# United States Department of the Interior

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Water Resources Division

March 27, 1981

Memorandum

To: U.S. Geological Survey Library, Serial Records Unit, MS 950, Reston, VA

From: L. M. MacCary, Denver, CO

Subject: PUBLICATIONS--Report, "Potentially favorable areas for large-yield wells in the Red River Formation and Madison Limestone in parts of Montana, North Dakota, South Dakota, and Wyoming" by L. M. MacCary, E. M. Cushing, and D. L. Brown

Enclosed is one copy of the subject report which has been released as Open File Report 81-220. Also enclosed is a copy of the memorandum releasing the report to the open file. The Reston office will issue a National press release for the report.

L. M. MacCary

L. M. MacCary

Enclosure:

U.S.G.S. Open File Report 81-220
Approval memorandum

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

Code 4251 5814
Mail stop 435

February 19, 1981
Date

Memorandum

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

From: Chief, Publications Unit, WRD

Subject: PUBLICATIONS -- Transmittal of manuscript approved for open-file release only

The following manuscript has been approved for release only to the open file and is (XXXXXXX) returned herewith: "Potentially favorable areas for large-yield wells in the Red River Formation and Madison Limestone in parts of Montana, North Dakota, South Dakota, Wyoming, and ~~Nebraska~~", by L. M. MacCary, E. M. Cushing, and D. L. Brown.

Open-File Report 81-220

Before placing the report in the depositories, please resolve all remaining unanswered comments and suggestions and transfer the final revisions to all open-file copies. Please retype all badly marked-up pages and other pages on which significant changes are made in response to comments and queries of the reviewers and send copies of these pages to the Publications Unit for our file copy of the report.

Open-file release will be announced in the May 1981 issue of the monthly list, "New Publications of the Geological Survey." Before the report is announced, one copy of the report, for inspection only, must be in each of the depositories indicated on the attached memorandum.

The copy of the report sent to the Geological Survey Library in Reston (attn: Serial Records Unit, mail stop 950) should be accompanied by a copy of the attached memorandum that lists depositories for the report.

Note: A reproducible copy of the open-file report must be sent to the USGS Open-File Services Section in Denver. Please refer to WRD Memorandum 79.117, June 14, 1979, for detailed instructions.

for Kathleen T. Iseri

Attachment
Copy to: Regional Hydrologist, CR
Julie Stewart

INT:2556-74

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY



# POTENTIALLY FAVORABLE AREAS FOR LARGE-YIELD WELLS IN THE RED RIVER FORMATION AND MADISON LIMESTONE IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

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Open-File Report 81-220

UNITED STATES

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U.S. GEOLOGICAL SURVEY

Open-File Report 81-220

Denver, Colorado

1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Doyle G. Frederick, Acting Director

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## METRIC CONVERSION TABLE

Inch-pound units[1] in this report may be converted to metric 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) |
| gal $min^{-1}$ (gallons per minute) | 3.785 | L $min^{-1}$ (liters per minute) |
| acre-ft (acre-feet) | 1233 | $m^3$ (cubic meters) |

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

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

# POTENTIALLY FAVORABLE AREAS FOR LARGE-YIELD WELLS IN THE RED RIVER FORMATION AND MADISON LIMESTONE IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

By L. M. MacCary, E. M. Cushing, and D. L. Brown

## ABSTRACT

The need for large quantities of energy has created interest in the Fort Union coal region of the Northern Great Plains. Extensive development of this coal, which may include onsite steam-power generation, gasification, liquefaction, and slurry-pipeline transport of the coal from this region, would place a heavy demand on the region's limited streamflow. Paleozoic rocks that underlie the Fort Union coal region and aquifers in these rocks, including the Red River Formation and the Madison Limestone, might supply, at least on a temporary basis, a significant part of the water required for coal development. 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.

This report, one of a series in the Madison Limestone study, uses hydrologic and geologic data to outline potentially favorable areas for well construction - that is, areas in which there is a good probability that large-yield wells (more than 500 gallons per minute) can be completed in the Red River Formation and in the Madison Limestone. Potentially favorable areas in terms of aquifer characteristics, for both the Red River Formation and the Madison Limestone, are given a numerical evaluation from 1 to 3 based on the

number of the following criteria that are met: (1) the presence of more than 100 feet of relatively porous rock, (2) the presence of more than 100 feet of dolomite, and (3) the presence of known geologic structures which could affect yield. Areas rated 3 are those in which all three criteria are satisfied; areas rated 2 are those in which two criteria are satisfied; and areas rated 1 are those in which only one criterion is satisfied. The criteria selected for this analysis were chosen because they can be recognized and mapped over the entire study area. Local features such as minor structures, solution zones, and rock facies of small extent were not included in this regional evaluation. In addition, water quality was considered in a general way in defining the favorable areas, by excluding areas in which the electrical resistivity of formation water, as calculated from geophysical well logs, was less than 1 ohm-meter. The numerical scales of the Red River Formation and Madison Limestone are summed to show potentially favorable areas for the combined aquifers. Certain additional factors which may be important to a prospective water user were not included in the numerical ranking - these include depths to the two aquifers, calcite saturation, water temperature, total dissolved solids, and piezometric head in relation to land surface. For a complete evaluation, potential users should consider these factors plus local structures, facies, and solution zones in conjunction with the numerical rankings reflecting aquifer characteristics. To facilitate consideration of piezometric head, maps are included in this report showing areas in which the piezometric head falls in certain ranges with respect to land surface.

# INTRODUCTION

Energy needs have caused government and industry to focus attention on the Fort Union coal region of the Northern Great Plains, where a major part of the United States' coal reserves occur (fig. 1). Extensive development of this coal, which may include onsite steam-power generation, gasification, liquefaction, and slurry-pipeline transport, could place a heavy demand on the region's limited water resources.

Streamflow in the region is poorly distributed. Where it is not already appropriated, development would require storage reservoirs and distribution systems; where it already is fully appropriated, its use would deprive present users of their supply.

Paleozoic rocks, which include the Madison Limestone, its equivalents, and associated rocks, underlie the Fort Union coal region and adjacent areas in Montana, North Dakota, South Dakota, Nebraska, and Wyoming. Aquifers in these rocks, including the Red River Formation and the Madison Limestone, might supply, at least on a temporary basis, a significant part of the water required for coal development.

The purpose of the Madison Limestone Project, begun in 1976, is to evaluate the quantity and quality of water in rocks of Paleozoic age. The project area covers approximately 200,000 $mi^2$ (square miles), and includes eastern Montana, western North Dakota and South Dakota, a small part of northwestern Nebraska, and northeastern Wyoming (fig. 1). The area of greatest interest, however, is the Powder River basin of Montana and Wyoming, the area surrounding the Black Hills in South Dakota and Wyoming, and the adjacent areas in Montana, North Dakota, and Nebraska. Throughout much of the project

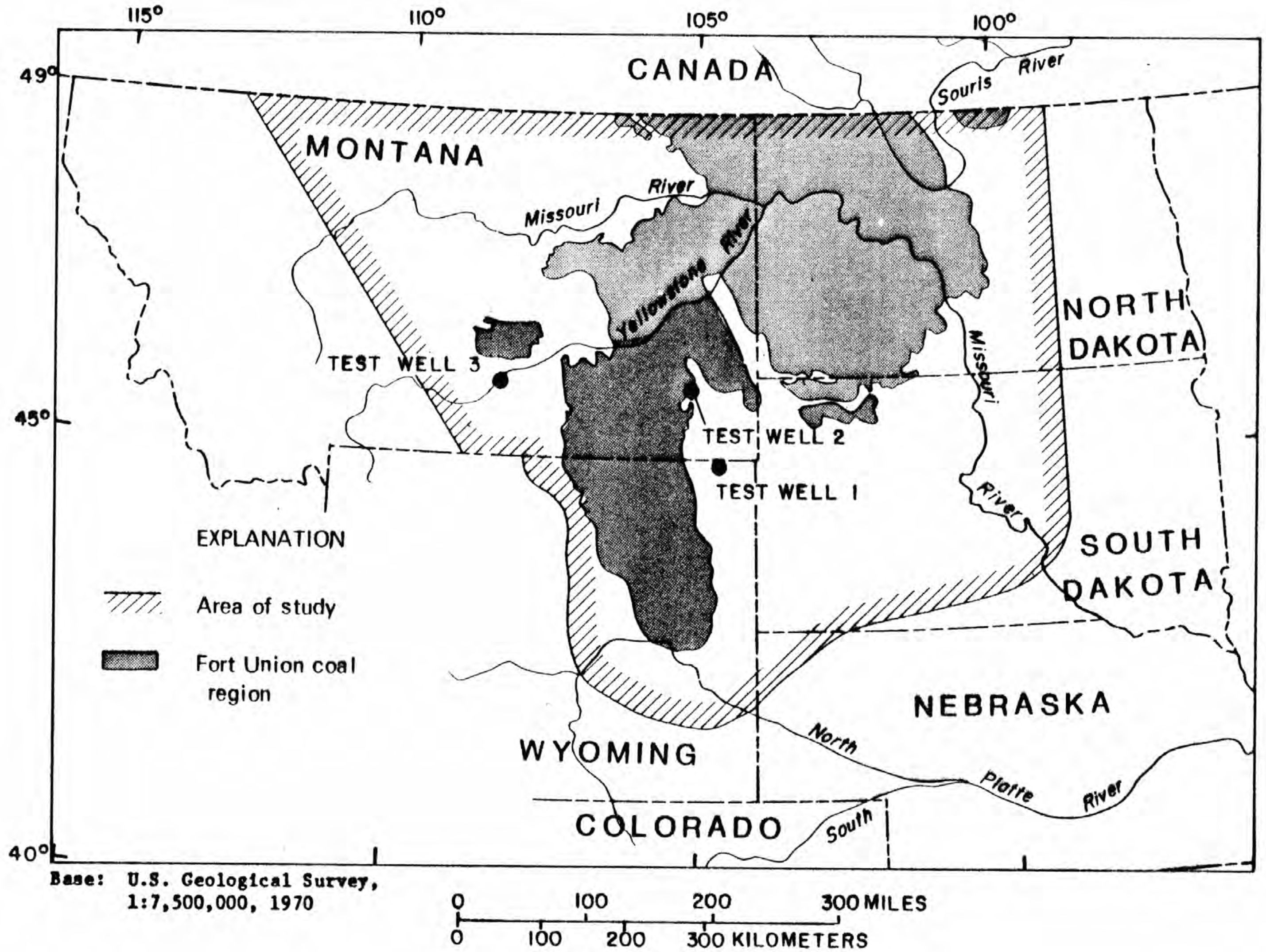


Figure 1.-- Location of study area.

area, particularly in the Williston basin, rocks of Paleozoic age lie at such great depths that few water wells are drilled. The Madison crops out in the mountainous areas; however, in much of the region, it ranges in depth from 2,000 to 16,000 ft (feet) below land surface.

The purpose of this report is to summarize and present geologic and hydrologic information outlining areas that are potentially favorable for obtaining large-yield (more than 500 gal/min) wells in the Red River Formation and Madison Limestone.

The Madison Limestone is undivided in parts of the project area. Where it is divided into formations, it is usually called the Madison Group (table 1, in pocket). For consistency, however, the term Madison Limestone is used in this report in reference to all areas, even those in which the subdivision into formations has been recognized. During the Madison Limestone project, marker beds that could be identified on geophysical logs were used to divide the Madison into chronostratigraphic units (fig. 2) (Peterson, in press). Two of these units, termed the M-3 to M-7 and the M-7 to M-8.5, were used in the analysis reported in this paper. Thus, the thicknesses of high-porosity sediment reported herein for the Madison Limestone are actually the total thicknesses within these two intervals, and the term Madison Limestone, as used in this discussion of potentially favorable areas, refers specifically to the M-3 to M-7 and M-7 to M-8.5 chronostratigraphic units.

## ACKNOWLEDGMENTS

The study of the Madison Limestone and related rocks was conducted jointly by personnel in the Central Region of the U.S. Geological Survey and

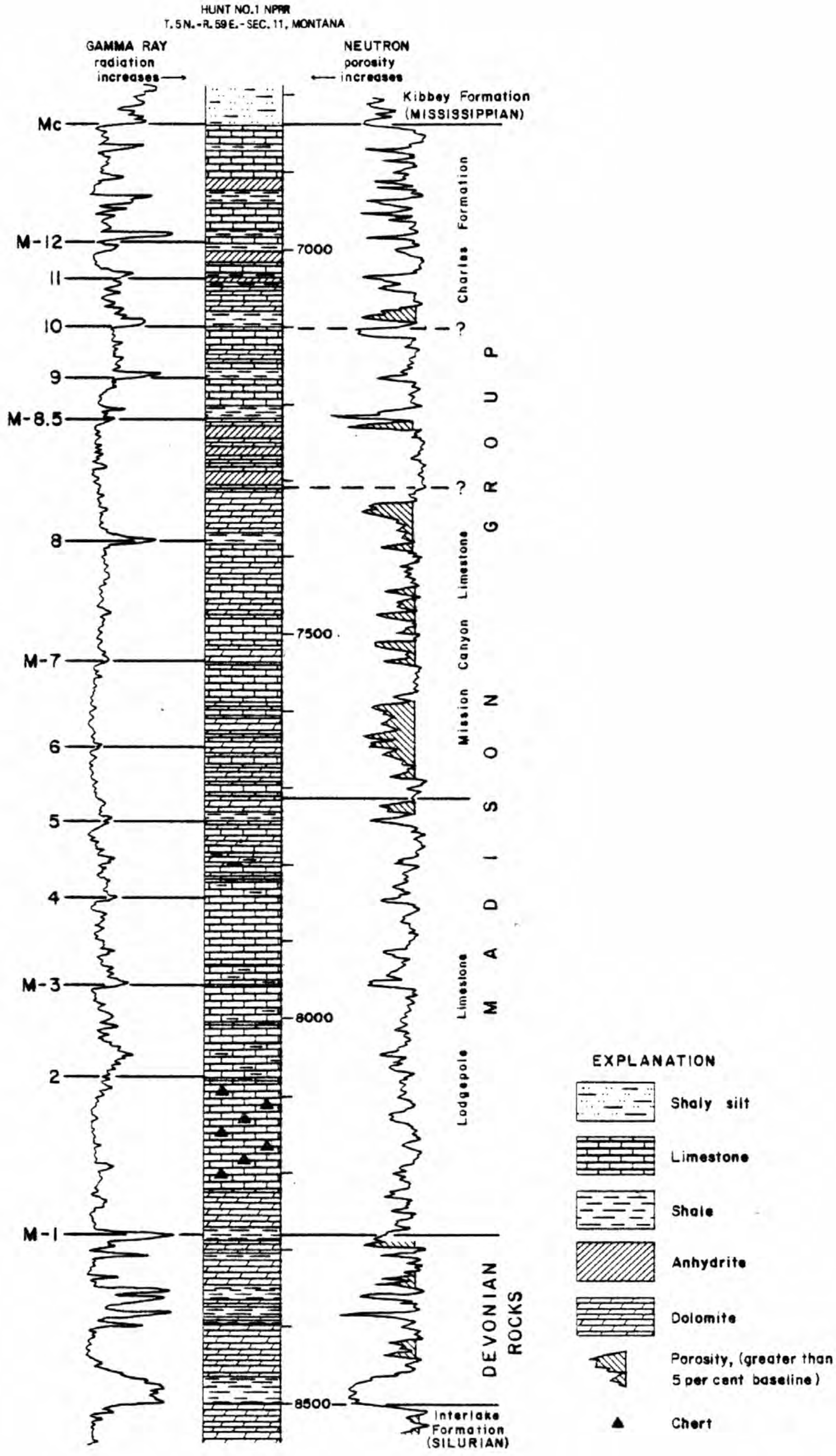


Figure 2.-- Examples of well-log patterns and lithology of Madison Group marker units.

in the district offices in the States of Montana, North Dakota, South Dakota, and Wyoming. The project was under the general supervision of Elliott M. Cushing. This report utilizes the subsurface geology and correlations made by Donald L. Brown, and the chronostratigraphic correlations established by James A. Peterson (in press).

## METHOD OF EVALUATING AREAS

Areas in which aquifer characteristics are potentially favorable for the construction of large-yield wells (more than 500 gal/min) in both the Red River Formation and the Madison Limestone were determined by delineating areas in which the apparent resistivity of the formation water, as calculated from geophysical well logs, is greater than one ohm-meter, and in which one or more of three geologic criteria were satisfied. These areas were given numerical ranking on a scale from 1 to 3. Areas of scale 3 are those in which all three criteria are satisfied; areas of scale 2 are those in which two criteria are satisfied; and areas of scale 1 are those in which only one criterion is satisfied. The potentially favorable areas for the combined Red River Formation and Madison Limestone were determined by summing their respective rankings in their areas of overlap.

The three criteria used in making the evaluation were: (1) the presence of more than 100 ft (thickness) of sediment in which the porosity, as indicated by electric log analyses, is 10 percent or greater; (2) the presence of more than 100 ft (thickness) of dolomite in which the average grain size is greater than 0.0625 mm (millimeters); and (3) the presence of geologic structures that could cause higher secondary permeability, and therefore higher well yield.

Thickness of porous rock was taken as a criterion for the selection of large-yield areas, because there is a good correlation between increasing porosity and increasing well yield in the Red River and Madison carbonate rocks. Thickness of dolomite was taken as a criterion because crystalline dolomites having a grain size larger than 0.0625 mm generally have very high porosities and permeabilities (Paul A. Thayer, in press). Geologic structures were taken as the third criterion, although the way they affect yield may differ from one place to another. Only detailed studies along each structure will reveal whether the structure actually contributes to an increase in secondary permeability and well yield. However, for purposes of this analysis, geologic structures were assumed to increase the potential for large yields. Local geologic structures and solution zones, which may be important controls at specific sites, were not included in this regional study.

Other factors which a prospective water user may wish to consider, but which were not used in the numerical ranking scheme, include depths to the two aquifers, calcite saturation of water, water temperature, relation of piezometric head to land surface, development of localized karst, and concentration of total dissolved solids in the water. Maps relating to two of these factors, piezometric head and total dissolved solids, are included in this report.

Total dissolved solids can be evaluated in an approximate sense on the basis of the apparent electrical resistivity of formation water, as determined from geophysical well log analyses. The general relationship between total dissolved solids and apparent resistivity of formation water has been recognized for many years, and is discussed more fully in a companion report

(L. M. MacCary, in press). An apparent formation water resistivity of 1 ohm-meter corresponds to a sodium chloride solution of approximately 5,500 mg/L (milligrams per liter) concentration. Although ions other than sodium and chloride are present in the formation water, an apparent resistivity of 1 ohm-meter or less was taken as indicative of unacceptably high total dissolved solids for the purpose of this report, and areas showing apparent water resistivity in this range were excluded from the potentially favorable areas for well development.

Maps of areas in which the apparent formation water resistivity is 1 ohm-meter or more are included for the Madison Limestone and for the Red River Formation. Outside these areas, the water generally is too mineralized for most uses; within these areas, its suitability depends upon the local dissolved solids content and the intended usage of the water. Contour maps of apparent formation water resistivity (L. M. MacCary, in press) may be used to provide further resolution in these areas.

The relationship between the elevation to which water can rise in a well, and land surface elevation determines whether or not the well will flow, and in conjunction with aquifer properties, determines the rate of flow. A high potentiometric head relative to land surface indicates a high level of energy available to produce flow, and in general means a higher yield from the well, other factors being equal. Maps showing the relationship of potentiometric head to land surface, in an approximate sense, are included in this report. These may be used to delineate favorable areas in terms of the potential for obtaining flowing wells, or for obtaining higher yields from pumped wells without excessive pumping lift.

## Potentially Favorable Areas in the Red River Formation

Potentially favorable areas for the development of large-yield wells in the Red River Formation, based on aquifer characteristics, but limited to areas in which apparent water resistivity is greater than one ohm-meter, are shown in figure 3. Figure 3 is a composite of three maps, corresponding to the three individual criteria used in the numerical ranking scheme. These three maps are shown individually in figures 4, 5, and 6, respectively. Figure 4 shows areas in which the Red River has more than 100 ft thickness of rock greater than 10 percent in porosity; figure 5 shows areas in which the Red River includes more than 100 ft thickness of dolomite having an average grain size larger than 0.0625 mm; and figure 6 shows areas in which there are geologic structures which may increase yields.

Figure 7 shows areas in the Red River Formation in which the apparent resistivity of formation water, Rwa, is greater than 1 ohm-meter. Within this area, water of acceptable chemical quality may be available, depending upon local conditions and the intended usage of the water.

Ranges in the elevation of the potentiometric surface in the Red River Formation, relative to land surface, are shown in figure 8, which is derived from a map by Miller and Strausz (1980a) and from land surface altitudes. This map denotes favorable areas in terms of the possibility of flowing wells, and in terms of minimizing pumping lift.

## Potentially Favorable Areas in the Madison Limestone

The potentially favorable areas for large-yield wells in the Madison Limestone, based on aquifer characteristics, but limited to areas in which

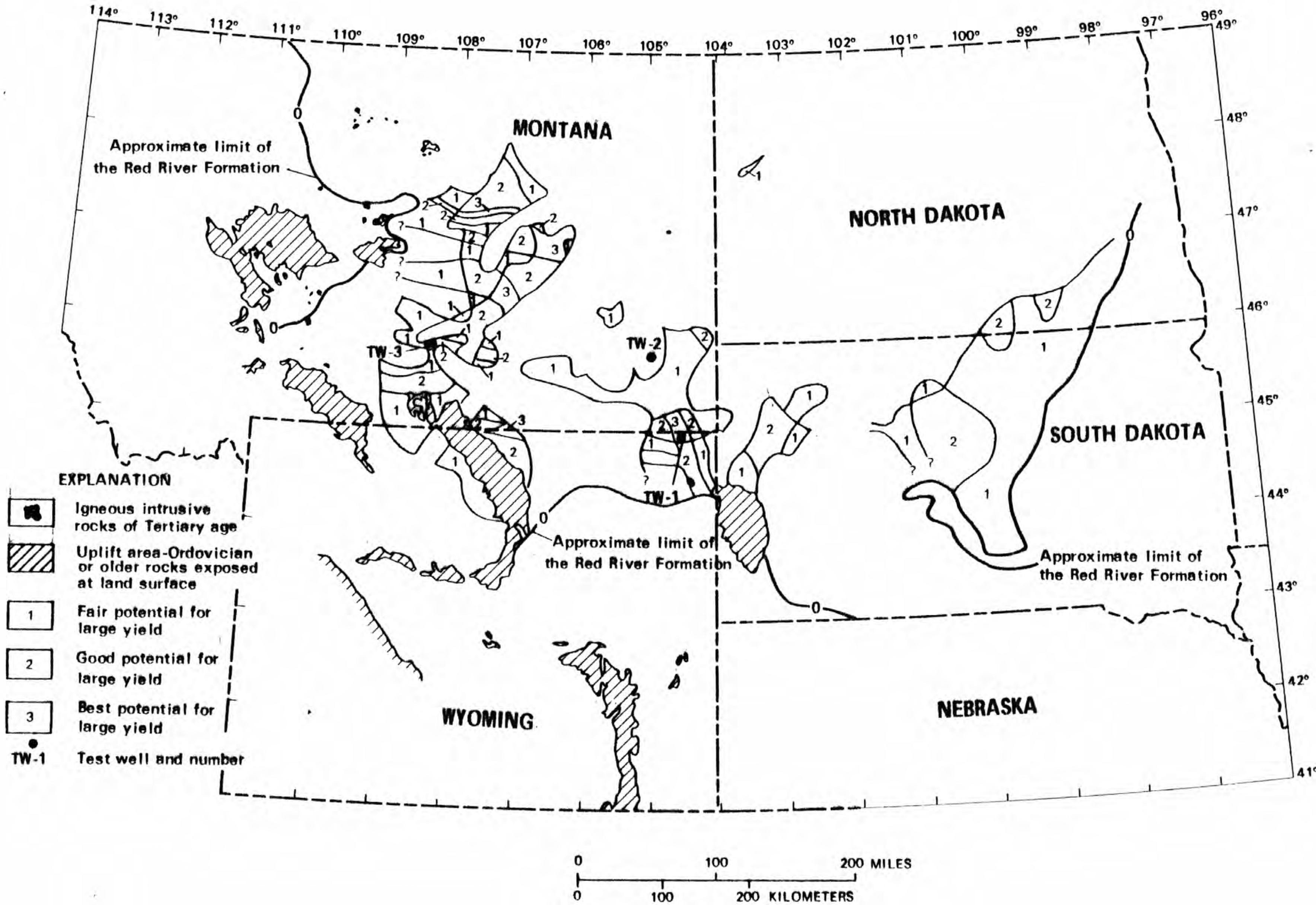


Figure 3.-- Potentially favorable areas for wells yielding more than 500 gallons per minute in the Red River Formation (Ordovician).

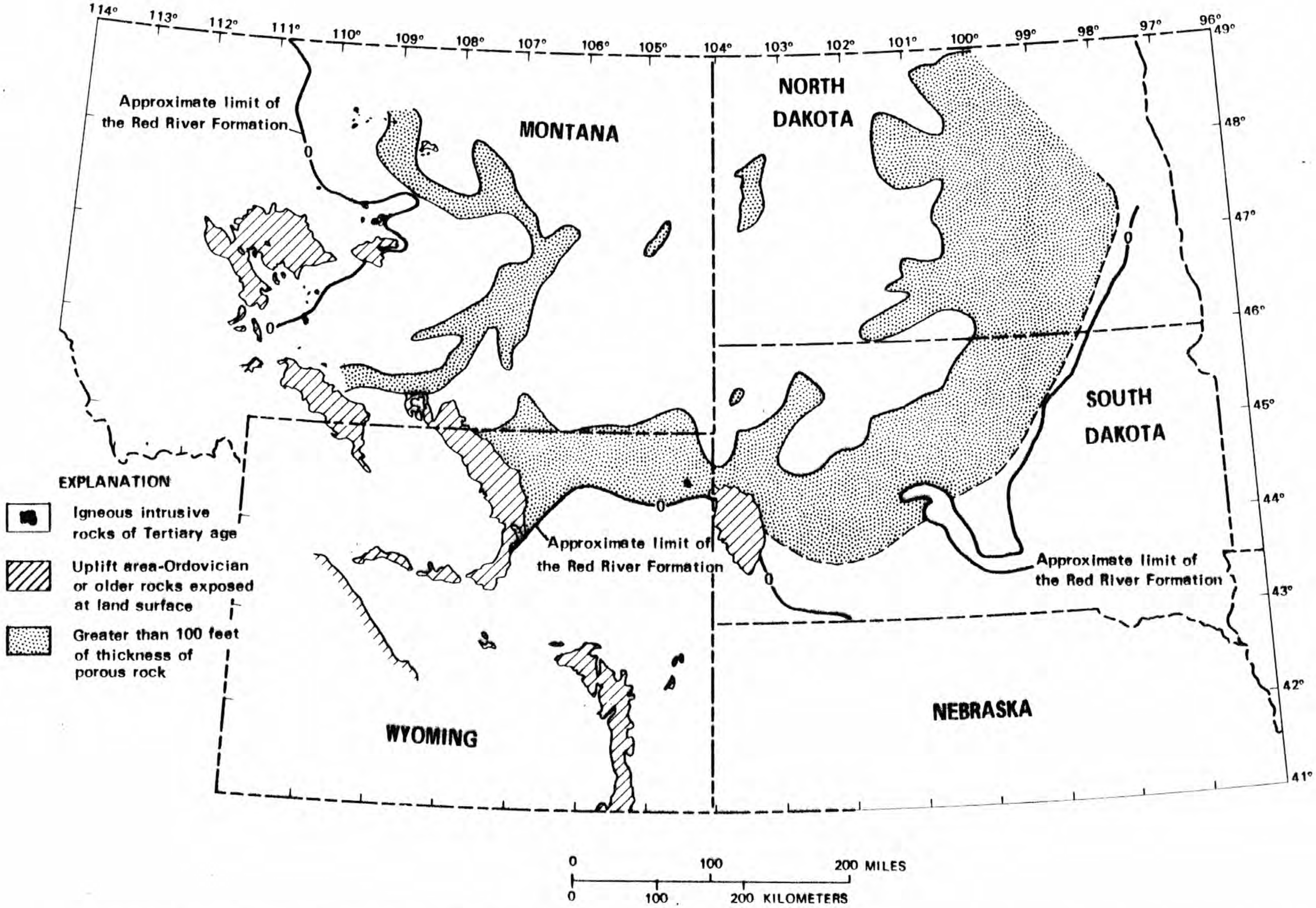


Figure 4.-- Areas of greater than 100 feet of rock thickness having porosity equal to or greater than 10 percent in the Red River Formation (Ordovician).

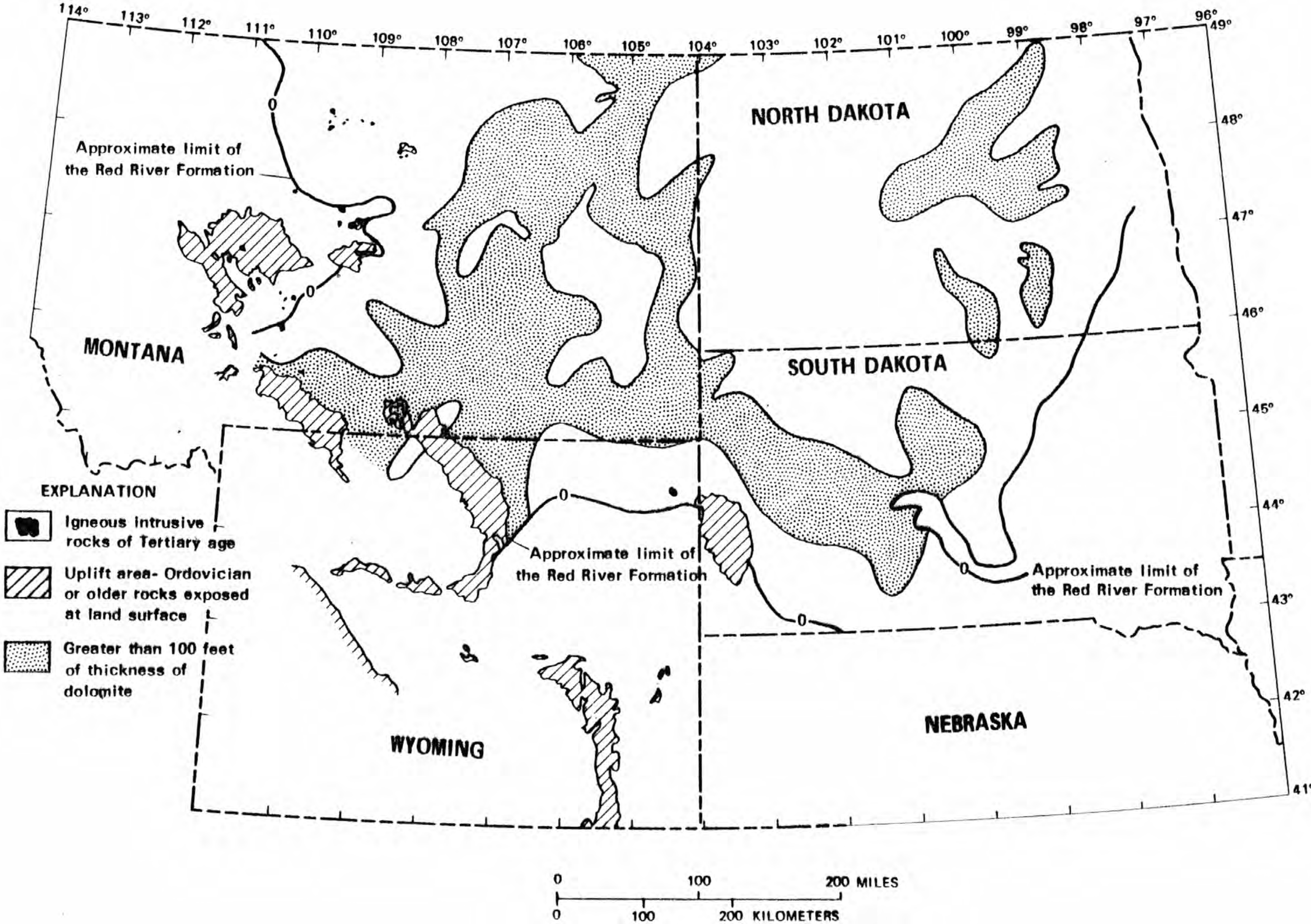


Figure 5.-- Areas of greater than 100 feet of thickness of dolomite in the Red River Formation (Ordovician) having an average grain size greater than 0.0625 millimeters.

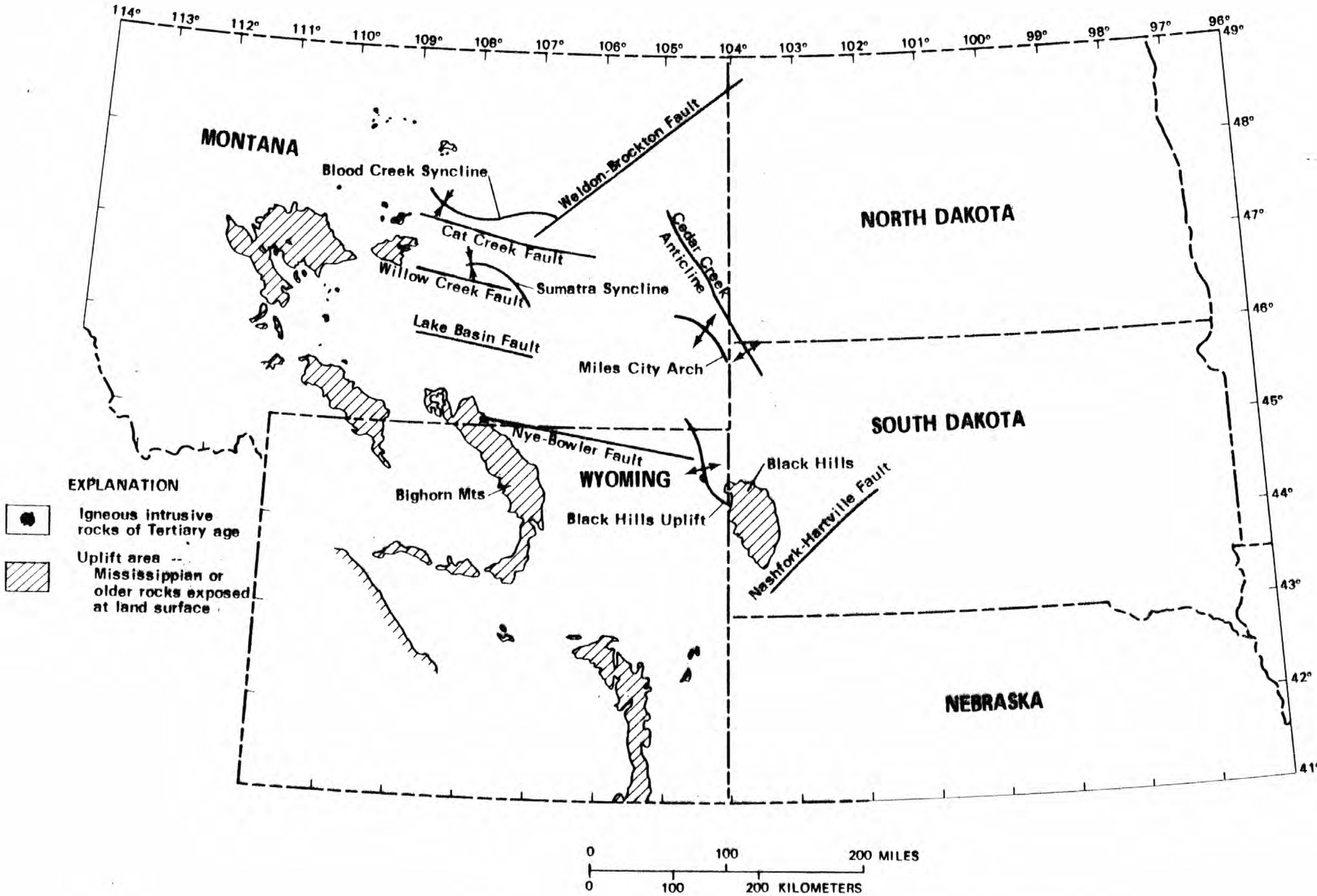


Figure 6.-- Geologic structures that may affect yield of wells.

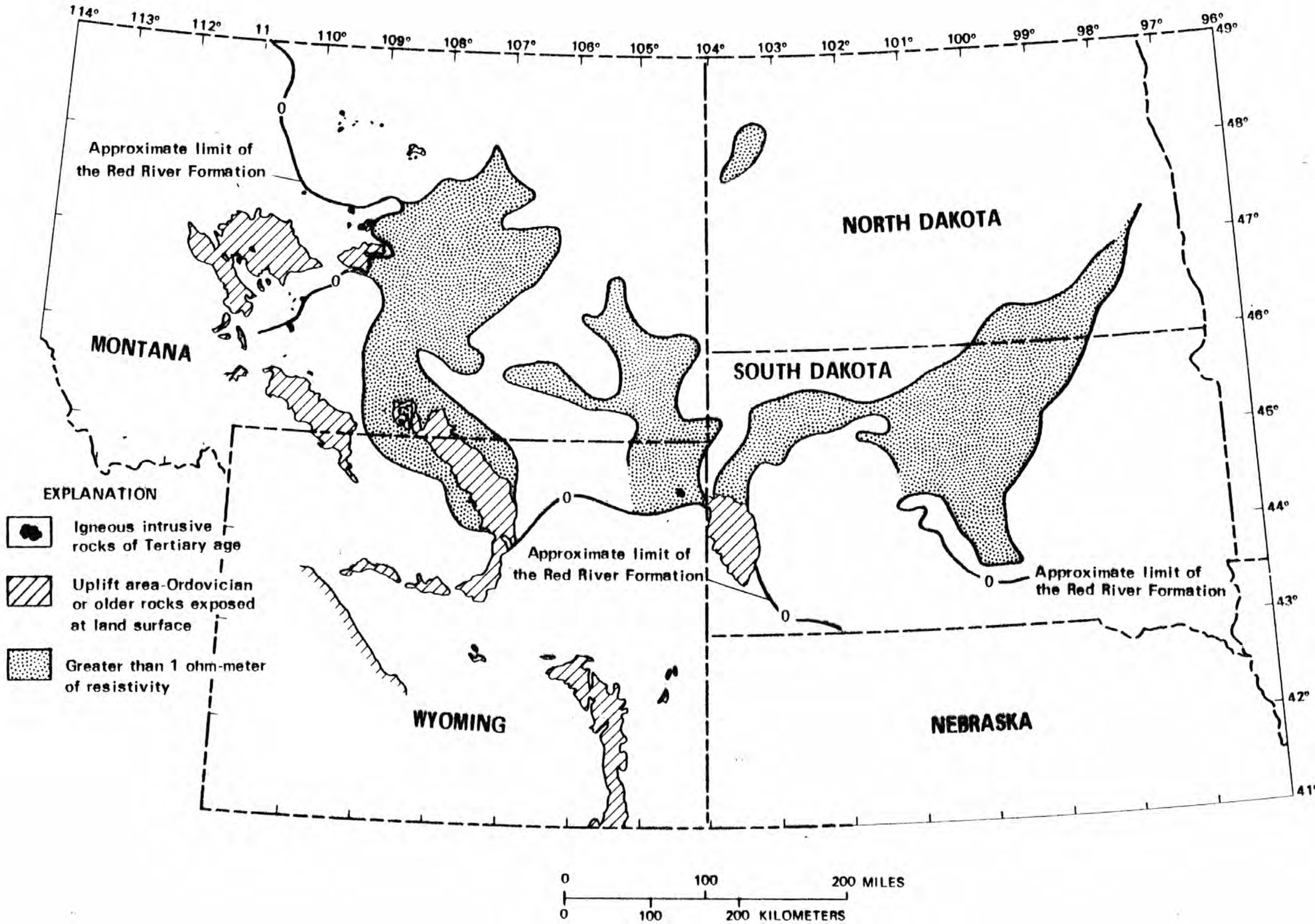


Figure 7.-- Areas of greater than 1 ohm-meter of apparent water resistivity (Rwa) in the Red River Formation (Ordovician).

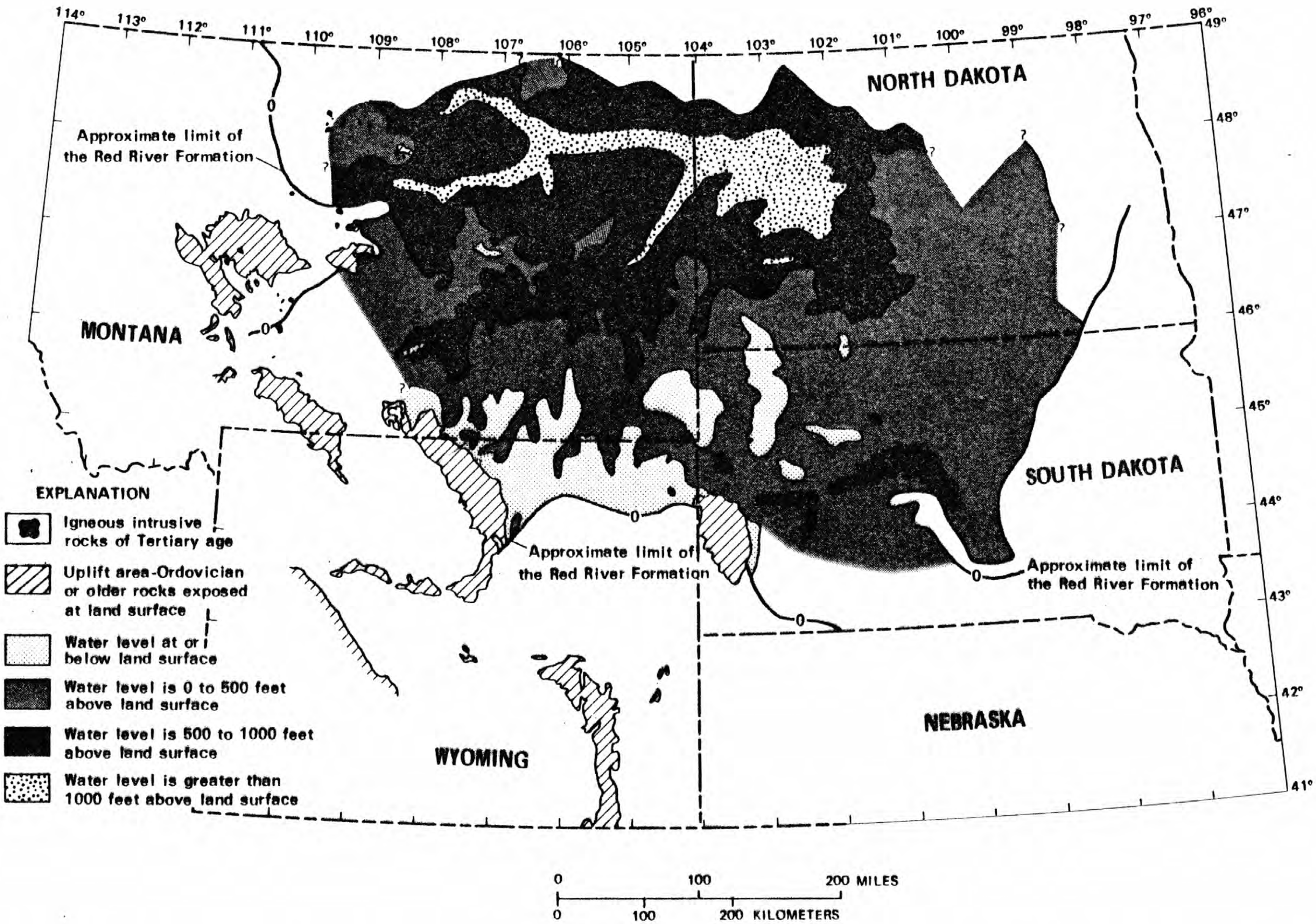


Figure 8.-- Height to which water will rise in wells drilled in the Red River Formation (Ordovician).

apparent water resistivity is greater than one ohm-meter, are shown in figure 9. Figure 9 is a composite of three maps corresponding to the individual criteria as follows: (1) more than 100 ft of rock of greater than 10 percent porosity in Madison Limestone intervals M-3 to M-7 and M-7 to M-8.5 (fig. 10); (2) more than 100 ft of dolomite having an average grain size larger than 0.0625 mm in Madison Limestone interval M-7 to M-8.5 (fig. 11); and (3) occurrence of geologic structures that may influence yields (fig. 6).

Figure 12 shows a map of areas in the Madison Limestone in which the apparent formation water resistivity is 1 ohm-meter or more. As for the Red River Formation, this map indicates areas where water of suitable quality may be available. Figure 13 was calculated from a map by Miller and Strausz (1980b) and from the land surface contours. Ranges in the height to which water will rise in wells drilled into the Madison Limestone relative to land surface are shown on this map.

## Potentially Favorable Areas For Red River Formation and Madison Limestone Combined

Figure 14 is a combined map for the Madison Limestone and the Red River Formation, showing potentially favorable areas for the development of ground-water supplies, on the basis of the apparent water resistivity criteria, and the three criteria relating to aquifer properties. In constructing figure 14, only areas of overlap between the potentially favorable areas shown in figures 3 and 9 were included. The numerical rankings from 2 to 6 were obtained by summing the rankings indicated on figures 3 and 9 for these areas of overlap.

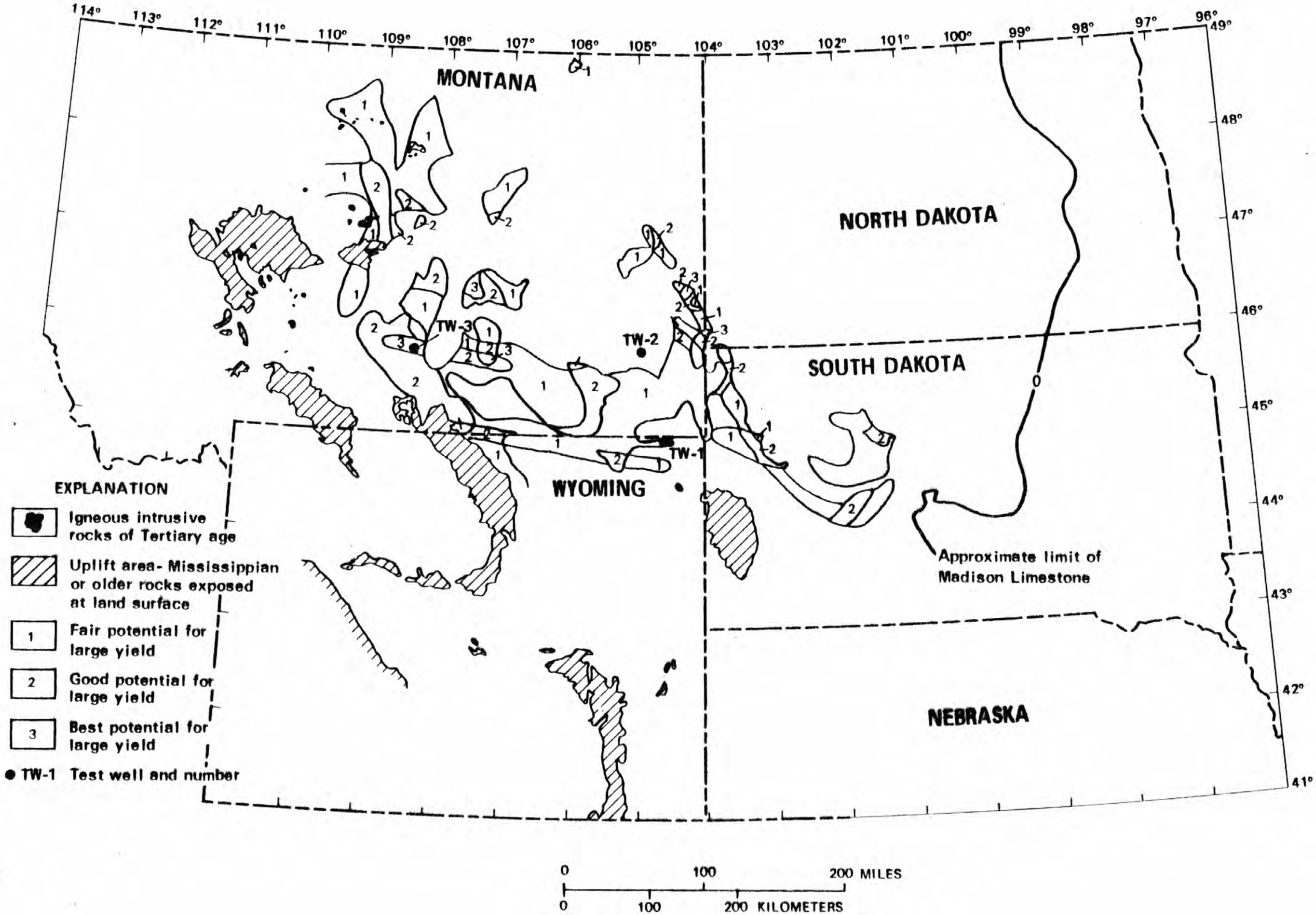


Figure 9.-- Potentially favorable areas for wells yielding more than 500 gallons per minute in the Madison Limestone (Mississippian).

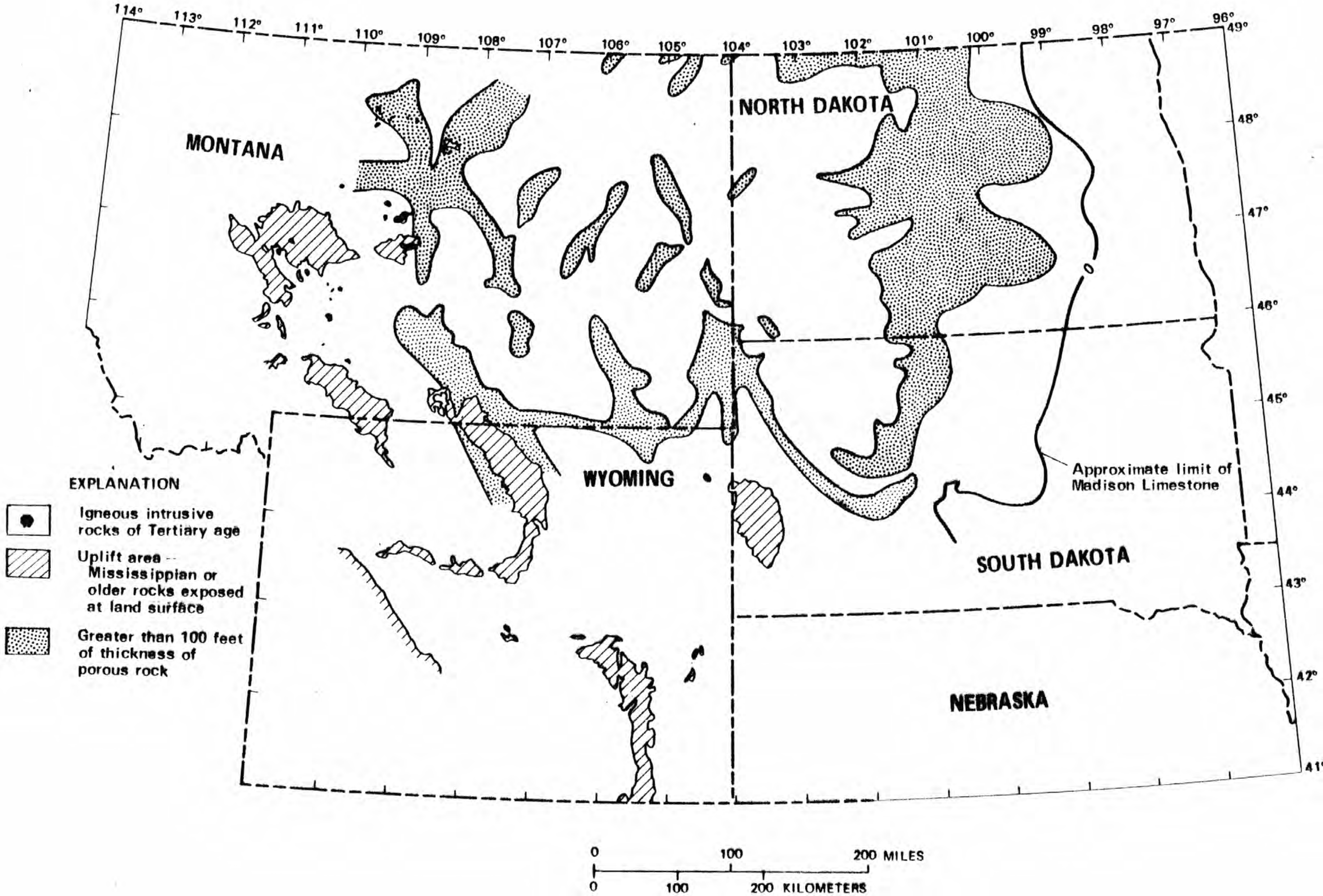


Figure 10.-- Areas of greater than 100 feet of thickness of rock having porosity equal to or greater than 10 percent in the Madison Limestone intervals M-3 to M-7 and M-7 to M-8.5 (Mississippian).

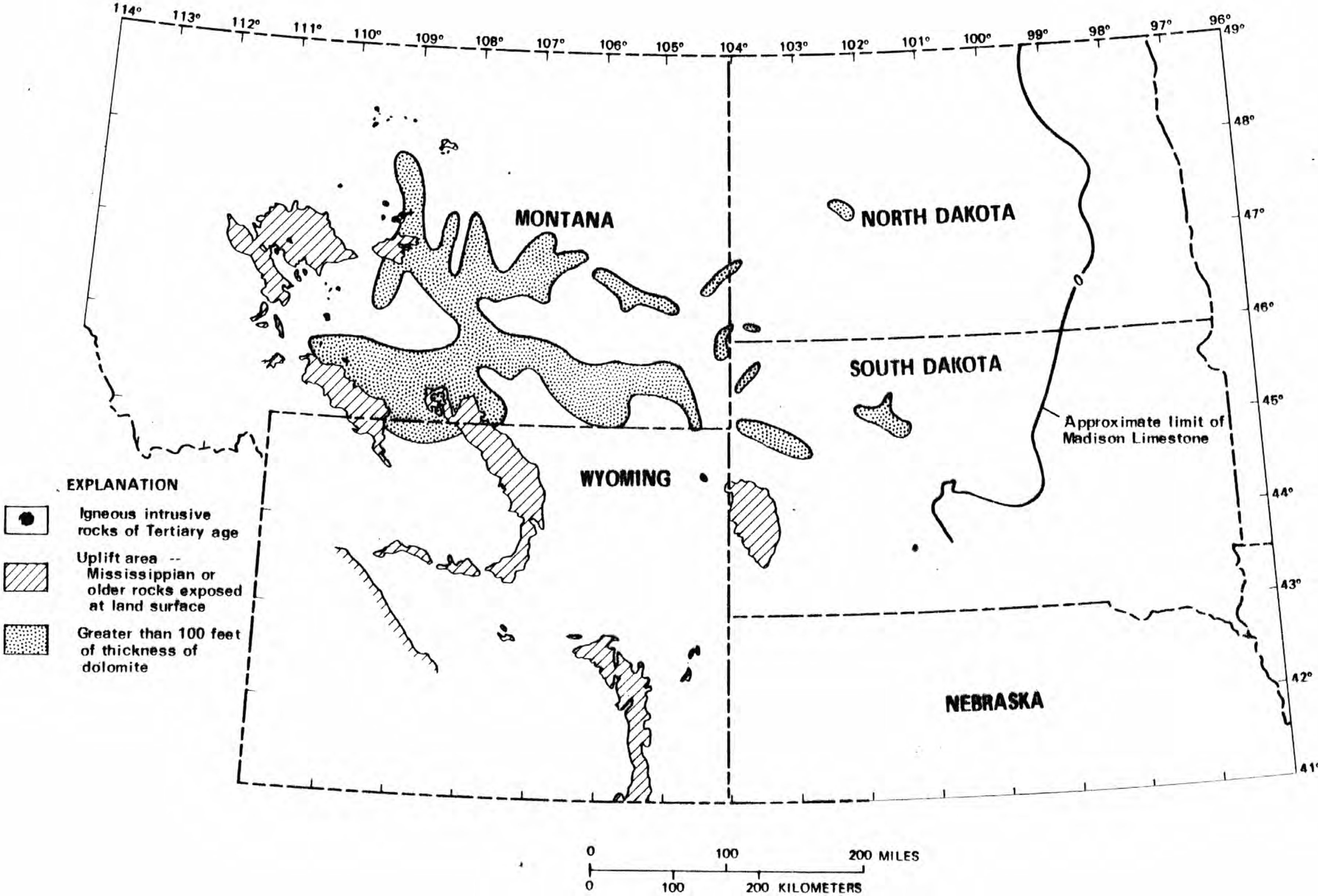


Figure 11.-- Areas of greater than 100 feet of thickness of dolomite in the Madison Limestone interval M-7 to M-8.5 (Mississippian) having an average grain size greater than 0.0625 millimeters.

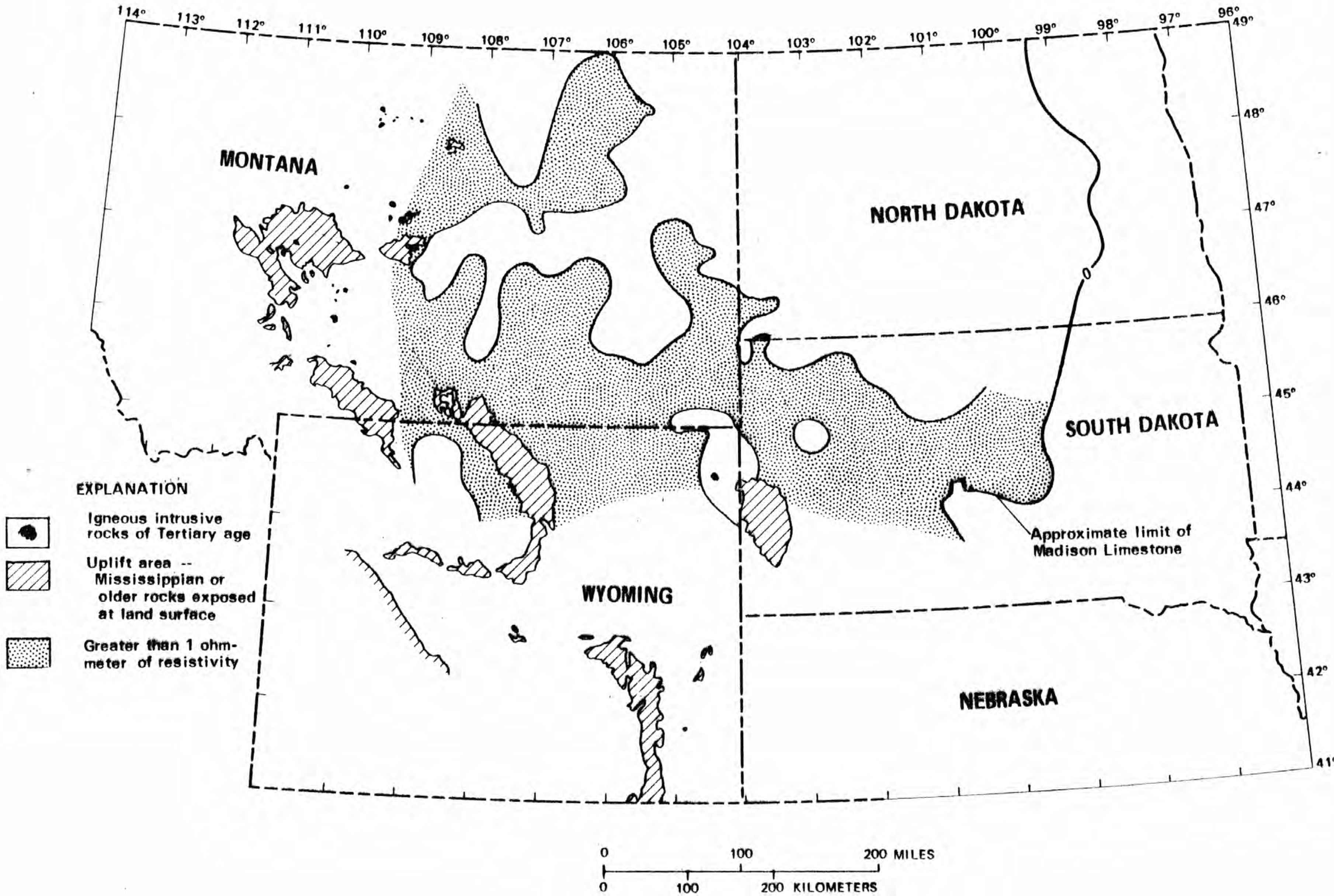


Figure 12.-- Areas of greater than 1 ohm-meter of apparent water resistivity (Rwa) in the Madison Limestone interval M-7 to M-8.5 (Mississippian).

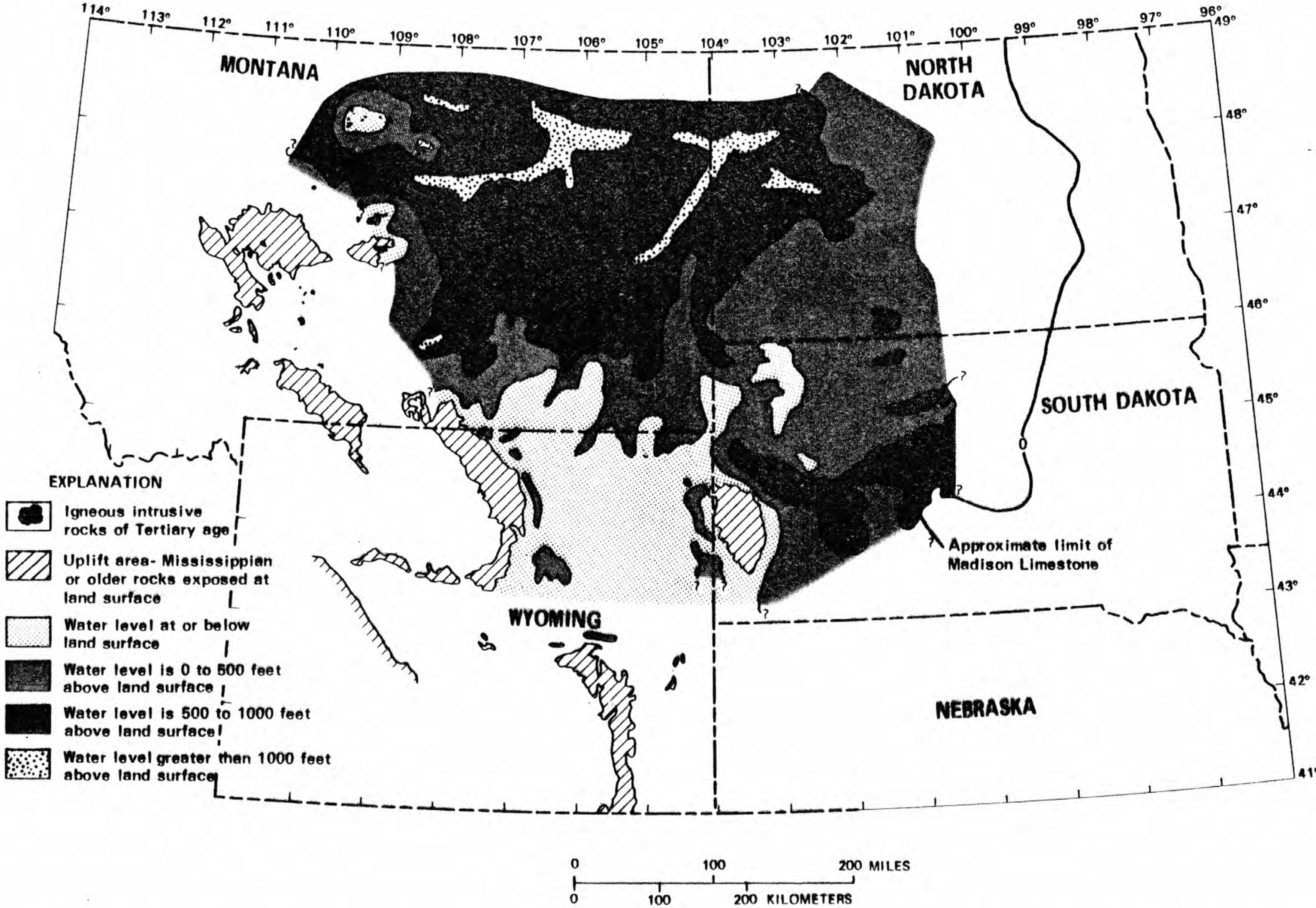


Figure 13.-- Height to which water will rise in wells drilled in the Madison Limestone (Mississippian).

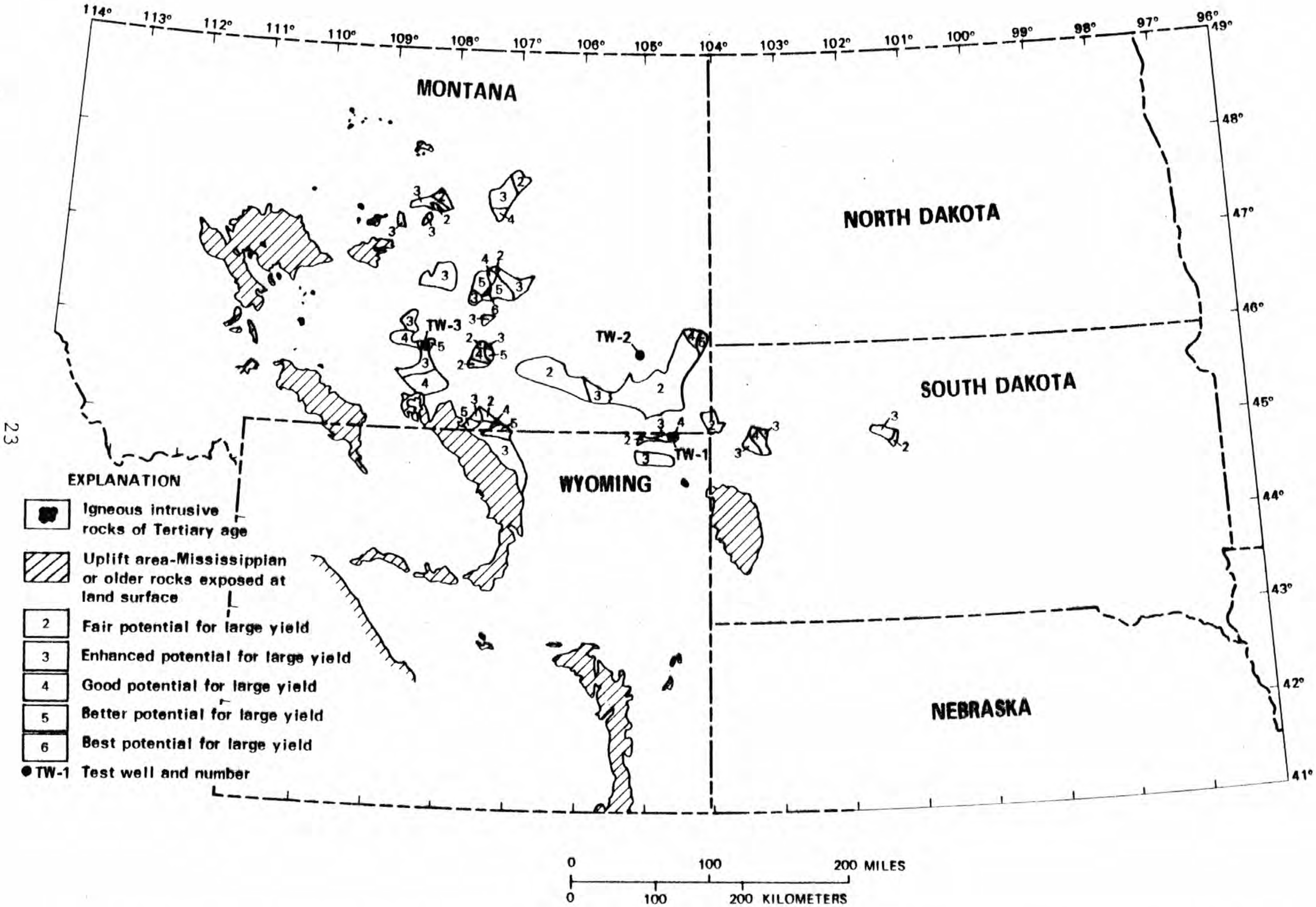


Figure 14.-- Potentially favorable areas for wells yielding more than 500 gallons per minute in both the Red River Formation (Ordovician) and the Madison Limestone (Mississippian).

## COMPARISON OF AREAL EVALUATIONS WITH YIELD RESULTS

An empirical evaluation of figures 3, 9, and 14 was made by examining the results of the three Madison Limestone test wells drilled by the U.S. Geological Survey. Test well 1 is in an area designated 3 for the Red River Formation, 1 for the Madison Limestone, and 4 for the two combined. The yield from test well 1 probably would be 650 to 700 gal/min if the well were allowed to flow freely (Blankennagel and others, 1977). Well-head valving prevented flowing the well at more than 520 gal/min. Velocity surveys in the wellbore indicate that about 70 percent of the yield is from the Red River Formation; the remainder is from the Madison Limestone. The well was not developed by acid fracturing. Drill-stem tests indicate that water from wells tightly cased in the Red River Formation at this site will rise 99 ft above land surface. Drill-stem tests in the Madison Limestone indicate that water will rise 97 ft above land surface at this site, in wells that are tightly cased in the Madison.

Test well 2 was drilled in a location that lies outside the favorable areas shown on all three maps (figs. 3, 9, and 14). The flow from the combined Madison Limestone and Red River Formation was about 44 gal/min (Brown and others, 1977). This well was drilled to test geologic and hydrologic theories, and the yield was not expected to be large. Drill-stem tests show that the potentiometric head of the Red River Formation is 770 ft above land surface at this site, while that of the Madison Limestone is 802 ft above land surface.

Test well 3 was drilled in an area shown as 2 for the Red River Formation, 3 for the Madison Limestone, and 5 for the combined formations. Fracture porosity and enhanced permeability were expected at this site because of the proximity of the Lake Basin fault. During a drill-stem test of the Red River Formation, the potentiometric head was measured as 1,024 ft above land surface and the flow was about 50 gal/min (Blankennagel and others, 1979). The water from this formation has a total dissolved solids concentration of about 4,000 mg/L, which was too high to permit its discharge into the Yellowstone River. For this reason, only a limited test was performed on the Red River Formation. Also, because of water-quality considerations, only two zones in the Madison Limestone were completed in test well 3. The combined yield from these two zones was about 90 gal/min. The relatively low yield indicated that if fracture permeability were present at this site, the voids might have been partly filled by precipitation of secondary calcite and evaporite minerals. The well was acidized and fractured hydraulically to dissolve secondary minerals and to intercept open fracture zones in the immediate vicinity. Preliminary evaluation, based on a 48-hour flow test, indicates that the combined yield from the two zones in the Madison Limestone increased to about 2,380 gal/min (Blankennagel, oral communication, 1980). Drill-stem tests showed that the potentiometric head of the Madison Limestone at this site is 1,038 ft above land surface.

## OTHER FACTORS AFFECTING WELL YIELD

Several additional factors that might influence the economics of ground-water development were not considered in this analysis. Depth of the aquifer below land surface is frequently an economic deterrent to the drilling of wells. The Red River Formation, for example, ranges in depth from about 2,000 ft below land surface in the potentially favorable area at the northern end of the Black Hills, to more than 9,000 ft deep in the favorable area near the common borders of Montana, North Dakota, and South Dakota.

As noted previously, the 1 ohm-meter criterion for apparent resistivity of formation water serves only to exclude highly mineralized water. If relatively fresh water is needed, it can be found only in restricted portions of the favorable areas shown in figures 3, 9, and 14. For the Red River Formation these portions would include areas in Wyoming at the northern end of the Black Hills, and areas in Wyoming and Montana at the northwestern end of the Bighorn Mountains. For the Madison Limestone they would include areas in Wyoming and Montana at the northeastern end of the Bighorn Mountains.

In much of the project area, waters in the Red River Formation and Madison Limestone are supersaturated with both calcite and carbon dioxide. The degree of this supersaturation increases with temperature. Consequently, as these waters, especially if they are hot (140°F (degrees Fahrenheit) or more) move into areas where pressure decreases, such as along a geologic structure or near a pumped or flowing well, carbon dioxide is released; this in turn may cause calcite to precipitate in the pores and fractures. This precipitation of calcite may have two significant results: (1) well yields may not be as large as expected, and (2) well yields may decrease with time because of fracture sealing. Both of the above problems sometimes can be alleviated by acidizing and fracturing the water-bearing zones penetrated by the well.

A final criterion that may have to be considered in some instances is the temperature of the water. The temperature of ground water increases with depth of the formation; it is highest in the deep basins and lowest in the recharge areas. Temperatures in the Madison Limestone range from less than 100°F in the area east of the Black Hills to approximately 200°F in the area east of the Bighorn Mountains in Wyoming. Temperatures in the Red River Formation range from less than 100°F at the northern end of the Black Hills, to more than 220°F in the area east of the Bighorn Mountains in Wyoming.

## CONCLUSIONS

Potentially favorable areas for large-yield wells (more than 500 gal/min) in the Red River Formation and the Madison Limestone were determined by overlaying various geologic and hydrologic maps, and delineating those areas where apparent formation water resistivity is greater than one ohm-meter and where selected lithologic criteria were satisfied. For the lithologic criteria, the areas are given a numerical scale depending on the number of criteria that are satisfied. The apparent electrical resistivity of formation water is used to identify areas in which water quality may be acceptable; maps showing ranges in potentiometric head relative to land surface are used to evaluate the potential for flowing wells. These two factors were not included in the numerical ranking, except for the exclusion of areas in which resistivity is less than 1 ohm-meter. Potentially significant factors that were not considered at all in this analysis include depth of formation, degree of calcite saturation, water temperature, presence of local geologic structures and solution zones, and greater resolution with regard to water quality than that provided by the 1 ohm-meter criterion.

The Red River Formation and the Madison Limestone, in parts of the potentially favorable areas, contain water of marginal quality. If relatively fresh water is needed, consideration should be restricted to areas where the apparent resistivity of formation water is 10 ohm-meters or greater.

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