Apparent Water Resistivity, Porosity, and Water Temperature of the Madison Limestone and Underlying Rocks in Parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1273-D

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By L. M. MACCARY

GEOLOGY AND HYDROLOGY OF THE MADISON LIMESTONE AND ASSOCIATED ROCKS IN PARTS OF MONTANA, NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

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METRIC CONVERSION TABLE

[Inch-pound units in this report may be converted to the International System (SI) of metric units by using the following conversion factors:]

Multiply inch-pound units	*By*	*To obtain metric units*
inch per 100 feet	0.83	millimeter per meter
inch	25.4	millimeter
(ft) foot	0.3048	meter
	30.48	centimeter
(mi^2) square mile	2.59001	square kilometer
(°F/100 ft) degrees Fahrenheit per 100 feet	18.2268	degrees Celsius per kilometer
(acre-ft) acre-foot	1233	cubic meter
mile	1.609	kilometer

Temperature is reported in degrees Fahrenheit (°F). To convert to degrees Celsius (°C) use:

$$°C=0.556\,(°F-32)$$

To convert thermal gradients into SI units, use the following conversion factors:

Multiply	*By*	*To obtain SI units*
(mcal/cm·s·°C) millicalories per centimeter-second-degree Celsius	0.4184	(w/m·K) watts per meter degree Kelvin

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada; formerly called "mean sea level." NGVD of 1929 is referred to as sea level in the text of this paper.

GEOLOGY AND HYDROLOGY OF THE MADISON LIMESTONE AND ASSOCIATED ROCKS IN PARTS OF MONTANA, NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

APPARENT WATER RESISTIVITY, POROSITY, AND WATER TEMPERATURE OF THE MADISON LIMESTONE AND UNDERLYING ROCKS IN PARTS OF MONTANA, NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

By L. M. MacCary

ABSTRACT

The need for large quantities of energy has increased interest in the Fort Union coal region of the Northern Great Plains. Extensive coal development would place a heavy demand on the region's limited streamflow. Some Paleozoic rocks that underlie the Fort Union coal region might supply, at least temporarily, a significant amount of the water required for coal development. This report provides information on ground-water resistivity, rock characteristics, and ground-water temperature, from which general inferences relating to water quality and flow direction may be drawn. The area of study covers about 200,000 square miles in eastern Montana, northwestern Nebraska, western North Dakota and South Dakota, and northeastern Wyoming.

Borehole geophysical data and bottom-hole temperature data were used to determine porosity, apparent electrical resistivity of ground water (Rwa), and temperature of water for the Red River Formation (Ordovician), Interlake Formation (uppermost Ordovician and Silurian), Duperow Formation (Upper Devonian), Birdbear Formation (Upper Devonian), and a chronostratigraphic interval within the Madison Limestone (Mississippian). Rwa indicates the areal distribution of fresh and salty water and the probable direction of water movement. Maps showing areal distribution of Rwa, rock porosity, and ground-water temperature were prepared for each formation.

Rwa values ranged from 0.04 to 13 ohm-meters. The largest Rwa is in recharge areas, and the smallest, in the areas of dense brine in the Williston basin. The areas of brine are not centered in the deepest part of the basin, but are shifted to the east and south, apparently in response to hydraulic effects associated with the flow of less salty water around the brine and into overlying formations. The distribution of water of different quality, which controls Rwa, is governed by the flow system, which in turn is affected by proximity of geologic structures, by the distribution of rock types, and by porosity trends within the rocks.

Temperatures of ground water ranged from about 80 degrees Fahrenheit to as much as 320 degrees Fahrenheit. Generally, temperatures are lowest nearer the mountains and uplift areas and highest in the deeper parts of the basins. Temperature anomalies may be caused by geologic structures, thermal conductivity of overlying beds, and deeper than expected circulation of water in fractures related to intrusive igneous rocks. Thermal gradients ranged from 1.0 to 4.2 degrees Fahrenheit per 100 feet of depth.

INTRODUCTION

A major part of the United States' coal reserves is in the Fort Union coal region of the Northern Great Plains (fig. 1). Development of these coal resources may include on-site steam-power generation, gasification, liquefaction, and slurry-pipeline transport of the coal from the region. Development would place a heavy demand on the region's limited water resources. Water from the Madison Limestone and underlying rocks might supply, at least temporarily, a large part of the water required for coal development. These rock units underlie the Fort Union coal region and adjacent areas in Montana, Nebraska, North Dakota, South Dakota, and Wyoming (fig. 1).

This report describes the use of borehole geophysical data to determine rock porosity and apparent electrical resistivity of formation water; it outlines the distribution of apparent water resistivity, porosity, and ground-water temperature in the Madison Limestone and associated rocks; and it outlines the average geothermal gradient in the study area. The areal distributions of these properties are compared to major geologic structures. Data were obtained from geophysical logs, sample studies by American Stratigraphic Co., drill-stem tests, and water analyses from Madison Limestone test wells 1, 2, and 3 (fig. 1). Any use of trade names is for descriptive purposes only and does

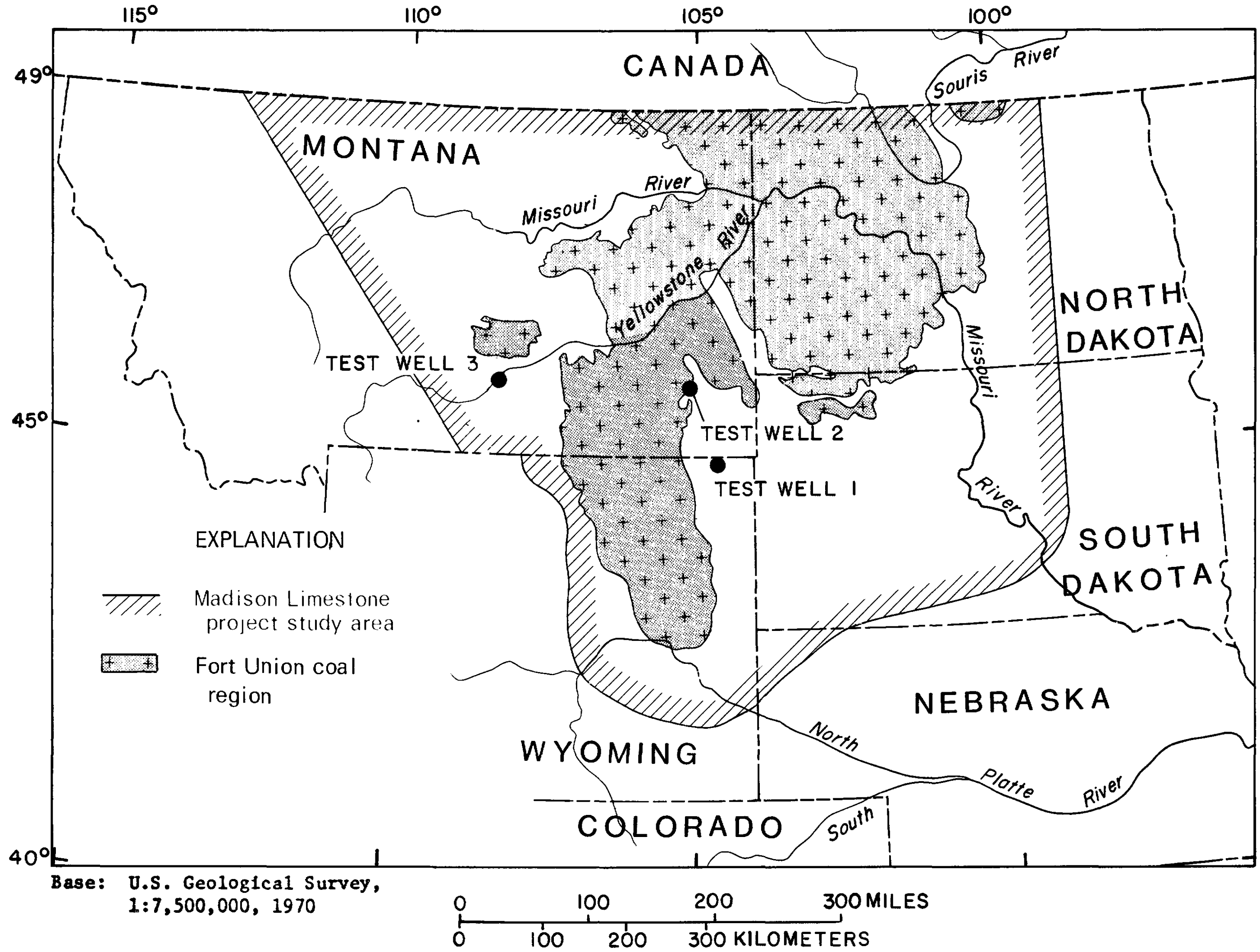

FIGURE 1.—Location of study area.

not constitute endorsement by the U.S. Geological Survey.

This report is one of a series describing results of the Madison Limestone Project. This project was established to determine the quantity and quality of water in rocks of Paleozoic age in an area covering about 200,000 mi^2 in eastern Montana, western North Dakota and South Dakota, northeastern Wyoming, and a small part of northwestern Nebraska (fig. 1). The area of greatest interest for evaluation of ground-water potential is in and near the Powder River basin and the Black Hills uplift (figs. 1 and 2).

Apparent water resistivity, porosity, and water temperatures are described for five water-bearing formations of Paleozoic age. From oldest to youngest, these are: Red River Formation (Ordovician), Interlake Formation (uppermost Ordovician and Silurian), Duperow Formation (Upper Devonian), Birdbear Formation (Upper Devonian), and Madison Limestone (Mississippian). Maps of rock type, based largely on lithologic logs, are presented for the Red River, Duperow, and Birdbear Formations.

Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks have been described by Peterson (1981). Generalized correlations of these units in the project study are shown in table 1.

The Red River Formation consists of fragmental limestone and dolomite; anhydrite is present in the upper part in the Williston basin. The Interlake Formation is mostly dolomite, but some shale, limestone, and anhydrite are present in parts of the report area. The Duperow and Birdbear Formations are composed principally of porous dolomite, limy dolomite, and dolomitic limestone in the areas described in this report.

The Madison Limestone is undivided in parts of the project area and is divided into formations in other

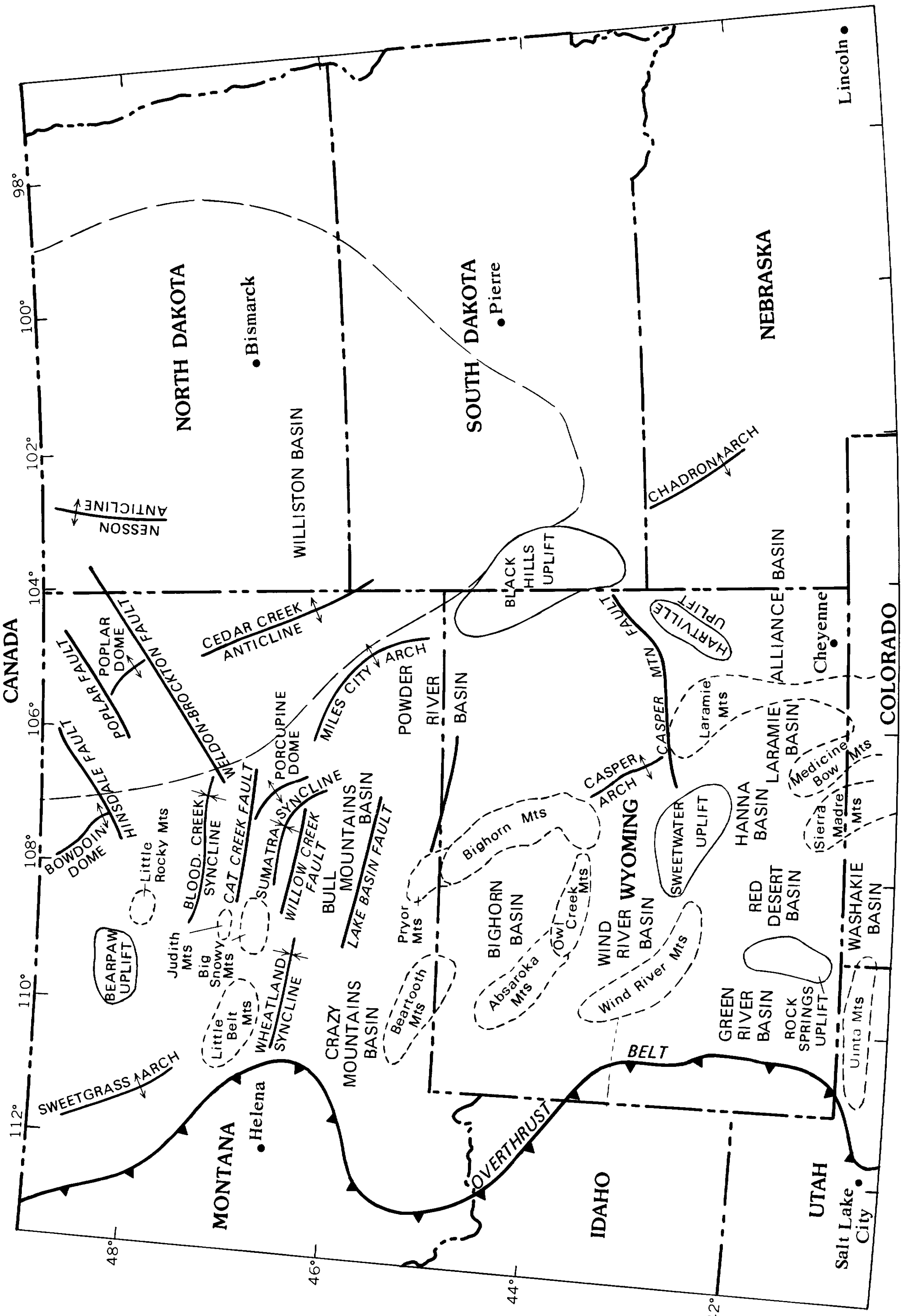

FIGURE 2.—Structural features, Western Interior, United States. (Modified from Grose, 1972, and Stone, 1971.)

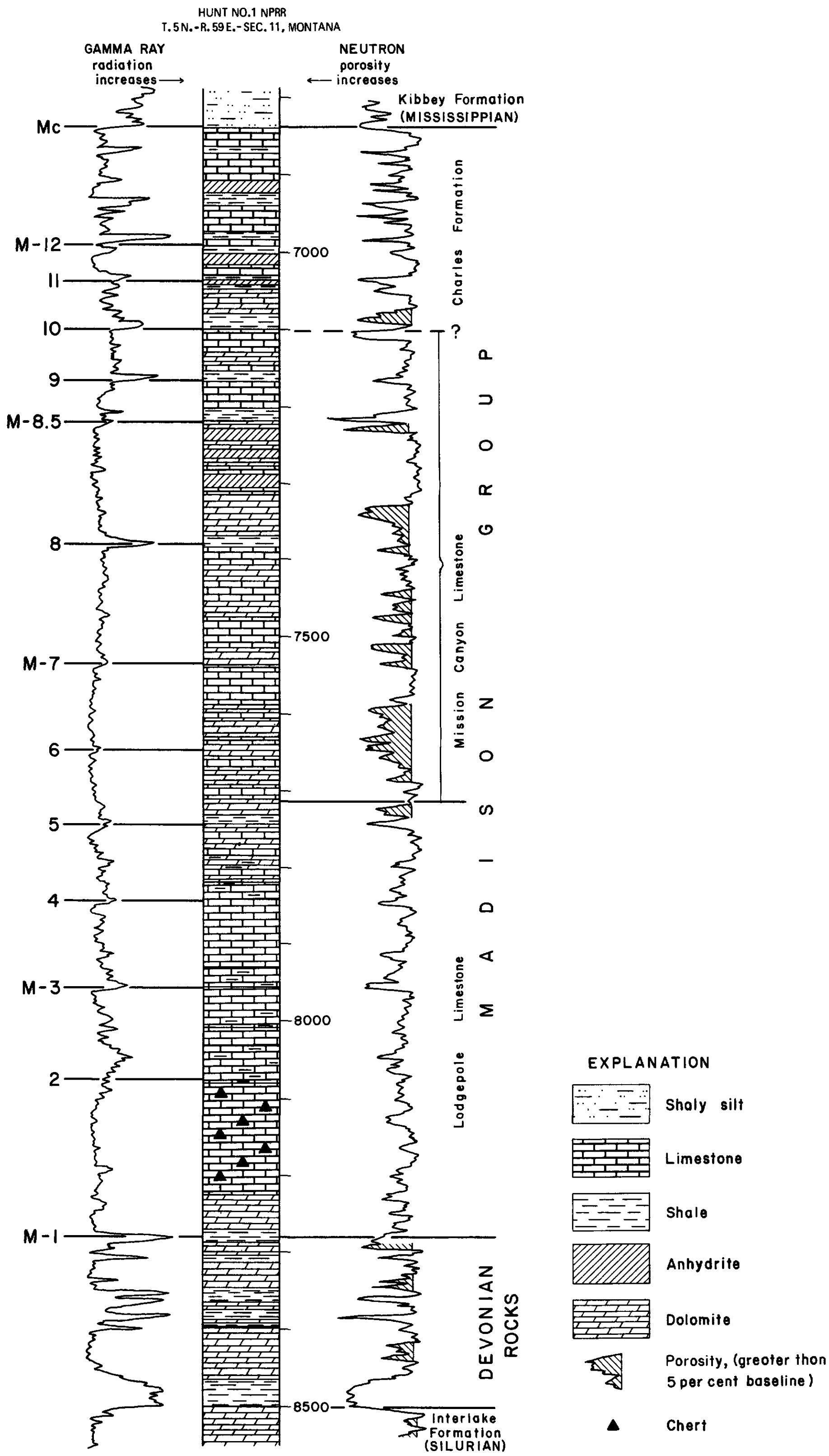

FIGURE 3.—Example of well-log patterns and lithology of Madison Group marker units.

parts of the area. Where it is divided into formations, it is called the Madison Group (table 1). For consistency, however, the term "Madison Limestone" is used in this report. Generally, the Madison Limestone, in ascending order, consists of thin- to medium-bedded argillaceous to shaly or silty, in places cherty, limestone; thick- to massive-bedded fossiliferous to oolitic carbonate rock; and anhydrite and halite interbedded with carbonate rock and shale. The Madison was divided into 13 units by means of marker beds that consist of thin and widespread shaly carbonate or dark shale. The marker beds can be identified on geophysical logs (fig.3). Only one unit, the M-7 to M-8.5 interval, is discussed in this report; this unit appears to have good overall porosity and potential as an aquifer within much of the study area. Of the Paleozoic units discussed in this report, the Madison Limestone has the greatest potential for ground-water development. The Madison crops out in the areas of uplift, but may be as much as 16,000 ft below land surface in the Powder River basin.

The general pattern of ground-water movement through the study area is toward the east, downgradient from western recharge areas. Some flow is into the Williston basin, and some flow is around it to the north and south. Within the Williston basin, some flow apparently is upward from the Paleozoic units into overlying rocks of Cretaceous age. On the eastern flank of the Williston basin, the Madison and Red River Formations contain highly mineralized water, indicating a region of slow-moving water.

ANALYSIS OF BOREHOLE GEOPHYSICAL DATA

An analysis to determine resistivity, porosity, and temperature from borehole geophysical logs and bottom-hole temperature data was completed for five stratigraphic units—the Red River, Interlake, Duperow, and Birdbear Formations, and the M-7 to M-8.5 interval of the Madison Limestone. The borehole geophysical logs that were available for analysis ranged in age from the early 1950's to the late 1970's and in quality from poor to excellent. As a result, careful screening was necessary to select logs from which reliable values of resistivity and porosity could be taken for use in the analysis.

Calculations of apparent water resistivity (Rwa) were based on the equations of Archie (1942):

$$F=\frac{Ro}{Rw} \qquad (1)$$

and

$$F=\frac{1}{\phi^{m}} \qquad (2)$$

where

F is the formation resistivity factor,
Ro is the resistivity of water-saturated formation, in Ω•m (ohm-meters),
Rw is the resistivity of formation water, in Ω•m,
m is an empirically derived exponent, and
ϕ is the formation porosity, as a decimal.

Combining equations 1 and 2 results in the equation

$$Rw=\phi^{m}Ro \qquad (3)$$

or, expressed in terms of apparent water resistivity,

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

The term "apparent water resistivity, Rwa," is usually used instead of Rw because equation 3 does not provide a direct measurement of water resistivity, but rather a calculated value derived from borehole geophysical logs.

The resistivities of the water-saturated formation, Ro, were read from electrical logs—in particular, the long normal or the laterolog; some deep induction logs were used where formation resistivities were less than 50 Ω·m. Weighted average values of Ro were calculated for the intervals in each unit having porosity values of 0.10 or greater (that is, for the major water-bearing zones). The procedure was to calculate the product of resistivity and thickness for every interval in the unit having a porosity of 0.10 or more and then to divide by the total thickness of such intervals in the unit. The resulting value of Ro was used in equation 4 to calculate Rwa.

Equilibrium temperature is the temperature of the undisturbed formation, however, the temperatures that are observed in a newly drilled test hole are lower than the equilibrium temperatures because circulating drilling mud is cooler than the adjacent undisturbed formation. Continuous temperature logs were not available for most drill holes, but maximum temperatures—presumably at the bottom of the hole—were measured by a maximum-reading thermometer. Observed bottom-hole temperatures can be corrected to equilibrium temperatures by methods described by Wallace and others (1979, p. 150), Summers (1972), and Fertl and Wichman (1977). The equilibrium bottom-hole temperature was used with the average surface temperature at each well to establish a temperature-depth relationship at that point. From this relationship, the temperature at any depth could be determined, and the average geothermal gradient at the point also could be established. This procedure was used to determine the undisturbed formation temperatures in each of the five stratigraphic units at each well location and to determine the average thermal gradient at each location.

Formation porosities were obtained from neutron, density, or sonic logs. In each well, depth intervals for which porosity was between 0.10 and 0.15, between 0.15 and 0.20, and greater than 0.20 were delineated.

The total thickness of material in the 0.10–0.15 range was multiplied by 0.10, the lower limit of the porosity range; the total thickness of material in the 0.15–0.20 range was multiplied by 0.15; and the total thickness greater than 0.20 was multiplied by 0.20. These figures were added and their sum was divided by the total thickness of material in all three categories within the formation. The result was taken as a conservatively estimated weighted-average porosity for the major water-bearing zones, that is, for those zones having porosity greater than 0.10. This value of porosity was used in equation 4 to calculate Rwa, the apparent formation water resistivity, at the point penetrated by the well. Porosity data were compiled in map form for each of the five stratigraphic units analyzed. For the Birdbear and Duperow Formations, lines show the total thickness of rock having porosity greater than 10 percent; for the remaining formations, areas are delineated within which the total thickness of material having porosity of at least 15 percent exceeds a specified value, and within which the total thickness of material having porosity of at least 10 percent exceeds a specified value. These variations in format were adopted to best depict the available porosity-thickness information for each interval.

The third element needed to solve equation 4 is m, or the empirically derived exponent. Values of m are listed in Carrothers (1968) and Traugott (1970) for various lithologies; m ranges from 1.54 for sandstone to 3 for some carbonate rocks. A value of 2 usually is used for carbonate rocks; however, with sufficient information m can be determined by empirical means for a particular aquifer. A slight variation of the pattern-recognition method of Pickett (1973) was used to determine m for the Red River Formation; for the other units considered in this report, an assumed value of 2 was used for m.

A semi-log graph of neutron porosity versus the resistivity of the water-saturated formation is used to evaluate m by the Pickett (1973) method. In a formation of constant water resistivity, the plotted points generally will define a straight line of slope, minus m ($-m$), which is called the cementation or porosity exponent. Extending the line to 100 percent porosity on the graph will establish a minimum resistivity, which is the resistivity of the formation water, Rw; Rw in theory would be recorded if only water filled the logging environment.

The variations of Pickett's method used for the Red River Formation required the estimation of the resistivity of the formation water where data on formation water chemistry were available from drill-stem and packer testing. These estimates were made by determining the ionic concentration of a pure sodium chloride solution equivalent to the formation water, and then consulting published tables or graphs to obtain the electrical resistivity of this equivalent sodium chloride solution. Where dissolved solids were less than 7,000 mg/L, concentration of the equivalent sodium chloride solution was determined by converting all ions to milliequivalents per liter, by dividing by the combining weights of each ion. Resulting values were summed, then multiplied by the combining weight of sodium chloride, to arrive at an equivalent sodium chloride solution in mg/L. When the dissolved solids were greater than 7,000 mg/L, the total ionic concentration was used in the estimation of the equivalent sodium chloride concentration using the method of Sinclair Variable Multipliers described by Desai and Moore (1969). The resistivities of the resulting solutions were determined from chart A6 in Schlumberger Limited (1972). These estimated formation water resistivities were plotted opposite 100 percent porosity on semi-log graphs of resistivity versus neutron porosity. A second point on each graph was obtained by plotting the weighted average resistivity of the water-saturated formation, Ro, opposite the weighted average porosity. A straight line between these two points then provided an estimate of the required slope, $-m$. Plots of this type for a number of wells penetrating the Red River Formation are shown in figure 4. The average value of m for all wells in the Red River, for which this analysis could be made, was 2.15; this value was used as the exponent in equation 4 to determine Rwa for the Red River Formation. That is, the weighted average porosity, the weighted average resistivity of the water-saturated formation, and an m of 2.15 were used in equation 4 to determine Rwa for each well at the corrected borehole temperature of the Red River Formation. The Rwa values were adjusted to 77°F by use of the Arps formula (Schlumberger Limited, 1972). Lines of equal Rwa are shown on plate 1. The same procedure was followed for each of the other units considered in this report, except that an assumed value of 2 was used for m.

Apparent water resistivity, Rwa, is a useful parameter because it provides a means of estimating concentrations of dissolved solids in ground water. Rwa in ohm-meters corresponds to an equivalent sodium chloride solution in milligrams per liter approximately as follows: 10 $\Omega \cdot m \approx$ 500 mg/L; 1 $\Omega \cdot m \approx$ 5,500 mg/L; 0.1 $\Omega \cdot m \approx$ 65,000 mg/L; and .04 $\Omega \cdot m \approx$ 361,000 mg/L, which is a saturated solution at 77°F.

Where Rwa is greater than about 1 Ω.m—that is, where the formation water is relatively fresh—sodium chloride may not be dominant, and ions such as calcium, magnesium, bicarbonate, and sulfate, may control the water resistivity. In these areas, the relation between resistivity and dissolved solids may differ considerably from that for a sodium chloride solution.

The correlation between the resistivity of the forma-

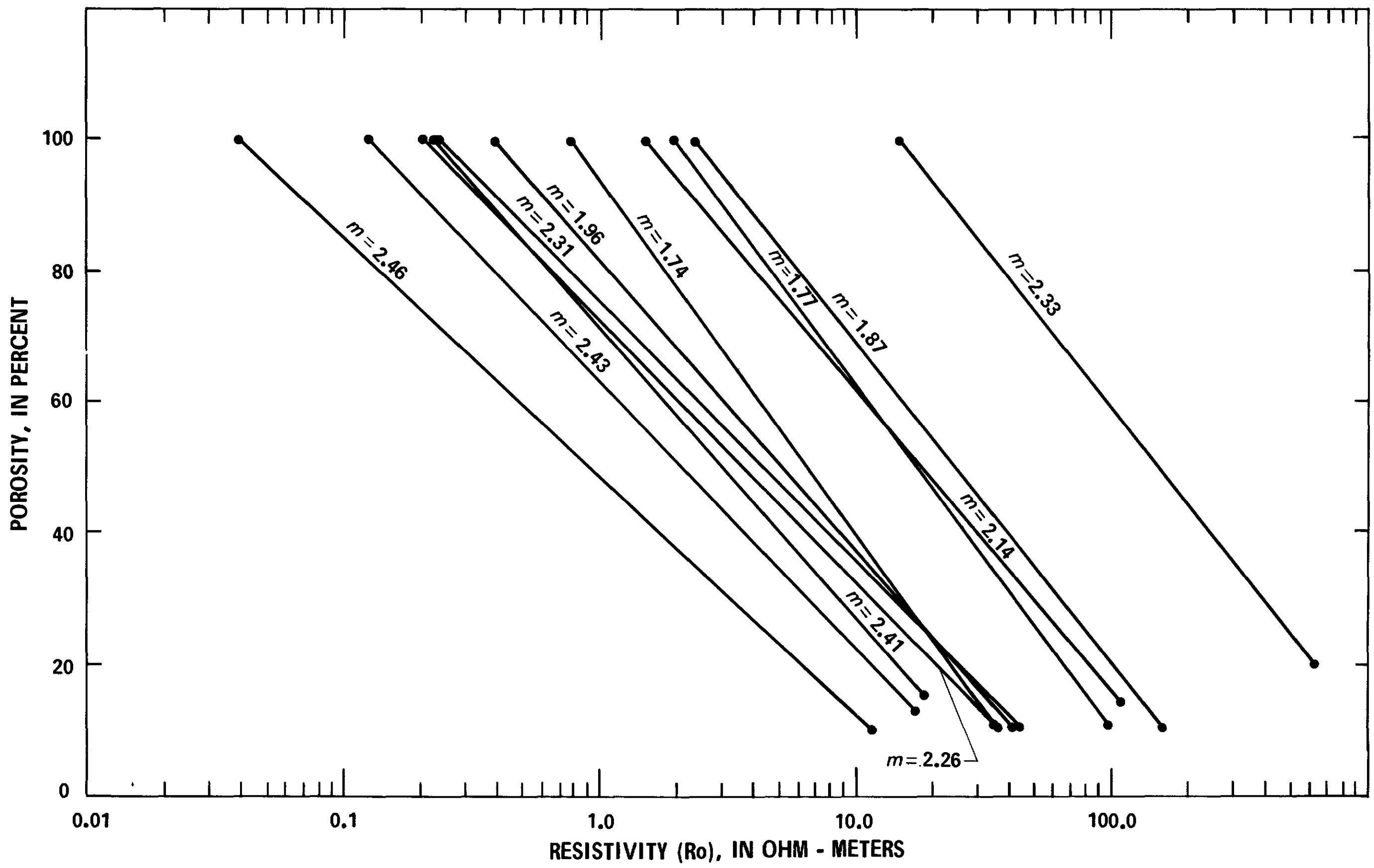

FIGURE 4.—Determination of *m* (slope) from porosity and resistivity of the water-saturated Red River Formation.

tion water, Rw, and dissolved-solids concentration for all available data for the Red River Formation is shown in figure 5. The graph can be used with the Rwa maps to estimate the approximate dissolved-solids concentrations, assuming that Rwa is approximately equal to Rw. The graph is most applicable where sodium chloride is the dominant dissolved solid, because most of the data were collected in areas where this was true.

The Rwa method of estimating dissolved-solids concentrations in ground water, like any empirical method, depends on numerous assumptions, and many tradeoffs may be involved in its application. Errors in the logs themselves are the most basic source of inaccuracy in determining Rwa. Rwa values computed using older log data often differ significantly from Rwa values calculated from newer logs in the same general area. Neutron logs made before 1960 were not scaled in porosity units and sometimes lacked any useful scale except for the indication of the direction of increase in radioactivity. Applying a porosity scale to these logs is a matter of empirically fitting a logarithmic scale between assumed values of high and low porosity (MacCary, 1980). The older electric logs were plotted on a linear resistivity scale, thus necessitating many off-scale deflections or backup curves to cover a wide range in resistivities. Determining the applicable resistivity scale for the older logs often is difficult, particularly where a depth scale of 1 in per 100 ft was used, or where the rocks consist of thick carbonate sequences with no low-resistivity shale beds to use as a calibration line. Modern resistivity logs of the laterolog type (LL3, LL7, LLd) are preferred for Rwa calculation because they have a large, fairly constant radius of investigation, and they give satisfactory measurements over a wide range of fluid resistivities.

Neutron logs generally record porosity values that are higher than actual values, whereas sonic and density logs tend to be more conservative. The sonic curve generally is preferred for porosity determination. If modern suites of logs are available, the average of compensated neutron porosity and compensated density porosity can be used.

An additional source of error in Rwa is in the value of the exponent *m*, which either must be estimated em-

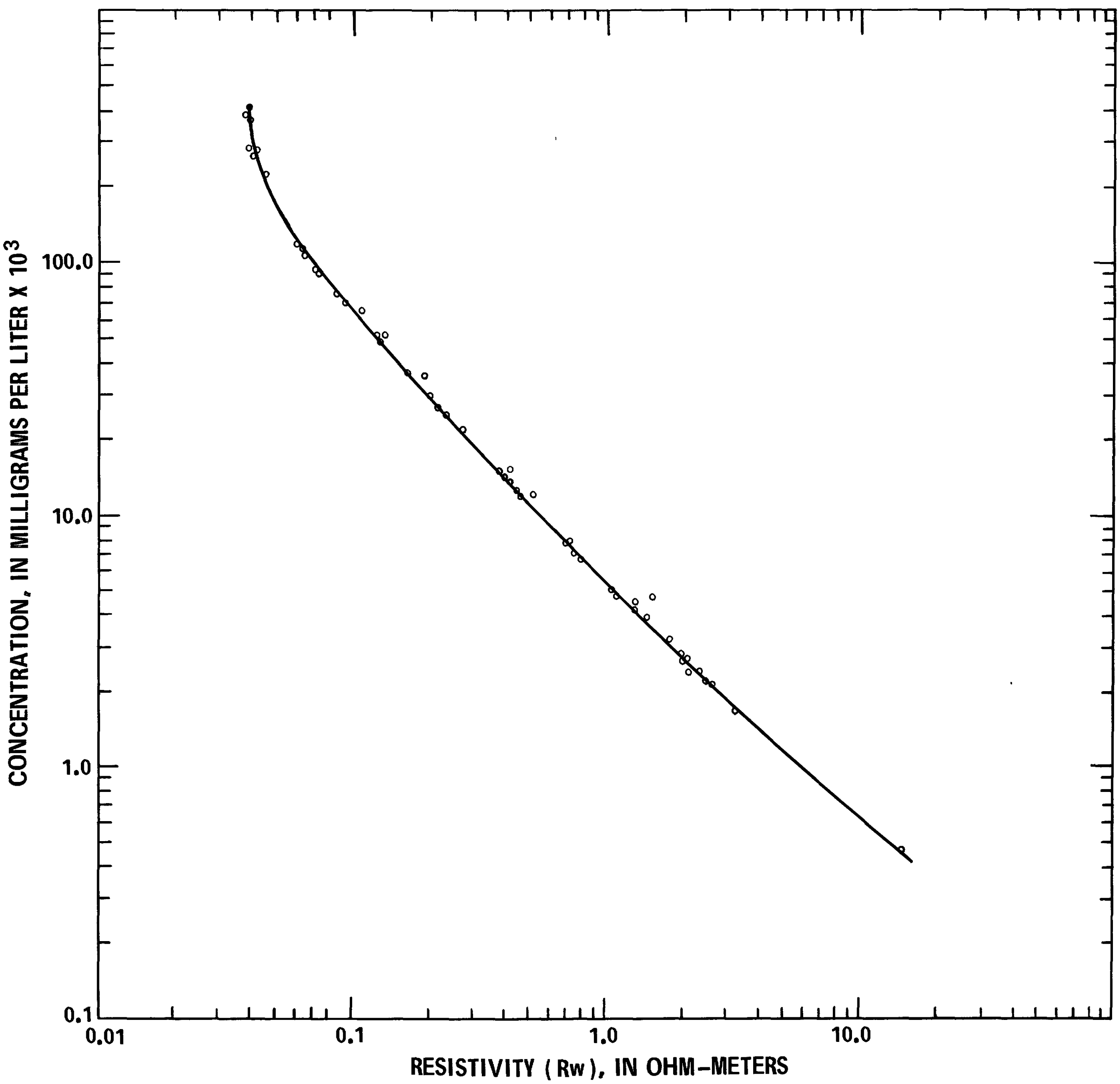

FIGURE 5.—Dissolved-solids concentration versus resistivity of formation water (Rw) in the Red River Formation.

pirically or must be assumed. However, deviation of the exponent from the "true" value will usually produce a relatively uniform error in Rwa values throughout the aquifer. Thus the general trends and relative values of Rwa, as indicated by the lines of equal Rwa, are probably approximately correct, although absolute Rwa values will differ from true formation water resistivities.

RESULTS OF ANALYSIS

The analytical procedures described above yielded values of apparent formation water resistivity, porosity, and formation temperature in each of the five stratigraphic units at each well location and also provided an average geothermal gradient at each well location. The resistivity, porosity, and temperature information is provided for each unit, from oldest to youngest, in the following sections. The thermal gradient results are summarized in a separate section following the discussion of results for the Red River Formation.

RED RIVER FORMATION (ORDOVICIAN)

The Red River Formation is the deepest potential aquifer of great areal extent in the Madison Limestone Project area. The formation yielded water in three test wells drilled during the Madison Limestone Project (fig. 1); the formation also has been tested by drill-stem methods in many oil wells. However, the Red River lies at such great depths, particularly in the Williston basin, that few water-production wells are drilled into the unit. Except for the three test wells, the well data used in this study are from holes drilled in search of oil or gas.

APPARENT WATER RESISTIVITY

Lines of equal apparent water resistivity, Rwa, for the Red River Formation are shown on plate 1. Values range from 0.04 Ω • m in the Williston basin in eastern Montana to 13 Ω • m in Crook County, Wyo. The highest values of Rwa, indicating relatively fresh water, occur in the recharge areas in the various mountains and uplift areas (fig. 2, pl. 1). Major recharge areas are in the Bighorn Mountains (Big Horn, Sheridan, Washakie, and Johnson Counties, Wyo.), the Pryor Mountains (Big Horn and Carbon Counties, Mont.), and the Black Hills (Lawrence, Pennington, and Custer Counties, S. D., and Crook County, Wyo.). Another area of high Rwa associated with recharge occurs on the east flanks of the Big Snowy and Judith Mountains (Fergus and Golden Valley Counties, Mont.). Low values of Rwa are present in the basins, especially the Williston basin where the water is a high-saline brine. Freshwater in the recharge areas moves down the hydraulic gradient toward the basins. Structure contours on the top of the Red River Formation are shown on plate 2. The Rwa contours (pl. 1) indicate that groundwater becomes progressively more saline along the path of flow, toward the areas of brine in the Williston basin. The dense brines (specific gravity about 1.22 g/cm^3) do not occur in the deepest part of the Red River Formation in the Williston basin, but are shifted to the east and south up the regional dip. The deepest part of the Red River Formation is in McKenzie and Dunn Counties, N. D., where it lies 11,000 ft below sea level. The area of lowest Rwa in the Red River Formation lies in a northeast-trending band mainly in Adams, Hettinger, Grant, Morton, Oliver, and McLean Counties, N. D. This hydrologic condition conforms to the theory presented by Hubbert (1953, p. 1994) if the brines are assumed to be virtually static, and less salty water higher in the section (for example, in Cretaceous units) flows updip to the east.

Many structural features of smaller extent apparently influence the flow pattern and thus the water-quality distribution, as indicated by the Rwa map contours. For example, in Valley, Garfield, and McCone Counties, Mont., a series of parallel Rwa lines in the range of 0.10–1 Ω • m is bounded on the northwest by the Hinsdale fault and on the southeast by the Weldon-Brockton fault (pl. 1 and fig. 2). In Roosevelt County, Mont., the Poplar dome (fig. 2) is outlined on the west, north, and east by lines indicating values of 0.10–0.50 Ω • m. The shape and direction of the Rwa lines near the Big Snowy and Judith Mountain area in Montana appear to be influenced by the Cat Creek fault and Blood Creek syncline in Petroleum and Garfield Counties, and by the Sumatra syncline in Musselshell and Rosebud Counties.

In eastern Yellowstone and western Big Horn Counties, Mont., the Lake Basin fault appears to function as a control on ground-water flow (fig. 2, pl. 1). The 2- and 3-Ω • m lines lie astride the fault, and Rwa increases rapidly to the north. A relatively broad area south of the fault has Rwa values between 0.50 and 1 Ω • m. Thus, relatively little freshwater seems to flow from areas north of the fault toward the saltier water on the south. In contrast, in central Yellowstone County, the 4 Ω • m lines continue northward as far as Petroleum County.

POROSITY AND ROCK TYPE

The distribution of rock type in the Red Rock Formation is shown on plate 3. A general trend of dolomitic limestone follows the west rim of the Williston basin and appears to influence the distribution of high-resistivity water extending northwestward from the Black Hills recharge area in Crook County, Wyo.

Areas in the Red River Formation are shown on plate 4 where the total thickness exceeds 50 ft, for material having at least 10 percent porosity and for material having at least 15 percent porosity. The control of Rwa lines by porosity zones is shown in the northeastward-trending area of high Rwa from the Black Hills toward Perkins County, S. D. (pls. 1 and 4). The area of rock having a thickness greater than 50 ft and porosity higher than 10 percent coincides roughly with the area enclosed by the 2 Ω • m line in Butte and Perkins Counties, S. D. A relation between porosity and Rwa in other areas is indicated although it is not as closely correlated as in the example above. Generally the areas of low Rwa correspond broadly to areas of poor porosity (pls. 1 and 4).

TEMPERATURE OF WATER

Temperatures of water in the Red River Formation are shown on plate 5. The lines actually show temperatures at the top of the Red River Formation, as taken from temperature-depth relationships established from bottom-hole temperatures of oil wells, using the procedures described previously. As expected, lowest temperatures occur in recharge areas around the Black Hills, Pryor Mountains, and Bighorn Mountains. High-temperature lines outline the deep basins; the highest temperature, 320°F, occurs in the Williston basin in Billings County, N. D.

The temperature of water in the Red River Formation depends on several factors: (1) Location of recharge areas; (2) rate of recharge; (3) depth of burial; (4) proximity of structural features; (5) thermal conductivity of overlying beds; and (6) deep circulation of water in fractured rock associated with igneous intrusives. So many factors enter into thermal effects that isolation of specific controls in each place is difficult. Recharge and intrusives are both localized and can be identified on the map. For example, the 100 to 140°F lines in Carter County, Mont., and Crook County, Wyo., probably reflect deep circulation associated with igneous intrusives in Crook County.

Some thermal anomalies that may be due to structural control are evident on plate 5. Along the Cedar Creek anticline north of Wilbaux County, Mont., the 200 to 260°F lines abruptly turn to the east around the northern flank of Poplar dome in Roosevelt County, Mont. The closed 200°F line in Garfield County, Mont., is bounded on the northwest by the Weldon-Brockton fault and follows the trend of the fault toward Cat Creek and Willow Creek faults in Garfield and Rosebud Counties (fig. 2 and pl. 5).

A large thermal anomaly lies between 160 and 180°F lines in Treasure, Yellowstone, and Musselshell Counties, Mont. The anomaly is bounded on the north by Willow Creek fault and on the south by Lake Basin fault. The anomaly may provide further evidence that relatively little flow occurs from areas north of the Lake Basin fault to areas south of it. A similarly shaped anomaly between the 160 and 180°F lines occurs in Fergus, Petroleum, and Garfield Counties, Mont., possibly related to the influence of the Hinsdale fault and the Poplar dome on the flow pattern.

In Custer, Prairie, Fallon, and Carter Counties, Mont., a broad area of small temperature change lies between the Cedar Creek anticline on the east and the Miles City arch on the west. The main, northward-trending area of freshwater from the Black Hills extends along the west margin of this thermal anomaly (pls. 1 and 5).

Two thermal anomalies that may be controlled by thermal conductivity of overlying formations occur in Billings County, N. D., and Meade County, S. D. These anomalies are discussed in the following section.

THERMAL GRADIENT

A map of average thermal gradient, prepared using the methods described previously, is shown on plate 6. The data consisted largely of bottom-hole temperatures of wells in the Red River Formation in Montana and North Dakota, and in the northern counties of Wyoming and South Dakota. Temperature data from the deepest available wells were used in areas where no wells penetrated the Red River Formation or where the Red River Formation was missing. The gradient map is contoured in degrees Fahrenheit per 100 ft., and generally agrees with the geothermal gradient map of North America (American Association of Petroleum Geologists, 1976). Factors affecting the thermal gradient are (1) the presence of heat sources at depth; (2) thermal conductivity of the intervening rocks, which in turn is influenced by the porosity and water saturation of the rocks; and (3) amount of ground-water circulation. Thermal conductivities of rocks generally are reported in millicalories per centimeter per second per degree Celsius (mcal/cm • s • °C) and range from 0.33 in lignite to 19 in quartzite. For most individual rock types, thermal conductivity may vary by a factor of two or three depending on porosity, water content, and grain or crystal orientation. Where other complications (particularly the presence of heat sources at depth) are absent, high thermal gradients indicate rocks that are good thermal insulators, whereas low gradients indicate rocks that are good thermal conductors.

Thermal gradients range from 1.0°F/100 ft in Blaine County, Mont., and Crook County, Wyo., to 4.2°F/100 ft in Lyman County, S. D. An anomaly, probably caused by deep circulation of water in fractured rock near igneous intrusive bodies, is located in Blaine County, Mont., where the gradient is 2.6°F/100 ft. A few oil wells in this area penetrated igneous intrusive rocks at several horizons. The cause of other thermal anomalies is not so obvious, because vertical changes in lithology, porosity, and water or hydrocarbon saturation can produce significant variations in thermal gradient.

Crude oil has a low thermal conductivity, about 0.3 mcal/cm • s • °C, and natural gas has an even smaller conductivity, from 0.04—0.08 mcal/cm • s • °C; therefore, hydrocarbons are good heat insulators. Oil and gas fields are generally in areas of little or no active ground-water circulation; this condition also enhances heat retention, because water is not transporting heat from the rocks. Thus, areas of petroleum accumulation may be characterized by high thermal gradients. This appears to be true in northern Rosebud County, Mont., where a closure in thermal-gradient lines coincides with known oil accumulations in rocks of Pennsylvanian age. A similar closure in thermal-gradient lines at the intersection of Roosevelt, Richland, and McCone Counties, Mont., may be related to known petroleum accumulations in rocks of Devonian and Mississippian age. The closed thermal gradient lines in Billings County, N. D., also occur in an area of known petroleum accumulation.

Basins filled with thick deposits of low-conductivity sediments may show high thermal gradients, especially where faulting brings these sediments into contact with basement materials of high temperature. An example may be the high thermal gradient area in Lyman and Tripp Counties, S. D. American Stratigraphic Co. logs of wells in the two counties indicate that the Paleozoic section is very thin over Precambrian basement. A thick sequence of Jurassic and Cretaceous shale and high-porosity sand overlies the Paleozoic rocks. Both shale and high-porosity sand are poor conductors of heat; thus, these rocks may form an insulating blanket, which retains the heat from the basement.

Areas of low thermal gradient may be attributed to several mechanisms. Ground-water circulation transports heat away from rocks, causing lower temperatures and a lower thermal gradient. Wells drilled on topographic highs generally will show lower temperatures and lower thermal gradients than wells drilled off the highs. Thermally conductive rocks, such as massive bedded evaporites, can cause lower thermal gradients if they constitute a significant proportion of the total rock volume.

At least four areas of low thermal gradient are most likely caused by the high thermal conductivities of evaporite deposits. One such area in Montana lies along the border between Wilbaux and Prairie Counties, and another is in northeastern Carter County, N. D. Low gradient areas in the southwestern part of McKenzie County and in Harding County, S. D., are both probably caused by evaporite beds.

Although some of the high and low gradients shown on plate 6 can be explained easily, others cannot. Many areas of high or low thermal gradient seem to be associated with geologic structures such as the Cedar Creek anticline, the Weldon-Brockton fault, the Powder River basin, and the Williston basin. However, the mechanisms responsible for the association are not so obvious.

INTERLAKE FORMATION (UPPERMOST ORDOVICIAN AND SILURIAN)

The analysis of borehole geophysical data for the subsurface Interlake Formation—unlike the Red River Formation, for which all available well logs were evaluated—included only those areas where the formation is known to be or thought to be a potential aquifer. Therefore, the area of evaluation was limited to eastern Montana, western North Dakota, and a small part of northwestern South Dakota. Rocks of Silurian age do not crop out in the report area because of truncation by pre-Middle Devonian erosion and burial by younger rocks (Gibbs, 1972). The Interlake is overlain by dolomites and shales of Middle to Upper Devonian age and is underlain by the Stony Mountain Formation and the Red River Formation (table 1). The limit of the Interlake Formation in the subsurface of the study area is shown on plate 7.

Because of the absence of outcrops, the Interlake Formation receives recharge only through leakage from other formations having higher hydrostatic heads. The formation contains freshwater in some areas, as indicated by the Rwa values as high as 4 Ω • m. The potentiometric head in the Red River Formation is higher than that in the Interlake Formation in some places, and lower in others.

APPARENT WATER RESISTIVITY

Rwa for the Interlake Formation was calculated from resistivity and porosity logs, using equation 4 and an assumed value of 2 for m. The lines of equal Rwa are shown on plate 7; Rwa ranges from 0.04 to 4 Ω • m.

Very little ground water apparently flows across the northwest-trending Cedar Creek anticline between Harding County, S. D., and Dawson County, Mont. Freshwater of as much as 4 Ω • m resistivity occurs on the west side of the structure, whereas salty water occurs on the east side (fig. 2 and pl. 7). Several other features on plate 7 also indicate the influence of geologic structure on ground-water flow. An area of low resistivity water extending across Richland and McCone Counties, Mont., is bounded on the northwest by the Poplar fault, and on the southeast by the Weldon-Brockton fault. The Rwa anomaly in Bowman County, N. D., and Harding County, S. D., occurs just east of the Cedar Creek anticline.

POROSITY

Areas of the Interlake Formation are shown on plate 8 where the total thickness exceeds 25 ft for material having at least 10 percent porosity and 50 ft for material having at least 15 percent porosity. Some features of the Rwa map (pl. 7) appear to correlate with the porosity distribution shown on plate 8.

TEMPERATURE OF WATER

Temperatures of water in the Interlake Formation are shown on plate 9. Temperatures range from about 160 to 300°F and gradually increase in a southeasterly direction as the formation dips into the Williston basin. A temperature slightly greater than 300°F occurs in Billings County, N. D. Lines of equal temperature appear to be influenced by structural features in some places. For example, temperature lines are alined parallel to the Cedar Creek anticline from Bowman County, N. D., to Dawson County, Mont. The temperature lines also outline the west side of the Poplar dome in Roosevelt County, Mont. (fig. 4).

DUPEROW FORMATION (UPPER DEVONIAN)

The analysis of data from the Duperow Formation was limited to northeastern Montana and western North Dakota where the formation probably has its greatest water-bearing potential. Devonian rocks crop out at several localities in north-central Montana; recharge from meteoric water and stream infiltration probably occurs in these areas.

APPARENT WATER RESISTIVITY

The Rwa values for the Duperow Formation were determined from resistivity and porosity logs and equation 4. An assumed value of 2 was used for m. The Rwa values for the Duperow Formation range from 0.04–7 $\Omega \cdot m$; the distribution is shown by the lines on plate 10. Water in the Duperow Formation is fresh along the southern boundary of the mapped area, where Rwa is at least 6.8 $\Omega \cdot m$, corresponding to a sodium chloride solution of about 700 mg/L.

The patterns of Rwa lines appear to be at least partly associated with structural features. The area of highest Rwa, extending from Fergus to Valley Counties, Mont., lies between the Poplar and Hinsdale faults; the area also is near the western ends of Blood Creek syncline and Cat Creek fault in Fergus and Petroleum Counties (fig. 2 and pl. 10). Another area of high Rwa is associated with the eastern end of the Cat Creek fault and with Porcupine dome in Garfield County, Mont. Rwa lines also outline the Poplar dome in Roosevelt County and a synclinal axis (not shown on fig. 2) that extends northwest from the dome into Valley County, Mont. (fig. 2). A conspicuous low in Roosevelt County, Mont., is located near the Weldon-Brockton fault, which bounds the low on the northwest.

POROSITY AND ROCK TYPE

The thickness of material in the Duperow Formation having porosity of 10 percent or greater is shown on plate 11. The highest Rwa values in the formation appear to be associated with the greatest thicknesses of porous rock. The distribution of rock types in the Duperow Formation is shown on plate 12. Areas of high Rwa values appear to correspond in part to areas in which the rock is predominantly dolomite.

TEMPERATURE OF WATER

Lines of water temperature for the Duperow Formation are shown on plate 13. The temperature ranges from 80 to 240°F. The 80 and 100°F lines are located where the formation lies at relatively shallow depths in the western part of the area. Temperatures gradually increase eastward, as the depth to the top of the formation increases. The 180 and 200°F lines lie between and are parallel to the Poplar and Weldon-Brockton faults in McCone and Garfield Counties, Mont. (fig. 2 and pl. 13). The 200 to 240°F lines outline Poplar dome in Roosevelt County, Mont. A 200°F high in Garfield County, Mont., lies near the intersection of the Weldon-Brockton and Cat Creek faults.

BIRDBEAR FORMATION (UPPER DEVONIAN)

The Birdbear Formation directly overlies the Duperow Formation. The unit crops out and receives recharge in the Bearpaw uplift and Little Rocky Mountains (fig. 2).

APPARENT WATER RESISTIVITY

The Birdbear Formation was analyzed using most of the geophysical logs that were used in the Duperow Formation analysis. Rwa was calculated from equation 4 using an assumed value of 2 for m. Rwa contours for the Birdbear Formation are shown on plate 14. Values of Rwa range from 0.04 $\Omega \cdot m$ in Williams and Divide Counties, N. D., to 7 $\Omega \cdot m$ in Phillips County, Mont.

POROSITY AND ROCK TYPE

The thickness of material in the Birdbear Formation having porosity greater than 10 percent is shown on plate 15; the distribution of rock type in the formation is shown on plate 16.

TEMPERATURE OF WATER

The temperature of water in the Birdbear Formation is shown on plate 17; in general, the temperature is similar to that in the Duperow Formation and ranges from about 80 to 240°F. Temperatures are lowest where the formation lies at shallow depth in the western part of the area and increase with increasing depth of the formation to the east. The closely spaced 180 and 200°F lines lie astride part of the Weldon-Brockton fault in McCone County (fig. 2 and pl. 17). The prominent low in Valley County is at the intersection of a syncline (not shown on fig. 2) lying northwest of the Poplar dome and the northeast-trending Hinsdale fault (fig. 2 and pl. 17).

MADISON LIMESTONE INTERVAL M-7 TO M-8.5 (MISSISSIPPIAN)

The M-7 to M-8.5 interval of the Madison Limestone was used in the Rwa analysis. Generally, this chronostratigraphic interval has good porosity; however, it contains evaporites, consisting mostly of anhydrite, in the upper part. Approximately 50 percent of the wells analyzed showed good porosity in predominantly limestone sections, and the other 50 percent, in predominantly dolomitic sections.

APPARENT WATER RESISTIVITY

Rwa for the M-7 to M-8.5 interval was calculated from borehole geophysical log data and equation 4, using a value of 2 for *m*. Rwa lines for the Madison are shown on plate 18. Rwa ranges from 0.04 Ω • m in the Williston basin of North Dakota to 10 Ω • m in Big Horn County, Mont. Areas of high Rwa generally are associated with recharge areas, such as the Bighorn Mountains, Pryor Mountains, and the Black Hills. Another area of high Rwa occurs in Fergus County, Montana, and apparently is related to recharge in the Big Snowy and Judith Mountains.

Two areas of freshwater extend from the Black Hills recharge area. The major area extends northward from Meade County, S. D., to Dawson County, Mont., and a smaller area extends northeastward from Meade County to Corson County, S. D. These two areas of freshwater near the Black Hills also are evident in the Rwa lines for the Red River Formation (pl. 1).

The major area of low Rwa, 0.04 Ω • m, is in Dunn, Stark, Morton, Hettinger, Adams, and Grant Counties, N. D. The low value represents dense brine extending up the eastern flank of the Williston basin, in a pattern similar to that in the Red River, and again consistent with the hydraulic principles outlined by Hubbert (1953). Smaller areas of low Rwa occur in Mountrail and Pierce Counties, N. D. An apparent water resistivity of 0.04 Ω • m represents a saturated brine having a density in excess of 1.22 g/cm^3.

Many smaller structural features also appear to influence the Rwa distribution in the M-7 to M-8.5 interval. For example, the major area of freshwater from the Black Hills uplift is bounded on the east by the Cedar Creek anticline from Harding County, S. D., to Dawson County, Mont. (fig. 2 and pl. 18). The high-resistivity area in Treasure County, Mont., divides into two lobes, one of which trends northwest generally parallel to the Sumatra syncline, and the other northeast along the southeastern edge of the Porcupine dome (fig. 2 and pl. 18).

Faults of Tertiary age also may influence ground water in the Madison in this area. The area of high Rwa that trends eastward from Big Horn County to Powder River County, Mont., is bounded on the north by Lake Basin fault and on the south by an unnamed fault. The Rwa high in Dawson County, Mont., occurs at the north end of the Cedar Creek anticline.

POROSITY

Areas in the M-7 to M-8.5 interval are shown on plate 19 where the total thickness exceeds 50 ft for material having at least 10 percent porosity and for material having at least 15 percent porosity. The northwest-trending Rwa high in Treasure County, Mont., coincides, at least in part, with areas in which the thickness of porous material is reasonably great. The Rwa high in Dawson County, Mont., and that extending northward from Musselshell County, Mont. show similar association with areas in which the thickness of porous rock is great.

TEMPERATURE OF WATER

Temperature of water for the M-7 to M-8.5 interval of the Madison is shown on plate 20. Temperatures range from about 100 to 260°F (pl. 20). Cooler temperatures occur in ground-water recharge areas in the Bighorn Mountains, the Black Hills, and Big Snowy Mountains (fig. 2 and pl. 20). Temperatures increase as the formation dips into the Powder River and Williston basins. The largest temperature, 260°F, occurs in the Williston basin in Billings County, N. D. The low-temperature area from Treasure to Rosebud Counties, Mont., and the high-temperature area from McCone to Musselshell Counties, Mont., occur in a region dominated by faults, synclines, anticlines, and domes.

SUMMARY AND CONCLUSIONS

Geophysical well-log data and bottom-hole temperature data were analyzed to determine formation porosity, formation water resistivity, and ground-water temperature in each of five stratigraphic intervals within the Paleozoic Erathem of Montana, Nebraska, North Dakota, South Dakota and Wyoming. The five intervals for which the analyses were made were the Red River Formation, the Interlake Formation, the Duperow Formation, the Birdbear Formation, and a chronostratigraphic interval within the Madison Limestone.

Values of apparent water resistivity, Rwa, which serve as indicators of the general level of dissolved solids in ground water, were calculated from borehole geophysical data. Maps showing lines of equal Rwa are presented for each of the five stratigraphic intervals. Formation porosity also was calculated from geophysical log data; for each of the five stratigraphic intervals, maps are presented showing areas of greatest thickness of porous rock.

Rwa lines indicate areas of recharge, probable direction of water movement, and areas of dense brine. Maps of Rwa for the Red River Formation and the Madison Limestone, the two rock units for which most data were available, indicate a range in Rwa from 0.04 Ω • m in brine zones, particularly on the eastern flank of the Williston basin, to 13 Ω • m in recharge areas. The brines are assumed to be essentially static and extend up to the eastern flank of the basin in accordance with the hydraulic principles described by Hubbert (1953).

Lines of Rwa appear to correlate well with structural features such as folds, faults, anticlines, domes, and basins. This condition indicates that ground-water flow patterns, and therefore the water-quality distribution, are strongly influenced by these structural features. Rwa lines also appear to correlate well with variations in rock porosity, indicating that porosity is also a major factor in controlling flow.

Temperatures of ground water were determined using bottom-hole temperatures in oil wells. A corrected temperature-depth graph was constructed at each location for which bottom-hole data were available, and temperatures in the five stratigraphic intervals were obtained from these relations. Temperature maps are presented for each of the five intervals. Temperatures range from 80 to 320°F. The highest temperatures occur in the deep basins and in those areas where ground water circulates deeply along fractures associated with igneous intrusive rocks. Thermal gradients range from 1°F/100-ft to 4.2°F/100-ft depth.

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