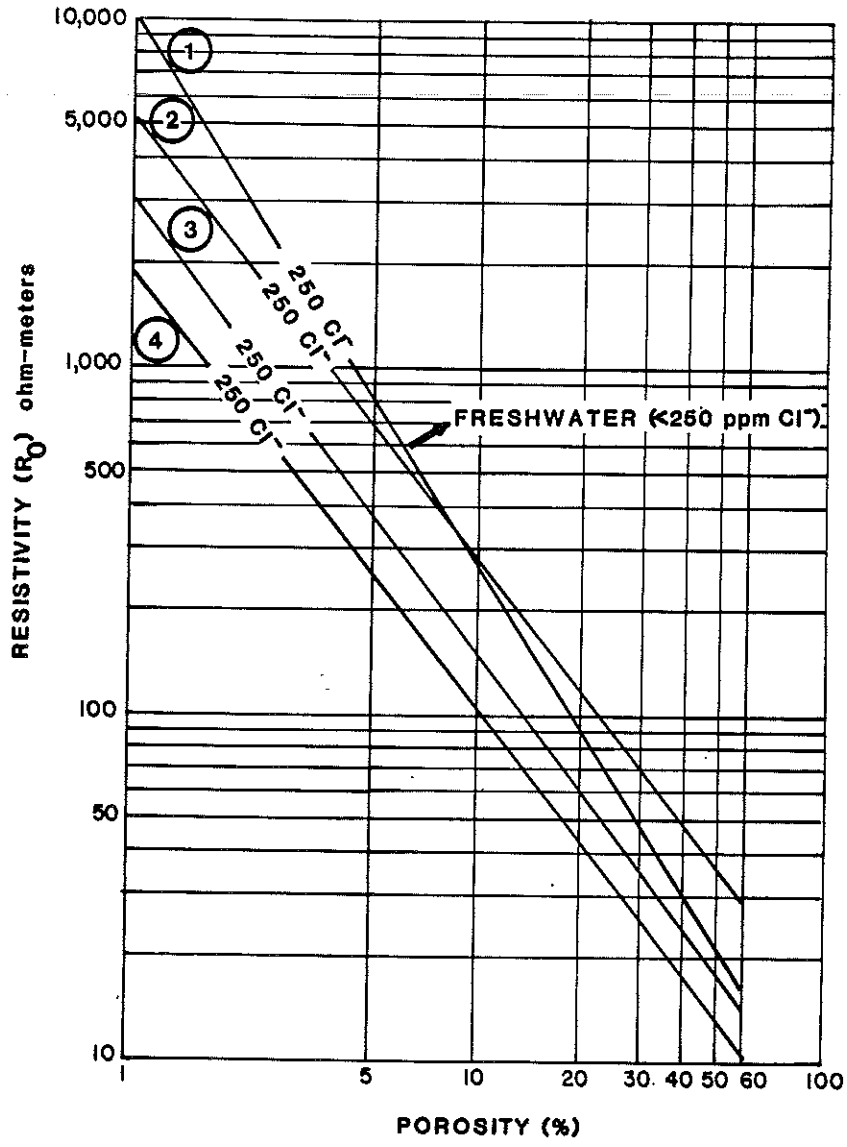

ESCAMBIA COUNTY
SANTA ROSA COUNTY
n = 120
r = 0.018
RECOMMENDED DRINKING WATER LIMIT
0.3
TOTAL IRON (Fe^{+2},Fe^{+3})
.01
.02
.05
0.1
0.2
0.5
1.0
2
5
10
SPECIFIC CONDUCTANCE (micromhos)
100,000
50,000
20,000
10,000
5,000
2,000
1,000
500
200
100
R_w RESISTIVITY (Ohm-METERS)
0.1
0.2
0.5
1
2
5
10
20
50
100

Figure 42.--R_o vs. porosity for determining freshwater zones of the four main aquifers in the study area.



		m	R_w*
(1)	FLORIDAN AQUIFER	1.6	7.21
(2)	BISCAYNE AQUIFER	1.3	14.14
(3)	SAND AND GRAVEL AQUIFER	1.3	7.73
(4)	SURFICIAL and INTERMEDIATE AQUIFER	1.3	5.15

$R_0 = \frac{R_w^*}{\phi^m}$ Based upon average R_w for 250 Cl^- limit for each aquifer

* based upon a weighted average of R_w for 250 p.p.m. chlorides for each aquifer system.

From this plot it is evident that electric logs may not be used directly to infer water quality without knowledge of formation porosity. Saturated formation resistivity (R_o), as graphed on Figure 42, can vary more than one order of magnitude and still contain water of the same quality.

DETERMINING FORMATION TRANSMITTING CHARACTERISTICS FROM GEOPHYSICAL LOGS

Formation Factor as an Indicator of Permeability

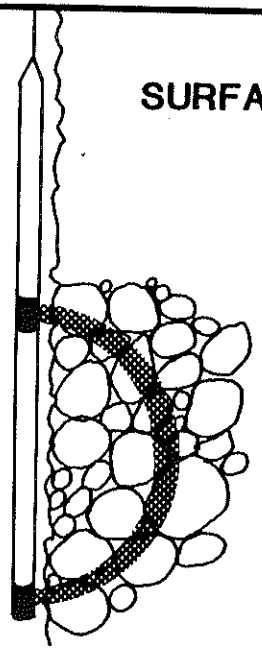
Archie (1942) first recognized the fact that water resistivity and porosity are directly related over a wide range of values by the equation;

$$F = R_o/R_w \quad (14)$$

The Formation Resistivity Factor (F), in deep well log interpretation is directly dependent upon grain size, sorting, and pore water resistivity. Producing formations (non-clays) where the grains have high contact area tend to have high resistivity due to the current being conducted primarily through the brine saturating fluid (by electrolytic conductance) rather than through the formation matrix. Smaller, less sorted, grains force the current to follow a more tortuous path and a greater portion of the current is directed through the matrix. Both of these factors serve to increase the resistivity recorded by electric logs.

Alger (1966) in interpreting electric logs in freshwater zones noted that the relationship of resistivity to grain size and sorting (grain contact area) was opposite in response to that observed in deep well log interpretation. It appears in freshwater zones (high R_w), electric current is preferentially conducted along the matrix-water interface rather than through the more resistive pore water (Figure 43). Formations composed of large, well sorted grains (low grain contact area) have high resistivity due to the current following a more tortuous path through the formation.

Figure 43.--Influence of surface conductance upon formation resistivity measurements.

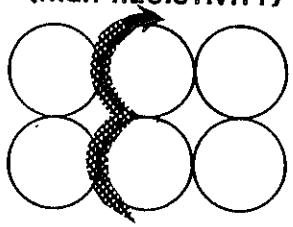


SURFACE CONDUCTANCE =

(Grain Size Factor) $\times \frac{\text{Porosity}}{\text{Grain Contact Area}}$

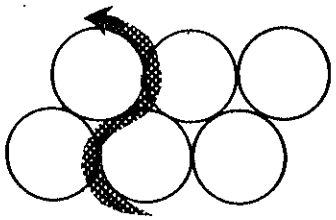
Since the current flows along the water/grain interface in freshwater zones, surface conductance is very closely related to permeability.

LOW SURFACE CONDUCTANCE
(HIGH RESISTIVITY)

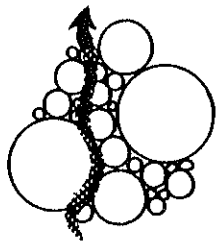


CUBIC CLOSE PACKING
(43% POROSITY)

INCREASING CONDUCTANCE



HEXAGONAL CLOSE PACKING
(27% POROSITY)



POORLY SORTED

HIGH SURFACE CONDUCTANCE
(LOW RESISTIVITY)

CLAY PARTICLES

Increasing the tortuosity increases formation resistivity in both freshwater and brine saturated formations. Tortuosity is defined as:

$$\text{tortuosity} = \frac{\text{current path length}}{\text{sample length}} \qquad (26)$$

Current conducted along the water matrix interface may be due to a low resistivity layer of very fine grained precipitated cement upon the grain matrix. If this theory is correct (a reduction in current resistivity along grain surfaces through very fine grained material) then "surface conductance" has widespread hydrologic implications relating to the formation's fluid transmitting capability (permeability). All of the factors reducing formation resistivity (R_0) in producing formations also have an effect on decreasing permeability. Smaller grain sizes and poor sorting also reduce porosity and permeability. Archie's equation for any clean producing formation ("clay free" and assumes matrix resistivity is extremely high) may then be rewritten as:

$$F = \frac{\text{Surface Conductance}}{R_W} \qquad (27)$$

$$\text{where surface conductance} = (\text{grain size factor}) \times \frac{\text{porosity}}{\text{grain contact area}} \qquad (28)$$

If R_W remains constant through a given zone, the saturated formation resistivity (R_0) recorded on the log will be directly related to the formation's permeability. If R_W changes with depth, then F (or k) can be normalized by dividing R_0 by R_W. Relative F-values can then determined and related to permeability (or transmissivity) for a given area. Croft (1971) demonstrated that F appeared to have a correlation to permeability in a sandstone aquifer in North Dakota. The present research is believed to be the first attempt at using F-values in carbonate aquifers to estimate permeability.

Formation Factor (F) Versus Permeability for Well GF-18

In order to properly evaluate the empirical relationship between F and permeability, another independent method of determining permeability was necessary to compare values of F against. The methodology for this comparison was used in analyzing a well in Gulf County, northwest Florida, having the following information available.

Normal electric logs, 16" and 64"
Flowmeter log (relative vertical fluid velocity)
Fluid resistivity (R_w)
Caliper log
Aquifer test data (well transmissivity)

Zones of relatively uniform permeability, based upon the flowmeter log, were divided into eight distinct hydrologic units. Permeability from each zone was obtained by multiplying the relative percent of flow from each zone (in percent from the flowmeter log) by the well transmissivity and then dividing by the zone thickness in order to obtain a permeability per unit thickness (Table 21). This number (a direct measurement of permeability) was then compared to F as obtained from the geophysical logs ($F = R_o/R_w$, where R_o = 16" normal electric, and R_w was obtained from fluid resistivity probe, Figure 44).

Results

Plotting of the data appears to show a good agreement between F, as determined from the logs, and permeability calculated from the flowmeter tests (Figure 45). The eight producing zones compared had a correlation coefficient (r) of 0.79. The relationship of F to permeability for this particular well, GF-18 can be expressed as:

$$k = 72 (F) - 284 \quad (29)$$

where: k is in gallons/day/ft^2.

The most productive zones, numbers 4, 5, 6, and 7 are located

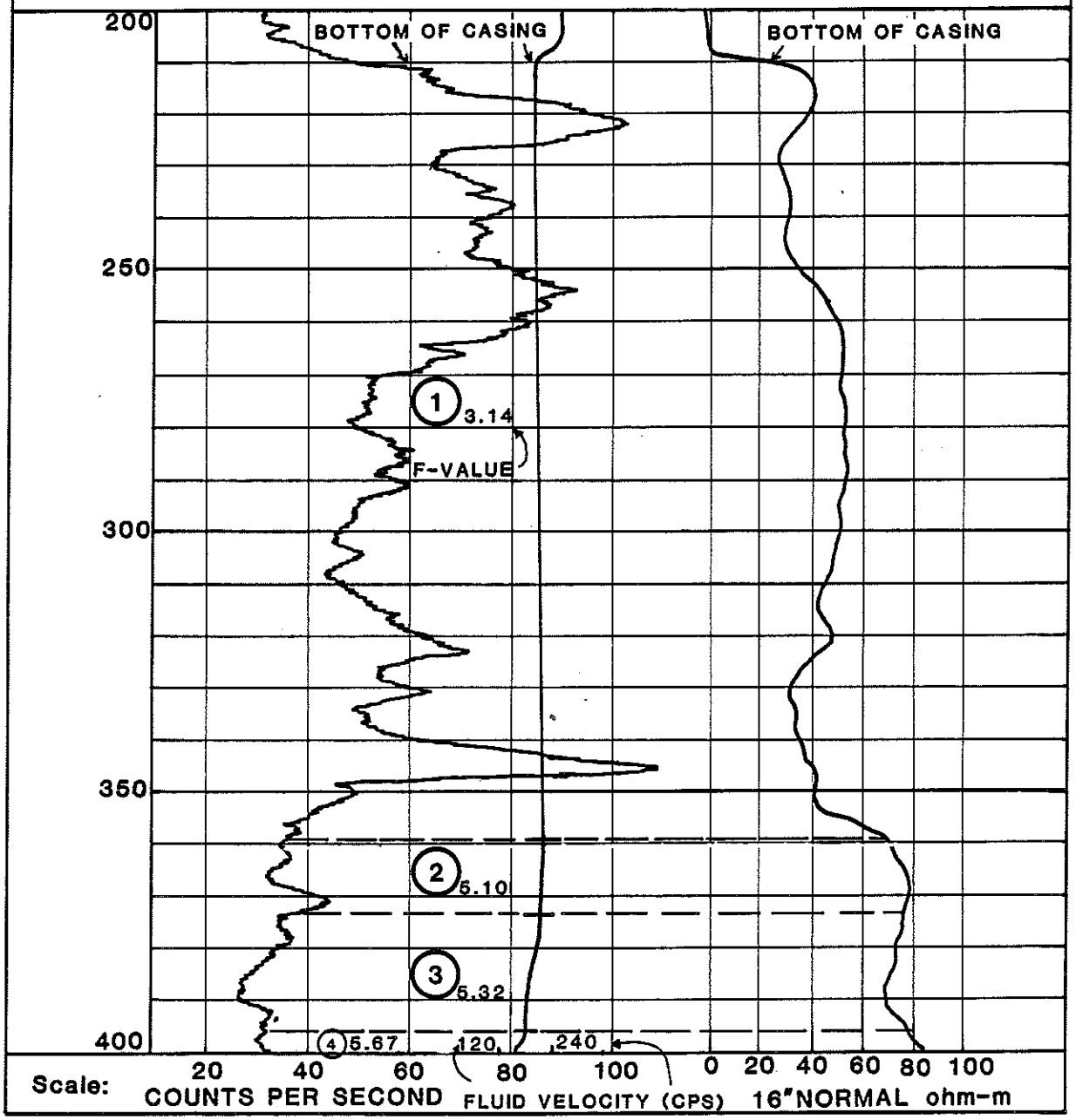
Figure 44.--Flowmeter, 16" normal electric, and natural gamma logs used in determining formation factor (F) from well GF-18.

NAME Fla. Power Corp. COUNTY Gulf W-

LOCATION T 7S R 10W SEC. 20 1/4 NWF- GF-18

DEPTH 610 CASING 210 DIA 12 AQUIFER Floridan

Notes:



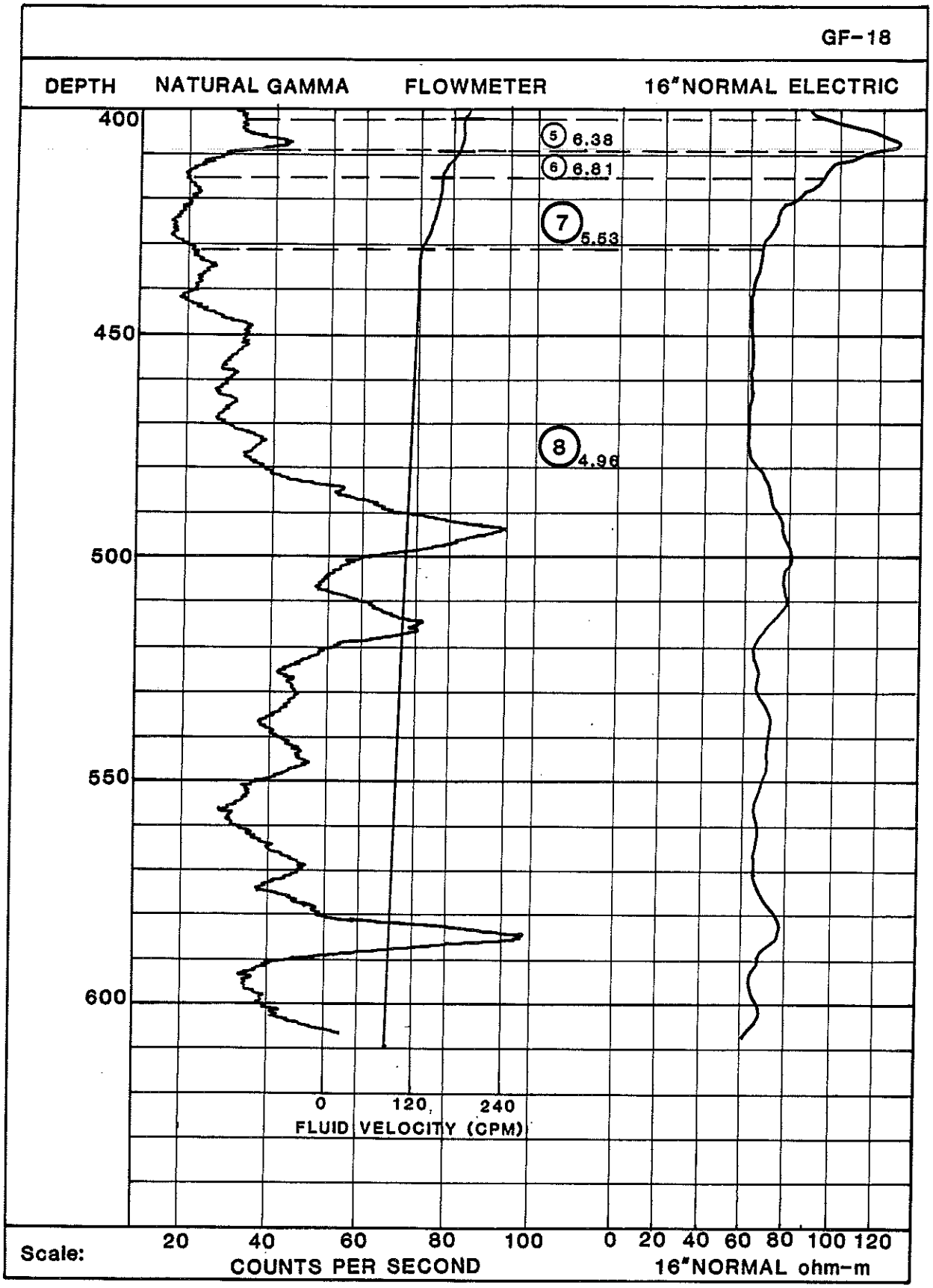
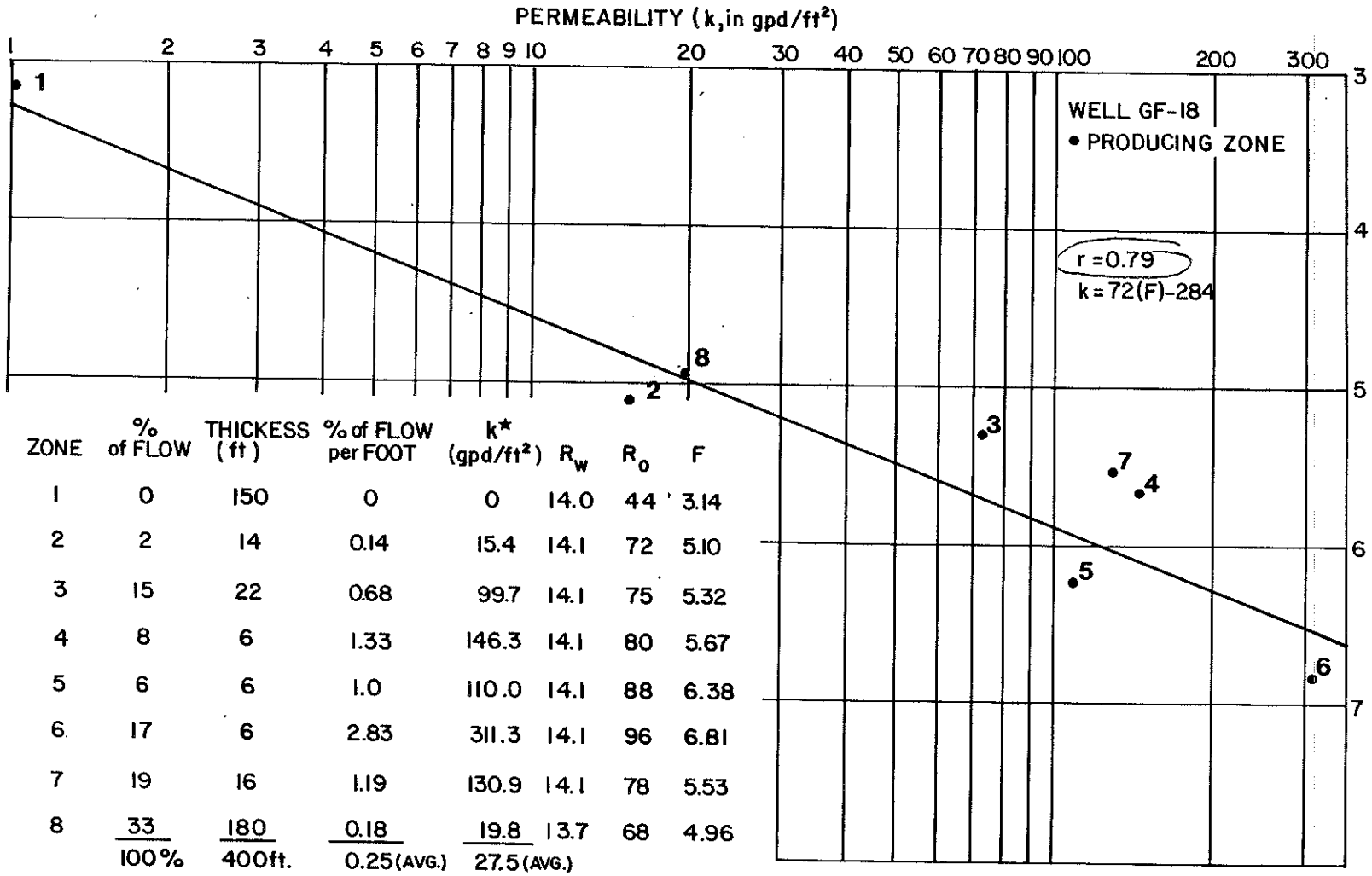

GF-18
DEPTH
NATURAL GAMMA
FLOWMETER
16"NORMAL ELECTRIC
400
450
500
550
600
5 6.38
6 6.81
7 5.53
8 4.96
0 120 240
FLUID VELOCITY (CPM)
Scale:
20 40 60 80 100
COUNTS PER SECOND
0 20 40 60 80 100 120
16"NORMAL ohm-m

Figure 45.--Permeability vs. formation factor (F) for well GF-18.



ZONE	% of FLOW	THICKESS (ft)	% of FLOW per FOOT	k* (gpd/ft²)	R_w	R_o	F
1	0	150	0	0	14.0	44	3.14
2	2	14	0.14	15.4	14.1	72	5.10
3	15	22	0.68	99.7	14.1	75	5.32
4	8	6	1.33	146.3	14.1	80	5.67
5	6	6	1.0	110.0	14.1	88	6.38
6	17	6	2.83	311.3	14.1	96	6.81
7	19	16	1.19	130.9	14.1	78	5.53
8	33 / 100%	180 / 400ft.	0.18 / 0.25 (AVG.)	19.8 / 27.5 (AVG.)	13.7	68	4.96

*Based upon a measured transmissivity of 11,000 gpd/ft.

Table 21.--Algorithm for Determining Permeability (k) and Formation Factor (F) from Fluid Velocity and Resistivity Logs.

1) Scale flowmeter log across the bottom of the page from 0 to 100 percent flow.

2) Divide flowmeter log into zones where the slope is relatively constant.

3) Find the percentage of flow from each zones.

4) From the transmissivity of the well (or converted from specific capacity), Table 22, divide the thickness of the producing zone (in percent of total length of producing zone) into the transmissivity to derive permeability (k) in gallons per day per feet squared (gpd/ft^2) for each producing zone.

5) Divide each R_o by R_w (obtained from fluid resistivity log or point samples taken after the well has stabilized) to obtain F ($F=R_o/R_w$).

6) Plot k vs. F and fit a line through these points. This relationship of F to k should be relatively constant over a large area if the pore water resistivity is constant or known and the lithology and cementation factor (m) remain relatively constant over the area under investigation.

Logs required: flowmeter, short-normal electric (16"), fluid resistivity, caliper, and transmissity or specific capacity (from aquifer test).

Assumptions:

A. Resistivity of pore water is known;
B. Borehole is relatively smooth or changes in diameter can be corrected for; and
C. Cementation factor (m) remains uniform throughout borehole.

Table 22.--Estimating Transmissivity from Specific Capacity

	Well Diameter	Multiplier*
Artesian:	2"	
	4"	2,532
	6"	2,439
	8"	2,373
	10"	2,321
	12"	2,280
Non-Artesian:	2"	2,163
	4"	2,002
	6"	1,909
	8"	1,843
	10"	1,791
	12"	1,750

*Transmissivity = Multiplier x specific capacity in gpd/ft. (Divide by 7.48 to obtain ft^2/d)

(From Meyer, 1963)

near the center of the open borehole. Although the total length of these zones comprised less than ten percent of the open hole length, approximately 50 percent of the flow is contributed by these four zones. Zone 6 had the highest F factor and also had the highest flow per unit length according to the flowmeter log. The upper portion of the borehole (about one-third of the total open hole length) is a very fine grained argillaceous limestone contributing no water to the well (according to the flowmeter log) and correspondingly has the lowest F factor.

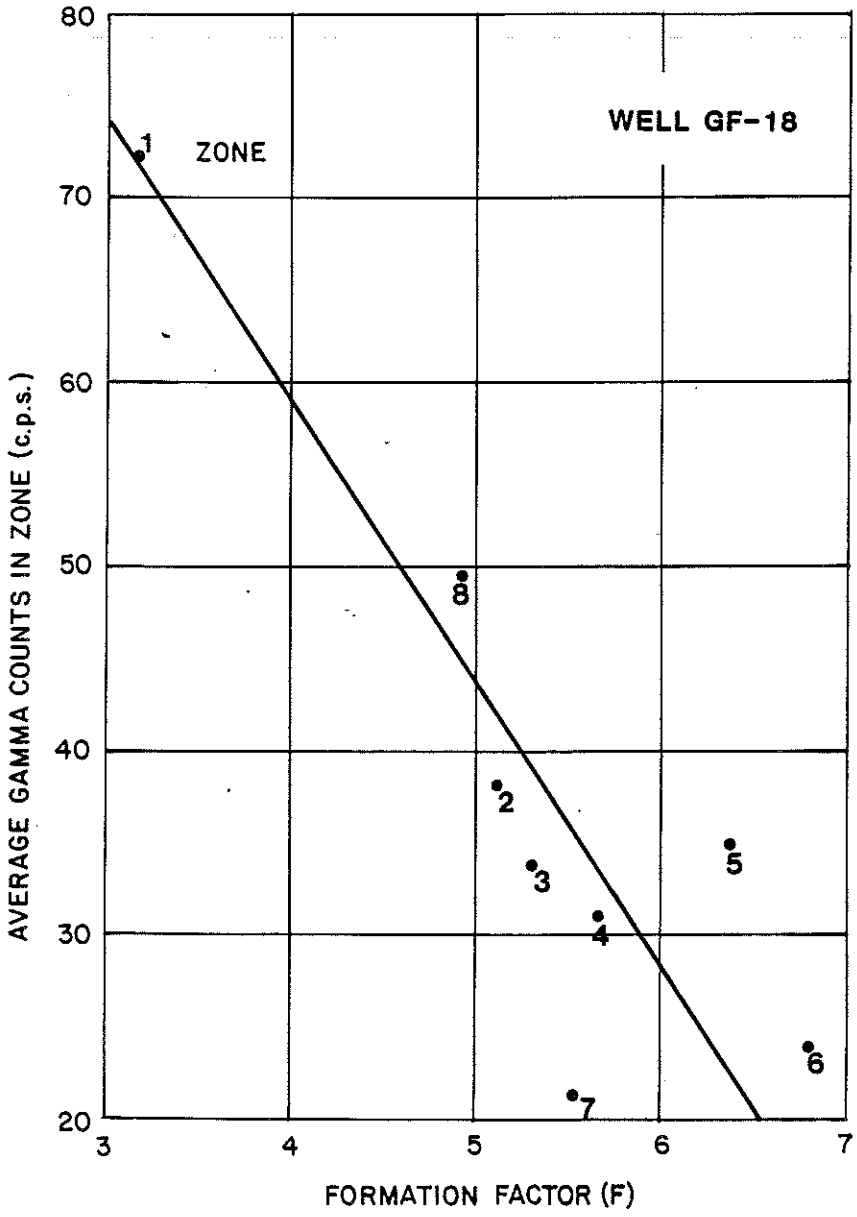
Natural Gamma Log as an Indicator of Permeability

Using data from the the same well, GF-18, a comparison was made between the "average" natural gamma activity of each hydrogeologic zone versus the formation factor (F). The purpose of this comparison was to observe if a correlation exists between clay content of the carbonate and F. It is assumed only one type of clay is present throughout the sequence, and the clay accounts for the major portion of the gamma activity recorded on the log. The plotted data indicate a strong correlation between high gamma activity and low permeability, i.e., increased clay content in the carbonates (as determined by increased gamma activity) lowers the fluid transmitting characteristics of the formation. Further analyses are needed to confirm this relationship (Figure 47).

Permeability, Gamma Activity and Resistivity Relationships
Permeability Versus Resistivity

As demonstrated earlier, if F and permeability are related for a given aquifer system, then saturated formation resistivity (R_0) is largely a function of permeability ($F = k = R_0/R_W$). In order to test this hypothesis, R_0 measurements were compared to aquifer transmitting

Figure 46.--Gamma activity vs. formation factor (F) for determining the relationship between permeability and clay content of the limestone aquifer in well GF-18. It is assumed that the clay is the primary gamma emitter and composition of the clay is relatively constant throughout the interval analyzed.


WELL GF-18
ZONE
1
2
3
4
5
6
7
8
80
70
60
50
40
30
20
3
4
5
6
7
AVERAGE GAMMA COUNTS IN ZONE (c.p.s.)
FORMATION FACTOR (F)

properties as determined from numerous cores and corresponding electric logs. In one example, twenty-one formation resistivity measurements (R_o from 16" normal) were compared to aquifer transmitting properties (well GA-39), based upon a scale of one to nine in the following manner:

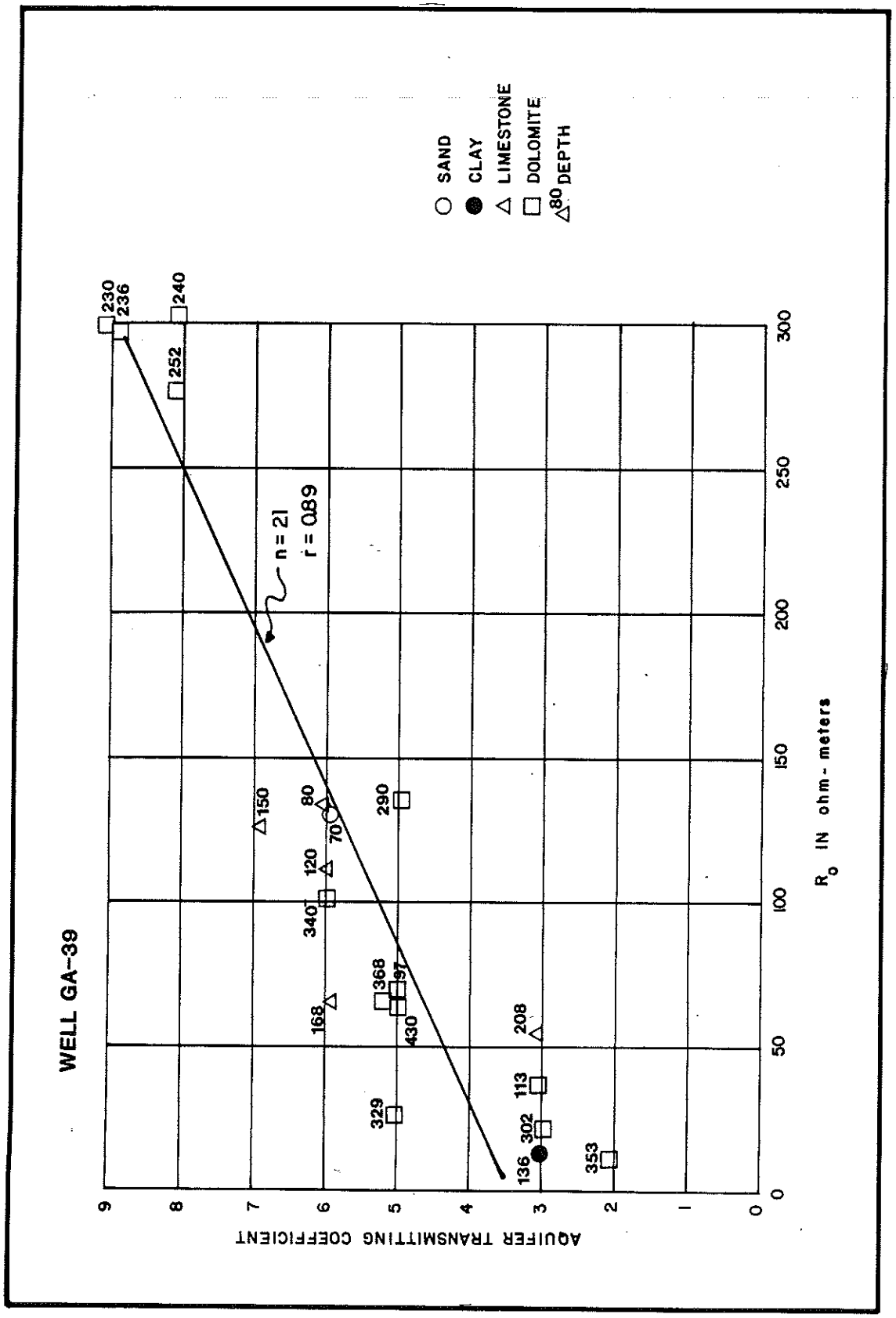
Aquifer transmitting: Coefficient		Hydrogeologic Character
Confining bed	1	- very fine grained clay, no silt or sand content
	3	- as above, some silt or sand in matrix
Aquiclude	5	- leaky confining bed, may transmit some water
	7	- poor aquifer - capable of transmitting a moderate amount of water to wells
Highly Permeable	9	- well developed secondary porosity, good producing zone

In this example, water resistivity was assumed to be constant (as determined from numerous point water samples and fluid resistivity log measurements), and R_o was plotted directly against the aquifer transmitting coefficient (Figure 47). Results show a correlation coefficient (r) of 0.89 (n = 21), indicating a good relationship between permeability (or F) and saturated formation resistivity (R_o) in freshwater environments.

Permeability vs. Uranium-Potassium Gamma Activity

Utilizing the same core as in the previous example, GA-39, it was observed that the zones of highest permeability appeared to have a significantly higher uranium-potassium ratio (determined by gamma spectrometry). Uranium-potassium ratios appeared to be influenced by the permeability of the formation rather than lithology. Generally, the more permeable zones had higher uranium/potassium ratios. One explanation of this phenomenon may be accounted for by adsorption of uranium

Figure 47.--Aquifer transmitting characteristics coefficient vs. saturated formation resistivity for well GA-39.


WELL GA-39
AQUIFER TRANSMITTING COEFFICIENT
R_o IN ohm-meters
SAND
CLAY
LIMESTONE
DOLOMITE
DEPTH
n = 21
r = 0.89
0
1
2
3
4
5
6
7
8
9
50
100
150
200
250
300
230
236
240
252
150
80
70
120
290
340
368
97
168
430
208
113
329
302
136
353

ions onto the fluid-matrix interface as ground waters percolate through the aquifer system (Cowart, 1974). Uranium ions appear to be leached from sediments in oxidized zones, near land surface, an environment where uranium ions are highly mobile. Uranium ions then migrate with the percolating ground water and precipitate, downdip, in more reducing environments. The concentration of uranium precipitated on the fluid-matrix interface would then appear to be a function of; the concentration of uranium in the percolating waters and; the volume of ground water flowing through the aquifer system. Many economical uranium deposits (in the western United States) are believed to have formed in this manner. Permeability may then be related to the uranium-potassium isotopic ratio (if potassium is not fractionated in the same manner as uranium). The use of gamma spectrometric probes (logging probes capable of quantifying uranium, thorium and potassium isotopes) may have some hydrologic significance as an indicator of permeability. Isotopic data from Well GA-39 vs. aquifer transmitting coefficients (as previously defined) are plotted on Figure 48. Twenty-four samples were compared and had a correlation coefficient of (r) = 0.80. The dominant lithology (lithology is noted by the symbol plotted) appears to have little correlation to permeability.

Uranium-Potassium Gamma Activity vs. Resistivity

Considering that the last two comparisons, resistivity vs. transmitting coefficient and uranium/potassium vs. transmitting coefficient, had statistically significant correlations (r's of 0.89 and 0.80, respectively), it may be postulated that uranium/potassium vs. resistivity should also correlate. The results are plotted for the same intervals of Well GA-39 (Figure 49). Twenty-one samples were plotted

Figure 48.-- Uranium/potassium gamma emission ratio vs. aquifer transmitting coefficient for various lithologies obtained from well GA-39.

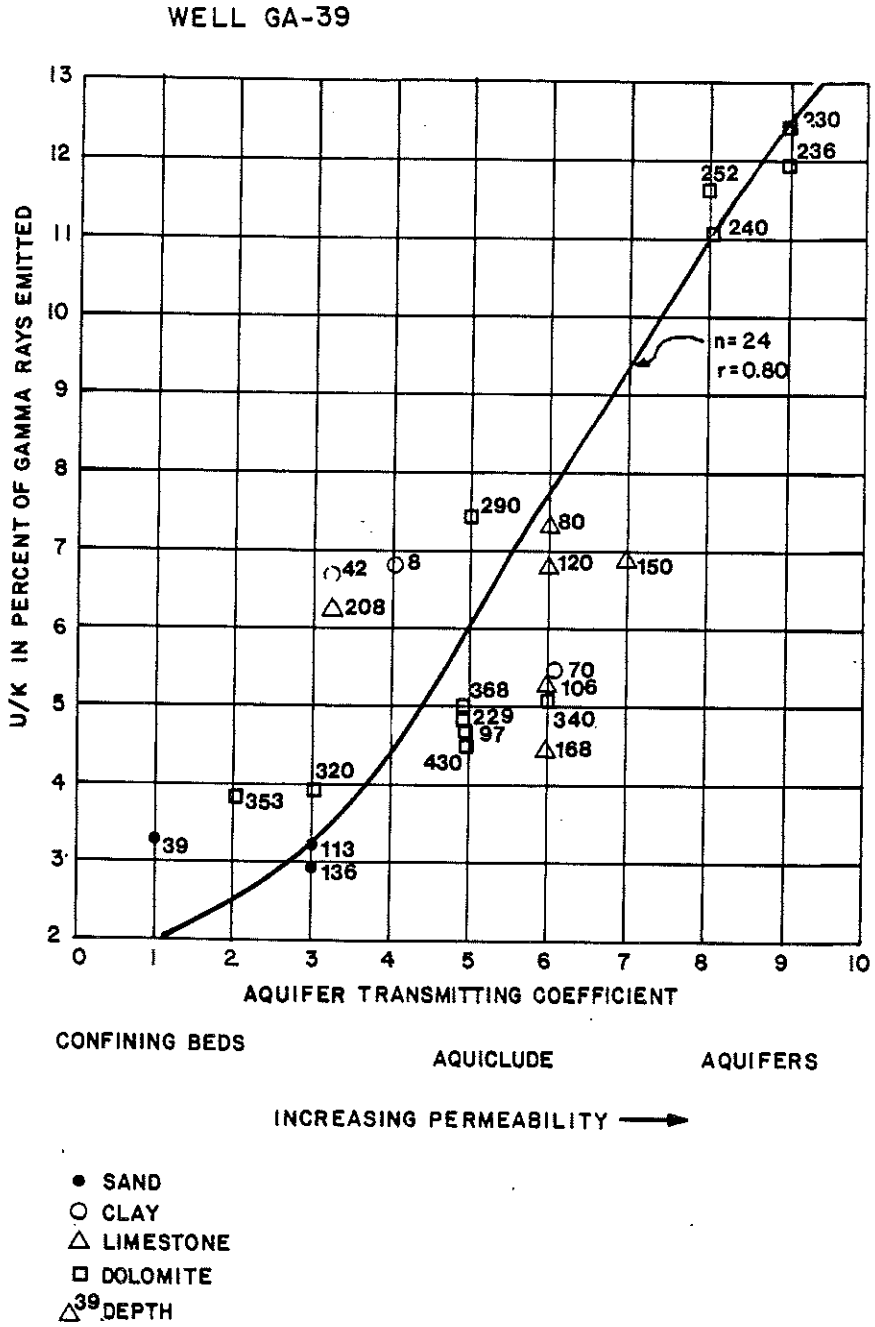
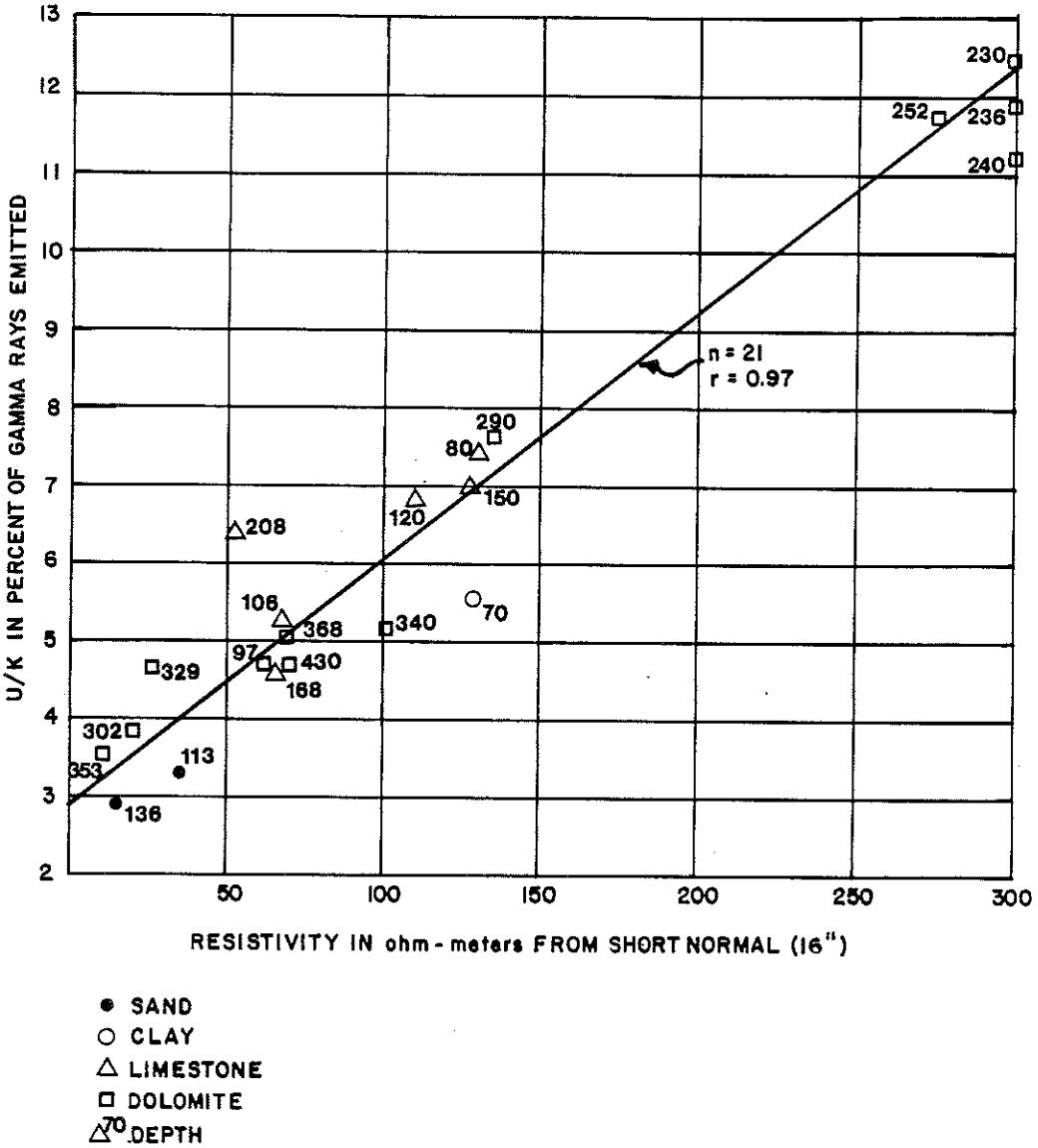

WELL GA-39
U/K IN PERCENT OF GAMMA RAYS EMITTED
AQUIFER TRANSMITTING COEFFICIENT
n= 24
r=0.80
230
236
252
240
290
80
42
8
120
150
208
70
368
106
229
340
97
168
430
320
353
39
113
136
CONFINING BEDS
AQUICLUDE
AQUIFERS
INCREASING PERMEABILITY
SAND
CLAY
LIMESTONE
DOLOMITE
DEPTH

Figure 49.--Uranium/potassium gamma emission ratio vs. saturated formation resistivity for various lithologies from well GA-39.


U/K IN PERCENT OF GAMMA RAYS EMITTED
RESISTIVITY IN ohm-meters FROM SHORT NORMAL (16")
n = 21
r = 0.97
SAND
CLAY
LIMESTONE
DOLOMITE
70 DEPTH

having a correlation coefficient of (r) = 0.97 indicating even a stronger relationship between resistivity and uranium concentration. Further analyses are necessary in order to determine if uranium concentration are preferentially concentrated in zones of high resistivity, i.e., "clay free" portions of aquifers.

From the above analyses, it appears that the electric log, gamma log, and relative uranium/potassium content may relate to permeability.

Further investigation of these relationships are necessary to confirm these hypotheses. If any (or all) of these relationships are valid, then a new method of approximating permeability may be available for use in freshwater environments.

Influence of Secondary Porosity Upon Permeability

Permeability in carbonate aquifers is greatly influenced by the degree of secondary porosity development. Secondary porosity in carbonates may be split into two types solution or fracture porosity. Solution type porosity is most notable in carbonates of moldic type porosity (dissolution of meta stable shell material). Secondary porosity is also dependent upon the clay content within the matrix. Very fine grained (chalky) limestones and argillaceous limestones rarely develop high permeability, except in recharge areas where active dissolution of the carbonate material is accelerated by acidic precipitation.

The process of dolomitization may be greatly influenced by the primary permeability of the carbonate. Even small amounts of clay are believed to hinder percolation of large volumes of ground water necessary for dolomitization (Hanshaw et al, 1971, Fanning et al, 1981,

Bloom, 1982). This hypothesis is also supported by the fact that argillaceous dolomites are relatively rare in the Tertiary rock record.. The absence of clay in dolomites, may also attribute to the low ductility of dolomites. Even in tectonically "quiet" areas, such as the Floridan Platform, dolomites are often highly fractured while being interlayered with limestones with little or no fracture porosity. Fractured dolomites are often associated with zones of extremely high permeability.

Determining Secondary Porosity-Solution Type

The determination and quantifying of secondary solution type porosity would yield valuable hydrologic information concerning aquifer permeability. Solution type porosity may range from a very few percent to more than 50 percent of a formation's volume. Secondary porosity is developed by ground water percolating along "preferred solution channels". Permeability, directly related to the number and size of the channels intersected, may vary considerably over extremely short horizontal distances. Acoustic velocity probes are often used to determine the presence of secondary porosity. Compression waves generated by the probe's transmitter travel fastest through the matrix and tend to bypass vugs and cavities. Since the arrival time of only the fastest acoustic waves are recorded, the acoustic velocity log will record "apparent" porosities lower than true in carbonates with secondary porosity. The amount of porosity "overlooked" may be compared with porosity values determined from other types of probes not sensitive to secondary porosity (neutron or density) and the difference between the porosities is due to secondary porosity. The M and N plot or the lithologic cross

plots may be used, if the lithology is known, to observe the presence of secondary porosity.

Determining Secondary Porosity-Fracture Type

Although fracture porosity rarely contributes to more than five percent of a formation's total porosity, fracture porosity is commonly the dominant type in the most productive aquifer systems. Fracture width has been related to permeability by:

Width of fracture in cm x 2,000 = permeability in darcys
(in inches x 12,200 = permeability in Ft^2/d)

(From Hilchie, 1982)

Fracture porosity is also the most difficult to detect and measure. Fractures often appear as low porosity on all three types of porosity logs. Fractures may also appear as very high or low resistivity on electric logs, depending upon the orientation of the fractures.

Permeability from fractures cannot be easily quantified, but the shape, orientation and width can be observed by; television surveys, impression packers, or by the borehole (sonic) televiewer. The borehole televiewer is superior to other methods for observing fracture porosity. Basically, the borehole televiewer is an acoustic type probe transmitting an acoustic pulse towards the borehole wall which is reflected back to a receiver. A continuous record of the borehole rugosity is recorded as the transmitter rotates in a 360 degree plane normal to the borehole. Vugs and cavities are recorded as dark spots on strip chart paper. Magnetic north is recorded by the probe and may be used in orienting the fracture directions. At this time, the borehole televiewer is primarily

a research probe, but has a great potential for detecting fractures in water resource investigations.

Tracer Logging

Measuring the rate of inner borehole flow has been accomplished using chemical, radioactive and thermal tracers. Tracer logging has very limited quantitative applications to hydrologic investigations. Inner borehole flow will yield relative head differences between aquifers penetrated, but is also dependent upon permeability of both zones and the rate of flow in the borehole is by no means indicative of flow through the adjacent formations.

Radioactive tracers (commonly I^{131}, 8 day 1/2 life; or Br^{32}, 36 hour one-half life) are often used but are expensive, cannot be stored for extended periods of time, require a license to handle and a permit to use in most potable aquifers. Thermal tracers have been successfully used in a number of instances with good results to determine lateral flow (injected plumes measured in adjacent monitor wells). Thermal plumes are not advisable for use in single boreholes (i.e., thermal changes should be measured in monitor wells) since the warmer water will rise faster, within the borehole, than the native fluid. Chemical tracers have been successfully used for determining lateral and vertical flow provided the tracer is a similar density and chemically inert to the surrounding formations and pore waters.

Any type of vertical flow measurements must be used in conjunction with a caliper log to correct changes in velocity due to variations in borehole diameter.

Permeability from Flowmeter Logging

Mechanical flowmeters directly measure vertical flow from boreholes (Figure 50). Flow meter logs are extremely useful for determining individual zone permeability, but require vertical velocities in excess of three feet per minute (to overcome inertia of propeller). Quantitative results also require the borehole to be uniform in diameter over long vertical spans or adjustments should be made accordingly using a caliper log. Variations in borehole diameter can be corrected using the following equation:

$$Q = 1/4\ d^2 \cdot v \quad (30)$$

where Q = flow in counts per second (cps)
d = diameter
v = velocity in cps

Flowmeter logs run up-hole have smoother and more representative curves than when run down-hole. Logging down-hole the flowmeter often bounces off ledges and may free fall short distances yielding anomalous spikes on the log.

Flowmeter logs, when used in conjunction with R_w measurements, can be used to infer water quality and quantity contributed from specific producing zones in open boreholes. This information can be very valuable in determining specific capacity and water quality at various pumping rates (Figure 51).

Figure 50.--Typical flowmeter log response to various borehole conditions.

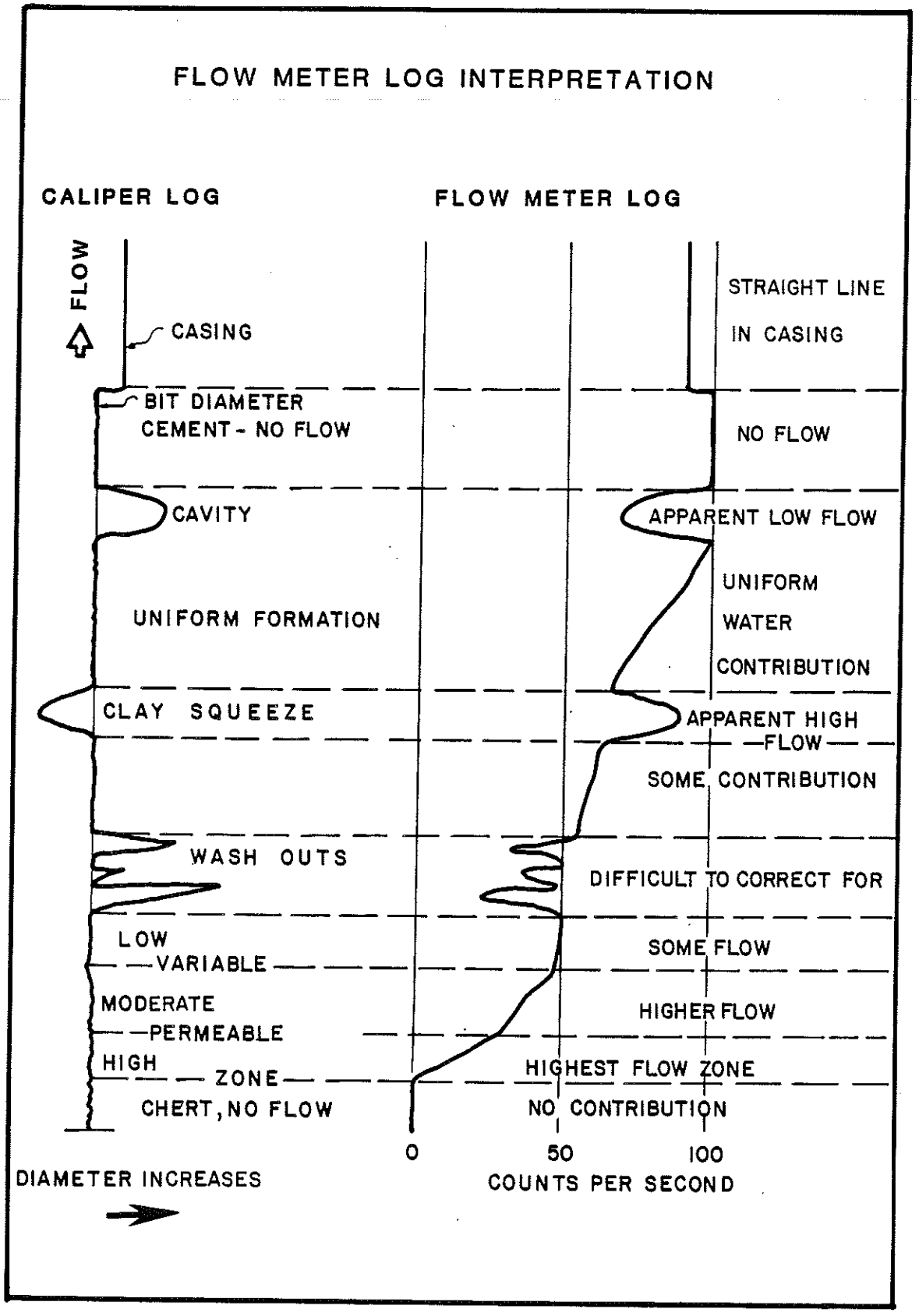
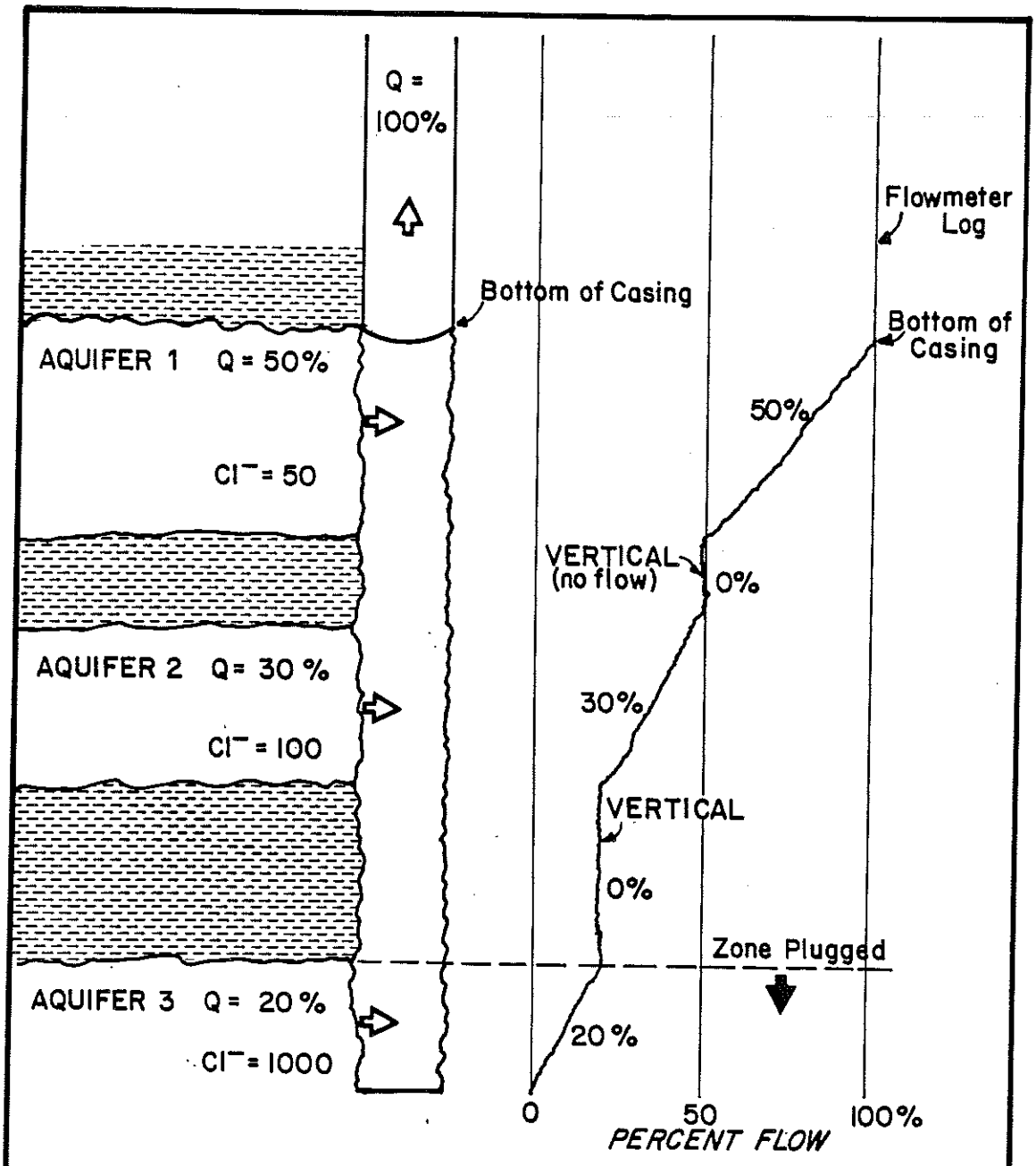

FLOW METER LOG INTERPRETATION
CALIPER LOG
FLOW METER LOG
FLOW
CASING
STRAIGHT LINE
IN CASING
BIT DIAMETER
CEMENT - NO FLOW
NO FLOW
CAVITY
APPARENT LOW FLOW
UNIFORM FORMATION
UNIFORM
WATER
CONTRIBUTION
CLAY SQUEEZE
APPARENT HIGH
FLOW
SOME CONTRIBUTION
WASH OUTS
DIFFICULT TO CORRECT FOR
LOW
VARIABLE
SOME FLOW
MODERATE
PERMEABLE
HIGHER FLOW
HIGH
ZONE
HIGHEST FLOW ZONE
CHERT, NO FLOW
NO CONTRIBUTION
0
50
100
DIAMETER INCREASES
COUNTS PER SECOND

Figure 51.--Maximizing water quantity at a desired quality using flowmeter logs and R_w of aquifers.



BEFORE PLUGGING:		AFTER PLUGGING AQUIFER 3
GALLONS PER MINUTE	- 1000	1000
DRAWDOWN (feet)	- 100	120
SPECIFIC CAPACITY (gpm/ft/dd)	- 10	8.3
CHLORIDES (ppm)	- 280	69

DISCUSSION

General

Borehole geophysical logs provide an accurate means of obtaining hydrogeologic information relating to lithology, formation pore water quality and transmitting properties of hydrogeologic units. Although none of these characteristics are directly measured by any particular log, strong inferences can be made provided; some knowledge of the local geology is available, cuttings and/or cores are collected to supplement log interpretations and extraneous effects affecting log responses are minimized.

Quality log interpretations in freshwater carbonate environments are based upon numerous assumptions and principles different than those employed in deep well log interpretation. Near surface freshwater carbonate formations are characteristically less compact, less cemented, lower in temperature, higher in porosity and permeability and at least two orders of magnitude greater in saturated formation resistivity than their more deeply buried counterparts. These physical differences affect every type of log currently run and in some cases to such a degree that certain probes cannot be utilized in both types of environments.

A major portion of this research is devoted to the interpretation of geophysical logs in freshwater carbonate environments. Many of the traditional log interpretation principles are based on the assumption that the formations evaluated are of a clastic or granular nature. Very little research has documented the response of porosity (neutron,

density and acoustic velocity), or electric logs in near surface carbonates. Results from this research, developed by empirical methods, strongly indicate that uncompacted Tertiary carbonates respond very similarly to unconsolidated to moderately cemented granular materials. Exceptions include dolomites, with fracture type porosity, and crystalline dolomites of extremely low porosity. Most limestones appear to have high porosity (commonly 25 to 45 percent) and respond on most logs as homogeneous, porous granular material. Sucrosic dolomites have intercrystalline type porosity and also appear to yield valid results for porosity, lithology, and water quality determinations. Formations dominated by fracture porosity and a high degree of secondary porosity (vugs, channels, etc.) are often highly permeable, but are difficult to detect or quantitize from any logs currently available. Acoustic velocity logs are sensitive to secondary porosity effects and the percentage of secondary porosity may be quantified by obtaining the porosity difference recorded from neutron or density logs. The affect of under saturated zones on various logs have not been determined and these zones should not be used for quantitative analyses.

In near surface environments, it is assumed all of the pore spaces in saturated zones are occupied by fresh water and never hydrocarbons. Most logs run in the vadose or unsaturated zone require water saturation percent (S_w%) correction factors for proper interpretation. Unsaturated formations will directly affect the response of natural gamma, neutron, density, acoustic velocity and electric logs. The affect of under saturated zones on various logs have not been determined and these zones should not be used for quantitative analyses.

Clays and argillaceous formations also affect quantitative analyses of neutron, acoustic velocity and electric logs. Non-effective clays (clay with low cation exchange capacities - kaolinite and chlorite; also chalk and dolosilts) respond as very fine granular material and may be interpreted without correction factors. Effective clays, clays incorporating water in their lattice structure (montmorillonite, illite and palygorskite) have an extremely variable effect on porosity and electric logs and should not be used in quantitative analyses. Fortunately, producing zones of hydrogeologic interest are predominantly composed of relatively pure limestone, dolomite or quartz sands and rarely need to be corrected for clay content. Clay content may also be quantified by cross plotting density log porosity vs. porosity from neutron or acoustic velocity logs. The latter two logs tend to "ignore" the water incorporated in the mineral structure of the clays. Apparent porosity differences between density and neutron log or acoustic velocity log, can be used to determine clay content (percent by volume).

Carbonates often exhibit an extremely diverse texture and composition (dolomites interlayered with limestones, etc.) in very short vertical spans. "Clean" carbonates (limestone or dolomite without clay) may act hydrologically as extremely productive zones (characterized by a high degree of secondary porosity) or as aquicludes (example; dense crystalline dolomite). Quantitative analyses using thin alternating beds exhibiting extreme hydrologic variations over very short distances should only be used for quantitative analyses with extreme caution. In many cases, the various logs will reflect properties of adjacent zones, depending upon the probes radius of investigation and bed thickness.

Smooth boreholes, uniform in gauge, are desirable for all types of log interpretation since most probes are influenced by material closest to the probes sensor. Activities and washouts appear on many logs as "clays" (low density-high water saturation) and should be identified and eliminated from interpretation by using caliper logs.

Lithologic Determinations

Lithology can be accurately determined by cross plotting data obtained from porosity logs (neutron, density and acoustic velocity). This technique yields the percentage of each lithology (assuming only two end members - quartz sand, limestone or dolomite), and provides a relatively accurate means for determining porosity.

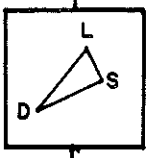
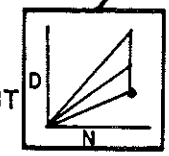
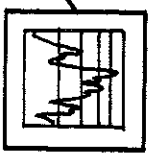
If a third lithologic type is suspected all three porosity logs may be used simultaneously in an M and N plot to determine the percent of each mineral present (calcite, dolomite and quartz). M and N plots also reveal information relating to secondary porosity and clay content of formations. Electric logs are rarely used for determining lithology since the main producing formations (quartz sand, limestone and dolomite) all exhibit similar and extremely high resistivities. Saturated formation resistivity is influenced to a much greater degree by pore water resistivity, porosity, and pore geometry than lithology.

A flow chart for determining the order of lithologic cross plotting is illustrated on Figure 52.

Lithologic determinations by gamma spectrometric techniques have failed to reveal any significant affinity for potassium, uranium or thorium to any particular type of lithology. The percentage of gamma rays emitted from each naturally occurring isotope for sand, clay,

Figure 52.--Flow chart for determining lithology and clay content by different cross plotting methods.

LITHOLOGY

TYPE of INFORMATION		TYPE of PLOT	INFORMATION REQUIRED	ASSUMPTIONS
LITHOLOGIC		POROSITY CROSS PLOT D vs N Δt vs N D vs Δt	N, D, V_a , C	CLEAN fms. ONE or TWO LITHOLOGIES 100% SATURATED
LITHOLOGIC		M and N	N, D, V_a , C	CLEAN fms. 100% SATURATED
CLAY CONTENT		D-N CROSS PLOT	D, N, C	KNOW CLAY (%) POINT
		or GAMMA INDEX	G	ONE TYPE OF CLAY
	ARGILLACEOUS LIMESTONES	CLAYEY SANDS		

limestone and dolomite, was relatively constant and calculated at approximately 61, 30 and 9 percent for uranium, thorium and potassium, respectively. Further analyses of clay minerals directly overlying and within carbonate units revealed their composition to be highly calcareous and are probably not "true" clays, but a residium from weathering of primary carbonate formations. Small percentages of clay minerals were deposited with the dissolved carbonate fraction and often yield characteristic clay mineral patterns on x-ray diffractograms (commonly palygorskite).

These calcareous clays appear to be composed of the resistant fraction of the dissolved carbonates and contain a high proportion of impurities and gamma emitting isotopes (but are similar in isotopic ratio to the parent carbonates). Although usually very thin, but areally extensive, these "clays" often serve as excellent stratigraphic marker beds on natural gamma logs.

Water Quality Determinations

Water quality within prospective producing zones is of a prime concern to hydrogeologists evaluating ground-water resources. Water quality is often related directly to the resistivity of the formation pore water. Water resistivity (R_W) can be derived from deep penetrating electric logs (measuring true saturated formation resistivity, R_O) and porosity logs used to determine the parameters in the following relationship:

$$R_W = \phi^m R_O$$

where; m is the cementation factor (approximately 1.3 for unconsolidated Tertiary granular materials and 1.6 for non-compacted Tertiary carbonates).

Once R_w is determined, water quality can be derived from water resistivity - ion cross plots. This relationship between the ion concentrations is normally established from water quality analyses from neighboring wells tapping the same water mass. In most instances, the ions influencing water resistivity (R_w) are also present in the highest concentrations such as; chloride, sulfate (or total dissolved solids) and are also the first ions to render the water unpotable. For example, chloride is normally the first ion to exceed concentrations recommended for public water supplies in the Floridan aquifer and ground water are generally not potable if the product of porosity and R_o measurements combined are less than 7.21 ohm-meters, when substituted into the following equation;

Chlorides exceed potable limits (250 ppm) if:

$$\phi^{1.6} (R_o) < 7.21 \text{ ohm-meters}$$

$$\text{from } \phi^{m} (R_o) = R_w \quad (16)$$

Precise water quality determinations rely upon accurately determining the formation cementation factor (m). Cementation factors cannot be determined in the laboratory and can only be calculated from porosity-resistivity cross plots. The cementation factor is obtained by plotting formation porosity vs. saturated formation resistivity on log-log paper, m is equal to the slope of the line fitted through the data points. A wide range of porosity and saturated formation resistivity values are necessary for a proper line fit and to observe if m remains constant throughout the interval plotted. An aquifer system with extreme ranges in porosity may exhibit a slight variation in cementation factor. Lithologically thick, homogeneous aquifers of uniform water quality may be difficult to analyze since the resistivity

and porosity range will be narrow rendering it difficult to properly fit a line through the data. In many wells open to multiple aquifer systems, or aquifers having an extreme range in porosity, various units may have a distinct m-values which must be applied to all determinations from those particular zones.

Once m is accurately determined, water resistivity for the entire interval can be analyzed using resistivity-porosity cross plot (RPCP) paper with the proper m spacing (Appendix N). Zones with fracture porosity, large vugs and zones where porosity is less than seven percent, should be avoided for the determination of R_w.

Saturated formation resistivity (R_o) should be obtained using multiple electrode resistivity probes in order to penetrate deep into the formation. Electric logs with varying depths of investigation also aid in determining the depth of mud flushing. Normal electric logs (16" and 64") are adequate for most freshwater environments, but are adversely affected in carbonate formations saturated with highly resistive pore waters (R_w > 100 ohm-meters). Under these conditions, focused resistivity logs, such as laterologs or guard logs, may be used to penetrate highly resistive formations.

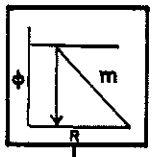
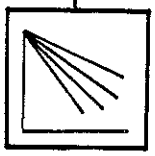
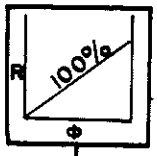
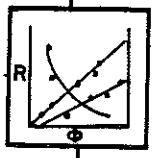
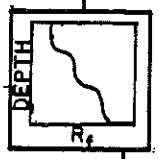
A flow chart depicting the different methods and procedures for determining water quality is illustrated on Figure 53.

Water Transmitting Properties

The water producing characteristics of wells tapping carbonate formations is highly dependent upon the type and development of secondary porosity distributed throughout the aquifer system. Solution type porosity is greatly influenced the: 1) chemical compatability of

Figure 53.--Flow chart for determining water quality by different plotting methods.

WATER QUALITY (R_w)

TYPE of INFORMATION		TYPE of PLOT	INFORMATION REQUIRED	ASSUMPTIONS
CEMENTATION FACTOR (m) and R_w		POROSITY-RESISTIVITY (LOG-LOG)	D or N or V_a	CLEAN fms. 100% SATURATED R_w at S.T.P
FORMATION RESISTIVITY FACTOR (F)		CHART $F = \frac{1}{\Phi^m}$	POROSITY	CLEAN fms. m-CONSTANT
WATER SATURATION (S_w)		RESISTIVITY-POROSITY CROSS PLOT (RPCP)	D or N or V_a and E	CLEAN fms. NO FRACTURE POROSITY
R_w OF DIFFERENT WATER ZONES		RPCP	D or N or V_a	CLEAN fms. m-CONSTANT KNOWN 100% SATURATED R_w at S.T.P.
	OR			
R_w		FLUID RESISTIVITY	R_f	WELL DEVELOPED NO INNER BOREHOLE FLOW BOREHOLE WQL = PORE fm WQL
SPECIFIC ION CONCENTRATION		R_w - ION	R_w, LOCAL WQL INFO.	LINEAR RELATIONSHIP R_w at S.T.P.

the ground water in contact with the carbonate (largely a function of distance to the recharge area; 2) volume of ground water flowing through the aquifer system; and 3) the original texture and mineralogy of the carbonate matrix. For example, carbonates, chiefly composed of unstable bryozoan remains tend to form "better interconnections (higher permeability) than small mollusk shells in a fine grained carbonate mud matrix. Dissolution of the original fossil material in the former case favors interconnection of pore spaces, but does not enhance permeability in the latter.

Carbonates containing even small proportions of clay rarely develop into highly productive aquifers. This may be accounted for by: 1) inability of percolating ground water to dissolve the clay and cause the clay to "plug" any secondary porosity channels that begin to develop; and 2) clay will tend to lower the ductility, of carbonates thus reducing the susceptability to fracture porosity (an effective method of increasing permeability).

The most significant difference between log response in fresh water versus brine saturated formations is the means of conducting electrical current through the formation. In brine saturated formations, electric current is by electrolytic conductance through the saturating fluid. Formation resistivity in brine saturated formations, therefore, is primarily a function of water resistivity and degree of matrix cementation. In freshwater environments, electrical current is more readily conducted along the fluid-matrix interface, rather than through the saturating fluid. This phenomenon has important hydrologic implications relating to permeability not applicable in the oil industry. Formation resistivity (F) in freshwater environments

increases with grain size and sorting since the current is forced to travel a more tortuous path between electrodes. All of the factors increasing tortuosity (i.e., formation resistivity) tend to increase permeability. In freshwater environments, producing zones correlative with zones of high resistivity are characteristic of formations having: 1) low clay content; 2) high surface conductance (high grain contact area ratio to pore volume); 3) "large" grain sizes; and 4) high water resistivity (an indicator of "good" water quality).

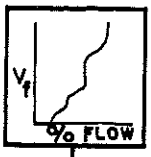
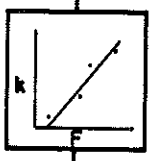
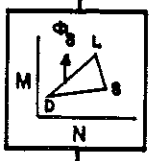
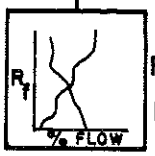
Fractured dolomites often have very high formation resistivity, but low porosity. Fortunately, the low porosity is offset by extremely high permeability and still appear as "good" productive zones on electric logs. Different methods of obtaining permeability in freshwater zones are illustrated on Figure 54.

Since the presence of clay tend to reduce permeability and in aquifer systems where clays are the primary gamma emitter, the natural gamma log may be used to approximate permeability. High gamma activity appears to be a good indicator of "low" permeability throughout the area researched. Notable exceptions to high gamma activity/permeability relationships are: 1) permeable "clean" medium quartz beach sands with accessory mica flakes (high percent of potassium -40) emitting high gamma counts; 2) "pure" montmorillonitic clays with very low gamma counts acting as an effective confining bed; and 3) low gamma activity from organic material often observed in cores and well cuttings (contrary to organics in the petroleum industry having very high gamma activity).

Preliminary results from gamma spectrometric analyses indicate a strong correlation between permeability and uranium/potassium isotopic

Figure 54.--Flow chart for determining water transmitting properties of aquifers by different plotting methods.

WATER TRANSMITTING PROPERTIES

TYPE of INFORMATION		TYPE of PLOT	INFORMATION REQUIRED	ASSUMPTIONS
PERCENT of FLOW FROM EACH ZONE		FLOWMETER	V_f , C	SMOOTH BOREHOLE 2 ft/min. MINIMUM VERTICAL FLOW
PERMEABILITY - F RELATIONSHIP		k vs F	(NONE)	GOOD F and R_w VALUES
SECONDARY POROSITY		M and N	N, D, Va, C	CLEAN fms. ONE OR TWO LITHOLOGIES
OPTIMIZING R_w AT A GIVEN QUANTITY (Q)		FLUID RESISTIVITY VS FLUID VELOCITY	V_f, R_f, C	WELL DEVELOPED NO INNER BOREHOLE FLOW SMOOTH BOREHOLE 2 ft/min. MINIMUM VERTICAL FLOW

ratios. Uranium appears to be preferrentially concentrated, with respect to potassium, in the higher permeability zones. A mechanism involving the adsorption of uranium ions on to aquifer type material accounts for this phenomena and is described in detail by Cowart (1974). Uranium appears to be mobile in recharge areas (oxidized zones) and percolates with ground waters until Eh-pH conditions favor precipitation (or adsorption) onto formation matricies. Permeable carbonates normally have a greater volume of ground water (and associated uranium in solution) circulation and are more likely to concentrate uranium by adsorption than less permeable zones. Potassium also appears to be unaffected by this process, which may contribute to the apparently high uranium/potassium ratios.

SUMMARY AND CONCLUSIONS

During the last decade, borehole geophysical logging has become a widely accepted method of obtaining information relating to ground-water resources. Although once considered a very expensive and cumbersome method for procuring hydrogeologic information, recent advances in microelectronics have made logging more feasible and economical to use in the water well industry.

Geophysical logs provide a continuous record of various physical parameters, at exact depths, relating to such hydrogeologic information as lithology, porosity, pore water quality and water transmitting properties of hydrogeologic units. Currently, well cuttings are the most common method of obtaining information on lithology, but represent only "point samples" which may be contaminated or have undergone density fractionation during circulation in the borehole. Clays and secondary porosity are rarely preserved in well cuttings. Cores are also a valuable means of obtaining subsurface information, but rarely obtain 100% recovery and are extremely expensive. Laboratory porosity and permeability measurements from cores still only represent "point samples" whereas geophysical logs depict a continuous record of these parameters. Values obtained from geophysical logs may actually be more representative than laboratory results considering the measurements obtained from logs are based upon a volume many times of those used for laboratory core analyses. Geophysical logs are also capable of obtaining information on existing wells and provide "on-site" results without extensive processing.

This research has compared numerous well cuttings and cores with accompanying geophysical logs from freshwater environments in order to evalute the application of various types of logs currently available for use in water resources investigations. Some of the more significant findings relating to the application of borehole geophysical logs to hydrogeologic investigations, as based upon this research, may be summarized as follows:

1) The optimal suite of geophysical logs for obtaining semi-quantitative information on lithology, water quality and water transmitting characteristics of coastal plain type sediments include; the natural gamma, neutron, density, acoustic velocity, normal electric logs (16" and 64"), caliper. Other important complimentary logs include the temperature, fluid velocity, fluid resistivity and fluid sampler.

2) The Tertiary carbonates (Eocene to Recent) examined in this research are generally poorly cemented and may be treated as granular materials for log interpretation purposes.

3) Lithology and porosity can be accurately determined for both carbonate and granular aquifer systems by cross plotting data obtained from any two of the porosity type logs (neutron, density or acoustic velocity).

4) Most of the "clays" examined from Miocene and older formations are not true clays (clay minerals) but are clay size calcareous particles (or residium) as a product of weathering carbonate units. These clays act, hydrologically, as confining beds and may be interpreted as clay minerals on all types of logs.

5) Pore water resistivity (R_w) may be accurately determined by cross plotting resistivity (R_o) and porosity measurements obtained from electric and porosity type logs. R_w can then be related to specific ion concentrations for a particular type of water mass (based on water chemistry) in both carbonate or granular aquifer systems.

6) In freshwater environments formation permeability appears to be related to formation resistivity (F, $F = R_o/R_w$). Electrical current, in freshwater environments, is conducted primarily along the

grain-matrix interface (surface conductance) rather than directly through the saturating fluid (electrolylic conductance). Generally, the higher the tortuosity of the current path the higher the formation resistivity. Formations of high resistivity, characteristically, are composed of well sorted, large, uniform grain diameters (i.e., low surface contact to pore volume ratios). Factors decreasing formation resistivity (small grain diameters, poor sorting, flatter grain shapes, increased clay content, etc.) also decrease formation permeability. This relationship has important hydrologic implications regarding the estimation of permeability in both granular and carbonate aquifer systems.

7) The tertiary dolomites examined quite often were low in porosity, low in clay content, high in saturated formation resistivity and were usually extremely permeable. The high permeability may be attributed to the low ductility of "pure" dolomites causing the units to be highly fractured even in tectonically "quiet" areas. Carbonate units with fracture type porosity are often highly productive and appear on electric logs as highly resistive material.

8) Gamma spectrometric analyses failed to reveal any appreciable fractionation of the naturally occuring gamma emitting isotopes (uranium, thorium or potassium) as related to lithologic type. Some fractionation was observed between uranium and potassium with respect to permeability. Isotopic ratios appeared to be at least a magnitude higher (uranium/potassium) in more permeable sections of single aquifer systems.

Conclusions and findings presented in this research are intended to aid in the interpretation of borehole geophysical logs. This information is urgently needed by hydrogeologists and will aid in;

1) determining the optimum water bearing zones to produce from small diameter test holes without actually casing, developing or pumping;

2) determining the suitability of proposed sites for landfills, industrial pits, ponds or lagoons used for storing hazardous wastes;

3) assessing the permeability and confinement of prospective receiving zones, in test holes, drilled for deep well injection of wastes;

4) recognizing facies changes, depositional environments and sedimentological features essential for a good understanding of regional aquifer flow systems; and

5) evaluating the type of numerical flow model to use in evaluating different aquifer systems. In addition to supplying basic hydrogeologic information concerning the aquifer system, many of the input parameters can be obtained from geophysical logs (i.e., vertical leakance, storage coefficients, boundary effects, etc.). Geophysical logs also aid in refining relative vertical permeability variations obtained from aquifer pumping tests.

APPENDICES

A. GLOSSARY OF HYDROGEOLOGIC AND WELL DRILLING TERMINOLOGY

B. SYMBOLS COMMONLY USED IN GEOPHYSICAL LOGGING AND HYDROGEOLOGY

C. BRITISH-METRIC UNITS AND CONVERSION FACTORS

D. FORMULAS RELATING TO LITHOLOGY, WATER QUALITY AND PERMEABILITY AS USED IN TEXT

E. PHYSICAL PROPERTIES OF MINERALS AND MATERIALS

F. THERMAL CONDUCTIVITY OF VARIOUS LITHOLOGIES AND MATERIALS

G. SIGNIFICANCE LEVELS FOR PEARSON PRODUCT - MOMENT CORRELATION COEFFICIENTS

H. DESCRIPTION AND SPECIFICATIONS OF LOGGING EQUIPMENT USED IN RESEARCH

I. CALIBRATING NEUTRON, DENSITY AND ACOUSTIC VELOCITY LOGS TO LIMESTONE POROSITY

J. GAMMA SPECTROMETRIC PROCEDURES AND ANALYSES

K. GEOPHYSICAL LOGS OF WELLS USED FOR HYDROGEOLOGIC INTERPRETATIONS

L. LITHOLOGIC DESCRIPTIONS OF WELLS USED IN RESEARCH

M. WATER RESISTIVITY (R_w) VERSUS SPECIFIC ION PLOTS FOR WATER MASSES USED IN RESEARCH

N. CHARTS AND CROSS PLOTS USED IN LOG INTERPRETATIONS

O. CORRECTION FACTORS AND CONVERSION CHARTS FOR PROBES USED IN RESEARCH

P. DESCRIPTION AND LOCATION OF WELLS WITH CUTTINGS AND CORES USED IN THIS RESEARCH

APPENDIX A

GLOSSARY OF HYDROGEOLOGIC AND WELL DRILLING TERMINOLOGY

AQUICLUDE - A formation which, although porous and capable of absorbing water slowly, will not transmit water sufficient enough to furnish an appreciable supply for a well or spring.

AQUIFER - A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

AQUIFUGE - A rock without inter-connected openings which can neither absorb or transmit water. Replaced by the term "confining bed".

ARTESIAN - Artesian is synonymous with confined. An artesian well is a well deriving its water from an artesian or confined water body. The water level in an artesian well stands above the top of the artesian water body it taps.

ARTESIAN WELL - A well tapping a confined or artesian aquifer in which the static water level stands above the water table.

ATTAPULGITE - A clay mineral with a fibrous structure and suspension properties depending on the mechanical dispersion of needle-like units which entangle to resist flow. Used as a drilling fluid component in saline formations. Replaced by the term palygorskite.

BRINE - Fluids comprised of more than the usual amount of dissolved salts contained in seawater.

COEFFICIENT OF STORAGE - The volume of water released from or taken into storage per unit surface area of an aquifer, per unit change in head normal to that surface. (S) is a dimensionless index and ranges from 3.0×10^{-1} to 10×10^{-5}.

COEFFICIENT OF TRANSMISSIBILITY - The field coefficient of permeability multiplied by the aquifer thickness.

CONDUCTANCE (SPECIFIC) - A measure of the ability of the water to conduct an electric current. It is related to the total concentration of ionizable solids in the water. It is inversely proportional to electrical resistance.

CONDUCTIVITY, HYDRAULIC - Replaces the term "field coefficient of permeability." If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is equal to the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

CONFINING BED - Is a term which will now supplant the terms "aquiclude," "aquitard," and "aquifuge" in reports of the U. S. Geological Survey and is defined as a body of "impermeable" material stratigraphically adjacent to one or more aquifers.

CONNATE WATER - Water entrapped in the interstices of a sedimentary rock at the time it was deposited.

DARCY - A unit of permeability. One Darcy is the rate of viscous flow of one cubic centimeter per square centimeter per second of a fluid of one centipoise viscosity with a pressure gradient of one atmosphere per centimeter. Equals 18.24 gallons per day per square foot (60°F.)

DRAWDOWN - Lowering of water level caused by pumping. It is measured for a given quantity of water pumped during a specified period, or after the pumping level has become constant.

EFFECTIVE POROSITY - The portion of pore space in saturated permeable material in which movement of water takes place.

FORMATION - An assemblage of rock masses grouped together into a unit that is convenient for description or mapping. Formation boundaries may be independent of hydrogeologic units.

GROUND WATER - Water in the zone of saturation.

HYDRAULIC GRADIENT - Is the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head. The gradient of the head is a

mathematical term which refers to the vector, h, whose magnitude dh/dl is equal to the maximum rate of change in head.

IRREDUCIBLE WATER SATURATION - Water that cannot be withdrawn even under pumping conditions.

LOG - The actual written record of the response of the probe.

PERMEABILITY - The capacity of water-bearing material to transmit water, measured by the quantity of water passing through a unit cross section in a unit time under 100 percent hydraulic gradient.

PERMEABILITY COEFFICIENT - As defined by Meinzer, the rate of flow in gallons a day through a square foot of the cross section of material, under 100 percent hydraulic gradient, at a temperature of 60°F. In field terms, it is expressed as the number of gallons of water per day at 60°F. That is conducted laterally through each mile of the water-bearing formation under investigation (measured at right angles to the direction of percolation) for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.

PERMEABILITY (INTRINSIC) - A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient.

POROSITY (EFFECTIVE) - The amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices. Although effective porosity has been used to mean about the same thing as specific yield, such use is discouraged.

POTENTIOMETRIC SURFACE - Replaces the term "piezometric surface," is a surface which represents the static head of an aquifer system. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

POROSITY LOG - Any of the three logs which indirectly measure porosity, which include the neutron, density or acoustic velocity.

PROBE - Also called sonde or tool, is the actual instrument attached to the end of the logging cable which is lowered into the borehole.

SATURATION, ZONE OF - The zone below the water table in which all interstices are filled with ground water.

SECONDARY POROSITY - Openings in rocks formed by processes affecting the rocks after they were deposited.

SOLIDS, TOTAL DISSOLVED AND SUSPENDED - Suspended solids are those which are not in true solution and can be removed by filtration. They may be imparted from small particles of insoluble matter, from turbulent action of water on soil. Dissolved solids are in true solution and cannot be removed by filtration. Total solids represent the sum of dissolved and suspended solids.

SPECIFIC CAPACITY - The rate of discharge of water from the well divided by the drawdown of water level within the well. It varies slowly with duration of discharge which should be stated when known. If the specific capacity is constant except for the time variation, it is roughly proportional to the transmissivity of the aquifer.

SPECIFIC CONDUCTANCE - The electrical conductivity of a water sample at 25°C (77°F), expressed in micro-mhos per centimeter.

SPECIFIC YIELD - The ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

STORAGE COEFFICIENT - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

TRANSMIS-SIBILITY - The hydraulic conductivity multiplied by the thickness of an aquifer.

TRANSMIS-SIVITY - The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It replaces the term "coefficient of transmissibility".

VADOSE WATER - Water in excess of pellicular water seeping toward the water table; used as a synonym for gravity water.

VADOSE ZONE - Same as zone of aeration.

WATER TABLE - That surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground water flow exists.

ZONE OF AERATION - The zone above the water table in which the interstices are partly filled with air.

ZONE OF SATURATION - The zone below the water table in which all interstices are filled with ground water.

APPENDIX B

SYMBOLS COMMONLY USED IN GEOPHYSICAL LOGGING AND HYDROGEOLOGY

A ..... Area
A ..... A current electrode used in electric logging (The current electrode nearest the measuring electrode "M" in 16" and 64" normal circuitry)
A ..... Amplitude
a ..... Constant in formation factor relationship ($F=a/^{m}$)
AC ..... Alternating current
AM ..... Normal (two electrode) device electrode spacing
AO ..... Lateral (three electrode) device electrode spacing
API ..... A specific unit of Radiation Concentrate (a standard from American Petroleum Institute)

B_{ti} ..... Borehole television
BHC ..... Borehole compensated
BHT ..... Bottom hole temperature (°F in USA)

°C ..... Centigrade
C ..... Caliper
C ..... Conductivity at a given temperature, usually formation temperature (in millimhos/m)
C_i ..... Current Induction log
CCL ..... Casing Collar log
CDL ..... Density log (compensated)
cm ..... Centimeter
cm^2 ..... Square centimeters
cm^3 ..... Cubic centimeters
cpm ..... Counts per minute
cps ..... Counts per second

D ..... Density log
D ..... Depth
d ..... Diameter
DC ..... Direct Current
d_h ..... Borehole diameter

E ..... Normal electric log
Eh ..... Reduction or oxidation potential (redox)
eV ..... Electron volt(s)

F ..... Formation resistivity factor (ratio of resistivity of porous medium 100% saturated with water to resistivity of the saturating water).
°F ..... Fahrenheit
F_f ..... Field-formation-resistivity factor

fpm ..... Feet per minute
ft ..... Foot or feet

G ..... Gamma Ray Log
G ..... Geometrical factor
G ..... Gravity
G_s ..... Gamma Spectrometry log
g ..... Gallon
g/cc ..... Grams per cubic centimeter
gm ..... Gram
gpm ..... Gallons per minute

h ..... Bed thickness

I.D. ..... Inside Diameter
I ..... Electrical current magnitude
I_t ..... Tracer Injection log
in ..... Inch

K ..... Coefficient in SSP formula $K = -70.7 \frac{460+°F}{537} + \log \frac{R_{mf}}{Rwe}$

k ..... Permeability
kg ..... Kilogram
km ..... Kilometer

lb ..... Pound
l ..... Liter
ls ..... Limestone
log ..... Logarithm base 10 (common logarithm)

M ..... Measuring electrode used in electrical logging (measuring electrode nearest current electrode "A" in 16" normal and 64" normal circuitry)
m ..... Exponent in formation factor-porosity formula (Archie "cementation" factor)
ma ..... Milliampere
md ..... Millidarcy (permeability)
Mev ..... Million electron volts
mg/l ..... Milligrams per liter
mi ..... Mile
mm ..... Millimeter
MN ..... Distance between two potential measuring electrodes
mv ..... Millivolt
µmhos/cm ... Micromhos per centimeter

N ..... Measuring electrode used in electric logging potential (measuring electrode farthest from current electrode "A" in 16" normal and 64" normal circuitry)
N ..... Neutron log

O.D. ..... Outside diameter
Ohm-m ..... Ohm-meter (a measure of resistivity, reduced from $ohm\text{-}m^2/m$)
oz ..... Ounce

P ..... Pressure
ppm ..... Parts per million (equals milligrams per liter/specific gravity of solution at STP)
psi ..... Pounds per square inch
PVC ..... Polyvinyl chloride

Q ..... Quantity

R ..... Resistivity in ohms meter squared/meter at a given temperature
R_{la} ..... Lateral Resistivity log
r ..... Radius
R_a ..... Apparent resistivity as recorded by a resistivity device
R_i ..... Resistivity of invaded zone
R_m ..... Resistivity of mud
R_{mc} ..... Resistivity of mud cake
R_{mf} ..... Resistivity of mud filtrate
R_{mx} ..... Microfocused Resistivity log
R_o ..... Resistivity of formation 100% saturated with formation water of resistivity R_w
RPM ..... Revolutions per minute
R_s ..... Resistivity of adjacent formation
R_t ..... Resistivity of uninvaded zone
R_w ..... Resistivity of formation water
R_{wa} ..... Apparent resistivity of formation water
R_{we} ..... Calculated resistivity of formation water uncorrected for salinity or ion type (apparent)
R_{xo} ..... Resistivity of flushed zone

S ..... Fluid sampler
S ..... Saturation (general term)
SG ..... Specific gravity
Sd ..... Sand
sh ..... Shale
ss ..... Sandstone
S_i ..... Saturation in invaded zone
SP ..... Spontaneous potential
SSP ..... Static SP (the maximum possible SP for a given R_{mf}/R_w)
STP ..... Standard temperature and pressure (i.e., 60°F at 14.7 psi)
S_w ..... Water saturation as a percent of pore volume
S_{xo} ..... Water saturation in flushed zone as a percent of pore volume

T ..... Temperature (°F U.S.A.)
T ..... Temperature log
t ..... Time
$t^{1/2}$ ..... Radioactive half life in units of time
TC ..... Time constant
TD ..... Total depth at time of logging

V ..... Volume
V_a ..... Acostic Velocity log
V_f ..... Fluid Velocity log (flowmeter)

V_{te} ..... Borehole Televiewer log
v ..... Velocity

ϕ ..... Porosity in percent

Δ ..... Change of any variable (an increment of change)

ρ ..... Density

ρ_b ..... Bulk density of formation within the area of investigation

ρ_f ..... Density of fluid in pores within the area of investigation

ρ_{ma} ..... Matrix (grain) density

Σ ..... A summation

Ω m ..... Resistivity ohms m^2/m

λ ..... Wave length (feet in U.S.A.)

∞ ..... Infinity

APPENDIX C

BRITISH-METRIC UNITS AND CONVERSAION FACTORS

multiply	by	to obtain
to obtain	by	divide
Flow		
gal/min	0.6309	l/s
		l/s
Transmissivity		
ft^2/d	0.0929	m^2/d
(gal/d)/ft	0.0124	m^2/d
Hydraulic conductivity		
ft/d	0.3048	m/d
Specific capacity		
(gal/min)/ft	0.2070	(l/s)/m
Time per unit length		
ms/ft	3.280	ms/s
DISTANCE/ DEPTH/LENGTH		
mm	0.039370	in
cm	0.39370	in
	0.03281	ft
	0.01	m
in	25.40005	mm
	2.54000	cm
	0.02540	m
	0.08333	ft
ft	30.48006	cm
	12.0	in
	0.3333	yd
	0.30480	m
m	10,000,000,000.0	A
	1,000,000.0	u
	1,000.0	mm

multiply	by	to obtain
to obtain	by	divide
DISTANCE/ DEPTH/LENGTH - continued		
	100.0	cm
	39.370	in
	3.2808	ft
	1.0936	yd
km	3,280.83	ft
	1,000.0	m
	.62137	mi
AREA		
cm^2	0.15499	in^2
in^2	6.4516	cm^2
ft^2	929.0341	cm^2
	0.092903	m^2
m^2	1,549.9969	in^2
	10.76387	ft^2
	1.19599	in^2
	0,000.0	m^2
km^2	247.104	acres
	0.386	mi^2
VOLUME/CAPACITY		
cm^3	1,000.0	mm^3
	0.001	l
	0.06102	in^3
	0.0002642	gal
	0.00003531	ft^3
in^3	16.387025	cm^3
	0.004329	gal
	0.01638	l
	0.0005787	ft^3
	0.0001031	bbl
l	1,000.0	cm^3
	1,000.0	ml
	61.02705	in^3
	1.057	qt
	0.26417	gal(U.S.)
	0.03532	ft^3
gal (U.S.)	3,785.0	cm^3
	231.0	in^3
	4.0	qt (U.S.)
	3.7853	l
	0.13368	ft^3
	0.003785	m^3

multiply	by	to obtain
to obtain	by	divide
VOLUME/CAPACITY - continued		
ft^3	1,728.0	in^3
	28.31684	l
	7.4809	gal(U.S.)
	0.037037	yd^3
	0.02831	m^3
m^3	264.17	gal(U.S.)
	1.3079	yd^3
	35.314	ft^3
yd^3	201.974	gal
	27.0	ft^3
DENSITY/ CONCENTRATION		
gm/cc	62.42976	lb/cu ft
	8.34544	lb/gal(U.S.)
	0.036127	lb/cu in
WEIGHT/MASS		
gm	15.43236	grain
	0.03528	oz
	0.00220	lb
oz	28.34952	gm
	0.0625	lb
kg	35.274	oz
	2.2046	lb
lb	453.59237	gm
	16.0	oz
	0.4536	kg
RESISTIVITY		
ohm cm^2/cm	0.01	ohms m^2/m
ohm m^2/m	100.0	ohms cm^2/cm
PRESSURE		
psi	70.3067	gm/cm^2
	0.0703070	kg/cm^2
	0.0689474	bar
	0.0680458	atm
	14.6960	psi
	1.01325	bar
lb/ft^2	47.88	N/m^2

multiply	by	to obtain
to obtain	by	divide

HEAT/ENERGY

btu	1.05×10^{10}	ergs
	1.054.8	joules
	251.996	cal
cal	4.19×10^{7}	ergs
	4.1840	joules
	0.003968	btu

TEMPERATURE

°F=(1.8°)C+32	°C=0.56(°F-32)	°K=°C+273

APPENDIX D

FORMULAS RELATING TO LITHOLOGY, WATER QUALITY AND PERMEABILITY AS USED IN TEXT

Porosity from density log:

(1) $$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Bulk density from density log:

(2) $$\rho_b = \phi \cdot \rho_f + (1-\phi)\ \rho_f$$

Porosity from acoustic velocity log:

(3) $$\phi = \frac{\Delta t_{ma} - \Delta t}{\Delta t_{ma} - \Delta t_f}$$

Ohms law:

(4) $$r = \frac{V}{I}$$

Spontaneous potential/resistivity relationship:

(5) $$SP = -K \log \frac{R_{mf}}{R_w}$$

Resistivity/current/formation volume:

(6) $$R = \frac{V}{I} \cdot \frac{A}{L}$$

Water saturated formation/true formation resistivity:

(7) $$R_o = \frac{R_t}{(S_w)^2}$$ where $R_o = R_t$ in formations saturated with freshwater.

M and N mineral plot:

(8) $$M = \frac{\Delta t_f - \Delta t}{\rho_b - \rho_f}$$

M and N mineral plot - (continued):

(9) $$N = \frac{n_f - n}{\rho_b - \rho_f}$$

Clay content from gamma log:

(10) Gamma Ray Index (GRI) = $$\frac{GR_{log} - GR_{clean\ sands}}{GR_{clay\ point} - GR_{clean\ sand}}$$

or;

(11) $$V_{clay} = 0.21 \times [2^{(2.9 \times GRI)} - 1]$$

q - factor:

(12) $$q = \frac{\phi V_a - \phi D}{\phi V_a}$$

Porosity correction:

(13) $$\phi \text{ corrected} = \frac{(\phi_n)^2 + (\phi_D)^2}{2}$$

Water Resistivity:

(14) $$R_w = \frac{R_o}{F}, \quad F = \frac{R_o}{R_w}$$

Formation factor:

(15) $$F = \frac{a}{\phi^m}$$ (general equation)

Combining equations 14 and 15:

(16) $$R_w = R_o\ \phi^m$$

for clean granular systems:

(17) $$F = \frac{0.62}{\phi^{2.15}}$$ (Humble equation, minimum 17% porosity)

for Tertiary carbonates:

(18) $$F = \frac{1}{\phi^m}$$ where m = 1.6 to 2.0 (Archie equation)

Cementation factor from log-log paper:

(19) $$m = \frac{\log X_1 - \log X_2}{\log Y_1 - \log Y_2}$$

Water resistivity from porosity/resistivity logs:

(20) $$\log R_w = \log R_o + m \log \phi$$

Specific conductance - R_w relationship:

(21) Specific conductance (in micromhos) $= \frac{10{,}000}{R_w}$ (R_w is in ohm-meters)

Chloride-R_w relationship for major aquifers:

(22) Sand-and-Gravel $\quad \text{Chlorides} = \frac{2{,}400}{R_w} - 5$

(23) Biscayne $\quad \text{Chlorides} = \frac{2{,}800}{R_w} + 50$

(24) Surficial and Intermediate $\quad \text{Chlorides} = \frac{1{,}600}{R_w} - 60$

(25) Floridan $\quad \text{Chlorides} = \frac{3{,}100}{R_w} - 200$

Tortuosity:

(26) $$\text{Tortuosity} = \frac{\text{current path length}}{\text{sample length}}$$

Formation factor/surface conductance/water resistivity relationship:

(27) $$F = \frac{\text{Surface conductance}}{R_w}$$

Surface conductance:

(28) $$\text{Surface conductance} = (\text{grain size factor}) \times \frac{\text{grain contact area}}{\text{porosity}}$$

Permeability/formation factor relationship:

(29) k(permeability) = slope (formation factor; F) - intercept

Flowmeter rate equation:

(30) $Q = \frac{1}{4} d^2 \cdot v$

APPENDIX E

PHYSICAL PROPERTIES OF MINERALS AND MATERIALS

MINERAL/MATERIAL FORMULA	DENSITY (g/cc)	RESISTIVITY (ohm-m)	MATRIX TRAVEL TIME US/FT. (avg.)(range)
Silicates			
Quartz SiO_2	2.65	10^{12}-10^{14}	55.0(52.5-57.5)
Silicates-Phylosilicates			
Kaolinite $Al_4Si_4O_{10}$	2.63	.3-100	(70-150)
Montmorillonite $Al_2Si_4O_{10}(OH)_2 \cdot xH_2O$	2.35	.3-100	(70-150)
Illite $KAl_4(Si, Al)_8O_{20}(OH)_4$	2.81	.3-100	(70-150)
Palygorskite $Mg_5Si_8O_{22}(OH)_{10} \cdot 4H_2O$			
Sepiolite $Mg6Si_{12}O_{30}(OH)_{10} \cdot 6H_2O$			
Biotite $K(Mg, Fe)_3(Al,Si_3O_{10})(OH)_2$	2.84	10^{14}-10^{15}	60.0(60-80)
Muscovite $KAl_2(AlSi_3O_{10})(OH)_2$	2.91	10^{12}-10^{14}	(38-73)
Glauconite $K(Fe, Mg, Al)_2(Si_4O_{10})(OH)_2$	2.30		
Chlorite $(Mg, Fe, Al)_6(Al, Si_4)O_{10}(OH)_8$	2.74		62.0
Carbonates			
Calcite $CaCO_3$	2.71	10^7-10^{12}	46.5(45.5-47.5)
Aragonite $CaCO_3$	2.93		53.0
Dolomite $CaMg(CO_3)_2$	2.85	$1\text{-}7\times10^3$	43.5(40.0-45.0)
Sulfates			
Gypsum $CaSO_4 \cdot 2H_2O$	2.32	10^6	53.0(52.5-53.0)
Anhydrite $CaSO_4$	2.96	10^6-10^{10}	50.5
Halides			
Halite NaCl	2.16	10^4-10^{14}	66.7

MINERAL/MATERIAL FORMULA	DENSITY (g/cc)	RESISTIVITY (Ohm-m)	MATRIX TRAVEL TIME US/FT. (Avg.)(RANGE)
Other Materials			
Limestone $CaCO_3$	2.69	$80\text{-}6x10^3$	42.0(47.7-53.0)
Sandstone	2.65	$10^{12}\text{-}10^{17}$	57.0(53.8-100.0)
Marl		up to 600	
Siltstone		up to 300	
Sand		up to 1,000	
Steel			57.1
Concrete	2.35		92.5(83.3-125.0)
Cement	1.99		95.0(83.3-95.1)
Water (100,000 ppm NaCl)	1.073		192.3
Water (50,000 ppm NaCl)	1.0365		199.8
Water (30,000 ppm NaCl)	1.022		202.7
Water (Pure)	1.00		207.0

APPENDIX F

THERMAL CONDUCTIVITY OF VARIOUS LITHOLOGIES AND MATERIALS

MATERIAL	THERMAL CONDUCTIVITY 10-3 (cal/cm^2-sec)*
Air (Dry) @ 68°F	.061
Cement(Portland)	.71
Water @ 68°F	1.43
Clay	2-3
Chalk	2-3
Gypsum	3.6
Shale	2-4
Sandstone	3-12.2
Limestone	2.4-8
Basalt	4-7
Granite	5-8.4
Calcite	5-13
Feldspar	5.8
Quartz C-axis A-axis	6-30 26 14
Salt	14.3 (8-15)
Dolomite	9.3-11.9
Anhydrite	7-13.4

*To convert to $BTU/ft^2hr/°F/ft$ multiply by 242.08,
BTU/ft^2-hr/°F/ft multiplied by 0.00413 = $(cal/cm^2/sec)/(°C/cm)$.
Values of thermal conductivity are commonly temperature dependent, increasing with temperature.
Moisture content and grain orientation are also important when measuring thermal conductivity.

(Gearhart-Owen, 1975)

APPENDIX G

SIGNIFICANCE LEVELS FOR PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS

Sample Size (m)	VALUES OF CORRELATIONS REQUIRED	
	At 5% Level	At 1% Level
5	.755	.875
10	.576	.714
15	.483	.605
20	.425	.538
25	.380	.488
30	.338	.440
35	.320	.417
40	.300	.394
45	.280	.370
50	.262	.346
60	.248	.328
70	.233	.308
80	.220	.290
90	.206	.272
100	.194	.255
150	.158	.209
200	.137	.182
250	.125	.163
500	.088	.115

(Fisher, 1965)

APPENDIX H

DESCRIPTION AND SPECIFICATIONS OF LOGGING EQUIPMENT USED IN RESEARCH. (ALL MANUFACTURED BY GEARHART-OWEN INDUSTRIES, INC., FORT WORTH, TEXAS)

Overview of equipment - The logs used in most of this research were obtained from borehole geophysical logging equipment manufactured by Gearhart-Owen, Industries, Fort Worth, Texas. The unit is completely self-contained in a four-wheel drive Chevrolet Suburban (1979). Power is provided by a portable 2,500 watt gasoline powered generator. The four conductor cable (3/16 inch) and associated nims modular electronics has the capability of logging to a depth of 3,500 feet.

Natural Gamma - Scintillation type, 4 x 1 inch thallium activated sodium iodide crystal is connected to a photo multiplier tube. This probe is normally logged up-hole at 22 feet per minute. The ratemeter is set on a time constant of two or three seconds. The internal electronics calibrate the analog scale in counts per second (CPS).

Neutron-Epithermal Neutron - The isotopic source for the neutron probe is a triple encapsulated Americium^{241}-Beryllium pill of 3.0 curies. Source to detector (He^3) spacing is 13 inches. Field calibration is with a polyurethane wrapped fiberglass sleeve, calibrated to 1,000 A.P.I. units (19% porosity). The strip chart paper is internally calibrated to CPS and converted is easily to A.P.I. units. No correction factor is necessary for 1/2 life of the neutron source (1/2 life = 453 years).

Density -The isotopic source for the density tool is a 125 millicurie Cs^{137} encapsulated pill inserted near the bottom of the density probe.

Distance from the source to the detector (scintillation type -same as natural gamma tool) is 13 inches, separated by lead spacers. The detector is a side collimated type held against the borehole wall by a decentralizing bow spring. This configuration of detector to borehole aids in minimizing extraneous effects due to irregular changes in borehole diameter and rugosity. Density probes are normally logged up-hole at 22 feet per minute at a 3 second time constant. Calibration of the gamma detector is with a 20 microcurie radium source held 36 inches from the crystal. The observed CPS may be converted to A.P.I. units.

Acoustic Velocity -The acoustic velocity is a centralized probe and is limited to borehole diameters from 5 to 12 inches. Electrical energy is transformed into acoustic energy emitted (about 20,000 hertz) by transmitters and is induced into the borehole wall. Three receivers are placed at various spacings from the transmitter in order to compensate for "noise" generated due to extreme borehole rugosity. Calibration is by wave frequencies observed on a surface mounted oscilloscope.

Caliper -The caliper is a three arm mechanical type where the arms are dependent upon each other, i.e., the measurement is always assumed to be a minimum value. Gauge range is from 1 1/2 to 32 inches at a sensitivity of 1/4 inch. Logging speeds range from 15 to 25 feet per minute, depending upon borehole rugosity.

Normal Electric Probe (16" and 64") AM spacings are set at 16 and 64 inches. An option 32" spacing electrode is also available. Calibration is in ohm-meters, calibrated at the surface by internal electronics and a test box to check the cable resistance. Grounding is by means of a lead electrode, usually placed in the mud pit. Logs are normally run up-hole at 30 to 40 feet per minute.

Spontaneous Potential and Single Point Resistance -Spontaneous potential logs are very difficult to calibrate in thick, freshwater hydrogeologic environments. The only useful spontaneous potential logs available were run in mud filled test holes of the sand-and-gravel aquifer (clastics the extreme western panhandle Florida). The spontaneous potential and point resistance logs are calibrated with internal resistors, in millivolts and ohm-meters respectively, logs are normally run up-hole at 30 to 40 feet per minute.

Fluid Resistivity -Internally calibrated in ohm-meters, this log is run down-hole, at speeds less than 15 feet per minute. The borehole fluid is forced through a cup, near the bottom of the probe, directing the borehole fluid between four gold electrodes located in the mid-section of the probe. Continuous measurements are recorded in analog form on chart paper.

Fluid Sampler -Down-hole point samples of one liter each are obtainable from the fluid sampling probe. This probe has a motor driven valve capable of being opened and closed at predetermined depths. The container is made of stainless steel.

Flowmeter -The vertical flowmeter has blades at 45 degrees which can be operated up-hole or down-hole with the same accuracy. A fluid movement of at least 3 feet per minute is necessary to overcome the internal friction of the impeller. Calibration is in counts per second, calibrated internally at the surface, which can be translated to vertical velocities at various borehole diameters to arrive at flow rates.

APPENDIX I

CALIBRATING NEUTRON, DENSITY AND ACOUSTIC VELOCITY LOGS TO LIMESTONE POROSITY

General

Most neutron, density and acoustic velocity probes (all three are referred to as porosity probes), as used in water resource investigations, are uncalibrated or uncompensated for changes in borehole diameter, fluid density, etc. These probes can be used to obtain useful data on formation porosity if the interpreter is aware of the factors affecting the probe's response. Correction charts and nomographs are available for most of the extraneous factors affecting the response of various probes. The more "corrections" necessary add to the associated error with the porosity values obtained. In order to minimize this error, it is desirable that: the borehole diameter is relatively constant throughout the borehole (less than 20% deviation from bit gauge); the zones analyzed are lithologically uniform and at least twice the thickness of the radius of investigation of the probe; the density of the borehole fluid is uniform, and the logging speed is constant during each log run.

Neutron

The neutron log is the most direct indicator of porosity of the three types of porosity logs. The neutron log is least affected by clay content, fractures and secondary porosity effects. Neutron porosity is scaled logarithmically (condensed towards high porosity) based upon limestone porosity (matrix density of 2.71 g/cc). If the scale is calibrated on dolomitic units an adjustment must be made for the increased matrix density

(2.85 g/cc, use Table 6). Zones used to calibrate neutron logs include; the mid-point of cavities greater than 24 inches in height and depth (assume 95% porosity), clayey units (approximately 60% porosity) and "tight" limestones and dolomites (porosities 5 to 15%). The critical end of the scale is the low porosity end since a few percent shift will change the porosity in the upper range considerably (where most of the measurements occur).

Density

The density log is not affected by the type of carbonate material, but measures matrix densities lower than true in clayey zones. These zones should be avoided for scale calibrations. Density is scaled in grams per cubic centimeter (g/cc) and is arithmetically scaled through the end points.

Acoustic Velocity

Acoustic velocity logs are also affected by clays and secondary porosity. Clean zones, tight zones and large washouts can be used to calibrate the sonic travel times (in microseconds per foot).

If cuttings or cores are not available to check the log calibrations, a few trial and error cross plots should be attempted to determine if any of the logs need to be readjusted. Cross plotting "clean" (non-clay) formations should plot as a 45 degree line between any two of the porosity logs (on arithmetic paper). If the plot is not at 45 degrees, then one (or both) of the logs should be readjusted.

APPENDIX J

GAMMA SPECTROMETRIC PROCEDURES AND ANALYSES

Gamma spectrometic data were analyzed from a number of granular, clay and carbonate formations in order to determine if fractionation of the common, naturally occurring, gamma emitting isotopes (potassium, uranium and thorium) had any relationship to lithologic type or hydrologic characteristics. No attempt was made to quantify the volumetric percentages of the isotopes present. Gamma spectrometric analyses were used to determine the relative percentages of gamma radiation emitted from each of the three isotopes as comparison to the total gamma activity. These numbers in turn are related to the relative volumes of the isotopes occuring in the formations. The equipment used was manufactured by Nuclear Data, model number ND-180F, a 512 channel pulse height analyzer. Gamma energies were counted over the range of approximately 0.5 to 3.0 MeV and stored in a Nuclear Data ND-180M memory unit. The scintillation detector is a thalium activated sodium iodide crystal connected to a photo multiplier tube.

Data used for analyses in this text were collected in the following manner:

1) A blank chamber was counted for an extended period of time in order to determine the natural background in the chamber. This step is necessary to subtract the background effect per given unit of time from each of the samples measured;

2) In order to determine ratio of gamma emissions from each isotope (K, U, and Th), it is useful to total the number of gamma rays counted under one of the most distinct daughter decay peaks, and compare the relative areas (number of counts over a given energy range) under each curve to one another. The three peaks chosen for comparison were K^{40} (1.46 MeV) for potassium, Bi^{214} (1.76 MeV) for uranium and Tl^{208} (2.62 MeV) for thorium. These peaks were distinct on each analog print-out. A six window width (approximately 0.03 MeV width) was chosen to represent the area under each curve;

3) Each of the three isotopes emit a characteristic gamma spectrum. Unfortunately, all three isotopes have daughter energy emissions overlapping one another throughout the spectrum. In order to examine the characteristic spectrum for each isotope, a relatively pure "hot" sample containing each individual isotope was run to establish the ratio between the six window area to the total area, under the gamma spectrum, for each particular isotope. The ratios of window counts to total gamma counts are summarized below (background has been subtracted).

Isotope ratio constants (95%$^{+}$ confidence interval)

Standard	Isotope	Window Peak	Multiplier to Obtain Total Gamma Counts
$K_2 CrO_4$	Potassium	K^{40}	10.93
Monazite Sand	Uranium	Bi^{214}	143.30
Zircon Sand	Thorium	Tl^{208}	227.57 ;

and;

4) The above ratios were normalized to 100 percent and used to calculate the relative proportions of total gamma activity from each isotope. The proportions were then compared to various lithologies and hydrologic properties.

Statistics for Gamma Analyses

1) $\frac{\Sigma 6 \text{ Window Counts}}{\text{Total Minutes Analyzed}} - \Sigma$ Background constant (in counts per minute - cpm)

$$N\ T\ cpm \pm \frac{\Sigma 6 \text{ window counts}}{\text{minutes}}$$

N=number of counts
T=time

2) $K^{40}_{cpm} + Bi^{214}_{cpm} + Tl^{208}_{cpm} = \Sigma cpm$

$$\text{Thus, } \frac{K}{} + \frac{Bi}{} + \frac{Tl}{} = 100\%$$

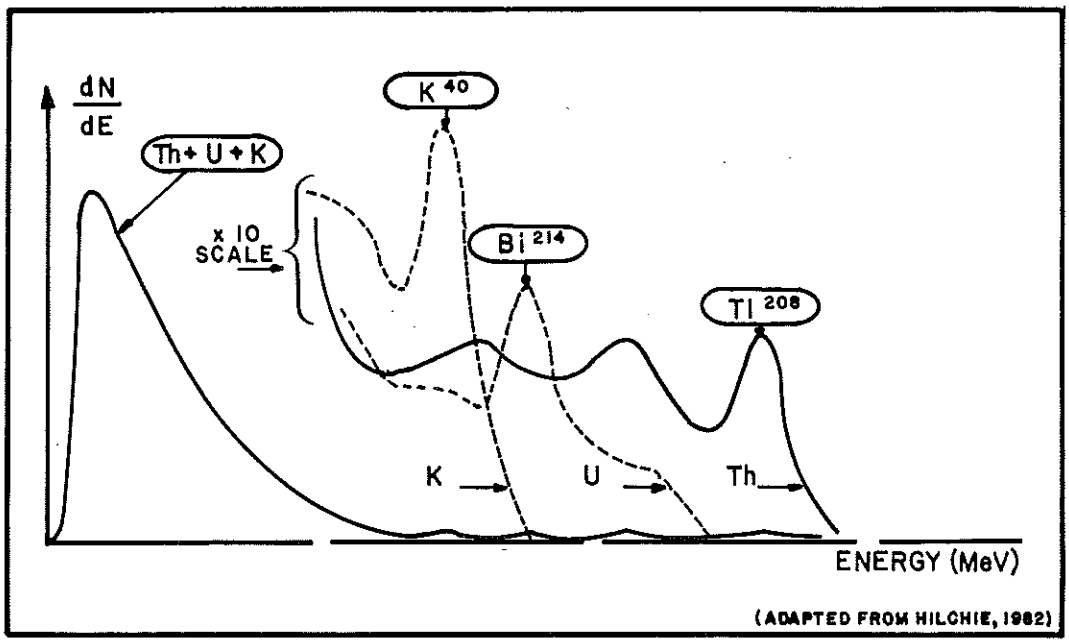
3) Constant, C, representing peak relative to entire gamma spectrum (from standards).

$$\frac{\frac{\Sigma 6 \text{ window counts}}{\text{minutes}} - \text{Background cpm}}{\frac{\Sigma \text{total spectrum counts}}{\text{minutes}} - \text{Background cpm}}$$

4) 6 window counts x $\frac{1}{C}$; for each peak using respective constant, normalized to 100% (as in Step 2).

Parameters appearing to have some correlative significance, as discussed in this text, include U/K vs. aquifer transmitting coefficient and U/K vs. resistivity from the short-normal electric log.

For a more detailed discussion on gamma spectrometry instrumentation and principles, the reader is referred to Adams, 1970.



Typical gamma spectrum and individual spectra for each of the gamma emitting isotopes - potassium, thorium and uranium.

APPENDIX K

GEOPHYSICAL LOGS OF WELLS USED FOR HYDROGEOLOGIC INTERPRETATIONS

Well FK-10, Neutron-density clay content of limestone units.

Well GA-39, Water saturation percent.

Well GF-12, Formation factor (F) gamma activity vs. permeability.

Well LE-7, Neutron-acoustic velocity lithology cross plot.

Well LV-1, Neutron-density lithology cross plot.

Well PB-1, Density-acoustic velocity lithology - M and N plot.

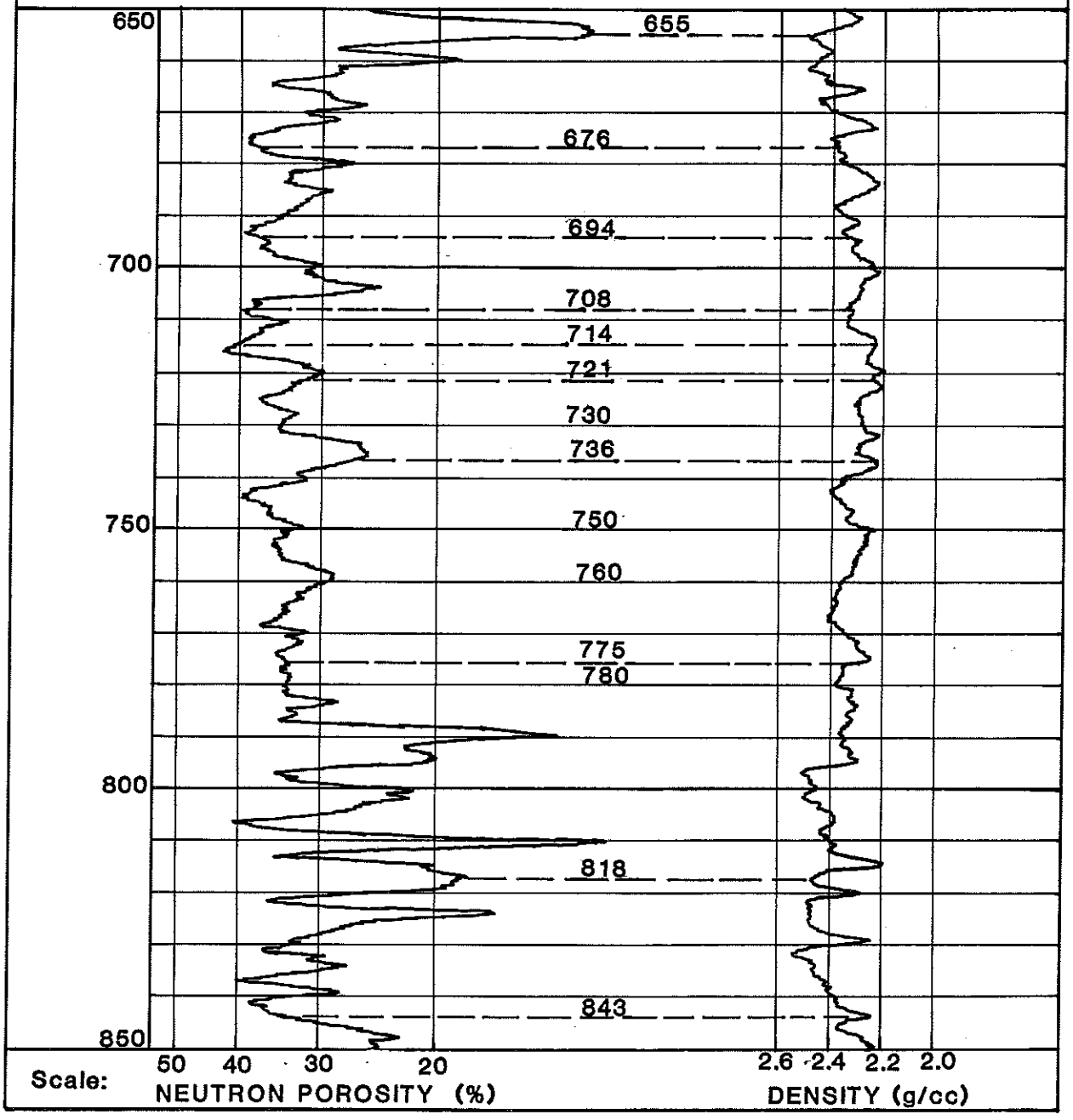
Well SR-15, Neutron-density-clay content of sand.

NAME St. George Island COUNTY Franklin W- 7574

LOCATION T 9s R 6w SEC. 22 1/4 SW NWF- FK-10

DEPTH 912 CASING 93 DIA 6 AQUIFER Floridan

Notes:

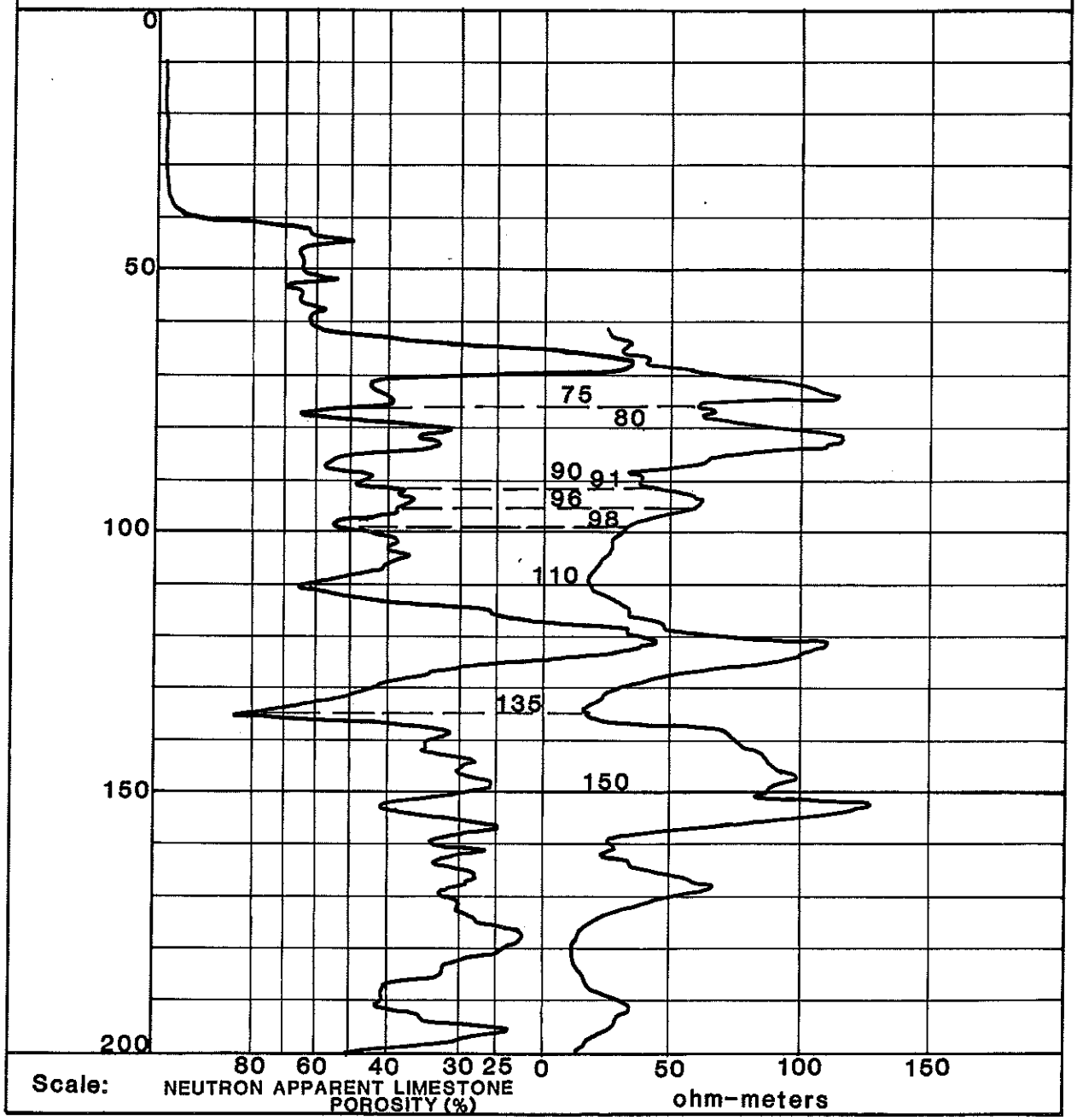


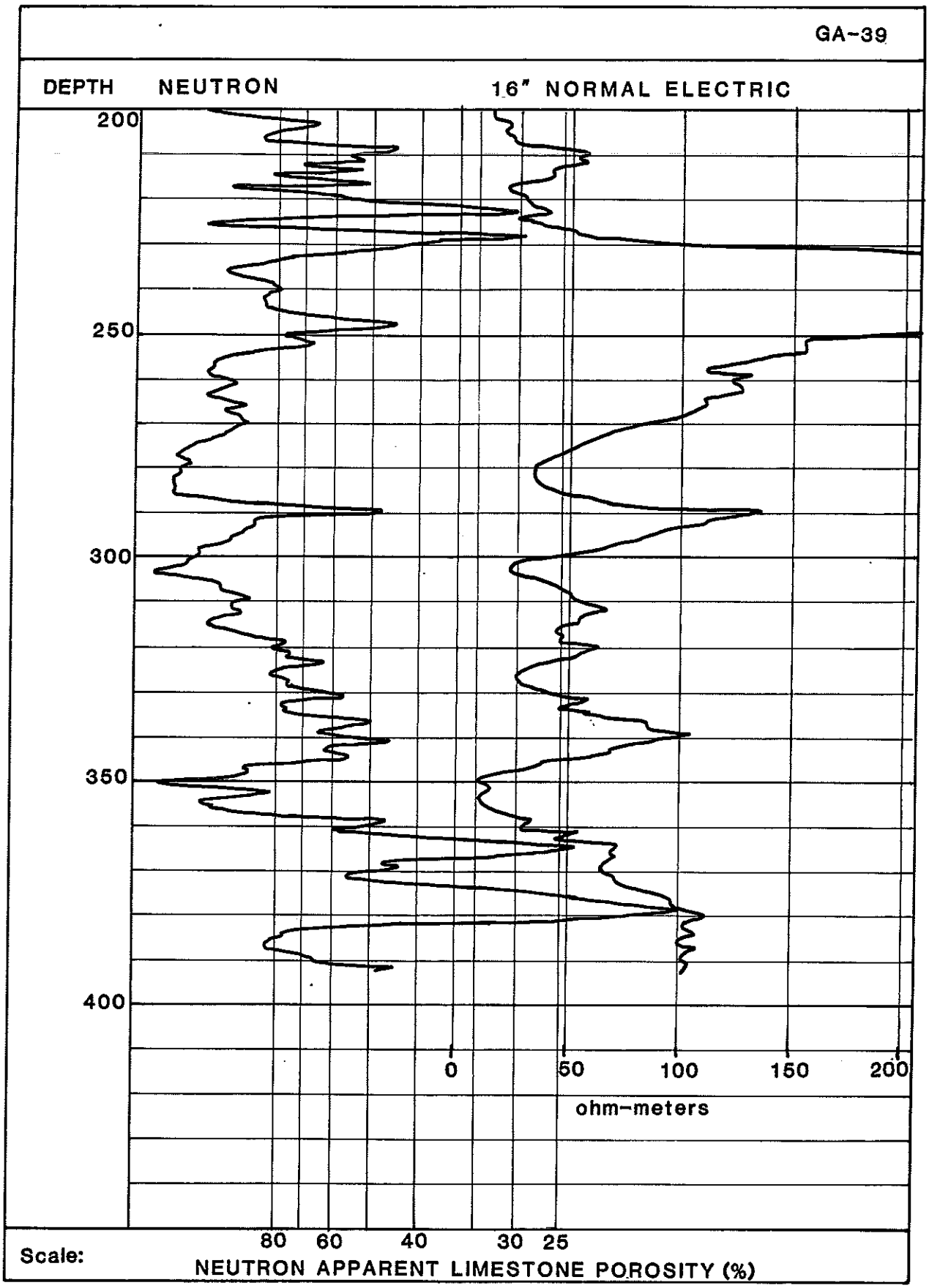
NAME NWFWMD-Core COUNTY Gadsden W-

LOCATION T 1N R 2W SEC. 06 1/4 NWF- GA-39

DEPTH 470 CASING 42 DIA 4 AQUIFER Floridan

Notes:



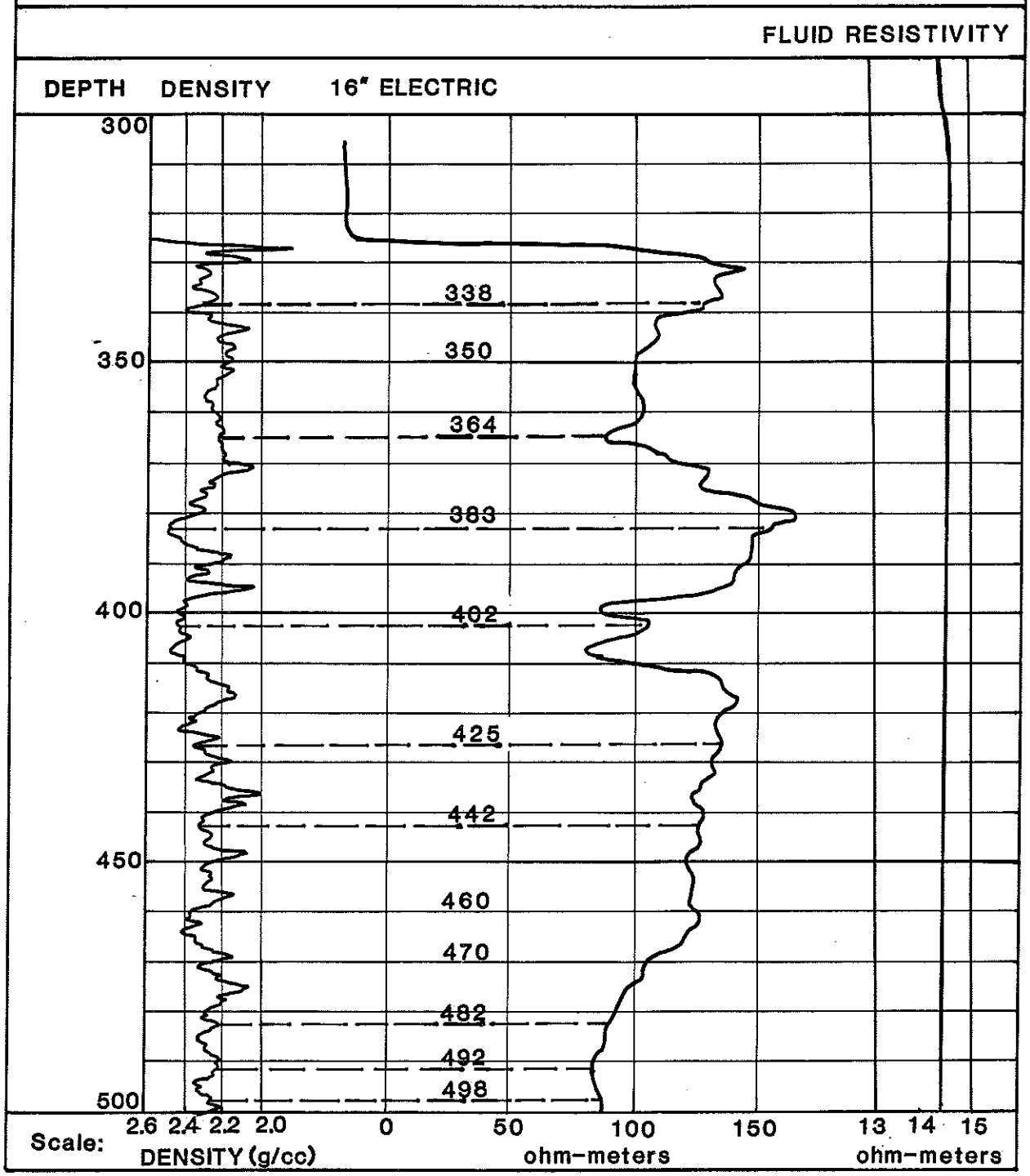

GA-39
DEPTH
NEUTRON
16" NORMAL ELECTRIC
200
250
300
350
400
0
50
100
150
200
ohm-meters
Scale:
80
60
40
30
25
NEUTRON APPARENT LIMESTONE POROSITY (%)

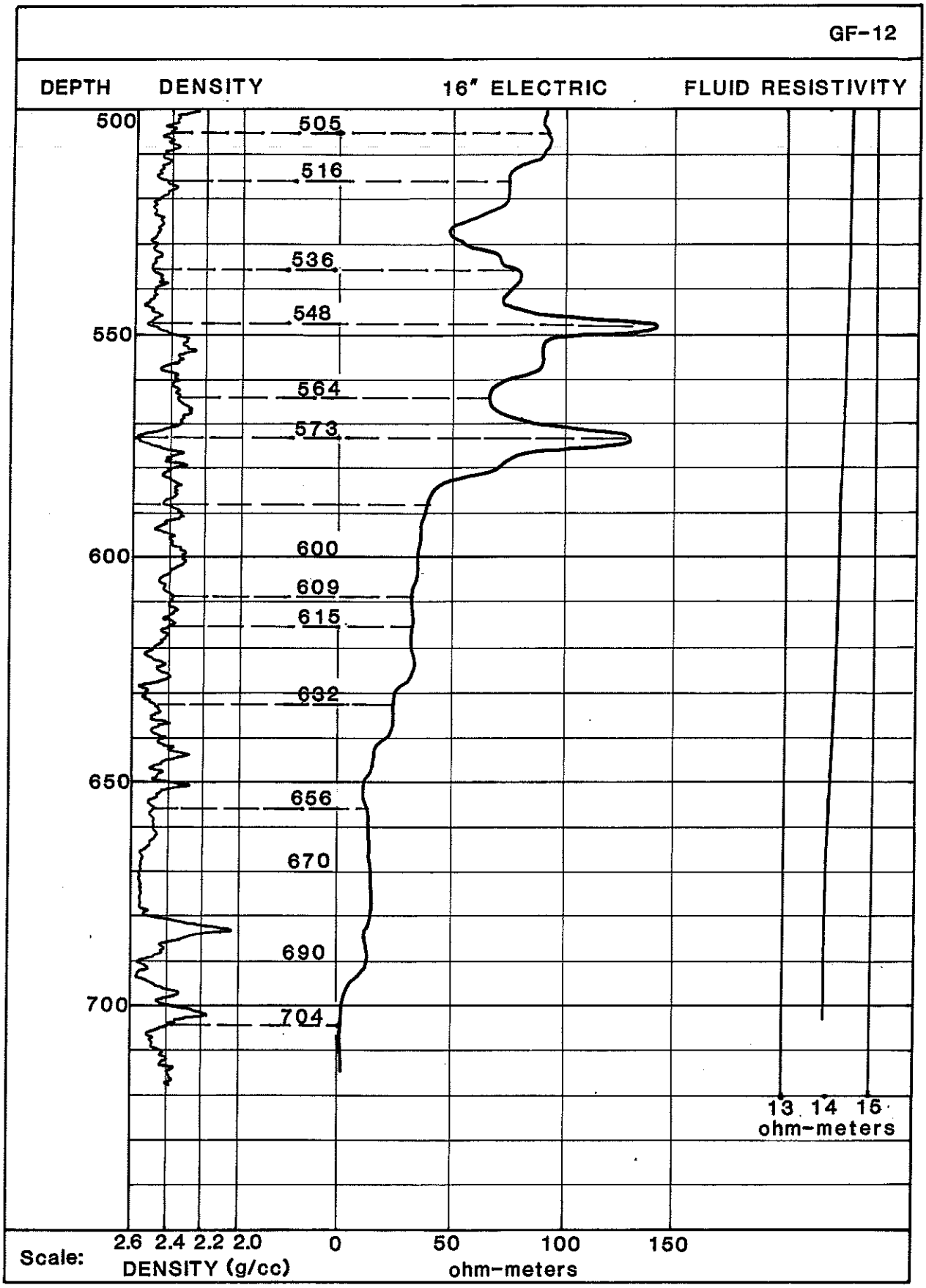
NAME Florida Power Corp. COUNTY Gulf W-

LOCATION T 5S R 11W SEC. 09 1/4 SE NWF- GF-12

DEPTH 721 CASING 324 DIA 12 AQUIFER Floridan

Notes:



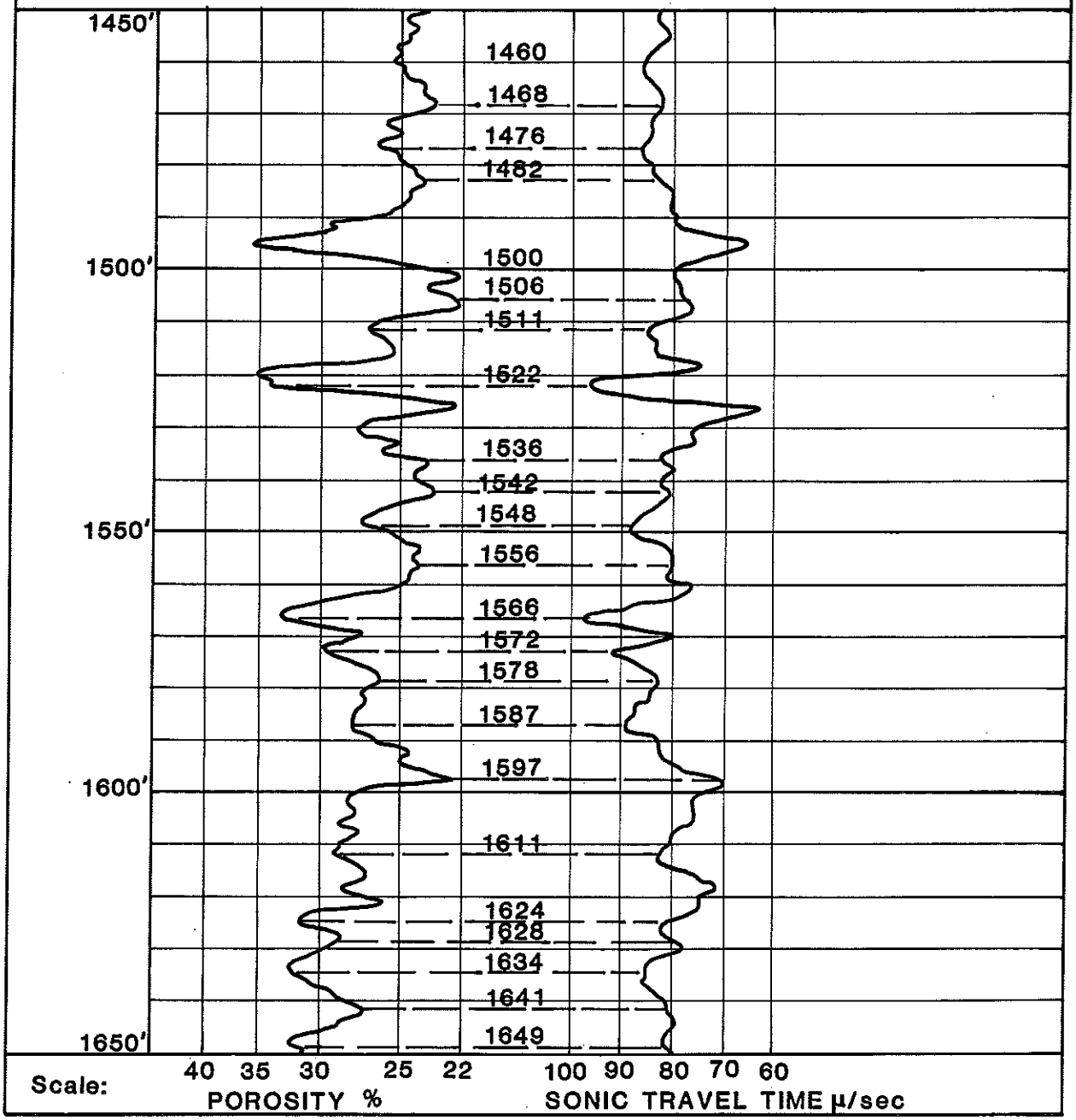

GF-12
DEPTH
DENSITY
16" ELECTRIC
FLUID RESISTIVITY
500
505
516
536
548
550
564
573
600
609
615
632
650
656
670
690
700
704
13 14 15
ohm-meters
Scale:
2.6 2.4 2.2 2.0
DENSITY (g/cc)
0 50 100 150
ohm-meters

NAME U. S. Gypsum COUNTY Lee W- _____

LOCATION T 43S R 26E SEC. 06 1/4 _____ NWF- LE-7

DEPTH 2105 CASING -- DIA 12 AQUIFER Floridan

Notes:

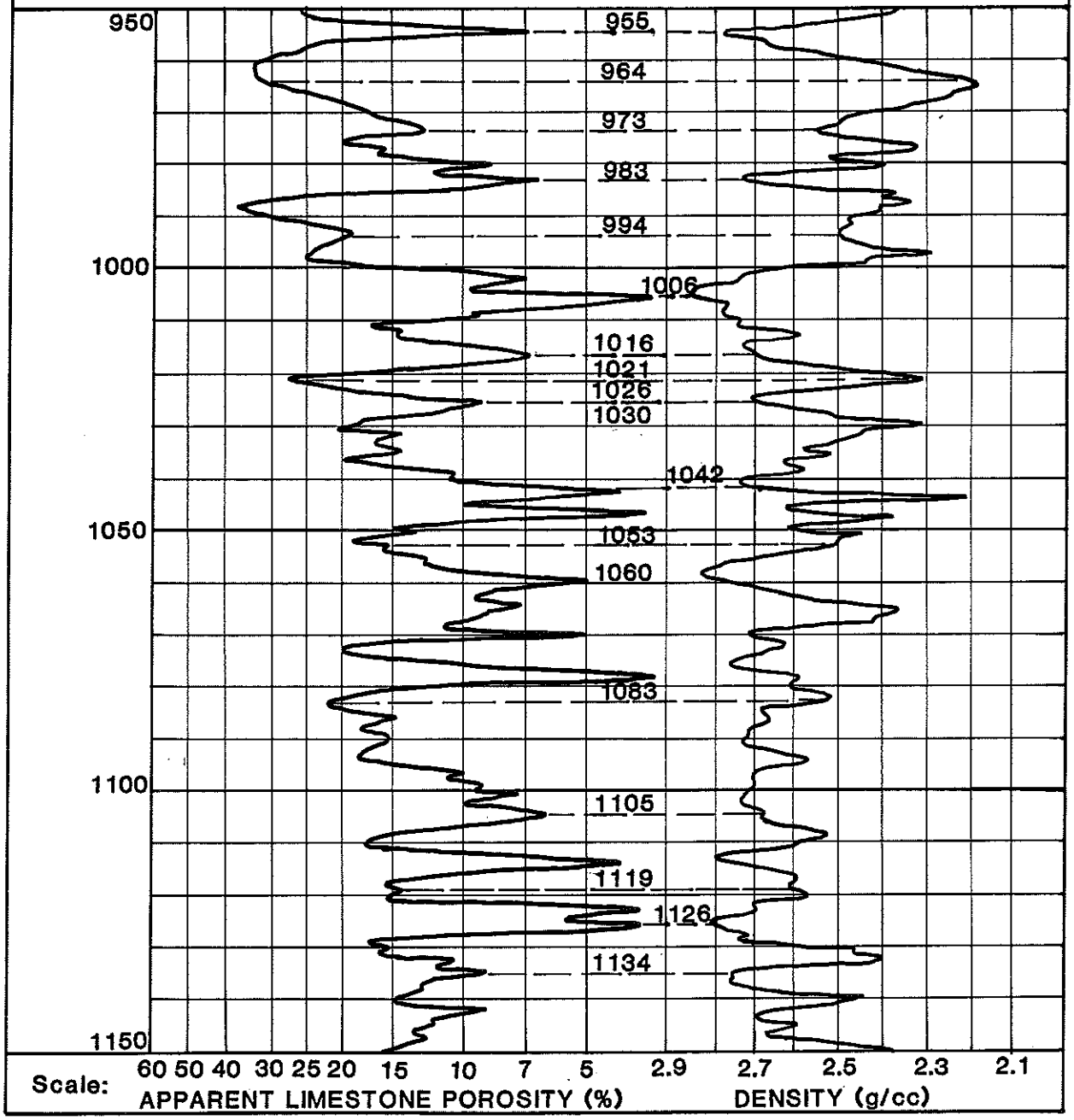


NAME SWFWMD #134 COUNTY Levy W- _____

LOCATION T 12S R 19E SEC. 19 1/4 _____ NWF- LV-1

DEPTH 1173 CASING 70 DIA 8 AQUIFER Floridan

Notes:

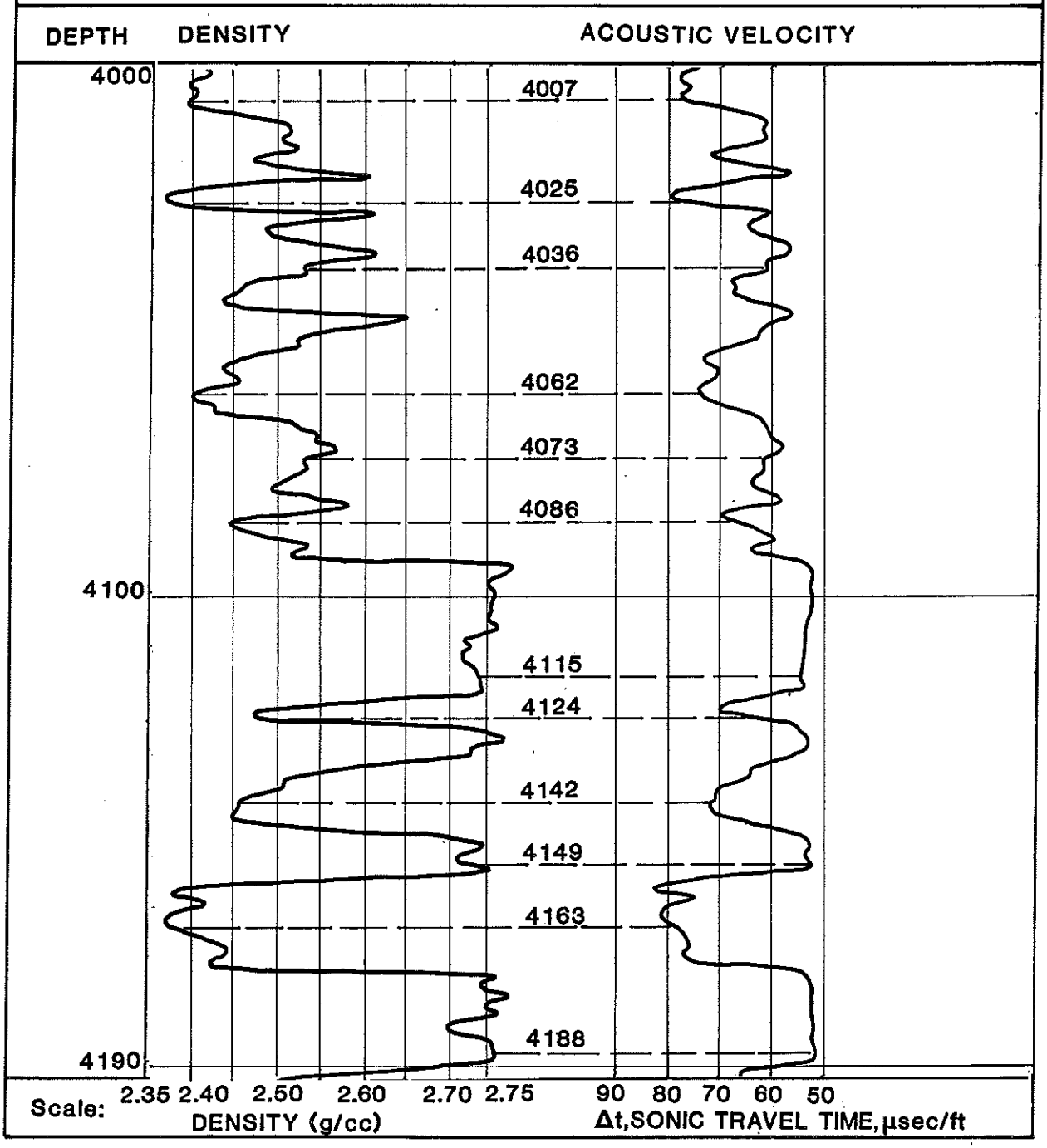


NAME State Lease #1 COUNTY Palm Beach W-

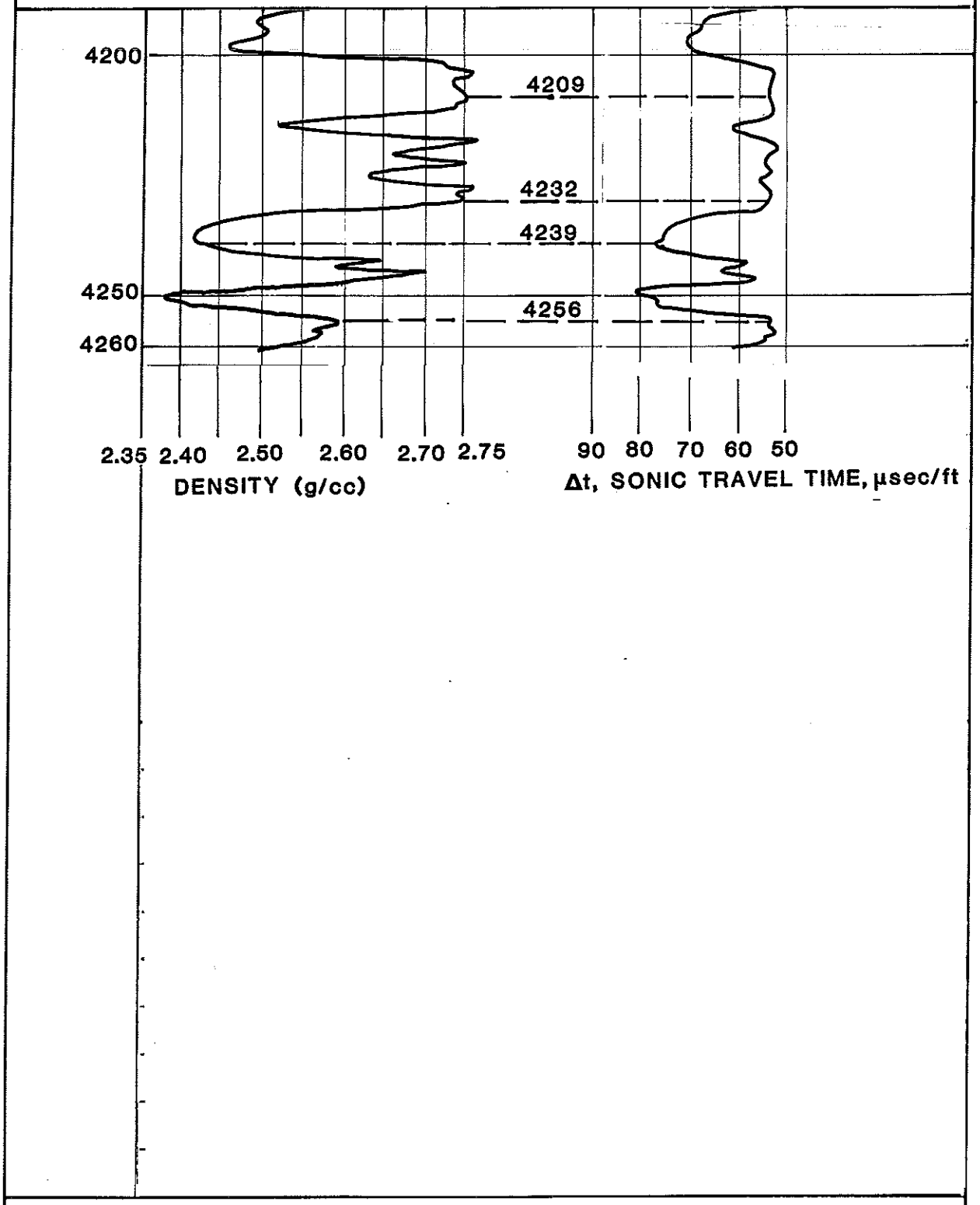
LOCATION T 43S R 39E SEC. 08 1/4 NWF- PB-1

DEPTH 11002 CASING 3995 DIA 8 AQUIFER Floridan

Notes:



PB-1


DEPTH
DENSITY
ACOUSTIC VELOCITY
4200
4209
4232
4239
4250
4256
4260
2.35 2.40 2.50 2.60 2.70 2.75
DENSITY (g/cc)
90 80 70 60 50
Δt, SONIC TRAVEL TIME, μsec/ft

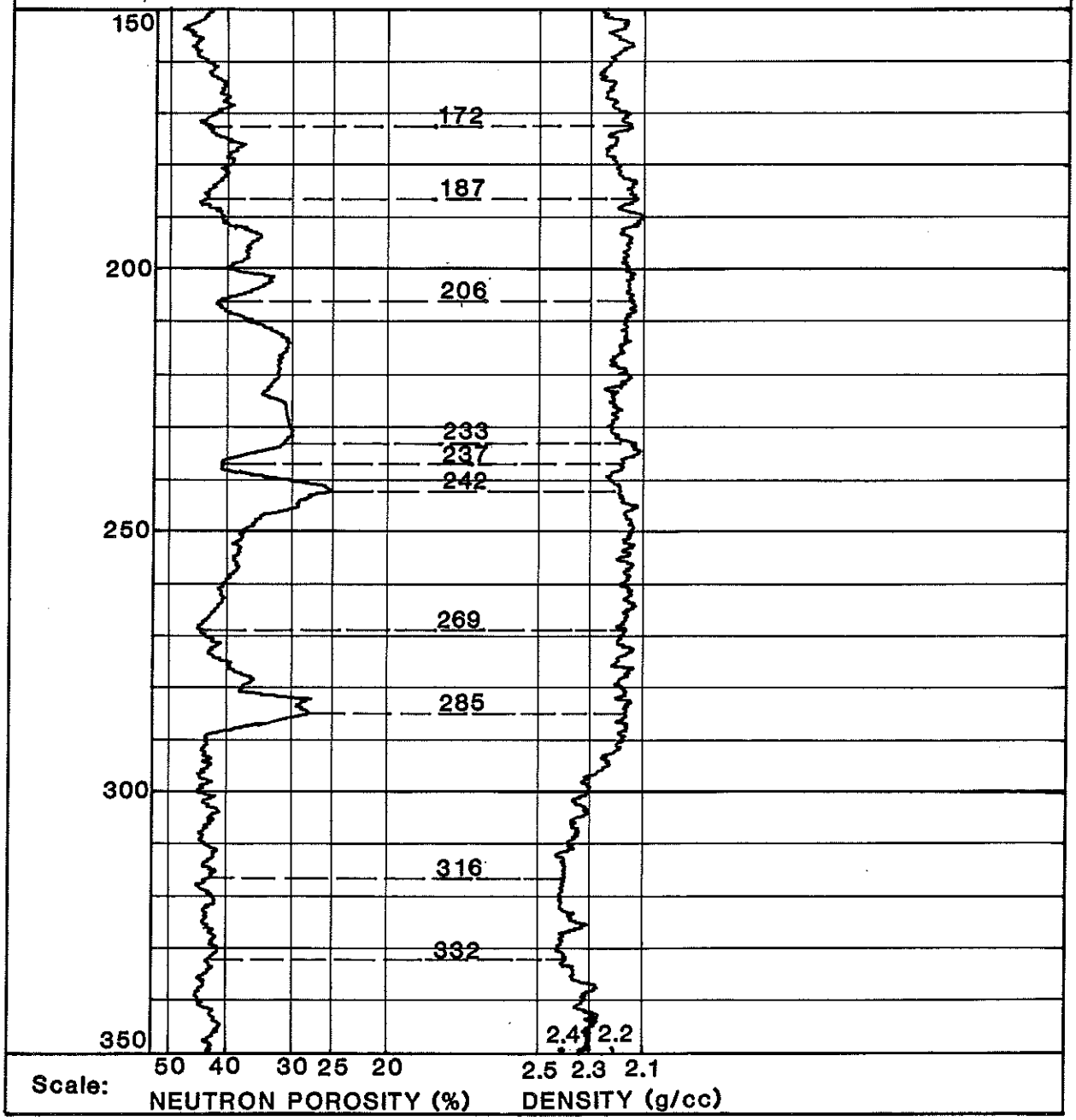
Scale:

NAME Midway #2 COUNTY Santa Rosa W- _____

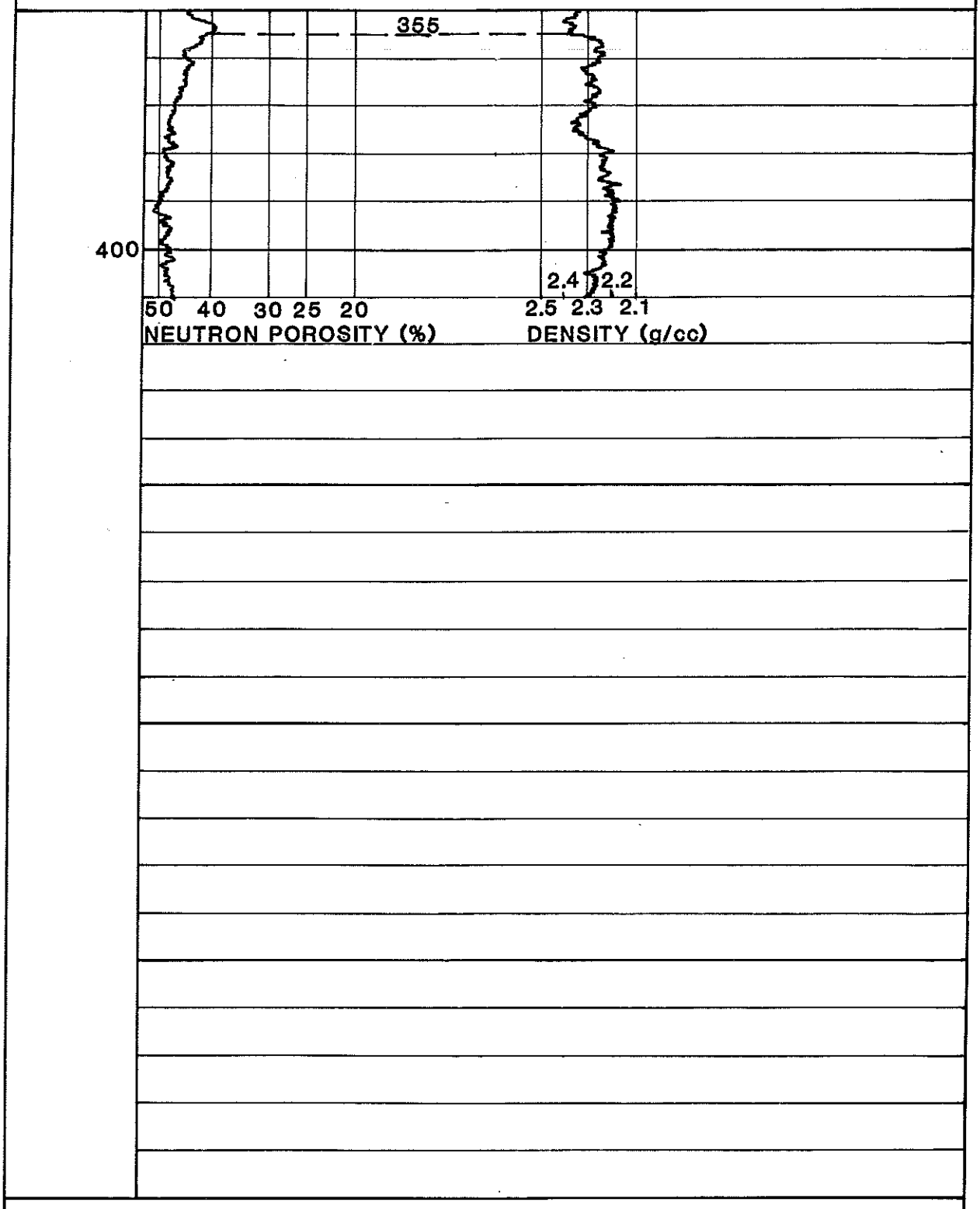
LOCATION T 2S R 26W SEC. 20 1/4 _____ NWF- SR-15

DEPTH 1091 CASING 760 DIA 4 AQUIFER Surficial

Notes:



SR-15


DEPTH
NEUTRON
DENSITY
355
400
50 40 30 25 20
NEUTRON POROSITY (%)
2.4 2.2
2.5 2.3 2.1
DENSITY (g/cc)

Scale:

APPENDIX L

LITHOLOGIC DESCRIPTIONS OF WELLS USED IN RESEARCH

LE-7, Lee County, Florida, depths 1,425 - 1,650 feet

LV-1, Levy County, Florida, depths 950 - 1,145 feet

LITHOLOGIC DESCRIPTION OF WELL LE-7, 1425 ft. to 1650 ft.

1425.0-1495.0	Limestone, very light orange to white, 15% porosity, intergranular, grain type: micrite, biogenic, skeletal, 85% allochemical constituents, grain size: medium, range: microcrystalline to coarse, good induration, micrite cement, sparry calcite cement, dolomite cement, 15% dolomite, benthonic foraminifera, mollusks, echinoid, bryozoa.
1435.0-1445.0	As above with Amphistegina sp.
1445.0-1495.0	Samples at 1455, 1465, 1475, 1485 all as above.
1495.0-1500.0	Dolomite, moderate yellowish brown, 14% porosity, intergranular, intercrystalline, 50-90% altered, euhedral, grain size: very fine, range: fine to microcrystalline, good induration, dolomite cement, micrite cement, 12% micrite, sucrostic, fossil molds, benthonic foraminifera, echinoid.
1500.0-1505.0	As above.
1505.0-1510.0	Dolomite, very light orange, 12% porosity, intergranular, intercrystalline, 50-90% altered, euhedral, grain size: very fine, range: fine to microcrystalline, good induration, dolomite cement, micrite cement, 40% micrite, benthonic foraminifera, mollusks, echinoid.
1510.0-1515.0	As above.
1515.0-1525.0	As above.
1525.0-1530.0	Dolomite, moderate yellowish brown, 13% porosity, intergranular, intercrystalline, moldic, 50-90% altered, euhedral, grain size: very fine, range: microcrystalline to fine, good induration, dolomite cement, micrite cement, 12% micrite, sucrostic, benthonic foraminifera, echinoid.
1530.0-1535.0	As above.
1535.0-1540.0	As above.
1540.0-1545.0	Dolomite, very light orange to grayish orange, 11% porosity, intergranular, intercrystalline, moldic, 50-90% altered, euhedral, grain size, very fine, range: microcrystalline to fine, good induration, dolomite cement, micrite cement, 35% micrite, benthonic foraminifera.

1545.0-1550.0	Limestone, very light orange, 11% porosity, intergranular, grain type: micrite, biogenic, skeletal, 60% allochemical constituents, grain size: very fine, range: microcrystalline to coarse, good induration, dolomite cement, micrite cement, sparry calcite cement, 35% dolomite, benthonic foraminifera, mollusks, echinoid.
1550.0-1555.0	As above.
1555.0-1560.0	Limestone, very light orange, 12% porosity, intergranular, intercrystalline, moldic, grain type: micrite, biogenic, crystals, 60% allochemical constituents, grain size: very fine, range: microcrystalline to medium, good induration, micrite cement, sparry calcite cement, dolomite cement, 20% dolomite, benthonic foraminifera, mollusks, echinoid.
1560.0-1575.0	Samples at 1565, 1570, and 1575 are as above.
1575.0-1580.0	Limestone, very light orange to white, 11% porosity, intergranular, intercrystalline, moldic grain type: micrite, biogenic, crystals, 40% allochemical constituents, grain size: microcrystalline, range: microcrystalline to medium, good induration, micrite cement, sparry calcite cement, dolomite cement, 15% dolomite, benthonic foraminifera, mollusks, echinoid.
1580.0-1590.0	Limestone, very light orange to white, 13% porosity, intergranular, grain type: micrite, biogenic, skeletal, 70% allochemical constituents, grain size: fine, range: microcrystalline to medium, good induration, micrite cement, sparry calcite cement, dolomite cement, 15% dolomite, benthonic foraminifera, mollusks, echinoid.
1590.0-1600.0	As above.
1600.0-1610.0	Limestone, very light orange, 12% porosity, intergranular, moldic, grain type: biogenic, micrite, skeletal, 75% allochemical constituents, grain size: medium, range: microcrystalline to coarse, good induration, micrite cement, dolomite cement, sparry calcite cement, 15% dolomite, benthonic foraminifera, mollusks, echinoid.
1610.0-1620.0	Dolomite, very light orange, 12% porosity, intergranular, moldic, intercrystalline, 50-90% altered, euhedral, grain size: very fine, range: very fine to microcrystalline, good induration, dolomite cement, micrite cement, 35% micrite, benthonic foraminifera, mollusks, echinoid, fossil molds.

1620.0-1630.0	Limestone, very light orange, 14% porosity, intergranular, grain type: biogenic, skeletal, crystals, 80% allochemical constituents, grain size: medium, range: microcrystalline to coarse, good induration, dolomite cement, micrite cement, sparry calcite cement, 25% dolomite, benthonic foraminifera.
1630.0-1640.0	Limestone, white to very light orange, 11% porosity, intergranular, grain type: biogenic, micrite, crystals, 40% allochemical constituents, grain size: microcrystalline, range: microcrystalline to medium, good induration, micrite cement, sparry calcite cement, 02% peat.
1640.0-1650.0	Limestone, very light orange, 14% porosity, intergranular, grain type: biogenic, skeletal, crystals, 80% allochemical constituents, grain size: medium, range: microcrystalline to coarse, good induration, micrite cement, dolomite cement, sparry calcite cement, 25% dolomite, benthonic foraminifera.

LITHOLOGIC DESCRIPTION OF WELL LV-1

950.0-951.0	CAVITY = some infilling by light brown, friable, dolomite sands and offwhite-light gray, slightly dolomitized, sparse biomicrite, moderate porosity.
951.0-958.0	DOLOSTONE = light brown, hard, friable, moldic dolomite alternating with dark tannish brown, very hard, partly recrystallized dolomite, low-moderate moldic porosity.
958.0-965.0	DOLOSTONE-LIMESTONE = dark brown-dark tannish brown, hard-very hard, partly recrystallized (microcrystalline), dolomite alternating with cream-offwhite-light gray, slightly dolomitized, microcoquinal biomicrite, some forams (some Dictyoconus americanus), low-moderate moldic porosity in dolostone, moderate-high porosity in limestone.
965.0-972.0	LIMESTONE = cream-offwhite-light gray in parts, soft, chalky, poorly cemented, microcoquinal biomicrite, abundant microfauna (common milliolids, some Valvulina floridana, common but eroded Amphistegina lopeztrigoi, trace of Gunteria floridana, Lepidocyclina cedarkeysensis, some Dictyoconus americanus), some light gray, slightly dolomitized limestone, some small echinoid tests (Echinocyamus vaughani?) and test fragments, moderate-high porosity.
972.0-977.0	LIMESTONE = cream-light tan-light gray in parts, soft-hard in parts, slightly indurated, chalky, poorly cemented, microcoquinal biomicrite, common microfauna (common milliolids, some Amphistegina lopezfrigoi, some Valvulina floridana, some light gray, heavily eroded Heliostegina gyralis?, some Dictyoconus americanus), common aragonitized, small echinoid test fragments, moderate-high porosity.
977.0-980.0	DOLOSTONE = light-dark brown, hard but tufaceous, slightly friable, moldic dolomite, some cream, chalky biomicrite fragments, low-moderate moldic porosity.
980.0-990.0	DOLOSTONE = light-dark brown, very hard, partly recrystallized, slightly moldic in parts, dolomite, low moldic porosity.
990.0-999.0	DOLOSTONE = light-dark brown, hard, partly recrystallized, slightly moldic in parts, dolomite, some tan dolomite sands, low moldic porosity.

999.0-1005.0	DOLOSTONE = light-dark tannish brown, very hard, recrystallized (microcrystalline-sucrosic) dolomite, very low porosity.
1005.0-1015.0	DOLOSTONE = light tannish brown, very hard, partly recrystallized (microcrystalline-sucrosic) dolomite, very low porosity.
1015.0-1020.0	DOLOSTONE = light tannish brown, very hard, recrystallized (microcrystalline-sucrosic) dolomite, thin seam of light gray chert nodules at 1018', chert nodules having offwhite weathering rinds, some light gray, silty, highly soluble clay, very low porosity.
1020.0-1040.0	DOLOSTONE = dark tannish brown-dark brown-brownish black mottling, very hard, recrystallized (microcrystalline-sucrosic in parts) dolomite, some offwhite-light gray, dolomitized sparse biomicrite, some light gray, silty, highly soluble clay, very low-low porosity.
1040.0-1050.0	DOLOSTONE = light tannish brown, hard, recrystallized (microcrystalline-sucrosic) dolomite, very low porosity.
1050.0-1055.0	DOLOSTONE = light-dark brown, very hard, recrystallized (microcrystalline-sucrosic) dolomite, some vugs infilled by offwhite-milky white recrystallized quartz crystals, very low porosity.
1055.0-1062.0	DOLOSTONE = light brown, hard, recrystallized (microcrystalline-sucrosic) dolomite, some vugs infilled by offwhite-milky white quartz masses, trace of echinoid test fragments, very low porosity.
1062.0-1070.0	DOLOSTONE = dark brown-dark tannish brown mottling, very hard, recrystallized (microcrystalline) dolomite, some light brown, friable, soft, sucrosic dolomite streaking this section, some light brown dolomite sands, some vugs infilled by offwhite-milky white quartz masses, very low-low porosity in dark brown dolomite, low porosity in light brown dolomite.
1070.0-1082.0	DOLOSTONE = light tannish brown, hard, recrystallized (microcrystalline-sucrosic), some dark tannish brown mottling, some quartz masses infilling vugs as described above, low porosity.
1082.0-1104.0	LIMESTONE-DOLOSTONE = cream-offwhite-light gray, soft-hard, indurated, sparse biomicrite, some heavily eroded microfauna (some Dictyoconus sp.?), trace of light tan, sticky clay fragments with some

	yellowish staining due to oxidation, moderate porosity, dolostone as above described.
1104.0-1106.0	DOLOSTONE = same as 1070.0-1082.0'.
1106.0-1120.0	LIMESTONE = same as 1082.0-1104.0', no dolostone.
1120.0-1145.0	DOLOSTONE = light tannish brown-buff, hard, partly recrystallized, fossiliferous dolomite, some vugs infilled by milky white recrystallized quartz crystal masses, low moldic porosity.

APPENDIX M

WATER RESISTIVITY (R_w) VS. SPECIFIC ION PLOTS FOR WATER MASSES USED IN RESEARCH

Floridan Aquifer, Quincy Area, R_w vs.:

- Chloride
- Total Dissolved Solids
- Potassium
- Magnesium
- Hardness
- Sulfate
- Sodium
- Fluoride
- Calcium
- Bicarbonate
- Dissolved Silica

Sand-and-Gravel Aquifer, Southern Escambia and Santa Rosa Counties, R_w vs.:

- Chloride
- Total Iron

Sand-and-Gravel Aquifer, Southern Okaloosa and Walton Counties, R_w vs.:

- Chloride

Biscayne Aquifer, Broward County, R_w vs.:

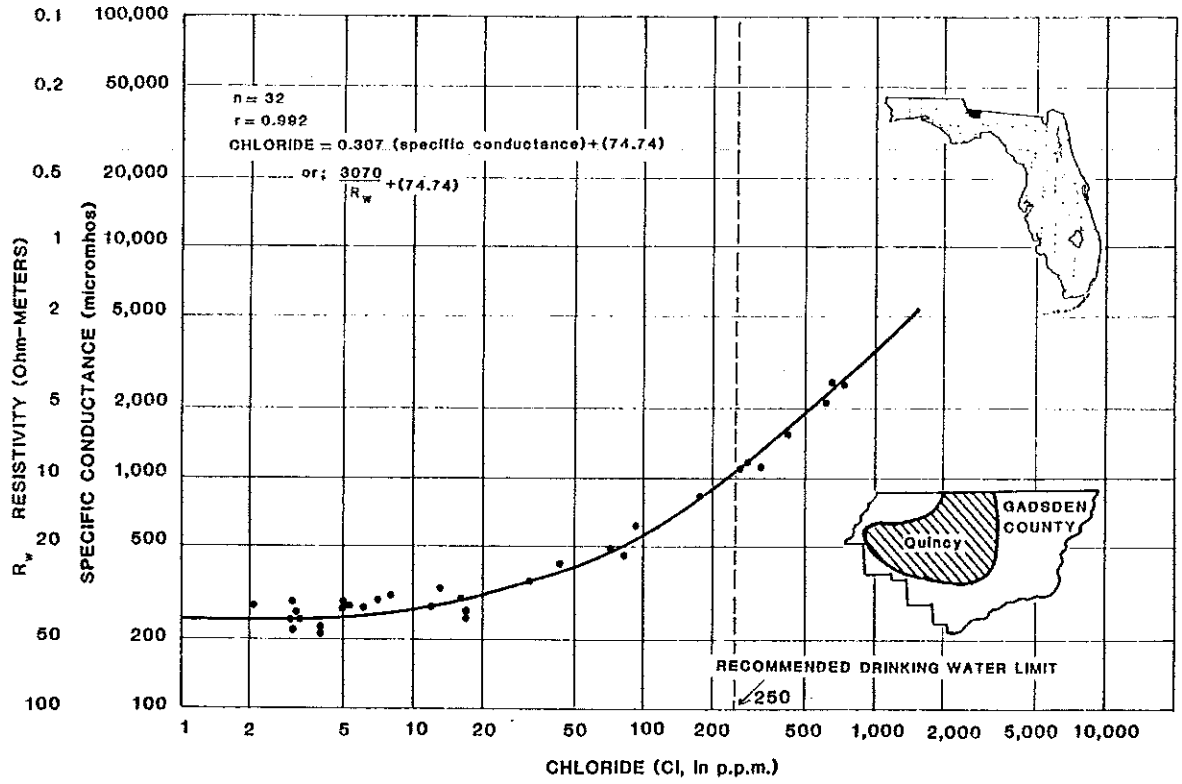
- Chloride

Surficial and Intermediate Aquifers, R_w vs.:

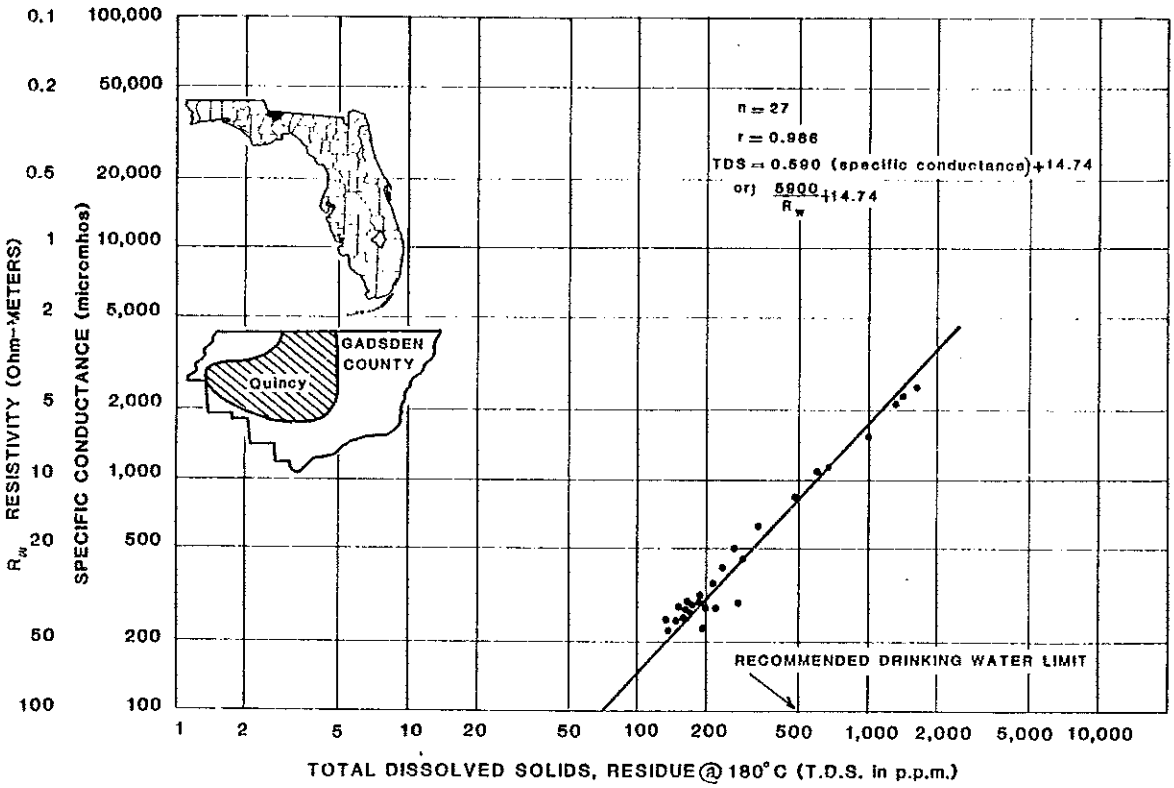
- Chloride, Duval County
- Chloride, East-Central St. Johns County
- Chloride, Palm Beach County

Floridan Aquifer, R_w vs.:

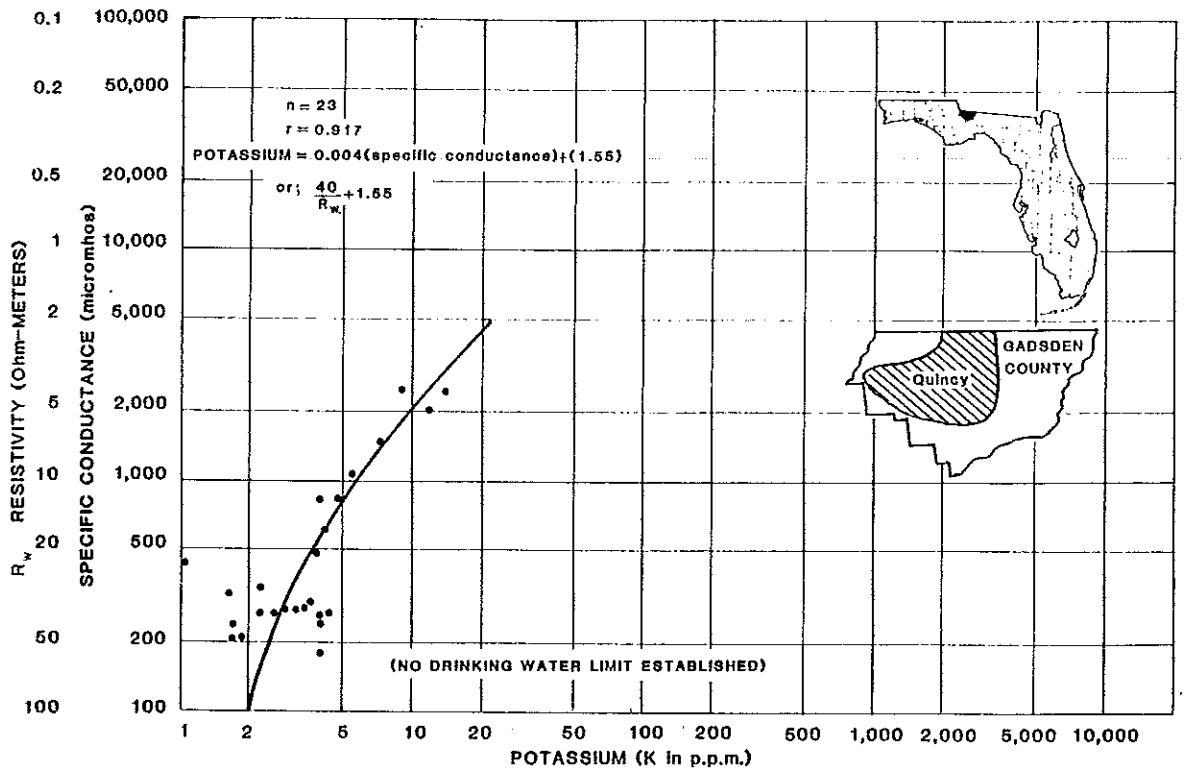
- Chloride, Southern Walton County
- Chloride, Northern Okaloosa and Walton Counties
- Chloride, Havana Area, Gadsden County
- Chloride, Northeastern Volusia County
- Chloride, Seminole County
- Chloride, Southeastern Orange County
- Chloride, Southwestern Hillsborough County
- Chloride, Sarasota County
- Chloride, Lee County
- Chloride, Dade and Monroe Counties
- Chloride, Nine-County Area of South Florida



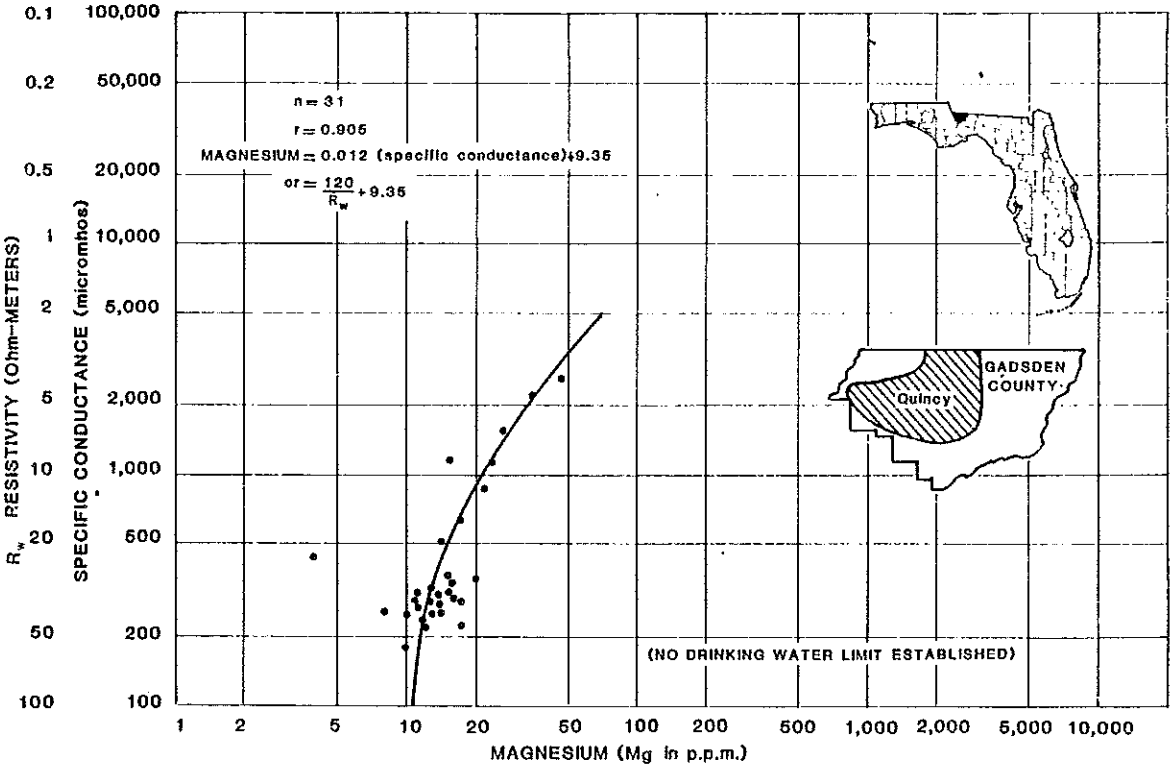
Floridan Aquifer, Quincy Area, R_W vs. Chloride



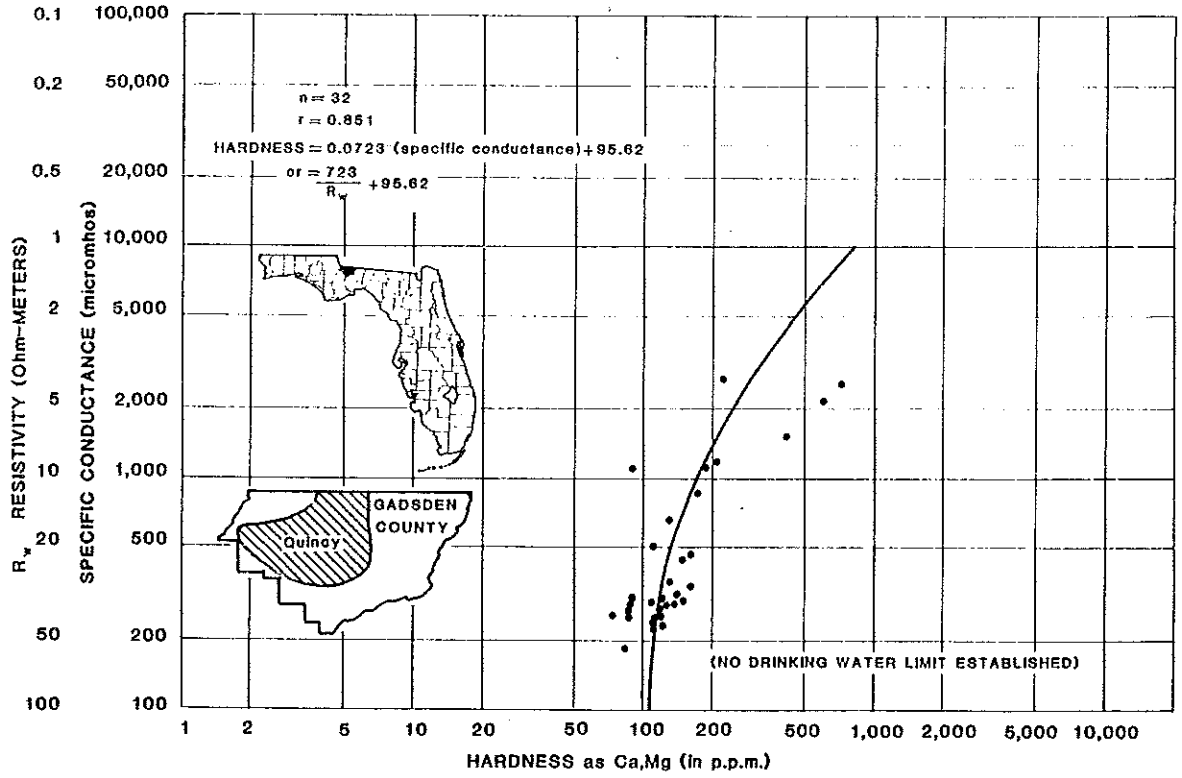
Floridan Aquifer, Quincy Area, R_W vs. Total Dissolved Solids



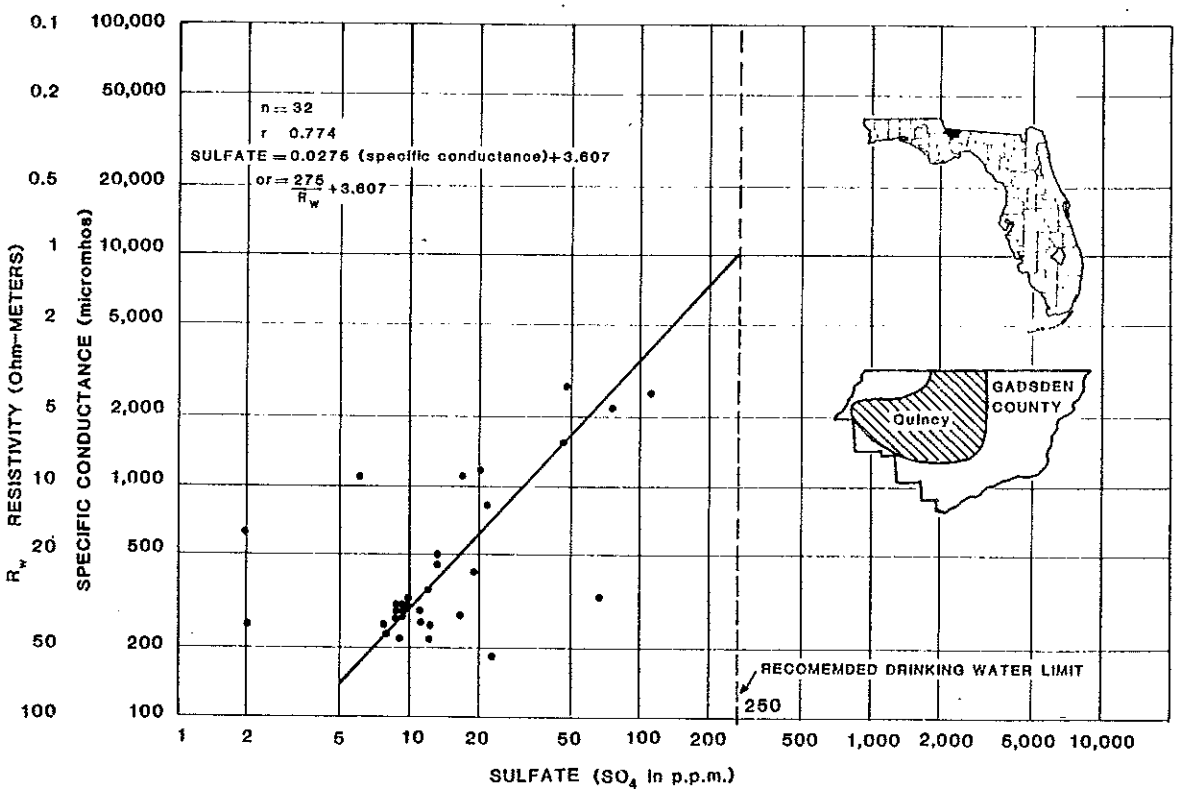
Floridan Aquifer, Quincy Area, R_W vs. Potassium



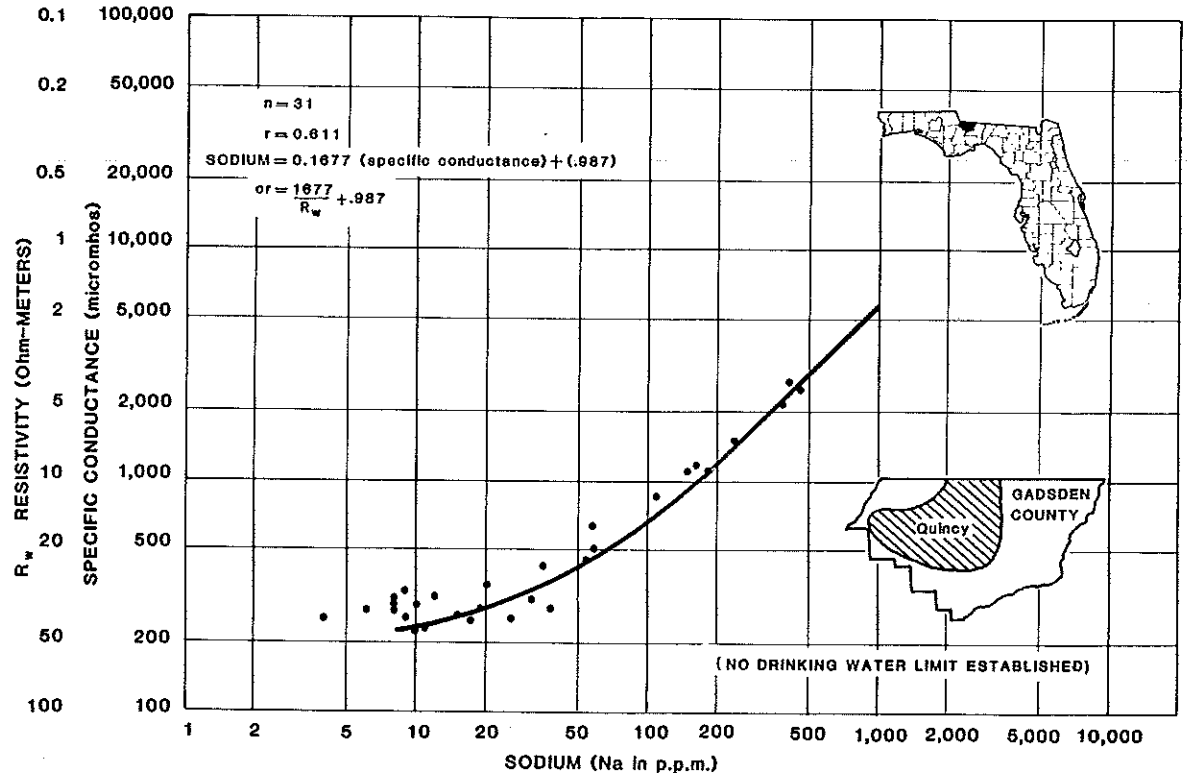
Floridan Aquifer, Quincy Area, R_W vs. Magnesium



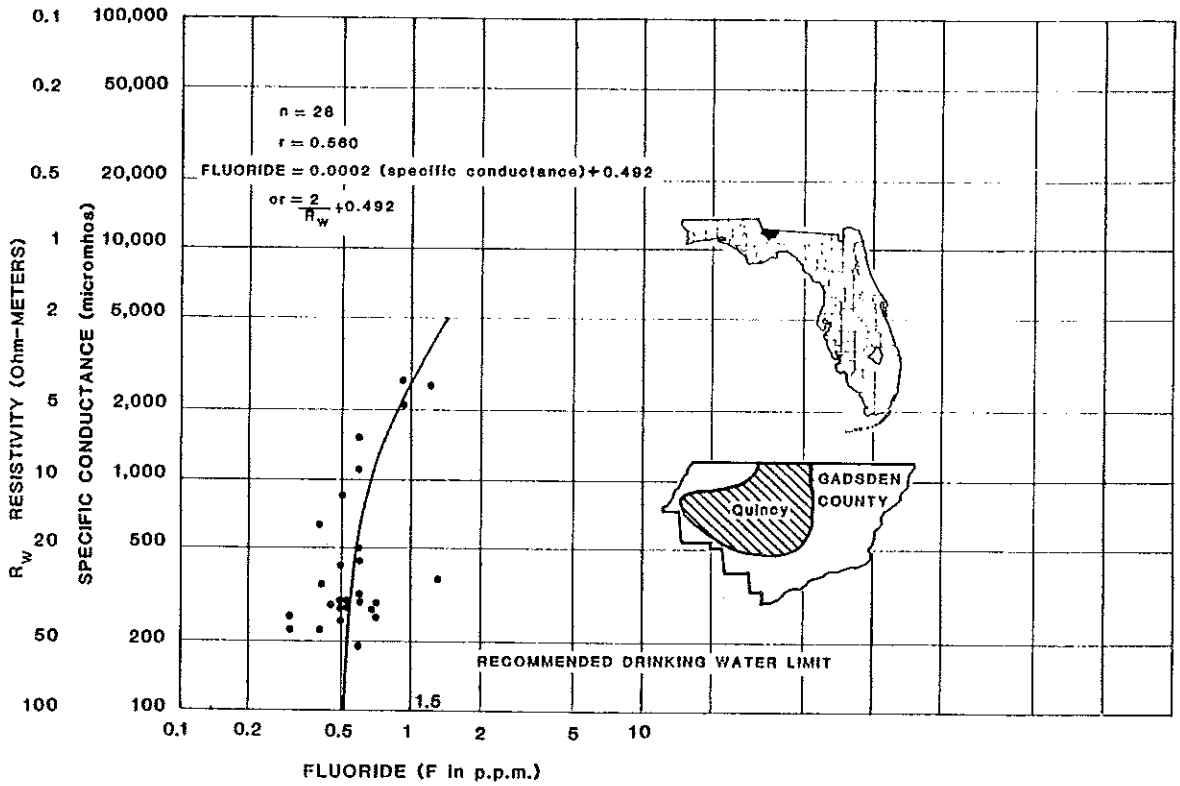
Floridan Aquifer, Quincy Area, R_W vs. Hardness



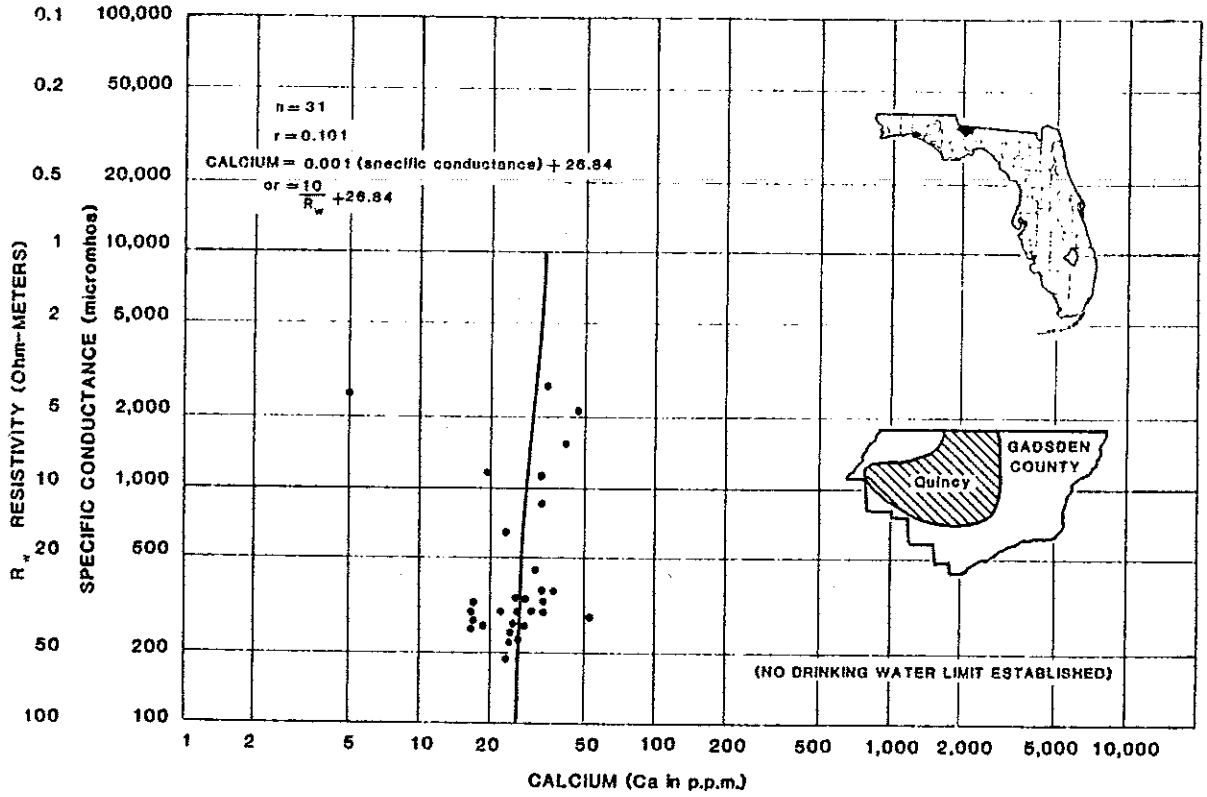
Floridan Aquifer, Quincy Area, R_W vs. Sulfate



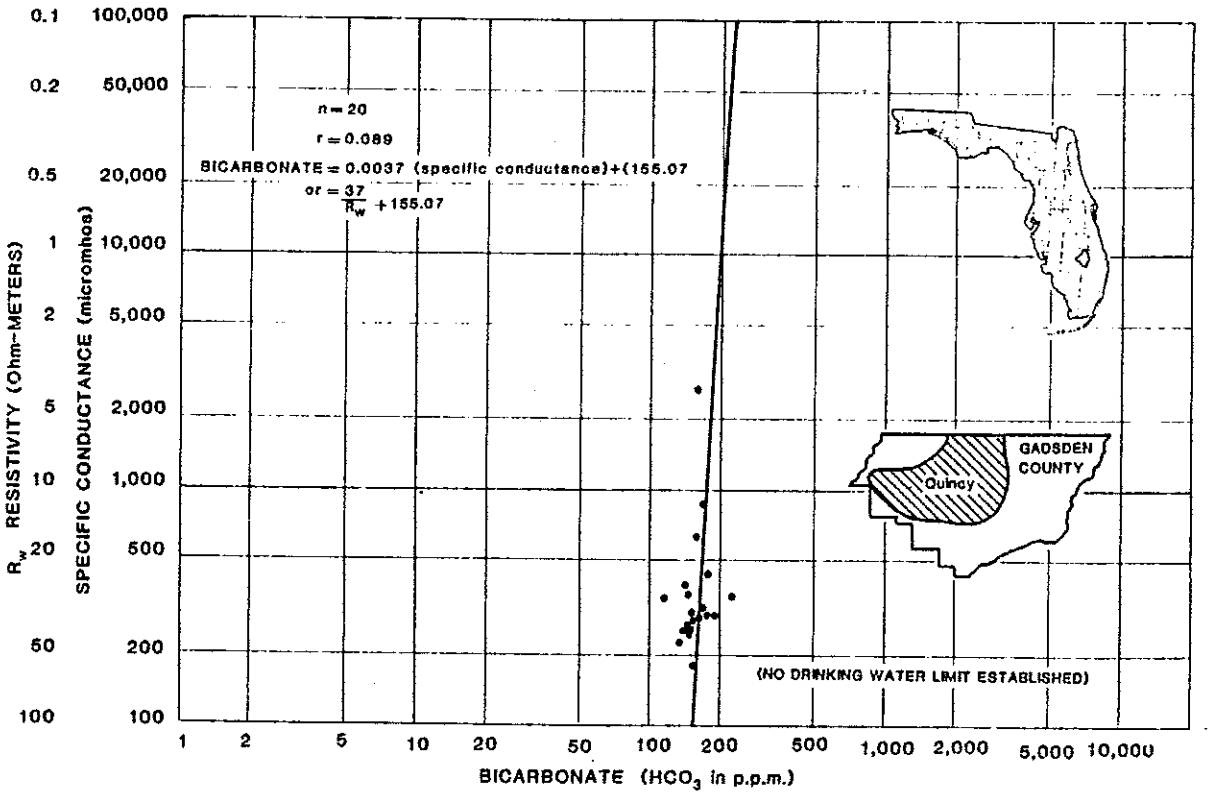
Floridan Aquifer, Quincy Area, R_W vs. Sodium



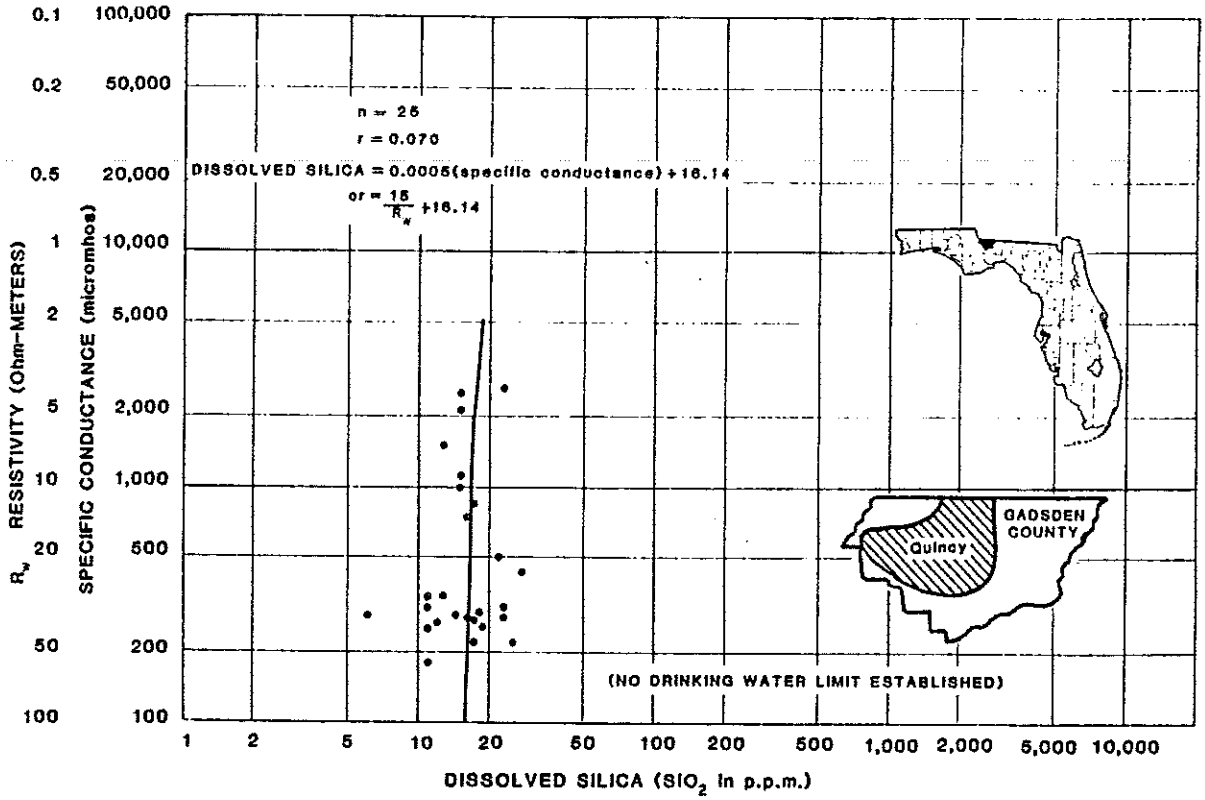
Floridan Aquifer, Quincy Area, R_W vs. Fluoride



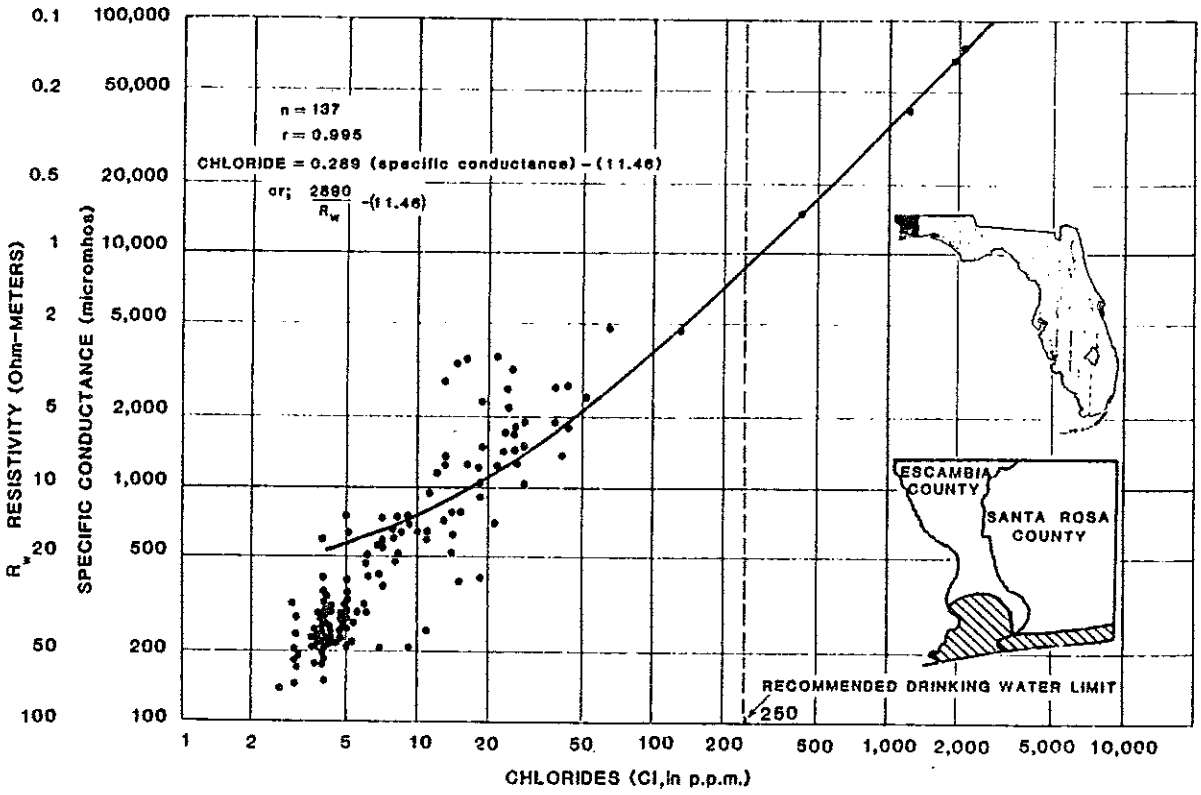
Floridan Aquifer, Quincy Area, R_W vs. Calcium



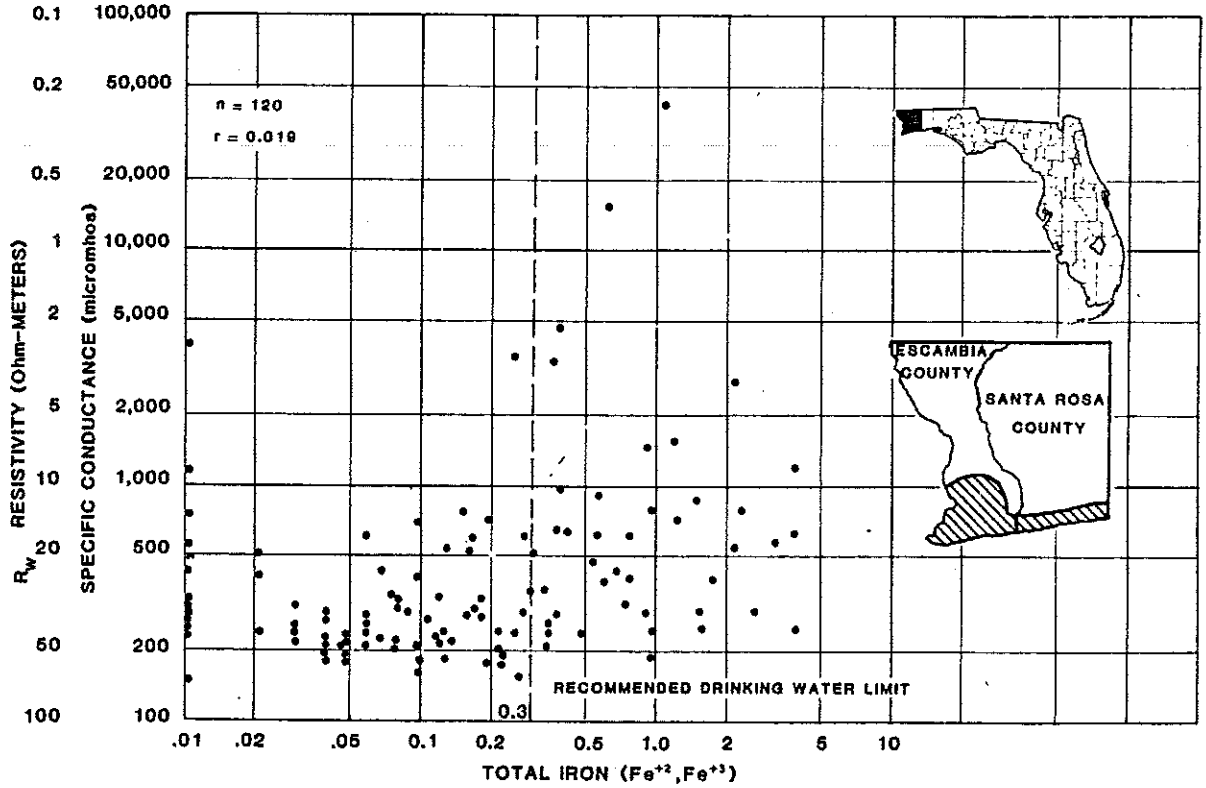
Floridan Aquifer, Quincy Area, R_W vs. Bicarbonate



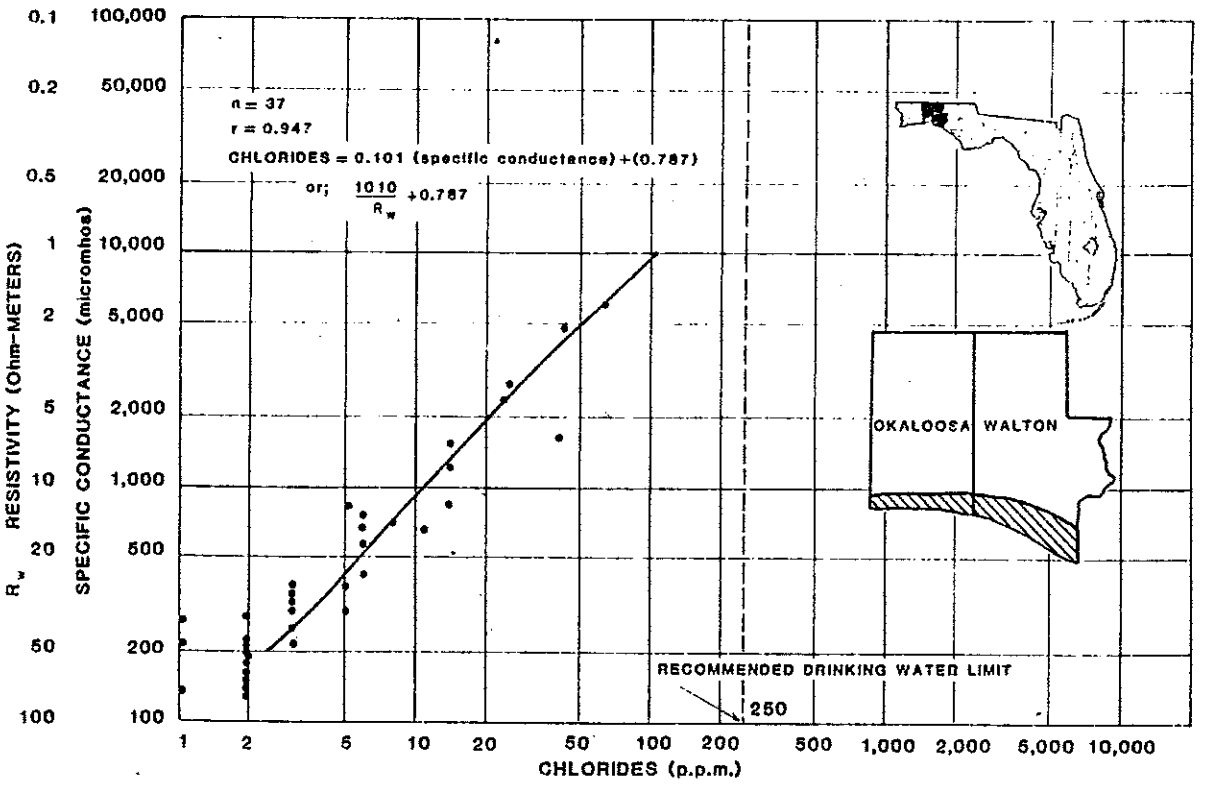
Floridan Aquifer, Quincy Area, R_W vs. Dissolved Silica



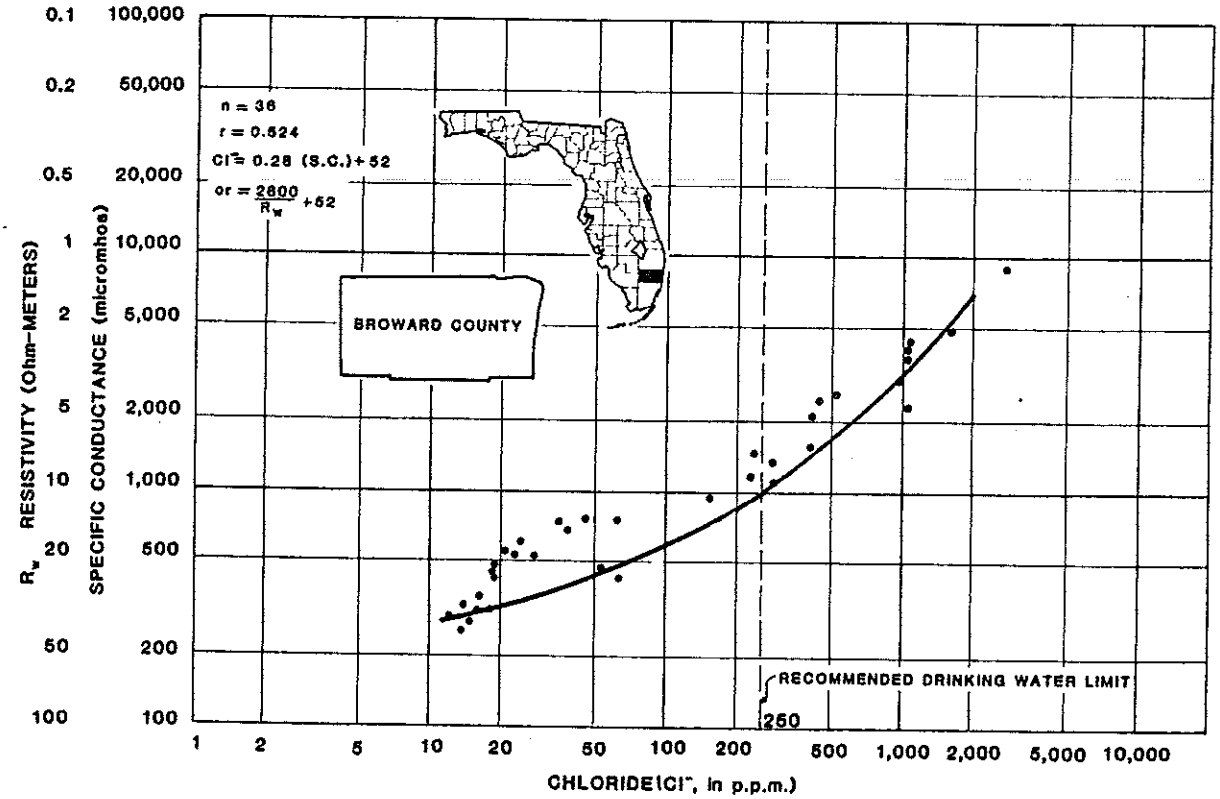
Sand-and-Gravel Aquifer, Southern Escambia and Santa Rosa Counties, R_W vs. Chloride



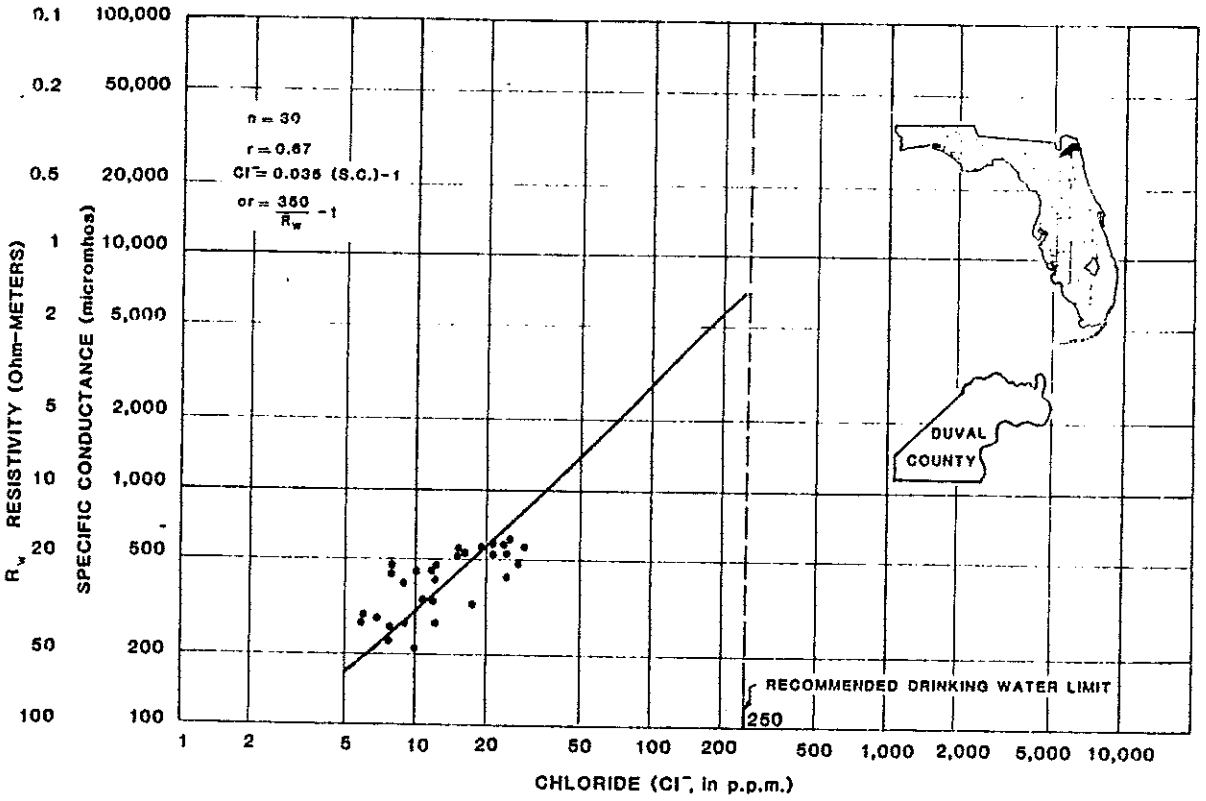
Sand-and-Gravel Aquifer, So. Escambia and Santa Rosa Cos., R_W vs. Total Iron



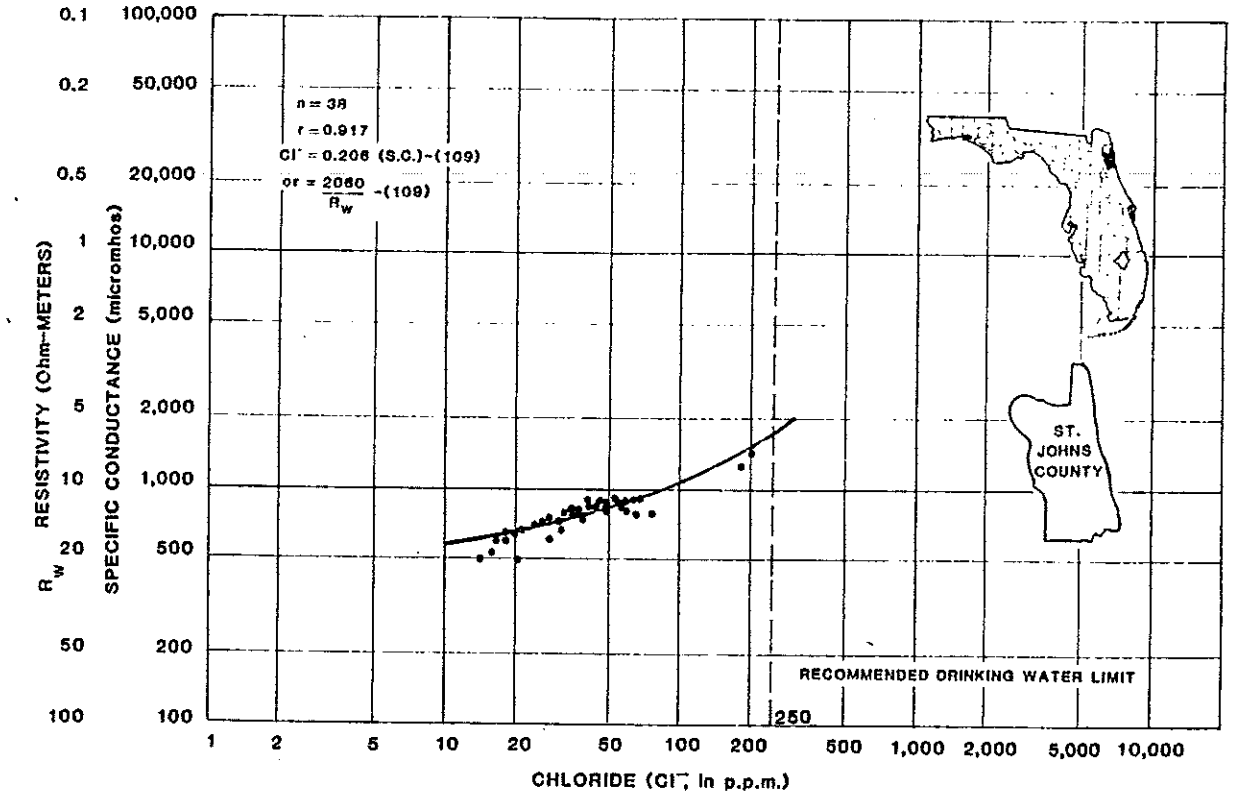
Sand-and-Gravel Aquifer, So. Okaloosa and Walton Cos., R_W vs. Chloride



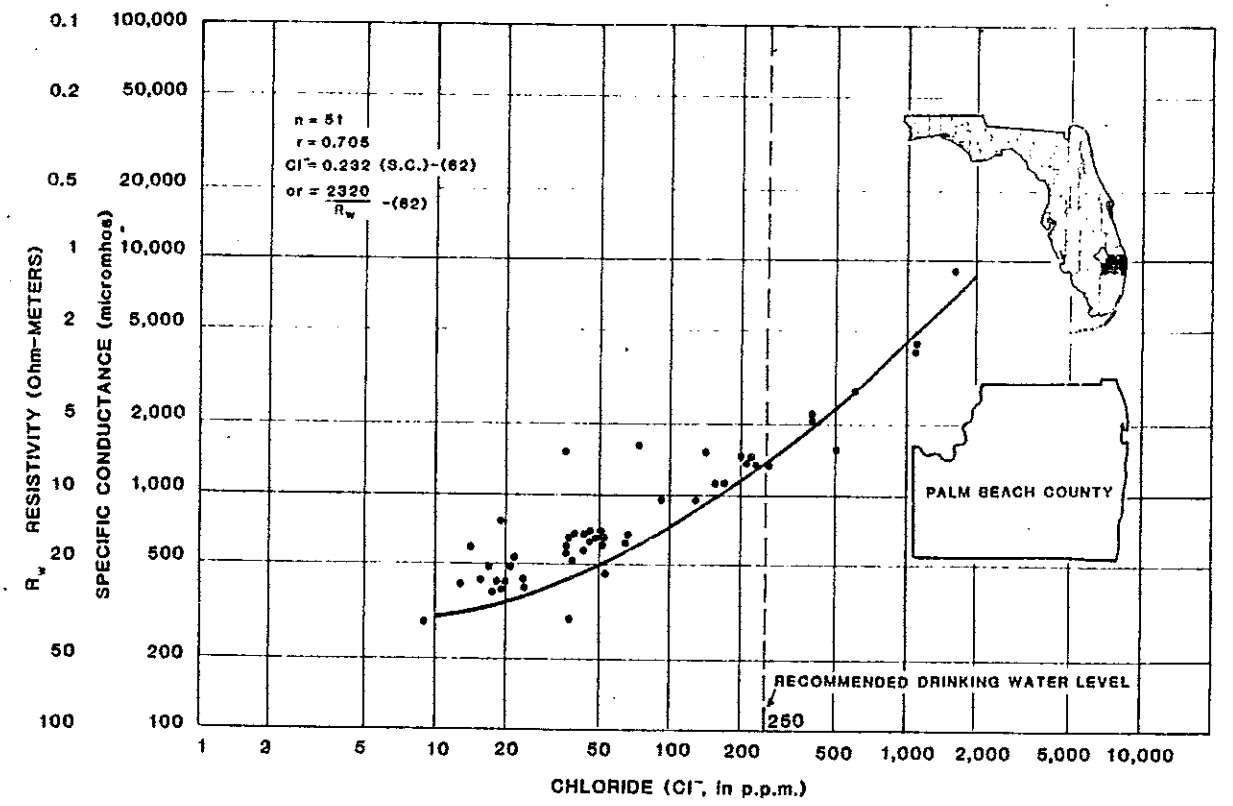
Biscayne Aquifer, Broward County, R_W vs. Chloride



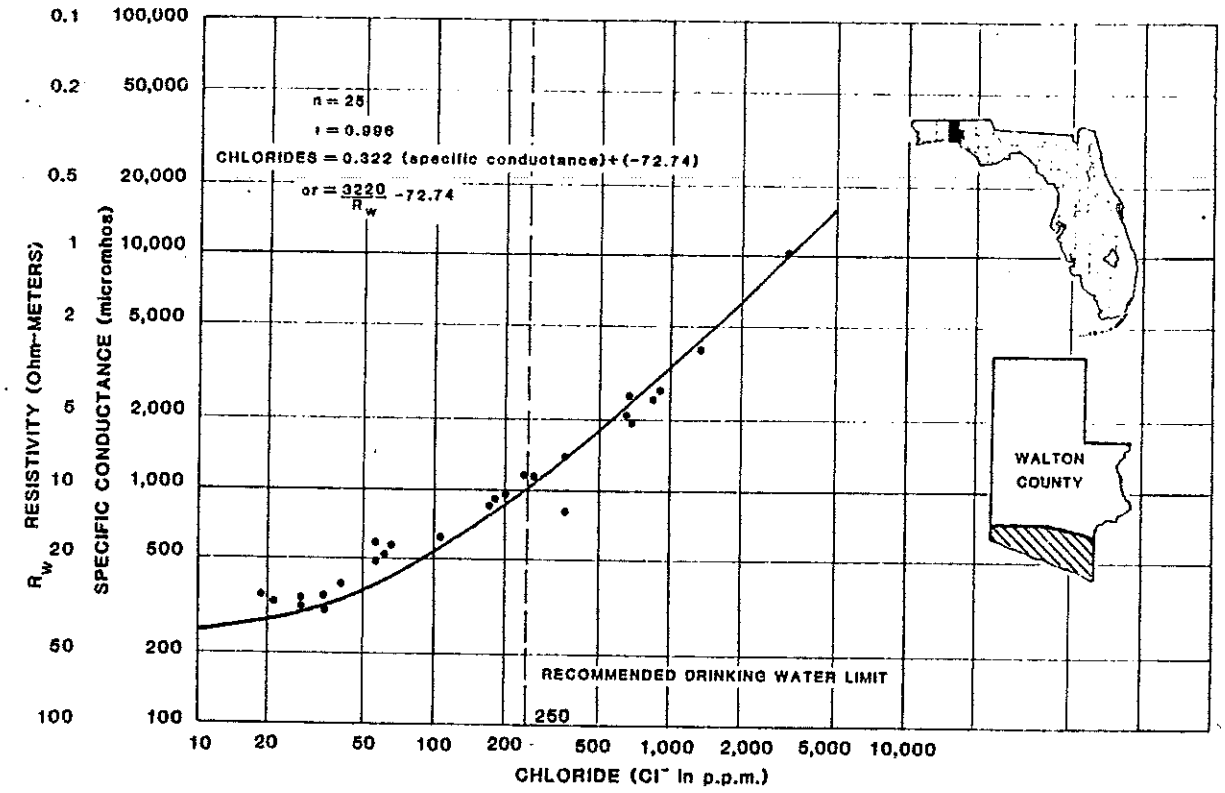
Surficial and Intermediate Aquifers, R_W vs. Chloride, Duval Co.



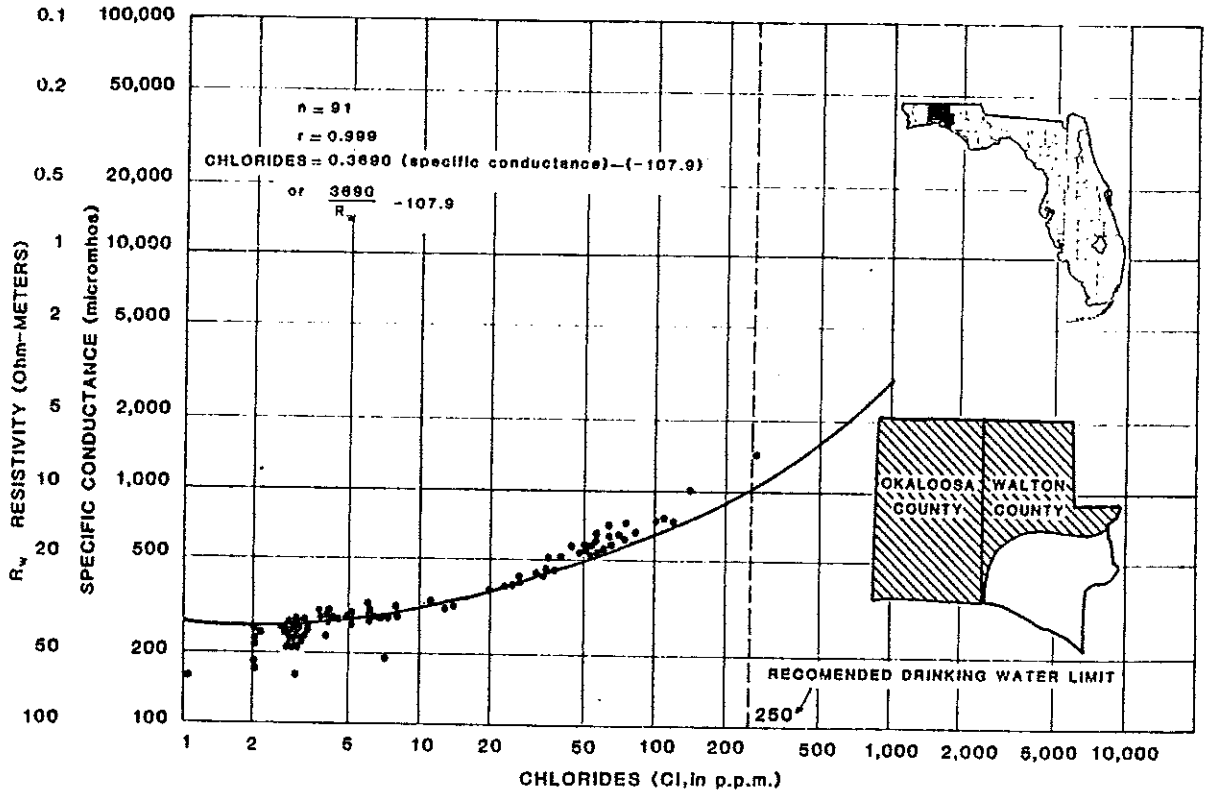
Surficial and Intermediate Aquifers, R_w vs. Chloride, East-Central St.Johns Co.



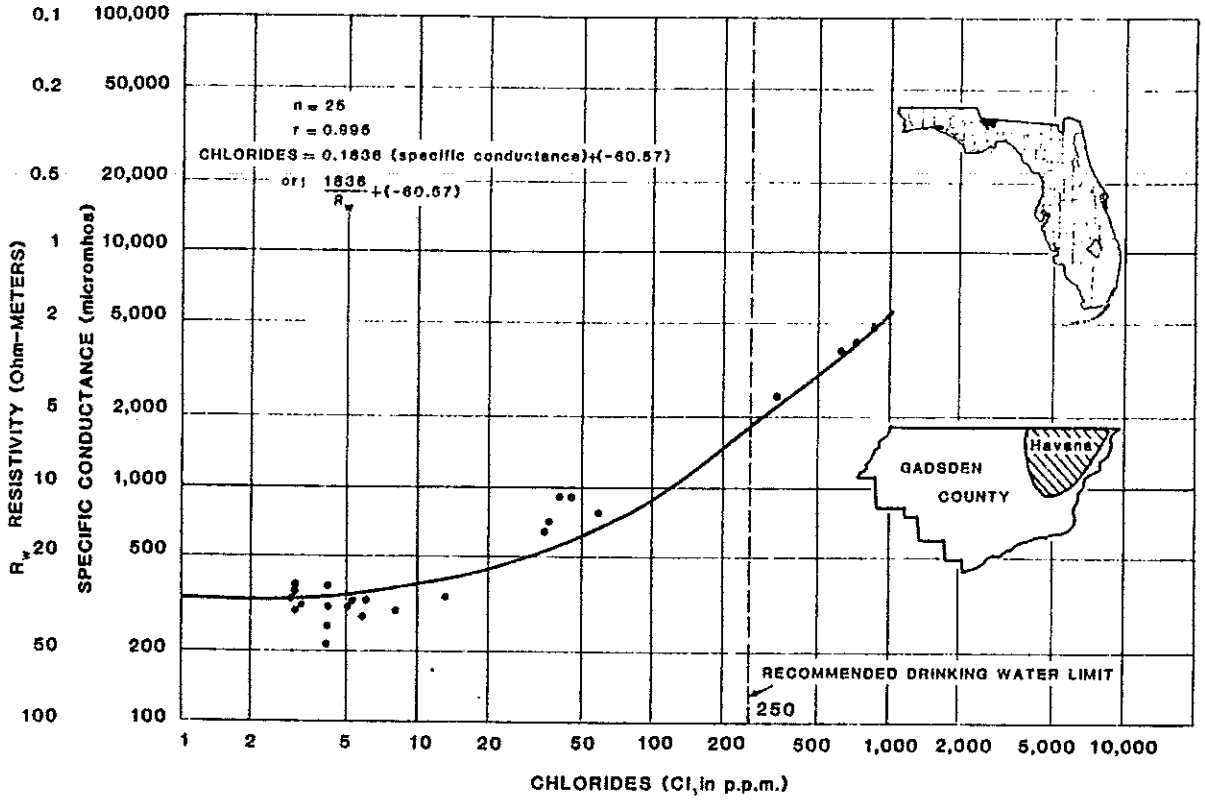
Surficial and Intermediate Aquifers, R_w vs. Chloride, Palm Beach Co.



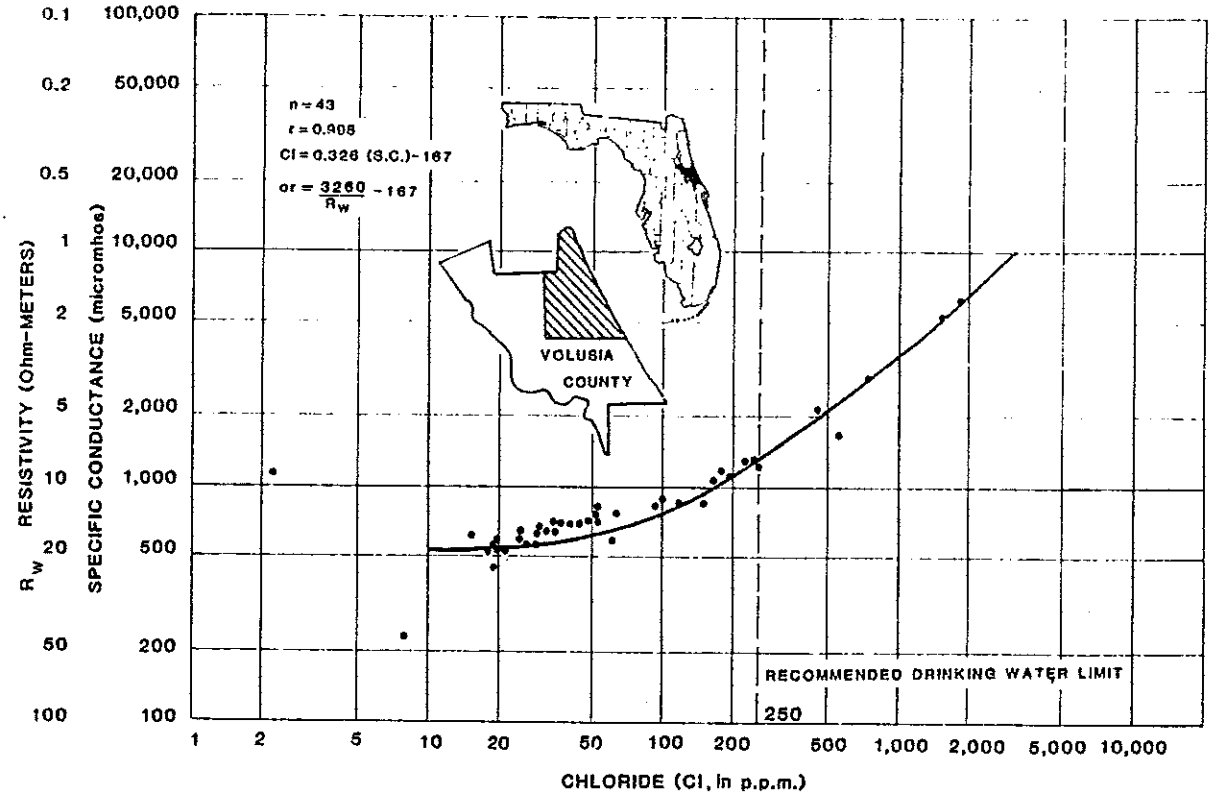
Floridan Aquifer, R_W vs. Chloride, Southern Walton County



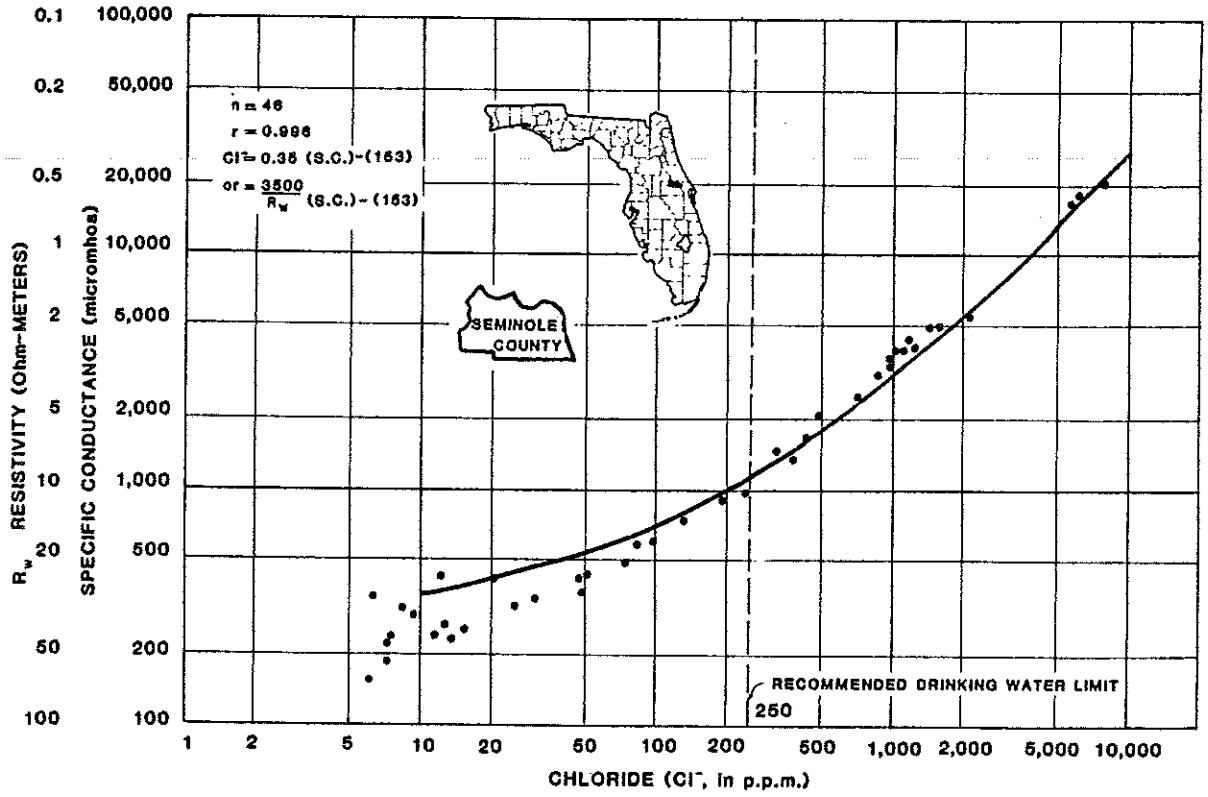
Floridan Aquifer, R_W vs. Chloride, Northern Okaloosa and Walton Cos.



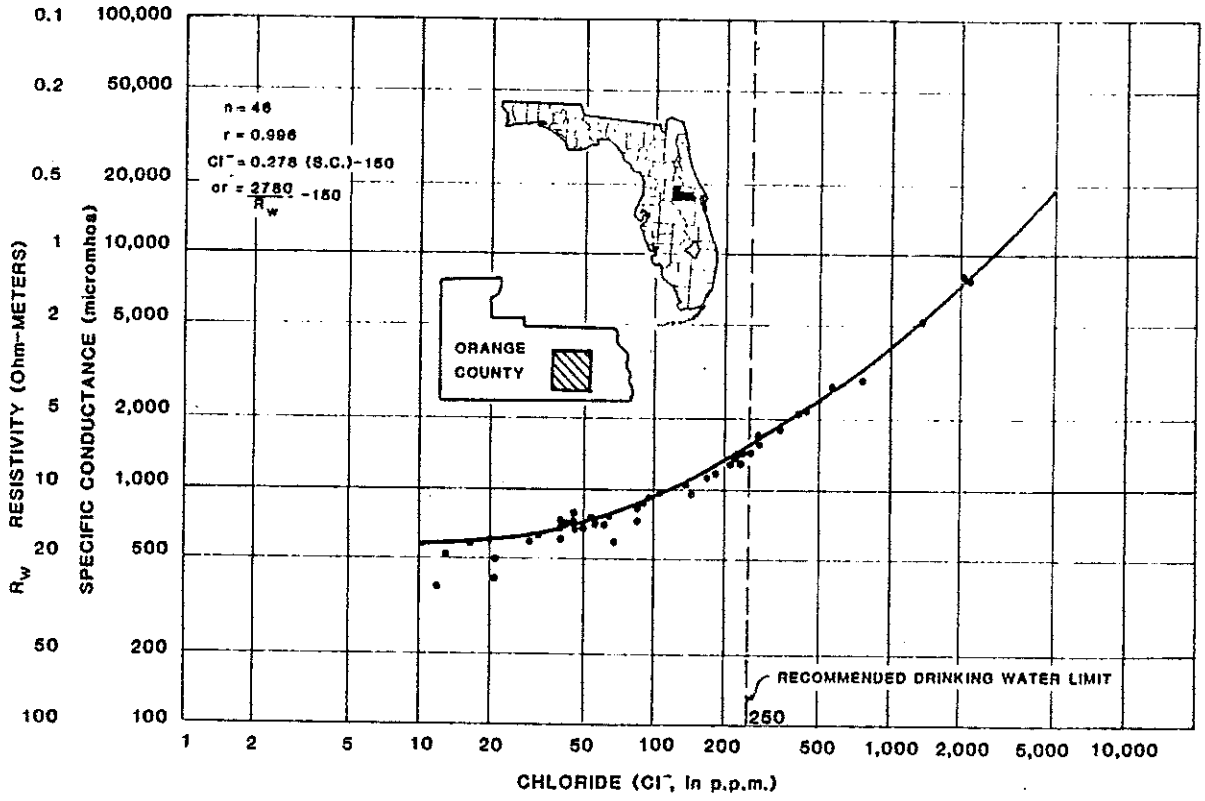
Floridan Aquifer, R_W vs. Chloride, Havana Area, Gadsden Co.



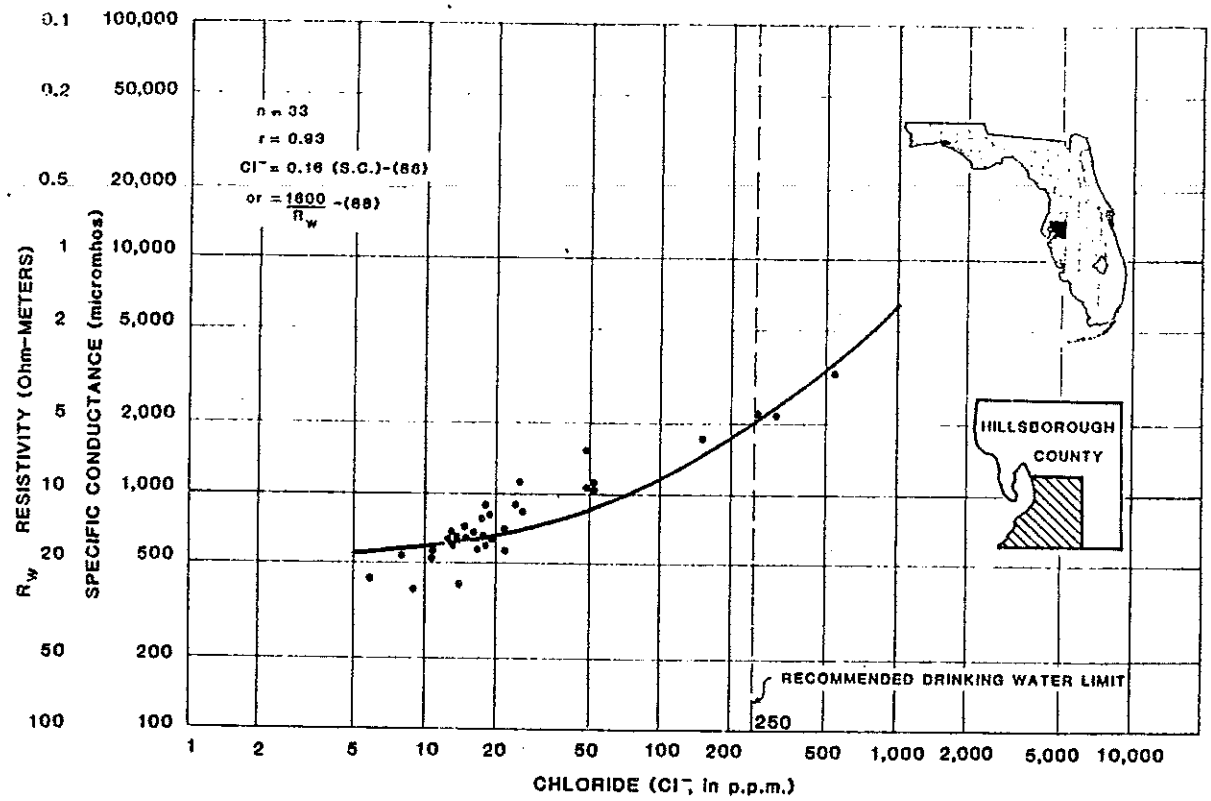
Floridan Aquifer, R_W vs. Chloride, Northeastern Volusia Co.



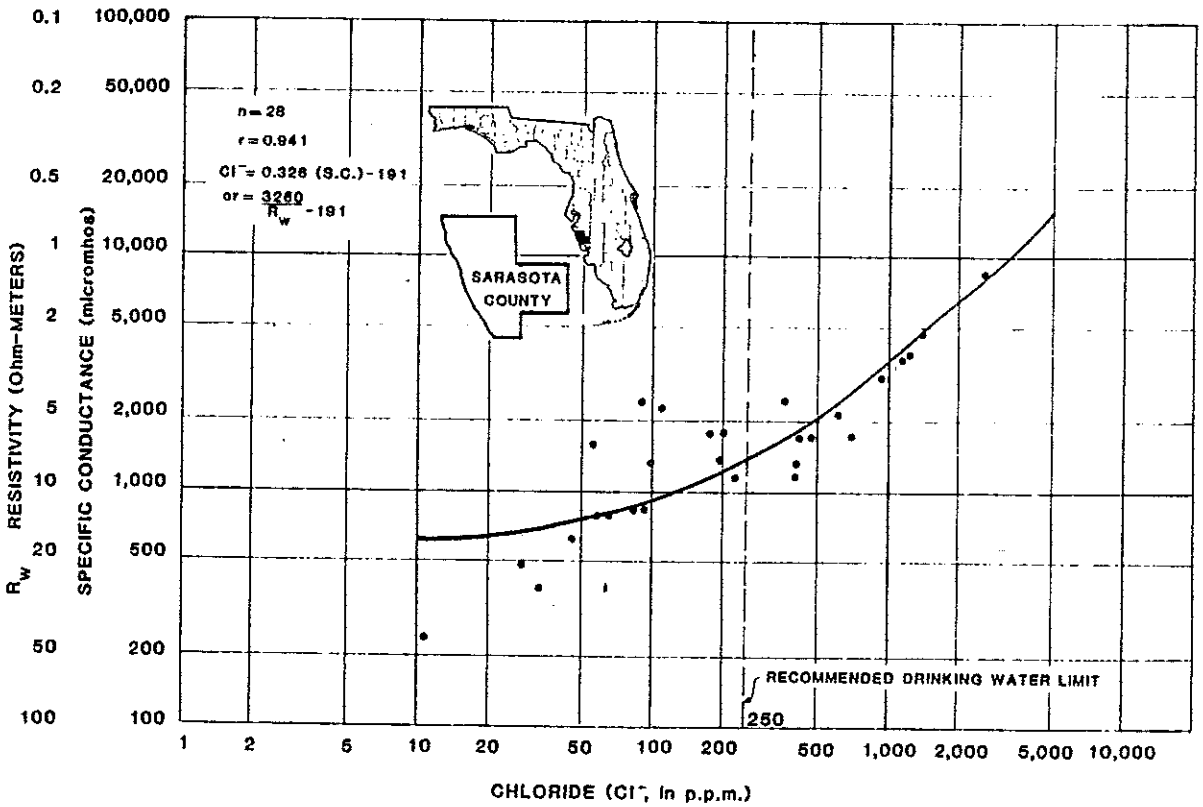
Floridan Aquifer, R_w vs. Chloride, Seminole Co.



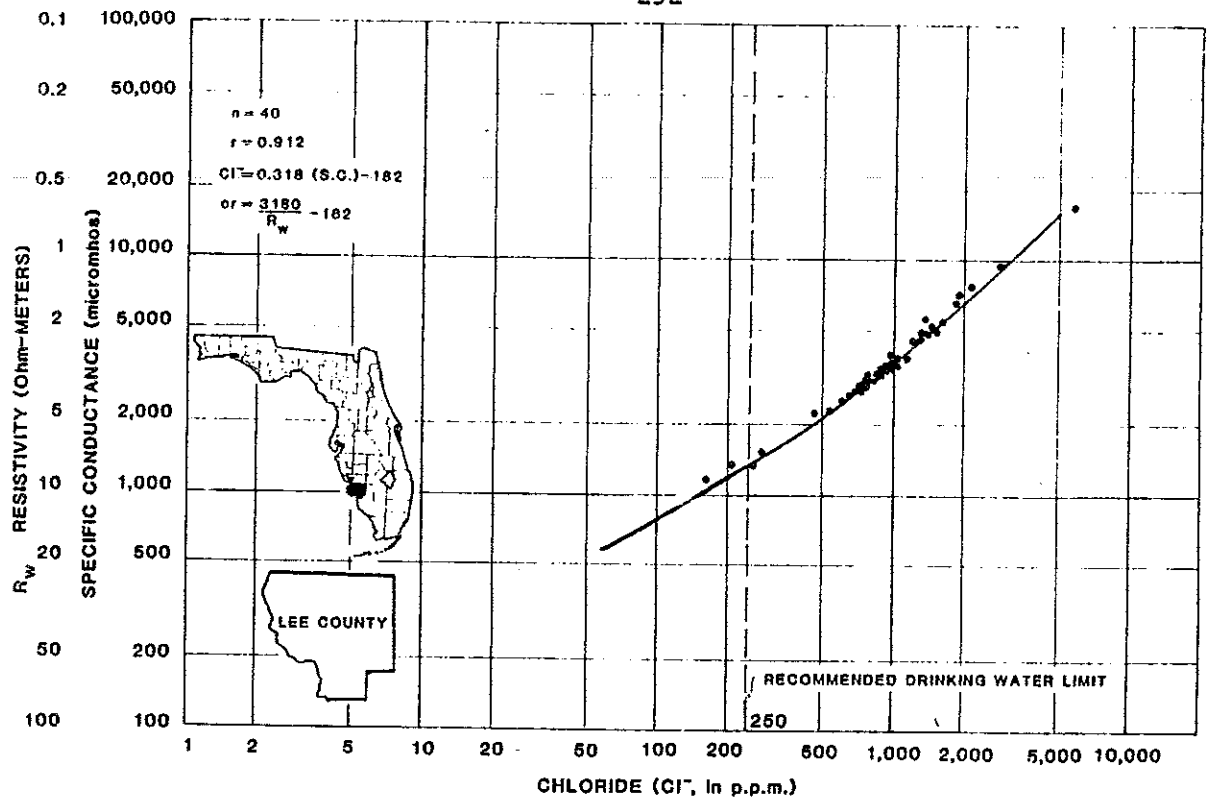
Floridan Aquifer, R_w vs. Chloride, Southeastern Orange Co.



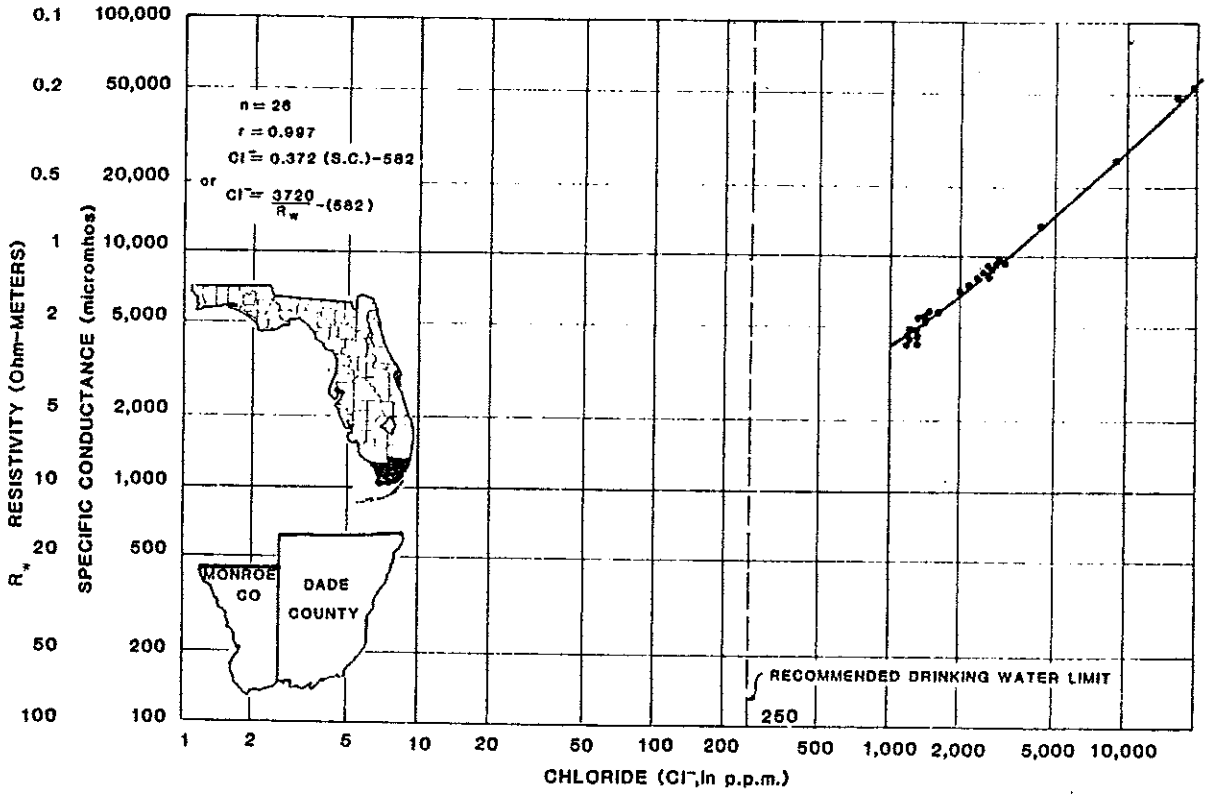
Floridan Aquifer, R_W vs. Chloride, Southwestern Hillsborough Co.



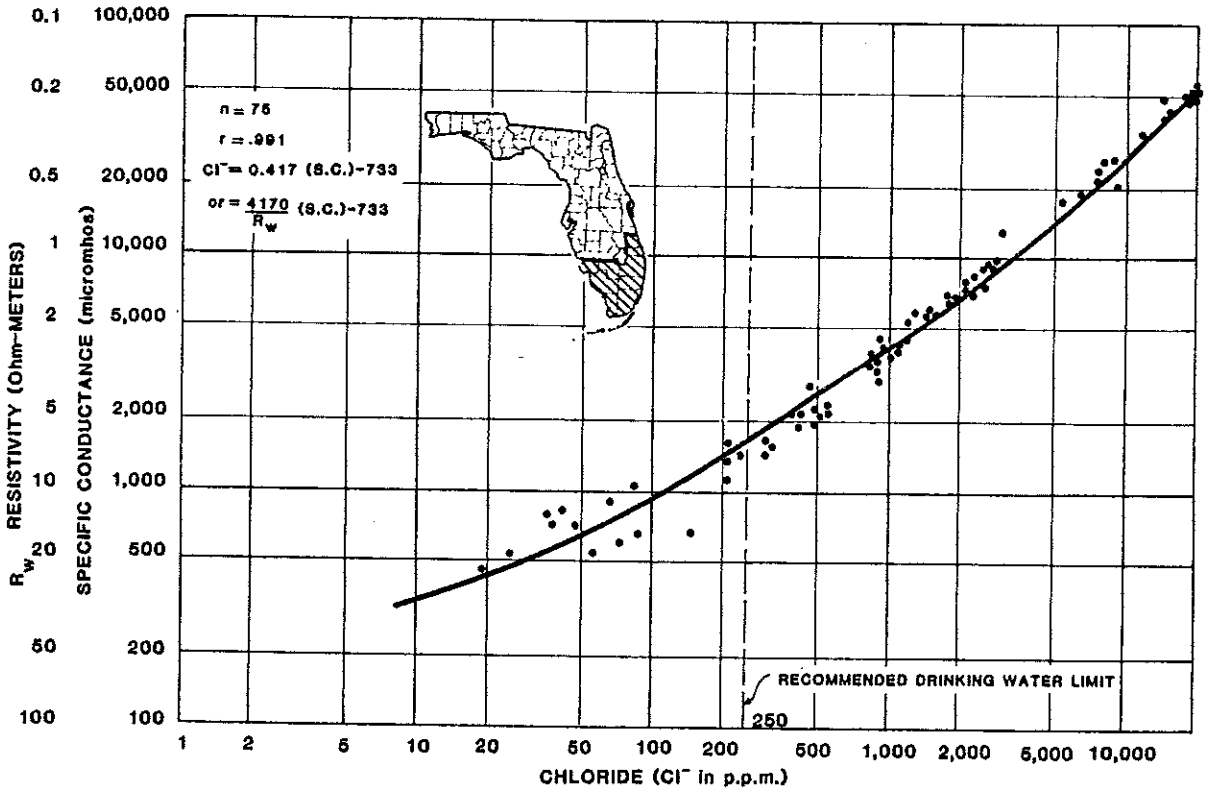
Floridan Aquifer, R_W vs. Chloride, Sarasota Co.



Floridan Aquifer, R_W vs. Chloride, Lee Co.



Floridan Aquifer, R_W vs. Chloride, Dade and Monroe Cos.



Floridan Aquifer, R_w vs. Chloride, Nine-Co. Area of So. Florida

APPENDIX N

CHARTS AND CROSS PLOTS USED IN LOG INTERPRETATIONS

Lithologic - Porosity Cross Plots:

- Bulk density vs. neutron
- Sonic transit time vs. neutron
- Bulk density vs. sonic transit time

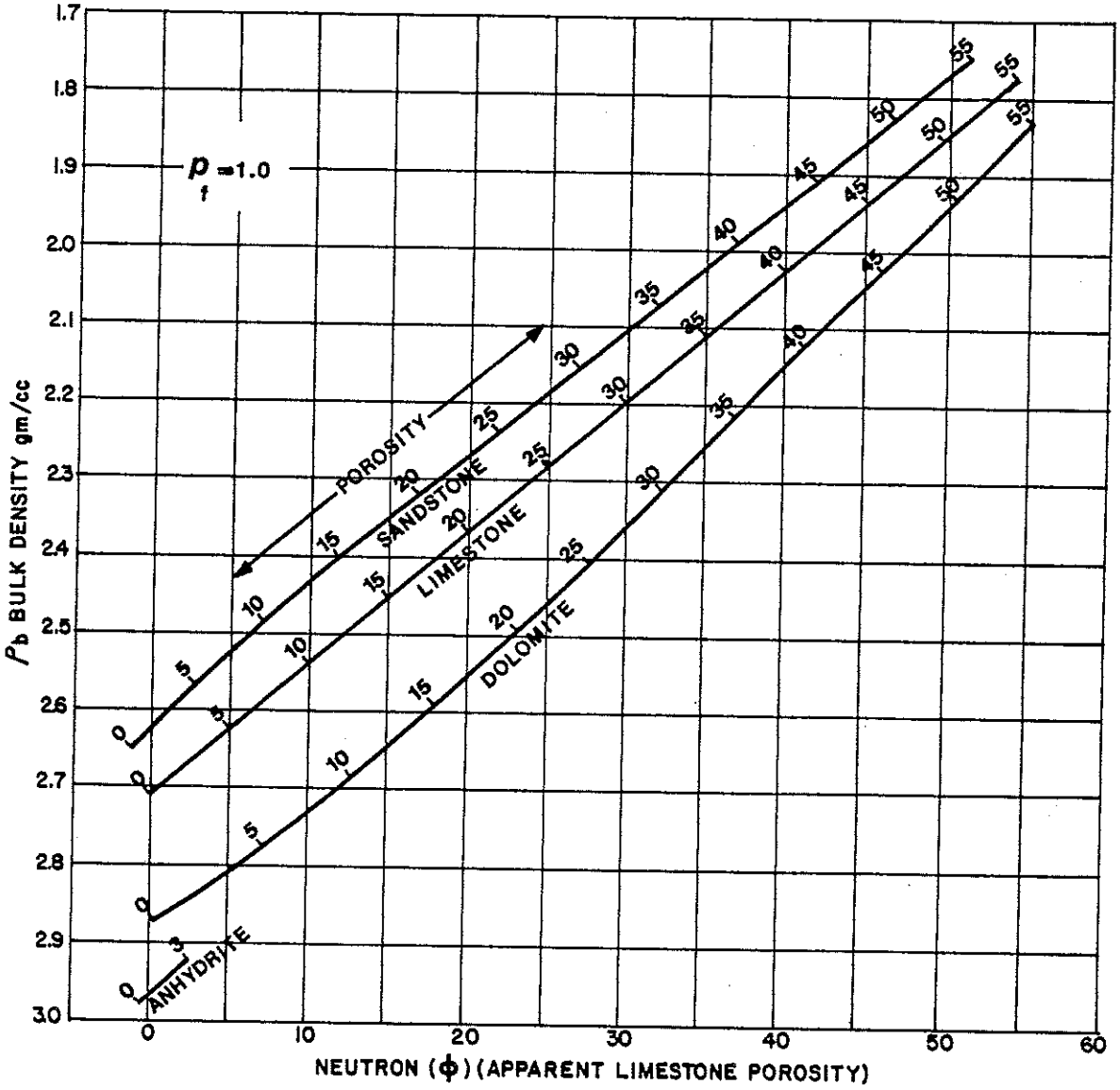
M and N Mineral Cross Plot

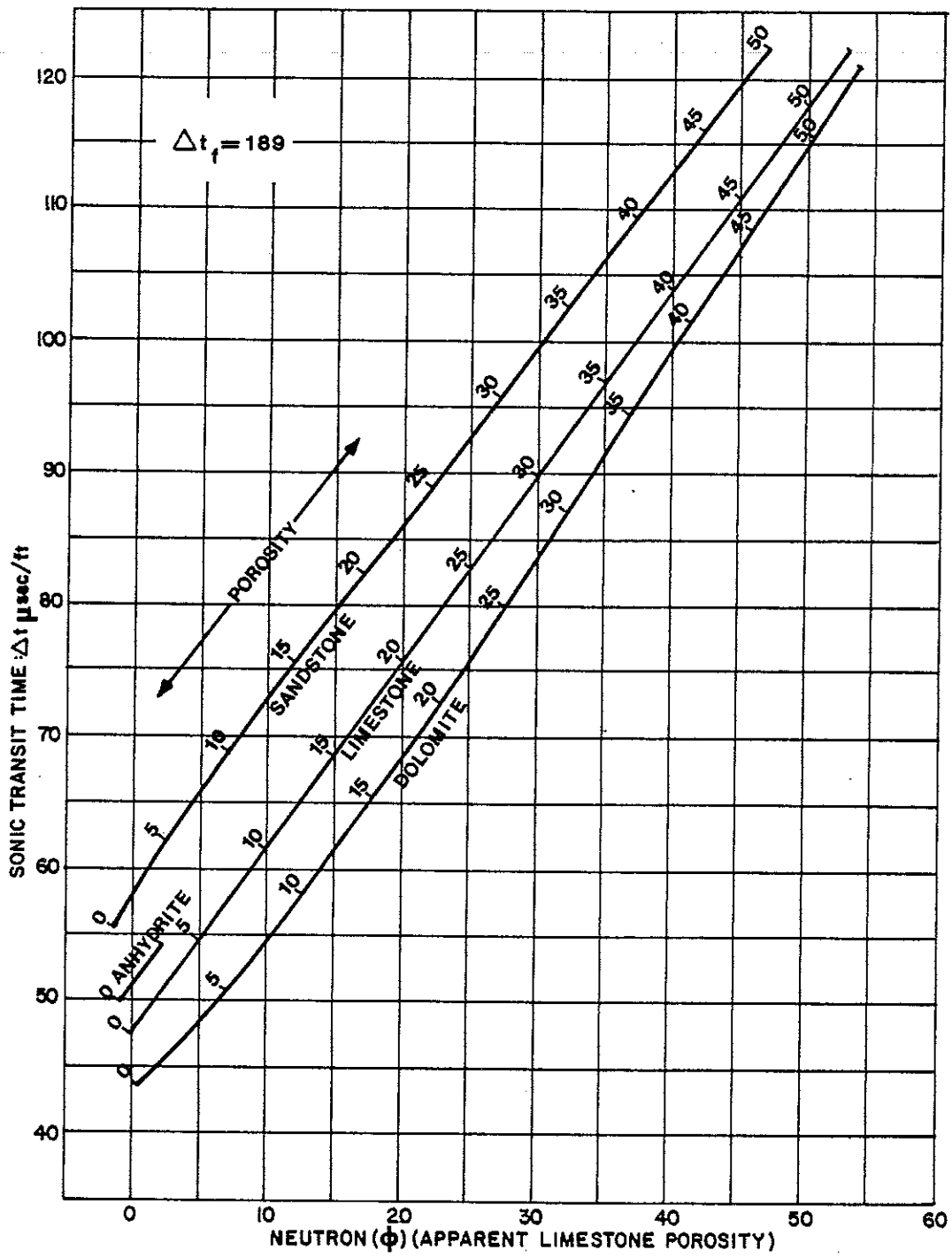
Resistivity Porosity Cross Plots (RPCP) for Carbonates:

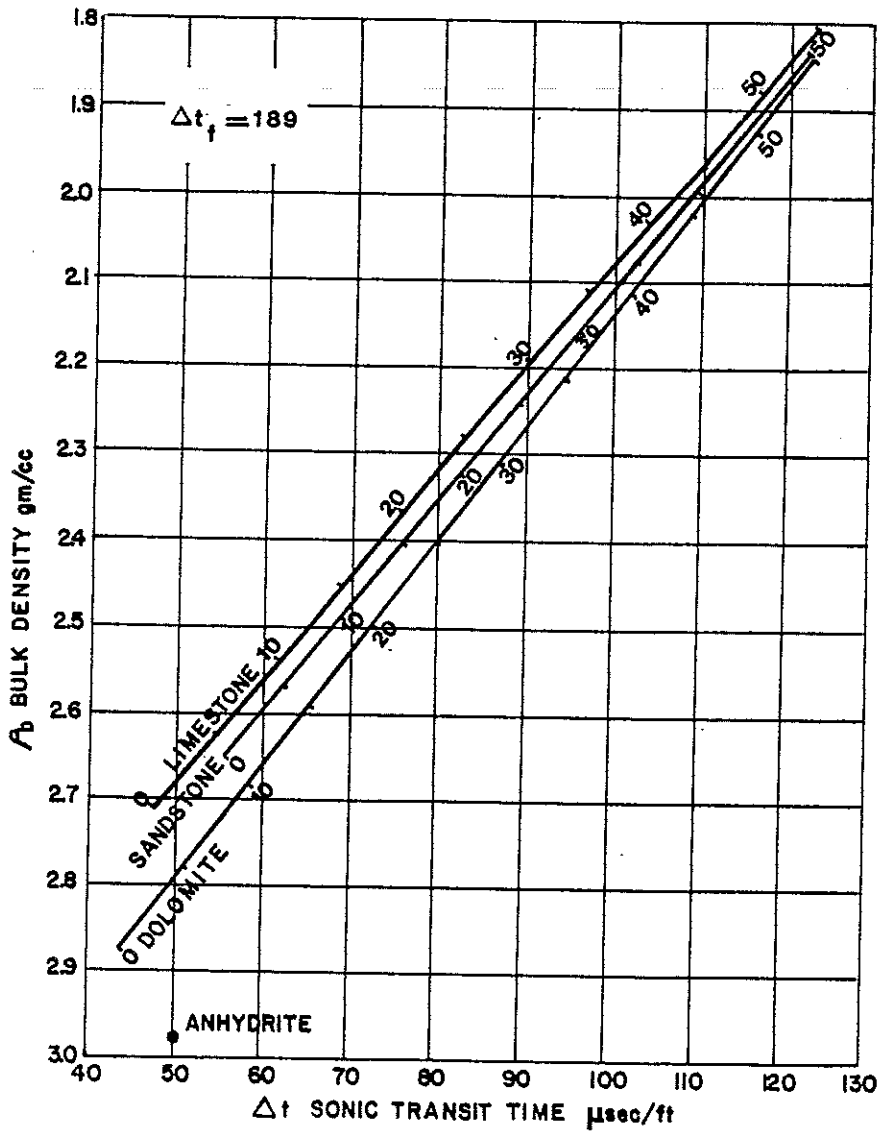
- m = 1.6, a = 1
- m = 1.8, a = 1
- m = 2.0, a = 1
- m = 2.2, a = 1

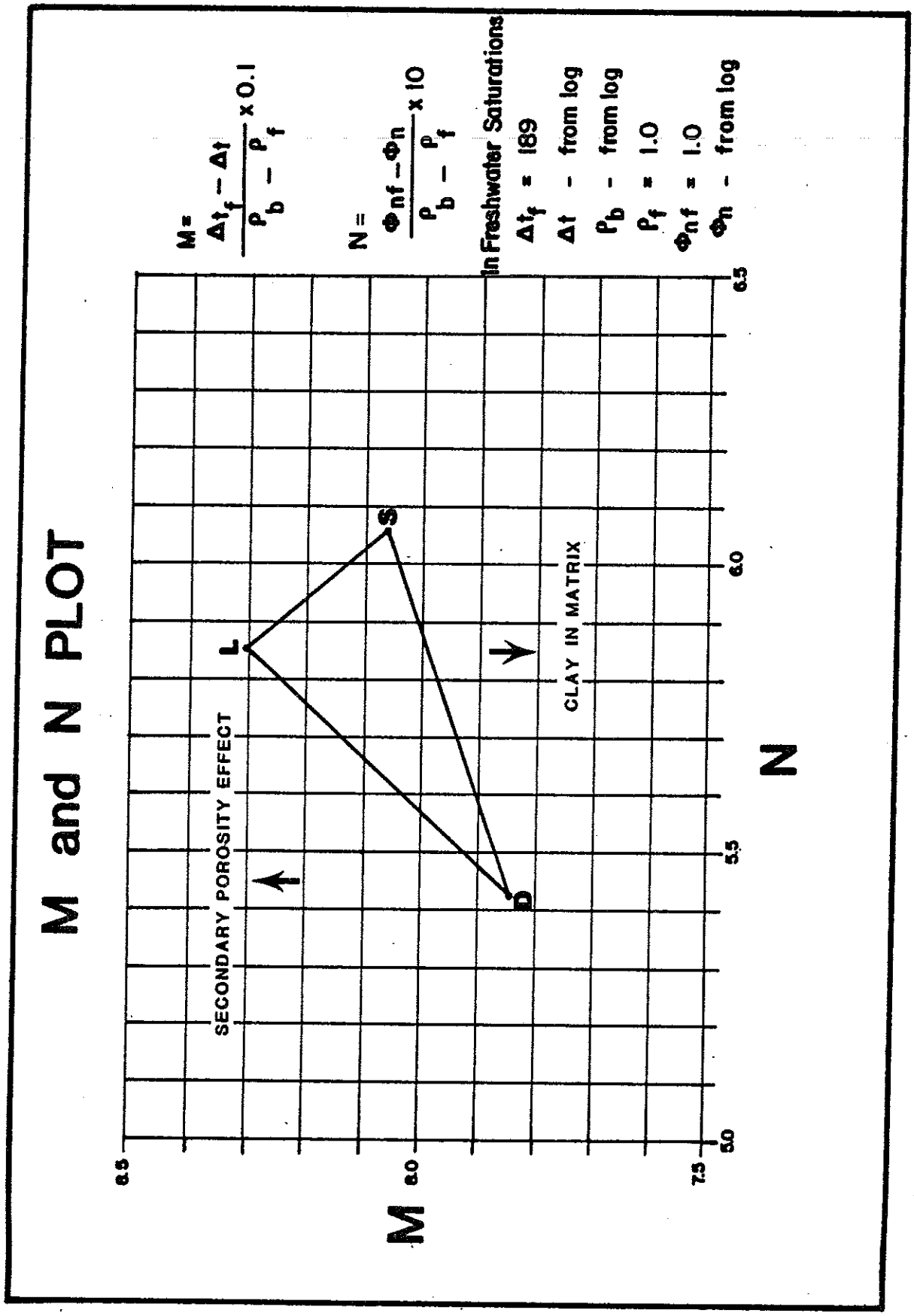
Unconsolidated (Humble Formula)

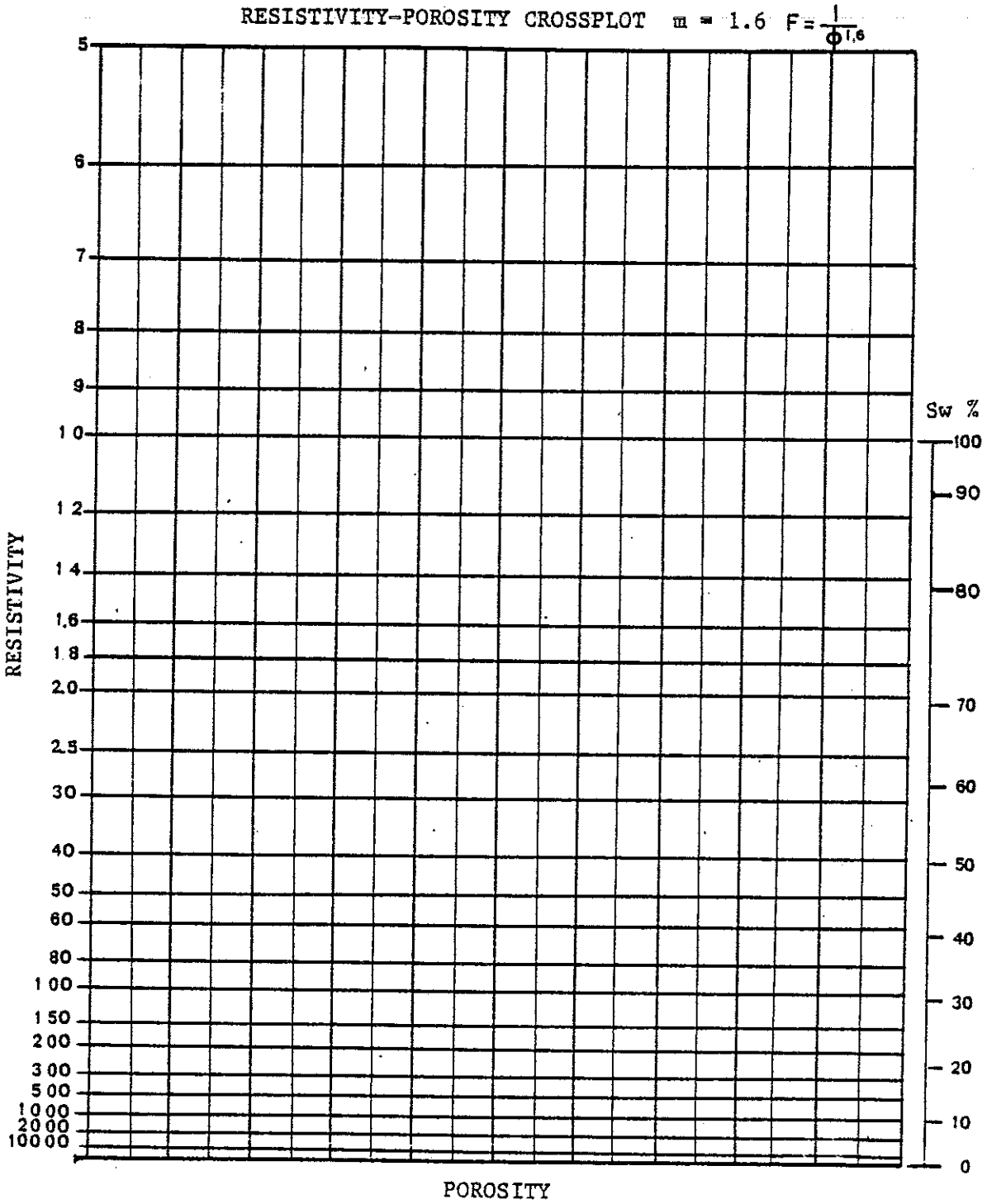
- m = 2.15, a = 0.62

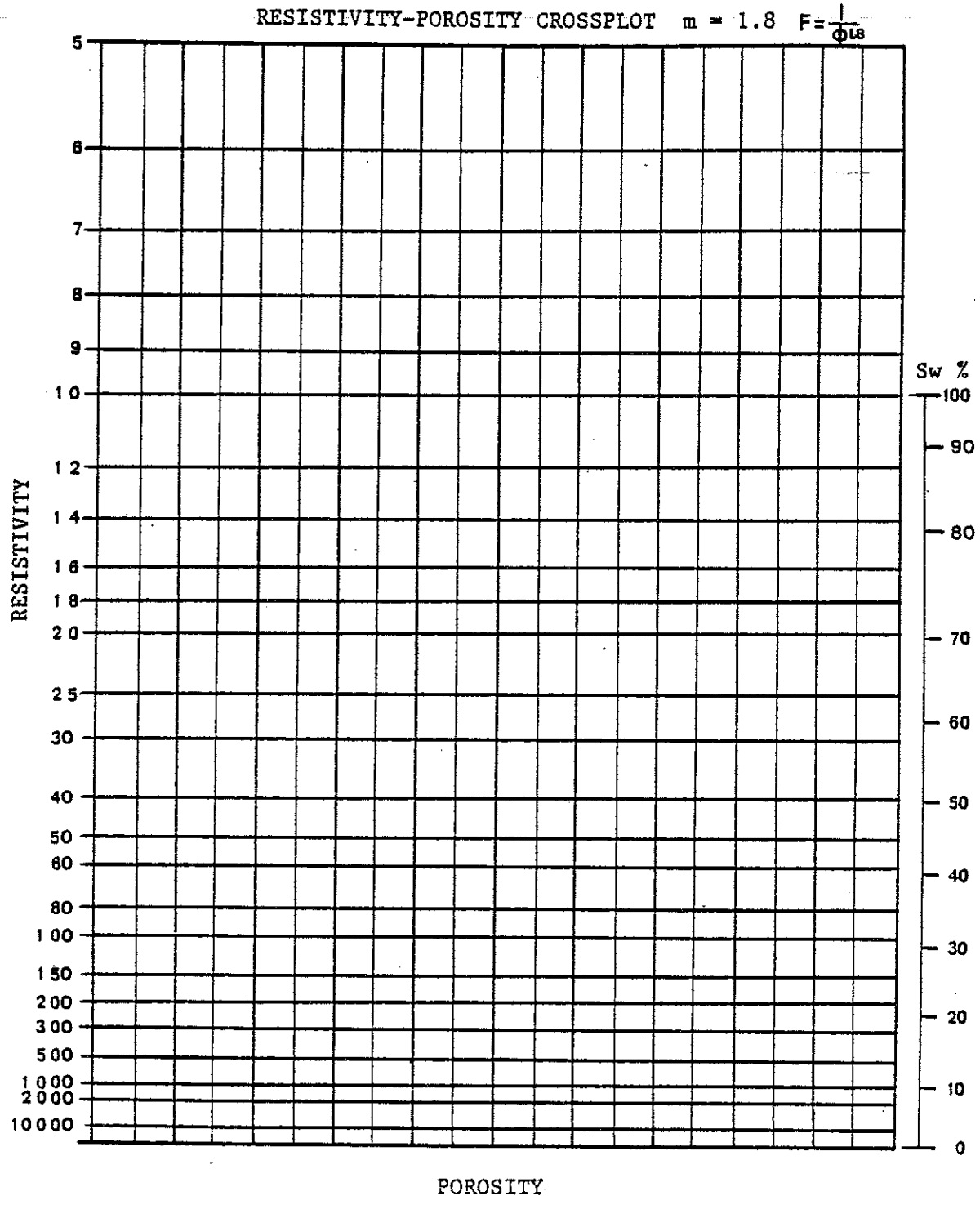

ρ_f =1.0
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ANHYDRITE
ρ_b BULK DENSITY gm/cc
NEUTRON (ϕ) (APPARENT LIMESTONE POROSITY)
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
0
10
20
30
40
50
60

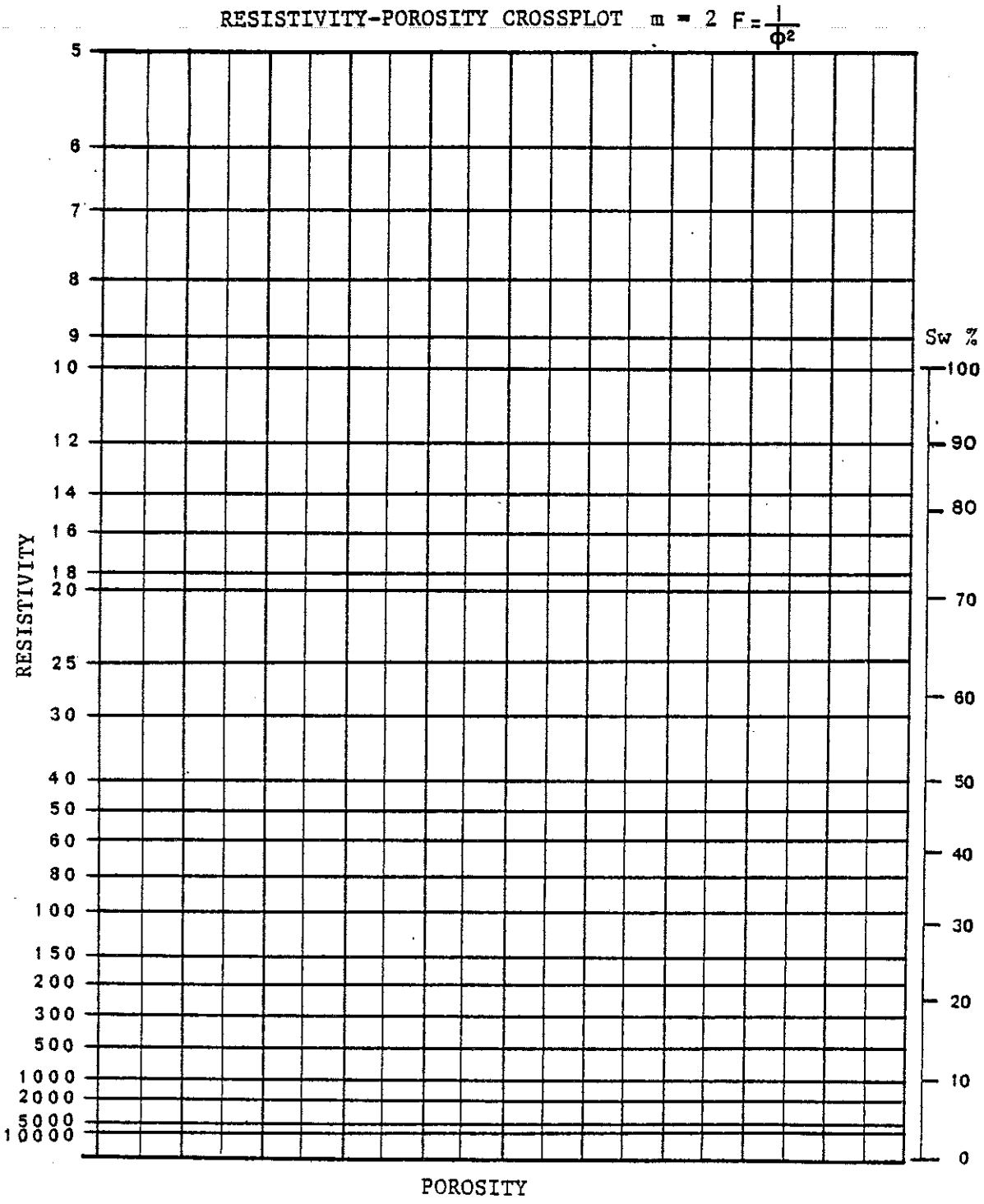

$\Delta t_f = 189$
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ANHYDRITE
SONIC TRANSIT TIME: Δt μsec/ft
NEUTRON (Φ) (APPARENT LIMESTONE POROSITY)
120
110
100
90
80
70
60
50
40
0
10
20
30
40
50
60

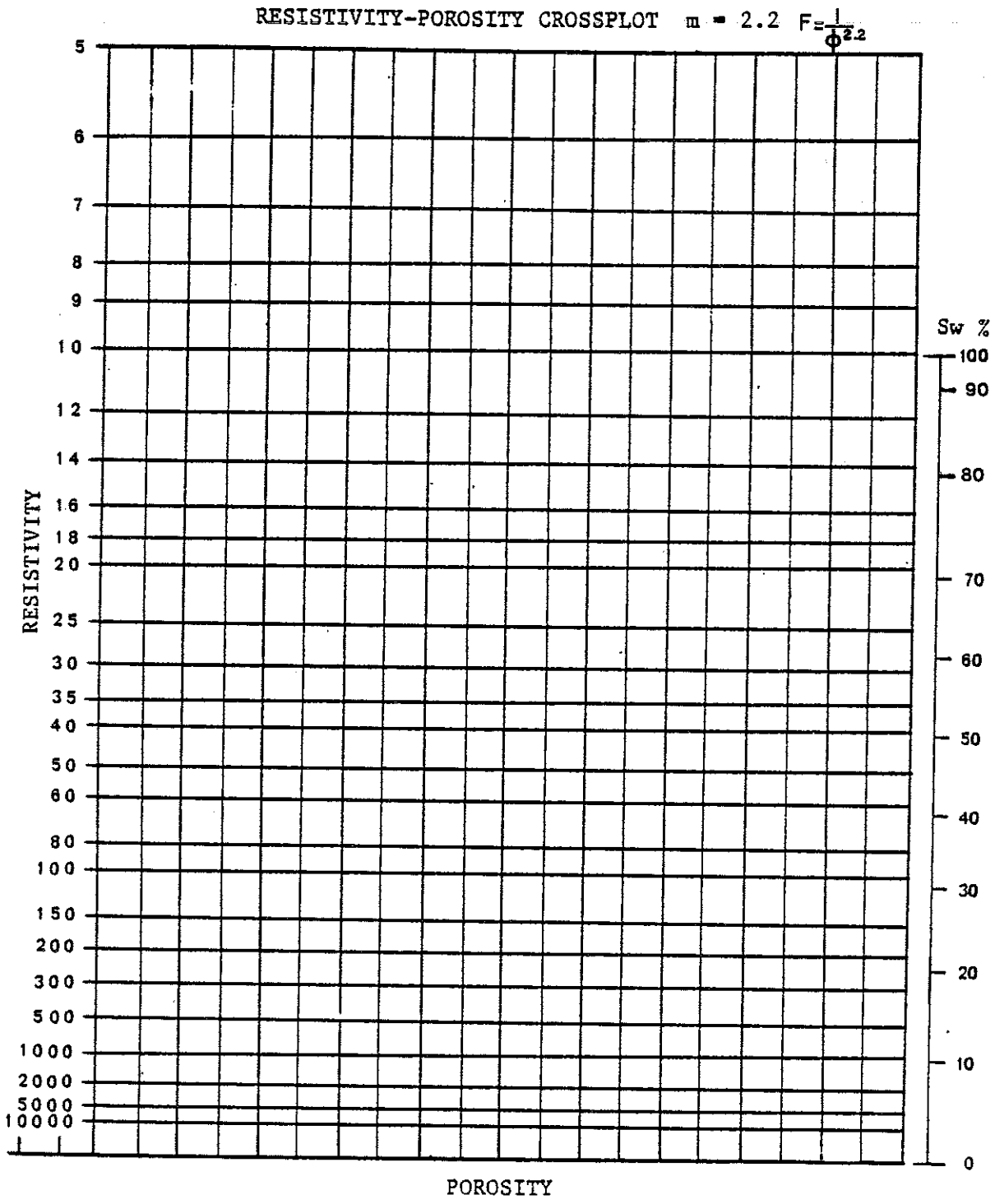

$\Delta t_f = 189$
LIMESTONE
SANDSTONE
DOLOMITE
ANHYDRITE
0
10
20
30
40
50
150
ρ_b BULK DENSITY gm/cc
Δt SONIC TRANSIT TIME μsec/ft
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
40
50
60
70
80
90
100
110
120
130

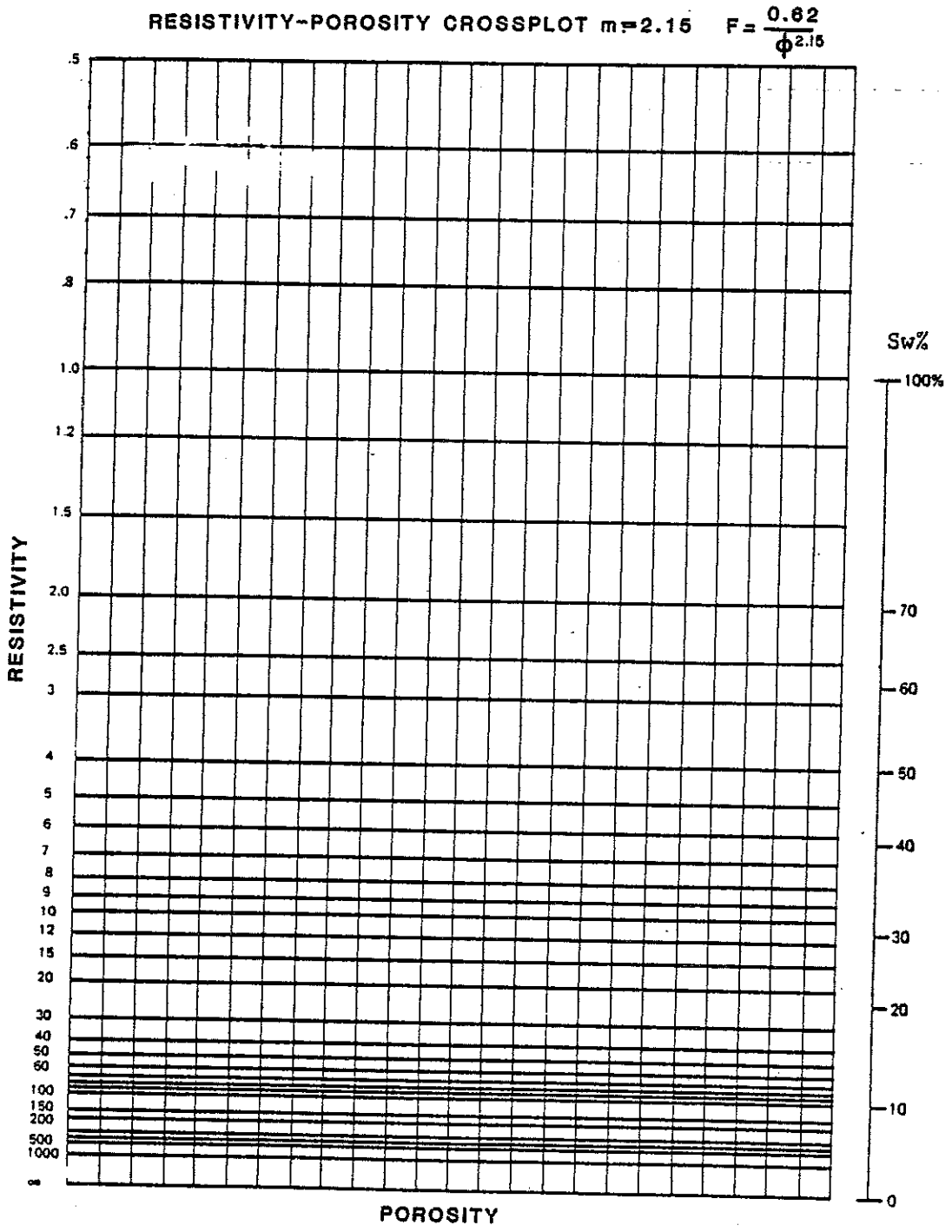

M and N PLOT
M = $\frac{\Delta t_f - \Delta t}{\rho_b - \rho_f} \times 0.1$
N = $\frac{\phi_{nf} - \phi_n}{\rho_b - \rho_f} \times 10$
In Freshwater Saturations
Δt_f = 189
Δt - from log
ρ_b - from log
ρ_f = 1.0
ϕ_{nf} = 1.0
ϕ_n - from log
SECONDARY POROSITY EFFECT
CLAY IN MATRIX
L
S
D
M
N
8.5
8.0
7.5
6.5
6.0
5.5
5.0


RESISTIVITY-POROSITY CROSSPLOT m = 1.6 $F = \frac{1}{\Phi^{1.6}}$
RESISTIVITY
5
6
7
8
9
10
12
14
1.6
1.8
2.0
2.5
30
40
50
60
80
100
150
200
300
500
1000
2000
10000
POROSITY
Sw %
100
90
80
70
60
50
40
30
20
10
0


RESISTIVITY-POROSITY CROSSPLOT m = 1.8 F=1/φ^1.8
RESISTIVITY
5
6
7
8
9
10
12
14
16
18
20
25
30
40
50
60
80
100
150
200
300
500
1000
2000
10000
POROSITY
Sw %
100
90
80
70
60
50
40
30
20
10
0


RESISTIVITY-POROSITY CROSSPLOT m = 2 F = 1/Φ²
RESISTIVITY
5
6
7
8
9
10
12
14
16
18
20
25
30
40
50
60
80
100
150
200
300
500
1000
2000
5000
10000
Sw %
100
90
80
70
60
50
40
30
20
10
0
POROSITY


RESISTIVITY-POROSITY CROSSPLOT m = 2.2 $F=\frac{1}{\Phi^{2.2}}$
RESISTIVITY
5
6
7
8
9
10
12
14
16
18
20
25
30
35
40
50
60
80
100
150
200
300
500
1000
2000
5000
10000
POROSITY
Sw %
100
90
80
70
60
50
40
30
20
10
0


RESISTIVITY-POROSITY CROSSPLOT m=2.15 F = 0.62 / φ^2.15
RESISTIVITY
.5
.6
.7
.8
1.0
1.2
1.5
2.0
2.5
3
4
5
6
7
8
9
10
12
15
20
30
40
50
60
100
150
200
500
1000
∞
POROSITY
Sw%
100%
70
60
50
40
30
20
10
0

APPENDIX O

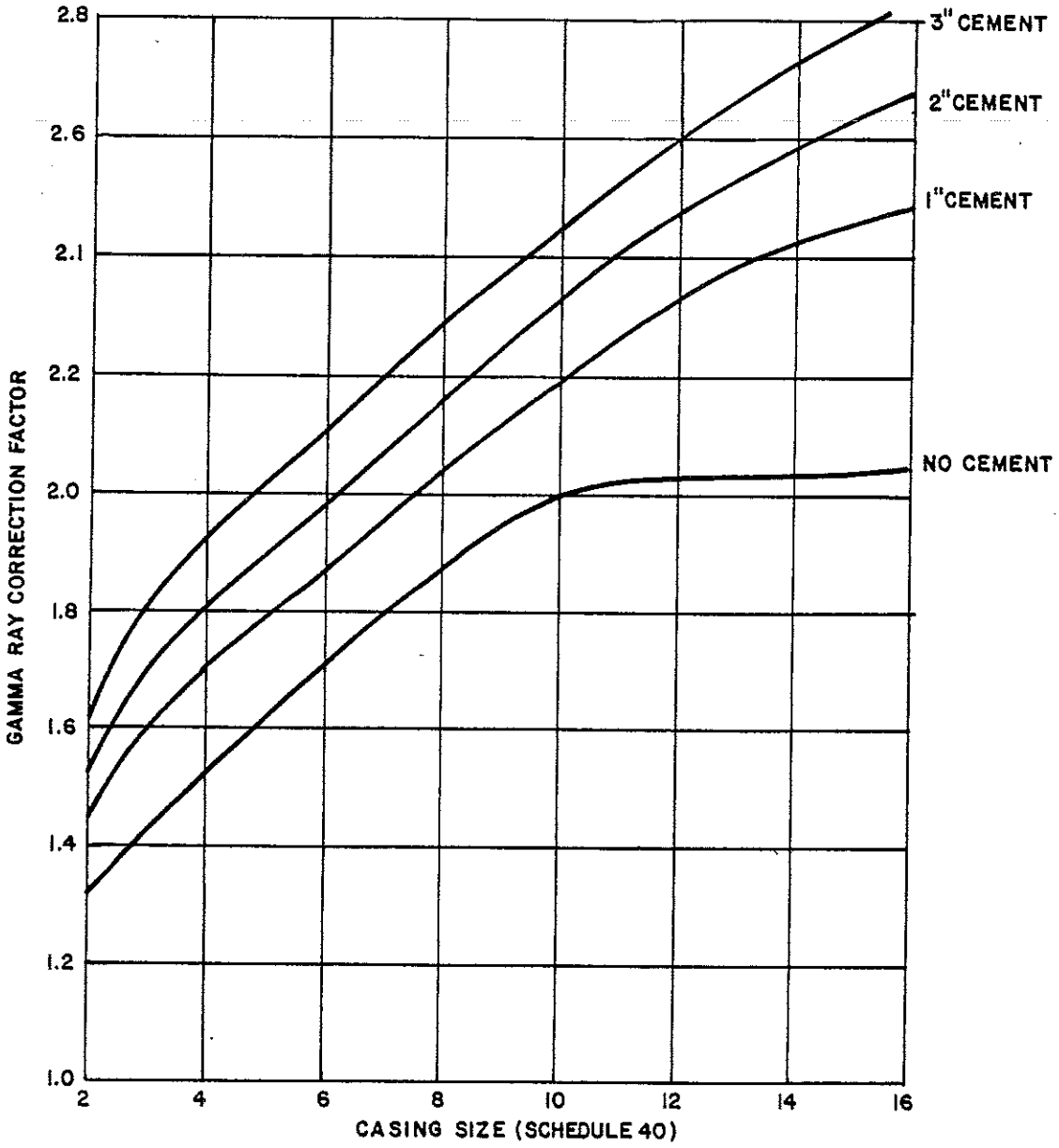
CORRECTION FACTORS AND CONVERSION CHARTS FOR PROBES USED IN RESEARCH

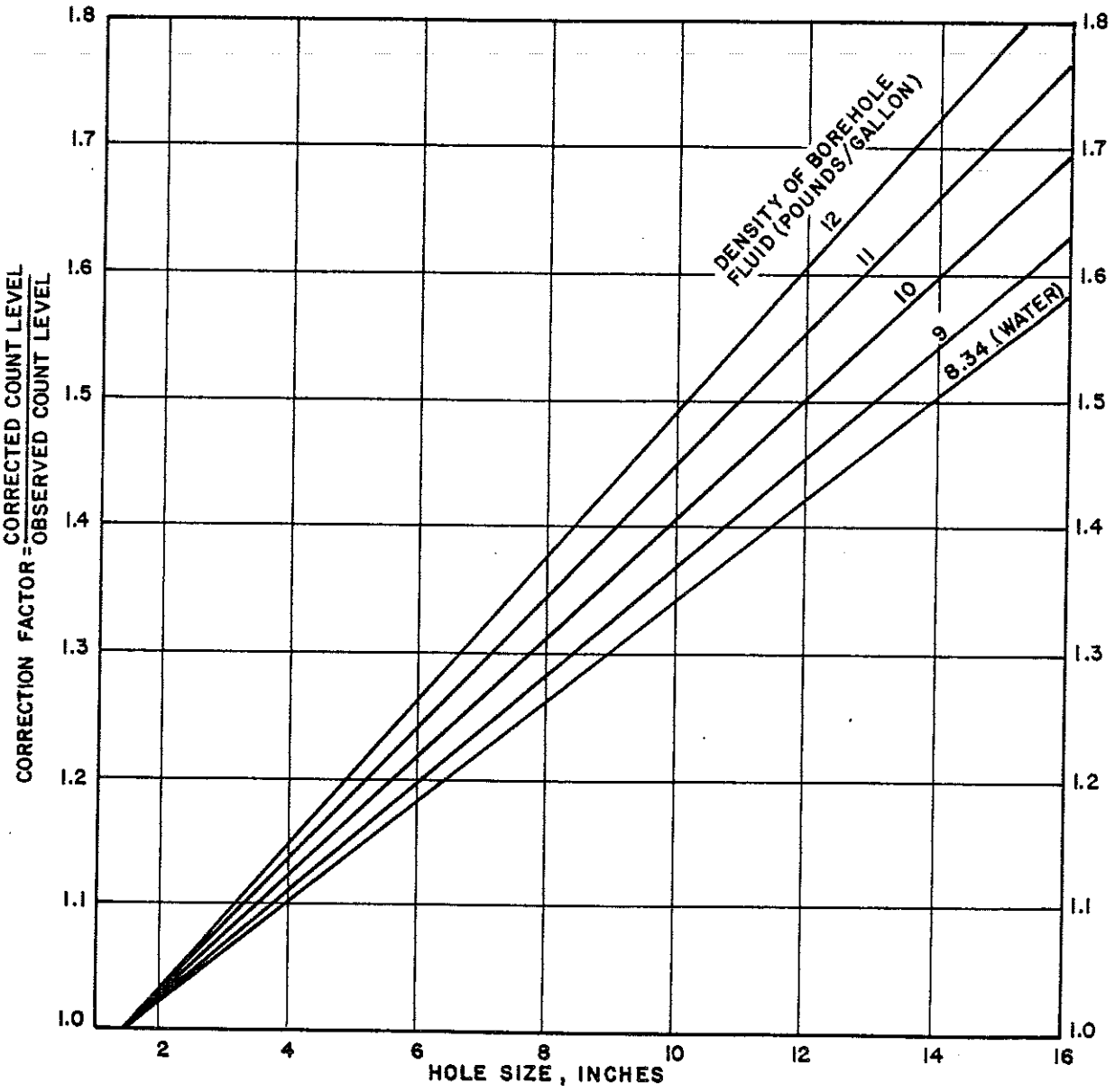
Gamma correction factor for casing and cement thickness

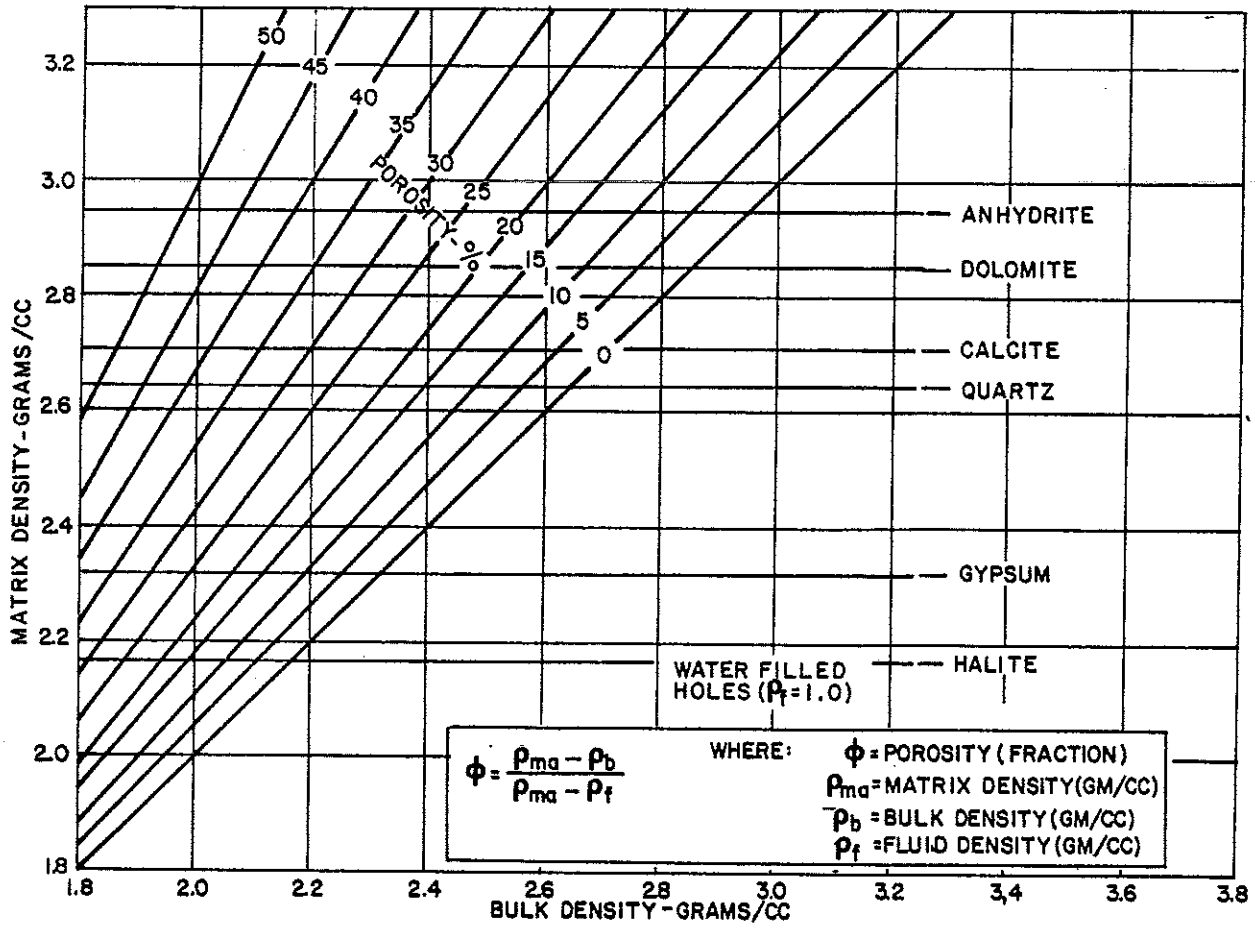
Gamma correction factor for hole size

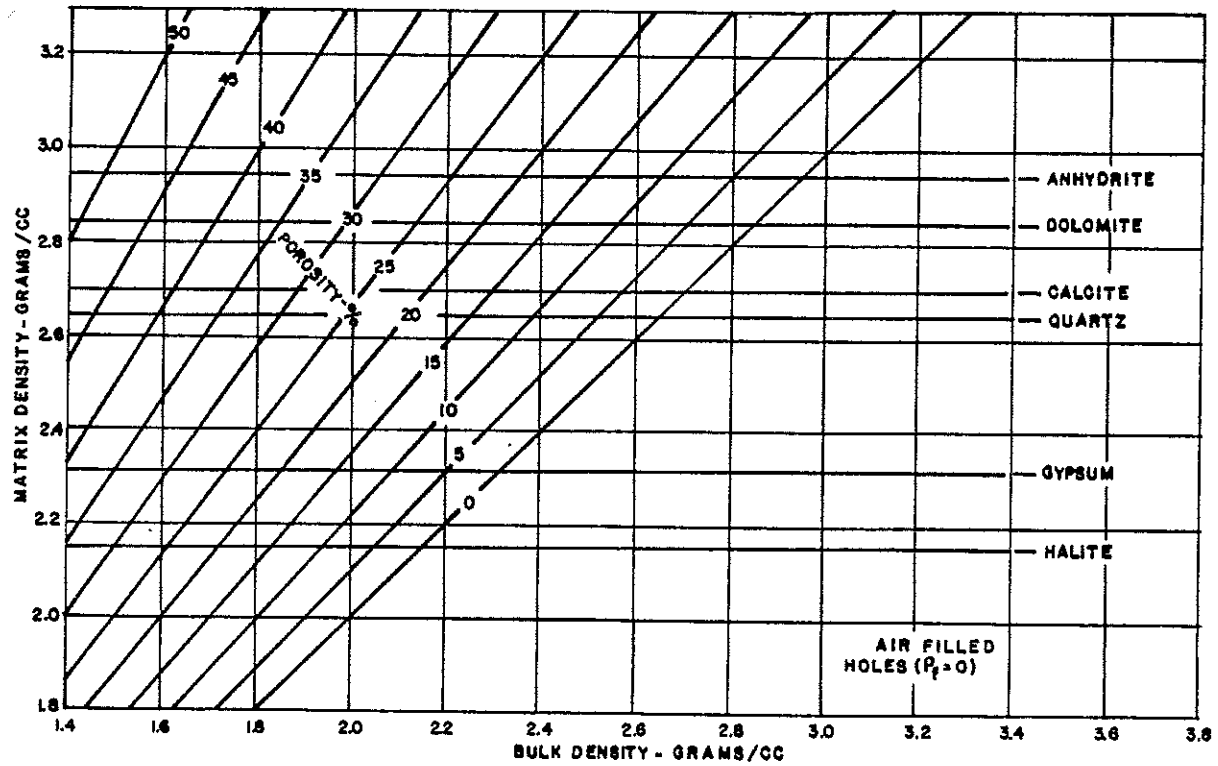
Porosity from bulk density in air and water filled holes

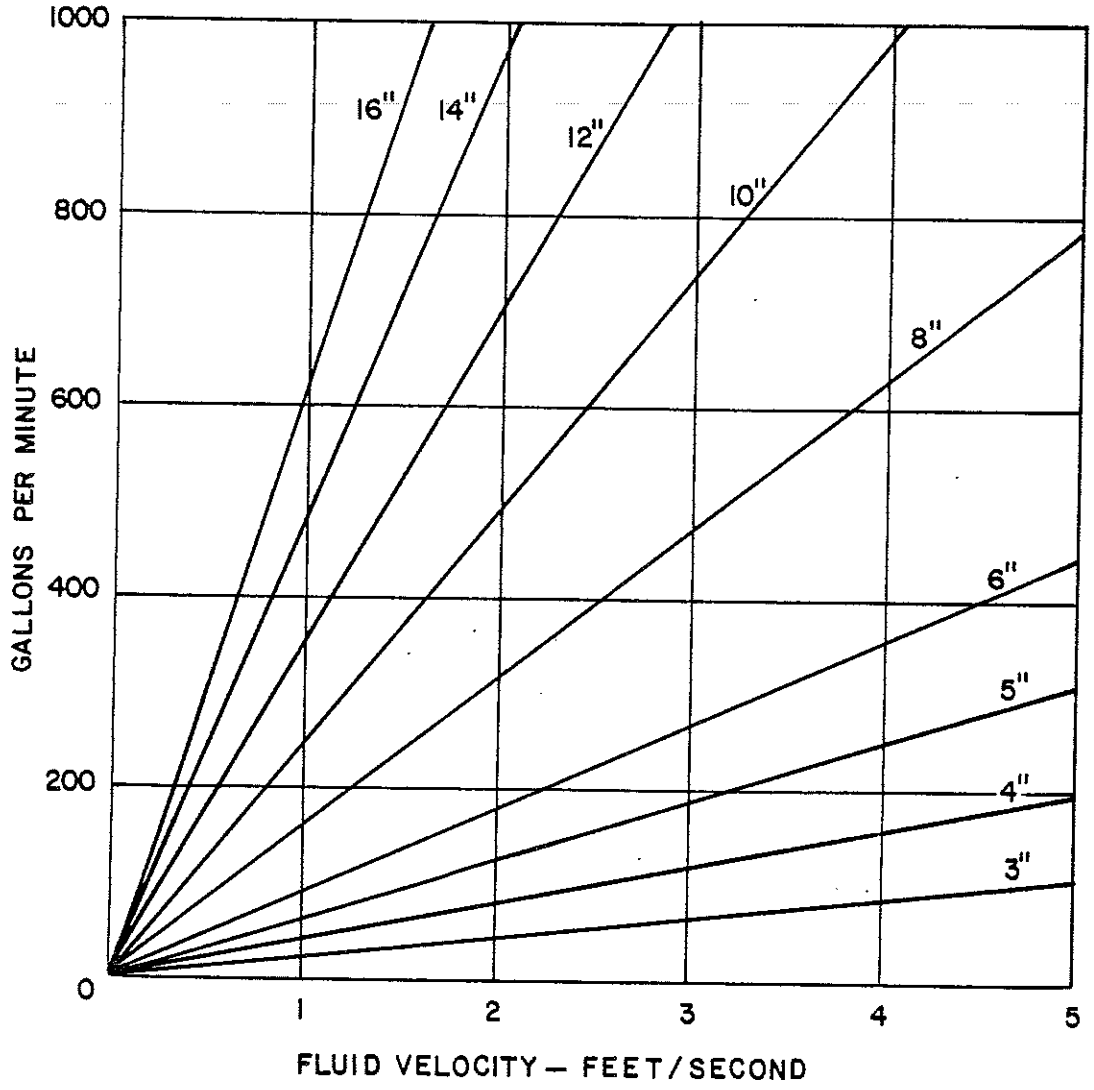
Flow, gallons per minute vs. fluid velocity


2.8
2.6
2.1
2.2
2.0
1.8
1.6
1.4
1.2
1.0
GAMMA RAY CORRECTION FACTOR
2
4
6
8
10
12
14
16
CASING SIZE (SCHEDULE 40)
3" CEMENT
2"CEMENT
1"CEMENT
NO CEMENT


CORRECTION FACTOR = CORRECTED COUNT LEVEL / OBSERVED COUNT LEVEL
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
2
4
6
8
10
12
14
16
HOLE SIZE, INCHES
DENSITY OF BOREHOLE FLUID (POUNDS/GALLON)
12
11
10
9
8.34 (WATER)


MATRIX DENSITY - GRAMS/CC
BULK DENSITY - GRAMS/CC
POROSITY - %
50
45
40
35
30
25
20
15
10
5
0
ANHYDRITE
DOLOMITE
CALCITE
QUARTZ
GYPSUM
HALITE
WATER FILLED HOLES (ρ_f = 1.0)
$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$
WHERE: ϕ = POROSITY (FRACTION)
ρ_{ma} = MATRIX DENSITY (GM/CC)
ρ_b = BULK DENSITY (GM/CC)
ρ_f = FLUID DENSITY (GM/CC)


MATRIX DENSITY - GRAMS/CC
BULK DENSITY - GRAMS/CC
POROSITY - %
50
45
40
35
30
25
20
15
10
5
0
ANHYDRITE
DOLOMITE
CALCITE
QUARTZ
GYPSUM
HALITE
AIR FILLED HOLES (ρ_f = 0)


1000
800
600
400
200
0
GALLONS PER MINUTE
16"
14"
12"
10"
8"
6"
5"
4"
3"
1
2
3
4
5
FLUID VELOCITY — FEET/SECOND

APPENDIX P

WELLS WITH CUTTINGS AND CORES USED IN THIS STUDY

Well Number[1] NWF/BOG, W-	Well Name	County	Location	Elev.[2]	Csg.[3]	Depth[4]	Geo. Info.[5]	Logs Run[6]	Other[7]
AA-28 14641	Devils Mill Hop.	Alachua	T9S,R19E,15	178	0	132	Core	G	X,GS,GL,DL
ES-58 13559	Schmidt #3	Escambia	T4N,R31W,20	--	0	202	Core	G	X,GS,GL,DL
FK-9	St. George Is.	Franklin	T9S,R6W,22	3	93	912	Cut	G,N,D,E,C,R_f	WQL,GL,DL
FK-10 7574	St. George Is.	Franklin	T9S,R6W,22	3	93	918	Core	G,N,D,C,E,R_f	X,GS,GL,DL
FK-16 14781	Tates Hell #1	Franklin	T7S,R7W,17	--	--	297	Core	G	X,GS,GL,DL
FK-17 14799	Tates Hell #2	Franklin	T7S,R5W,18	12	35	140	Core	G,N,D,E	X,GS,GL,DL
FK-18 14844	Tates Hell #3	Franklin	T6S,R5W,13	20	45	370	Core	G,N,D,C	X,GS,GL,DL
FK-20 14890	Tates Hell #4	Franklin	T6S,R6W,09	11	90	465	Core	G,N,D,C,E	X,GS,GL,DL
GA-39	NWFWMD-Core	Gadsden	T1N,R2W,06	201	42	470	Core	G,N,D,E,C	X,GS,DL,GL
GF-12	Fico Farms-West	Gulf	T5S,R11W,09	22	324	744	Cut	G,N,D,V_f,C,E,R_f	WQL,GL
GF-18	Fla. Power Corp.	Gulf	T7S,R10W,20	15	210	610	Cut	G,N,D,V_f,C,E,R_f	GL,DL
GF-26 14719	Indian Swamp #1	Gulf	T7S,R9W,12	10	80	278	Core	G,N,D,C	X,GS,GL,DL
GF-27 14746	Depot Creek	Gulf	T8S,R10W,26	12	140	404	Core	G,N,D,E	X,GS,GL,DL
LB-16 14906	New River #1	Liberty	T5S,R7W,03	35	100	255	Core	G,N,D,C,E	X,GS,GL,DL

LB-18	14969	Gregory Mill	Liberty	T3S,R8W,32	42	130	500	Core	G,N,D	X,GS,GL,DL
LE-7		U.S. Gypsum	Lee	T43S,R26E,06	26	--	2105	Cut	G,N,V_a,C,E	GL
LK-1	14880	Bay Lake #101	Lake	T23S,R24E,29	--	116	406	Core	G,N,D,C	WQL,GL,DL
LV-1		SWFWMD #134	Levy	T12S,R19E,19	68	70	1173	Cut	G,N,D,E,R_f,C	WQL,GL
OA-41		Docie Bass	Okaloosa	Santa Rosa Is.	3	5200	5490	--	G,N,D,E	DL
PB-1		State Lease #1	Palm Beach	T43S,R39E,08	12	3995	11002	--	G,N,D,E,V_a	
SR-2		Wilbur Weeks	Santa Rosa	T4N,R29W,06	--	84	439	Cut	G,E	GL,DL
SR-15		Midway #2	Santa Rosa	T2S,R26W,20	20	760	1091	Cut	G,N,D,E	GL,WQL,DL
SR-31	13604	Schmidt #9	Santa Rosa	T3N,R28W,21	200	0	201	Core	G	X,GS,GL,DL
WL-26		Camp Rucker	Walton	T1S,R21W,24	20	201	880	Cut	G,N,D,E,C,T	GL,WQL,DL
WL-27		331 and 98	Walton	T2S,R19W,30	15	220	683	Cut	G,N,D,E,C,T	GL,DL,WQL

[1]NWF -- Northwest Florida Water Management District log number, first two letters are county abbreviations, B.O.G. -- Florida Bureau of Geology well file number

[2]Elev. -- Elevation in feet above mean sea level

[3]Casing -- Casing depth in feet below land surface

[4]Depth -- Depth in feet below land surface

[5]Geo. Info. -- Type of geologic information available; Cut = cuttings, Core; D.L.= drillers log; G.L. = geologist log, based on cuttings or core

[6]Logs Run -- Geophysical logs available at Northwest Florida Water Management District; G = natural gamma; N = neutron; D = density; E = electric logs; V_a = acostic velocity; C = caliper; T = temperature; V_f = fluid velocity

[7]Other -- Other types of information available; WQL = water quality; X = X ray; GS = gamma spectrometry on core

Literature Cited

Adams, John A. S., 1970, Gamma-ray spectrometry of rocks, methods in geochemistry and geophysics, No. 10, Elsevier, Amsterdam, p. 295.

Alger, R. P., 1966, Interpretation of electric logs in fresh-water wells in unconsolidated formations: Soc. Prof. Well Log Analysts, 7th Ann. Logging Symposium, Houston, TX., Trans., pp. CC1-CC25.

_____, 1967, "Aquifer evaluation with radioisotope well logs", Amer. Water Resources Assn. Proc. Ser. No. 4, pp. 319-328.

_____, 1971, "Geophysics and ground water, an introduction-part I, applied use of geophysics-part II, Water Well Journ., Vol. 25, No. 7; Vol. 25, No. 8, p. 35.

Allen, L. S., Caldwell, R. L., and Mills, W. R., 1965, Borehole models for nuclear logging: Soc. Petroleum Engineers Jour., v. 5, no. 2, pp. 109-112.

American Petroleum Institute, 1974, Recommended Practice for Standard Calibration and Format for Nuclear Logs, A.P.I., R. P. 33, Third Edition Dallas, Texas, p. 13.

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Am. Inst. Mining Metall. Engineers Trans., v. 146, pp. 54-62.

_____1952, Classification of Carbonate Reservoir Rocks and Petrophysical Considerations, AAPG Bull. V. 36, No. 2, pp. 278-298.

Asquith, George B., 1978, Log Analysis by Microcomputer, The Petroleum Publishing Co., Tulsa, Oklahoma, p. 105.

Atkins, E. R., Jr., 1961, "Techniques of electric log interpretation", Jour. Petrol. Tech., Vol. 13, No. 2, February, pp. 118-123, 46 refs.

Barraclough, Jack T., 1962, Ground Water Resources of Seminole County, Florida, Florida Bureau of Geology, Report of Inv. No. 27, p. 91.

Bathurst, Robin G. C., 1971, Carbonate sediments and their diagenesis in developments in sedimentology, V. 12, Elsevier Publishing Co., New York, p. 620.

Beaven, T. R., and Meyer, F. W., 1978, Record of Wells in the Floridan Aquifer in Dade and Monroe Counties, Florida, U. S. Geol. Surv. Open File Report 78-881, p. 30.

Belknap, W. B., Dewan, J. T., Kirkpatrick, C. V., Mott, W. E., Pearson, A. J., and Robson, W. R., 1959, API Calibration Facility for Nuclear Logs, Drilling, and Production Practice: Am. Petroleum Inst., pp. 289-316.

Bennett, G. D., and Patten, E. P., Jr., 1960, Borehole geophysical methods for analyzing specific capacity of multiaquifer wells: U. S. Geol. Survey Water-Supply Paper 1536-A, pp. 1-25.

Bleakley, W. B., et al., 1965, "The sidewall epithermal neutron porosity log", Soc. Petrol Eng., A.I.M.E., Preprint No. 1180, p. 20.

Bloom, Jonathan, 1982, A Mineralogical Model of the Floridan Aquifer in the Southwest Florida Water Management District, Abstracts, Second Symposium on Florida, Northwest Florida Water Management District Public Information Bulletin 82-3, Havana, Florida, p. 31.

Boggess, D. H., 1974, Saline Ground-Water Resources of Lee County, Florida, U. S. Geol. Surv. Open File Report 74-247, p. 61.

Brannon, H. R., Jr., and Osaba, J. S., 1956, Spectral gamma-ray logging: Am. Inst. Mining Metall. Petroleum Engineers Trans., v. 207, pp. 30-35.

Bredehoeft, J. D., 1964, Variation of permeability in the Tensleep Sandstone in the Bighorn Basin, Wyoming, as interpreted from core analyses and geophysical logs: U. S. Geol. Survey Prof. Paper 501-D, pp. D166-D170.

Brown, Donald L., 1970, Techniques for Water Quality of Water Interpretations from Calibrated Geophysical Logs, Atlantic Coastal Area, Ground Water Vol. 8 #5, pp. 25-38.

Brown, Michael P., and Anderson, Steve, 1979, South Florida Water Management District, Natural Gamma-Ray/Neutron Porosity Logging, Memorandum Report, 1979, p. 25.

Brown, Michael P., Hynes, Sharon D., and Wedderburn, Leslie A., 1981, Guidebook to the South Florida Water Management District's geophysical logging and digitized data processing techniques, Technical Memorandum, May 1981, South Florida Water Management District, West Palm Beach, Florida, p. 222.

Bunker, C. M., and Bradley, W. A., 1961, Measurement of bulk density of drill core by gamma-ray absorption, in Short papers in the geologic and hydrologic sciences: U. S. Geol. Survey Prof. Paper 424-B, pp. B310-B313.

Bunker, C. M., and Bush, C. A., 1967, A comparison of potassium analyses by gamma-ray spectrometry and other techniques: U. S. Geol. Survey Prof. Paper 575-B, pp. B164-B169.

Burke, J. A., Schmidt, A. W., and Campbell, R. L., 1969, The litho-porosity cross plot: Log Analyst, V. 10, No. 3, pp. 25-43.

Caldwell, R. L., 1962, Gamma-ray spectroscopy in well logging: Cracow, Poland, Nuclear Geophysicists Conf., 1962, v. 1, pp. 165-199.

Causey, L. V., and Leve, G. W., 1976, Thickness of Potable Water Zone in the Floridan Aquifer, Florida Bureau of Geology, Map Series No. 74, 1 sheet.

Chilingar, George V., Bissell, Harold J., and Fairbridge, Rhodes W., 1967, Carbonate rocks in developments in sedimentology, V. 9 a & b, Elsevier Publishing Co., New York, p. 471.

Chilingar, George V.,, Manor, R. W., Rieke, H. H., 1972, Oil and Gas Production from Carbonate Rocks, Elseiver Publ. Co., Inc., New York, p. 397.

Chombart, L. G., 1960, Well logs in Carbonate Reservoirs, Geophysics, Vol. 25, No. 4, pp. 779-853.

Choquette, P. W., and Pray, L. C., 1970, Geologic Nomenclature and Classification of Porosity in Sedimentory Carbonates, AAPG V. 54, No. 2, pp. 207-250.

Cowart, James B., 1974, U^{234}/U^{238} in the Carrizo Sandstone Aquifer of South Texas, unpublished Ph. D. dissertation, Florida State University, p. 80.

Cregeen, D. J., and Moir, H., 1961, Evaluation of Limestone Formation characteristics from well logs, Journ. Petrol. Tech., Vol. 12, No. 11, November, pp. 1087-1092, 4 figs., 3 tabs. 4 refs.

Croft, M. G., 1971, A method of calculating permeability from electric logs, in Geological Survey research, 1971: U. S. Geol. Survey Prof. Paper 750-B, pp. B265-B269.

Dabous, A. A. A., 1981, Mineralogy, Geochemistry and Radioactivity of Some Egyptian Phosphorite Deposits, unpublished Ph. D. dissertation, Geology Department, Florida State University, pp. 36-40.

Desai, K. P., 1951, The laterolog, a new resistivity logging method with electrodes using an automatic focusing system: Am. Inst. Mining Metall. Engineers Trans., v. 192, pp. 305-316.

Desai, K. P., and Moore, E. J., 1969, Equivalent NaCl determiniation from ionic concentrations: Log Analyst, v. 10, no. 3, pp. 12-21.

Dresser Atlas, 1975, Log Interpretation Fundamentals, Dresser Industries, Inc., Houston, Texas, p. 108.

Duerr, A. Dan, 1975, Hydrological Data from Wells in Southwestern Hillsborough County, Florida, U. S. Geol. Surv., Open File Report 74-031, p. 53.

Evans, H. B., 1965, GRAPE-A device for continusous determination of material density and porosity: Soc. Prof. Well Log Analyst, 6th Ann. Logging Symposium, Dallas, Tex., May 1965, Trans., v. 2, pp. B1-B25.

Fairchild, Roy W., 1972, The Shallow-Aquifer System in Duval County, Florida, Florida Bureau of Geology, Report of Inv. No. 59, p. 50.

Fanning, Kent A., Byrne, Robert H., Breland, Jabe A., II, Betzer, Peter R., Moore, Willard S., Elsinger, Robert J., and Pyle, Thomas E., 1981, Geothermal Springs of the West Florida Continental Shelf: Evidence for Dolomitization and Radionuclide Enrichment, Earth and Planetary Science Letters, Vol. 52, pp. 345-354.

Ferronsky, V. I., Danilin, A. I., Dubinchuk, V. T., Goncharov, V. S., Polyakov, V. A., Seletskiy, Ur. B., and Flekser, N. Ya., 1968, Radioisotope investigative methods in Engineering Geology and Hydrogeology (Radioizopnye methody issledovanija v inzhenernoy geologii i gidrogeologii): Moscow, U.S.S.R., Atomizdat.

Fisher, G. H., 1965, The New Formal Statistical Tables, Table X, University of London Press, London.

Franks, Bernard J., 1982, Principal Aquifers in Florida, U. S. Geological Survey, Water Resources Investigations Open File Report 82-255, Map Series, 4 sheets.

Gaur, R. S., and Singh, Inderjit, 1965, Relation between permeability and gamma-ray intensity for the Oligocene sand of an Indian field, India (Republic): Oil and Natural Gas Comm. Bull. 2, pp. 74-77.

Gearhart Owens Inc., 1975, Formation Evaluation Data Handbook, Fort Worth, Texas.

_____1972, Pulse Logging Systems Instruction Manual, Fort Worth, Texas, p. 165.

Grantham, Rodney G., and Sherwood, C. B., 1968, Chemical Quality of Waters of Broward County, Florida, Florida Bureau of Geology, Report of Inv., No. 51, p. 52.

Guyod, Hubert, 1952, Electrical well logging fundamentals: Houston, Tex., Well Instrument Developing Co., p. 164.

_____1966, Interpretation of electric and gamma ray logs in water wells: Log Analyst, v. 6, no. 5, pp. 29-44.

Guyod, Hubert, and Shane, L. E., 1969, Introduction to geophysical well logging-Acoustical logging, v. 1 of Geophysical well logging: Houston, Tex., Hubert Guyod, p. 256.

Ham, William E., 1962, Classification of carbonate rocks, Memoir I Symposium by American Association of Petroleum Geologists, p. 279.

Hanshaw, Bruce B., Back, William and Deike, Ruth G., 1971, A Geochemical Hypothesis for Dolomitization by Ground Water, Economic Geology, Vol. 66, pp. 710-724.

Harms, J. C., and Choquette, P. W., 1965, Geologic evaluation of a gamma-ray porosity device: Soc. Prof. Well Log Analyst, 6th Ann. Logging Symposium, Dallas, Texas, May 1965, Trans., v. 2, pp. C1-C37.

Hayes, E. C., 1981, The surficial aquifer in East-Central St. Johns County, Florida, U. S. Geol. Surv., Water Res. Inv. 81-14, p. 19.

Hickey, J. J., 1981, Borehole Data-Collection Methods Applicable for the Regional Observation and Monitor Well Program, Southwest Florida Water Management District, U. S. Geological Survey, Water Resources Investigation, 81-57, p. 10.

Hilchie, D. W., 1968, Caliper logging-Theory and Practice: Log Analyst, v. 4, no. 1, pp. 3-12.

_____,1979, Old Electric Log Interpretation, Institute for Energy Development, p. 161.

_____, 1982_A, Advanced well log interpretation, (in press), Douglas W. Hilchie, Inc., Golden Colorado, p. 353.

_____, 1982_B, Applied openhole log interpretation, Douglas W. Hilchie, Inc., Golden Colorado, p. 340.

International Atomic Energy Agency, 1971, Nuclear Well Logging in Hydrology, Tech. Report Series 126.

Jarrett, A. A., 1946, Statistical methods used in the measurement of radioactivity with some useful graphs and nomographs: U. S. Atomic Energy Commission, AECU-262, p. 43.

Jenkins, R. J., 1966, Accuracy of porosity determinations: Log Analyst, v. 7, no. 2, pp. 29-34.

Johns, E. S., Jr., 1966, Tracing fluid movements with a new temperature technique: Fort Worth, Tex., Gearhart-Owens, Inc., Bull. EJ-416, p. 23.

Jones, P. H., and Buford, T. B., 1951, Electric logging applied to groundwater exploration: Geophysics, v. 16, no. 1, pp. 115-139.

Jones, P. H., and Skibitzke, H. E., 1956, Subsurface geophysical methods in ground-water hydrology, in Advances in Geophysics, v. 3: New York, Academic Press, Inc., pp. 241-300.

Keys, W. S., 1967, Aquifer evaluation with radioisotope well logs, Proc. Natl. Sump. Groundwater Hydrol., Am. Water Res. Assoc., San Francisco, pp. 319-328.

_____, 1967, Borehole geophysics as applied to ground water, Mining and Ground Water Geophysics/1967, Geol. Survey Canada, Econ. Geol. Report 26, pp. 598-614, 20 refs.

_____, 1967, The application of radiation logs to ground-water hydrology: Vienna, Austria, Internat. Atomic Energy Agency Symposium on Use of Isotopes in Hydrology, Nov. 14-18, 1966, Proc., pp. 477-488.

_____, 1968, Well Logging in Ground Water Hydrology, Ground Water, Vol. 6, No. 1, January-February, pp. 10-18, 12 refs.

_____, 1969, Well logging in ground water hydrology, Ground Water Vol. 6, No. 1, January-February, p. 9.

_____, 1979, Borehole Geophysics in Igeneous and Metamorphic Rocks, Society of Professional Well Log Analysts 12th Annual Logging Symposium, Proceedings, p. 26.

Keys, W. S., and Boulogne, A. R., 1969, Well logging with californium 252: Soc. Prof, Well Log Analysts, 10th Ann. Logging Symposium, Houston, Texas, May 1969, Trans., pp. P1-P25.

Keys, W. S., and Brown, R. F., 1971, The use of well logging in recharge studies of the Ogallala Formation in west Texas, in Geological Survey reserach, 1971: U. S. Geol. Survey Prof. Paper 750-B, pp. B270-B277.

Keys, W. S., and Brown, R. F., 1978, The Use of Temperature Logs to Trace the Movement of Injected Water, Ground Water V. 16, No. 1, pp. 32-48.

Keys, W. S., and MacCary, L. M., 1971, Application of Borehole Geophysics to Water-Resources Investigations, U. S. Geol. Surv. Tech. Water Resources Inv., Book 2, Chapt. #1, p. 133, 120 refs.

Klein, Howard, 1975, Depth to Base of Potable Water in the Floridan Aquifer, Florida Bureau of Geology, Map Series No. 42 Revised, 1 sheet.

Kokesh, F. P., Schwartz, R. J., Wall, W. B., and Morris, R. L., 1965, A new approach to sonic logging and other acoustic measurements: Jour. Petroleum Technology, v. 17, March, pp. 282-286.

Kwader, Thomas and Schmidt, Walter, 1978, Top of the Floridan Aquifer, Northwest Florida, Florida Bureau of Geology Map Series No. 86, 1 pg.

Land, L. F., 1977, Ground Water Resources of the Riviera Beach Area, Palm Beach County, Florida, U. S. Geol. Surv., Water Resources Inv. 77-47, p. 38.

Larsen, Gunnar, and Chilingar, George V., 1979, Diagenesis in sedimentary rocks in developments in sedimentology, V. 25a, Elsevier Publishing Co., New York, p. 579.

Lehr, Jay H., and Campbell, Michael D., 1973, Water Well Technology, McGraw-Hill Book Co., New York, pp. 165-211.

Linck, C. J., 1963, Geophysics as an Aid to the Small Water Well Contractor, Ground Water, Vol. 1, No. 1, January, pp. 33-37, 5 refs.

Lynch, E. J., 1962, Formation evaluation: New York, Harper and Row, Publishers, p. 442.

MacCary, L. M., 1962, Resistivity and Neutron Logging in Silurian Dolomite of Northwest Ohio, U. S. Geol. Surv. Prof. Paper 750-D, pp. D190-D197, 17 refs.

_____, 1978, Interpretation of Well Logs in A Carbonate Aquifer, Water Resource Investigation 78-88, p. 30.

_____, 1980, Use of Geophysical Logs to Estimate Water Quality Trends in Carbonate Aquifers, U. S. Geological Survey, Water Resource Inv. 80-57, p. 23.

Mason, Brian and Berry, L. G., 1968, Elements of Mineralogy, W. H. Freeman and Co., p. 550.

Meyer, R. R., 1963, Specific capacity and the Coefficients of transmissibility and storage, in bentall, ray, compiler, methods of determining permeability, transmissibility, and drawdown, U. S. Geol. Survey, Water-Supply Paper 1536-I, pp. 338-340.

Meyer, W. R., 1963, Use of a neutron moisture probe to determine the storage coefficient of an unconfined aquifer, in Short papers in geology, hydrology, and topography: U. S. Geol. Survey Prof. Paper 450-E, pp. E174-E176.

Milliman, J. D., 1974, Recent sedimentary carbonates, part I, marine carbonates, Springer-Verlag, New York, p. 375.

Morris, R. L., Grine, D. R., and Arkfeld, T. E., 1964, The use of compressional and shear acoustic amplitudes for the location of fractures: Jour. Petroleum Technology, v. 16, June, pp. 623-632.

Muench, N. L., 1957, Identification of earth materials by induced gamma-ray spectral analysis: Jour. Petroleum Technology, v. 9, no. 3, pp. 89-92.

Muir, D. M., and Zoeller, W. A., 1967, New acoustic tool logs cased holes: Oil and Gas Jour., Oct. 23, pp. 106-112.

Patten, E. P., and Bennett, G. D., 1962, Methods of flow measurement in well bores: U. S. Geol. Survey Water-Supply Paper 1544-C, p. 28.

_____1963, Application of electrical and radioactive well logging to groundwater hydrology: U. S. Geol. Survey Water-Supply Paper 1544-D, p. 60.

Patterson, Sam H., 1974, Fuller's Earth and Other Industrial Mineral Resources of the Meigs-Attapulgus-Quincy District, Georgia and Florida, U. S. Geological Survey Professional Paper 828, p. 45.

Peacock, R. S., 1981, The Post Eocene Stratigraphy of Southern Collier County, Florida, unpublished Masters of Science thesis, Geology Department, Florida State University.

Peterson, F. L., and Lao, C., 1970, Electric Well Logging of Hawaiian Basaltic Aquifers, Ground Water, Vol. 8, No. 2, March-April, pp. 11-18, 10 refs.

Pickett, G. R., 1960, The use of acoustic logs in the evaluation of sandstone reservoirs: Geophysics, v. 25, no. 1, pp. 250-274.

_____1973, Pattern recognition as a means of formation evaluation, Society of Prof. Well Log Analysts, 14th Ann. Logging Symposium, 1973, Transactions, pp. A1-A21.

Pirson, S. J., 1963, Handbook of well log analysis for Oil and Gas Formation Evaluation: Englewood Cliffs, N. J., Prentice-Hall, Inc.

_____1971, Geologic well log analysis, Gulf Publishing Co., Houston, p. 370.

Pryor, W. A., 1956, Quality of Ground Water Estimated From Electric Resistivity Logs, Ill. State Geol. Surv., Circ. 215, p. 15.

Rabe, C. L., 1957, A relation between gamma radiation and permeability, Denver-Julesburg basin: Am. Inst. Mining Metall. Petroleum Engineers Trans., v. 210, pp. 358-360.

Reineck, H. E., and Singh, I. B., 1973, Depositional sedimentary environments, Springer-Verlag, New York, p. 439.

Rhodes, D. F., and Mott, W. E., 1966, Quantitative interpretation of gamma-ray spectral logs: Geophysics, v. 31, no. 2, pp. 410-418.

Rieke, Herman H., and Chilingarian, George V., 1974, Compaction of Argillaceous sediments in developments in sedimentolofy, V. 16, Elsevier Publishing Co., New York, p. 424.

Sammel, E. A., 1968, Convective flow and its effect on temperature logging in small-diameter wells: Geophysics, v. 33, no. 6, pp. 1004-1012.

Sarma Jagannadha, V. V., and Rao, V. Bhaskara, 1962, "Variation of Electrical Resistivity of Rover Sands, Calcite and Quartz Powders with Water Content", Geophysics, Vol. 17, No. 4, August, pp. 450-479.

Schimschal, Ulrich, 1981, Flowmeter Analysis at Raft River, Idaho, Ground Water, V. 19, No. 1, pp. 93-97.

Schlumberger, Conrad, and Schlumberger, Marcel, 1929, Electrical logs and correlations in drill holes: Mining and Metallurgy, v. 10, no. 275, pp. 515-518.

Schlumberger Well Surveying Corp., 1958, Introduction to Schlumberger well logging (Schlumberger Doc. No. 8): Houston, Tex., p. 176.

_____1975, Log interpretation charts: Houston, Tex.

_____1975, Log interpretation Volume I - Principles: Houston, Tex.

_____1975, Log interpretation Volume II - Applications: Houston, Tex.

Scott, J. H., Dodd, P. H., Droullard, R. F., and Mudra, P. J., 1961, Quantative interpretation of gamma-ray logs: Geophysics, v. 26, no. 2, pp. 182-191.

Scott, Thomas M., and MacGill, Peter L., 1981, The Hawthorn Formation of Central Florida, Florida Bureau of Geology, Report of Investigation No. 91, Part I, Tallahassee, Florida, pp. 1-32.

Scott, W. B., 1976, Hydraulic Conductivity and Water Quality of the Shallow Aquifer, Palm Beach County, Florida, U. S. Geological Survey, Water Resources Inv. 76-119, p. 22.

Skibitzke, H. E., 1955, Electronic flowmeter: U. S. Patent No. 2,728,225.

Smith, C. A., Lidt, Lauralee, and Meyer, F. W., 1982, Data on Selected Deep Wells in South Florida, U. S. Geol, Surv. Open File Report 82-348, p. 144.

Smith, Douglas L., 1980, Initial Heat Flow Survey of Portions of the Gulf Coast Plain, for Los Alamos Scientific Laboratory, University of California, p. 73.

Sutcliff, H., and Miller, R. L., 1981, Data on Ground Water Quality with Emphasis on Radionuclides, Sarasota County, Florida, U. S. Geol. Surv. Open File Report 80-1223, p. 13.

Swayze, Leo J., McGovern, Michael C., and Fischer, John N., 1980, Lithologic Logs and Geophysical Logs from Test Drilling in Palm Beach County, Florida, Since 1974. U. S. Geological Survey Open-File Report 81-68, p. 92.

Sweeney, John W., and Windham, Steve R., 1979, Florida: The New Uranium Producer, Florida Bureau of Geology, Special Publication No. 22, Tallahassee, Fla., p. 13.

Thomas, G. E., 1962, Grouping of Carbonate Rocks into Textural and Porosity Units for Mapping Purposes, AAPG Memoir 1, Edited by William E. Ham, pp. 193-223.

Tibbals, C. H., and Frazee, J. M., Jr., 1976, Ground Water Hydrology of the Cocoa Well-Field Area, Orange County, Florida, U. S. Geol. Surv. Open File Report 75-676, p. 66.

Tittman, J., Sherman, H., Nagel, W. A., and Alger, R. P., 1965, The sidewall epithermal neutron porosity log [abs.]: Jour. Petroleum Technology, v. 17, no. 9, pp. 1060-1061.

Tittman, J., and Wahl, J. S., 1965, The physical foundations of formation density logging (gamma-gamma): Geophysics, v. 30, no. 2, pp. 284-294.

Tittman, J., 1966, The Sidewall Epithermal Neutron Porosity Log, Journ. of Petrol. Tech., Vol. 18, No. 10, October, pp. 1351-1362, 12 refs.

Tixier, M. P., Alger, R. P., Biggs, W. P., and Carpenter, B. N., 1963, Dual induction-laterolog-A new tool for resistivity analysis: Soc. Petroleum Engineers, Am. Inst. Mining Metall. Petroleum Engineers Paper SPE-713, pp. 1-18 (Preprint).

Tixier, M. P., and Alger, R. P., 1971, Log Evaluation of Non-Mettalic Mineral Deposits, Schlumberger Well Services, Houston, p. 23, 18 figs. 2 tabs., an Appendix, 17 refs.

Turcan, A. N., Jr. 1962, Estimating water quality from electrical logs, U. S. Geological Survey Professional Paper 450-C, pp. C135-C136.

_____1966, Calculation of water quality from electrical logs- Theory and practice: Louisiana Geol. Survey, Water Resources Pamph. 19, p. 23.

Vonhoff, J. A., 1966, Water quality determinations from spontaneous-potential electric log curves: Amsterdam, Netherlands, North-Holland Publishing Co., Jour. Hydrology, v. 4, pp. 341-347.

Weaver, Charles E., and Beck, Kevin C., 1977, Miocene of the S. E. United States: A Model for Chemical Sedimentation in a Peri-Marine Environment, Sedimentary Geology, Vol. 17, No. 1 and 2, p. 234.

Welex, A Division of Halliburton Services, 1968, Charts for the interpretation of well logs (Welex Bull. A 133): Houston, Tex., Welex, A Division of Halliburton Services, p. 76.

Wiley, Ralph, 1981, The Borehole Televiewer: An Update on Application, World Oil, March 1981, pp. 47-53.

Wilson, James L., 1975, Carbonate facies in geologic history, Springer-Verlag, New York, p. 471.

Wood, R. D., 1966, The gamma ray-neutron log (Dresser Atlas Gamma Ray Neutron Technical Bull.): Houston, Tex., Dresser Industries, Inc., p. 18.

Wyllie, M. R. J., 1960, Log Interpretations in Sandstone Reservoirs, Geophysics, Vol. 25, No. 4, pp. 748-778.

_____1963, The fundamentals of well log interpretation: New York, Academic Press, p. 238.

Wyrick, Granville G., and Leutze, Willard P., 1956, Ground Water Resources of the Northeastern Part of Volusia County, Florida, Information Circ. No. 8, p. 75.

Youmans, A. H., and Hopkinson, E. C., 1964, The neutron lifetime log: Soc. Prof. Well Log Analyst, 5th Ann. Symposium, Midland, Tex., May, Trans., pp. M1-M26.

Zoeller, W. A., and Muir, D. M., 1969, Acoustilog-Nuclear Logging in Cased Wells, A.P.I. Drill. and Prod. Pract., Cements and Cementing, pp. 61-67, 3 refs.

Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R., 1974, Application of Surface Geophysics to Ground-Water Investigations, U. S. Geological Survey Tech. of Water Res. Inv., Book 2, Chapter D1, p. 116.

VITA

Thomas Kwader was born on November 2, 1952, in Scranton, Pennsylvania. He attended Florida State University, Tallahassee, Florida, from 1972 through 1975 where he received a B.S. degree in Geology. Continuing at Florida State University, he received a M.S. in 1979 and a Ph.D. in Geology in 1982.

Currently, he is employed by the Northwest Florida Water Management District where he has worked as a hydrogeologist since 1976. He is a member of the Society of Professional Well Log Analysts, American Water Resources Association, National and Florida Water Well Association and the Southeastern Geological Society. As a registered Professional Geologist in Georgia (license #582), he has completed many hydrogeologic investigations in Southwest Georgia, for the firm of KWM Water Resources, Inc., of which he founded in 1981.