

Assessment of the 3,000 ppm and 10,000 ppm Total Dissolved Solids Boundaries in the Mississippian and Pennsylvanian Aquifers of Southwestern Indiana

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Assessment of the 3,000 and 10,000 ppm Total Dissolved Solids Boundaries in the Mississippian and Pennsylvanian Aquifers of Southwestern Indiana

W. M. Mitchell

Abstract

The Indiana Geological Survey (IGS), in cooperation with the Indiana Department of Natural Resources' Division of Oil and Gas, conducted a study of Mississippian and Pennsylvanian aquifers in southwestern Indiana to identify and depict the 3,000 and 10,000 ppm total dissolved solids (TDS) boundaries. Those boundaries, particularly the 10,000 ppm TDS level, are used to define the limits of aquifers denoted as Underground Sources of Drinking Water (USDW); under current federal regulations those aquifers are subject to protective measures to prevent contamination.

The Indiana Division of Oil and Gas, as the primary state agency concerned with ensuring that USDWs are protected from contamination by the activity of the petroleum industry, has an ongoing interest to develop a regionally appropriate methodology. These data will facilitate the activity of the Division of Oil and Gas in the permitting and monitoring of various types of injection wells involved in secondary recovery and the subsurface disposal of oil field waters (Class II wells). Maps that show the structural configuration of the critical TDS boundaries within the petroleum-producing counties of southwestern Indiana, therefore, are highly useful.

The TDS values for individual formations were obtained from two sources: actual brine samples, and from calculations utilizing resistivity and porosity readings from geophysical surveys that were run in petroleum industry wells. The data provided by over 2,500 oil and gas industry wells and approximately 10,000 individual-formation TDS calculations were used to make isosalinity maps. Maps depicting the elevations of the 3,000 and 10,000 ppm TDS boundaries were generated using the interpolated data from the log calculations and from brine samples.

Five boreholes ranging from 449 ft to 609 ft were drilled and cored to calibrate the log evaluation techniques used. Each corehole was logged with a resistivity tool and a neutron/density device, which providing the same type of borehole evaluation data that was derived from petroleum industry wells used for calculation. TDS calculations were made from the logs on selected formations penetrated by the coreholes. The same zones were isolated by inflatable straddle packers, and actual samples of the formation waters were brought to the surface by a compressed-air operated pump. The water samples from 13 zones were analyzed using for TDS levels two different lab techniques and compared to log-derived calculated TDS values. None of the zones tested exceeded measured TDS levels of 2,000 ppm. Fifty percent of the measured zones correlated favorably with the calculated zones. The methodology was designed for saline fluids; the relatively low TDS levels and the presence of gas are thought to be responsible for the reduced correlation found in the remaining fifty percent.

The study demonstrated that TDS values derived from geophysical log can be used to predict salinity trends with reasonable reliability; however, exact TDS concentrations cannot be as reliably determined from log-derived data alone when formation fluids having salinities less than 5,000 ppm are present. It was also demonstrated that the 3,000 and 10,000 TDS ppm surfaces form generally basinward dipping surfaces that are much more irregular than anticipated. The 3,000 and 10,000 TDS surfaces occur in southwestern Indiana at greater depths than expected. Numerous salinity anomalies and salinity reversals or inversions were observed to exist within the study area. Those salinity

anomalies and inversions can indicate several conditions, including the upwelling of deep fluids, faulting, and/or the circulation of more shallow subsurface fluids, and perhaps even the mixing of surface waters and the subsequent introduction into deep aquifers that normally would contain fluids of higher TDS levels.

Introduction

The area of the study includes all or parts of sixteen southwestern Indiana counties (fig. 1). Geologically, the study area is located on the east flank of the Illinois Basin. The bedrock units exposed in the study area are Mississippian and Pennsylvanian in age and generally dip westward at a rate of 25 to 40 ft per mile. The water-bearing zones that pertain to this project are predominantly sandstones in the Pennsylvanian and both sandstones and limestones in the Mississippian. Most of the project area is overlain by a veneer of glacially-derived unconsolidated sediments of varying thickness. Previously recognized faulting and fault zones are confined to the southwestern and southern parts of the study area (Ault and Sullivan, 1982). The project area contains the bulk of Indiana's past and current oil and gas activity. Approximately 37,000 oil- and gas-related boreholes have been drilled in the area. The wells represent nearly half of the petroleum-related wells drilled in the entire state.

This research was conducted in an eighteen-month period from mid- 1992 to the end of 1993 and was a collaborative effort between the Indiana Geological Survey at Indiana University and the Indiana Department of Natural Resources' Division of Oil and Gas. The intent and scope of the project was to generate definition of the 3,000 and 10,000 TDS boundaries in the form of structure maps that can be used by the Division of Oil and Gas. This state agency has regulatory responsibility to ensure the protection of all USDWs that the petroleum industry may drill into or through. The information from this report is relative also to the agency's responsibility for permitting, monitoring, and regulating all injection wells used for various types of oil-field injection. Current federal regulations require protective measures to prevent contamination of all aquifers containing waters having TDS concentrations of 10,000 ppm or less. It is highly beneficial for the Division of Oil and Gas to have information regarding what depths (elevations) the critical TDS thresholds occur so that surface casing in boreholes can be required to a sufficient depth to protect potential sources of fresh water.

Background Theory

It has been demonstrated in the Illinois portion of the Illinois Basin, as well as (Meents, 1952) that the non-nal occurrence of the spatial distribution of salinity gradients is a linear increase in TDS concentrations from the surface to greater depths. TDS concentrations in any given aquifer generally increase from outcrop areas toward the basin center. It has also been noted in any given formation that there generally is an increase in salinity with residence time or age of the rock unit (Sanders, 1990). Assuming relatively consistent salinity levels in normal sea water throughout geologic time, a sediment deposited in the normal marine environment would be expected to have connate or original formation waters near the 35,000 ppm TDS concentration levels. It is common to observe formation fluids that exceed the "normal marine" TDS levels by factors of five to ten times. Actual brines exceeding 200,000 ppm TDS (Keller, 1983) have been measured in Indiana. Levels exceeding

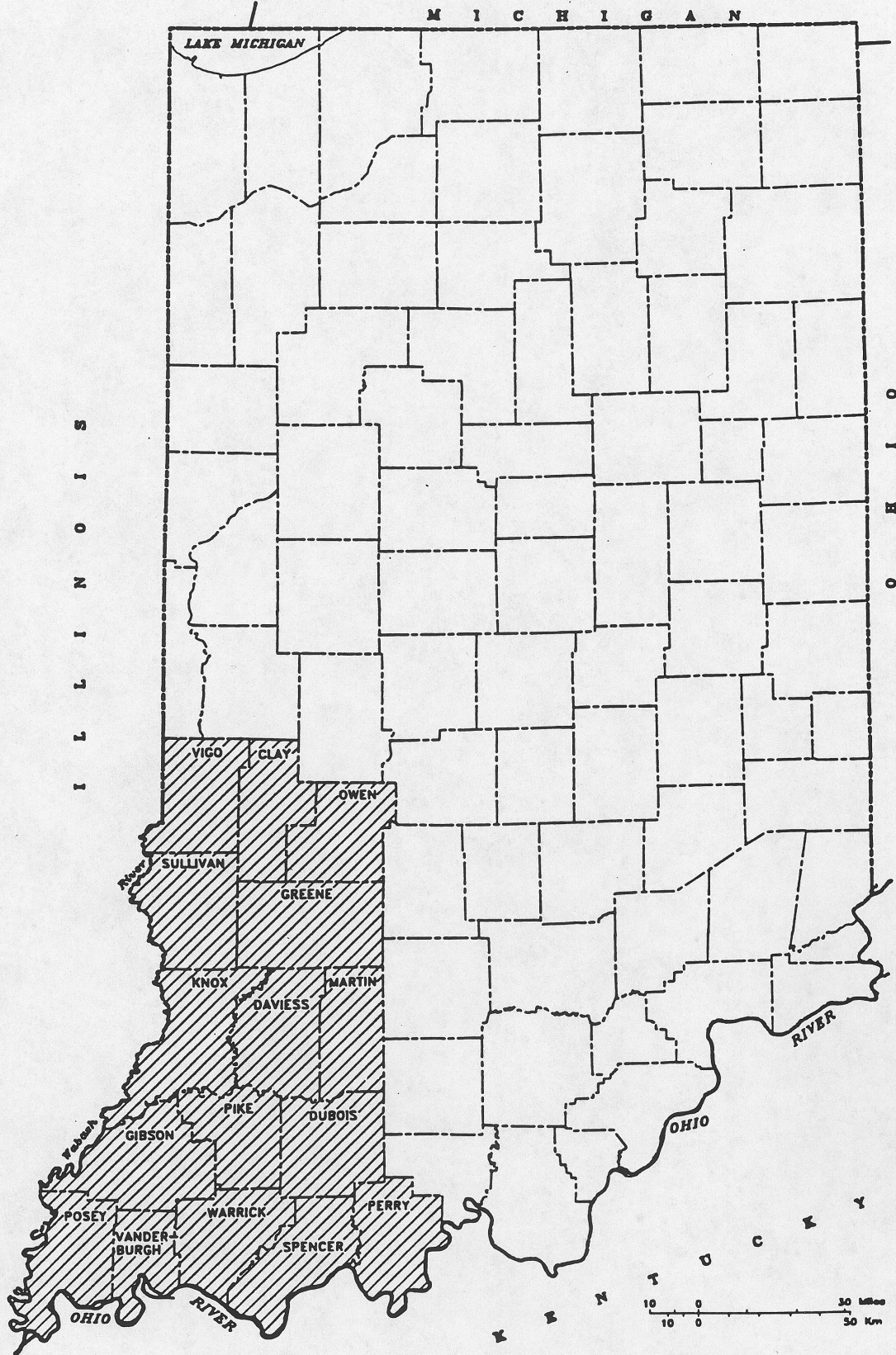


Figure 1. Project study area.

157,000 ppm (Meents, 1952) and 340,000 ppm (Knapp and Stith, 1989) have been measured in Illinois and Ohio, respectively. The highest calculated TDS concentration within the Mississippian and Pennsylvanian aquifers calculated in this investigation exceeded 300,000 ppm, in many instances.

The presence of elevated total dissolved solids concentrations (above 35,000 ppm) has been, and to a large extent, remains the subject of much discussion, research, and conjecture. The chemistry and salinity of a formation's contained water is influenced by many factors and processes. In general, the nature of formation fluids is determined by any of the following or a combination of one or more of the following:

- 1) original seawater,
- 2) mixing of original seawater and meteoric waters,
- 3) dissolution of salts or other evaporites contained within the local stratigraphic section,
- 4) selected ion enrichment by membrane (shales/clays) filtration,
- 5) introduction of fresh water by release of water due to complex rock/fluid reactions, and
- 6) introduction of fluids generated by metamorphic processes.

While several researchers (Land and others, 1992; Morton, 1987) have observed consistently that three types of formation fluids - NaCl, acetate, Ca-rich - predominate in the Cenozoic section of the Gulf Coast, the formation fluids of the Illinois Basin are predominately of the sodium chloride type; that is, the major anion/cation components are sodium and chloride. Occasionally a shallow aquifer will be observed having elevated bicarbonate or sulfate levels (Geoscience Research Associates, 1984; Keller, 1983; Meents and others, 1952).

Methodology

In order to generate usable maps depicting salinity or total dissolved solid concentrations, it is necessary to assume that any given aquifer will have uniform TDS values throughout the permeable portion of the aquifer. It is possible in certain situations, particularly with a thick aquifer, to actually have stratification or density layers of differing fluids between the top and bottom of a finite aquifer. For purposes of mapping, we assume that transitions between differing TDS concentrations do not take place within the aquifers. As will be noted later in this report, this results in a conservative placement of critical threshold boundaries. This, in turn, results in maximum protection. Assuming that the formation waters exhibit uniform TDS concentrations in any aquifer permits one to treat any level of TDS concentration as a planer surface and to generate a structure map on that surface. Using this assumption, structure maps on the 3,000 and 10,000 ppm TDS surfaces were constructed.

The nature of formation fluids can be evaluated in two ways:

1) TDS concentrations can be obtained by direct measurement from actual aquifer sampling and analysis of the recovered fluids. Direct measurement of actual formation fluids provides the most accurate information but requires drilling and aquifer testing that is cost-prohibitive for the acquisition of TDS information on a large scale. The actual brine database for this project includes some 250 samples (Keller, 1983), and samples from five shallow wells that were drilled and sampled specifically for this project. This brine data set, except for use in generating individual isosalinity or isoconcentration maps of specific formations, has limited utility in the generation of the detailed structure maps on the 3,000 and 10,000 ppm TDS boundaries. Brine data, to be most meaningful,

should include a complete set of samples representative of every aquifer from surface to a depth great enough to reach the highest TDS level of interest. This type of data set seldom exists.

2) The second method is to utilize the information collected by various types of borehole geophysical surveys to calculate values for TDS in given aquifers. The types of surveys are frequently conducted in wells drilled by the oil and gas industry. This latter technique is explained in detail in the following section.

TDS Values Derived From Geophysical Logs

Previous research (Rupp and Pennington, 1987; Geoscience Research Associates, 1984) conducted in Indiana utilizing TDS values derived from geophysical logs has demonstrated the utility of calculated log-derived TDS values. Log-evaluation techniques are used to derive a value for the resistivity (R_w) of the water contained in a formation (Schlumberger, 1984). Long-established relationships among fluid resistivity, log-measured resistivity, spontaneous potential (SP) development, formation porosity and total dissolved solid concentrations have been used by the petroleum industry for reservoir evaluation from wireline-generated geophysical logs. These relationships are recognized and are most consistent when the fluid contained in a formation has the predominant constituents of sodium and chloride at relatively high levels. Formation waters high in sodium chloride are frequently associated with and produced with oil and gas.

TDS concentrations determined by calculations using the information provided by geophysical logs provide a best estimate of fluid salinity that in many instances, depending on fluid chemistry, can be very accurate. Elevated levels of certain constituents, such as bicarbonate, very low saline fluids, or the presence of hydrocarbons, can often yield highly inconsistent TDS determinations. When low salinity fluids are involved, individual TDS determinations should be used with caution when attempting to define precise concentrations at specific locations. This type of data can be used, with considerable reliability however to define salinity trends. For instance, if a given aquifer is calculated to contain water with a TDS concentration of 2,200 ppm, one can be reasonably certain that within that specific zone, the salinity is less than 3,000 ppm.

The ability of a formation's fluid content to either impede or facilitate the flow of an electric current allows for estimations of an aquifer's TDS concentration. The typical rock unit (composed of nonconductive materials) will not conduct an electrical current when totally dry; however, that nonconductive medium becomes an electrical conductor when the pore space of the rock is filled or partially filled with water. If the water is fresh (low salinity), it will be a poor conductor; as salinity increases, it becomes a more efficient conductor of electrical current. The increase in salinity is simply an increase in dissolved salts, which dissociate into cations and anions—the transmitters of the current. The resistivity measured by the geophysical log is high in rocks having a low salinity water content; resistivity decreases as the salinity increases. Resistivity measured by the geophysical log is a combination of the rock, pore space fluid, and drilling fluid that were introduced while drilling the borehole. It is usually assumed that the aquifer being evaluated is 100 percent saturated with water. The presence of hydrocarbons in a formation will result in a high resistivity value. The recorded measured resistivity is used to derive the formation water resistivity, which can be used to derive TDS concentration.

Log-evaluation techniques, whatever the method, provide the formation water resistivity (R_w). There are three basic log-evaluation techniques that can be used to arrive at a TDS determination. Those methods are:

- 1) the spontaneous potential method
- 2) the resistivity ratio method, and
- 3) the resistivity/porosity method

For definition of terms, see appendix A.

The SP method can be a reasonably reliable way to arrive at a TDS determination when salinity values or TDS concentrations exceed 10,000 ppm. Some research (Gondouin, 1957) has yielded results indicating that calculated and measured TDS values in saline brines are within 10 percent of each other. Because this project is concerned with lower TDS concentrations, and it is impossible to obtain a usable SP value in fresher waters, the SP technique was not used because of the poor development of the SP curve. It becomes difficult to impossible to determine the SP from an electric log, because in fresher fluids the SP curve is suppressed, and in the case of very fresh water ($< 3,000$ ppm), the SP curve is actually reversed.

The resistivity ratio method was utilized in earlier work (Rupp and Pennington, 1987) to evaluate the fluid content of zones present in wells using an early type of electric log, when a complementary porosity log was not available. This method uses the resistivity of the mud filtrate and the ratio between the deep and shallow resistivity as measured by the electric log. This technique yields the least accurate results and is used when a modern suite of logs is not available. This method was not used for this project.

The resistivity/porosity method was used to determine R_w and the TDS concentration for this project. In this technique, two types of geophysical surveys are necessary—a resistivity log and some type of porosity log. Three types of porosity devices are commonly used in the Illinois Basin: sonic, density and neutron logs. Many industry operators use a combination of the neutron and density logs which yield a very good porosity determination. Given the deep resistivity and the formation porosity, R_w and the TDS concentration can be determined (see appendix B). To generate the most useful type of data set, it is best to run the geophysical logs from as near to the surface as possible to the total depth (T) of the well.

Once a R_w value has been determined for a specific aquifer, a TDS value can be determined either manually from log interpretation charts (Schlumberger, 1984, chart Gen. 9) or by using a mathematical relationship (see appendix B). The latter method was used in this project to facilitate the generation of a relatively large database. This also eliminated the interpolation errors that are inherent when graphical means are used to derive mathematical solutions. The database generated for this project includes calculations from approximately 10,000 individual zones in 2,500 wells. The software Quattro Pro was used to derive all mathematical solutions, and the software Paradox was used to build the relational database. The database that was assembled includes formation depths, formation resistivity, water resistivity, formation porosity, formation factor, formation temperature, bottomhole temperatures, and TDS values.

When recording data directly from the various geophysical logs, a prudent effort was made to collect information from the thickest zones, and resistivity readings were taken at depths coincidental with the best porosity development in any given aquifer. Zones at shallow depths exhibiting porosity of 10 percent or less, were avoided. Those zones, where porosity values of less than 10 percent were utilized, invariably resulted in an erroneously high value for the TDS

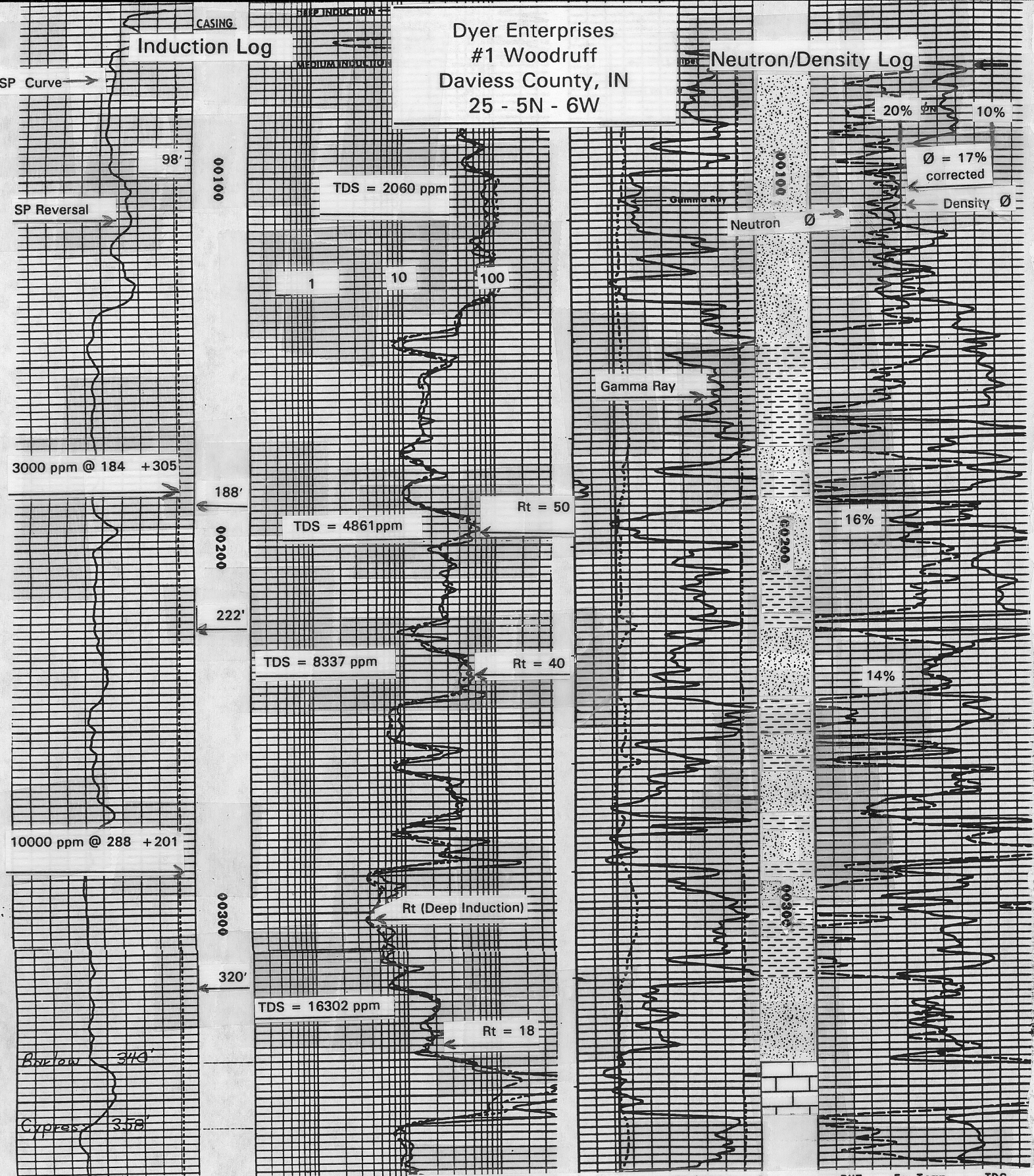
concentration. Those values derived from low-porosity zones (< 10%) often exceed 300,000 ppm and are probably not indicative of actual formation water.

Figure 2 depicts a representative resistivity log that was used in the project along with a porosity log. Critical parameters that were collected and compiled in the database are identified. Calculated TDS concentrations at the depths they occur are also indicated, as well as the interpolated positions of the 3,000 ppm and 10,000 ppm boundaries. The individual depths where the critical boundaries are placed represent an interpretation of the data using the following guidelines to insure that any potential stratigraphic zones that may develop with water less than the critical TDS threshold being picked will be included in the section structurally above that level. The 3,000 ppm or 10,000 ppm TDS boundary was always placed at the base of the aquifer having a TDS concentration calculated just under the boundary being picked. If geophysical log characteristics suggested the presence of a porous zone that could be the edge of a significantly better developed aquifer near the wellbore then that interval is placed above the boundary being picked and the boundary is placed at the top of the first aquifer having TDS concentrations that exceed the boundary value being mapped.

In addition to the log suites that allow for the calculation of values of 3,000 and 10,000 ppm TDS within aquifers, some log suites can be used to bracket the location within the stratigraphic column. Many log suites within the study area do not record the interval from the surface of the borehole to several hundred feet down into the well. This is due to the presence of surface casing in the uppermost portion of the borehole or a lack of interest by the oil and gas operator in logging this portion of the borehole. Unfortunately, it is often within this uppermost several hundred feet of the section that the aquifer containing waters of 10,000 ppm TDS and less is located. Logs from such boreholes can never the less be used to bracket the position of these boundaries by inference. If, for example, a suite of logs only exists to within 500 ft of the surface and calculations of TDS values in the uppermost portion of the log are still above 10,000 ppm at the top of the recorded section then it can be inferred that the 10,000 TDS boundary is no deeper than 500 ft. It can be stated then that the position of the 10,000 ppm TDS boundary is bracketed somewhere between zero and 500 ft below the surface. Bracketed values were used to supplement absolute values or data points.

Coring Program

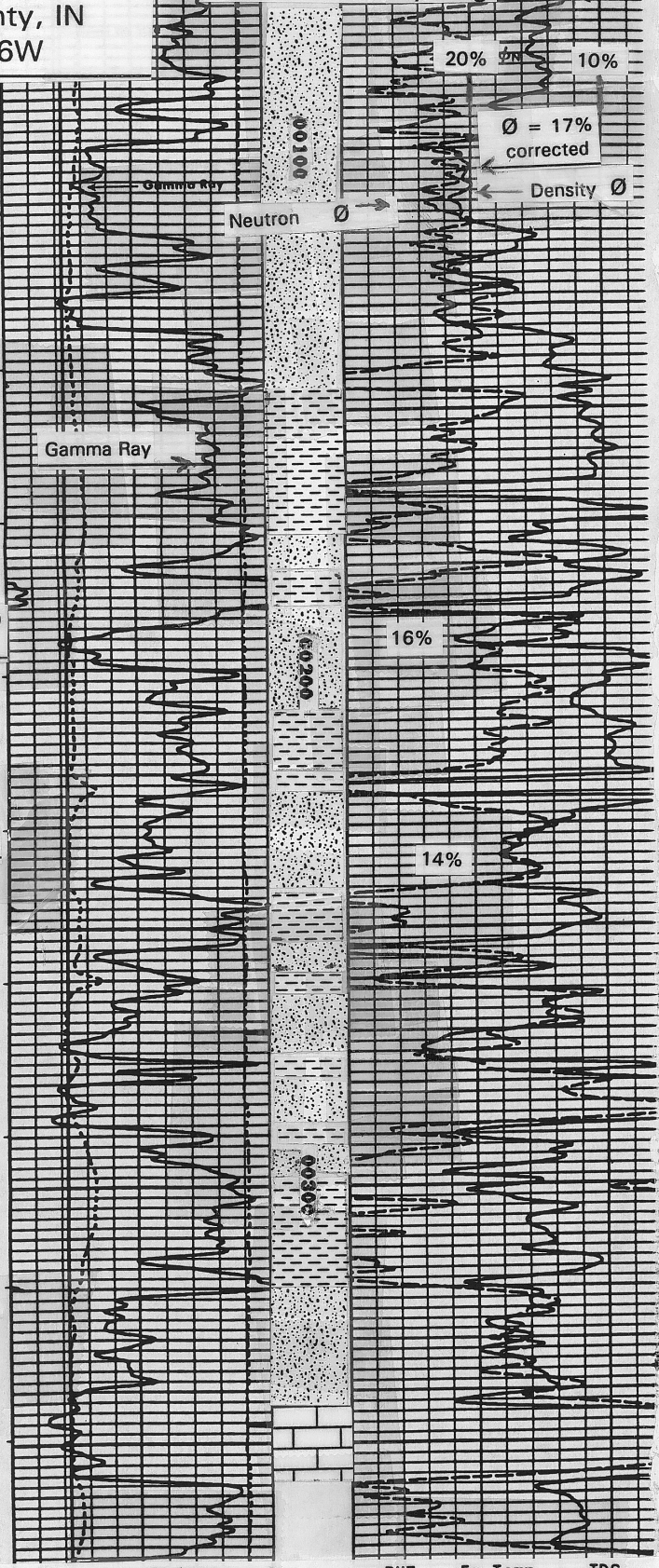
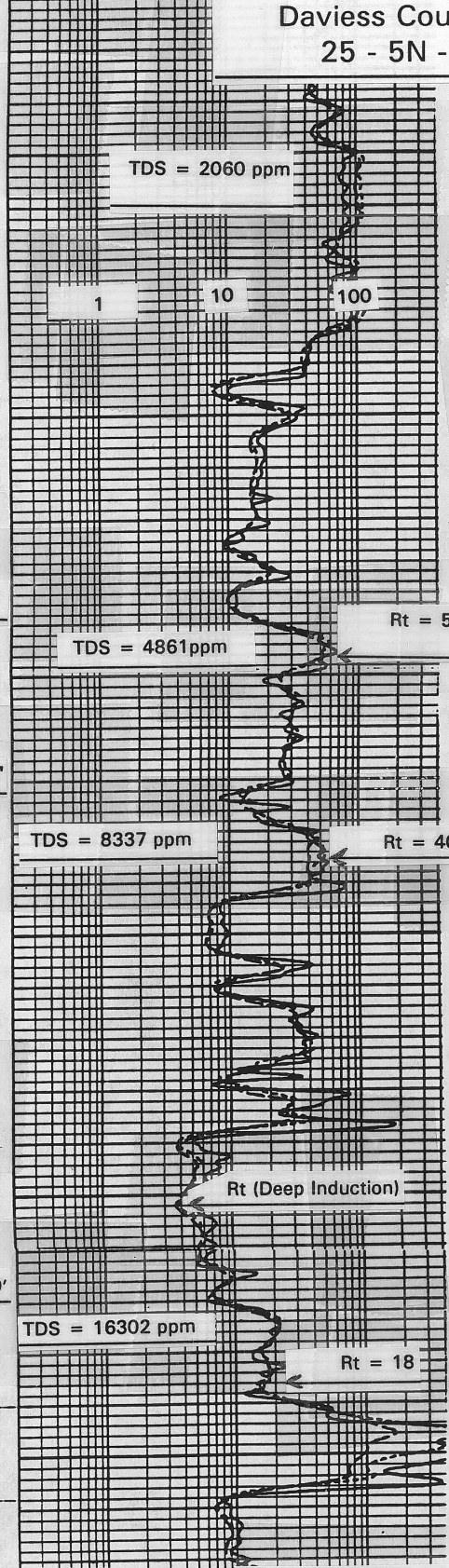
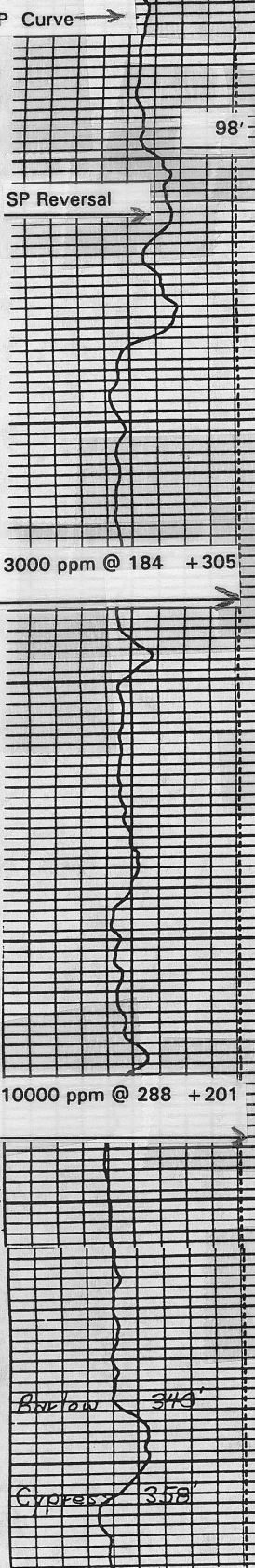
A series of five 3-inch-diameter coreholes, ranging in depth from 449 ft to 609 ft were drilled to provide a calibration suite of holes from which both analyzed formation fluids and log calculations could be compared. The coreholes were drilled in a downdip transect across the project area to provide a reasonable spatial distribution. Figure 3 depicts the distribution of the coreholes. The locations were chosen along with the specific total depths, based on a preliminary structure map depicting the first occurrence of 10,000 ppm TDS concentrations. The coreholes provided an opportunity to run an adequate combination of geophysical surveys that would permit TDS concentrations to be calculated for the aquifers penetrated by the boreholes. After the geophysical surveys were conducted, each zone for which a TDS concentration was calculated, had formation water recovered from it and analyzed for TDS levels. This gave a direct comparison of measured versus calculated TDS values.



Dyer Enterprises
#1 Woodruff
Daviess County, IN
25 - 5N - 6W

Induction Log

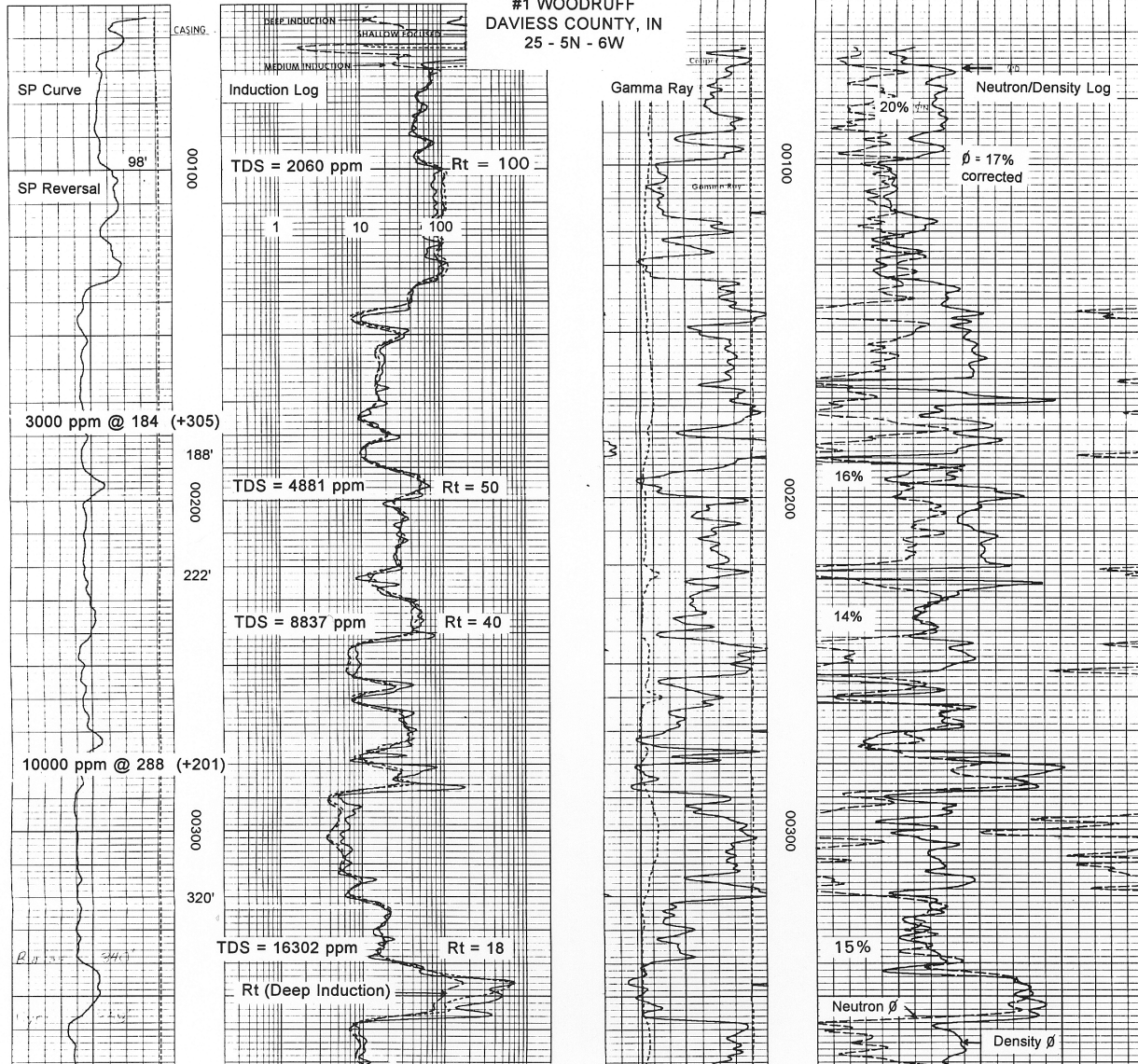
Neutron/Density Log



Depth (Subsea)	Formation	Rtdeep	Por	BHT	Fm Temp	TDS
98 (+391)		100	.17	72	58	2060
188 (+301)		50	.16	72	59	4861
222 (+267)		40	.14	72	60	8337
320 (+169)		18	.15	72	62	16302
358 (+131)	Cypress	16	.15	72	62	18295
379 (+110)	Cypress	12	.18	72	63	16241

Figure 2

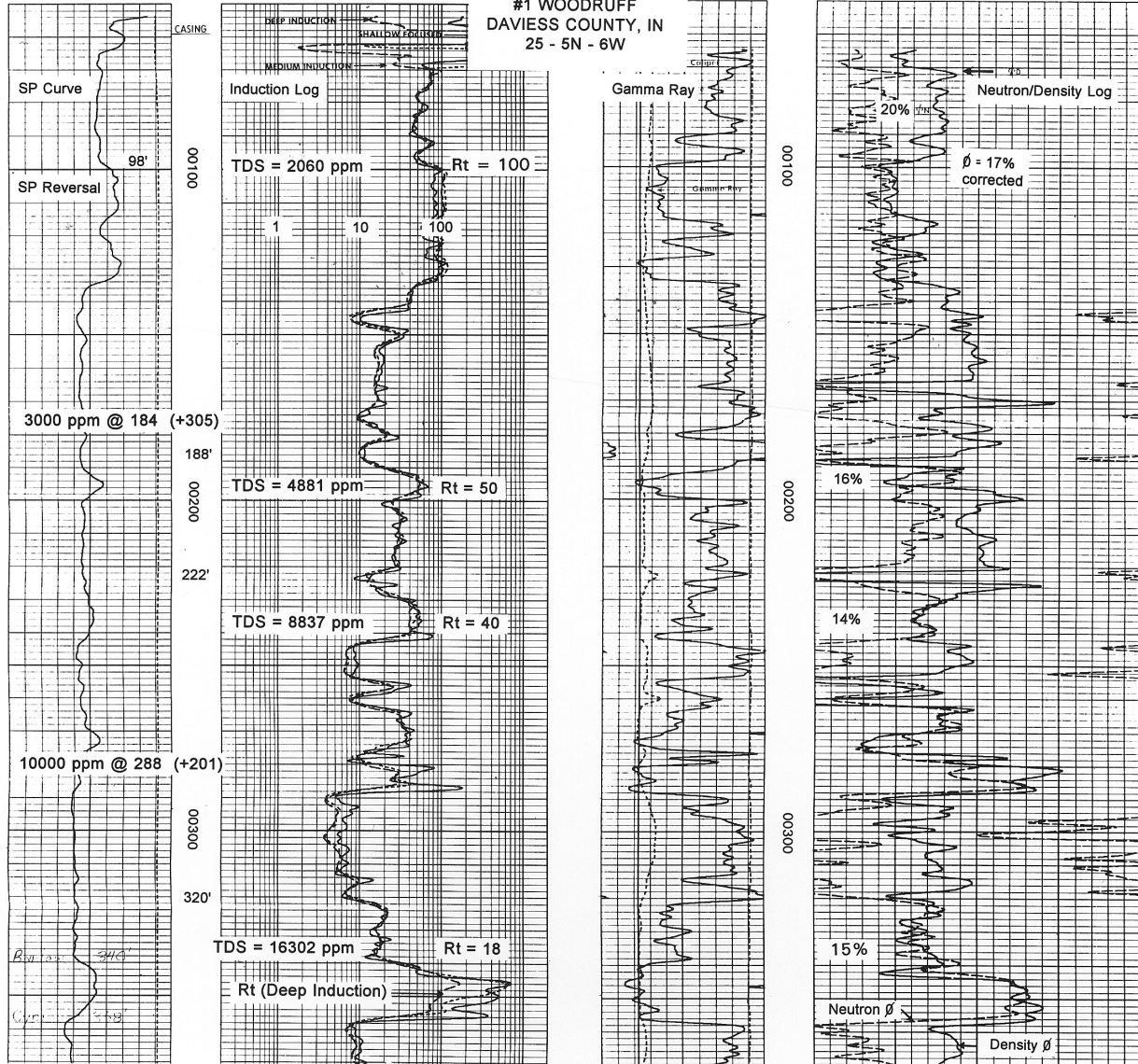
DYER ENTERPRISES
 #1 WOODRUFF
 DAVIESS COUNTY, IN
 25 - 5N - 6W



Depth (Subsea)	Formation	Rtdeep	Porosity	BHT	Formation Temperature	TDS
98	(+391)	100	0.17	72	58	2060
188	(+301)	50	0.16	72	59	4861
222	(+267)	40	0.14	72	60	8337
320	(+169)	18	0.15	72	62	16302
358	(+131) Cypress	16	0.15	72	62	18295
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Figure Showing Typical Neutron/Density and Resistivity Log Responses with Salinity Calculations

DYER ENTERPRISES
 #1 WOODRUFF
 DAVIESS COUNTY, IN
 25 - 5N - 6W



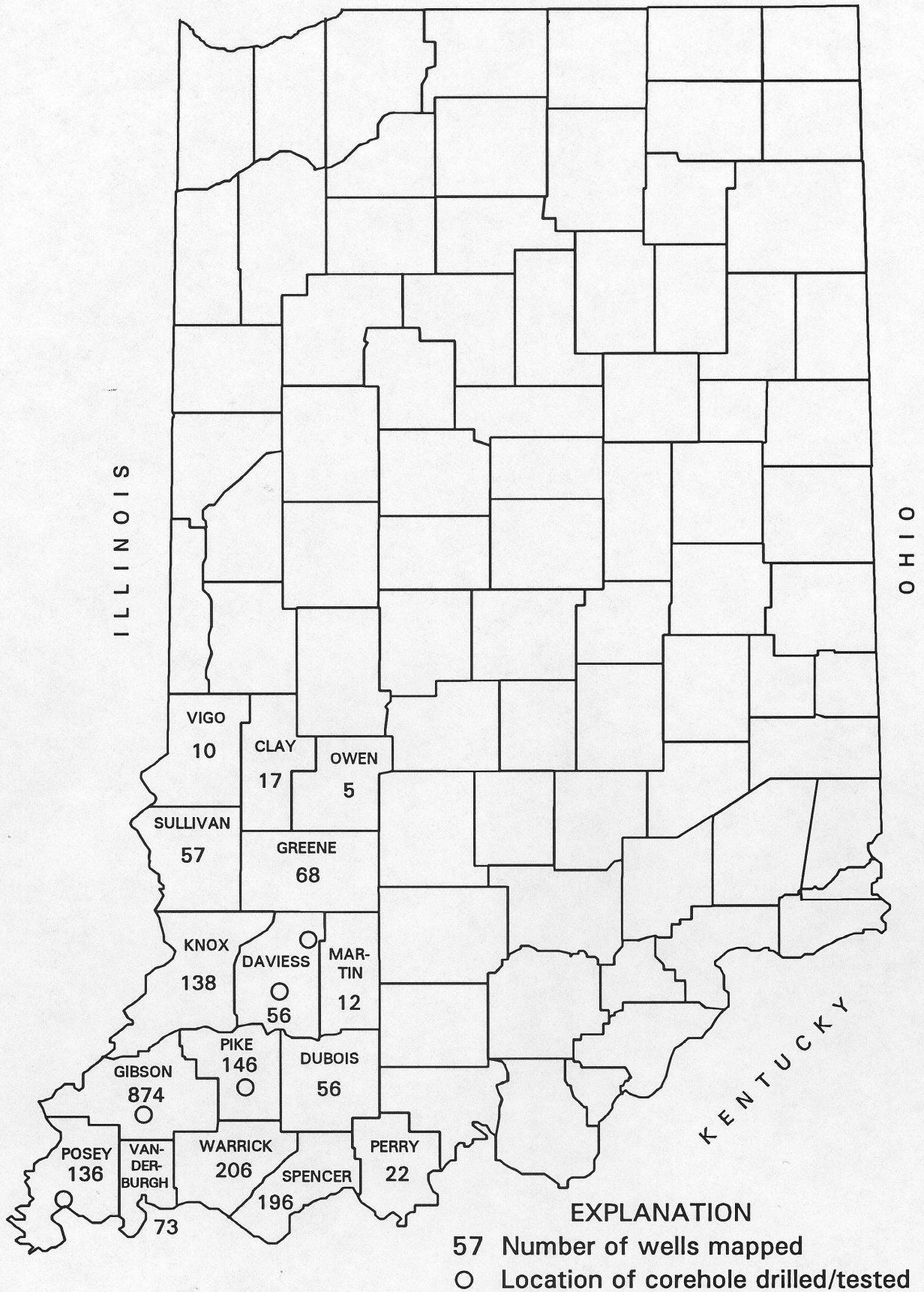
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Figure 2 Figure Showing Typical Neutron/Density and Resistivity Log Responses with Salinity Calculations



Figure 3. Map showing number of wells mapped and distribution of coreholes drilled.

M I C H I G A N



EXPLANATION

- 57 Number of wells mapped
- Location of corehole drilled/tested

Map showing number of wells mapped and distribution of coreholes drilled.

A conventional core was cut from the top of bedrock to the total depth of each corehole. Visual observation of each potential zone to be tested complemented the log-derived observations. The cores will be used in the future for additional evaluation of porosity, permeability, and cementation, and formation factors. After each well was cored to total depth, a resistivity log and gamma ray - neutron/density logs were run in the borehole. Onsite log and core evaluation determined what zones exhibited sufficient reservoir properties (primarily porosity and observed permeability) to warrant aquifer tests. Once the zones to be tested were selected, a packer and pump assembly was lowered into the borehole. Inflatable packers that isolated the test zone by sealing off the top and base of the zone, permitting recovery of formation fluid from the test zone.

The packer assembly was lowered into the borehole to a depth that would permit the packers to “straddle” the aquifer. The packers were then inflated with nitrogen, which produced a seal against the borehole above and below the test zone. The individual packers were separated by stainless steel tubing equal in length to the thickness of the aquifer being tested. The lower part of the tubing had perforations to allow formation fluid to flow into the test equipment from the aquifer. Once the packers had been inflated and seated against the borehole wall, an air-driven downhole piston pump was used to draw water from the formation and deliver the water to the surface. The pump assembly was relatively small, having a diameter of 1.8 inches, and only had the capability to deliver approximately two gallons per minute to the surface. It had a maximum lift (vertical) capability of approximately 1,000 ft.

The pump and packer assembly was lowered into the borehole by means of a tubing bundle. That bundle was composed of a stainless steel suspension cable, which bore all the weight, the plastic packer inflation tubing, inlet and outlet plastic tubing supplying and exhausting the compressed air to drive the pump, water discharge tubing, and an electric cable to power a water-depth indicator. The entire bundle was wrapped in plastic tape and had an approximate outside diameter of 2.5 inches. The bundle assembly was stored on a trailer mounted electric reel that was used to lower and retrieve all the test equipment. The electric reel and air compressor were powered by a portable electric generator. Figure 4 shows the delivery assembly and packer/pump assembly being lowered into a borehole.

The testing procedure involved simultaneously inflating the packer and initiating pumping. The manufacturer's specifications called for an inflation period of twenty minutes to ensure complete inflation and proper seating of the packers. As the project progressed we developed the protocol of initiating pumping and inflating the packer at the same time; by monitoring the pump rate, the actual time of packer seating could be observed (a decline in the pump rate). This observation combined with waiting a minimum time of twenty minutes prior to commencing the formation purge period (for analysis) ensured that complete inflation and seating of the packers had taken place. A change from muddy turbid water to clear water could also be observed after packer seating had been accomplished.

The protocol for actually sampling the formation water, involved pumping the equivalent of three borehole volumes after the packer had been inflated and seated. Throughout the pumping phase, temperature, pH and conductivity of the produced water was monitored. The actual sampling for analysis purposes took place after three volumes had been pumped and stable conductivity readings had been established. Stable conductivity readings of the produced fluid, indicating actual formation water, always occurred long before three volumes had been pumped. Waiting until three volumes of water had been produced to achieve stable conductivity readings provided confidence that representative formation fluids would be sampled and that any fluids introduced while drilling through



Figure 4 - Drill rig with Packer Assembly being lowered into core hole for aquifer testing.

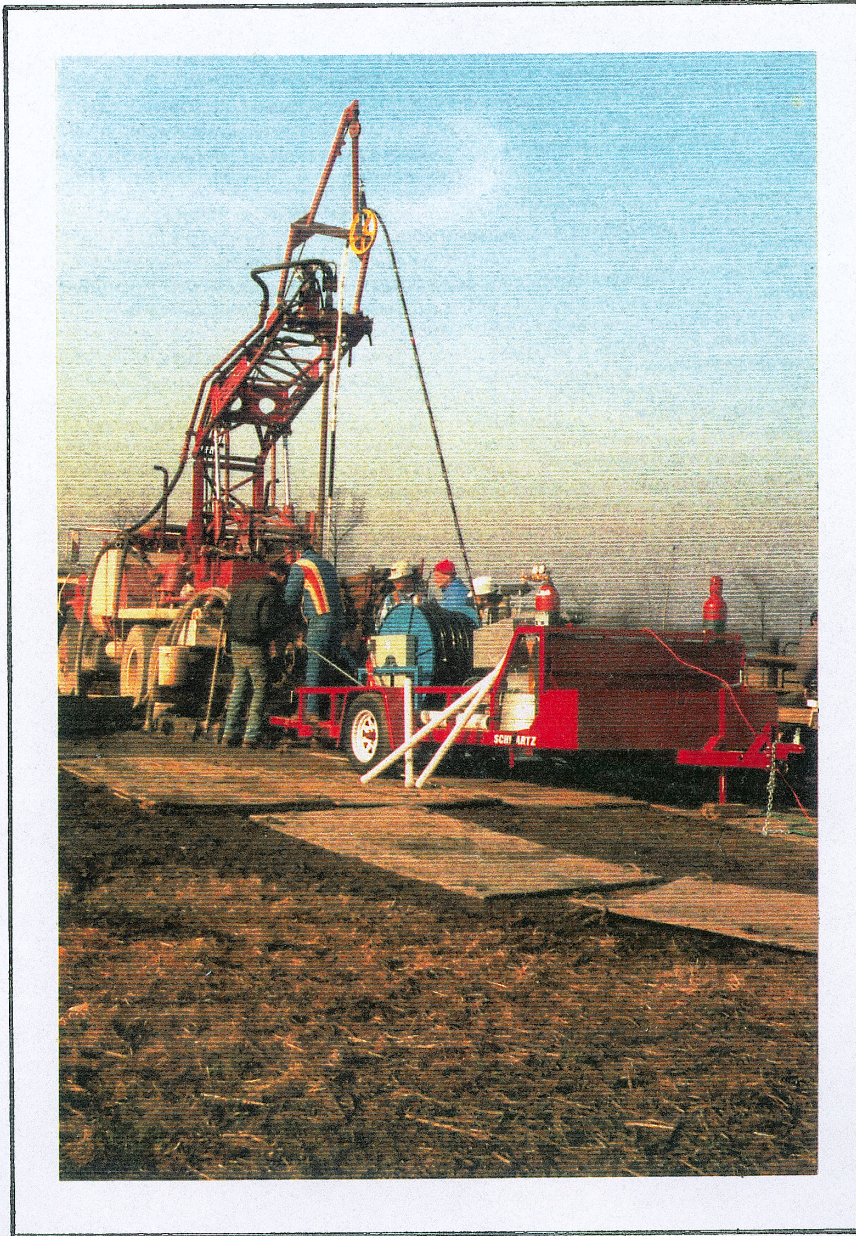


Figure 4 - Drill rig with Packer Assembly being lowered into core hole for aquifer testing.

invasion would have been removed. All water removed from the boreholes and aquifers, except the small portion contained for analysis was produced into the driller's tank truck. This water was later used for mixing the grout used to plug the well.

A total of thirteen aquifers in the five coreholes were isolated, and tested, and fluids were recovered successfully for analysis for TDS concentrations. A cut of formation fluid was provided to the testing contractor, and a second sample set was taken to the Indiana Geological Survey's geochemical laboratory for TDS determination.

The testing contractor, Atec Associates, used an evaporation and weighing method to determine the total TDS. The IGS lab analyzed the water for all major anions and cations and mathematically determined the TDS concentrations. This also provided a sampling of the respective abundances of the major components of the waters tested. The results of the analyses and a comparison of measured versus calculated (log-derived) TDS concentrations is provided in appendix C. Those results will be discussed in more detail later in this report. A discussion of the analyses and the field and lab techniques that were used is presented in a separate report, IGS Open File Report 94-1.

Aquifer Test Results

The data generated as a result of the aquifer tests conducted in the five boreholes drilled for the project are tabulated in appendices C, D, and E. A total of 13 individual aquifers were isolated and formation fluids were recovered. There were six formations, all Pennsylvanian in age in which aquifer tests were attempted, from which no water or less than preferred amounts of water could be recovered. Fluids from three of those tests were analyzed, although the minimum standard protocol of producing three well volumes could not be achieved. They were used because the zones yielded enough water (1 to 1½ volumes) to potentially represent formation fluid. Monitoring of the pH while pumping revealed that the formation fluids had a different pH than that of the borehole water.

All of the boreholes were drilled with fresh water obtained at the drill site. No additives or mud were used in the drilling. Three of the wells (SDH # 377, 380, and 382) were drilled using the county municipal water supply. The municipal water supplies were floridated, and the recovered waters showed no levels of fluoride that would suggest contamination or invasion of the formation by the drilling fluid.

All the failed aquifer tests were in formations that exhibited density-log porosity of 15 percent or less. Those zones would invariably yield some water during the initial pumping period, but would exhibit a drawdown to a very low pump rate or no yield within five to twenty minutes of pumping. In some instances, the drawdown to no-flow rate would occur very rapidly (within 3 to 5 minutes). Those same zones typically exhibited neutron-log porosity values that exceeded the density-log values by as much as 10 percent. It is assumed that the higher neutron-log porosity reflects a high clay and bound-water content contained within the pore space of the rocks and that those zones have significantly reduced permeabilities that limit the productive capability of the rock.

The waters recovered from all zones tested were relatively fresh, ranging from a low TDS concentration of 345 ppm to a high of 1,598 ppm. The depths tested (log depth) ranged from 90 ft to 596 ft.

TDS Comparisons-Measured Versus Calculated

Appendices D and E tabulate the TDS concentrations that were derived in the laboratory by Atec and the Indiana Geological Survey. Average porosity and Rt log values for each zone are also shown in Appendix E. The average of the two separate laboratory determinations and the calculated values (from geophysical logs) is shown as well as a column that depicts how the calculated TDS for each zone differed from the average of the measured values. It can be seen from this limited population of samples, particularly when relatively fresh fluids are involved, that geophysical determination of TDS concentrations is not absolutely accurate in a quantitative sense. The geophysical determinations, however, can be demonstrated to have significant qualitative value. Six of the thirteen zones evaluated had calculated TDS concentrations within (or less) than 500 ppm of the laboratory-derived TDS concentrations. Two additional zones had calculated TDS concentrations that exceeded the laboratory-derived samples by less than 600 ppm. (The two samples exceeded 500 ppm by an average of 28 ppm.) The lowest correlation between the geophysically derived TDS concentrations and measured values occurred in the four zones evaluated in SDH # 380.

Exhibits Generated

The database that was generated as a result of this project includes a total of 146 interpolated determinations for the elevation of the 3,000 TDS boundary and 416 determinations for the 10,000 TDS boundary. A structure map on each of these boundaries were constructed at a scale of 1: 250,000 across the entire project area. Additionally maps on these same boundaries were also constructed on a county basis at a scale of 1" = 1 mile on eleven of the sixteen counties in the study area. Three regional cross sections and an isosalinity map for the Cypress Formation were also constructed. A total of twenty-five maps are included in this report. The entire database assembled for this project is also available in digital format. This includes the data derived from geophysical logs, such as resistivity and porosity values; calculated parameters such as TDS concentrations, Rw, and formation factors; and well header information.

General Observations

Regional Boundary Structural Configurations

Structural configuration maps that depict the 3,000 ppm and 10,000 ppm boundaries were constructed for the entire study area at a scale of 1: 250,000 (plates 1, 2). It is noted that sufficient data points exist to construct a reasonably reliable general representation of the 10,000 ppm TDS boundary. The nature of oil and gas well drilling leads to clusters of data points. The resulting spatial distribution of those points is rarely uniformly distributed. The maps presented with this report are primarily derived from actual points that provide an absolute elevation point for the mapped datum. Wells that provide bracketed elevation negative control points are also used to provide the greater accuracy in mapping and constrain the position of the contours. A total of 416 absolute points were used to construct the 10,000 ppm TDS boundary map, and an additional 1,856 bracketed points were used to maximize reliability. Maps are contoured relative to sea level. It should also be noted that it is always possible to generate multiple interpretations of the configurations of the boundaries when

contouring the data. In the case of the TDS values that are contoured on the enclosed maps, an effort was made to contour the data in the simplest manner possible.

The elevation of the 10,000 ppm TDS boundary ranges from more than 600 ft above sea level near the outcrop in the eastern part of the study area to more than 400 ft below sea level in the southwestern, part of the project area. The 10,000 ppm boundary is depicted as a highly irregular boundary that dips overall to the west and southwest and conforms to the general structural configuration of the Indiana portion of the Illinois Basin. Although the configuration of the 10,000 ppm TDS boundary conforms generally to the basin's structural configuration, there are numerous local TDS anomalies where the elevation of the mapped boundary occurs either higher or lower than would be expected based on the regional gradient established. Some of the mapped TDS anomalies are probably meaningful and have geologic significance and some probably have no significance and may simply be artifacts of too little control or incorrect data. The scope and extent of this research effort did not permit the development of sufficient data that could be used to formulate conclusions as to the meaning of the mapped TDS anomalies. Given that caveat, it is possible to draw some limited conclusions relative to certain aspects of the TDS anomalies shown on the contour map.

There appears to be a strong correlation between some of the high points on the 10,000 ppm TDS boundary and some of the known Silurian reefs, particularly in Greene and Daviess Counties. It is possible that the 10,000 ppm concentration occurs at a higher elevation over the reef features due to fractures and microfractures that are present over and on the reefs. These would facilitate upward migration of more saline waters resulting in local 10, 000 ppm highs that coincide with the deep reefs. It also appears that TDS gradients can also be indicative of faults present in the subsurface. The relationship between steep (unmappable without faulting) TDS gradients and faults is evident at several locations. There is also a recurring relationship between some TDS anomalies and known oil and gas fields, although no confidence exists about the significance of that relationship at this point. Although there is frequently an associated anomaly on the TDS boundary, the association is not universal with every hydrocarbon accumulation related to an individual TDS anomaly. Some of the mapped TDS anomalies are probably artifacts of the non-uniform distribution of data points generated by oil and gas drilling.

The map depicting the first occurrence of the 3,000 ppm TDS boundary also shows an overall basinward dipping surface that is interrupted by numerous local anomalies. This horizon was constructed using 146 absolute points of control and 2,034 negative points of control. This horizon is relatively conformable to the 10,000 TDS boundary and is more simpler due to the less dense data set. The elevation of the 3,000 ppm TDS boundary ranges from above 600 ft in elevation along the eastern part of the study area to more than 200 ft below sea level in the southwestern corner of the study area.

Regional Cross Sections

Three cross sections are submitted with this report (plates 3, 4 and 5). The sections are regional in extent and traverse the study area. Plates 3 and 4 (sections A-A', B-B') are oriented east-west and plate 5 (section C-C') is oriented generally north-south across the study area. The precise location of the sections is shown on the 3,000 and 10,000 ppm boundary maps.

Three structural cross sections show the overall relationship of the 3,000 ppm and 10,000 ppm TDS boundaries relative to the surface topography and subsurface structural configuration. Observed relationships in the cross sections suggest that structure and topography contribute more significantly to TDS boundary configuration than stratigraphy. Cross sections of this scale cannot show or reflect local structure precisely. The sections show that there is more of a consistent relationship between the surface configuration and the configuration of the 3,000 and 10,000 ppm boundaries than there is between those boundaries and the subsurface structural configuration of the Mississippian and Pennsylvanian rock units. There is also with some exceptions, relatively good coincidence the two mapped TDS boundaries. There is a divergence between the 3,000 and 10,000 ppm TDS boundaries in some areas.

County TDS Maps

Maps showing eleven of the sixteen counties that are located within or partially within the study area accompany this report (plates 6 through 27). These plates depict the 3,000 and 10,000 ppm TDS boundaries at a scale of 1" = 1 mile. The base maps were generated using the software PC ARC INFO. The following counties were mapped at this scale: Daviess, Dubois, Gibson, Greene, Knox, Pike, Posey, Sullivan, Spencer, Vanderburgh, and Warrick. Each of the above counties and the general details of the 3,000 and 10,000 ppm TDS boundary maps will be discussed in the following.

Daviess County (Plates 6 and 7)

The elevation of the 10,000 ppm TDS boundary in Daviess County ranges from greater than 400 ft above sea level in the northern part of the county to sea level or slightly below in several parts of the county. The 3,000 ppm TDS boundary ranges from greater than 500 ft above sea level in the northern part of the county to below 200 ft above sea level in the northwestern part of the county. Structurally high areas (TDS high areas) at either the 3,000 ppm or 10,000 ppm datums are evident at and coincident with the following field areas:

<u>Area</u>	<u>Field</u>
2N-5W	Cannelburg
4N-6W	Cornettsville
3N-6W	Montgomery East
4N-5W	Epson

A steep gradient at both the 3,000 ppm and 10,000 ppm boundaries in the Epson Field area is suggestive of the presence of faulting, with a fault postulated in the NE corner of 4N-6W.

Dubois County (Plates 8 and 9)

The elevation of the 3,000 ppm boundary varies from greater than 500 ft above sea level to slightly below 100 ft above sea level. The 10,000 ppm TDS boundary ranges from above 400 ft elevation to slightly below sea level. There is a relatively strong TDS anomaly over Huntingburg Field (3S-5W) and broad anomalies over Jasper South (2S-5W) and Britzville (3S-5W) fields.

Gibson County (plates 10 and 11)

The 3,000 ppm boundary ranges in elevation from above 400 ft to slightly below sea level. The 10,000 ppm boundary varies from greater than 400 ft to 300 ft below sea level. There are TDS anomalies coincident with the following hydrocarbon-producing fields in Gibson County:

<u>Area</u>	<u>Field</u>
3S-12W	Mounts-Fleener Consolidated
1N-10W	Union Bowman
2S-11W	Owensville Consolidated & Princeton West
3S-10W	Haubstadt, Fort Branch, West Fork Consolidated
2S-10W	Frisco Consolidated

High TDS gradients suggest the existence of faulting in the Mounts-Fleener Consolidated Field area (3S-12W) and Princeton West Field area (2S-11W).

Greene County (plates 12 and 13)

The 3,000 ppm TDS boundary ranges from greater than 400 ft to just below 100 ft above sea level, and the 10,000 ppm boundary ranges from above 400 ft to under 200 ft below sea level. Both 3,000 ppm and 10,000 ppm anomalies are associated with the following oil fields, which are all overlying Silurian Reefs.

<u>Area</u>	<u>Field</u>
6N-6W	Lyons
7N-6W	West Lyons
6N-5W	Plummer
8N-5W	Worthington

The pattern of distribution of the 10,000 ppm elevation points at Lyons (16-6N-6W) suggests the presence of a fault, which is indicated on the 10,000 ppm boundary map.

Knox County (plates 14 and 15)

The elevation of the 3,000 ppm boundary ranges from above 400 ft to slightly below 100 ft above sea level across Knox County. The 10,000 ppm boundary varies from above 300 ft to 100 ft below sea level. There is general conformity between the two datums.

TDS boundary anomalies or high areas are associated with the following field areas:

<u>Area</u>	<u>Field</u>
1N-10W	Union Bowman
2N-10W	Iona
3N-8W	Monroe City
4N-8W	Bicknell & Bicknell East
5N-10W	Oaktown
2N- 11W	St. Francisville

Pike County (plates 16 and 17)

The elevation of the 3,000 ppm boundary varies from high areas of greater than 300 ft above sea level to low areas less than 200 ft above sea level. The 10,000 ppm boundary varies from high elevations of greater than 400 ft above sea level to lower than 200 ft below sea level.

A number of anomalies or boundary highs are evident at various locations in Pike County at both the 3,000 ppm and 10,000 ppm boundaries. The areas that have coincident or broad anomalies associated or partly associated with them are as follows:

<u>Area</u>	<u>Field</u>
1N-7W	Algiers, Thomas, & Alford Fields
2S-7W	Fritz Comer, Pikeville Fields
1S-7W	Winslow Field
1N-9W	parts of Union Bowman Field

There is a single anomalous well, located in the location 11 area of 1N-9W, with a data point for the 10,000 ppm boundary of 270 ft that is surrounded by wells with the same boundary occurring at the 20 ft to 50 ft range. The anomalous point appears to be reliable to the extent the geophysical data was properly used. The density of the surrounding well control makes the abnormal point impossible to honor on the 10,000 ppm boundary map. The same density of control precludes the introduction of faulting at that location. It is assumed that the geophysical log has either provided incorrect information or the abnormality is correct and indicative of some type of contamination. Data density and an unusual TDS gradient does permit speculation and the interpretation of a small fault on the 10,000 ppm map in the SE part of 1N-9W.

Posey County (plates 18 and 19)

The elevation of the 3,000 ppm boundary varies across Posey County from above 300 ft to just below sea level (0 ft). The 10,000 ppm boundary varies from above 200 ft to more than 400 ft below sea level. TDS boundary anomalies, particularly at the 10,000 ppm boundary, are interpreted to be present in the following areas:

<u>Area</u>	<u>Field</u>
6S-13W	Mt. Vernon Consolidated, Oliver, & Oliver South
6S-12W	Parker Consolidated

Much of the central and western parts of the county exhibits a NE-SW strike component at the two mapped TDS boundaries, with that strike component most evident at the 10,000 ppm boundary. The NE-SW strike is considered to reflect the faulting that is present in the county. Parts of the Wabash Valley Fault System are known to transect the county, and the data presented on plates 18 and 19 reflect the known faults and possibly extensions of those faults along with additional faulting. Known faults are depicted with solid lines and postulated faults are illustrated with dashed lines.

Sullivan County (plates 20 and 21)

The 3,000 ppm boundary ranges from above 400 ft to below 200 ft. The 10,000 ppm boundary varies from above 400 ft to more than 300 ft below sea level. A single broad structural high at the 10,000 ppm horizon dominates the northwestern part of the county. This broad feature centered in Township 8 and 9 north, Range 10 west, overlies Shelburn Consolidated, Denny, Graysville, and Sullivan Consolidated Fields. A second broad high is located in the southwestern part of the county, but is not associated with any significant oil and gas production.

Spencer County (plates 22 and 23)

The elevation of the 3,000 ppm boundary is highly variable ranging from above 400 ft to sea level (0 ft). The 10,000 ppm boundary is equally as variable, ranging from above 300 ft to more than 100 ft below sea level. TDS elevation anomalies are associated with the following areas:

<u>Area</u>	<u>Field</u>
7S-6W	Rockport South
7S-6W	Rockport Consolidated
6S-5W	Grandview
6S-5W	Chrisney South
5S-5W	Liberal
7S-6W	Lake Mills, Rock Hill

Three areas of relatively steep TDS gradients in the county suggest the presence of faulting. Those areas are centered in Township 5 south, Range 4, and 5 west. All three areas are on trend with

the northeastern extension of Hurricane Island Fault, which is known to be present on the south boundary of the county.

Vanderbureh County (plates 24 and 25)

The 3,000 ppm boundary ranges from above 400 ft elevation in the northernmost part of the county to below 200 ft above sea level in the southern part of the county. The 10,000 ppm boundary ranges from over 400 ft in the north to just under sea level in the south. There are only three data points that provide absolute values for the 10,000 ppm horizon in the county. There is an inadequate amount of data to define any anomalous areas in Vanderburgh County.

Warrick County (plates 26 and 27)

The 3,000 ppm boundary ranges from above 400 ft to below 100 ft above sea level. The 10,000 ppm boundary varies from above 400 ft to approximately 100 ft below sea level. There is general conformity between the two horizons. There are TDS anomalies associated with the following areas:

<u>Area</u>	<u>Field</u>
4S-7W	Folsomville Field
5S-8W	Chandler, Booneville Fields
5S-7W	SE corner of township, no associated production

The overall structural grain of both horizons has a strong component of NE-SW orientation. There is also a steep TDS gradient at Heilman East Field (4S-6W) that could be suggestive of faulting, however no faults are mapped.

Salinity Distribution Mapping - Cypress Formation (plate 28)

A map showing salinity or TDS concentration distributions of fluids contained in the Cypress Formation across the study area is also included in this report. This exhibit was generated to demonstrate the utility of the database assembled for the project. The salinity distribution of Cypress Formation fluids is depicted at the regional scale of 1: 250,000. The map utilizes a data set of 1,600 individual wells from which a TDS calculation was done or an actual brine analysis was available. The following ranges of salinity are shown:

- 0-3,000 ppm
- 3,001-10,000 ppm
- 10,001-35,000 ppm
- 35,001-100,000 ppm
- > 100,000 ppm

The pattern of salinity distribution mapped suggests an increase in fluid salinity from the outcrop area basinward, however, numerous areas exist in which plumes of higher (or lower) salinity fluids are

shown to occur across the study area. It is likely that many of the anomalous areas of fluid salinity are caused by unique local geologic factors. The anomalous areas also could be simply artifacts of data distribution. Many of the anomalous plumes are located in areas of known or suspected faulting and may be related to that faulting. Areas of existing hydrocarbon production are also shown on this map. The distribution of Cypress Formation fields shows that there is a correlation between those hydrocarbon occurrences and Cypress fluids having salinity concentrations in the 35,000 ppm to 100,000 ppm range. The map also shows that most of the project area contains Cypress Formation that is saturated with water having salinity of 35,001 ppm to 100,000 ppm.

Summary and Conclusions

This research focused on the identification and depiction of the subsurface points at which formation fluids reach total dissolved solids concentration thresholds of 3,000 ppm and 10,000 ppm. Derivation of total dissolved solids concentrations was achieved utilizing data generated by water samples and the geophysical logs run in oil and gas industry boreholes. The technique is useful with limitations. It is important to evaluate any specific area that may be examined relative to the density of control present. The technique is most usable and accurate in the identification of TDS trends. The boundary maps should be used with a reasonable amount of caution when site-specific salinity determinations are being evaluated. Every effort should be made to complement the boundary maps provided with this study with the additional data wells drilled subsequent to this report.

This research generates far more questions than it provides answers. It shows that with increasing depth the first occurrence of a given formation fluid salinity, particularly those thresholds critical to regulatory efforts, is not always the last occurrence of that salinity. Such TDS inversions or reversals have causes that are not readily apparent using the information generated by the current work. There are also strong suggestions that TDS mapping can have utility in the identification of faulting, along with possible exploratory significance relative to the recurring association of TDS elevation highs with known oil and gas fields. There are implications that such mapping could assist in the potential identification of areas of contamination in the state's freshwater resources, as well as giving a greater understanding of local and regional movement of subsurface fluids. The database assembled for this project also includes such parameters as formation porosity, fluid salinity, fluid resistivity (R_w), formation temperature, and calculated formation factors. All these data can be mapped to depict spatial distribution and have potential utility for the petroleum industry and other researchers. Clearly, additional research is warranted and will ultimately be undertaken.

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Daniel O. Barry assisted in the final production of the computerized maps. James T. Cazee was instrumental in the finalization of the graphic images. Their efforts are greatly appreciated. Additionally, without the generous contributions of many different oil and gas operators throughout the state who contributed data over the years, this investigation would not have been possible.

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Appendix A

Log Evaluation Terms

- SP** - Spontaneous Potential Curve, is a recording of the naturally occurring electrical potential produced by the formation water and the drilling fluid. The magnitude of the deflection of the SP curve is a qualitative indicator of porosity and permeability.
- GR**- The gamma ray curve is a recording of the natural radioactivity emitted by a formation.
- Rt**- Resistivity true - typical resistivity logs will measure or record a shallow, medium and deep resistivity measurement (relative distance from the borehole), with Rt is the deepest resistivity reading.
- BHT**- The temperature at the bottom of the borehole.
- Tf** Formation temperature.
- i** - Formation porosity
- F**- Formation factor is a variable dependent on lithology that relates the tortuosity of permeability, cementation factor, and porosity.

Appendix B

The Resistivity/Porosity Technique to Derive TDS Concentrations

To obtain R_w (resistivity of the formation fluid) using this technique, the following relationship is used:

$$R_w = \frac{R_t}{F}$$

Where R_t is the deep resistivity read directly from the log, and F , the formation factor, which is derived from the following:

$$F = \frac{.62}{i^{2.15}} \quad \text{when the zone being evaluated exhibits porosity greater than 10\%, or}$$
$$F = \frac{1}{i^2} \quad \text{when the porosity is less than 10\%.$$

Once R_w has been derived, the temperature of the formation has to be determined. The bottomhole temperature read from the log heading is inserted in this equation:

$$T_f = 56 + (BHT - 56) \frac{\text{depth of formation}}{\text{total depth of well}}$$

With R_w solved, and the temperature of the formation calculated, Schlumberger chart Gen 9 can be used to interpolate a TDS concentration.

Enter the chart along the temperature axis, proceed to the appropriate R_w value; the TDS level will be read at the intersection of the temperature and R_w values; interpolation is required when the intersection point falls between the TDS lines.

TDS concentrations can be calculated more precisely by using the following equation:

$$Wt\% = 10^{(\log_{10} R_w - 5.408 + (1.014 \log_{10} T_f)) / -.09263}$$

$$PPM = (Wt\%)10$$

Appendix C
Corehole Aquifer Analyses Data
From IGS Open File Report # 94

Table 2. Chemical data for water samples collected from 5 survey drill holes. Units expressed in milligrams per liter (mg/L) except where noted in parentheses or footnotes.

	SDH-377 ¹	SDH-377 ²	SDH-377 ¹	SDH-378 ¹	SDH-378 ²	SDH-378 ¹	SDH-379 ¹	SDH-380 ¹	SDH-380 ¹	SDH-380 ¹	SDH-380 ²	SDH-382 ¹	SDH-382 ¹
Depth (ft)	90	305-360	540-596	212-227	384-399	422-437	34-82	197-229	229-261	296-363	436468	136-156	333-373
Collect. Date	2/10	2/10	2/10	3/01	3/01	3/01	3/17	3/29	3/29	3/29	3/29	4/20	4/20
Field Temp °C	7.8	17.2	17.8	11.8	13.0	12.5	5.0	22.0	20.0	15.2	18.4	17.3	16.3
SpC (F mhos/cm)	425	2070	1820	766	591	1042	1231	1164	1117	845	1650	492	403
Field pH	7.5	7.4	7.0	7.8	9.0	7.7	6.2	7.9	7.2	7.0	6.8	7.9	8.0
D.O.	4.4	2.2	9.6	2.2	0.4	2.4	4.6	0.9	1.7	1.3	0.3	0.9	0.4
Eh vs SHE (mV) ³	337	411	398	298	-91	338	292	255	186	185	151	323	351
Methane (ppmV) ¹	0	14714	3131	3766	2520	4203	0	0	0	53547	26360	247	1673
Alkalinity	320	340	310	280	220	370	130	380	380	350	440	220	150
Bicarbonate	400	420	380	350	260	450	160	470	460	430	530	270	190
Carbonate	0	0	0	0	0	0	0	0	0	0	0	0	0
Chloride	11	550	420	28	30	11	6	92	95	94	340	11	13
Bromide	nd ⁸	1	1	nd	nd	nd	nd	nd	nd	nd	1	nd	nd
Nitrate	nd	1	1	3	nd	nd	nd	46	50	43	43	1	7
Sulfate	37	46	69	270	100	340	1000	100	110	95	89	79	98
Fluoride	0.2	0.7	0.5	0.5	0.9	0.8	0.8	0.3	0.3	0.6	0.5	0.6	0.7
Calcium	56	48	39	52	15	34	230	100	92	92	53	14	26
Magnesium	53	34	30	38	6	30	220	55	52	42	25	3	6
Potassium	nd	2	4	nd	3	3	2	nd	nd	1	11	5	10
Sodium	56	470	360	190	170	260	48	67	71	91	330	110	58
Total iron	nd	0.1	2.6	3.0	7.2	0.1	0.3	nd	nd	2.0	1.1	nd	0.1
Manganese	0.1	0.1	0.2	0.5	0.1	0.1	6.1	nd	nd	0.1	0.1	nd	0.1
Zinc	0.1	0.1	0.2	0.4	0.2	0.1	0.2	nd	nd	nd	0.1	nd	nd
Strontium	0.6	0.5	0.5	1.0	0.1	0.7	0.9	0.9	0.8	0.6	0.5	0.1	0.1
Barium	0.5	0.6	0.4	0.4	0.1	0.2	0.1	0.1	nd	0.3	0.8	nd	nd
Silicon	9.1	4.9	4.9	4.2	5.9	3.5	6.8	10.5	9.6	8.2	8.1	3.1	2.4
Anion Sum ⁵	7.6	23.5	19.5	12.2	7.2	14.8	24.0	13.1	13.4	12.3	20.9	6.3	5.6
Cation Sum ⁵	9.6	25.4	20.4	14.1	9.3	15.4	31.8	12.6	12.0	12.2	19.4	5.8	4.6
EPM Balance ⁶	11.7	4.0	2.3	7.1	12.3	2.1	14.0	-2.1	-5.5	-0.4	-3.5	4.9	-9.5
Total Dissolved Solids	620	1600	1300	940	600	1100	1700	940	950	900	1400	490	410
Total Hardness ⁷	360	260	220	290	64	210	1480	480	440	400	230	49	91
Noncarb. Hard. ⁷	40	0	0	8	0	0	1350	100	60	50	0	0	0

¹field measurements taken from water collected in a bucket

²field measurements taken from water in flow-through cells

³ millivolts

⁴parts per million by volume

⁵milliequivalents per liter (meq/L)

⁶ percent

⁷ alkalinity, total hardness and noncarbonate hardness expressed as mg/L of calcium carbonate

⁸nd - not detected (below detection limit)

Appendix D

TDS Comparisons- Measured Versus Calculated

<u>Corehole/depth</u>	<u>Atee lab</u>	<u>IGS lab</u>	<u>Lab Age</u>	<u>Calculated</u>
	ppm	ppm	ppm	ppm
<u>SDH # 377</u>				
90'	-----	620	620	2192
305'-360'	1600	1575	1587	1687
540-596'	1100	1316	1208	1985
<u>SDH # 378</u>				
212-227'	700	940	820	493
384-399'	700	601	650	604
422-437'	940	1127	1033	1501
<u>SDH # 379</u>				
34-82'	1500	1696	1598	1659
<u>SDH # 380</u>				
197-229'	579*	940	759	3388
229-261'	644*	950	797	2157
296-363'	589*	900	745	1271
436-468'	990*	1400	1195	2192
<u>SDH # 382</u>				
136-156'	370	490	430	960
333-373'	280	410	345	783

*Lab work rerun several weeks later at IGS request; data shown above is average of the two analyses.

197-229'	648/510
229-261'	698/590
296-363'	627/550
436-468'	1080/900

Appendix E

Comparisons of lab, log data, and differences between calculated and measured TDS Values.

Corehole	Porosity	Rt	Lab Average ppm	Calculated ppm	Difference* ppm
<u>SDH #377</u>					
90'	12%	200	620	2192	+1572
305-360'	18%	100	1587	1687	+100
540-596	18%	80	1208	1985	+747
<u>SDH # 378</u>					
212-227'	17%	375	820	493	-327
384-399'	17%	300	650	604	-41
422-437'	20%	90	1033	1501	+468
<u>SDH # 379</u>					
34-82'	18%	110	1598	1659	+61
<u>SDH # 380</u>					
197-229' **	15%	80*	759	3388	+2629
229-261' **	15%	120*	797	2157	+1316
296-363'	18%	130*	745	1271	+526
436-468'	15%	75*	1195	2192	+997
<u>SDH #382</u>					
136-156'	18%	180*	430	960	+530
333-373'	21%	150*	345	783	+438

* Gas in water, causing Rt to be less representative of formation water.

**Did not produce three borehole volumes prior to sampling, zones drew down to low- or no-flow rate after 1.5 volumes produced.

Appendix F

Data Summary by County

County	Total wells drilled (through 1992)	Wells that provided usable data (log or brine)	No. of wells with 10,000 ppm pick	No. of wells with 3,000 ppm pick
Clay	554	17	12	4
Crawford	114	9	5	3
Daviess	1878	77	38	16
Dubois	1176	66	33	8
Gibson	7884	1075	49	16
Greene	1208	68	22	4
Knox	2107	188	28	12
Martin	386	13	4	4
Owen	176	5	3	2
Perry	765	27	9	6
Pike	4346	159	60	32
Posey	6368	212	17	9
Spencer	3867	244	51	14
Sullivan	2509	69	26	5
Vanderburg	1930	86	4	1
Vigo	900	31	3	3
Warrick	753	206	52	7