W. Steinkampff

PB80-224124

Price $6.50

Use of Geophysical Logs to Estimate Water-Quality Trends in Carbonate Aquifers

(U.S.) Geological Survey
Denver, CO

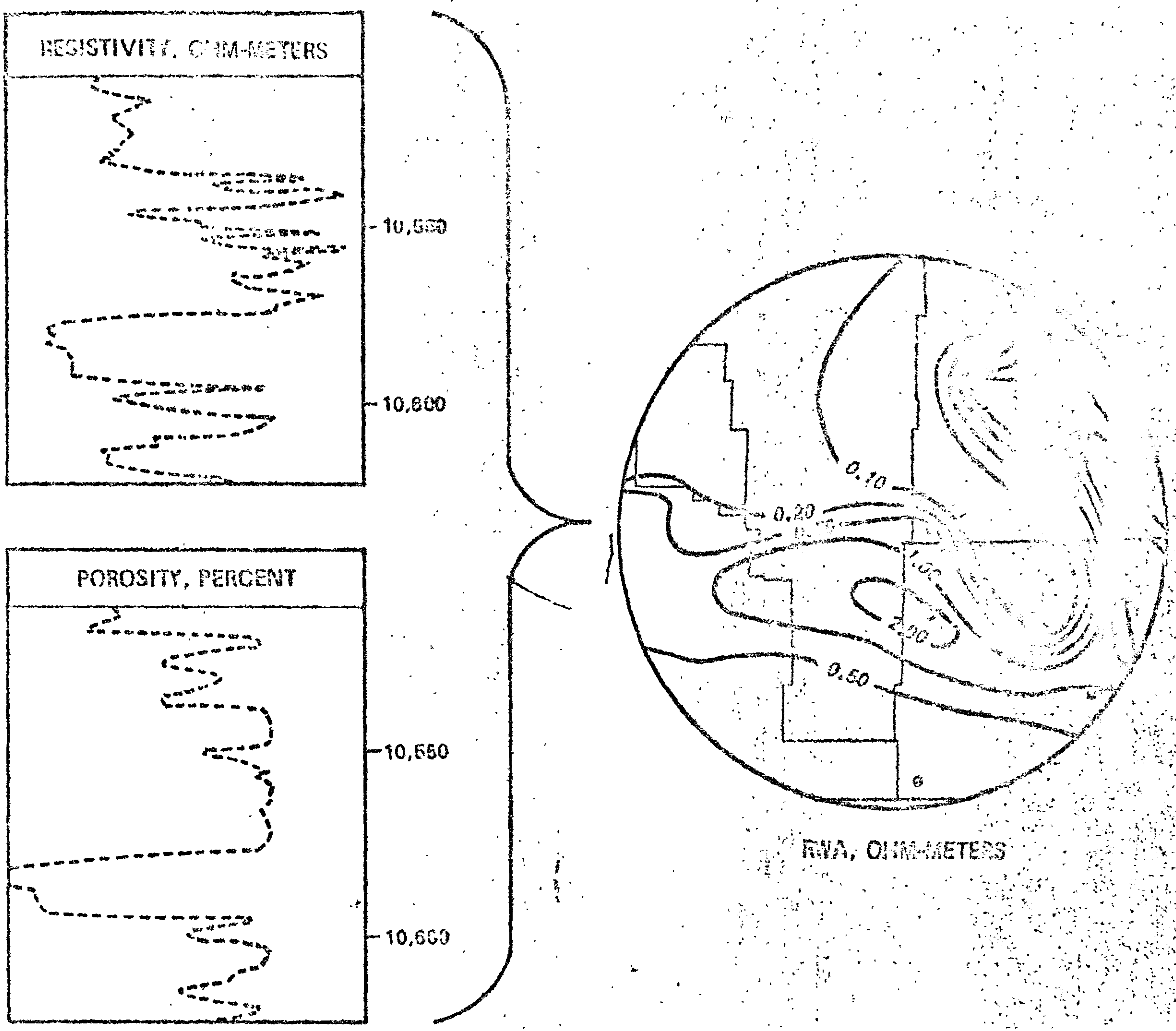
21 80-57

Aug 80

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB80-224124

USE OF GEOPHYSICAL LOGS TO ESTIMATE WATER-QUALITY TRENDS IN CARBONATE AQUIFERS



U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-57

REPORT DOCUMENTATION PAGE

1. REPORT NO. USGS/WRD/WRI-80/007

2.

3. Recipient's Accession No. PB80-224124

4. Title and Subtitle
USE OF GEOPHYSICAL LOGS TO ESTIMATE WATER-QUALITY
TRENDS IN CARBONATE AQUIFERS

5. Report Date August 1980

6.

7. Author(s) L. M. MacCary

8. Performing Organization Rept. No. No.

9. Performing Organization Name and Address
U.S.Geological Survey, Water Resources Division
Mail Stop 418, Box 25046
Denver Federal Center
Denver, Colorado 80225

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered Final

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Water-quality trends in carbonate aquifers can be determined by analysis of resistivity and porosity logs. When supporting data from water analyses are available the value of the cementation exponent m can be determined more precisely. Data for this study were taken from logs of oil-test wells, Amstrat sample studies, drill-stem tests and water test wells in parts of Montana, North and South Dakota, and Wyoming.

The preferred resistivity curves for apparent water resistivity (Rwa) analyses are the deeply focused laterolog and the induction log. The standard electric log can be used if the drilling mud is not saturated with salt. The preferred porosity logs are the sonic, sidewall neutron, compensated neutron, and the density logs. Older, uncalibrated neutron curves can be empirically calibrated in some instances; however, resulting porosities are frequently anomalous when compared to those determined from core or modern logs.

When apparent water resistivity is determined for many wells, the data can be plotted and contoured to outline areas of recharge, direction of probable ground-water movement, and location and salinity of brine areas.

17. Document Analysis a. Descriptors

Carbonate rocks, Radioactive well logging, Electrical well logging

b. Identifiers/Open-Ended Terms

Apparent water resistivity (Rwa), Porosity logs, Resistivity logs, Dissolved solids, Water quality from electric logs

c. COSATI Field/Group

18. Availability Statement
No restriction on distribution.
Prepared for NTIS by U.S. Geological Survey, WRD

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 29

22. Price

(See ANSI–Z39.18)

See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SE OF GEOPHYSICAL LOGS TO ESTIMATE WATER-QUALITY TRENDS IN CARBONATE AQUIFERS

y L. M. MacCary

Water-Resources Investigations 80-57

Denver, Colorado
1980

UNITED STATES DEPARTMENT OF INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

For additional information write to:

Regional Hydrologist
Water Resources Division, Central Region
U.S. Geological Survey
Mail Stop 418, Box 25046
Denver Federal Center
Lakewood, Colorado 80225

CONTENTS

ILLUSTRATIONS

TABLES

METRIC CONVERSION TABLE

Inch-pound units in this report may be converted to metric units by using the following conversion factors:

Multiply	By	To find
inches (in)	25.4	millimeters (mm)
inches	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
feet	30.48	centimeters

USE OF GEOPHYSICAL LOGS TO ESTIMATE WATER-QUALITY TRENDS IN CARBONATE AQUIFERS

By L. M. MacCary

ABSTRACT

This report describes the use of well-log analysis to determine the water-quality trends in carbonate aquifers by use of apparent water resistivities (Rwa). The data were obtained from geophysical logs run by the U.S. Geological Survey or purchased from Petroleum Information Corporation and from sample logs purchased from American Stratigraphic Company (Amstrat logs)[1]. Drill-stem test data and water analyses of oil and water test wells in parts of Montana, North and South Dakota, and Wyoming were obtained from the computer files of the U.S. Geological Survey.

Depending on rock and mud resistivities, two useful resistivity curves for water-quality studies are the deeply-focused laterolog and the induction log. For older wells, the standard electric log may be the only resistivity curve available; it, too, can be used in some instances. The preferred porosity logs are the sonic, sidewall neutron, compensated neutron, and the density log. Wells drilled before the 1960's were generally logged with an uncalibrated neutron curve. In some instances, this curve can be empirically calibrated, but frequently the resulting porosities are anomalous compared to core porosities, or those determined from modern logs.

The wells described in this report penetrated both limestone and dolomite; the highest porosity zones are within the dolomitic rocks. Experience gained during the Madison Limestone project indicates that meaningful Rwa values cannot be calculated when rock porosities are less than 7 percent. Accuracy of Rwa calculations can be improved when water analyses are available from drill-stem tests or pumped samples. Ionic content of the water is recast as an equivalent sodium chloride solution and resistivity of this solution is determined graphically or calculated. Resulting resistivities are used to develop the parameter m in the Rwa equation.

Rwa contour maps derived from geophysical data are useful to outline areas of recharge, direction of probable ground-water flow and location and salinity of brine areas.

---

[1] Use of brand names in this report is for identification and does not imply endorsement by the U.S. Geological Survey.

INTRODUCTION TO GEOPHYSICAL METHODS

Ground-water-quality data used by hydrologists generally consist of chemical analyses of water samples from pumping or flowing wells. Although analysis of actual water samples may be the preferred method in most water-quality studies, two indirect methods, based on the responses of geophysical logs, are also available. The geophysical methods usually will not give specific ion concentrations, but do characterize ground water, and can be used to estimate total dissolved solids. Carbonate aquifers often occur as higher porosity zones within a body of massive, low-porosity rock. Exploring for and analyzing these higher porosity zones requires a more specialized logging program than is needed to study massive sand aquifers. The examination of many cores and geophysical logs from carbonate aquifers during the Madison Limestone project indicates that the porosity must be greater than 7 percent for the Rwa method to yield consistent results. Furthermore, resistivity and porosity logging instruments capable of accurate readings in thin slices of rock are required. All of the example well logs in this report were abstracted from the Madison Limestone study. The porosity ranges of 10 to 15, 15 to 20, and greater than 20 percent porosity were calculated where possible, although porosities as low as 7 percent were used in some wells.

The example logs in this report are in wells penetrating the Birdbear Formation of Devonian age and the Red River Formation, Bighorn Dolomite, or equivalent rocks of Ordovician age, herein called the Red River Formation.

Spontaneous Potential (SP) Method

One geophysical method frequently used in petroleum studies makes use of the SP curve. Water resistivity is determined by substitution in the generalized equation:

$$SP = -K \log \frac{Rmf}{Rw} \qquad (1)$$

where

SP is deflection, in millivolts, of SP curve from shale baseline,

K is a constant approximated by 60 + 0.133 T, where T is borehole temperature in degrees Fahrenheit,

Rmf is resistivity of mud filtrate in ohm-meters,

Rw is resistivity of formation water in ohm-meters.

Use of equation (1) assumes that the borehole fluid (mud filtrate) and formation water both contain the same salt in solution. A second assumption is that the water-bearing formation is a sand bounded by shales that are ideal ion-sieving membranes (Patton and Bennett, 1963). Optimum results from this method are obtained when the formation water contains a minimum of 10,000 milligrams per liter (mg/L) dissolved solids (DS) (Keys and MacCary, 1971). The method works satisfactorily at less than 10,000 mg/L DS provided both the mud filtrate and the formation water are of similar composition, and provided that Rmf is much greater than Rw (Vonhoff, 1966). For a comprehensive discussion of the SP method with examples, see Alger (1966).

Although the SP method works well in sand-shale sequences, it works poorly, if at all, in thick carbonate rocks of low porosity. The SP curve in carbonate lithology tends to spread above and below the bed boundary; frequently the SP becomes a straight line parallel to or slightly inclined to the log axis. The lack of definition at bed boundaries and the possibly great vertical distance to an ion-sieving shale bed makes it impossible to read a deflection of SP millivolts with any degree of certainty. The behavior of the SP in low porosity carbonate rocks is discussed in Schlumberger (1972).

Resistivity-Porosity Method

The other commonly used geophysical method to evaluate water quality makes use of the apparent water resistivity (Rwa) based on the equations by Archie (1942):

$$F = \frac{Ro}{Rw}, \text{ for non-shaly formations, 100 percent water saturated} \qquad (2)$$

and

$$F = \frac{1}{\phi^m}, \text{ for consolidated formations} \qquad (3)$$

where

F is formation resistivity factor,
Ro is resistivity of water-saturated formation in ohm-meters,
Rw is resistivity of formation water in ohm-meters,
ϕ is porosity as a decimal between 0 and 1, and
m is cementation exponent.

Combining equations (2) and (3), and substituting Rwa for Rw gives:

$$Rwa = \phi^m Ro. \qquad (4)$$

Rwa is substituted for Rw in equation (4) because the equation is not a representation of actual water resistivity, but rather it is an apparent resistivity that is indirectly related to Rw through Ro and ϕ. Equation (4) means that the product of the formation resistivity and the formation porosity raised to the power m is equal to a number that bears more or less a direct relation to the water resistivity, Rw. Rwa, as used here, is assumed to be a measure of the resistivity of a sodium chloride solution or an equivalent sodium chloride solution. Equation (2) is an empirical relation determined from the analysis of oil-field waters having resistivities less than one ohm-meter. When Rwa is greater than about one ohm-meter, other ions such as calcium (Ca), magnesium (Mg), bicarbonate (HCO_3), and sulfate (SO_4) will affect water resistivity in a manner different than sodium chloride (NaCl) (Alger, 1966). Fairly consistent approximations of Ro and ϕ, which are the keys to the Rwa method, can be determined from modern resistivity and porosity log suites.

In addition to accurate measurements of ϕ and Ro, the value of m must be selected for equation (4). Values of m for several lithologies are listed in Carrothers (1968) and Trougott (1970). Generally, m = 2 is used for carbonate rocks; however, m can be determined empirically for a specific aquifer, when resistivity, porosity, and water-quality analyses are available. The pattern-recognition method, described by Pickett (1973), can be used to find the value of m for a specific formation. When several ϕ and Ro measurements of an aquifer are plotted on a log-log graph, the points will generally define a straight line, whose slope equals m, the exponent of ϕ in equation (4). Typically, many ϕ and Ro points from several wells are plotted; then the fitted line is extrapolated to the 100-percent-porosity level to determine Rw. Rw would be the minimum resistivity recorded if only formation water filled the logging environment. In the method used here, Rw is known from water quality analyses, with at least one measurement of ϕ and Ro in the same well. These points are plotted on the log-log graph, and the slope of the connecting line is solved for m. Figure 1 illustrates the method of finding m from wells in the Ordovician Red River Formation. Rw, ϕ, and Ro from many wells are needed to arrive at an average m for use in equation (4).

Determining Water Resistivity (Rw) From Water Analyses

To use the cross-plot method (fig. 1) for finding m, the Rw of formation water must be determined. Most laboratories specializing in the analysis of oil-field water will report Rw at 25°C on the analysis. Other water-quality laboratories may report the specific conductance in micromhos per centimeter (μmhos/cm), which can be converted to resistivity in ohm-meters by the following equation:

$$\text{Ohm-meters} = \frac{10{,}000}{\mu\text{mhos/cm}} . \qquad (5)$$

Some analyses do not report resistivity or specific conductance, especially when highly concentrated oil-field waters are analyzed. If the major anions, cations, and DS are reported in these analyses, a reasonable value for Rw can be calculated. Although graphs of DS and resistivity can be used to determine the Rw of a solution, a more accurate resistivity will be obtained by converting the ionic constituents to an equivalent sodium chloride solution. Resistivity of the equivalent solution is determined by a formula or from a graph. The method described here uses the Sinclair Variable Multipliers (Desai and Moore, 1969), which consider total ionic concentration of the water and convert all ionic constituents of the water into an equivalent NaCl concentration. The relationship between electrical conductance and increasing ionic concentration is linear for solutions containing less than a few thousand mg/L of ionic constituents. At the higher concentrations, the rate of conductivity increases more slowly than the rate of ionic concentration, even if only one salt, such as NaCl, is present. Conductivity may even decline with increasing salt concentration, because some of the free water is taken up and the solution may increase in viscosity. When more than one salt is present, the contribution of each salt to total conductivity depends on its ionic concentration, the concentration of the other salts, and the formation of ion pairs. The purpose of the Sinclair Variable Multipliers is to adjust the conductivity contribution of each ion based on total concentration of all ions in the solution. The Sinclair multipliers are tabulated

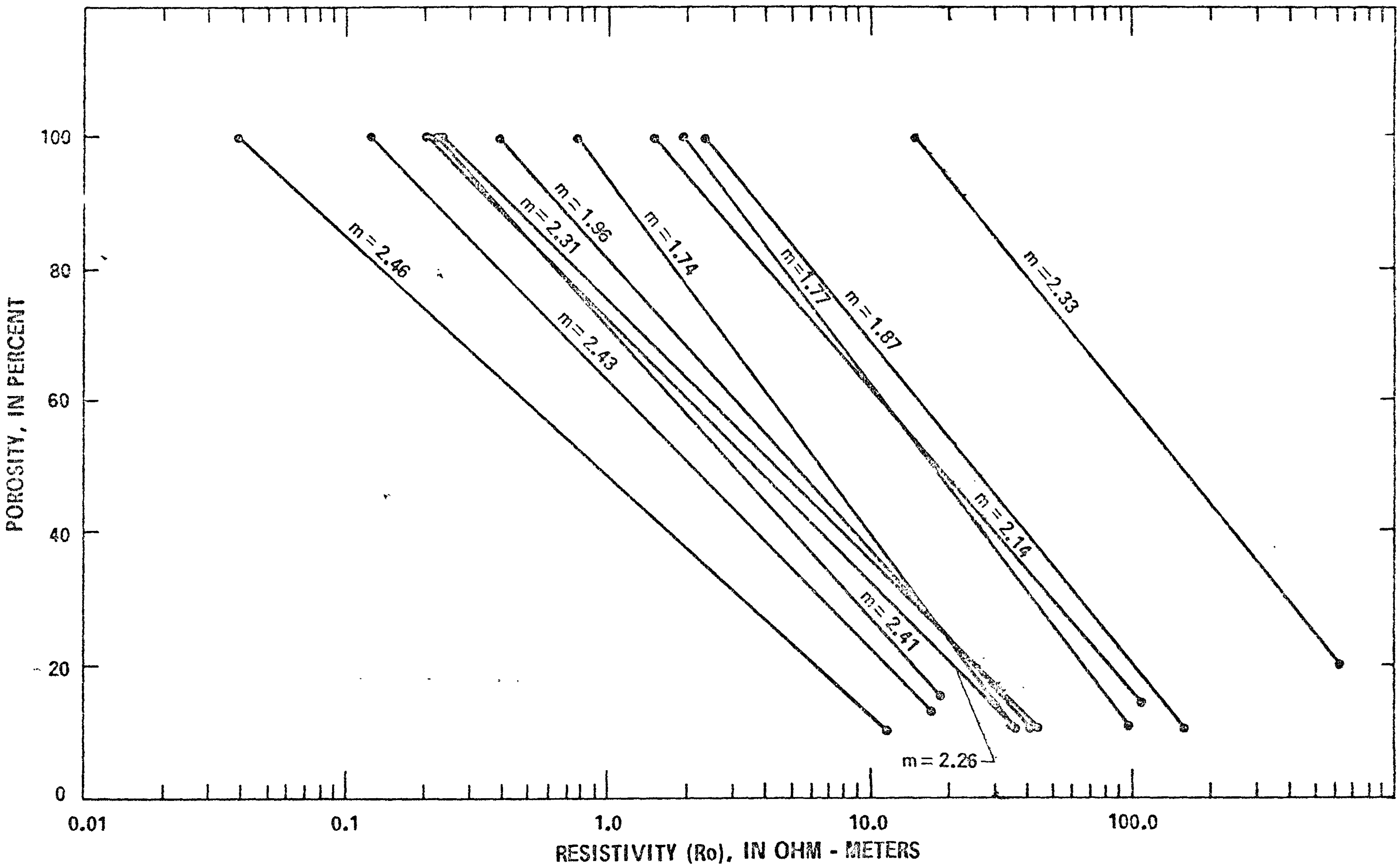


Figure 1.--Relation of m to porosity and resistivity

by parts per million (ppm), so analyses reported in mg/L must be converted to the weight per weight unit by dividing the mg/L of each constituent by the specific gravity of the solution. The Sinclair Variable Multipliers are reproduced as table 1-3 in Dresser Atlas (1979).

An example of this method using water-quality data for the Red River Formation in a North Dakota well is illustrated in table 1. The water analysis is listed with the appropriate multiplier for each ionic constituent (Desai and Moore, 1969). The last column in the table lists the product of ppm and the multiplier. The sum of the products is the concentration of an equivalent NaCl solution in ppm. Resistivity of this solution can be determined from nomograph 1-4 in Dresser Atlas (1979). The formula from Dresser-Atlas (1979),

$$Rw = 0.0123 + \frac{3647.5}{[\text{NaCl ppm}]^{0.955}}, \qquad (6)$$

can be used to calculate Rw, when the total ppm as NaCl is less than 100,000 ppm. The calculated resistivity in table 1 differs from the measured value by about 9 percent. In most cases the difference between the calculated and the measured resistivities will be less than plus or minus 10 percent, and should be within plus or minus 5 percent according to Desai and Moore (1969).

Table 1.--*Analysis of water from drill-stem tests in a North Dakota well*

Constituent	Concentration (ppm)	Sinclair variable multiplier	Resultant (ppm)
Calcium	7,640	0.349	2,666
Magnesium	1,420	-.652	-926
Sodium	66,056	1.0	66,056
Bicarbonate	60	.100	6
Sulfate	1,235	.200	247
Chloride	118,600	1.0	118,600
Dissolved solids calculated	194,880	-----	-------
Equivalent NaCl	-------	-----	186,649

Specific gravity	1.129 g/cc
Measured resistivity	0.056 ohm-meters
Calculated resistivity (from nomograph, Dresser-Atlas, 1979)	0.051 ohm-meters

One source of water-quality data is drill-stem tests of oil wells. Usually the water samples are analyzed for dominant anions, cations, total solids, specific gravity, and resistivity. Occasionally, groups of analyses will be found, which report only Na, SO_4, DS, and specific gravity. The Rw of these incomplete analyses can be estimated if one assumes the most probable salts or hypothetical combinations are dominant. These salts are usually NaCl, calcium sulfate ($CaSO_4$), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$) in an oil-field water (Collins, 1975). A further assumption is that DS are high enough that carbonate and bicarbonate are negligible. The method of calculation allots a certain amount of the total ppm to each of the most probable compounds.

The calculations are most easily accomplished in a series of steps so that each concentration can be determined in the right order. For example, water from a drill-stem test in the Red River Formation of Ordovician age in Montana contains 3,422 mg/L Na, 988 mg/L SO_4, 11,723 mg/L DS, and a specific gravity of 1.009 grams per cubic centimeter (g/cm^3). The reconstructed analysis and calculated resistivity is done in the following steps:

1. Convert the mg/L of ions and DS to ppm by dividing each by the specific gravity, which gives 3,391 ppm Na, 979 ppm SO_4, and 11,618 ppm DS.

2. Use gravimetric factors (Hamilton, Simpson, and Ellis, 1969, p. 112-133) to determine the concentrations of the two most probable salts of the reported ions. Thus,

$$\text{ppm } CaSO_4 = \frac{(\text{ppm } SO_4)\text{X}(\text{molecular weight of } CaSO_4)}{(\text{molecular weight of } SO_4)}$$

$$= \frac{979 \text{ X } 136.14}{96.06}$$

$$= 1{,}387$$

and,

$$\text{ppm NaCl} = \frac{(\text{ppm Na})\text{X}(\text{molecular weight of NaCl})}{(\text{atomic weight of Na})}$$

$$= \frac{3{,}391 \text{ X } 58.45}{22.99}$$

$$= 8{,}621$$

3. Calculate the concentrations of $CaCl_2$ and $MgCl_2$. The sum of NaCl and $CaSO_4$, determined in step 2, is 10,008 ppm and the difference between this sum and the DS of 11,618 ppm is 1,610 ppm. This value is the sum of $CaCl_2$ and $MgCl_2$. The ratio of Ca to Mg in ground water increases as DS increase (Collins, 1975). Different aquifers will often have different ratios, even though the DS may be nearly equal. The Ca to Mg ratio in Red River Formation water is about 4, when the water contains less than 15,000 DS. Therefore, we allot 4/5 of the remaining 1,610 ppm to $CaCl_2$ and 1/5 to $MgCl_2$, 1,288 and 322 ppm, respectively. The reconstructed concentrations of the most probable salts are, therefore, 8,621 ppm NaCl, 1,387 ppm CaSO , 1,288 ppm $CaCl_2$, and 322 ppm $MgCl_2$.

Use gravimetric factors (step 2, above) to calculate the ppm of each ion in the reconstructed salt concentrations. For example, in $CaCl_2$,

$$\text{ppm Cl} = (\text{ppm } CaCl_2) \times \frac{2(\text{atomic weight of Cl})}{(\text{molecular weight of } CaCl_2)}$$

$$= 1{,}288 \times \frac{2 \times 35.45}{110.98}$$

$$= 823$$

and ppm Ca = 465.

The calculated anion and cation distribution is listed in table 2 along with the Sinclair Variable Multiplier for each ion. The sum of the products gives an equivalent NaCl solution of 10,954 ppm with a calculated resistivity of 0.52 ohm-meters.

Table 2.--*Computed analysis of water from drill-stem test in a Montana well*

Constituent	Concentration (ppm)	Sinclair variable multiplier	Resultant (ppm)
Calcium (from $CaSO_4$ plus $CaCl_2$)---	873	0.778	679
Magnesium (from $MgCl_2$)-------------	82	1.273	104
Sodium (from NaCl)-----------------	3,391	1.0	3,391
Sulfate------------------------------	979	.497	487
Chloride (from NaCl plus $CaCl_2$ plus $MgCl_2$)---------------------	6,293	1.0	6,293
Total------------------------------	11,618		
Equivalent NaCl-------------------			10,954

Resistivity (from equation (6)) = 0.52 ohm-meters

Resistivity Logs

Standard electric logs (normals and laterals) depend on electrical conductivity of borehole fluid to couple the logging current into the formation. Furthermore, they have variable depths of penetration depending on the ratio of mud resistivity (Rm) to Rw and on the porosity of the rock. When Rm is low compared to Rw, and when rock porosity is low, most of the logging current traverses the borehole, and little penetrates the rock. This results in an apparent resistivity (Ra) which bears little resemblance to the actual resistivity of the water-saturated environment (Ro). These logs will produce acceptable measurements in the higher porosity zones, provided the beds are thicker than the electrode spacing (Schlumberger, 1972).

Other resistivity logs that may give acceptable measurements in carbonate aquifers are the induction log and the deeply penetrating guard logs (includes such industry-named devices as the LL3, LL7, and LLd). The induction log works well where rock resistivities are less than 50 to 100 ohm-meters, and the borehole fluid is not saturated with salt. The induction device samples rock in about 40-in vertical increments; the focusing is such that most of the signal comes from a cylindrical zone lying between 40 and 120 in from the well bore. The induction device is suitable for examining thin aquifers of low porosity, because drilling fluid would have to invade beyond 40 in to adversely affect the resistivity value. The deep laterolog works well when salt mud is used in drilling, or when rock resistivities are greater than the limits of the induction tool. Salt mud is widely used in areas where thick sections of halite must be drilled; saturated mud inhibits the solution of the salt, which otherwise would cause severe hole enlargement problems. Laterolog devices are deeply penetrating systems that measure the resistivity of beds as thin as one foot. They are affected by invasion more strongly than induction logs, and their readings must be corrected if invasion proceeds beyond a few well diameters. Laterologs work well in fresh mud, provided the ratio of Ro to Rm is greater than 50. This is not an unattainable situation in a fresh water regime, because Ro/Rm is often greater than 50 and may be more than 100. In a hole with 2 ohm-meter mud, rock resistivities should be greater than 100 ohm-meters to be an acceptable measurement.

Porosity Logs

Porosity-logging technology has undergone many changes and improvements since the neutron tools of the early 1950's. Early neutron sondes were neither shielded from the borehole nor focused into the formation; thus, porosity measurements were strongly affected by the borehole roughness and the fluid. Some service companies produced logs with a scale in standard neutron units; some produced logs with scales in API units; and some produced logs with no scale other than an arrow showing the direction in which radiation increased. Porosity is estimated from these early logs from published graphical solutions, or by empirically fitting a logarithmic scale between known or presumed maximum and minimum porosities. Many of the neutron logs currently run by small, water-well loggers are unshielded and uncollimated, similar to those run by service companies 25 or 30 years ago. These logs also can be rescaled in porosity units by an empirical method described later in this report.

Some of the improved neutron tools that have appeared in the last two decades include the sidewall-neutron log and the compensated-neutron log. The sidewall-neutron method employs a shielded, collimated sonde which rides against the wall of the borehole minimizing fluid and borehole effects. The compensated-neutron method uses two or more detectors at various spacings to compensate for the borehole effects.

Another family of porosity tools are the so-called density sondes. These produce curves that can be used to estimate porosity from bulk-density measurements. Modern density sondes are shielded, collimated, and decentralized to minimize borehole effects. Modern log suites usually combine a density-porosity curve with a compensated-neutron-porosity curve. The neutron curve tends to read higher-than-actual porosity and the density lower-than-actual porosity. An average of the two porosity readings compensates for the lithology effects and agrees closely with the cross-plot porosity shown in Schlumberger (1969).

The third family of porosity curves suitable for Rwa calculations are acoustic or sonic logs. The sonic curve tends to respond to total intergranular porosity. Secondary porosity, such as vugs and fractures, will not be accurately recorded because acoustic waves travel preferentially through the rock matrix around the openings. For studies requiring an accurate evaluation of secondary porosity, another porosity tool, such as the neutron, must be used in conjunction with the sonic log (MacCary, 1978).

DETERMINING POROSITY (ϕ) AND RESISTIVITY (Ro) FROM LOGS

Examples of several log combinations will be used to illustrate the Rwa method. Each log suite was analyzed for porosity and resistivity using consistent criteria. The total footage of porosity for three porosity increments, 10 to 15, 15 to 20, and greater than 20 percent, was tabulated for each water-bearing formation in a well. The product of footage and porosity is called porosity-feet. The porosity-feet values for the 10 to 15 increment, the 15 to 20 increment, and the more than (>) 20 percent increment for each water-bearing formation are added, and this sum is then divided by the total footage in the water-bearing formation to derive a weighted average porosity (10 percent or greater).

Resistivities corresponding to each water-bearing formation are read from the best available resistivity curve. In a manner similar to the porosity evaluations, resistivities are tabulated by footage and the total resistivity-feet for each water-bearing formation is divided by total feet to obtain a weighted average of resistivity. Multiplying resistivity or porosity by the footage tends to offset the effects that thin beds of very high or very low values might have on average values. Other curve averaging techniques could be used instead of the porosity-feet and resistivity-feet method.

Figure 2 shows the electric and neutron logs of only the Red River Formation in a 1952 oil-test well in Custer County, Mont. The electric log has two normals, a lateral, and the SP curve. Three resistivity scales, 0 to 50, 0 to 500, and 0 to 5,000 ohm-meters are needed to cover the wide range of resistivities in this hole. Resistivity is generally less than 50 ohm-meters in the sand and shale sequences down to a depth of 6,300 ft. Carbonate rocks occur below this depth, and they become the dominant rock type below 7,200 ft. Resistivities exceed 1,500 ohm-meters in some anhydrite beds within the carbonate rocks. The lithology between 8,810 and 9,175 ft is dolomite and limestone, with four beds of higher porosity at 8,865, 8,925, 8,990, and 9,110 ft. Except for the uppermost bed, none of the bed boundaries could be picked with accuracy from the SP curve. A prominent shale occurs at 8,810 ft; however, it is not shown by the SP curve, but is defined by the gamma-ray log. The neutron curve is uncalibrated; one possible way it can be related to porosity changes is by using a logarithmic scale between high and low porosity rocks, such as shale and anhydrite or a tight limestone. Anhydrite is a dense rock of less than 3 percent porosity; tight limestones will frequently have 3 percent or less porosity. These logs record many thousands of feet of well bore; only a small part can be shown on the figures. For purposes of illustration, horizontal deflections of the log curves at certain beds are shown on the figures, even though these beds may be much higher or lower on the original logs. For example, a massive anhydrite bed occurs between 7,545 and 7,560 ft, but the horizontal deflection of the neutron curve at the anhydrite bed is projected onto figure 2.

The neutron response is affected by the mineralogy of rock matrix; therefore, the porosity calibration lines occupy different positions on the log for limestone, dolomite, and sandstone. The porosity of dolomite as represented on the limestone scale would be as follows: 10-percent porosity falls at 12.5 percent; 15 percent falls at 17.7 percent; and 20 percent falls at 23 percent, respectively. Lithology of a zone must be known before a porosity calibration line can be constructed. The neutron curve is also affected by hole size; thus hole enlargements appear as an increase in porosity. Unfortunately, caliper curves were not run with older neutron logs, which sometimes makes hole-size changes very difficult to recognize.

Shale is a rock of variable porosity, depending on the amount of compaction. Near the surface, shale may have a porosity of 40 percent; but, at a depth of 10,000 ft, it is typically about 10 percent or less, except in over-pressured areas, such as the Gulf Coast. For this reason, a shale near the surface should be used for the high porosity point in calibration calculations; however, the neutron log in figure 2 does not go above 6,600 ft. The next best choice in these circumstances is to use the shallowest shale, which occurs at 6,685 ft; its horizontal deflection on the neutron curve is projected on to figure 2. A logarithmic scale is fitted between these assumed 2-percent (anhydrite at 7,545 to 7,560 ft) and 40-percent (shale at 6,685 ft) porosity points, and the 10-, 15-, and 20-percent porosity lines for dolomite are drawn on figure 2. The main porosity zones between 8,810 and 9,175 ft all seem to have porosities greater than 10 percent, and the upper three are greater than 20 percent. This might seem reasonable, except that analysis of many wells in the area indicates that porosity rarely exceeds 20 percent and seldom goes as high as 13 percent in these intervals. Clearly, calculations are in error by assuming that the shale is uncompacted and has a porosity of 40 percent. In fact, the shale at 8,810 ft shows a porosity of 32 percent on the calibration scale. Clearly, this old neutron log cannot be accurately scaled in porosity units by this empirical method and the log should not be used in Rwa calculations.

Some older neutron logs were scaled in counts per second and can be related to porosity by graphs or nomographs. Finding graphs for archaic logging tools may be difficult, but the curves can sometimes be calibrated by the empirical method, particularly if a neutron zero was recorded on the log. Neutron zero then becomes a pivot point about which the logarithmic scale is rotated until the 2 percent line coincides with the neutron curve in an anhydrite.

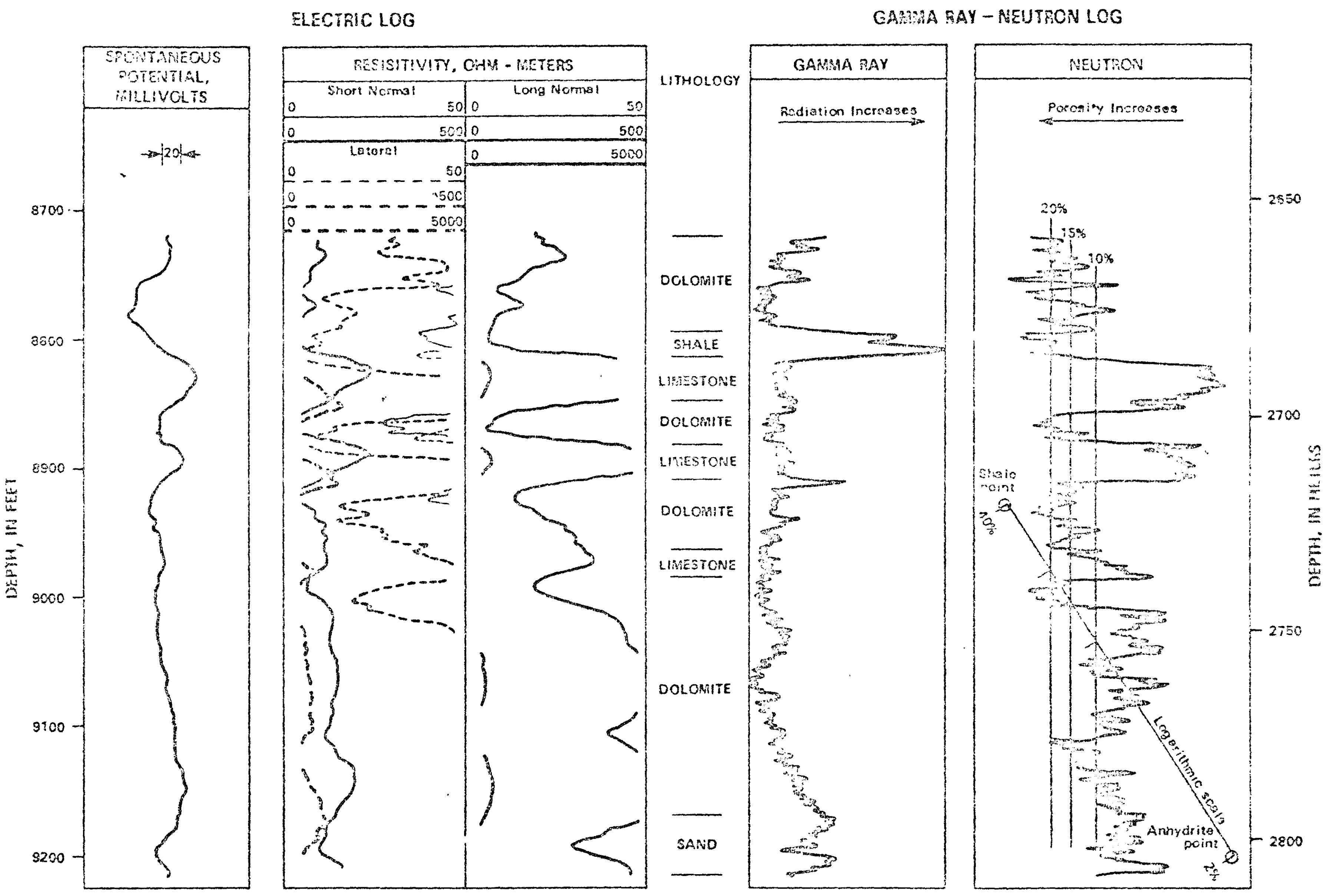


Figure 2.--Electric and neutron logs of Red River Formation

Figure 3 shows the electric and neutron curves of the Red River Formation in an oil well drilled in Carter County, Mont., in 1955. The neutron log is scaled in counts per second, and the neutron zero is indicated on the heading. Using the neutron zero pivot point and an assumed 2 percent anhydrite bed at 4,860 ft (projected onto log), the 10- and 15-percent lines for dolomite are constructed. The resulting porosities in the interval between 5,300 and 6,360 ft average about 13 percent, which is within reason for this interval. When the calibration lines are projected to a thick shale at 6,400 ft (not shown on log), shale porosity falls at about 30 percent, illustrating the effects of compaction. Another shale bed at 6,900 ft has between 25 and 30 percent porosity, indicating even more compaction at greater depth. Shales near the surface plot at 40 percent porosity on this log. The long normal resistivity curve in figure 3 has an average reading of 133 ohm-meters for the three porosity zones. This is the resistivity as measured at borehole temperatures and must be corrected to a standard temperature 77°F (25°C), so that Rwa values will be comparable.

Using chart 1-1 in Dresser Atlas (1979) at a mean annual surface temperature of 40°F, and GEN-9 in Schlumberger (1969), the temperature at 5,300 ft is 114°F, and the 133 ohm-meter resistivity at this depth, when corrected to 77°F, is 197 ohm-meters. This corrected resistivity, 13 percent porosity, and m = 2 are used in equation (4) to solve for Rwa:

$$\begin{aligned} \text{Rwa} &= (0.13)^2 \times 197 \text{ ohm-meters} \\ &= 3.3 \text{ ohm-meters at } 77^\circ\text{F} \end{aligned}$$

A further refinement can be made by first adjusting the bottom-hole temperature for disequilibrium, using the formula in Muffler (1979). The formation temperature is then calculated, and the resistivity at this temperature is adjusted to standard temperature. Disequilibrium calculations take into account the cooling effects of mud circulation, and adjust the bottom-hole temperatures upward by a statistical method.

An example of an induction curve and sidewall-neutron log used in Rwa calculations is shown in figure 4. The sidewall-neutron curve is relatively simple to use, because three porosity calibrations for each dominant sedimentary lithology (limestone, dolomite, and sandstone) are shown on the log heading. The logs of figure 4 are from a 1966 oil-test well in McCone County, Mont. This well penetrated dolomite and limestone in the Red River Formation from 9,550 to 9,863 ft. Average porosity of the dolomite peaks is 10 percent, and average induction resistivity uncorrected for disequilibrium and formation temperature is 6.2 ohm-meters. When corrected for both effects, resistivity becomes 15.8 ohm-meters; the importance of making these corrections is apparent.

Figure 5 is the dual laterolog and the compensated-neutron formation-density log of dolomite in the Birdbear Formation, penetrated in a 1977 oil-test well in Richland County, Mont. The deep laterolog (dashed curve) in the right-hand track should be used for resistivity calculations. The scale on the resistivity curves is a four-decade logarithmic scale from 0.2 to

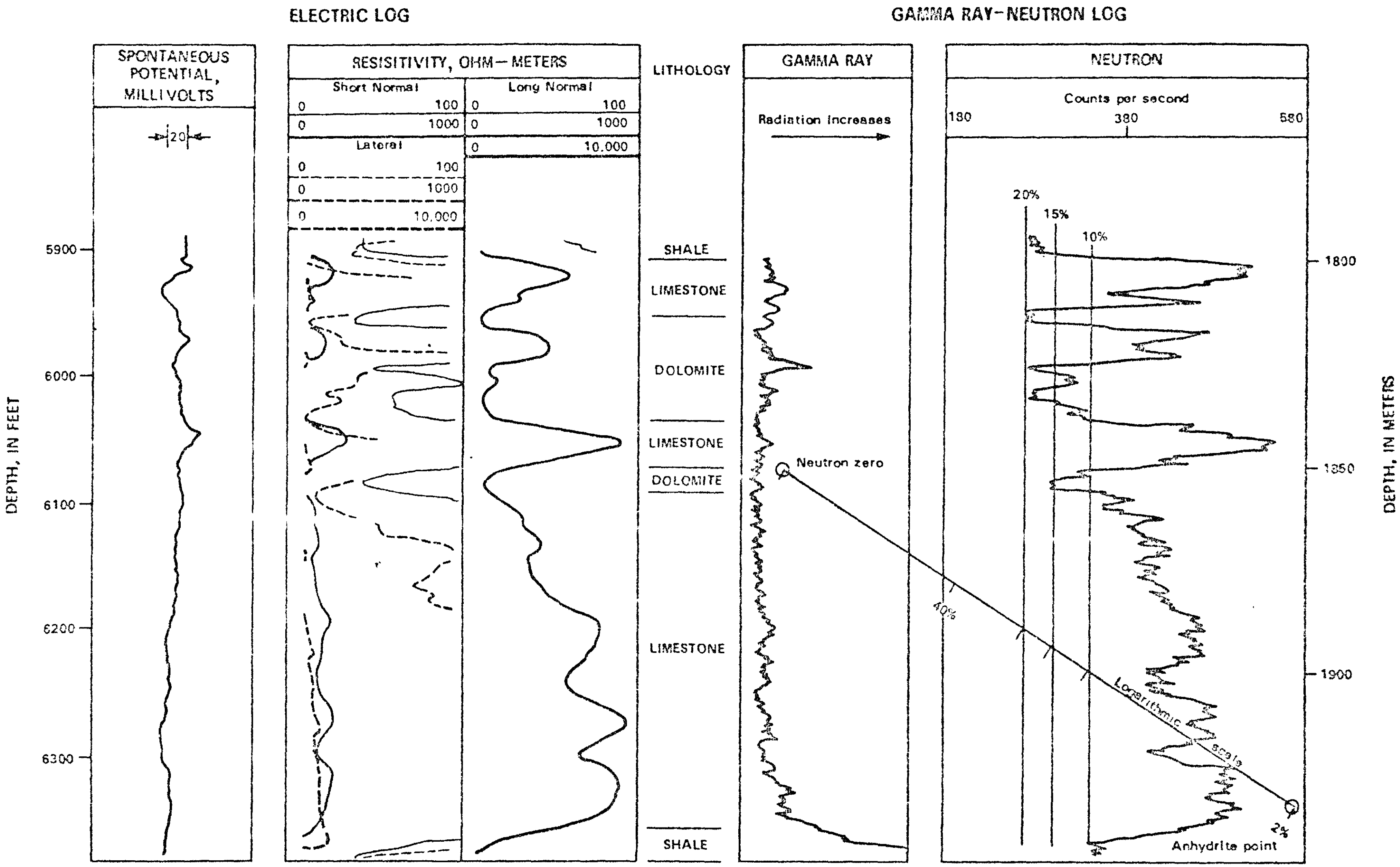


Figure 3.--Electric and neutron logs of Red River Formation in Carter County, Mont.

GAMMA RAY – SIDEWALL NEUTRON LOG

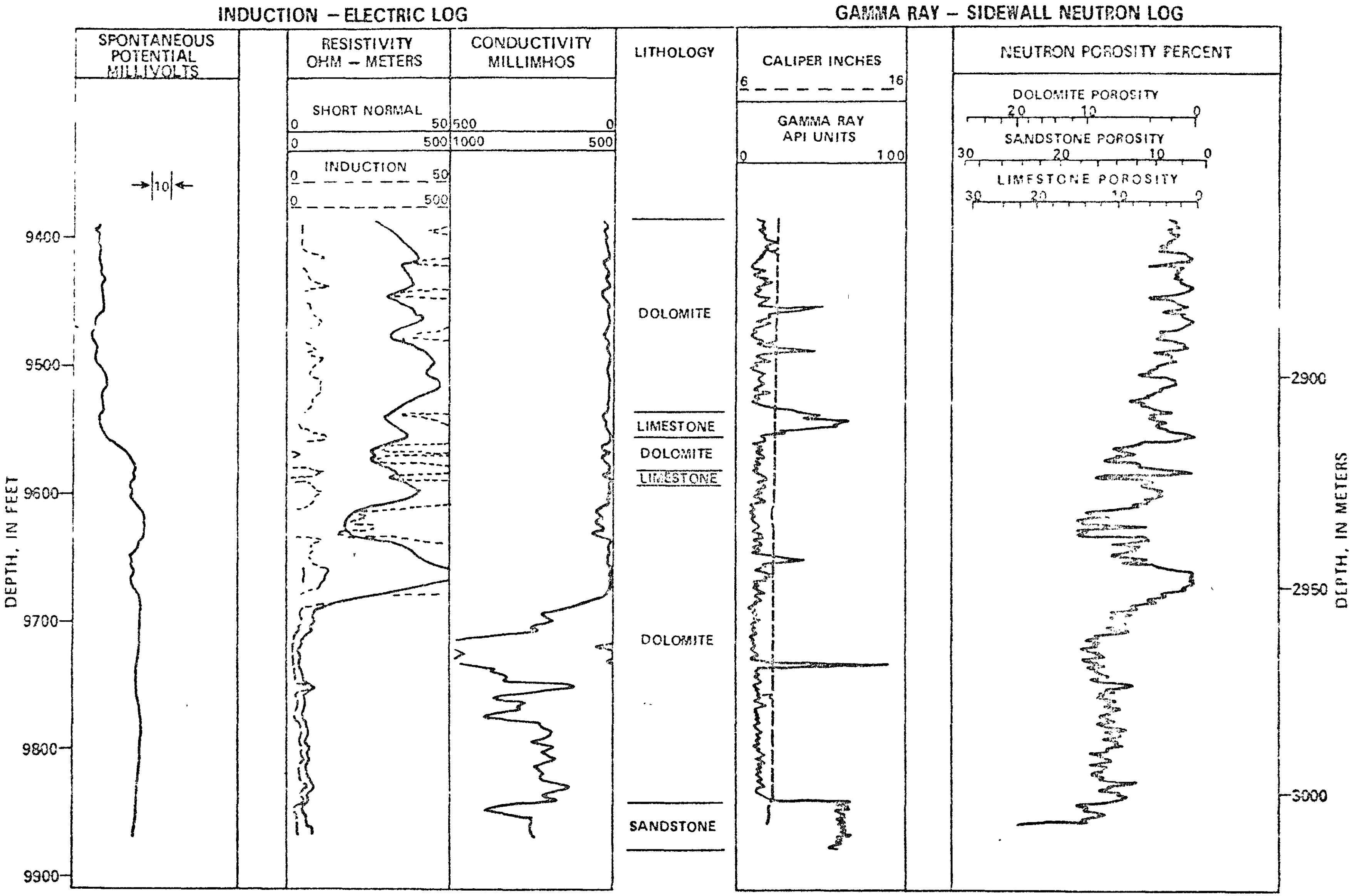


Figure 4.--Induction and sidewall neutron logs of Red River Formation in McCone County, Mont.

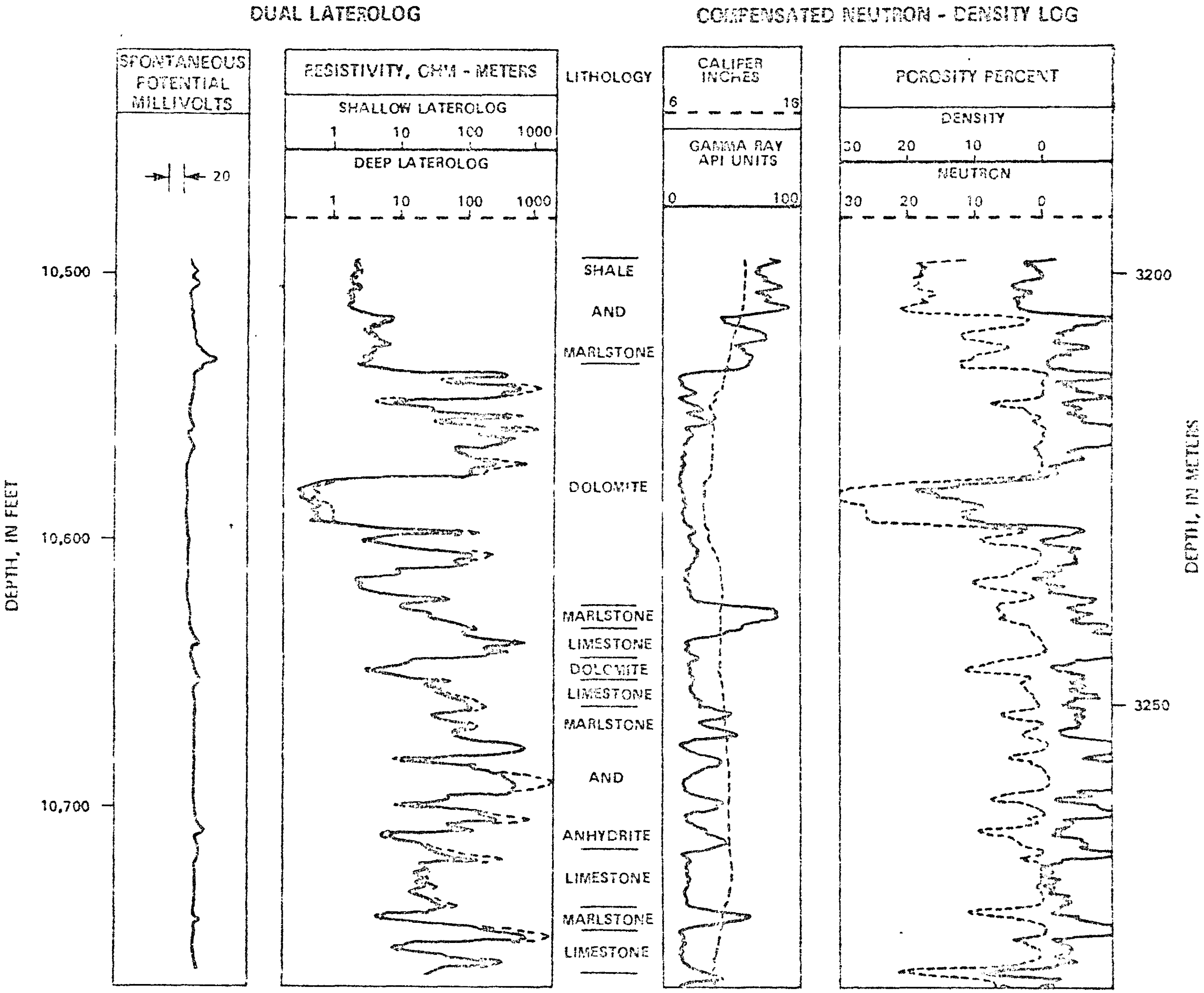


Figure 5.--Dual laterolog and compensated-neutron formation-density log of Birdbear Formation in Richland County, Mont.

2,000 ohm-meters. This type of scale simplifies recording and reading a wide range of resistivities. The average uncorrected resistivity in the most porous zone between 10,575 and 10,595 ft is about 0.8 ohm-meters. Porosity of the zone is found by taking the midpoint between neutron porosity and density porosity. Average porosity thus obtained is approximately corrected for lithology of the formation. Average porosity in this zone is 22.1 percent. Using a temperature corrected resistivity of 2.30 ohm-meters and 22.1 percent porosity in equation (4) gives an Rwa of 0.05 ohm-meters, which is a nearly saturated brine solution.

If either the compensated neutron or the density log is used alone to calculate porosity, lithology of the zone must be known so proper porosity calibration lines can be constructed. Porosity can be calculated from the density log by the equation:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad (7)$$

where

ϕ is porosity, as a decimal between 0 and 1,

ρ_{ma} is density of rock matrix in g/cm^3,

ρ_b is bulk density in g/cm^3 read from log curve,

ρ_f is density of formation water, 1.0 g/cm^3 if fresh water.

Dolomite will have a ρ_b of 2.68 g/cm^3, 2.59 g/cm^3, and 2.50 g/cm^3 for porosities of 10 percent, 15 percent, and 20 percent, respectively.

Figure 6 shows the dual laterolog and sonic log of Red River Formation limestone and dolomite in a 1977 water-test well drilled in Custer County, Mont. As with neutron and density curves, the sonic log is affected by rock matrix; porosity lines for each rock type must be drawn on the log. Although limestone makes up much of the rock from 8,105 to 8,560 ft, it does not reach 10 percent porosity. Dolomite has an interval transit time (Δt_1) of 57.8 microseconds per ft, 65.0 microseconds per ft, and 72.2 microseconds per ft for porosities of 10 percent, 15 percent, and 20 percent, respectively. Dolomite zones between 8105 and 8560 ft have an average porosity of 14.4 percent. The average uncorrected resistivity of these zones is 48 ohm-meters. When corrected to equilibrium and adjusted to 77°F, resistivity becomes 116.4 ohm-meters, and Rwa from equation (4) is 1.8 ohm-meters. Porosity can be calculated from the sonic log by the equation:

$$\phi = \frac{\Delta t_1 - \Delta t_{ma}}{\Delta t_f \quad \Delta t_{ma}} \qquad (8)$$

where

ϕ is porosity as a decimal between 0 and 1,

Δt_1 is interval transit time from log, in microseconds per ft,

Δt_{ma} is interval transit time of rock matrix, in microseconds per ft,

Δt_f is interval transit time of formation fluid, in microseconds per ft.

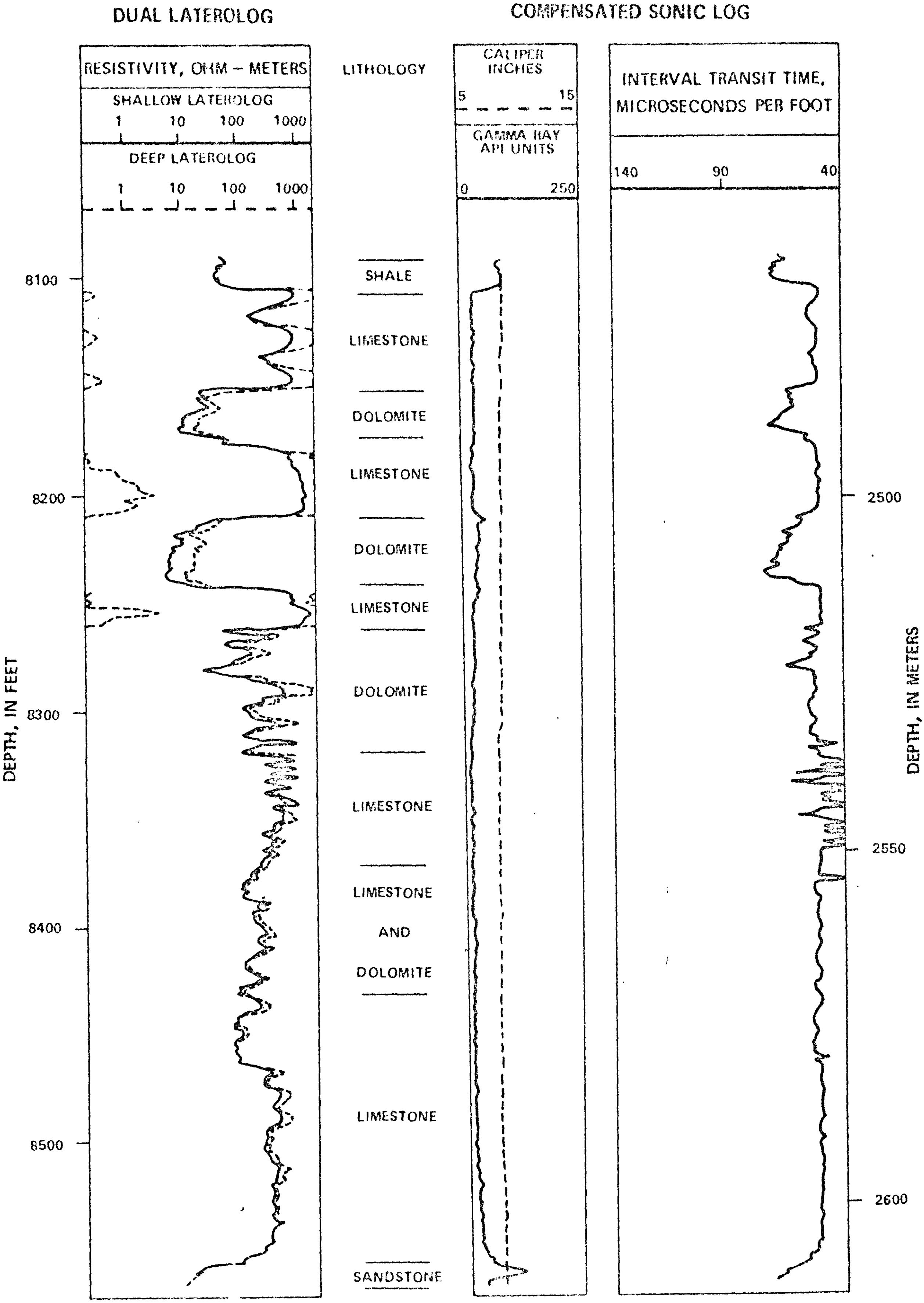


Figure 6.--Dual laterolog and sonic log of Red River Formation in Custer County, Mont.

Typical values of Δt_{ma} and Δt_f can be found in logging literature, such as Dresser-Atlas (1974), Schlumberger (1972), and Gearhart-Owens (1975).

APPLICATION OF APPARENT WATER RESISTIVITY (Rwa)

When resistivity and porosity logs of several wells in an aquifer are available, Rwa can be calculated, and the resistivities contoured. Rwa contours will show areal distribution of water quality, as water moves from the recharge area into deeper basins. In some regions, such as the Northern Great Plains, large areas of dense, saturated brine occupy the deeper basins. Rwa contours indicate that less mineralized water moves along the perimeter of the brine area, the brine remaining as an undiluted, stagnant body. Figure 7 is the Rwa map for the Ordovician Red River Formation in part of the Northern Great Plains. Lobes of fresher water (high Rwa) originating in the Black Hills extend northward into Montana and northeastward across South Dakota. The axis of the deepest part of the Red River is shown by the stippled line. The hydrodynamic effects of moving water have displaced some of the body of saturated brine, 0.04 ohm-meters, east and north, away from the axis of the basin. Much useful information can be gleaned from Rwa maps, such as areas of fresh recharge, areas of dense brine, and probable directions of ground-water movement.

Water concentration as sodium chloride can be approximated from a Rwa map. Figure 8 is a graph of all available data from the Red River Formation showing the relation between dissolved solids (DS) and water resistivity (Rw). The graph can be used with the Rwa map to estimate approximate dissolved solids, assuming that Rwa is approximately equal to Rw, and sodium chloride is the dominant dissolved solid.

SUMMARY

Resistivity and porosity logs, with supporting data from lithologic sample studies and water analyses, can be used to determine the resistivity of ground water over large areas. Apparent water resistivity (Rwa) contours outline areas of recharge, probable directions of flow, and areas of highly-mineralized water. Rwa values can be related to dissolved solids, as sodium chloride, by graphs. Porosity and resistivity determinations can be accomplished by hand-plotting on the geophysical logs; resistivity of water samples and Rwa calculations can be done on a desk calculator.

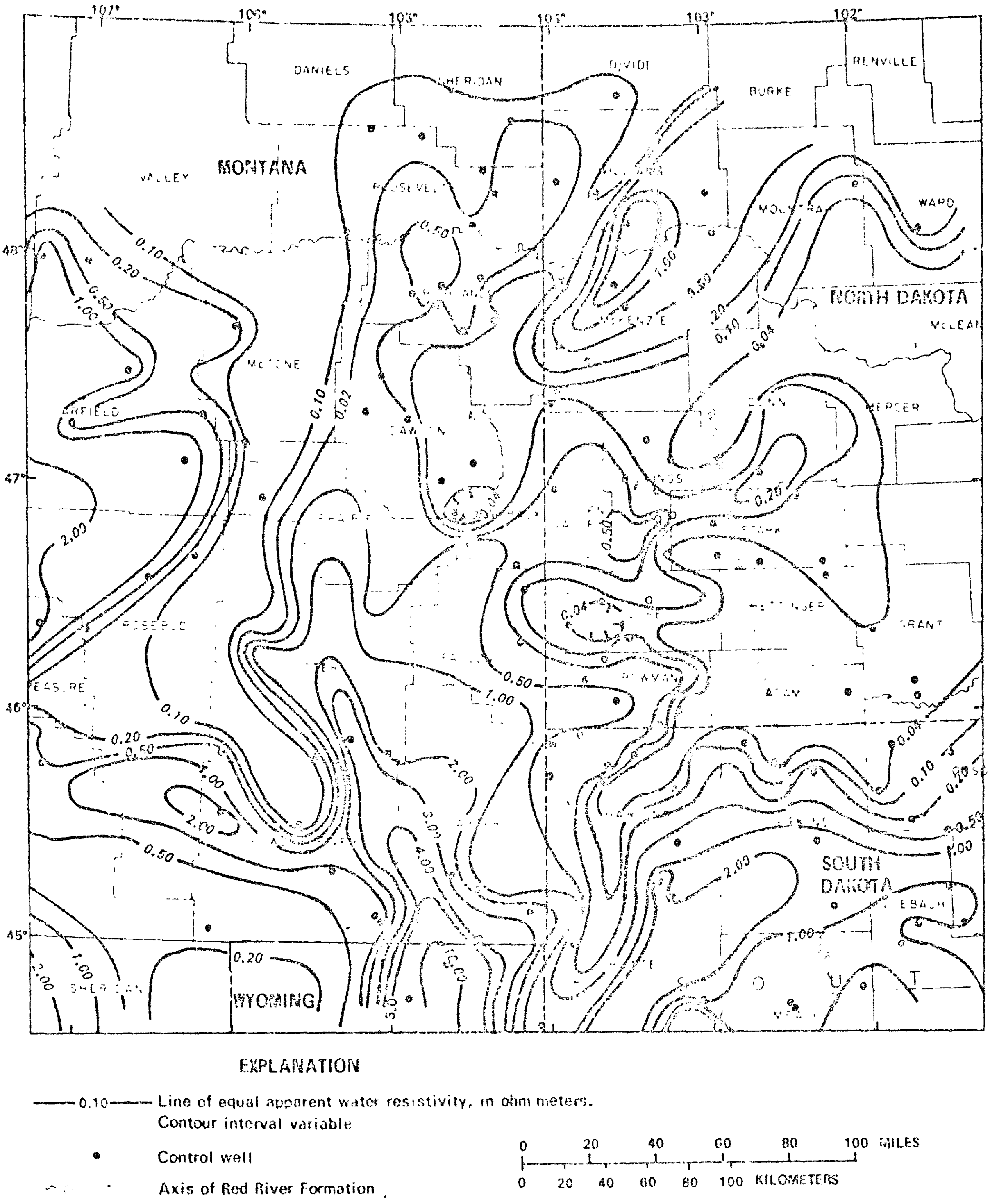


Figure 7.--Apparent water resistivity (RWA) contour map for the Red River Formation in parts of Montana, North and South Dakota, and Wyoming.

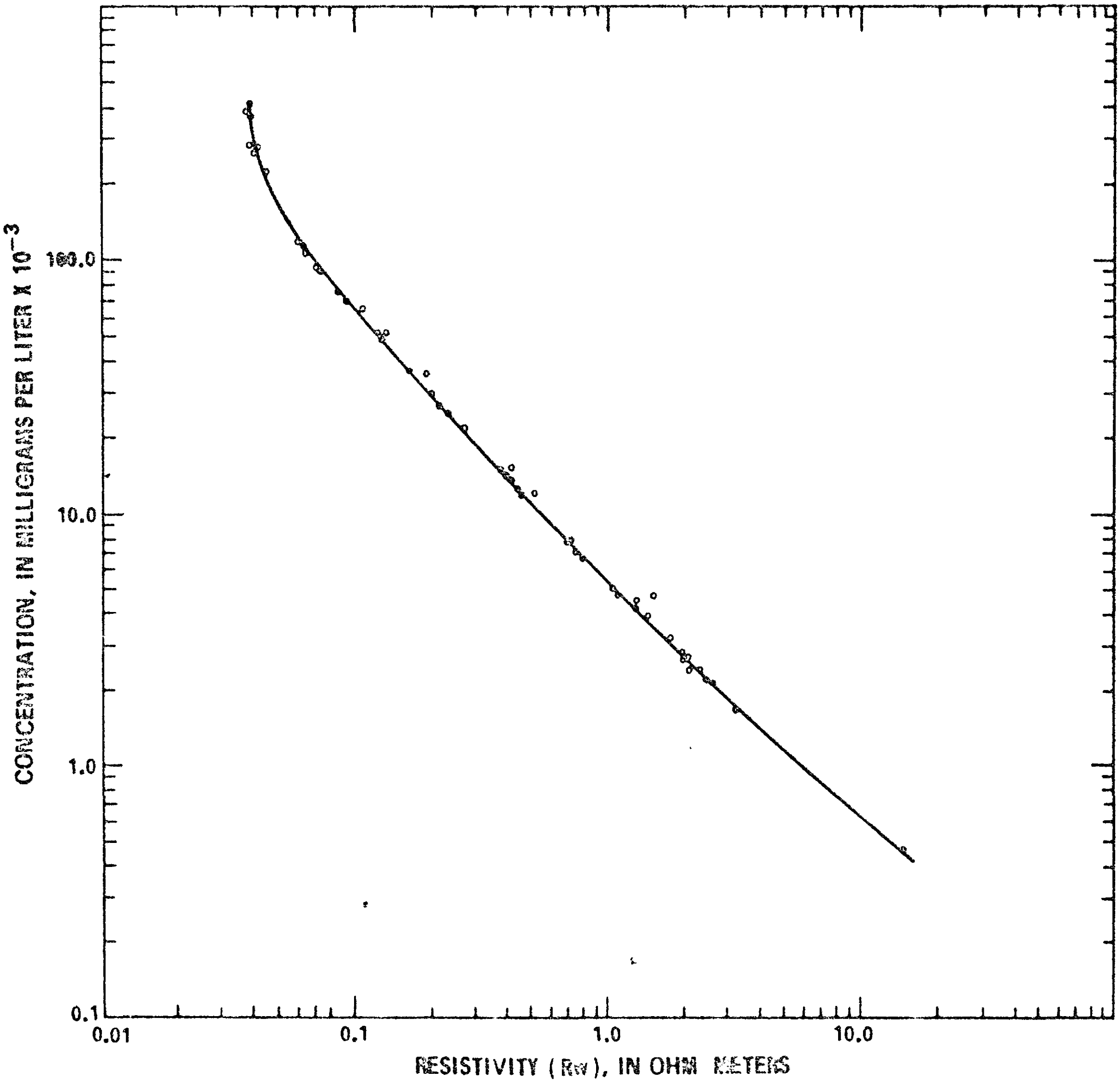


Figure 8.--Dissolved solids concentration and water resistivity, Red River Formation.

REFERENCES CITED

Alger, R. P., 1966, Interpretation of electric logs in fresh-water wells in unconsolidated formations: Society of Professional Well Log Analysts, 7th Annual Logging Symposium, Tulsa, Okla., May 1966, Transactions, p. CC1-CC25.

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: American Institute of Mining and Metallurgical Engineers Transactions, v. 146, p. 54-62.

Carruthers, J. E., 1968, A statistical study of the formation factor relationship: The Log Analyst, v. 9, no. 5.

Collins, A. G., 1975, Geochemistry of oilfield waters: New York, Elsevier Scientific Publishing Co., 496 p.

Desai, K. P., and Moore, E. J., 1969, Equivalent NaCl determination from ionic concentrations: The Log Analyst, v. 10, no.3.

Dresser-Atlas Division, 1974, Log review 1: Dresser Industries, Inc., Houston, Tex.

Dresser-Atlas Division, 1979, Log interpretation charts: Dresser Industries, Inc., Houston, Tex.

Gearhart-Owen, 1975, Formation evaluation data handbook: Gearhart-Owen Industries, Inc., Fort Worth, Tex.

Hamilton, L. F., Simpson, S. G., Ellis, D. W., 1969, Calculations of analytical chemistry: New York, McGraw-Hill Book Co., 511 p.

Keys, W. S., and MacCary, L. M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E-1, 126 p.

MacCary, L. M., 1978, Interpretation of well logs in a carbonate aquifer: U.S. Geological Survey Water-Resources Investigations 78-88.

Muffler, L. J. P., ed., 1979, Assessment of geothermal resources of the United States--1978: U.S. Geological Survey Circular 790, 163 p.

Patten, E. P., and Bennett, G. D., 1963, Application of electrical and radioactive well logging to ground-water hydrology: U.S. Geological Survey Water-Supply Paper 1544-D, 60 p.

Pickett, G. R., 1973, Pattern recognition as a means of formation evaluation: Society of Professional Well Log Analysts, 14th Annual Logging Symposium, Lafayette, La., May 1973 Transactions, p. A1-A21.

Schlumberger Limited, 1969, Log interpretation charts: Houston, Tex.

Schlumberger Limited, 1972, Log interpretation--principles: Houston, Tex.

Traugott, M. O., 1970, Log evaluation of a heterogeneous carbonate reservoir, Cata San Andres Field: Society of Professional Well Log Analysts, 11th Annual Logging Symposium, Los Angeles, Calif., May 1970 Transactions, p. E1-E9.

Vonhoff, J. A., 1966, Water quality determinations from spontaneous-potential electric log curves: Amsterdam, Netherlands, North Holland Publishing Co., Journal of Hydrology, v. 4, p. 341-347.