UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

APPARENT WATER RESISTIVITY, POROSITY, AND GROUND-WATER TEMPERATURE

OF THE MADISON LIMESTONE AND UNDERLYING ROCKS IN PARTS OF MONTANA,

NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

Open-File Report 81-629
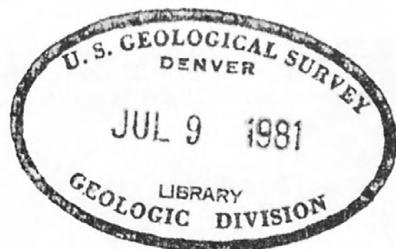
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By L. M. MacCary

Open-File Report 81-629

Denver, Colorado

1981

UNITED STATES DEPARTMENT OF THE INTERIOR

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In Reply Refer To:
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Date May 6, 1981

Memorandum

To: Branch of Plans and Program Management, Geological Survey,
        Mail Stop 342

From: Chief, Publications Unit, Water Resources Division

Subject: New U.S. Geological Survey Open-File Report

The following report was authorized by _____Henry Spall_____ for the
Director on __April 24, 1981__ for release to the open files:

TITLE: "Apparent water resistivity, porosity, and ground-water temperature of the
        Madison Limestone and underlying rocks in parts of Montana, Nebraska,
        North Dakota, South Dakota, and Wyoming"

AUTHOR(S): L. M. MacCary

CONTENTS: __50__ p., _____over-size sheets (i.e., large than 8½ x 11 inches)

          Map scale: _____

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Release
date: July 1981

Area: Regional

OFR No. 81-629

Copy to: Regional Hydrologist, CR
          L. M. MacCary

          Barbara M. Gundersen
  for   Kathleen T. Iseri

United States Department of the Interior

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To: U.S. Geological Survey Library, MS 914, Denver, CO

From: L. M. MacCary, Denver, CO

Subject: PUBLICATIONS--Report, "Apparent water resistivity, porosity,
         and ground-water temperature of the Madison
         Limestone and underlying rocks in parts of Montana,
         Nebraska, North Dakota, South Dakota, and Wyoming",
         by L. M. MacCary

Enclosed is one copy of the subject report which has been released to the
Open File as report 81-629. Also enclosed is a copy of the memorandum
releasing the report to the open file. A National press release announcing
the report will be issued by the Reston office.

L. M. MacCary

Enclosure

    U.S.G.S. Open File Report 81-629
    Approval memorandum

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Water Resources Division
Reston, Virginia 22092

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May 6, 1981
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Memorandum

To: L. M. MacCary, WRD, MS 418, Lakewood, Colorado

From: Chief, Publications Unit, WRD

Subject: PUBLICATIONS -- Transmittal of manuscript approved for open-file
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The following manuscript has been approved for release only to the open
file and is (XXXXXX) returned herewith: "Apparent water resistivity, porosity,
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parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming", by
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Open-File Report 81-629

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NO. ILLUSTRATIONS 25

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CONTENTS--Continued

ILLUSTRATIONS

[All plates are in pocket at end of report]

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METRIC CONVERSION TABLE

Inch-pound units[1] in this report may be converted to metric (SI) units by using the following conversion factors:

Multiply inch-pound units	By	To find metric units
inches (in)	2.54	centimeters (cm)
inches	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
feet	30.48	centimeters
mi^2 (square miles)	2.59001	km^2 (square kilometers)
°F/100 ft (degrees Fahrenheit per 100 ft)	18.2268	°C/km (degrees Celsius per kilometer)
acre-ft (acre-feet)	1233	m^3 (cubic meters)

[1]Temperature is reported in degrees Fahrenheit. To convert to degrees Celsius use:

$$\text{Temperature } °C = \frac{(\text{Temperature } °F - 32)}{1.8}$$

APPARENT WATER RESISTIVITY, POROSITY, AND GROUND-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 on a temporary basis, 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 approximately 200,000 square miles, and includes eastern
Montana, western North Dakota and South Dakota, northeastern Wyoming, and
northwestern Nebraska.

Borehole geophysical data and bottom-hole temperature data were used to
determine porosity, apparent electrical resistivity of ground water (Rwa), and
temperature of ground 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.

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Rwa values ranged from about 13 ohm-meters to 0.04 ohm-meter. The highest Rwa is in recharge areas, and the lowest, 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°F to as much as 320°F. 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°F/100 ft to 4.2°/100 ft.

INTRODUCTION

A major part of the United States' coal reserves occur 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. Ground water from the Madison Limestone and underlying rocks might supply, at least on a temporary basis, a large part of the water required for coal development. These rock units underlie the Fort Union coal region and adjacent areas in Montana, North Dakota, South Dakota, Nebraska, 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 groundwater temperature in the Madison Limestone and associated rocks; and also outlines the average geothermal gradient in the study area, Comparisons are made of the areal distributions of these properties to major geologic structures. Data were obtained from geophysical logs, sample studies by American Stratigraphic Co.,[1] drill-stem tests, and water analyses from Madison Limestone test wells 1, 2, and 3 (fig. 1).

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

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[1]Any use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Base: U.S. Geological Survey,
1:7,500,000, 1970

| 0 | 100 | 200 | 300 MILES |

| 0 | 100 | 200 | 300 KILOMETERS |
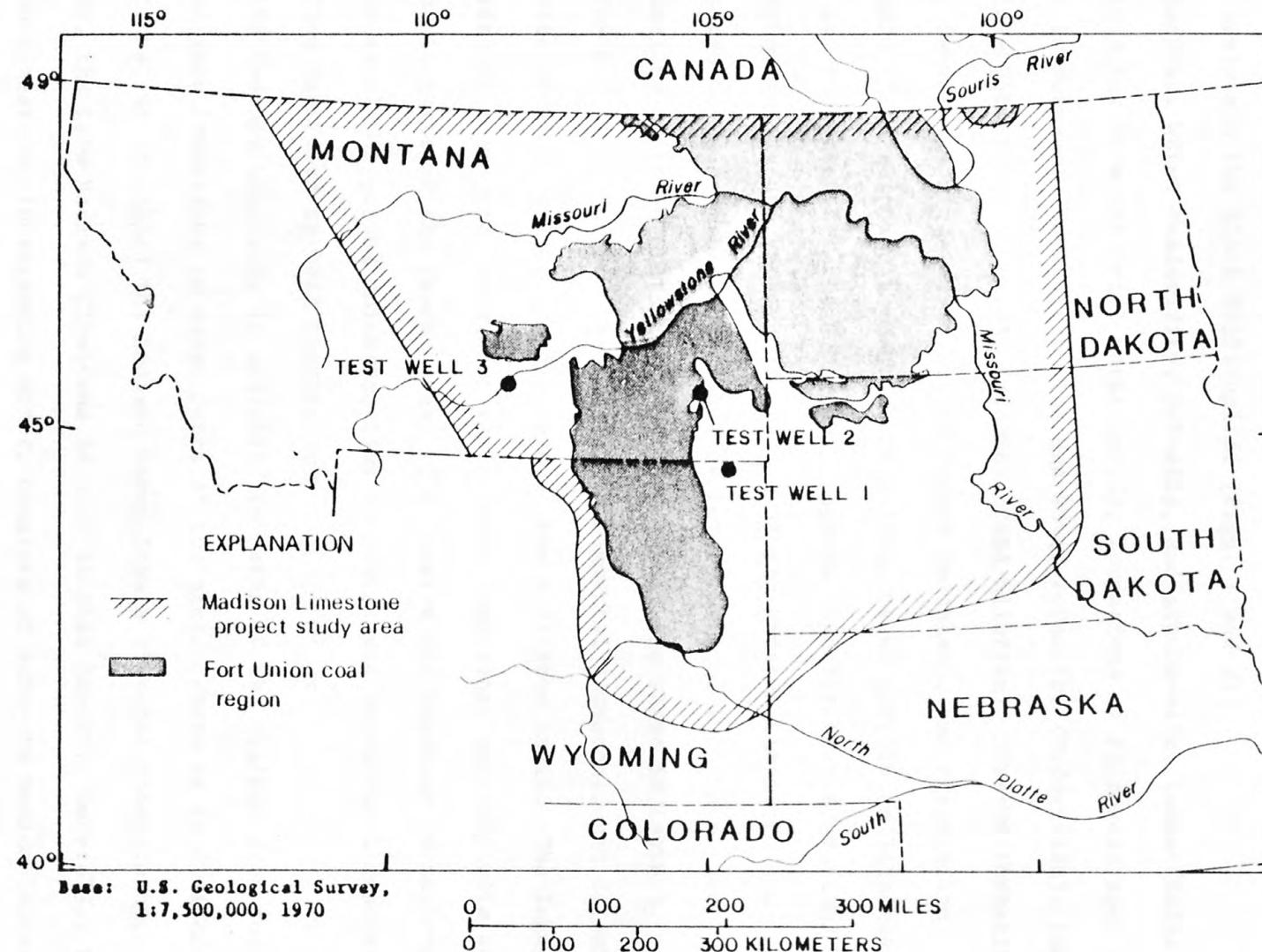
Figure 1.-- Location of study area.

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 ground-water temperatures are described for five potential water-bearing formations of Paleozoic age. From oldest to youngest, these are: The Red River Formation (Ordovician), the Interlake Formation (Uppermost Ordovician and Silurian), Duperow Formation (Upper Devonian), Birdbear Formation (Upper Devonian), and the 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 of 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 made up mainly 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 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

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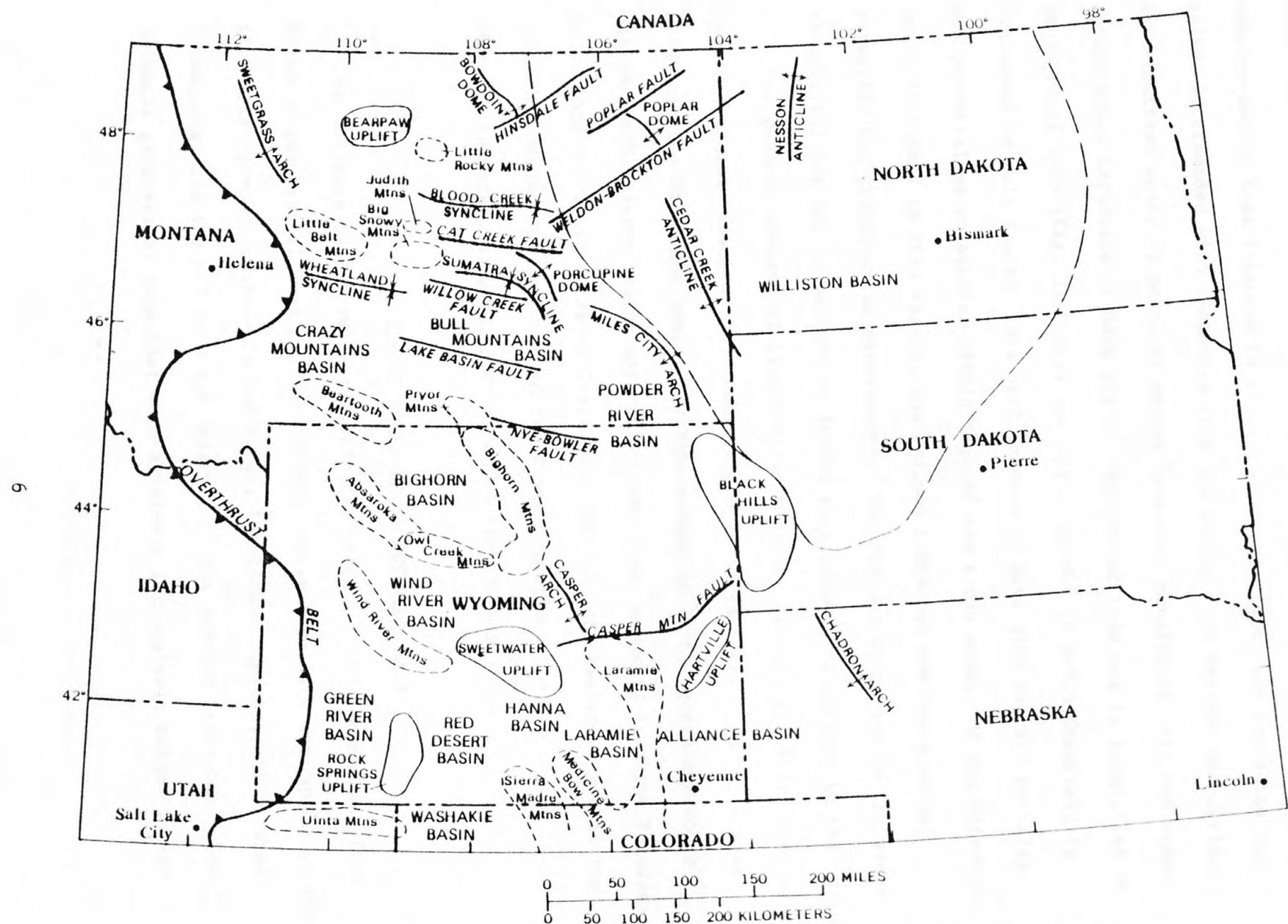
Figure 2.--Structural features, Western Interior, United States.
(modified from Grose, 1972 and Stone, 1971).

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 thirteen units by means of marker beds that consist of thin and wide-spread 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 uplifts, but may be as much as 16,000 feet below land surface in the basins.

The general pattern of ground-water movement through the study area is toward the east, downgradient from western recharge areas. There is some flow into the Williston basin, and some around it to the north and south. Within the Williston basin, apparently some flow 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, suggesting 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
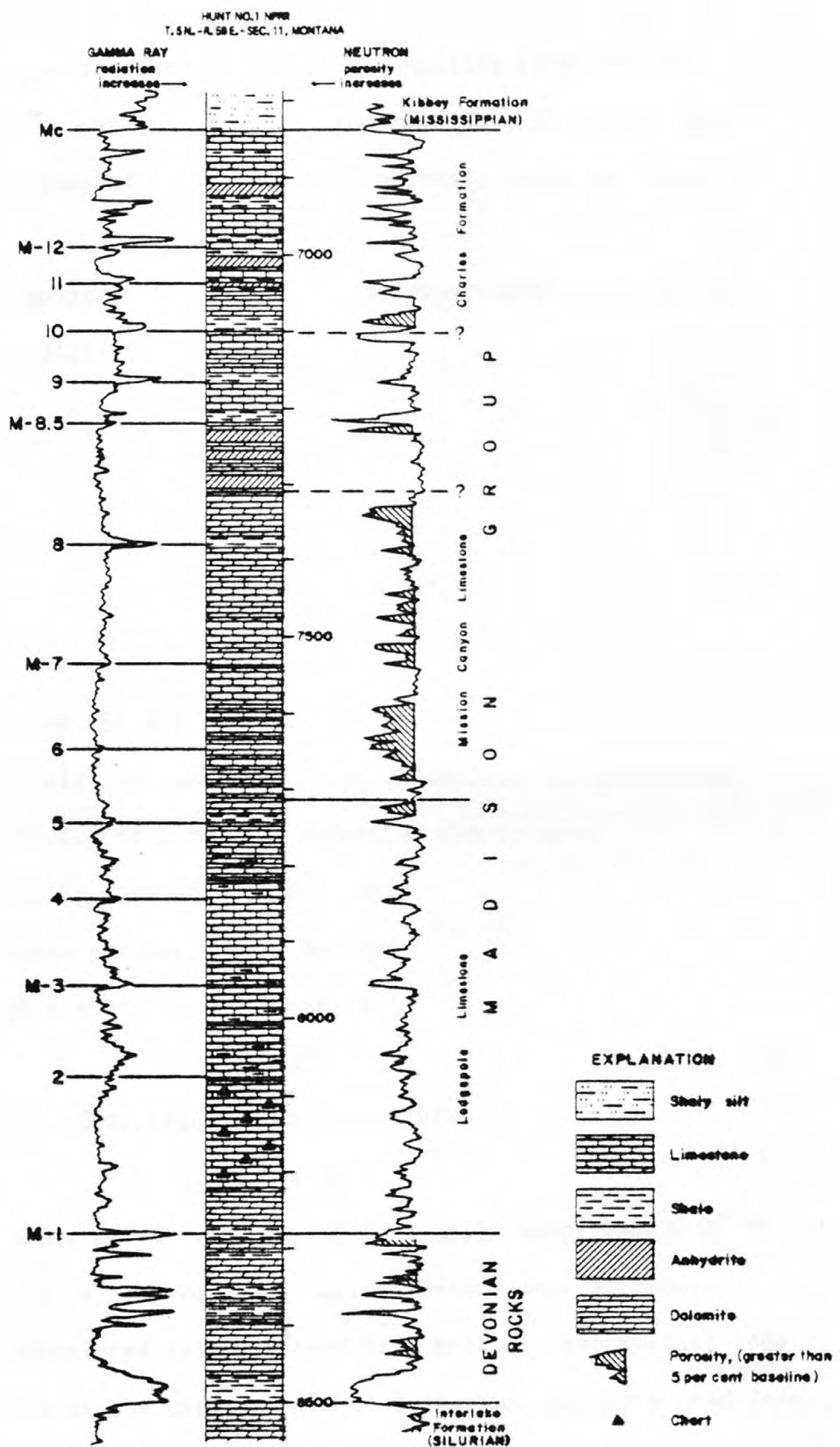
Figure 3.—Examples of well-log patterns and lithology
of Madison Group units.

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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 ohm-meters,

Rw is the resistivity of formation water, in ohm-meters,

m   is an empirically derived exponent, and

ϕ is the formation porosity, as a decimal.

Combining (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 an actual measurement of water resistivity, but 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

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induction logs were used where formation resistivities were less than 50 ohm-meters. Weighted average values of Ro were calculated for those intervals in each unit having porosity values of 0.10 or greater (that is, for the major water-bearing zones). This was done by calculating the product of resistivity and thickness for every interval in the unit showing a porosity of 0.10 or more, and dividing 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, which is the temperature of the undisturbed formation, was required to correct values of Ro that were obtained at the observed logging temperatures. 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. The observed bottom-hole temperatures were corrected to the equilibrium temperatures by a method described by Wallace and others (1979, p. 150). 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.

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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 to 0.15 range was multiplied by 0.10, the lower limit of the porosity range; the total thickness of material in the 0.15 to 0.20 range was multiplied by 0.15; and the total thickness in the over 0.20 range 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 was compiled in map form for each of the five stratigraphic units that were analyzed. For the Birdbear and Duperow Formations, contours are shown giving the total thickness of rock in the interval 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 in order 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 a maximum of 3 for some carbonate rocks. Usually a value of 2 is used for carbonate

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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 log-log graph of porosity versus the resistivity of the water-saturated formation is required 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) (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 a few thousand mg/L (milligrams per liter), concentration of the equivalent sodium chloride solution was found by converting all ions to meq/L (milli-equivalents 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.

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Where the dissolved solids are greater than a few thousand 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 (1972). These estimated formation water resistivities were plotted opposite 100 percent porosity on log-log graphs of resistivity versus 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 the equation (4) to determine Rwa for the Red River. That is, the weighted average porosity, 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, 1972), plotted on the base map, and contoured (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 to estimate concentrations of dissolved solids in ground water. Rwa in ohm-meters corresponds to an equivalent sodium chloride solution in mg/L

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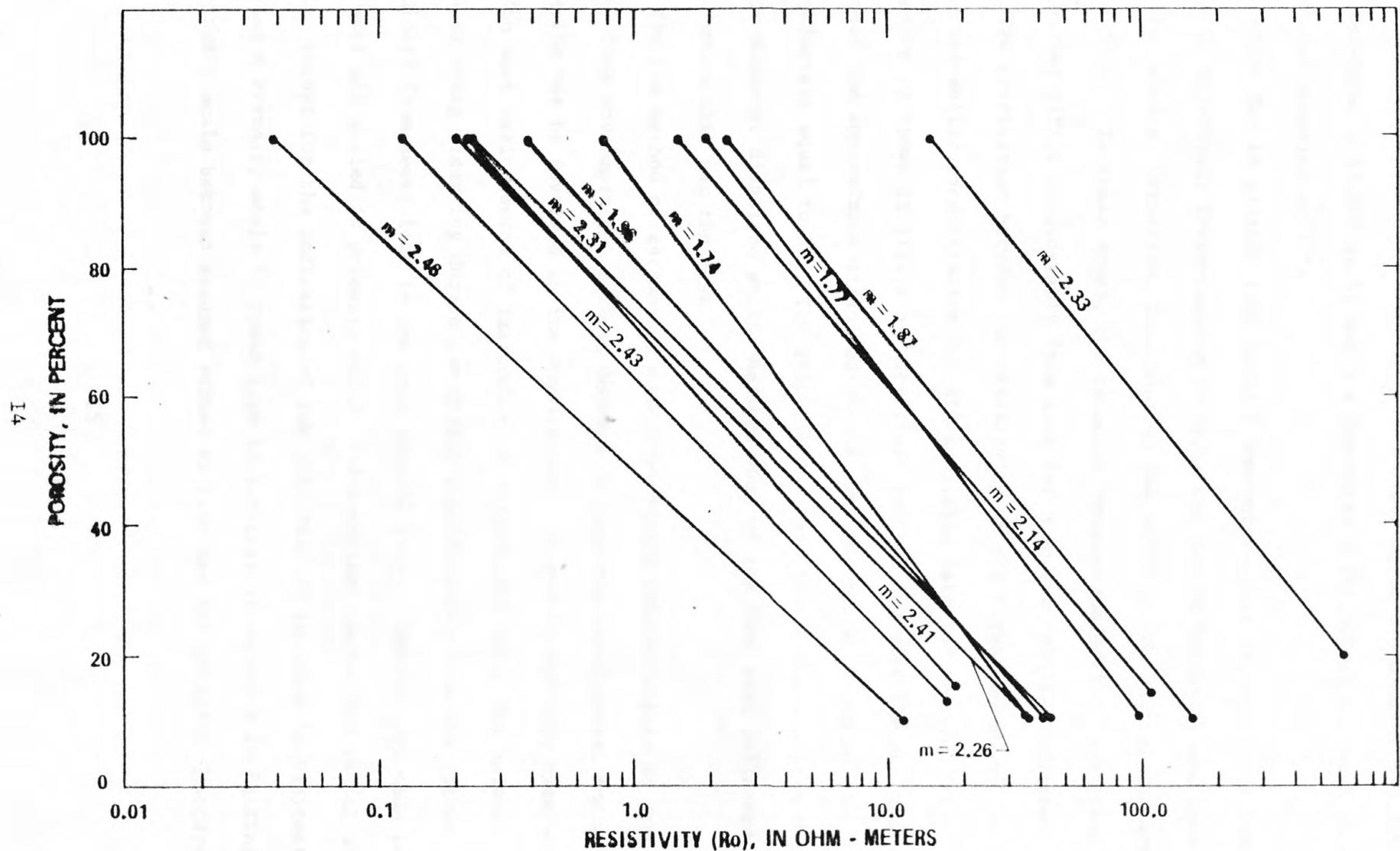
Figure 4.--Determination of m (slope) from porosity and resistivity
of the water-saturated formation (Red River).

approximately as follows: 10 ohm-meters ≈ 500 mg/L; 1 ohm-meter ≈ 5,500 mg/L; 0.1 ohm-meter ≈ 65,000 mg/L; and 0.4 ohm-meter ≈ 361,000 mg/L, which is a saturated solution at 77°F.

Where Rwa is greater than about 1 ohm-meter--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 formation 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 the case.

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 at all, 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,

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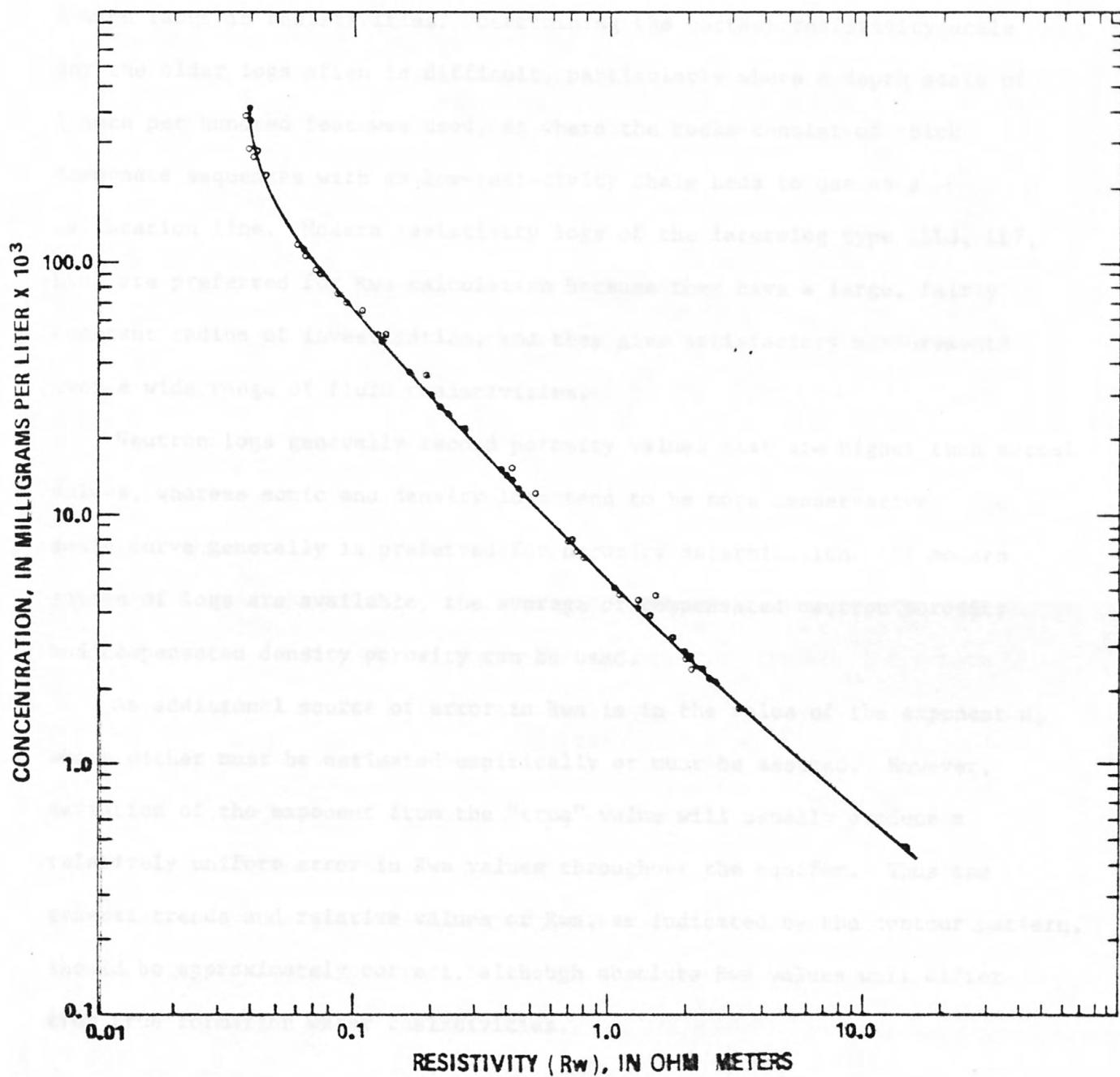
Figure 5.—Dissolved-solids concentration versus resistivity
of formation water, Rw, Red River Formation.

1980). The older electric logs were run on a linear resistivity scale, thus necessitating many off-scale deflections or back-up curves in order to cover a wide range in resistivities. Determining the current resistivity scale for the older logs often is difficult, particularly where a depth scale of 1 inch per hundred feet 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 empirically 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 contour pattern, should be 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

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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 yields water to

three test wells drilled during the Madison Limestone Project (fig. 1), and

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 noted above, the well data used in this study are from holes

drilled in search of oil or gas.

Apparent Water Resistivity

Contours of apparent water resistivity, Rwa, for the Red River Formation

are shown on plate 1. Values range from a high of 13 ohm-meters in Crook

County, Wyoming, to a low of 0.04 ohm-meter in the Williston basin in eastern

Montana. The high 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, Wyoming), the Pryor Mountains (Big Horn and

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Carbon Counties, Montana), and the Black Hills (Lawrence, Pennington, and Custer Counties, South Dakota, and Crook County, Wyoming). Another Rwa high associated with recharge occurs on the east flanks of the Big Snowy and Judith Mountains (Fergus and Golden Valley Counties, Montana). Low values of Rwa are present in the basins, especially the Williston basin where highly saline brines occur. Freshwater in the recharge areas moves down the hydraulic gradient toward the basins. Structure contours on the top of Red River Formation are shown on plate 2. The Rwa contours (pl. 1) suggest that ground water becomes progressively saltier 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 (grams per cubic centimeter)] 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, North Dakota, where it lies 11,000 ft below sea level. The lowest Rwa area in the Red River Formation lies in a northeast-trending band mainly in Adams, Hettinger, Grant, Morton, Oliver, and McLean Counties, North Dakota. This conforms to the theory presented by Hubbert (1953, p. 1994) if it is assumed that the brines are essentially static and that freshwater 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 contours. For example, in Valley, Garfield, and McCone Counties, Montana, a series of parallel Rwa contours in the range of 0.10 to 1 ohm-meter 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, Montana, the
Poplar dome (fig. 2) is outlined on the west, north, and east by 0.10 to
0.50 ohm-meter contours. The shape and direction of the Rwa contours 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, Montana, the Lake
Basin fault appears to act as a control on ground-water flow (fig. 2, pl. 1).
The 2 and 3 ohm-meter contours lie astride the fault, and Rwa increases
rapidly to the north. A relatively broad area is located south of the fault
where Rwa is between 0.50 and 1 ohm-meter. Thus, there seems to be relatively
little flow of freshwater from areas north of the fault toward the saltier
water on the south. In contrast, in western Yellowstone County, the 4 ohm-
meter contours continue northward as far as Petroleum County.

Porosity and Rock Type

The distribution of rock type in the Red River 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, Wyoming.

Areas in the Red River Formation for which the total thickness of material
having porosity of at least 10 percent exceeds 50 feet, and for which the total
thickness having porosity of at least 15 percent exceeds 50 feet are shown
on plate 4. The control of Rwa contours by porosity zones is shown in the
northeastward-trending area of high Rwa from the Black Hills toward Perkins

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County, South Dakota (pls. 1 and 4). The area of rock thicker than 50 ft with porosity greater than 10 percent coincides roughly with the area enclosed by 2 ohm-meter contour in Butte and Perkins Counties, South Dakota. A relation between porosity and Rwa in other areas is suggested although it is not as closely correlated as in the example above. Generally the areas of low Rwa correspond broadly with areas of low porosity (pls. 1 and 4).

Temperature of Ground Water

Temperatures of ground water of the Red River Formation are shown on plate 5. The contours 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, coolest temperatures occur in recharge areas around the Black Hills, Pryor Mountains, and Bighorn Mountains. High-temperature contours outline the deep basins; the highest temperature, 320°F, occurs in the Williston basin in Billings County, North Dakota.

The temperature of ground 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 ground water in fractured rock associated with igneous intrusives. So many factors enter into thermal effects that it is difficult to isolate specific controls in each place. Recharge and intrusives are both localized and can be identified on the map. For example, the 100- to 140-degree contour areas in Carter County, Montana, and Crook County, Wyoming, probably are influenced by deep circulation associated with igneous intrusives in Crook County.

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Some thermal anomalies that may be due to structural control are evident on plate 5. Along the Cedar Creek anticline north of Wilbaux County, Montana, the 200- to 260-degree contours abruptly turn to the east around the northern flank of Poplar dome in Roosevelt County, Montana. The closed 200-degree contour in Garfield County, Montana, 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-degree contours in Treasure, Yellowstone, and Musselshell Counties, Montana. 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-degree contours occurs in Fergus, Petroleum, and Garfield Counties, Montana, possibly related to the influence of the Hinsdale fault and the Poplar dome on the flow pattern.

In Custer, Prairie, Fallon, and Carter Counties, Montana, 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, North Dakota, and Meade County, South Dakota. These anomalies are discussed in the following section.

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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 Red River Formation wells 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 F per 100 feet, and generally agrees with the Geothermal Gradient Map of North America (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 (millical/cm/sec/°C) and range from a low of 0.33 in lignite to a high of 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, Montana, and Crook County, Wyoming, to 4.2°F/100 ft in Lyman County, South Dakota. An anomaly, probably caused by deep circulation of water in fractured rock near igneous intrusive bodies, is located in Blaine County, Montana, where the

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gradient is 2.6°F/100 ft. A few oil wells in this area penetrated igneous intrusions 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 millical/cm/sec/°C, and natural gas has an even lower conductivity, from 0.04 to 0.08 millical/cm/sec/°C; therefore, both hydrocarbons are good heat insulators. Oil and gas fields are generally in areas where little or no active ground-water circulation occurs; this is a factor that also enhances heat retention, because water is not transporting heat out of the rocks. Thus areas of petroleum accumulation may be characterized by high thermal gradients. This appears to be the case in northern Rosebud County, Montana, where a closure in thermal gradient contours coincides with known oil accumulations in rocks of Pennsylvanian age. A similar closure in thermal gradient contours at the intersection of Roosevelt, Richland, and McCone Counties, Montana, may be related to known petroleum accumulations in rocks of Devonian and Mississippian age. The closed thermal gradient contours in Billings County, North Dakota, 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, South Dakota. 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

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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 will transport heat away from rocks, causing lower temperatures and lower thermal gradient. Wells drilled on topographic highs generally will show lower temperatures and thermal gradients than wells drilled off the highs. Thermally conductive rocks, such as massive, bedded evaporites, can cause lower thermal gradients if they make up 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. In North Dakota, a low gradient area in the southwestern part of McKenzie County and a prominent low in Harding County, South Dakota, are both probably caused by evaporite beds.

Although some of the high and low gradients shown on plate 6 can be explained, others are not so readily explained. 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 open to debate.

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 ohm-meters. 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 Rwa contours are shown on plate 7; Rwa ranges from a low of 0.04 ohm-meter to a high of 4 ohm-meters.

There apparently is very little ground-water flow across the northwest-trending Cedar Creek anticline between Harding County, South Dakota, and Dawson County, Montana. Freshwater of up to 4 ohm-meters resistivity occurs on the west side of the structure while salty water occurs on the east side

(fig. 2 and pl. 7). Several other features on plate 7 also suggest the influence of geologic structure on ground-water flow. An area of low resistivity water extending across Richland and McCone Counties, Montana, is bounded on the northwest by the Poplar fault, and on the southeast by the Weldon-Brockton fault. The Rwa anomaly lying in Bowman County, North Dakota, and Harding County, South Dakota, occurs just east of the Cedar Creek anticline.

Porosity

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

Temperature of Ground Water

Temperatures of ground 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, North Dakota. Temperature contours appear to be influenced by structural features in some places. For example, temperature contours are aligned parallel to the Cedar Creek anticline from Bowman County, North Dakota, to Dawson County, Montana. The temperature contours also outline the west side of the Poplar dome in Roosevelt County, Montana (fig. 4).

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Duperow Formation (Upper Devonian)

The analysis of data from the Duperow Formation was limited to north-
eastern 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 7 to 0.04 ohm-meters; the
distribution is shown by the contours on plate 10. Water in the Duperow
Formation is quite fresh along the southern boundary of the contoured area,
where Rwa is at least 7 ohm-meters, corresponding to a sodium chloride
solution of approximately 700 mg/L.

The Rwa contour patterns appear to be at least partially associated with
structural features. The area of highest Rwa contours, extending from Fergus
to Valley Counties, Montana, 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 high Rwa
area is associated with the eastern end of Cat Creek fault and with Porcupine
dome in Garfield County, Montana. Rwa contours also outline the Poplar dome
in Roosevelt County and the synclinal axis that extends northwest from the dome
into Valley County, Montana (fig. 2). A prominent low in Roosevelt County,
Montana, is located near the Weldon-Brockton fault, which bounds the low on
the northwest.

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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, and there also appears to be some correspondence between areas of high Rwa and areas in which the rock is predominantly dolomite.

Temperature of Ground Water

Contours of ground-water temperature for the Duperow Formation are shown on plate 13. The temperature ranges from 80°F to 240°F. The 80- and 100-degree contours 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-degree contours lie between and are parallel to the Poplar and Weldon-Brockton faults in McCone and Garfield Counties, Montana (fig. 2 and pl. 13). The 200- to 240-degree contours outline Poplar dome in Roosevelt County, Montana. A 220-degree high in Garfield County, Montana, 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 Bear Paw uplift and Little Rocky Mountains (fig. 2).

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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 a high of 7 ohm-meters in Phillips County, Montana, to a low of 0.04 ohm-meter in Williams and Divide Counties, North Dakota.

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 Ground Water

The temperature of ground 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°F 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-degree contours lie astride part of the Weldon-Brockton fault in McCone County (fig. 2 and pl. 17). The prominant low in Valley County is at the intersection of a syncline (not shown on fig. 2) lying north-west 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 time-stratigraphic 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 contours for the Madison are shown on plate 18. Rwa ranges from a high of 10 ohm-meters in Big Horn County, Montana, to a low of 0.04 ohm-meter in the Williston basin of North Dakota. 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, South Dakota, to Dawson County, Montana, and a smaller area extends northeastward from Meade County to Carson County, South Dakota. These two areas of freshwater near the Black Hills also are evident in the Rwa contours for the Red River Formation (pl. 1).

The major area of low Rwa, 0.04 ohm-meter, is centered around Dunn, Stark, Morton, Hettinger, Adams, and Grant Counties, North Dakota, and represents a

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, North Dakota. Apparent water resistivities of 0.04 ohm-meter represent 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 form Harding County, South Dakota, to Dawson County, Montana (fig. 2 and pl. 18). The high-resistivity area in Treasure County, Montana, 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 high Rwa area that trends eastward from Big Horn County to Powder River County, Montana, is bounded on the north by Lake Basin fault and on the south by Nye-Boweler fault. The Rwa high in Dawson County, Montana, occurs at the north end of the Cedar Creek anticline.

Porosity

Areas in the M-7 to M-8.5 in which the thickness of material having porosity of at least 10 percent exceeds 50 feet, and in which the thickness of material having porosity of at least 15 percent exceeds 50 feet are shown on plate 19. The northwest-trending Rwa high in Treasure County, Montana,

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coincides, at least in part, with areas in which there is a reasonably good thickness of porous material. The Rwa high in Dawson County, Montana, and that extending northward from Musselshell County, Montana show similar association with areas in which there is a considerable thickness of porous rock.

Temperature of Ground Water

Temperature of ground water for the M-7 to M-8.5 interval of the Madison is shown on plate 20. Temperatures range from about 100°F 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 highest temperature, 260°F, occurs in the Williston basin in Billings County, North Dakota. The low-temperature area from Treasure to Rosebud Counties, Montana, and the high-temperature area from McCone to Musselshell Counties, Montana, occur in a region dominated by faults, synclines, anticlines, and domes.

SUMMARY AND CONCLUSIONS

Analyses of geophysical well log data and bottom-hole temperature data were carried out to determine formation porosity, formation water resistivity, and ground-water temperature in each of five stratigraphic intervals within the Paleozoic system of Montana, Wyoming, North Dakota, and South Dakota. 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.

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Values of apparent water resistivity, Rwa, were calculated from borehole geophysical data and serve as indicators of the general level of dissolved solids in ground water. Maps showing contours of 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 contours 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, show a range in Rwa from as much as 13 ohm-meters in recharge areas to values lower than 0.04 ohm-meter in brine zones, particularly on the eastern flank of the Williston basin. It is speculated that the brines are essentially static and extend up the eastern flank of the basin in accordance with the hydraulic principles described by Hubbert (1953).

Contours of Rwa appear to correlate well with structural features such as folds, faults, anticlines, domes, and basins. This suggests that ground-water flow patterns, and therefore the water-quality distribution, are strongly influenced by these structural features. Rwa contours 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 taken from these relations. Temperature contour maps are presented for each of the five intervals.

Temperatures range from 80°F 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 per 100 ft depth to 4.2°F per 100 ft depth.

REFERENCES

American Association of Petroleum Geologists, 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey, Geologic Maps of North America Series, scale 1:5,000,000, 2 sheets.

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.

Carrothers, J. E., 1968, A statistical study of the formation factor relation, *in* The Log Analyst: Houston, Texas, Society of Professional Well Log Analysts, v. 9, no. 5, p. 13-20.

Desai, K. P., and Moore, E. J., 1969, Equivalent NaCl determination from ionic concentrations, *in* The Log Analyst: Houston, Texas, Society of Professional Well Log Analysts, v. 10, no. 3, p. 12-21.

Gibbs, F. K., 1972, Silurian system, *in* Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, Colorado, p. 86-89.

Hubbert, M. K., 1953, Entrapment of petroleum under hydrodynamic conditions: Bulletin of the American Association of Petroleum Geologists, v. 37, no. 8, p. 1954-2026.

MacCary, L. M., 1971, Resistivity and neutron logging in Silurian dolomite of
northwest Ohio: U.S. Geological Survey Professional Paper 750-D,
p. D19-D197.

_____, 1980, Use of geophysical logs to estimate water-quality trends in
carbonate aquifers: U.S. Geological Survey Water-Resources Investigations
80-57, 27 p.

Peterson, J. A., 1981, Stratigraphy and sedimentary facies of the Madison
Limestone and associated rocks in part of Montana, North Dakota, South
Dakota, Wyoming, and Nebraska: U.S. Geological Survey Open-File Report
81-642, 96 p.

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

Schlumberer Limited, 1972, Log interpretation charts: Houston, Texas,

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

Wallace, R. H., Jr., Kruemer, T. F., Taylor, R. E., and Wesselman, J. B.,
1979, Assessment of geopressured - geothermal resources in the northern
Gulf of Mexico basin, *in* Assessment of geothermal resources of the
United States--1978, Muffler, L. J. P., ed.: U.S. Geological Survey
Circular 790, 163 p.