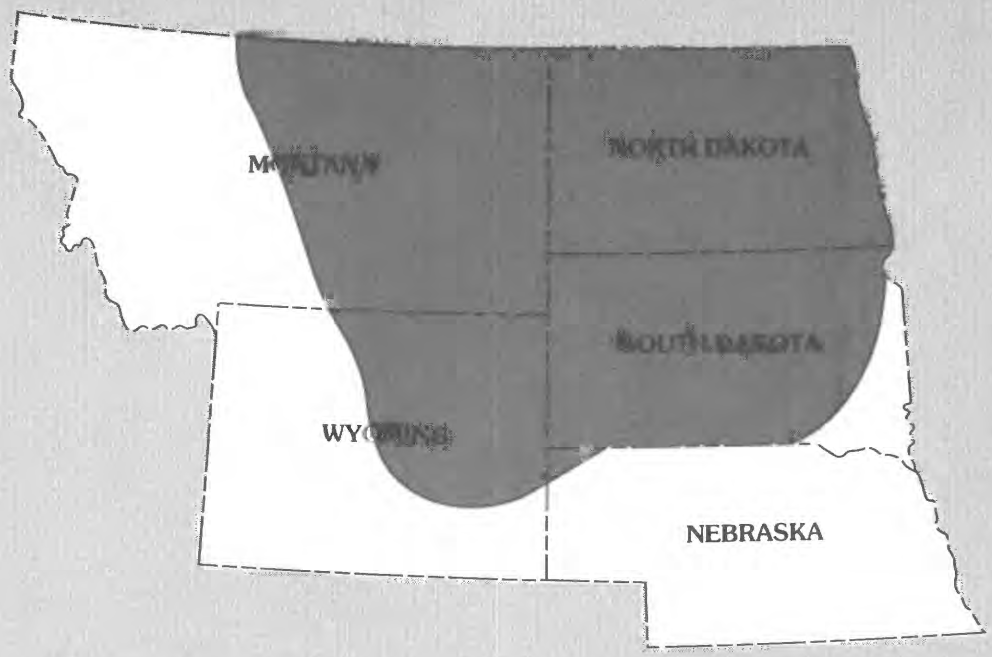
THE REGIONAL AQUIFER SYSTEM UNDERLYING THE NORTHERN GREAT PLAINS IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING—SUMMARY

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1402–A

The Regional Aquifer System Underlying the Northern Great Plains in Parts of Montana, North Dakota, South Dakota, and Wyoming—Summary

By JOE S. DOWNEY *and* GEORGE A. DINWIDDIE

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPERS ISSUED AS A PART OF THE NORTHERN GREAT PLAINS REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

1402–A The regional aquifer system underlying the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: By Joe S. Downey and George A. Dinwiddie.

1402–B Geologic framework of the ground-water system in Jurassic and Cretaceous rocks in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: By Lawrence O. Anna.

1402–C Geochemical evolution of ground water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: By Thomas Henderson.

1402–D Freshwater heads and ground-water temperatures in aquifers of the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: By David H. Lobmeyer.

1402–E Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: By Joe S. Downey.

1402–F Geochemistry of ground water in aquifers and confining units of the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: By J.F. Busby, B.A. Kimball, J.S. Downey, and K.D. Peter.

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[Plates are in pocket]

CONVERSION FACTORS

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

Multiply inch-pound units	By	To obtain SI units
acre	4,047.	square meter
acre-foot (acre-ft)	1,233.0	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic mile (mi^3)	4.827	cubic kilometer
foot (ft)	0.3048	meter
	30.48	centimeter
foot per second (ft/s)	0.3048	meter per second
foot squared per day (ft^2/d)	0.0929	meter squared per day
inch (in.)	2.540	centimeter
	25.40	millimeter
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.003785	cubic meter per day
pound per square inch (lb/in^2)	0.07037	kilogram per square centimeter
square foot (ft^2)	929.0	square centimeter
square mile (mi^2)	2.59001	square kilometer

Multiply SI units	By	To obtain inch-pound units
degree Celsius (°C)	°F=9/5(°C)+32	degree Fahrenheit

THE REGIONAL AQUIFER SYSTEM UNDERLYING THE NORTHERN GREAT PLAINS IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING—SUMMARY

By JOE S. DOWNEY and GEORGE A. DINWIDDIE

ABSTRACT

The Northern Great Plains Regional Aquifer-System Analysis is the first of a series of planned nationwide regional geohydrologic studies. This summary is principally a graphic presentation of the major results of four basic facets of investigation designed to provide the best possible understanding of a large (about 300,000 square miles) and extremely complex ground-water flow system. The reader is encouraged to refer to subsequent volumes in this series for the details of treatment of components and of results of the study.

The geologic framework within which the ground-water flow system operates has been defined. The study area basically consists of highland areas of sediment sources and basin areas of sediment deposition. The geologic investigation principally involved definition of the types of sediment (any rocks), the areal extent and thickness of sediment (any rocks), and the mechanisms that controlled deposition of the sediments.

The spatial distribution of hydraulic pressure has been portrayed as potentiometric surfaces mapped for several aquifers. The implied ground-water flow system is one of recharge in and near the highland areas in the western and southwestern part of the study area and one of generally eastward and northeastward flow of ground water toward areas of discharge in Canada, North Dakota, and South Dakota.

The distribution of chemical quality of the ground water has been defined with available data, and the mechanisms controlling changes in chemical quality have been interpreted. The chemistry of water from aquifers of Paleozoic through Mesozoic age is controlled by a variety of geochemical mechanisms, with dissolution of evaporites and mixing of water being dominant. Dedolomitization is a significant mechanism, and sulfate reduction and cation exchange are probably active mechanisms as well.

The entire system of ground-water flow with all of its controlling factors has been defined as a conceptual model and has been simulated with a mathematical model. Five major aquifers have been defined and simulated, and the digital model has been used to interpret areas and rates of recharge, areas and rates of discharge, areas and rates of leakage, and rates and directions of flow. The model has been further used to simulate several hypothetical pumping alternatives to determine the cause-and-effect relationship between pumping, drawdown, and assumed conditions.

INTRODUCTION

The northern Great Plains region of North America is, except for the Black Hills, a fairly flat, gently rolling surface underlain mostly by sandstone and shale (pls. 1, 2). The land surface is interrupted at places by several hundred feet of topographic relief where streams have dissected relatively soft rock. The northern Great Plains study area, shown in figure 1, covers about 300,000 mi^2 in the Great Plains and Central Lowland physiographic provinces. The study area is bounded on the west by the central and northern Rocky Mountains, on the east by the Red River of the North, on the south by the central High Plains, and on the north by the United States–Canadian border. The rocks consist of sediments that were eroded from present and ancestral mountains to the west, and from the Black Hills, and were deposited in the subsiding Williston and Powder River basins and surrounding areas to thicknesses of more than 15,000 ft. Subsequently, several hundred feet of these sedimentary rocks were eroded, leaving remnants of resistant rock. The principal aquifers, which generally are areally extensive, crop out along the flanks of two major basins (Powder River and Williston basins) and along other major structural features. Significant aquifers also occur in unconsolidated glacial drift in North Dakota and South Dakota.

Developing energy resources, generating power, developing industry, increasing irrigation, and satisfying the greater requirements for domestic and municipal water in the northern Great Plains area will depend in large part on the development of supplies of ground water. Streamflow historically has satisfied many of the water needs; however, surface water is fully appropriated in much of the area and is not always a dependable supply because flows are extremely variable. Long-term, large-scale water needs will require development of productive aquifers, some of which have been little used heretofore. Large, sustained yields of ground water cannot be produced efficiently, and sound management plans cannot be formulated without a knowledge of the physical and hydrologic characteristics of the ground-water system and its response to withdrawals. Ground water needs to be developed in a logical manner and

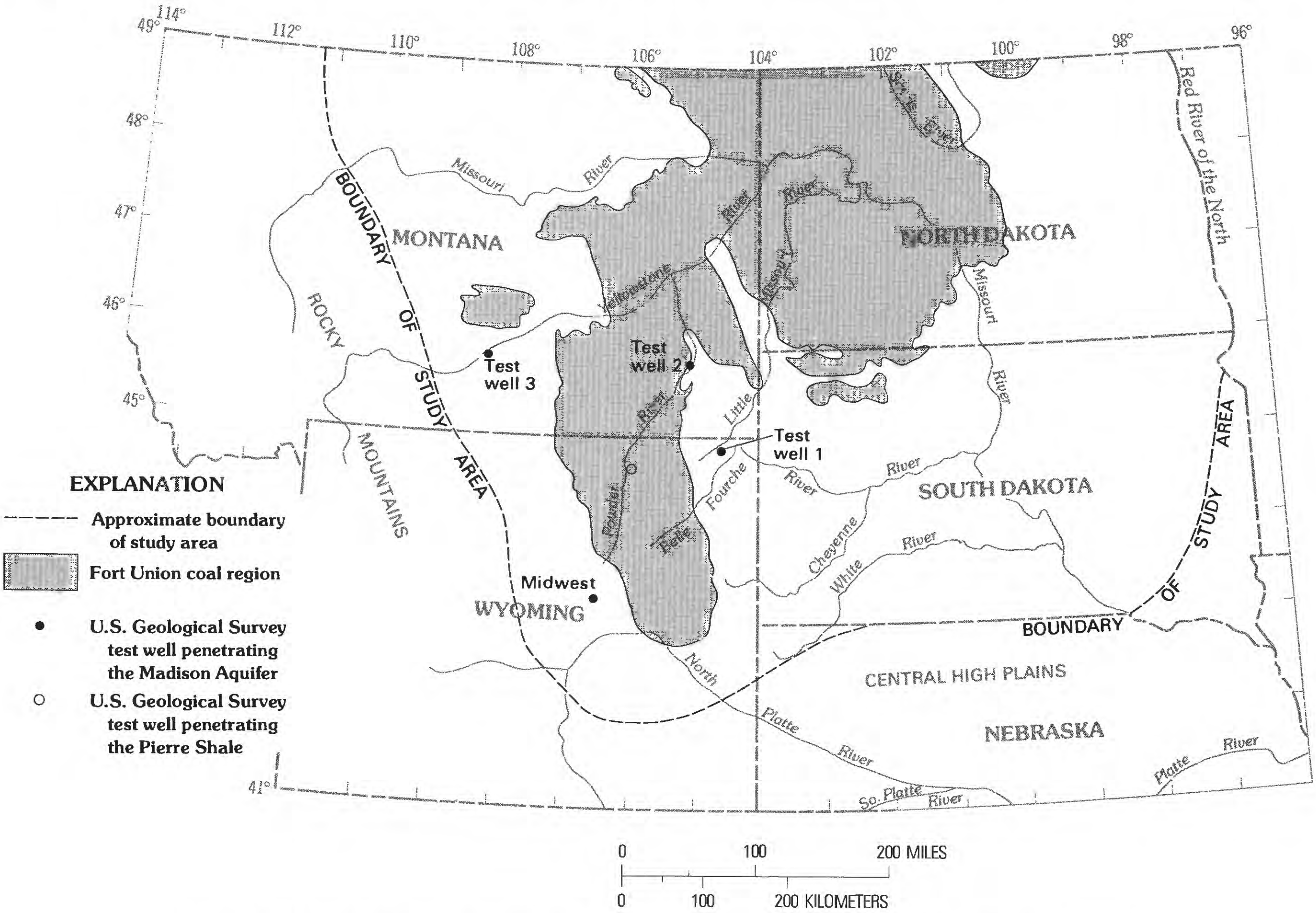

FIGURE 1.—Location of study area, Fort Union coal region, and sites of principal subsurface control.

needs to be used with regard for the consequences of extraction and consumption.

Comprehensive study of the geology and hydrology of the northern Great Plains area by the U.S. Geological Survey (USGS) began in 1975 with the Madison Limestone study. The Madison study was conceived and begun in response to a generally recognized need for knowledge about potential supplemental sources of large quantities of water to support possible large-scale development of coal reserves. A major part of the United States' coal reserves is in the Fort Union coal region of the northern Great Plains (fig. 1). Major development of the coal, which can include onsite steam power generation, gasification, liquefaction, and slurry pipeline transport of coal, would place a major demand on the area's limited water resources. Large quantities of water would be needed; estimates exceed 200,000 acre-ft per year. Preliminary studies by the USGS and State agencies in Montana, South Dakota, and Wyoming have indicated that the Madison Limestone and associated rock units might provide a significant percentage of the total water requirements for the coal development.

The Northern Great Plains Regional Aquifer-System Analysis (RASA) is the first study in the USGS RASA Program, the general purpose of which is to fully understand the Nation's ground-water resources. Studies of ground-water resources have been on a local scale, responsive to local, immediate needs. These studies usually have been restricted within political boundaries. However, for defining total ground-water resources and for planning the most effective development and use of these resources, hydrologic studies are needed on a regional scale. Thus, the concept of regional aquifer-system analyses as described in the Foreword was developed.

The northern Great Plains regional aquifer-system study was a logical extension and culmination of the Madison Limestone study. The study was designed to complete the definition of the total ground-water flow system above the rocks of Precambrian age and was conducted with a four-component approach to the problem:

1. Geology—The geologic framework within which ground water flows and the mechanisms that controlled sediment deposition were defined.
2. Hydrology—The spatial distribution of hydraulic pressure, which is the ultimate driving force of ground-water movement, was defined.
3. Geochemistry—Chemical quality of the ground water and the mechanisms controlling changes in chemical quality were interpreted.
4. Geohydrology—The entire system of ground-water flow with all of its controlling factors was defined as a conceptual model; then a mathematical simulation model was developed with which unknown areas and unknown values could be defined in the terms and within the limits of the model.

This report presents summary results from both the Madison Limestone project and the northern Great Plains regional aquifer-system study. Because of the nature of topics, some discussions may be in greater detail than others. However, for comprehensive information on a specific subject, the reader should refer to the subsequent reports in this professional paper series listed in the front of this report. For further information, the reader also can consult the selected references for this report.

GEOLOGIC UNITS COMPOSING THE REGIONAL AQUIFERS

The present-day geologic structure of the northern Great Plains (fig. 2) is related directly to the geologic history of the Cordilleran platform, which is a part of the stable interior of the North American continent. During geologic time, many structural features developed that affected the deposition of the various sedimentary units. Most of these structural features are present today and are important in determining the present hydrologic regime existing in all the aquifer systems underlying the northern Great Plains (Weimer and others, 1982).

During Paleozoic time, the study area (fig. 1) was part of the Cordilleran platform, a broad flat area that was bordered on the west by Cordilleran miogeosyncline. Most of the detrital sediments in the synclinal trough came from the Antler orogenic belt, which probably was an island-arc system to the west that underwent intermittent tectonism during Paleozoic time. The Transcontinental arch, southwest of the study area, was low lying and contributed minor quantities of sediment that were spread thinly across the platform. In general, the Cordilleran platform was a shallow-water depositional shelf that received predominantly carbonate and evaporite sediments during most of Paleozoic time.

The Black Hills uplift (fig. 2) was not a regionally significant tectonic element until Late Cretaceous time (Agnew and Tychsen, 1965) and had little influence on Paleozoic sedimentation. During Mississippian time, the study area generally was covered by a shallow warm sea probably less than a few feet deep (Sando, 1976b). Shoals and reefs were common but continually changed and shifted because of the effects of geologic forces in time and space. Many of these shallow areas had small reefs and associated oolite-and crinoid-bank shoals and lagoons. The lagoons were evaporating basins in which evaporites precipitated and became incorporated into the lime-rich bottom sediments. Gypsum often could precipitate in a lagoonal environment that frequently received influxes of sea water, whereas evaporation seldom would proceed to the point of halite precipitation. Areas in the Williston basin and the Central Montana trough with restricted sea-water circulation or higher evaporation rates are evidenced by accumulations of bedded evaporites.

During Cretaceous time, the study area was covered by a north-trending sea that extended from the Gulf of Mexico to the Arctic Ocean. Source areas to the west provided clastic sediments that were deposited in the Cretaceous sea. The Precambrian shield area, northeast of the study area, was a positive Cretaceous feature and provided sediments that were deposited in the eastern part of the Cretaceous sea. The Sioux uplift in eastern South Dakota provided sediment for two major delta systems that prograde into southeastern Montana.

PRECAMBRIAN ROCKS

Crystalline rocks of Precambrian age form the basement in the northern Great Plains region. Depth to the Precambrian basement varies greatly; basement crops out in the eastern and western parts of the study area (fig. 3) but lies greater than 15,000 ft below land surface at the center of the Williston basin. Precambrian rocks also are found in the central cores of the many mountain ranges located in the western part of the study area.

On a regional basis, little is known about the water-yielding properties of the Precambrian rocks. Available data indicate that they contain only small quantities of water in joints and fractures. These rocks therefore are generally not considered to be water yielding; however, along major fractures, Precambrian rocks can produce water that is available from leakage from the overlying sedimentary sequence. Precambrian rocks in

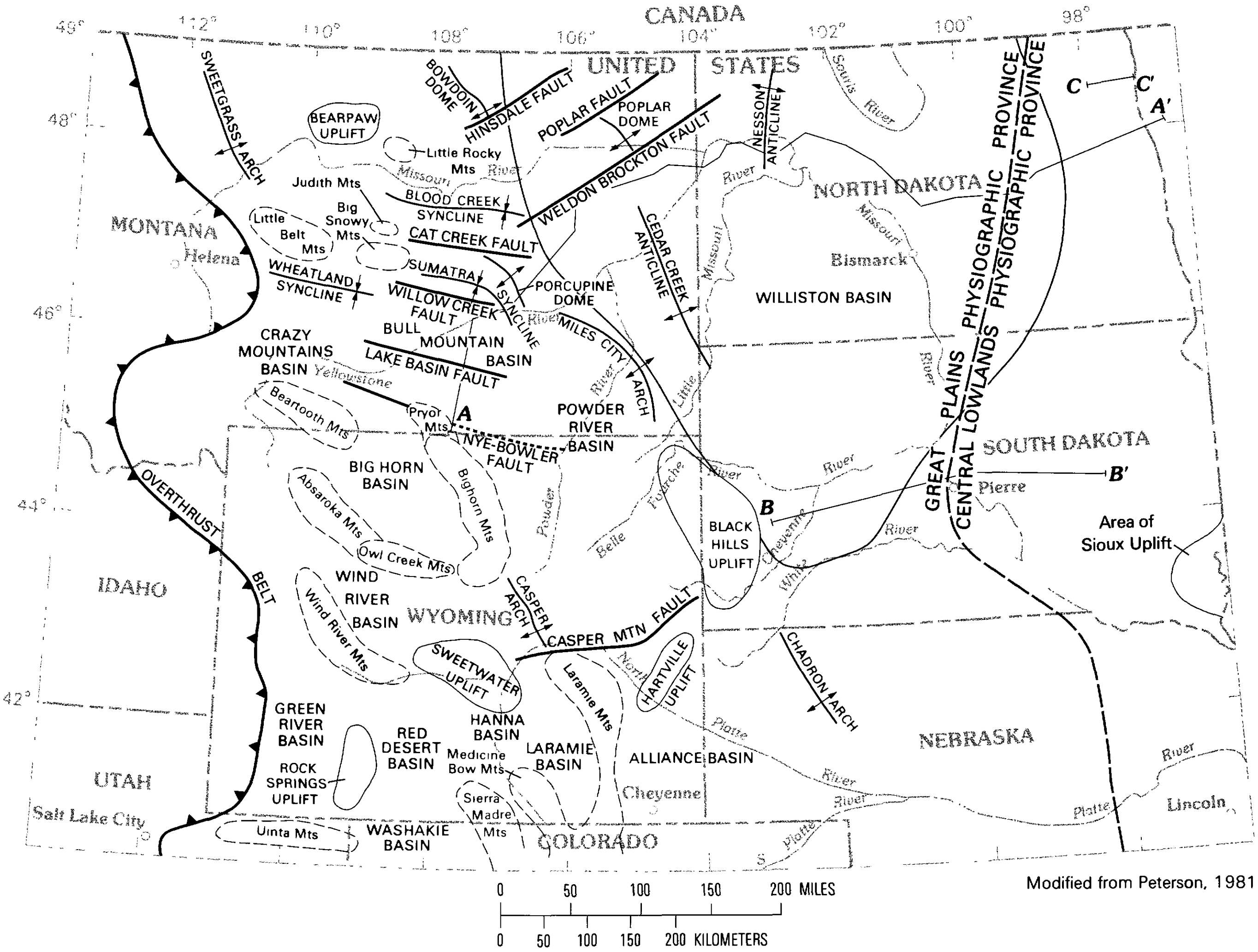

FIGURE 2.—Present-day structural and physiographic features of the northern Great Plains and vicinity (includes lines of sections *A-A'*, *B-B'*, and *C-C'*).

the study area represent the lower boundary of the hydrologic system. In the eastern part of the study area where Precambrian rocks crop out, the rocks act as no-flow boundaries to the hydrologic system.

CAMBRIAN AND ORDOVICIAN ROCKS

Rocks of Cambrian and Ordovician age (pl. 1; fig. 3) in the northern Great Plains consist of marine sandstone, shale, limestone, and dolomite that represent the shoreward facies of a transgressive sea which occupied the area during Cambrian and Ordovician time (Peterson, 1981). Several formations of Cambrian and Ordovician age, such as the Deadwood, the Winnipeg, and the Red River Formations, are aquifers (fig. 4); however, their great depth has prevented their use as a major source of water, and few hydrologic data concerning these aquifers are available on a regional scale. Most of the data are from tests performed in connection with the development of oil and gas wells.

Ordovician rocks are major petroleum reservoirs in the Williston basin, and many exploratory wells penetrate these rocks. Ordovician rocks are not present in southeastern Wyoming, western Montana, and a small portion of southwestern South Dakota because of nondeposition, or erosion, during Devonian and Early Mississippian time. Thickness increases eastward and northward from central Montana and northeastern Wyoming to more than 1,000 ft in the central part of the Williston basin.

The Winnipeg Formation is stratigraphically equivalent to the St. Peter Sandstone of the midwestern United States. In the western part of the study area

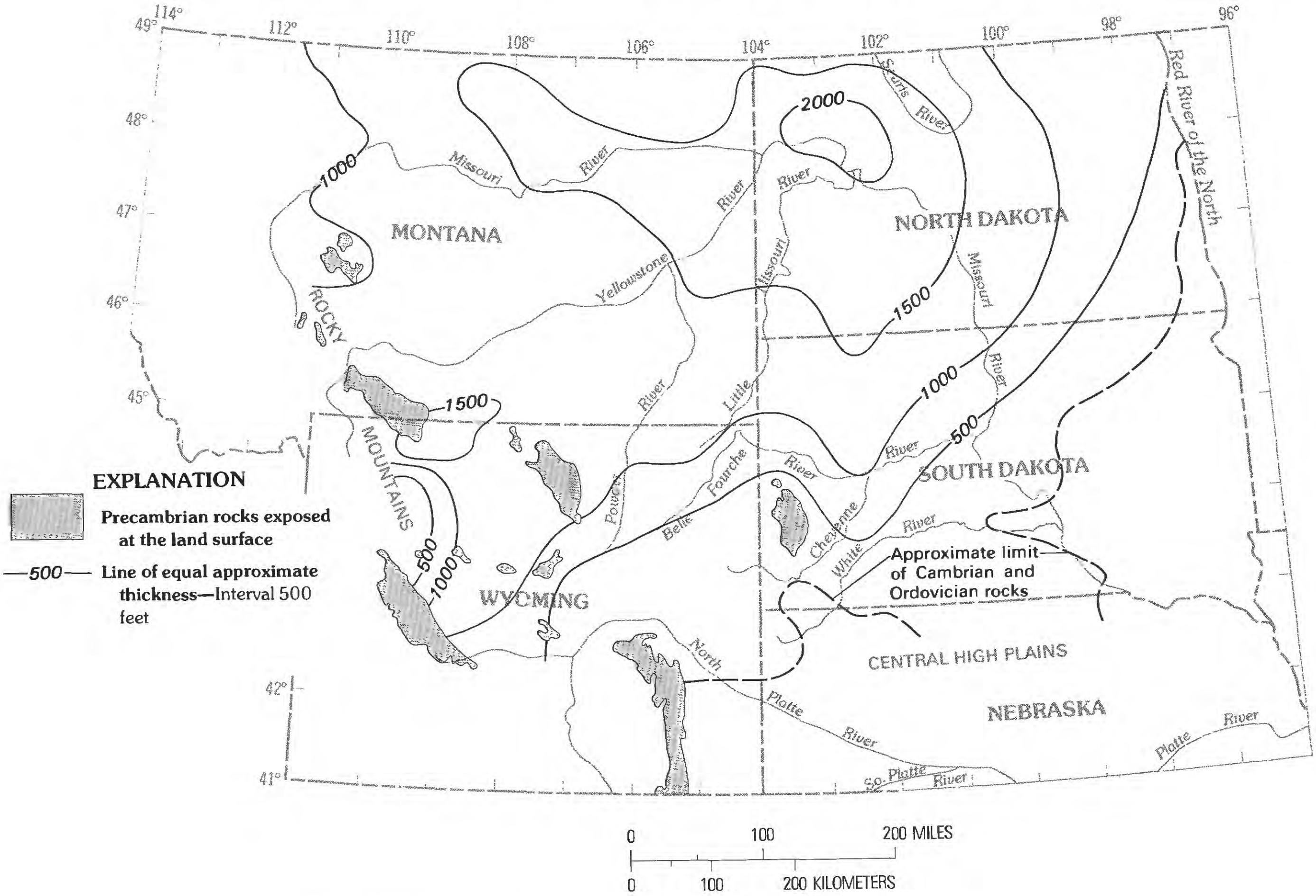

FIGURE 3.—Approximate thickness of rocks of Cambrian and Ordovician age.

where it is not deeply buried, the Winnipeg Formation consists of a clean, well-sorted, medium-grained, porous sandstone (Peterson, 1978). Where it is deeply buried, the unit has little porosity and permeability because of silica cementation and related compaction. In the eastern discharge area of the hydrologic system (pl. 3), the Winnipeg Formation consists of a sequence of shale, sandstone, and shaly limestone ranging in thickness from 20 to about 140 ft (Armstrong, 1980). The sandstone units consist of very fine to fine rounded quartz grains with interbedded siltstone and shale.

The Red River Formation (pl. 1), a carbonate sequence that overlies the Winnipeg Formation, extends outward past the borders of the Williston basin. The Red River Formation is more than 700 ft thick in the central part of the Williston basin and was truncated by Devonian erosion in the western part of the study area along a line extending between the central Black Hills and the southern Bighorn Mountains (Peterson, 1981).

The Stony Mountain Formation, which conformably overlies the Red River, is composed of carbonate, shaly carbonate, and anhydrite beds and lithologically is similar to the overlying Interlake Formation of latest Ordovician and Silurian age. Both the Red River and Stony Mountain Formations were truncated by Devonian erosion around the periphery of the Williston basin. The Stony Mountain erosional edge is closer to the basin center than that of the underlying Red River Formation.

SILURIAN AND DEVONIAN ROCKS

Rocks of Silurian and Devonian age (pl. 1; fig. 5) overlie the formations of Ordovician age in most of the study area. Silurian and Devonian units consist mainly of shaly carbonate rocks, shale, and evaporite deposits, including Devonian halite (fig. 5), near the center of the Williston basin where the units have a total thickness greater than 3,000 ft. The halite units of Devonian age

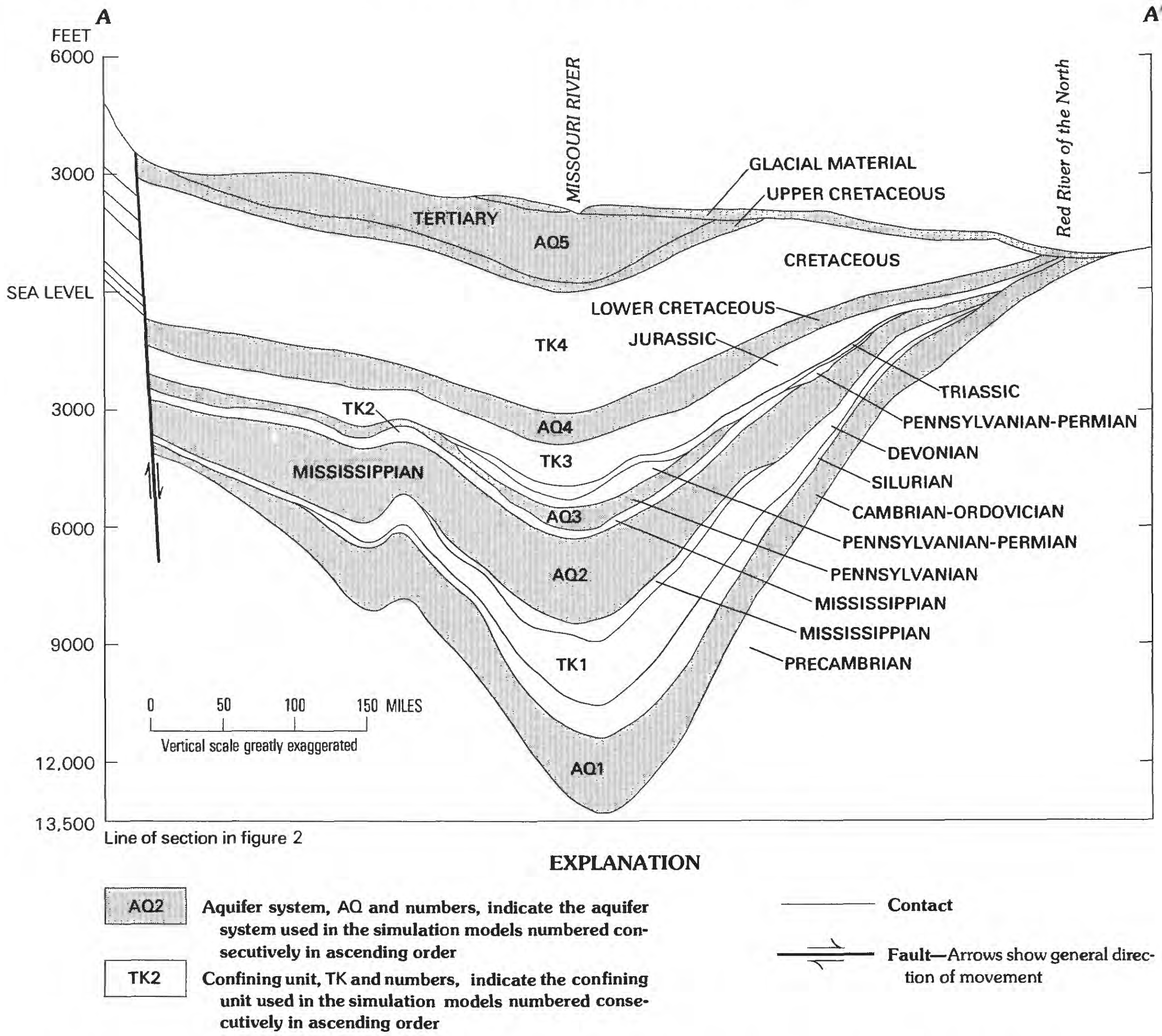

FIGURE 4.—Generalized geohydrologic section showing relationship of aquifers and confining layers from a ground-water recharge area in Montana to a discharge area in North Dakota.

extend northward into Canada for about 1,200 mi, underlying the Provinces of Alberta, Saskatchewan, and Manitoba and reaching into the Northwest Territories. The Prairie salt (informal subsurface usage), one of the principal halite units of Devonian age in the study area, contains many structural lows along its margin and locally within it. These structural lows have been attributed to postdepositional solution of halite, allowing collapse of the overlying formations into the void created by dissolution (DeMille and others, 1964; Grossman, 1968). Because of the fine-grained lithology and the presence of evaporite deposits in the Silurian and Devonian units, these formations act as confining beds for the underlying Cambrian-Ordovician aquifer (fig. 4).

MISSISSIPPIAN ROCKS

Rocks of Mississippian age (pl. 1; fig. 6) overlie the Devonian formations. The Mississippian rocks have been subdivided into several formations and one stratigraphic group.

The lowermost Mississippian unit is the upper part of the Bakken Formation, which overlies the Devonian Three Forks Formation. The Bakken Formation consists of more than 100 ft of black, organic shale and siltstone and appears to be an excellent hydrologic confining bed where it is present in the study area. This confining bed was delineated into the Devonian-Silurian confining unit shown in figure 4. The Bakken Formation is considered to be a source bed for much of the

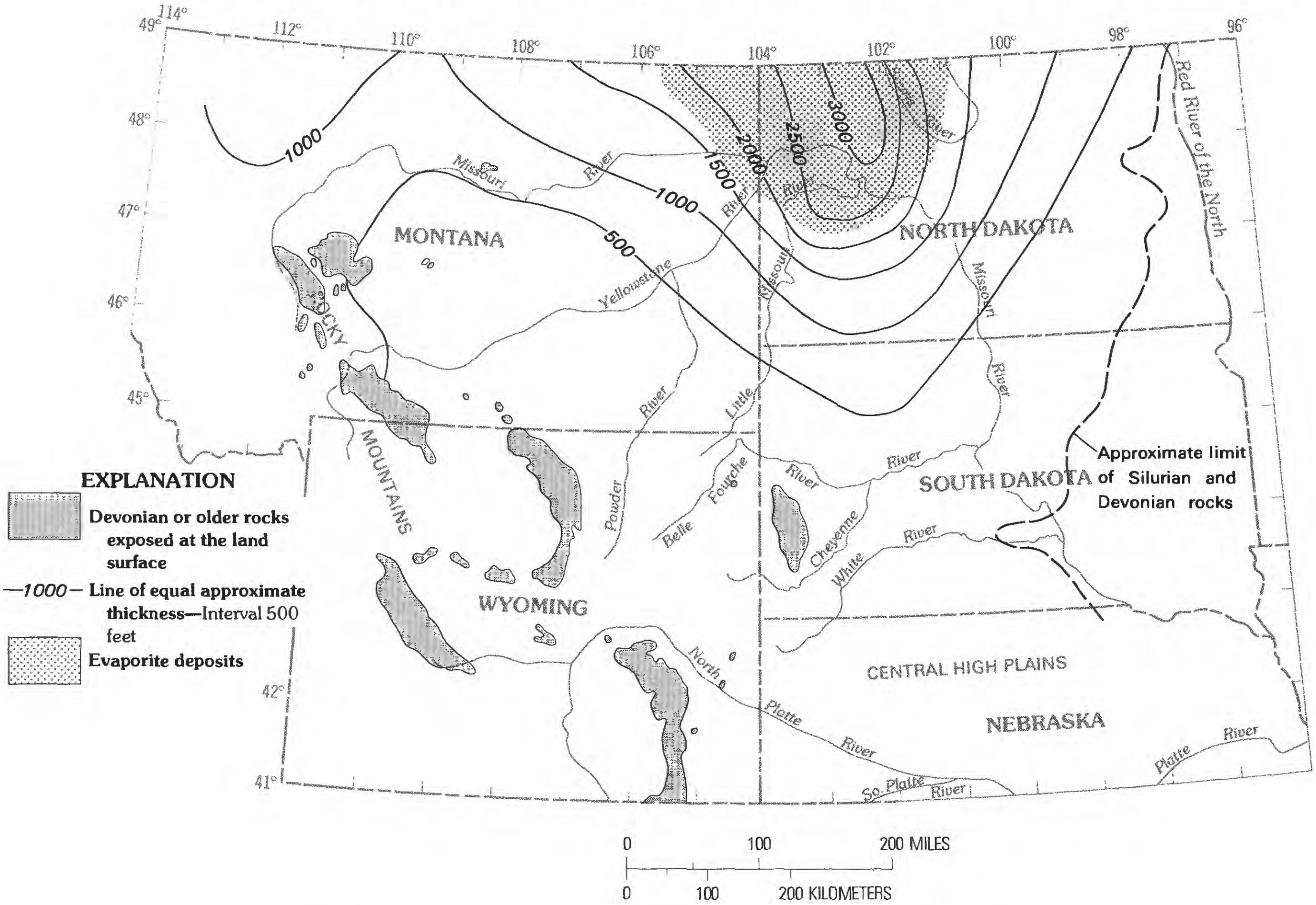

FIGURE 5.—Approximate thickness of rocks of Silurian and Devonian age.

petroleum found in overlying formations. Overlying the Bakken Formation is a sequence of Mississippian rocks, mainly limestone and dolomite, that are termed the Madison Group (where divided) or Madison Limestone, a major aquifer system in the study area (fig. 4).

The Madison Limestone in the study area consists of a sequence of marine carbonate rocks and evaporite deposits distributed mainly in a warm shallow-water environment similar to that which exists today near the coast of southern Florida and the Yucatan Peninsula in Mexico. Depositional environments grade both laterally and vertically from shallow-marine carbonate and evaporite facies to deep-water clay and siltstone facies. The Madison Group, from oldest to youngest, consists of the Lodgepole Limestone, the Mission Canyon Limestone, the Charles Formation, or their stratigraphic equivalents in other parts of the study area (pl. 1).

The Lodgepole Limestone is predominantly a cyclic carbonate sequence largely consisting of fossiliferous to micritic dolomite and limestone units that are argillaceous and thin bedded in most of the study area (Smith, 1972). The unit ranges from 0 to more than 900 ft in thickness, with an average thickness of about 300 ft in the study area. The Lodgepole Limestone overlies the Bakken Formation in the Williston basin.

The Mission Canyon Limestone consists of coarsely crystalline limestone at its base, grading upward to finer crystalline limestone and evaporite deposits near the top (Peterson, 1981). The formation contains one evaporite cycle and shares a second evaporite cycle with the lower part of the Charles Formation. Bedded evaporite units are absent in most of Wyoming and South Dakota, but evaporite deposits occur in southeastern Montana and northwestern North Dakota and gradually thicken from central Montana toward their maximum thicknesses in the Williston basin. The Mission Canyon Limestone ranges from 0 to more than 650 ft in thickness, with an average thickness of about 300 ft in the study area.

The Charles Formation, the uppermost unit of the Madison Group, is a marine evaporite sequence

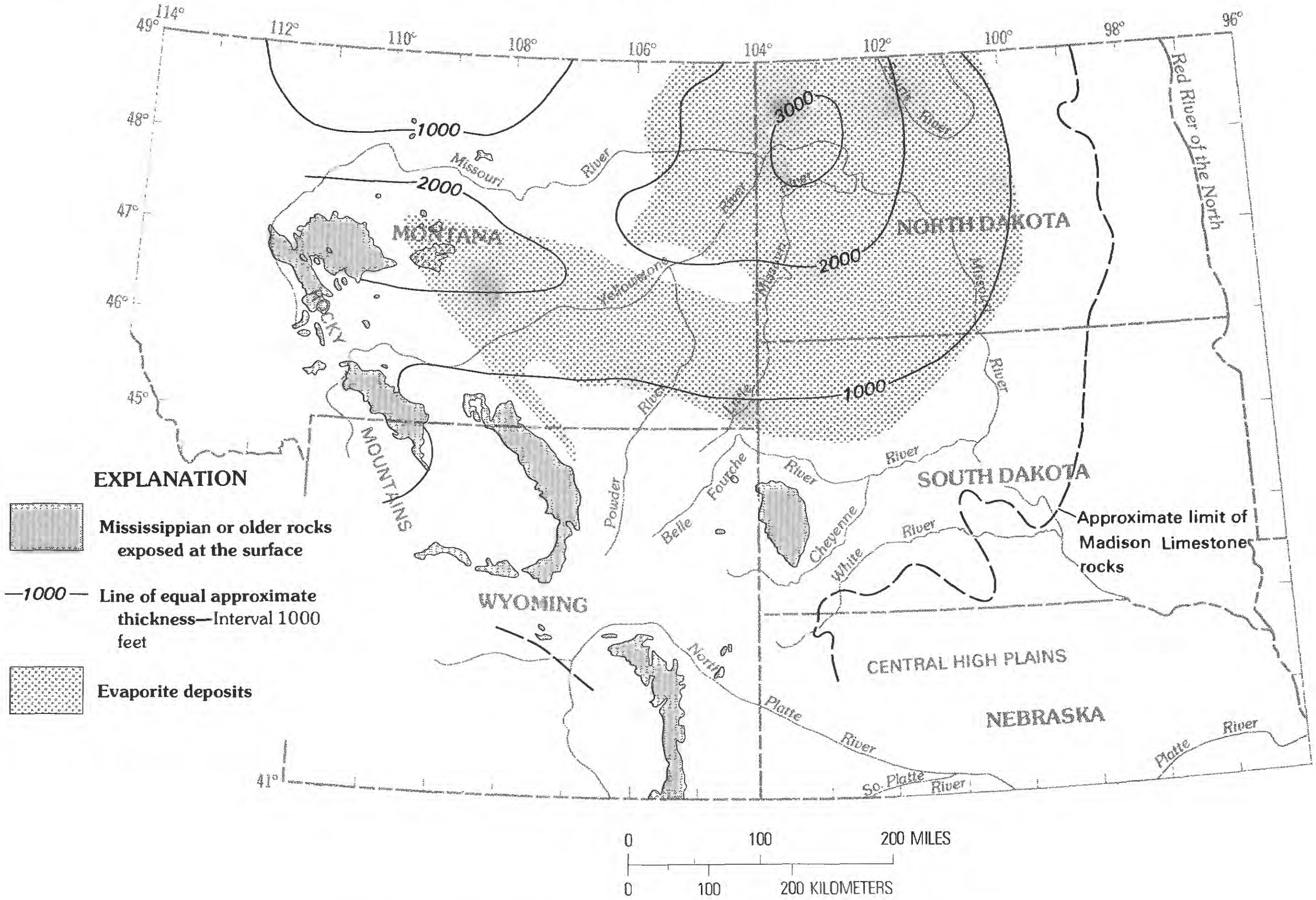

FIGURE 6.—Approximate thickness of rocks of Mississippian age.

consisting of anhydrite and halite with interbedded dolomite, limestone, and argillaceous units. The Charles Formation ranges from 0 to more than 300 ft in thickness, with an average thickness of about 250 ft in the study area. Pre-Jurassic erosion has removed most of the Charles Formation in the western and southern parts of the study area.

Overlying the Charles Formation in parts of Montana, North Dakota, and South Dakota are rocks of Late Mississippian age belonging to the Big Snowy Group. The Big Snowy Group consists mainly of shale and sandstone with minor limestone. Where present, the Charles Formation and rocks of the Big Snowy Group act as a hydrologic confining bed for the underlying aquifers (fig. 4).

PENNSYLVANIAN AND PERMIAN ROCKS

Rocks of Pennsylvanian age (pl. 1; fig. 7) overlie the Mississippian units in most of the study area and consist of marine sandstone, shale, siltstone, and carbonate rocks. The Pennsylvanian rocks are divided by many formational names; however, most are equivalent units.

The Tyler Formation generally is restricted to the Central Montana trough and the central Williston basin, but the formation grades southward and appears to be equivalent to the lower part of the Amsden Formation in south-central Montana. The Tyler Formation also appears to be equivalent to the lower part of the Minnelusa Formation in northwestern South Dakota and western North Dakota.

Middle Pennsylvanian rocks are represented by the Tensleep Sandstone in southern Montana and north-central Wyoming and by part of the Minnelusa Formation in the Williston basin in northeastern Wyoming and western South Dakota. Porous sandstone units of Pennsylvanian age are present in the Tensleep Sandstone in central to north-central Wyoming and south-central Montana, and in the middle part of the Minnelusa Formation in western South Dakota and

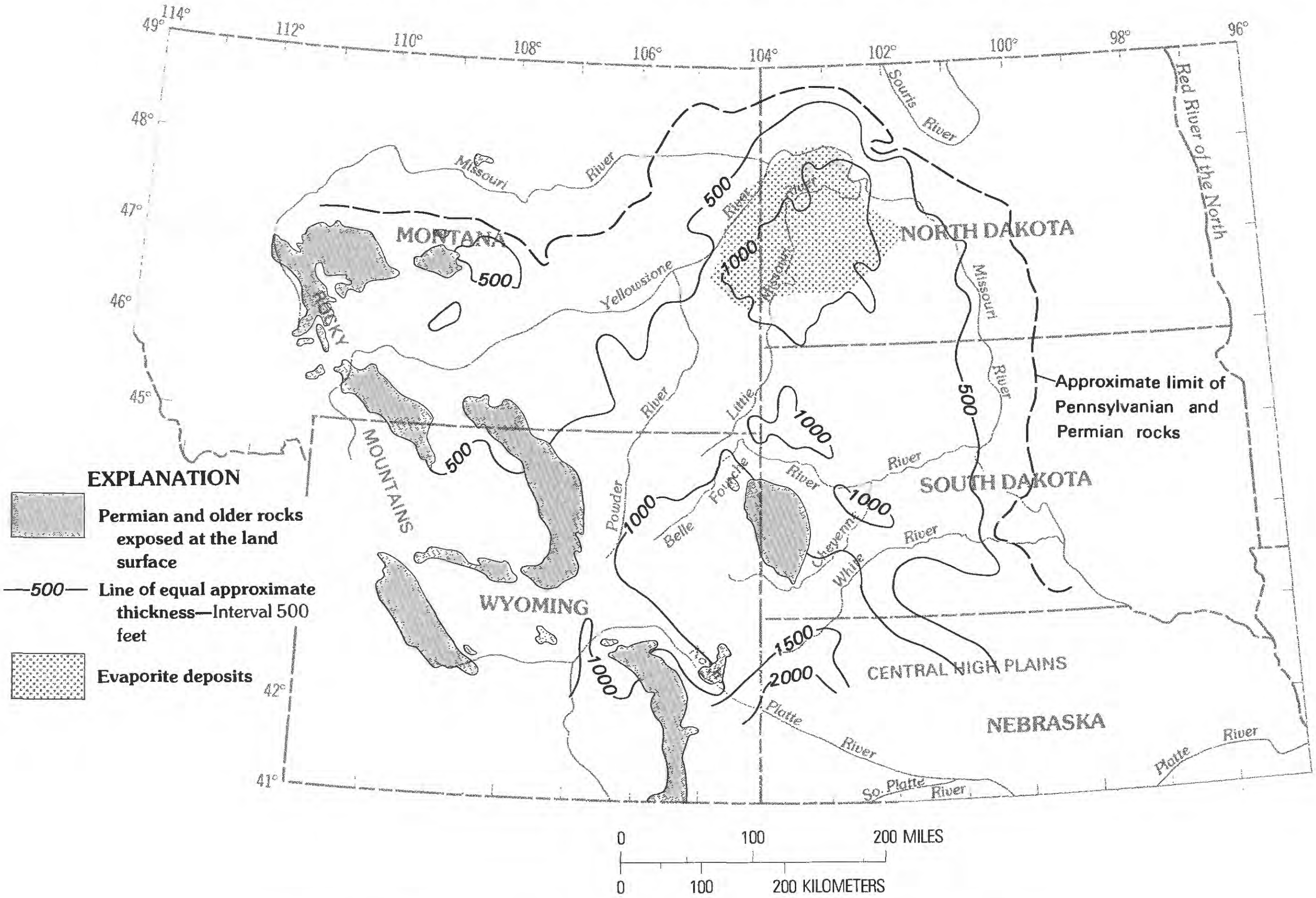

FIGURE 7.—Approximate thickness of rocks of Pennsylvanian and Permian age.

along the east side of the Williston basin. These rocks have been truncated progressively northward across central Montana by pre-Jurassic erosion.

The upper part of the Minnelusa Formation in the Powder River and Williston basins and in the western part of South Dakota consists of sandstone, shale, and carbonate rocks with interbedded anhydrite of Permian age. The sandstone facies extends northward to include the southeastern part of the Williston basin. The source of the sands in the upper part of the Minnelusa Formation is interpreted to be the reworking of earlier deposited Pennsylvanian sands from paleostructures to the west. Additional source areas were the Sioux uplift and the Canadian Shield on the eastern and northeastern borders of the Williston basin.

Overlying the upper part of the Minnelusa Formation are the Permian Opeche Formation, the Minnekahta Limestone, and the lower part of the Spearfish Formation. The Opeche Formation is interbedded in the central part of the Williston basin with halite beds informally termed the Opeche salt. The Minnekahta Limestone overlies the Opeche Formation and halite units. Above the Minnekahta Limestone, the Pine salt (informal usage) of the Spearfish Formation contains more than 300 ft of bedded halite, which limits the vertical flow of water through this formation (fig. 4).

TRIASSIC AND JURASSIC ROCKS

Rocks of Permian age in the study area are overlain by a sequence of red shale, siltstone, and evaporite deposits belonging to the upper part of the Goose Egg and Spearfish Formations of Triassic age (pls. 1, 2; fig. 8). These formations are about 200 to 400 ft thick in the central Williston basin and thicken southwesterly to more than 900 ft in the Powder River basin.

Although shale and siltstone are the principal lithologies of the Triassic units in the study area, sandstone occurs to a limited extent in the eastern part of the Williston basin as elongate northeast-trending sandy belts probably deposited by streams flowing off the

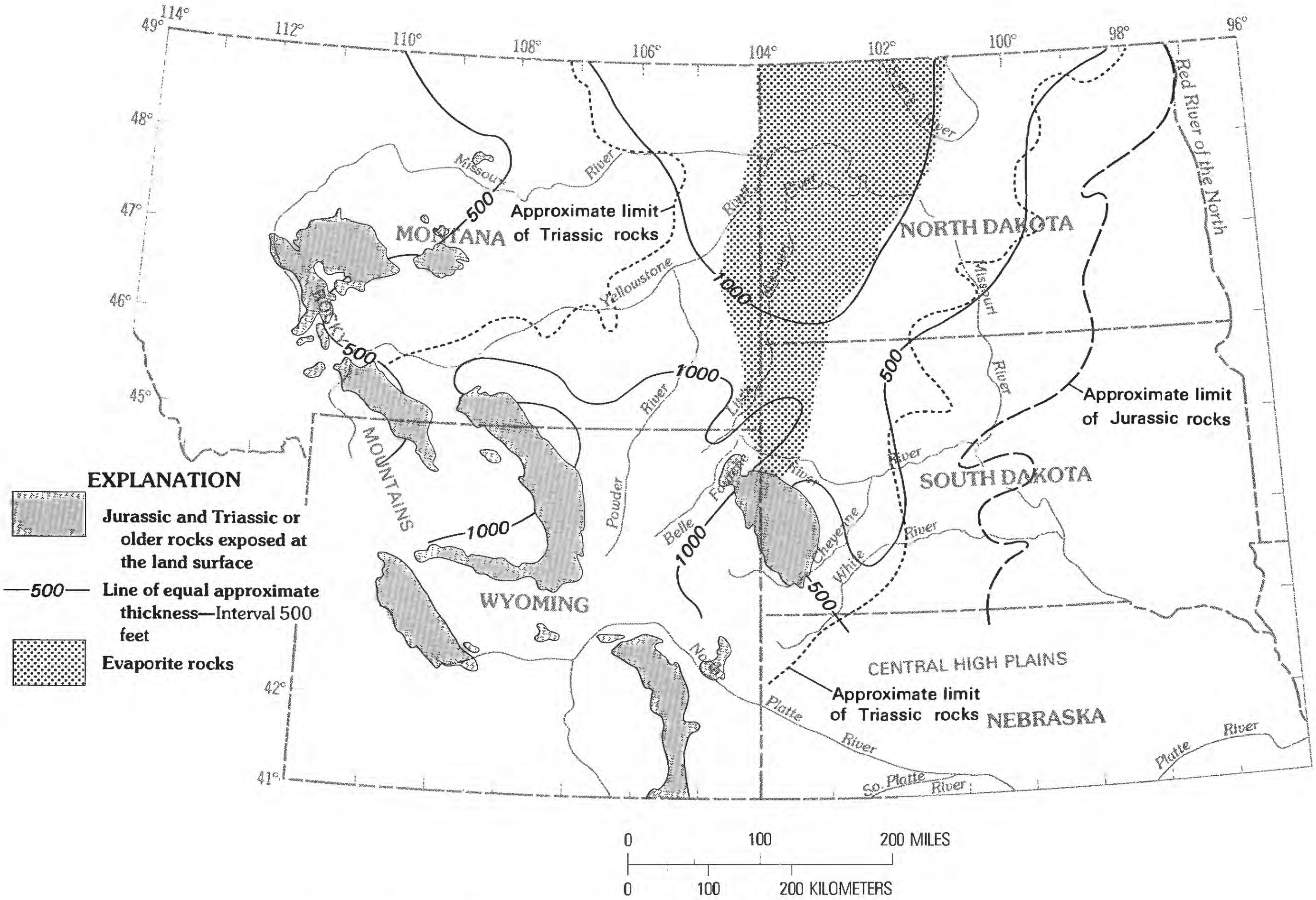

FIGURE 8.—Approximate thickness of rocks of Triassic and Jurassic age.

adjacent Sioux uplift and Canadian Shield source areas to the east. Triassic beds have been truncated by pre-Middle Jurassic erosion along the southern and eastern margins of the Alberta shelf and on the east side of the Williston basin. Rocks of Triassic age, along with those of Permian age, are considered to be a confining bed for the flow of ground water from the underlying aquifers to the overlying aquifers of Cretaceous age (fig. 4).

Rocks of Jurassic age overlie formations of Triassic age with a pronounced disconformity. These rocks, consisting of the Nesson, Piper, Rierdon, Swift, and Morrison Formations and their equivalents, are predominantly carbonate rocks, shale, and calcareous shale. The Nesson Formation is subdivided into three informal members: a lower anhydrite, which includes the Dunham salt, occurring in parts of the Williston basin; a middle shale; and an upper carbonate-rock sequence. The Piper Formation also is subdivided into three members: a lower shale and sandstone unit, a middle sandstone, and an upper shale. In north-central Montana, the Piper Formation thins appreciably and consists chiefly of sandstone. The Rierdon Formation mainly consists of shale, siltstone, and calcareous shale, with small amounts of sandstone along the eastern fringes of the Williston basin.

The Swift Formation was deposited under marine conditions, and in the western part of the study area it consists of sandstone deposited as offshore bars in a shallow sea. In the eastern part, the formation consists mostly of silty shale with coarser sediments occurring in the upper part of the formation. The formation is about 600 ft thick along the northern axis of the Williston basin and thins to near nonexistence in western Montana and in eastern North Dakota and South Dakota. Generally, cementation of the Swift Formation is less than that of adjacent formations, possibly due to a lower primary porosity and to less active diagenetic processes. The Swift Formation is less porous than the sandstones occurring in units of Early Cretaceous age, although in several localities more than 50 ft of sand occurs with greater than 20 percent porosity.

The Morrison Formation was deposited as a continental deposit of sand, silt, and clay on a plain that emerged after the regression of the sea which existed during deposition of the Swift Formation. The Morrison Formation is about 250 ft thick in south-central Montana and thins eastward to near nonexistence in western North Dakota and South Dakota. A regional unconformity at the base of the Lower Cretaceous units locally truncates both the Morrison Formation and the upper part of the Swift Formation. Total thicknesses of the Jurassic units in the study area range from less than 50 ft along the periphery of the Williston and Powder River basins to more than 1,000 ft north of the deepest part of the Williston basin.

CRETACEOUS ROCKS

Rocks of Cretaceous age (pl. 2; fig. 9) consist of marine and nonmarine clastic sediments that range in thicknesses from 0 ft in eastern North Dakota and South Dakota to more than 6,000 ft in northeastern Wyoming. The stratigraphic sequence consists of interbedded shale, siltstone, and sandstone layers with a few beds of limestone or marl. A number of formational names have been applied to the various Cretaceous units in the northern Great Plains region; however, in several instances, these formational names are used only in one State or subregion, as shown on the geologic correlation chart (pl. 2). The Lakota and Fuson Formations of Early Cretaceous age are composed of fluvial sandstone, siltstone, and shale. The Lakota Formation consists mainly of sandstone and occasional conglomerate overlying an erosional surface cut into the underlying Morrison Formation of Jurassic age. Generally, the Lakota Formation is a channel- and valley-fill deposit; however, in the subsurface, it is difficult to distinguish between the valley fill of the Lakota Formation and the valley fill of the overlying Fuson Formation.

The Fuson Formation consists mostly of valley-fill and channel margin deposits of silty shale with occasional sandstone units. Thickness of the Fuson

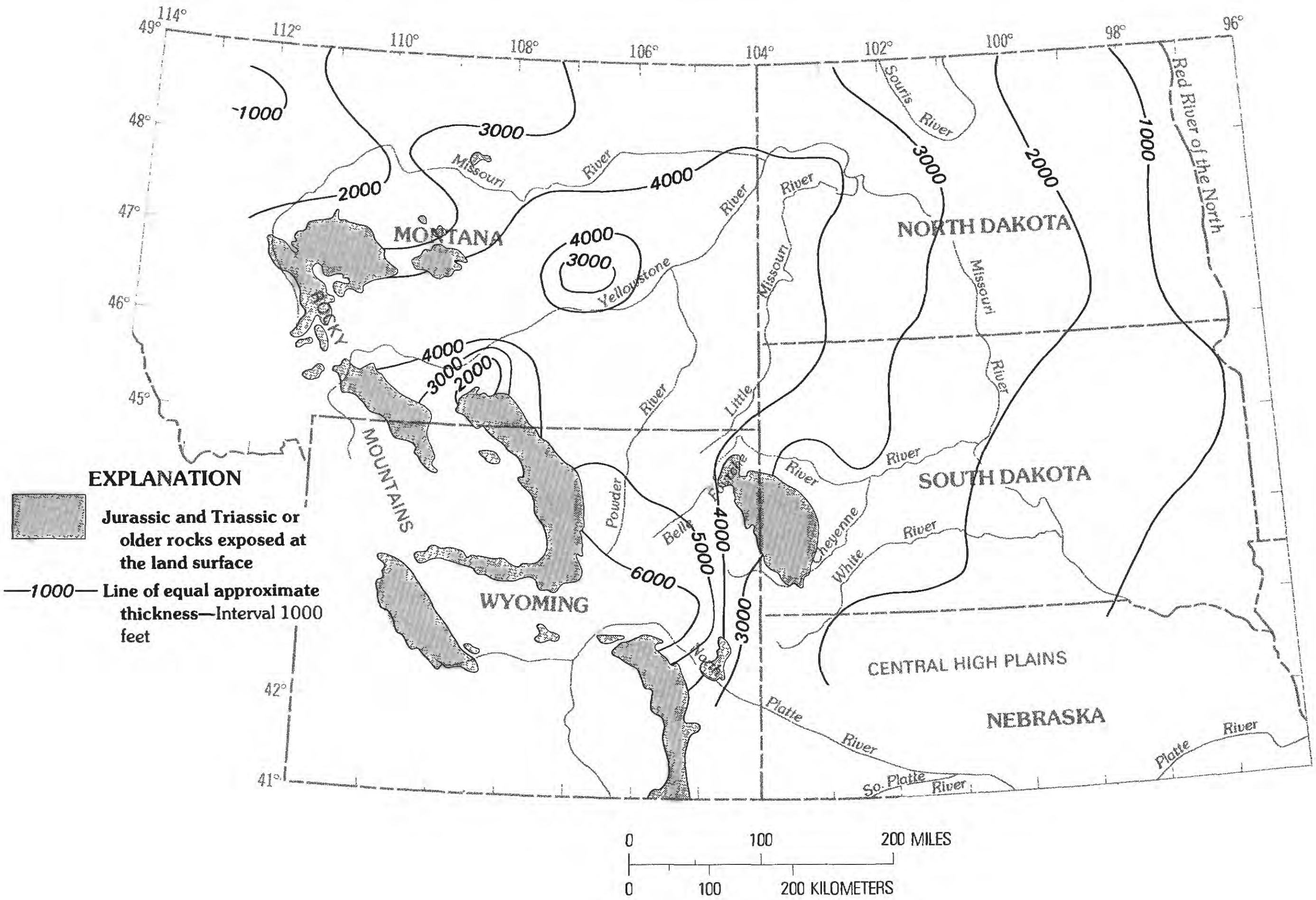

FIGURE 9.—Approximate thickness of rocks of Cretaceous age.

Formation decreases from about 400 ft in central Montana to nearly nonexistence in eastern North Dakota and South Dakota.

The Fall River Formation of Early Cretaceous age represents the initial advance of the Early Cretaceous sea, which deposited fine sand, silt, and clay under shallow-marine, tidal-flat, coastal-swamp, and deltaic conditions. Silt and shale deposits in central Montana and Wyoming indicate a deeper water environment in this part of the study area.

In the Williston basin, analysis of cementation data indicates that these Lower Cretaceous formations have a greater degree of silica cementation than calcite cementation (Anna, 1986). The analysis also indicates that (1) areas of less cementation tend to overlie lineaments, or fracture zones, and (2) areas of more cementation overlie interlineament zones.

The Lakota, Fuson, and Fall River Formations thin eastward, with thickness of the three formations decreasing from about 700 ft in central Montana to near 0 in eastern North Dakota and South Dakota.

The Skull Creek Shale of Early Cretaceous age consists of two marine facies: a lower, glauconitic siltstone, commonly termed basal silt, and an upper shale. The silt facies extends regionally but has increasing sand content in central and south-central Montana. The upper shale facies was deposited under extreme reducing conditions and consists mainly of black organic shale with associated pyrite. The formation ranges in thickness from 0 in eastern South Dakota to more than 250 ft in parts of Montana, Wyoming, and western South Dakota and North Dakota.

Withdrawal of the sea ended deposition of the Skull Creek Shale and resulted in an unconformity separating the Skull Creek Shale from the Newcastle Sandstone in eastern Wyoming and from the Muddy Sandstone in southeastern Montana. Later, the sea transgressed from west to east across the area, with development of extensive delta systems in eastern Montana, northeastern Wyoming, and southeastern South Dakota. Sediment supply to the deltas originated in eastern South Dakota, whereas the deltas supplied sediment to shelf areas in east-central Montana and Wyoming.

Thickness of the Newcastle Sandstone or its equivalent is quite variable, ranging from 0 in large areas of North Dakota to tens of feet in central Montana and Wyoming to an abrupt increase of several hundred feet in southeastern North Dakota and eastern and south-central South Dakota. Porosity of sandstone beds in the Newcastle Sandstone appears to be greater in areas where Newcastle sand accumulation is thicker. Calcite is a more dominant cementing agent than silica in the Newcastle Sandstone (Anna, 1986).

As the sea transgressed eastward during late Newcastle time, the dark siliceous shale of the Mowry Shale was being deposited in a large part of the study area. In most of the area, a bentonitic clay marks the top of the Mowry Shale and is used as a regional time marker dividing the Lower and Upper Cretaceous rocks. The Mowry Shale ranges in thickness from 0 in eastern North Dakota and South Dakota to more than 700 ft in central Montana.

The environment at deposition of formations of Late Cretaceous age in the northern Great Plains is associated with four main transgressions and regressions of a shallow sea. The shale and siltstone of the Belle Fourche Shale, Frontier Formation, and Greenhorn Formation were deposited as a continuation of the transgression of the sea during the Late Cretaceous. The Belle Fourche Shale (or equivalent rocks) consists of gray to black marine shale with numerous bentonite beds. The Greenhorn Formation (or equivalent rocks) consists of a thick sandstone sequence with interbedded shale and chalky shale. The Carlile Shale consists of gray marine shale with interbeds of thin sandstone.

The Niobrara Formation ranges in thickness from nearly 0 to about 160 ft; it consists of gray marine shale with lenticular chalky beds and is characterized by small white calcareous lenses. Lithologic variations range from a chalk facies in the east to mostly shale facies in the west.

The Pierre Shale directly overlies the Niobrara Formation in the study area. The Pierre consists of more than 3,000 ft of dark, montmorillonitic shale and interbedded sandstone that were deposited under marine conditions. Many of the sandstone units have been given formational status in western and central Montana and in the Powder River basin of Wyoming. Although the Pierre Shale contains a number of sandstone units that act as aquifers in restricted areas, the Pierre acts as a regional confining unit to the underlying Lower Cretaceous aquifer throughout most of the area.

The final regression of the Late Cretaceous sea deposited the Fox Hills Sandstone and the Hell Creek Formation, or Lance Formation, or their equivalent rocks (pl. 2). These formations are areally extensive, with the Fox Hills Sandstone and the Hell Creek Formation cropping out throughout sizable areas in southern and central North Dakota, and the Lance Formation being extensive in Wyoming.

The Fox Hills Sandstone (or equivalent rocks) consists of about 300 ft of deltaic and interdeltaic sandstone, siltstone, and shale. The Hell Creek or Lance ranges from about 350 to 1,500 ft thick and consists of fluvial sandstone, siltstone, and carbonaceous claystone, with occasional thin lenticular coal beds. The Hell Creek or Lance is the meander-belt and delta-plain facies of the Fox Hills delta system.

On the basis of permeability contrast among formations and the areal extent of the formations, most of the Lower Cretaceous rocks, except Neocomian, were delineated as an aquifer system (fig. 4; pl. 2), and most of the Upper Cretaceous rocks were delineated as a confining unit (fig. 4). However, several formations of the Upper Cretaceous rocks, such as Fox Hills Sandstone and Hell Creek and Lance Formations, were delineated together with Tertiary rocks as an aquifer system (fig. 4; pl. 2).

TERTIARY ROCKS

Tertiary formations (pl. 2) in the northern Great Plains contain important ground-water aquifers for development of domestic and agricultural water supplies; they have a relatively shallow drilling depth, and their water is less mineralized than that in the deeper aquifers. These formations generally were deposited in a continental environment. Exceptions are the Cannonball Member of the Fort Union Formation in western North Dakota, deposited in a marine environment, and the upper part of the Ludlow Member, deposited in a shallow-marine environment. Most of the sediments that make up the Tertiary deposits were derived from highlands to the west and northwest during and after the Laramide orogeny.

The Fort Union Formation of Paleocene age consists of alternating gray to buff sandstone, siltstone, and claystone with thin-to-thick lignite and subbituminous coal beds. Contact with the underlying Cretaceous Hell Creek or Lance is at the base of the lowest persistent coal bed.

Thickness of the Fort Union Formation decreases from more than 3,000 ft in the Powder River basin to less than 300 ft in the Williston basin in central North Dakota and northeast Montana. The sandstone units in the Powder River basin generally are coarser grained and better sorted than in eastern Montana, North Dakota, and South Dakota, and generally are more permeable.

The Wasatch Formation of Eocene age is present only in the Powder River basin and consists of about 1,000 ft of alternating beds of valley- and channel-fill sandstone, siltstone, and claystone; this formation is similar to the Tongue River Member of the Fort Union Formation, although mineralogical differences have been noted. The contact between the Wasatch Formation and the underlying Fort Union Formation is unconformable and is placed at the top of the Roland-Anderson coal bed (Anna, 1986). This bed is about 50-100 ft thick and is areally extensive throughout most of the southern Powder River basin.

The Golden Valley Formation of Eocene age consists of about 150 ft of kaolinitic claystone, mudstone, lignite, and micaceous sandstone. The formation is present only in western North Dakota and usually as remnants underlying younger rocks. The formation has been subdivided into upper and lower units, the lowermost of Paleocene age and the uppermost of Eocene age.

The White River Formation, or Group where divided, of Oligocene age unconformably overlies the Eocene formations and is about 150 ft thick. The formation is exposed only as erosional remnants, capping buttes in several localities in the Williston basin, and as areally extensive deposits in the Badlands of south-central South Dakota. The White River Group is subdivided into the lower Chadron Formation, consisting of a basal conglomerate with overlying tuffaceous sandstone, siltstone, and shale, and the upper Brule Formation, consisting of claystone, siltstone, and sandstone.

The Arikaree Formation of Miocene age is exposed as remnants resulting from Pliocene and Pleistocene erosion of higher buttes in North Dakota and South Dakota. The formation rests unconformably on the White River Formation and consists of about 250 ft of massive tuffaceous sandstone and siltstone and a few thin beds of quartzite, dolomite, and volcanic ash.

The Ogallala Formation of Miocene age is present only in southwestern South Dakota but is an extensive veneer of interbedded sandstone and claystone throughout most of the central Great Plains region. The Flaxville Formation of Miocene and Pliocene age is a thin widespread pediment capping numerous plateaus and consists of poorly cemented sandstone and conglomerate. The formation is recognized only in northeast Montana but may be correlative to local pediments along flanks of major buttes.

QUATERNARY DEPOSITS

Deposits of Quaternary age (fig. 10) in the study area consist of alluvium and glacial materials. Alluvial deposits, varying in thickness, fill major drainage of the area. Glacial-till and glacial-outwash deposits occur only in eastern North Dakota, northeastern South Dakota, and northernmost Montana. The outwash deposits can range in thickness from a few feet to several hundred feet and consist of silt, sand, and gravel. Widths of Quaternary deposits generally range from less than 1 to several miles, and they commonly are tens of miles in length. Glacial-outwash deposits are a major source of water in a large part of the study area.

During this study, the Upper Cretaceous and Tertiary rocks and the Quaternary deposits were delineated as a single aquifer system (fig. 4; pl. 2) overlying the

ERA	PERIOD	EPOCH	GLACIATION AND INTERGLACIATION	
CENOZOIC	QUATERNARY	HOLOCENE		
		PLEISTOCENE	WISCONSIN GLACIATION	0.010 MILLION YEARS AGE ESTIMATE AT BOUNDARY
			SANGAMON (INTERGLACIATION)	
			ILLINOIAN (GLACIATION)	
			YARMOUTH (INTERGLACIATION)	
			KANSAN (GLACIATION)	
			AFTONIAN (INTERGLACIATION)	
			NEBRASKAN (GLACIATION)	
	TERTIARY	PLIOCENE	PRE-NEBRASKAN	2 MILLION YEARS AGE ESTIMATE AT BOUNDARY

FIGURE 10.—Pleistocene glaciation and interglaciation units.

low-permeability Cretaceous rocks. No effort was made to delineate aquifers and confining layers among the Upper Cretaceous rocks, the Tertiary rocks, and the Quaternary deposits.

During the Pleistocene Epoch, the hydrologic system in the aquifers of the northern Great Plains was subject to major changes in the recharge-discharge relationships associated with the four glaciations and three interglaciations shown in figure 10.

At the time of maximum glacial advance, the discharge areas of all the aquifers were covered by thick masses of ice, blocking discharge and causing flow in the aquifers to be southeastward, as shown diagrammatically in figure 11. During interglaciation, glacial ice was absent from the aquifer discharge areas, and the inferred flow direction was northeastward, similar to the flow pattern of the present day, as shown on plate 3.

Except for local mountain glaciation, the highland areas in the western part of the northern Great Plains were not affected by continental glaciation and continued to be recharge areas for the bedrock aquifers.

GEOLOGIC STRUCTURE

The structural history of the northern Great Plains is reflected in the sediments. The forces involved in developing geologic structures are among the important factors controlling the distribution of porosity and permeability in carbonate and sedimentary rocks. Movement along structural zones creates porosity and increases permeability by fracturing; this can be modified at a later time by chemical processes occurring in the aquifer as water moves through the fracture system.

Much of the present-day structure in the study area (figs. 12–14) is the result of the Laramide deformation that occurred in Late Cretaceous and early Tertiary time. Many zones of weakness that existed prior to Laramide deformation were the most common avenues for the release of stress during the deformation; northwest-, east-southeast-, and northeast-trending structural features of Precambrian, Paleozoic, and Mesozoic age occur throughout the study area. Many of these structural features were initiated as shear zones of Precambrian age that developed in the basement rocks and since have been zones of weakness. For example, the Nashfork–Hartville fault trend in Wyoming and South Dakota is a component of a broad Precambrian shear zone called the Colorado lineament (Warner, 1978). Warner postulated that this shear zone, which extends from Arizona to the Great Lakes, divides the Precambrian basement into provinces of two different ages, one of 2,400 million years on the north and one of 1,750 million years on the south.

The large fault and lineament systems that have developed in many bedrock units of the northern Great Plains during geologic time are important features in the analysis of the existing hydrologic system. Both faults and lineaments appear to provide paths for increased movement of ground water (Chilingar and others, 1972; Weimer and others, 1982). These features also can be barriers to the flow of water normal to the direction of the fault or lineament. An example of this barrier effect was presented by Konikow (1976) in his analysis of the flow system in the Powder River basin; geologic structure along the eastern edge of the Bighorn Mountains appears to limit water movement from the recharge area in the Bighorn Mountains to the Powder River basin.

Structural movement along major faults and lineaments affects the porosity and permeability distribution throughout a large area and through a long geologic

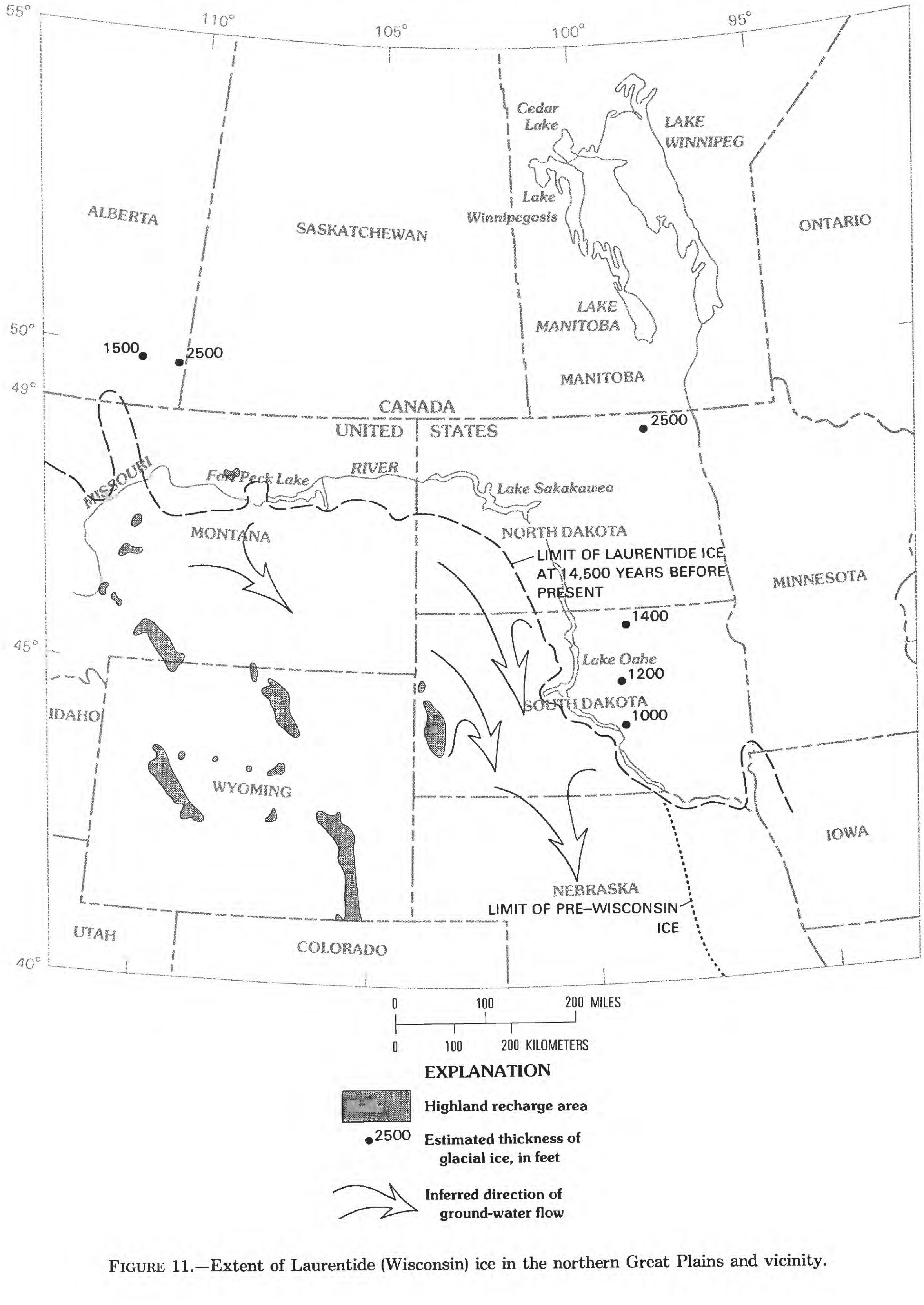

FIGURE 11.—Extent of Laurentide (Wisconsin) ice in the northern Great Plains and vicinity.

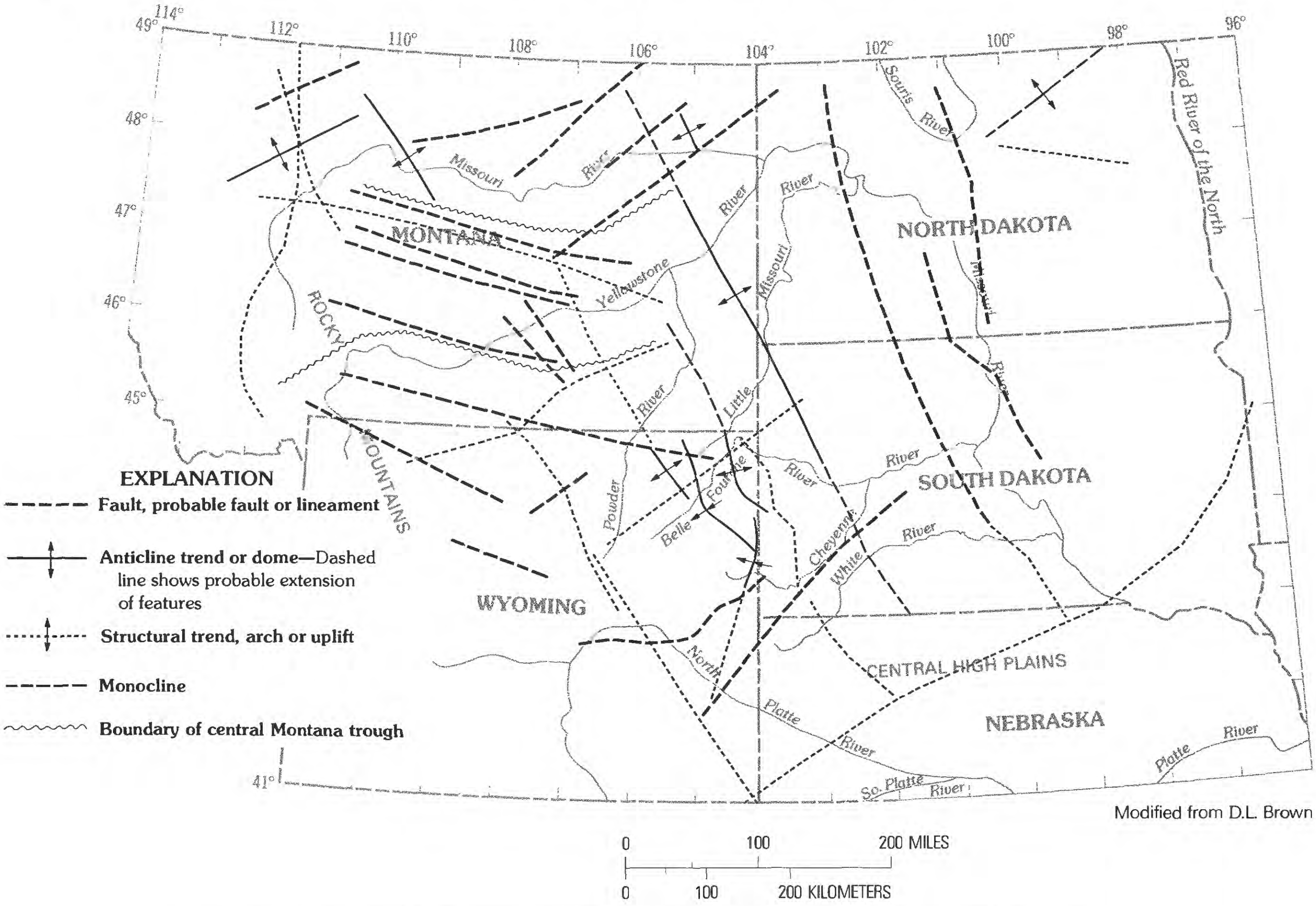

FIGURE 12.—Major Paleozoic structural features in the northern Great Plains and vicinity.

time. Structural adjustments between large blocks of geologic material modify the existing primary porosity and permeability of the rock by fractures or by development of a secondary porosity. Structural adjustments also may result in a decrease in porosity and permeability by precipitation of minerals in rock pore spaces.

Structural movement along or between these large blocks also affected sedimentation of clastic materials, such as those in the Lower and Upper Cretaceous bedrock units. Block movement may result in shallow-water, near-shore environments where coarse-grained sediments are deposited. Later, movement between the blocks may result in a lowered, deep-water environment where fine-grained or calcareous sediments are deposited. Maps drawn by R.K. Blankennagel (USGS, written commun., 1982) show patterns of linear structural trends that apparently relate to changes in sedimentation rates and lithologic type because of adjustments between structural blocks.

Many of the structural features in the northern Great Plains are associated with present-day physiographic features that affect both the deep and shallow ground-water flow systems and surface-water drainage patterns. A set of lineaments—A, B, and C—shown in figure 14 were selected to indicate such effects. Lineament A, which is located in northeastern North Dakota, may be a control on stream channel and lake location in this part of North Dakota. Also, a deep, bedrock trench filled with glacial materials (Downey and Armstrong, 1977) appears to lie along the trend of this feature. This bedrock trench may have been a zone of weakness that was eroded by glacial action during the Pleistocene. Lineament B, a major fault offsetting the eastern flank of the Bighorn Mountains, also affects the surface-water drainage pattern and ground-water flow system in this part of the study area. Lineament C, a major lineament cutting the Black Hills in South Dakota, has a major effect on the ground-water flow system near the Black Hills area.

Carbonate rocks are relatively soluble in water, and the development of karstic features is common wherever these rocks are exposed to the weathering

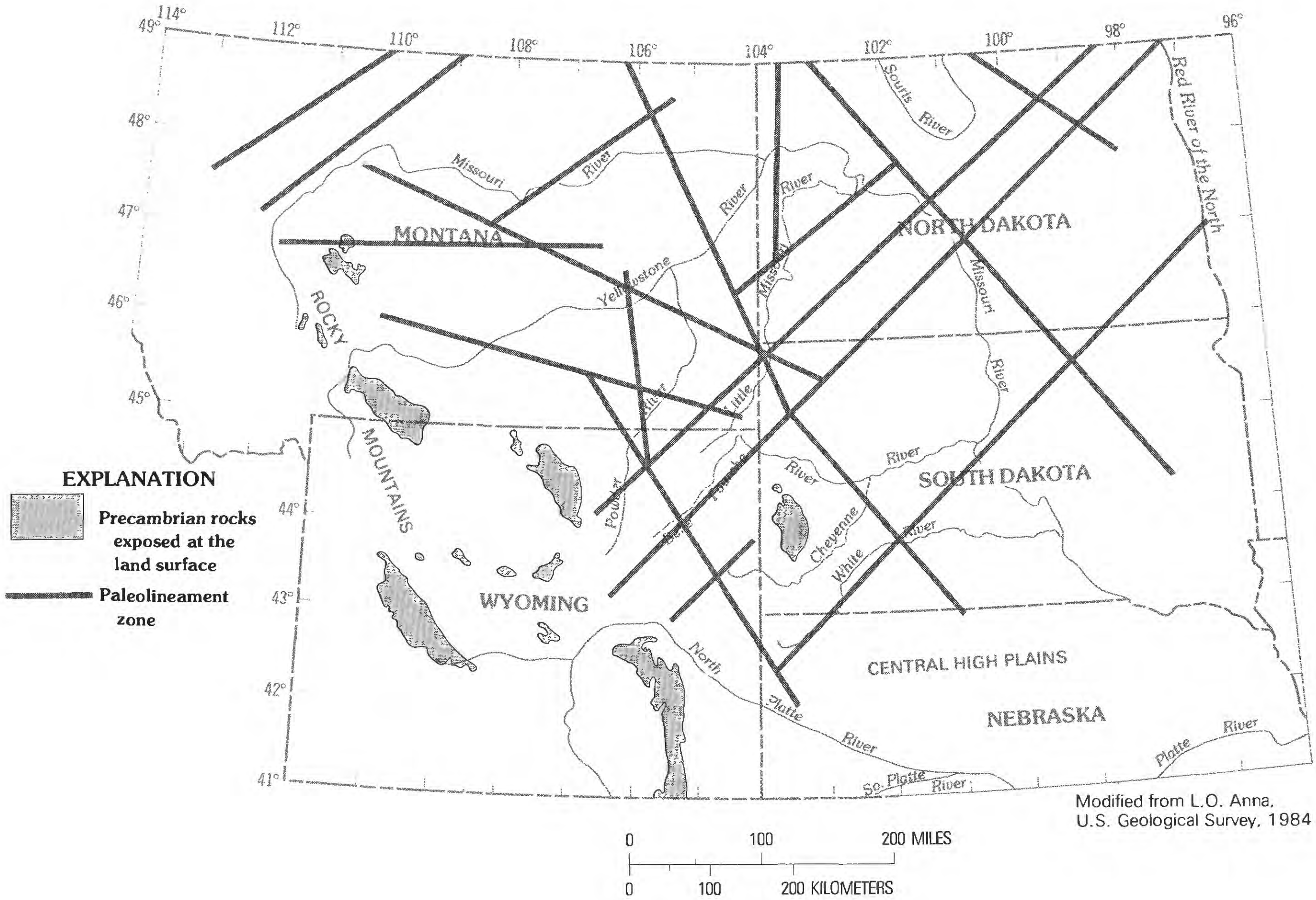

FIGURE 13.—Subsurface paleolineament zones of Jurassic and Cretaceous age in the northern Great Plains and vicinity.

process. The complex interconnected solution features that develop in carbonate rocks during relatively short periods of weathering are illustrated in figure 15. Sando (1974) described ancient karstic features, including enlarged joints, sink holes, caves, and solution breccias, that developed in the Mississippian limestone in north-central Wyoming. He further stated that most of the open spaces were filled by sand and residual products reworked by a transgressive sea during Late Mississippian time. Large and extensive cave systems in outcrop areas of carbonate rocks in the Bighorn Mountains and in the Black Hills are further evidence of the importance of the dissolution process in the development of secondary permeability in carbonate rocks underlying the northern Great Plains.

REGIONAL HYDROLOGY

The confined ground-water system of the northern Great Plains includes numerous permeable horizons, many of which are discontinuous, and all of which vary considerably in hydraulic properties from one location to another. During the study, five major subdivisions (pls. 1 and 2) of the regional aquifer system were made: Cambrian-Ordovician aquifer system; Mississippian aquifer system including Madison Limestone; Pennsylvanian aquifer system; Lower Cretaceous aquifer system; and Upper Cretaceous aquifer system. Each of these is an aggregate of permeable, low-permeable, and semiconfining materials; each has been identified as an aquifer system primarily because vertical head differences within each system tend to be much smaller than those between the adjacent systems. To some extent, the division is arbitrary; it has been made to assist in analysis and discussion of the northern Great Plains regional aquifer system as a whole.

These five major aquifer systems within the regional system make up one of the largest confined aquifer systems in the United States (pl. 3). The flow system extends more than 600 mi from mountainous recharge areas in Montana, Wyoming, and South Dakota to

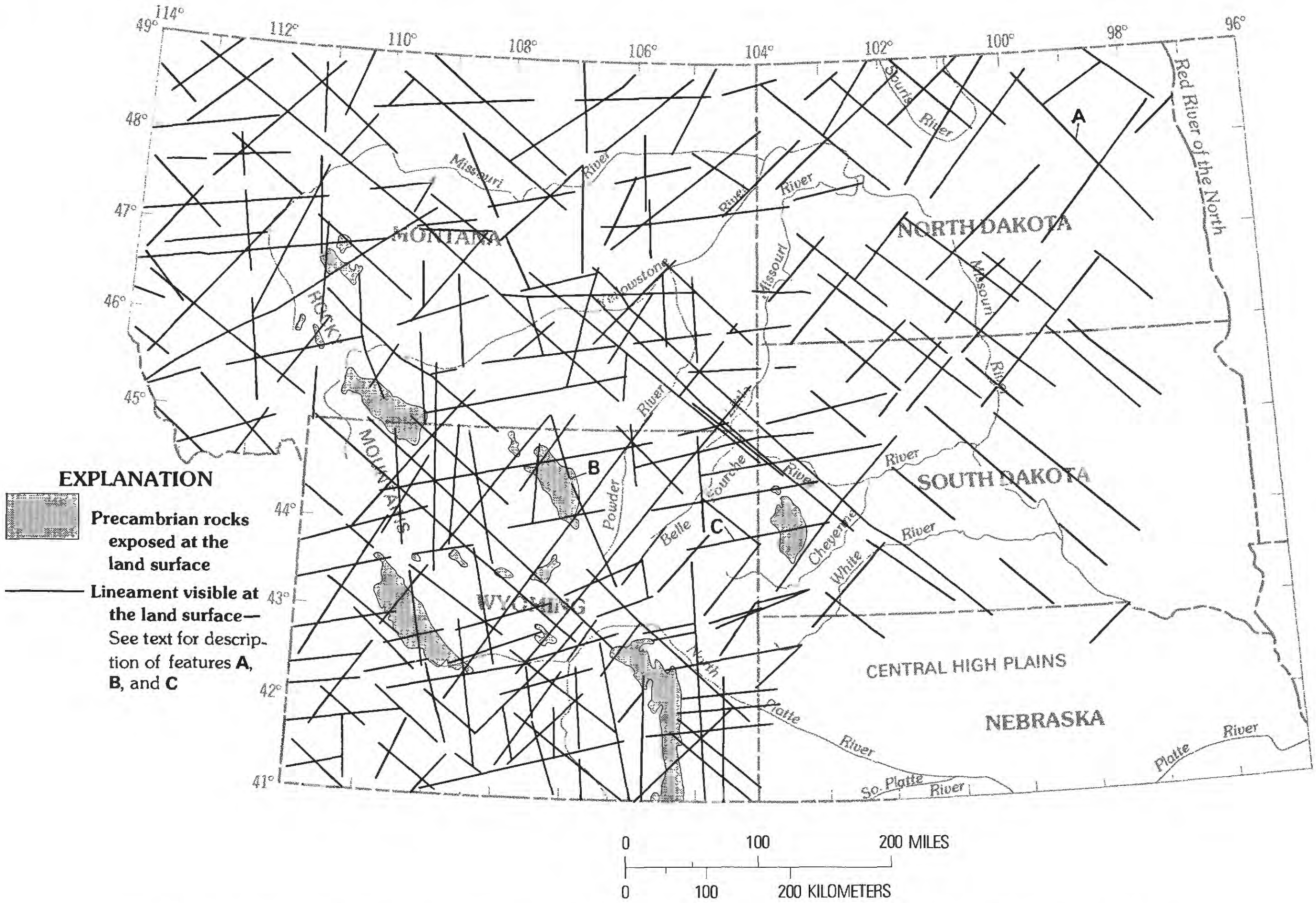

FIGURE 14.—Lineament patterns, delineated using Landsat imagery, in the northern Great Plains and vicinity.

discharge areas in the eastern Dakotas and the Canadian Province of Manitoba. The total area involved is more than 300,000 mi². The geologic units that make up each of the five major aquifers and the intervening semiconfining zones are summarized on plates 1 and 2.

POTENTIOMETRIC SURFACES

The predevelopment potentiometric-surface maps (before 1950) for the aquifer systems containing rocks of Paleozoic age (figs. 16–18) are those developed by Miller and Strausz (1980a, b). The potentiometric-surface map for the Pennsylvanian aquifer (fig. 19) is from unpublished data developed by W.R. Miller (USGS, written commun., 1980) from drill-stem tests.

The predevelopment potentiometric-surface maps developed by Miller and Strausz (1980a, b) show the altitudes of freshwater heads that were determined from shut-in pressures of drill-stem tests according to a procedure outlined by Miller (1976, p. 17). He used the following equation, modified from Murphy (1965):

$$h=(\text{FSIP}\times C)-\text{PRD}+\text{LSD},$$

where

h=altitude freshwater surface in feet above mean sea level,
FSIP=final bottom-hole pressure in pounds per square inch,
C=factor to convert FSIP to feet of water,
PRD=depth to pressure recorder in feet below land-surface datum (LSD),
LSD=altitude of land surface in feet above sea level; land-surface datum.

The factor C equals 2.307 ft of water per pressure increment of 1 lb/in². It assumes pure water at a temperature of 4 °C and a density of 1.00 g/cm³. The resultant map indicates the altitude at which water

FIGURE 15.—Solution features in marine limestone developed in subtropical conditions similar to those postulated to exist during Late Mississippian time. A, Opening in rock due to removal of limestone by solution. Photograph shows north wall of a cenote, or well, near Chichén Itzá, Yucatán, Mexico.

levels would stand in tightly cased wells open to an aquifer if the water in the well had a density of 1.00 g/cm^3. Gradients of freshwater head in a variable-density ground-water system are not always proportional to the magnitude of flow, and they do not always indicate the actual direction of flow. However, flow velocity can be calculated from freshwater-head information if fluid density is known throughout the system.

Overall accuracy of the hydraulic-head data shown on the predevelopment potentiometric-surface maps for the Cambrian-Ordovician and Madison aquifers is estimated to be about ±150 ft. Accuracy of hydraulic-head data for the Pennsylvanian aquifer and Devonian formations may be less accurate. It should be noted that the predevelopment potentiometric-surface maps are not corrected for chemical-osmotic potential. Chemical-osmotic effects have been suggested (Hitchon, 1969) as the cause for anomalous potentiometric surfaces and salinities in several formations in Canada north of the study area. Berry and Hanshaw (1960) noted a closed potentiometric low in the Lower Cretaceous Viking Formation of Canada that they attributed to the effects of chemical-osmotic forces.

The predevelopment potentiometric-surface data from the Lower and Upper Cretaceous aquifers (figs. 20, 21) are from a report by Lobmeyer (1982). Lobmeyer primarily used data from drill-stem tests and a conversion procedure from pressure to feet of freshwater similar to that used by Miller and Strausz (1980a, b) for the aquifer systems consisting of rocks of Paleozoic age. Lobmeyer pointed out that inaccuracies exist in the maps, which are similar to those in the Paleozoic potentiometric-surface maps of Miller and Strausz (1980a, b). He stated that the accuracy of the potentiometric surface shown on the maps is only about ±250 ft in those areas around the Black Hills on the South

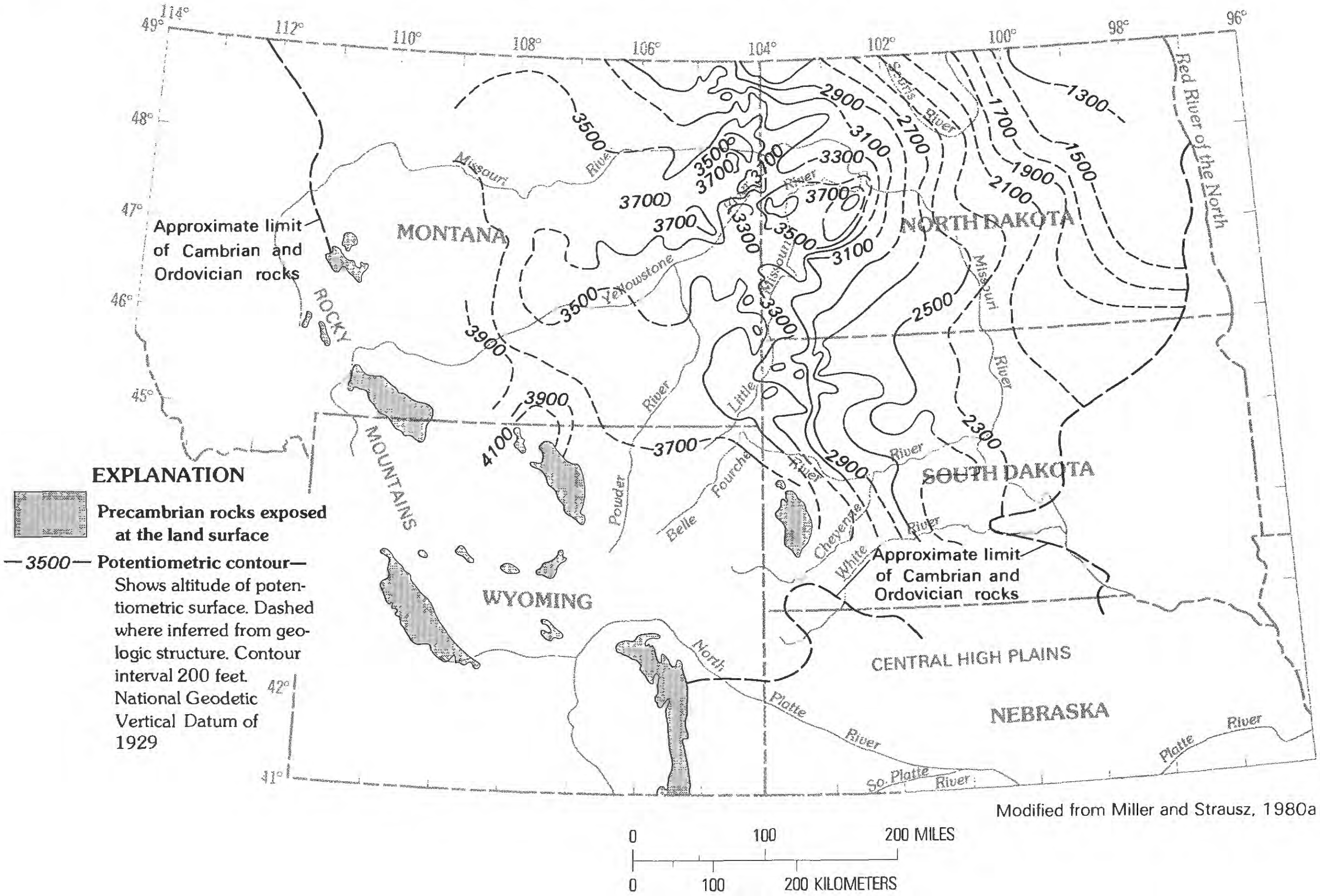

FIGURE 16.—Predevelopment potentiometric surface of the Cambrian-Ordovician aquifer system (before 1950).

Dakota–Wyoming border, around the edge of the Powder River basin, and in central Montana. The Upper Cretaceous potentiometric-surface map is believed to be accurate within one contour interval except where contours are inferred from land-surface altitudes obtained from 1:1,000,000-scale contour maps.

GEOCHEMISTRY

The geochemical system existing in the aquifers of the northern Great Plains is complex, involving numerous rock–water interactions as water moves along flow paths from the highland recharge areas to the discharge areas. The two principal geochemical mechanisms along all the major flow paths in aquifer systems consisting of rocks of Cambrian through Pennsylvanian age are evaporite dissolution and dedolomitization; however, cation exchange and sulfate reduction also occur at places within the geochemical flow system.

Ground-water temperatures vary considerably in the major aquifers of the northern Great Plains; the maximum temperatures are in the Cambrian-Ordovician (more than 150 °C) and Mississippian aquifer systems (more than 130 °C) (figs. 22, 23). Because of relatively shallow depths of burial, maximum temperatures of ground water in the Lower Cretaceous (more than 120 °C) and Upper Cretaceous aquifer systems (more than 60 °C) (figs. 24, 25) are not as high as those in the deeper aquifers systems consisting of rocks of Paleozoic age.

Solution of halite along the western margins of the Williston basin contributes quantities of sodium chloride to the ground water, forming brines in the deep part of the basin. The brine is associated with the deeper aquifer systems (figs. 26–29) and does not occur in the Triassic and Jurassic formations or in the Lower and Upper Cretaceous aquifer systems (figs. 30–32).

The major conclusions from the geochemistry study are as follows:

1. The chemistry of water from aquifer systems consisting of rocks of Paleozoic through Mesozoic

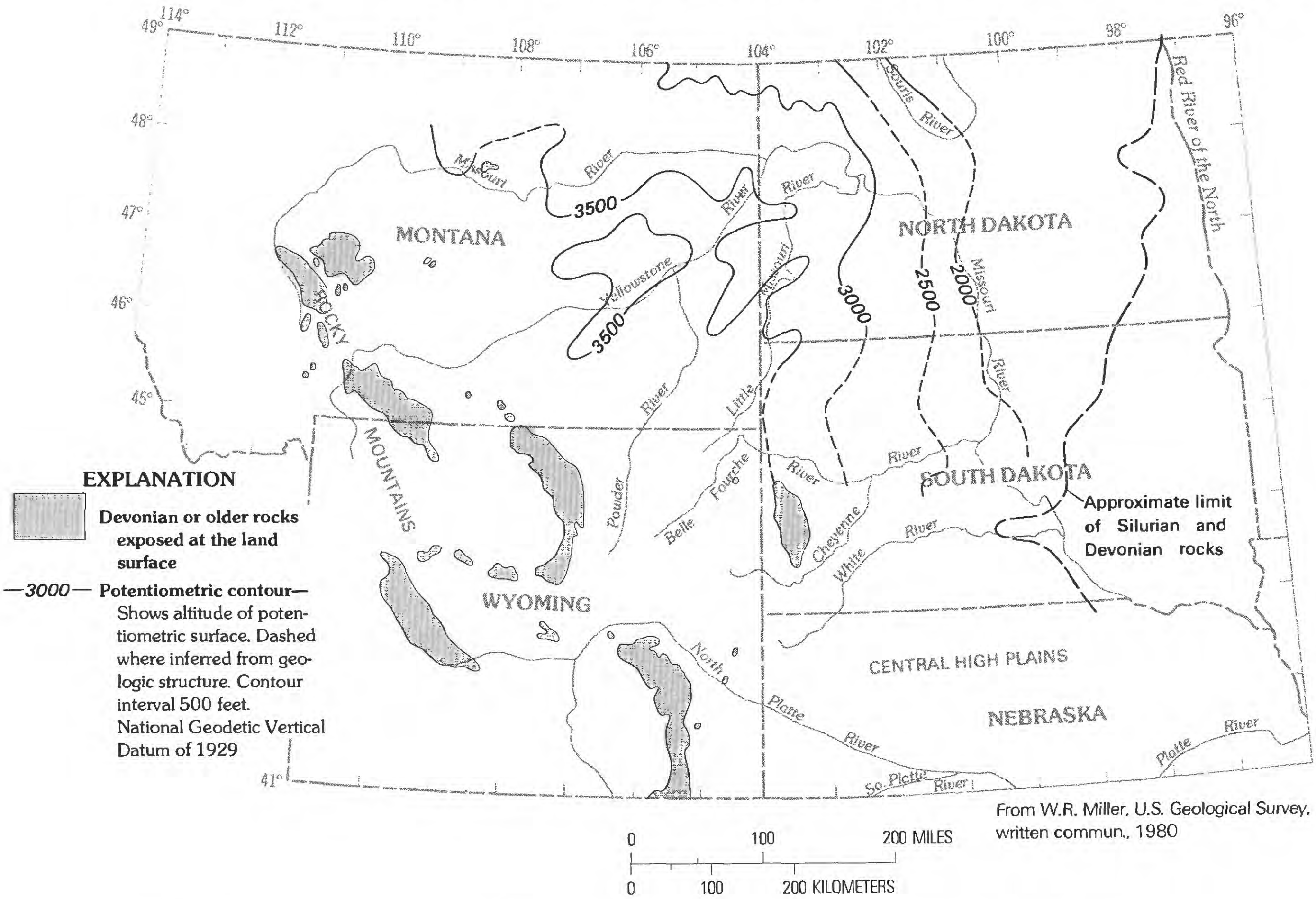

FIGURE 17.—Potentiometric surface derived from measurements of head in locally permeable parts of the Devonian rocks.

age is controlled by a variety of geochemical mechanisms, with dissolution of evaporites and mixing of water being dominant. Although not a dominant control, dedolomitization also is a significant geochemical mechanism.

2. The dominant geochemical control on water from the aquifer systems consisting of rocks of Paleozoic age in Montana and North Dakota is the evaporite deposits of the Central Montana trough and the Williston basin.
3. Geochemical evidence from each delineated aquifer system indicates that sulfate reduction and cation-exchange mechanisms are active.
4. Geochemical evidence indicates that ground-water leakage between the Cambrian-Ordovician, Mississippian, and Pennsylvanian aquifer systems is extensive.
5. The Triassic and Jurassic formations are a confining bed for the underlying aquifer systems.
6. Geochemical data indicate that ground-water flow in Montana is principally from the western recharge areas northeastward toward Canada and eastward toward the Williston basin.
7. Ground-water flow in rocks of Paleozoic and Mesozoic age appears to be relatively slow in North Dakota where the flow probably is diverted northward and southeastward around the Williston basin.
8. With the exception of ground water in comparatively small areas in the immediate vicinity of recharge areas and of ground water in the Williston basin, the dominant type of ground water in aquifer systems consisting of rocks of Cambrian through Pennsylvanian age is a sulfate water (figs. 33–36). Stratigraphically above the Pennsylvanian aquifer are the Lower Cretaceous aquifer system, in which the ground water is generally a mixed type (fig. 37), and the Upper Cretaceous aquifer system, in which the ground water is dominantly a bicarbonate type (fig. 38).
9. Water of the sodium chloride type generally is found within the Williston basin.

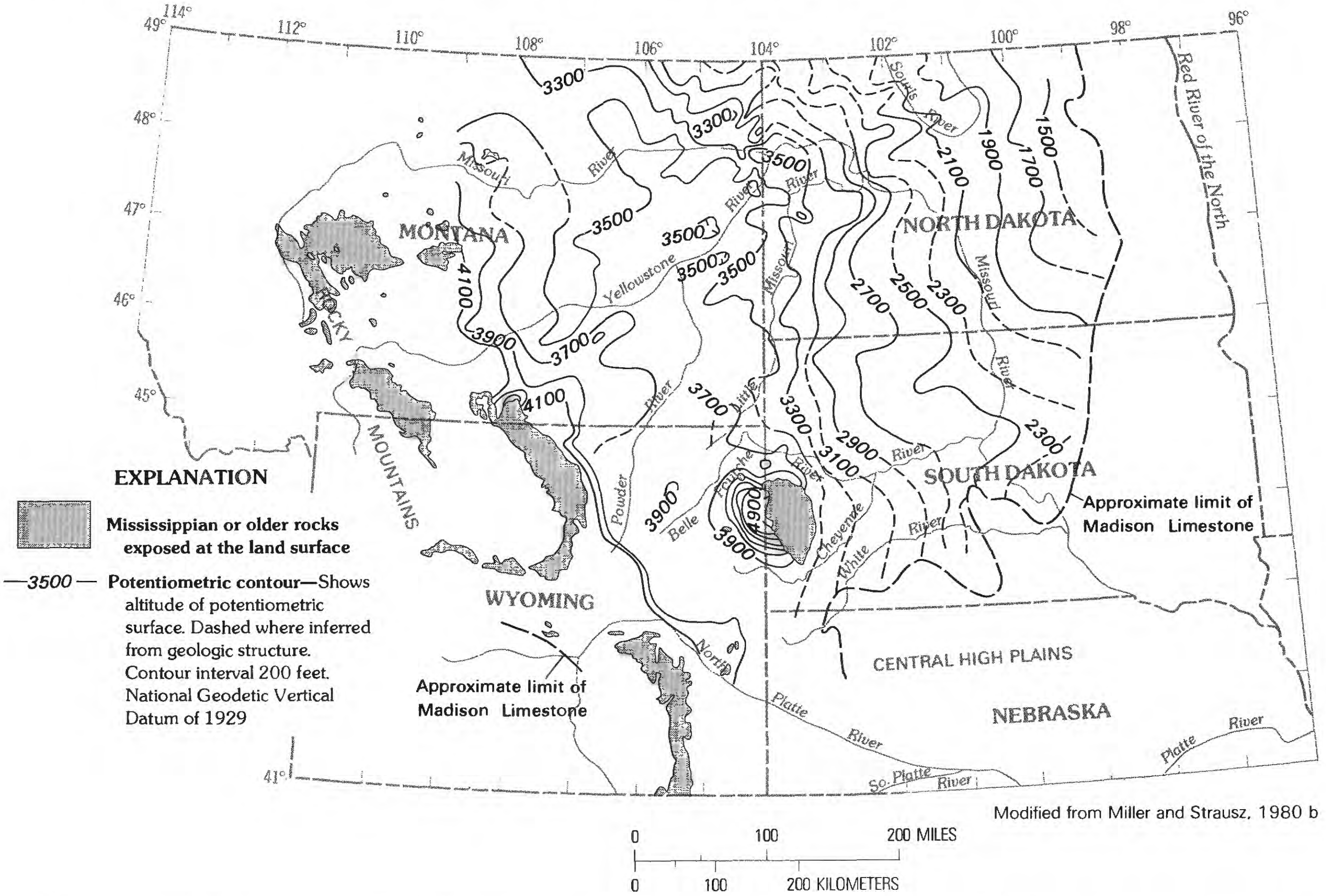

FIGURE 18.—Predevelopment potentiometric surface of the Mississippian aquifer system (including the Madison Limestone) (before 1950).

GEOHYDROLOGY

The five major aquifer systems (pls. 1, 2) underlying the northern Great Plains area compose one of the largest confined aquifer systems in the United States. The flow system (pl. 3) extends more than 600 mi from mountainous recharge areas in Montana, Wyoming, and South Dakota to discharge areas in the eastern Dakotas and the Canadian Province of Manitoba. The total area of the aquifer system in both countries is approximately 300,000 mi^2.

All aquifer systems crop out and receive recharge in the highland areas in the western part of the study area (pl. 3). Recharge also occurs in aquifer outcrops in the Black Hills uplift area of South Dakota (fig. 2). The major recharge area for the Madison Limestone (part of the Mississippian aquifer system) in the Black Hills is a plateau on the west flank of the Black Hills uplift where the limestone shows many solution features such as caves and sink holes. The Wyoming State Engineer's Office (1974) states that estimated recharge in an area of 187,000 acres is about 6.8 in. per year, roughly 146 ft^3/s. Virtually all eastward-flowing streams draining the recharge areas lose a part of their flow (Swenson, 1968a, b; Wyoming State Engineers Office, 1974) as they cross the aquifer outcrops. Recharge also results from infiltration of precipitation falling directly on the exposed rocks in lowland areas.

Streamflow measurements on several streams draining the east side of the Black Hills (fig. 2) indicate that as much as 10 ft^3/s were lost from the streams as they crossed the outcrop of the Madison Limestone of the Mississippian aquifer system (Swenson, 1968a, b). Prior to a program of stream-channel sealing in 1937, streamflow losses of about 100 ft^3/s were reported by Powell (1940). Based on similar lithology and degree of weathering, it is reasonable to assume that most streams draining comparable western mountainous areas, such as the Bighorn Mountains, would lose similar quantities of flow as they cross the outcrop areas of aquifer systems consisting of rocks of Paleozoic age.

Recharge to the Lower Cretaceous aquifer system

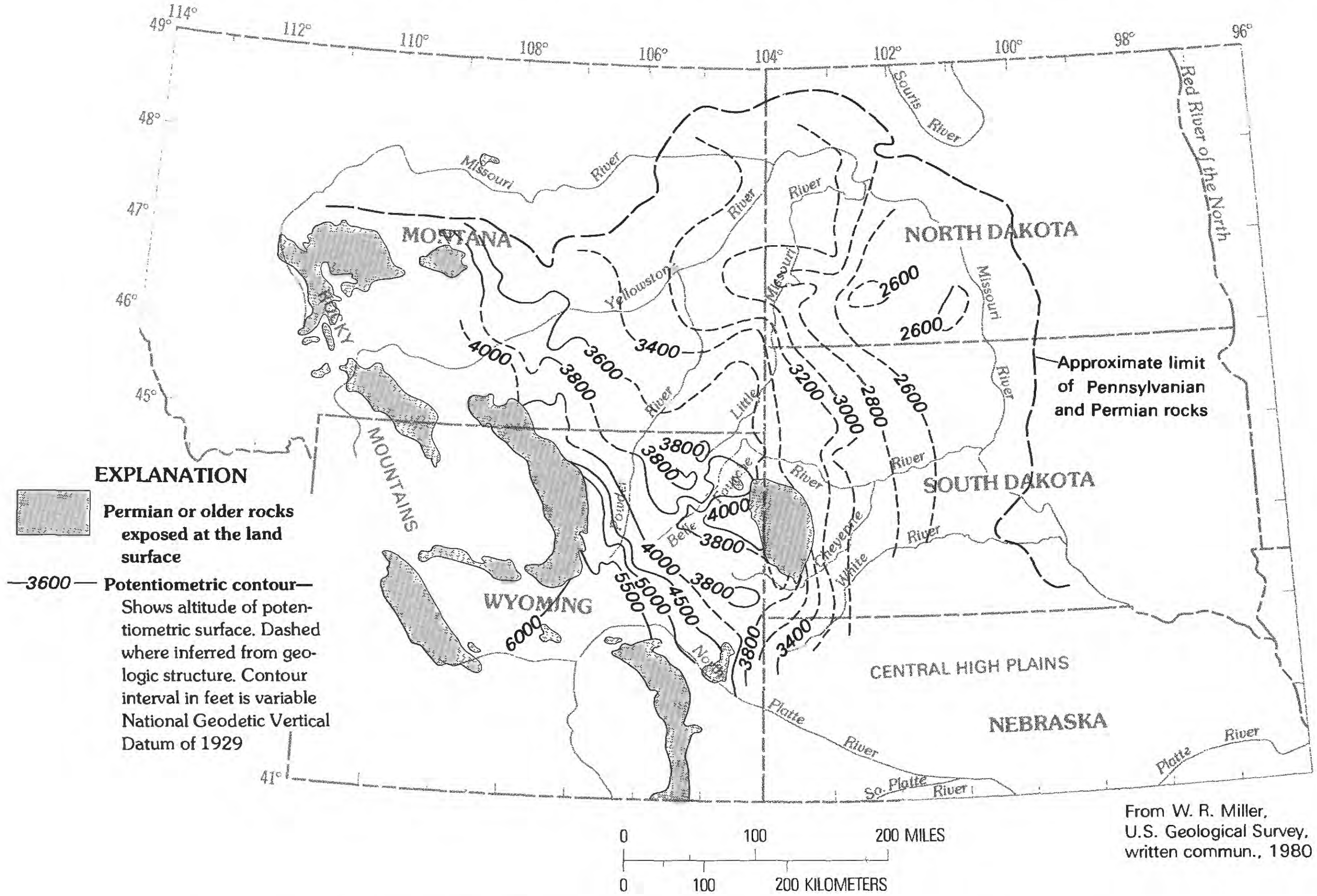

FIGURE 19.—Predevelopment potentiometric surface of the Pennsylvanian aquifer system (before 1950).

takes place by infiltration at outcrop areas and leakage from the underlying aquifer systems. Miller and Rahn (1974) calculated 0.8 in./yr of recharge at outcrops of Lower Cretaceous sandstone in the Black Hills. An outcrop area for the Lower Cretaceous aquifer system of about 334 mi^2 (H.L. Case, III, USGS, written commun., 1982) in the Black Hills area and a recharge rate of 0.8 in./yr, results in about 20 ft^3/s of recharge to the Lower Cretaceous aquifer system in the Black Hills area. Brown (1944) gaged many streams along the eastern flank of the Black Hills. In contrast to water losses to the Paleozoic aquifer systems, Brown noted that no measurable stream loss from any of the observed streams was detected at the outcrop of Cretaceous rock. It is possible that recharge to the Cretaceous aquifer systems occurs as upward leakage from Paleozoic rocks at shallow depth in the recharge area of the Black Hills. Schoon (1971) postulated that recharge occurs in the Black Hills area but did not distinguish relative quantities of recharge and sources of the recharge.

Although the available data indicate that large quantities of water enter the aquifers along the outcrop areas in the western highlands, not all of this water recharges the deep, regional aquifer system and moves to the eastern discharge area. A large part of the recharged water discharges in a short distance through springs and seeps along the flanks of the mountainous areas (Swenson, 1968a, b; Rahn and Gries, 1973; Hodson, 1974). The fraction of the total recharge that remains in the deeper aquifer systems becomes the regional flow. The diagrammatic expression of the flow conditions (pl. 3*A*, *B*) summarizes the predevelopment (about 1950) flow regime for both the Cambrian-Ordovician and the Mississippian aquifer systems. These flow conditions were synthesized on the basis of digital-model simulations and interpretation of available geologic and hydrologic information.

The rates of recharge shown for selected recharge areas are the infiltration which enters the aquifers in areas where they are close to or at land surface and which remains within the regional-flow system.

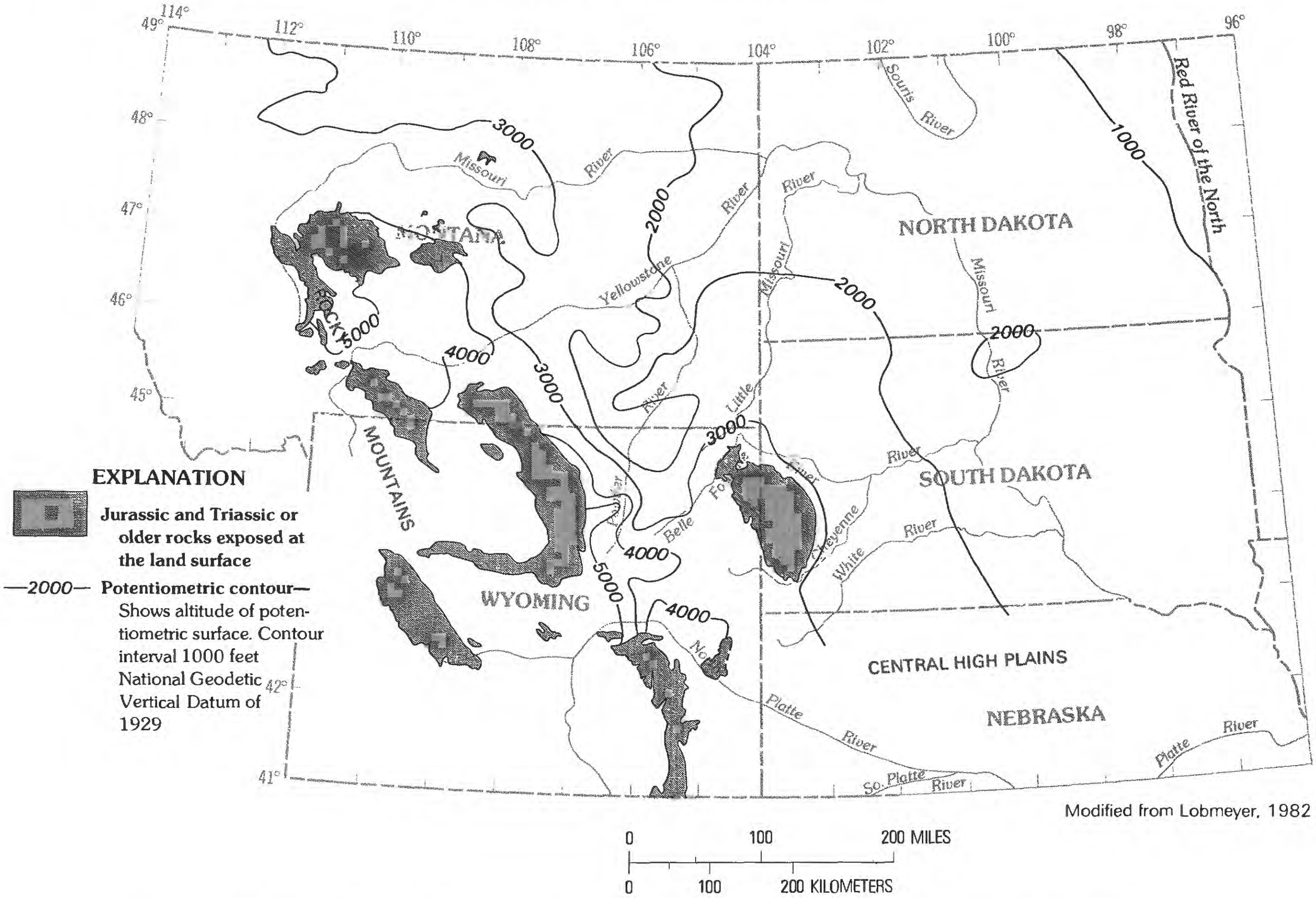

FIGURE 20.—Predevelopment potentiometric surface of the Lower Cretaceous aquifer system (before 1950).

Discharge from the Mississippian and Pennsylvanian aquifers is to adjacent and overlying aquifer systems along the eastern subcrops (pl. 3*B*, *C*). Discharge from the Cambrian-Ordovician aquifer system is to adjacent shallow aquifer systems or through springs and seeps in the Lake Agassiz basin of North Dakota and in Canada where the Cambrian and Ordovician formations crop out (pl. 3*A*).

Discharge from the Lower Cretaceous aquifer system is mainly upward to the overlying aquifer systems in eastern South Dakota (figs. 39, 40) and along the subcrop of the Lower Cretaceous rocks (fig. 41) in the Lake Agassiz basin of North Dakota (pl. 3*D*). At the present time, considerable water is discharged from the Lower Cretaceous aquifer system through unused wells along the Missouri and James River valleys of South Dakota (H.L. Case, III, USGS, written commun., 1982). Discharge estimates from the Lower Cretaceous aquifer system based on model simulation and interpretation of available data are shown on plate 3*D*.

Ground-water discharge through springs located along the outcrop of Paleozoic rocks in the Canadian Province of Manitoba (van Everdingen, 1968) appears to have an effect on the composition of water in Lake Winnipegosis and Lake Manitoba (pl. 3). Water from both lakes contains as much as 600 mg/L of chloride. Springs along the lakes discharge as much as 0.1 ft^3/s of water with a dissolved-solids concentration ranging from about 29,000 to 63,000 mg/L. The dominant ions present are sodium and chloride. Seven springs located on the shore of Lake Winnipegosis in northern Manitoba were shown by Cole (1915) to discharge about 0.2 ft^3/s from Devonian rocks underlying the lake. Because ground-water flows slow (figs. 42, 43) and the time since ice covered this area of Manitoba is short (12,000 to 14,000 years), it is possible that the water being discharged through springs is a mixture of brine from the deeper part of the aquifer and glacial melt water injected into the aquifer while it was covered by glacial ice. The range in dissolved-solids concentration suggests that the water is a mixture of three flow components: (1) flow from the brine area, (2) injected water

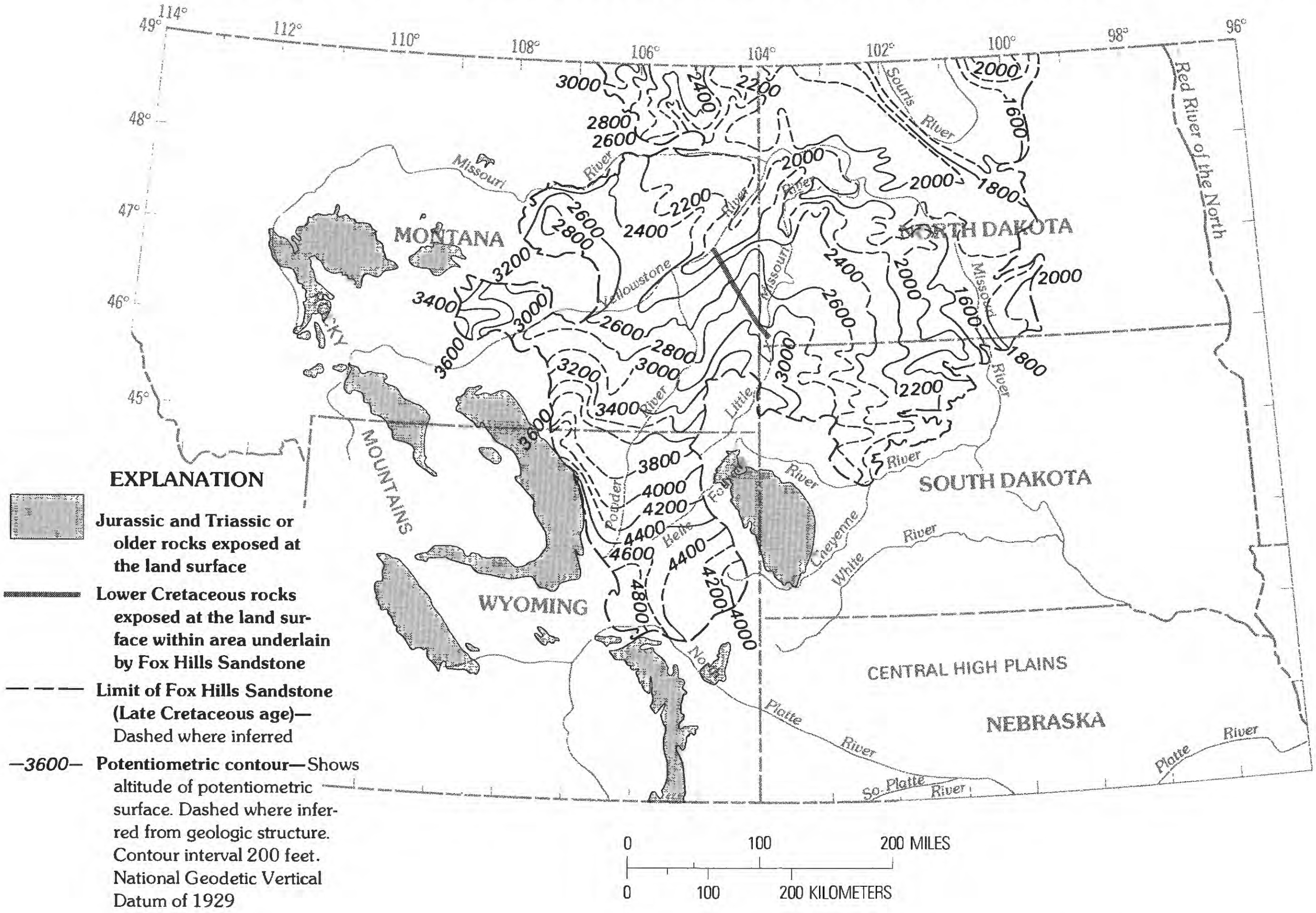

FIGURE 21.—Predevelopment potentiometric surface of the Upper Cretaceous aquifer system (before 1950).

from the Pleistocene glacial ice, and (3) fresher water flowing from the south along a flow path from the Black Hills (pl. 3*A*).

The Mississippian aquifer system does not crop out in the eastern part of the study area. The formations that make up the aquifer system terminate in the subsurface and are overlain by younger rocks consisting mostly of Cretaceous shales. Thus, the discharge from the Mississippian aquifer system in this area consists of upward leakage through the overlying confining systems and lateral leakage (pl. 3*A*, *B*) to the Cambrian-Ordovician aquifer system. Ground-water discharge is concentrated along the eastern rather than the northern limits of the Mississippian aquifer system because stratigraphic unconformities between the Paleozoic aquifer system and the overlying confining systems in the Canadian Provinces of Saskatchewan and Manitoba have resulted in conditions favorable to accumulation of oil and gas in stratigraphic traps (McCabe, 1963). As a corollary to this, conditions in the area of trapping oil and gas must have low-permeability cap rocks, thus being unfavorable for discharge of ground water upward from the Mississippian aquifer system to the overlying aquifer systems.

An area of minimal ground-water flow on the eastern flank of the Williston basin coincides with an area of high concentration of dissolved solids resulting in substantial fluid density (figs. 26, 28, 44). Three hypotheses were considered in explaining the hydrologic flow system in and near the areas of the dense brine. The first hypothesis is that the brine is static and that the hydrologic situation is similar to what was described by Hubbert (1969): freshwater flowing through a synclinal structure comes into contact with static, dense brine along a sharp fluid interface. Hubbert (1969) showed that the body of saline water under these conditions does not lie uniformly in the deepest part of the structure but, rather, is displaced upward along the base of the outflow flank; that is, whereas the inflow flank is occupied entirely by moving freshwater, the

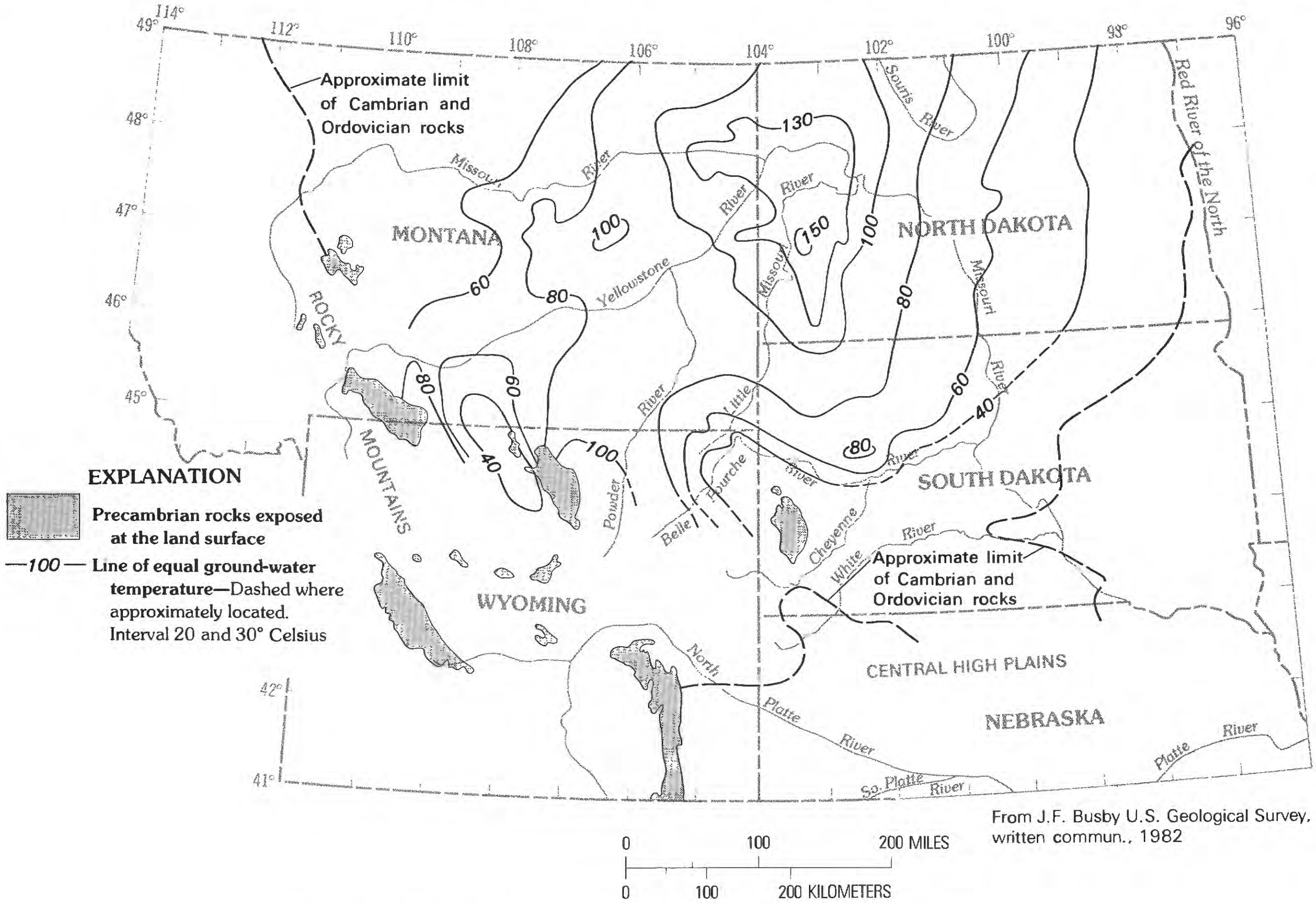

FIGURE 22.—Water temperatures in the Cambrian-Ordovician aquifer system.

outflow flank contains static brine in the lower part of the aquifer and moving freshwater above. The flow of freshwater in the Williston basin is around the dense brine area, as well as above, and this reflects the fact that the structure is actually a basin rather than the simple syncline analyzed by Hubbert (1969). The flow above the brine apparently is by upward leakage to aquifer systems overlying the Mississippian aquifer system rather than to the upper part of the aquifer system itself. However, model simulations of the flow system indicate slow flow velocities in the brine areas of the Mississippian aquifer system, indicating that the brine is not static as stated in Hubbert's (1969) hypothesis.

Simulation results show slow but consistent flow velocities generally directed to the east and northeast through the dense brine in both the Cambrian-Ordovician and Mississippian aquifer systems. This indicates that a small component of the regional flow actually moves directly across the Williston basin from west to east through the brine areas. These simulation results suggest a second hypothesis regarding the brine; that is, the brine actually represents a very slow moving segment of the regional flow system. This hypothesis suggests one explanation for the origin of the brine, which can be attributed to solution of salt from halite beds as the water moves through the basin, as described by Grossman (1968). The process of solution of salt is enhanced by increasing water temperature with depth; the maximum salinities are found in regions of maximum temperature. Decrease in salinity in up-dip areas on the eastern flank of the basin presumably is due, at least in part, to precipitation of halite associated with lower temperature, although dilution by fresher water also is undoubtedly a factor. To the extent that precipitation of halite occurs, it should result in a very gradual decrease in permeability during geologic time intervals in the areas where precipitation occurs.

Finally, with regard to the second hypothesis, it should be noted that even though some flow exists, the situation is still similar to Hubbert's static brine hypothesis. Velocities of flow are very low relative to

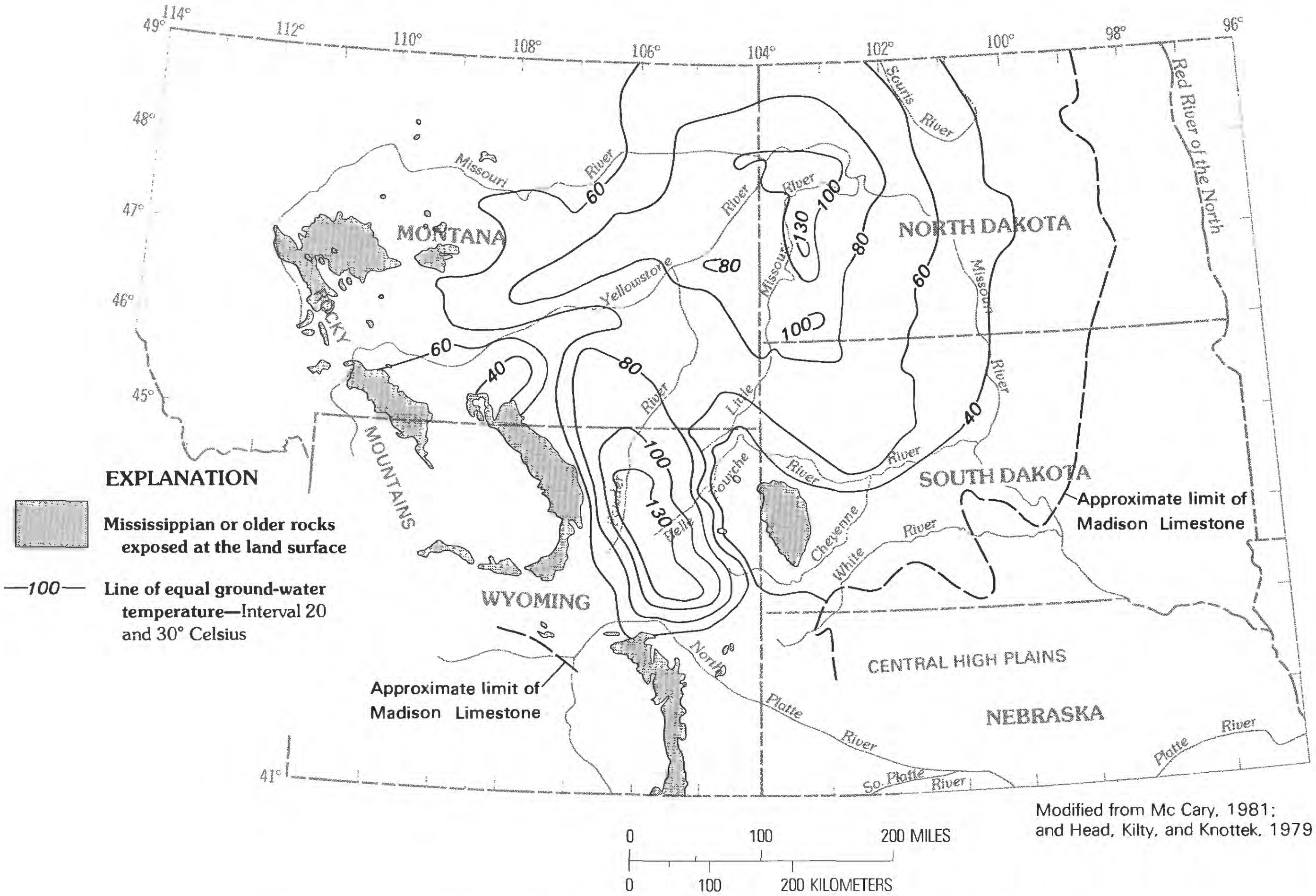

FIGURE 23.—Water temperatures in the Mississippian aquifer system, including the Madison Limestone.

those elsewhere in the system, and most of the flow of fresher water appears to be deflected around the brine to the north or south or through the confining system into aquifer systems overlying the Mississippian aquifer system. Thus, both the hydraulics and the density distribution seem to be fairly close to what would be observed in a system of totally static brine conforming to Hubbert's (1969) analysis.

A third hypothesis regarding the brine is that it is in motion but that its movement represents an attempt of the system to adjust to changes in recharge and discharge associated with the end of Pleistocene glaciation. These changes were discussed in detail by Downey (1984a). If during Pleistocene glaciation the brine were in a static configuration of the type described by Hubbert (1969), the configuration could not be at equilibrium with the new boundary conditions imposed with the retreat of the ice sheets. Thus, the brine would begin to move at the end of glaciation, seeking a new equilibrium configuration compatible with the new recharge and discharge patterns; this readjustment still could be in progress at present. Such a process could be contributing to some extent to the apparent movement of the brine; however, ground-water flow velocities computed by simulation appear to conform more to the interpretation of a simple flow across the basin than to delayed adjustment to the Pleistocene glacial changes.

In summary, the second hypothesis—that the brine represents a sluggish segment of the regional flow pattern across the basin—seems to agree best with simulation results and with existing field data. Origin of the brine appears to have been the dissolution of halite, and as the density of the brine has increased, undoubtedly it has had an increasing effect on the flow pattern, causing fresher water to divert around it to the north and south or above it into other aquifer systems overlying the Mississippian aquifer system. Although the second hypothesis seems most acceptable, elements of the other hypotheses also are probably reflected in the actual situation. The present configuration of the brine on the outflow side of the basin and its generally slow

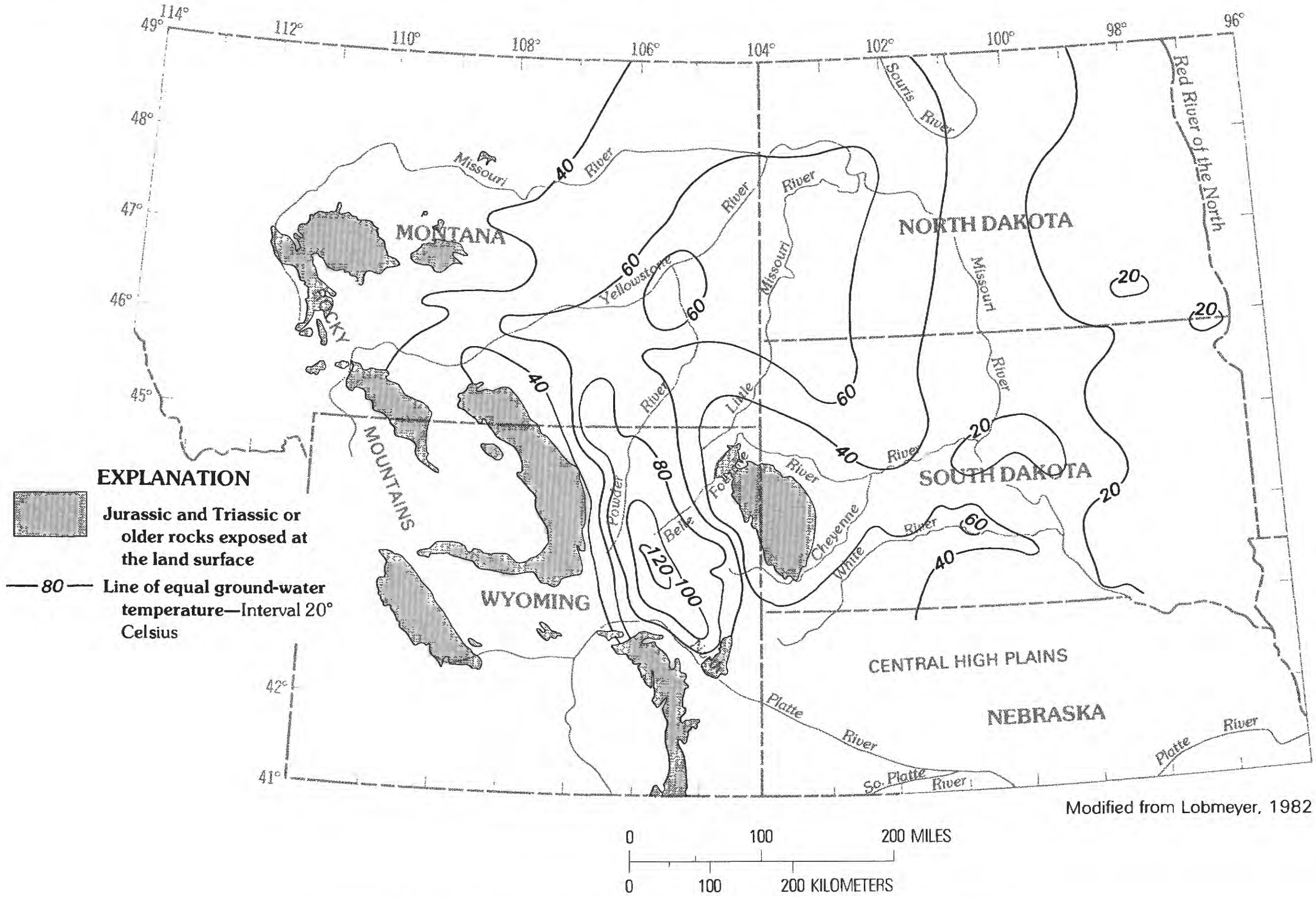

FIGURE 24.—Water temperatures in the Lower Cretaceous aquifer system.

velocity of ground-water flow approximate the static brine situation described by Hubbert (1969), even though the brine is not totally static; distribution of the saline water still might be shifting in response to changes in recharge and discharge at the end of Pleistocene glaciation.

Saline water also is found in other parts of the study area—for example, in deeper parts of the Powder River basin—although not at the concentration of the brine in the Williston basin. However, similar processes presumably control the saline water's distribution and movement.

Because the highland recharge areas were not covered by major ice sheets (fig. 11) during the glacial stages of the Pleistocene, recharge to the deep aquifer systems from these areas continued. The resulting ground-water flow system (fig. 11) allowed the dissolution of halite along the western edge of the Williston basin to continue during the glacial period; however, because of the short geologic time and the slow flow velocities involved, the brine could not move out of the hydrologic system and tended to remain in the same general location, as shown on plate 3*A* and *B*.

The flow pattern in the Cambrian-Ordovician aquifer system (pl. 3*A*) generally is similar to that in the Mississippian aquifer system, although the Cambrian-Ordovician aquifer system extends farther to the east and north than the Mississippian aquifer system and crops out in the Canadian Province of Manitoba (fig. 39). A generalized geohydrologic section showing the ground-water movement in the Cambrian-Ordovician aquifer system in North Dakota is shown in figure 41. The location is near the eastern terminus of the Cambrian-Ordovician aquifer, and the figure illustrates the general relationship of the Cambrian-Ordovician aquifer system to shallow ground-water systems and surface-water bodies.

The Cambrian-Ordovician aquifer system contains the same characteristic dense brine as does the Mississippian aquifer system on the eastern flank of the Williston basin (fig. 26). The Cambrian-Ordovician aquifer system apparently discharges in part to a number of saline

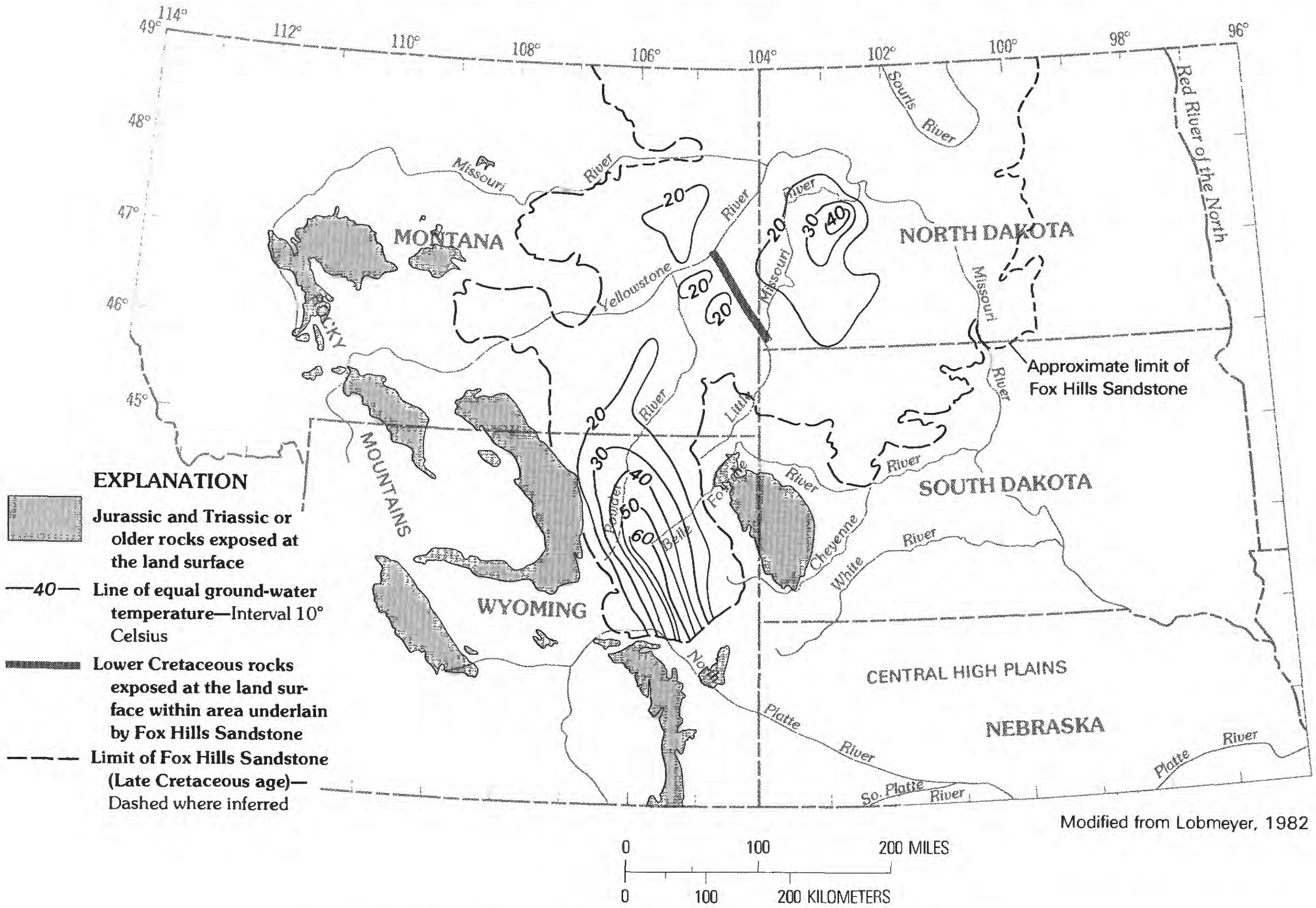

FIGURE 25.—Water temperatures in the Upper Cretaceous aquifer system.

lakes in eastern North Dakota, and the component of flow to the north of the Williston basin is accordingly larger than in the Mississippian aquifer system. The hypothesis of discharge to these lakes is supported by several types of evidence. The saline lakes in question are located in the eastern discharge area of the Cambrian-Ordovician aquifer system (fig. 41) and are associated with depressions that overlie deposits of fine sand and gravel. These lake depressions have been attributed to artesian water discharging from deep regional flow systems (Laird, 1944).

A supporting hypothesis is (Downey, 1969, p. 12) that during Pleistocene glaciation of the area, melt water resulting from melting at the base of the ice sheet (Gow and others, 1968; McGinnis, 1968) was forced into the aquifer systems by hydrostatic pressure. After deglaciation, the hydrostatic pressure was greatly decreased, allowing large quantities of water to move rapidly out of the aquifer systems. This relatively rapid movement of water through overlying material resulted in erosion of the overlying lake sediments, forming the depressions in which the lakes exist today. Test drilling indicates that fairly thick deposits of glacial sand and gravel underlie the depressions and are hydraulically connected with underlying bedrock (Downey, 1973). Chemical analyses of water samples collected from the test holes and lakes (Downey, 1971) indicate a chemical similarity to water taken from the Cambrian-Ordovician aquifer system. These analyses indicate that ground water is able to move upward from the deep aquifer systems through the glacial sand and gravel deposits to discharge points at the bottom of the lakes, which in the eastern discharge area function as ground-water drains for the underlying aquifer systems.

The existence of water at the base of continental ice sheets has been suggested by many authors (Robin, 1955; Gow and others, 1968; McGinnis, 1968; Weertman, 1972). The water is the result of melting at the base of ice because of geothermal and frictional heat. McGinnis (1968) estimated that the heat available to a temperate ice sheet from these sources could produce about 0.32 ft^3 of melt water per square foot of surface

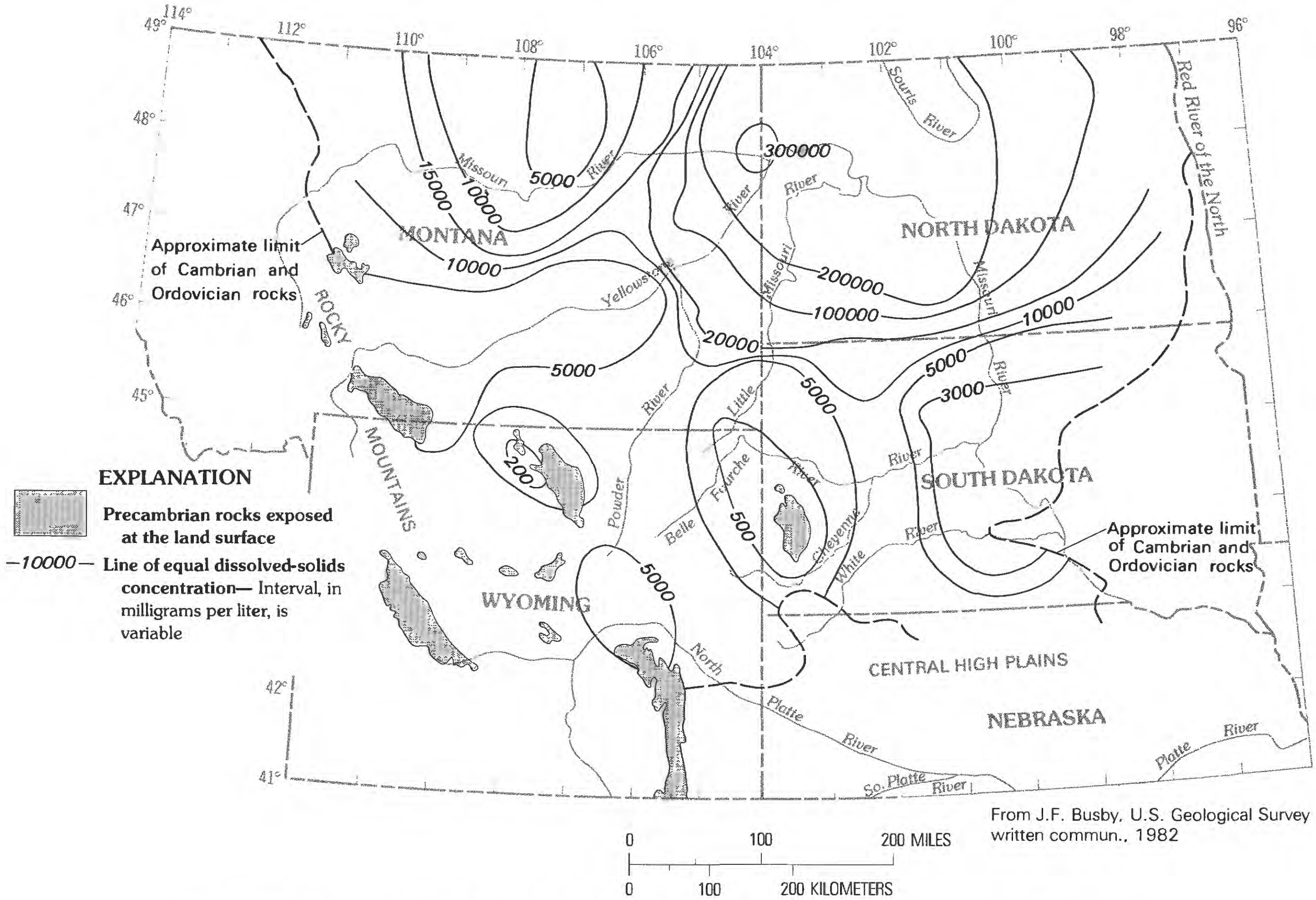

FIGURE 26.—Concentration of dissolved solids in water from the Cambrian-Ordovician aquifer system.

area of the ice sheet per year. The continental ice sheet that existed in the northern Great Plains during the late Pleistocene covered an area of about 121,500 mi^2 in the United States. Based on 0.32 ft^3 per square foot of surface area, this analysis results in about 7 mi^3 of water per year available for recharge to the underlying aquifer systems. The water would be under significant hydrostatic pressure from the weight of overlying ice.

Upward leakage through confining beds appears to be one of the major discharge mechanisms (fig. 39) for all the aquifer systems underlying the northern Great Plains. Vertical leakage between aquifers may be detected by geochemical methods, although the lack of geochemical data for many areas limits definition of the areas of leakage. Leakage occurs both through the confining-bed matrix and along fractures associated with the lineament zones in the confining bed (Weimer and others, 1982). Confining beds are not present everywhere: they were either removed by erosion or they were never deposited. In those areas where the confining beds are absent, such as eastern South Dakota, substantial hydraulic connection exists between aquifers, and leakage may occur from one aquifer to the adjoining one at a rate that is dependent on existing hydraulic-head differences. Where the confining bed is thick and unfractured, leakage through the confining bed is minimal. Leakage along fractures is dependent on the degree of fracturing, the cross-sectional area of the fractures, and the interconnection between fractures.

Geochemical facies maps such as those shown in figures 33, 35, 36, and 37 for the Cambrian-Ordovician, Mississippian, Pennsylvanian, and Lower Cretaceous aquifer systems can be used to indicate areas where leakage is occurring between aquifer systems. Similar water types at the same location in adjoining aquifer systems indicate that water is able to move between the two systems through the confining beds at these sites. This type of geochemical data is of value in the adjustment of the vertical-leakage data sets in the calibration of simulation models of the aquifer system.

Halite units, such as those in the Charles Formation,

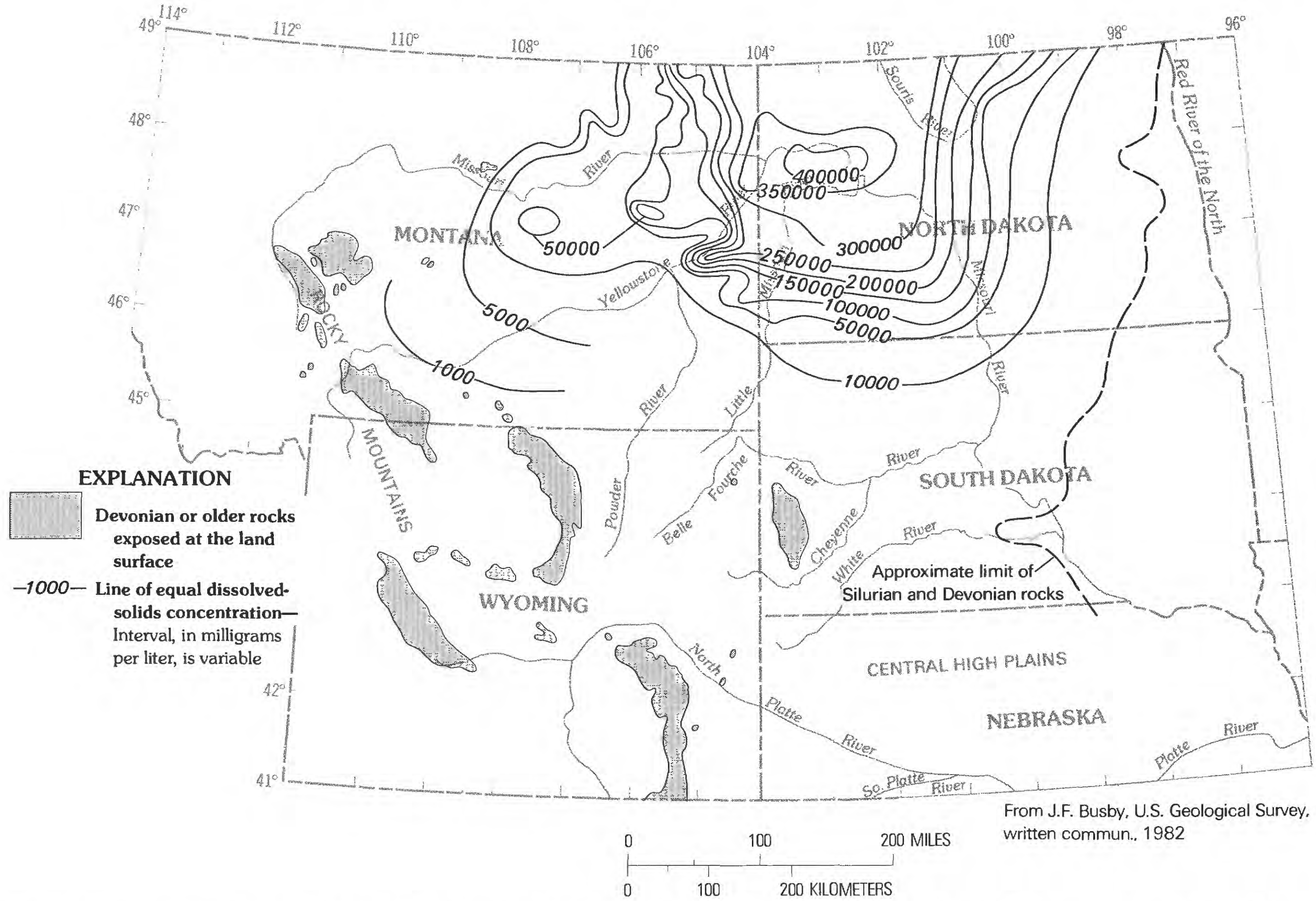

FIGURE 27.—Concentration of dissolved solids in water from the Silurian and Devonian rocks (a major confining system or unit overlying the Cambrian-Ordovician aquifer system).

are considered in this study to be impermeable. However, geochemical evidence (J.F. Busby, USGS, written commun., 1982) indicates extensive leakage between the Cambrian-Ordovician, Mississippian, and Pennsylvanian aquifer systems in the northern Great Plains. The Triassic and Jurassic formations, then, provide the zone of minimal vertical permeability that limits leakage between the aquifer systems consisting of rocks of Paleozoic and Mesozoic age to a very slow rate. Extensive development of the Paleozoic aquifer systems would not affect the Mesozoic aquifer systems in most of the area within a reasonable time frame (40 years). Plans for future development of the deep aquifer systems in the northern Great Plains region need to consider leakage from, and storage in the associated confining beds, because water yielded by the aquifer systems will be derived, in part, from storage in the associated confining beds, except at places where the confining beds are absent or are extensively fractured. Water from the confining beds may have an entirely different chemical quality than water from the developed aquifer system.

Leakage between the Mississippian aquifer system and the Lower Cretaceous aquifer system in eastern South Dakota has been noted in several studies and was the basis for Swenson's (1968a) theory of recharge to the artesian basin of the Dakotas. Swenson suggested that water enters the Madison Limestone in the Black Hills area, moves generally eastward approximately two-thirds across the State of South Dakota, and is discharged by vertical leakage to the Lower Cretaceous (Dakota) aquifer. Swenson's area of discharge from the Mississippian aquifer system to the Lower Cretaceous aquifer system as suggested by simulation results is similar to that shown on plate 3*D*.

In the areas of substantial leakage shown on plate 3*D*, confining beds are thin or absent between the Mississippian aquifer system and the overlying Lower Cretaceous aquifer system. Also, the Pennsylvanian aquifer system is less than 200 ft thick in this area (Swenson,

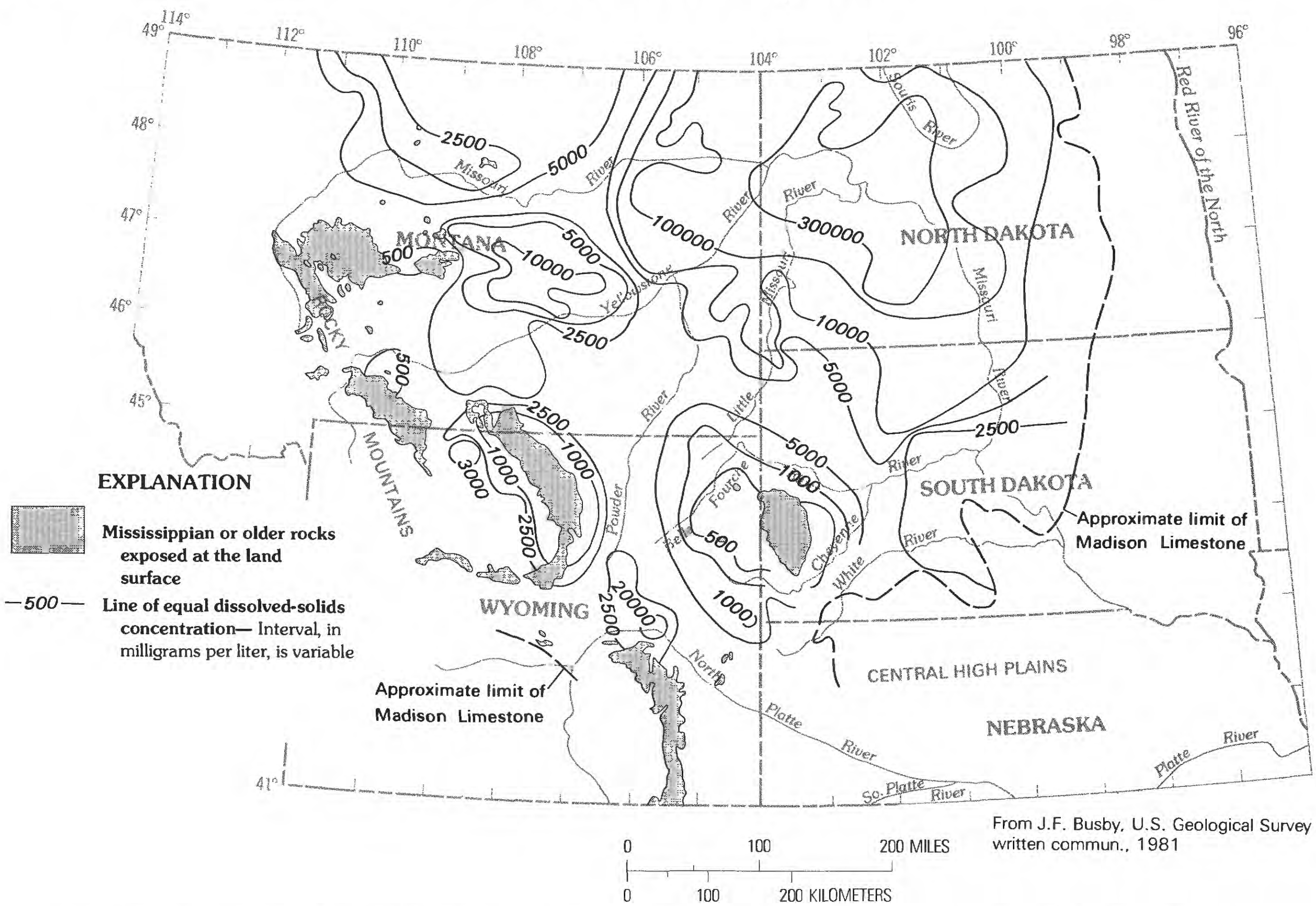

FIGURE 28.—Concentration of dissolved solids in water from the Mississippian aquifer system, including the Madison Limestone.

1968a). Geochemical facies maps (figs. 35, 36) indicate that water from the Pennsylvanian aquifer system is similar to water in the underlying Mississippian aquifer system and that vertical leakage is occurring between these two aquifer systems in this area. Swenson (1968a) presented evidence to indicate water from the Lower Cretaceous (Dakota) aquifer system (fig. 37) is similar in chemical type to that in both the Mississippian and Pennsylvanian aquifer systems in the area of high leakage shown on plate 3*D*.

Except for flow volumes, simulation results indicate that the theory advanced by Swenson (1968a) concerning the ground-water regime in the Lower Cretaceous aquifer system of South Dakota is basically correct. Geochemical data (Swenson, 1968a; K.D. Peter, USGS, written commun., 1982) also support the conclusion that water is moving from the Mississippian and Pennsylvanian aquifer systems to the Lower Cretaceous aquifer system in eastern South Dakota and North Dakota, as illustrated on plate 3*B* and *D*.

Geologic structure appears to be an important control (Weimer and others, 1982) of the rate and direction of ground-water movement in the study area. For example, the Casper fault (fig. 2) appears to prevent ground-water flow to the south from the Powder River basin, and the major fault system bounding the Bighorn Mountains on the east (fig. 14, B) limits recharge to the Powder River basin. Recharge from the Bighorn Mountains appears to be channeled by faults and joints associated with major lineament zones and moves northeastward (pl. 3) across the northern part of the Powder River basin (south of the Cedar Creek anticline) to join the flow system from the Black Hills recharge area. This flow system continues around the southern part of the Williston basin northeastward to the discharge area in northeastern North Dakota and eastern Manitoba. The Weldon–Brockton fault zone (fig. 2) appears to be a major conduit for ground-water movement (pl. 3*A*, *B*) from the Big Snowy Mountains and associated highland areas in Montana to discharge areas in Canada north of the Williston basin. The reader may refer to Professional Paper 1402–E for a detailed

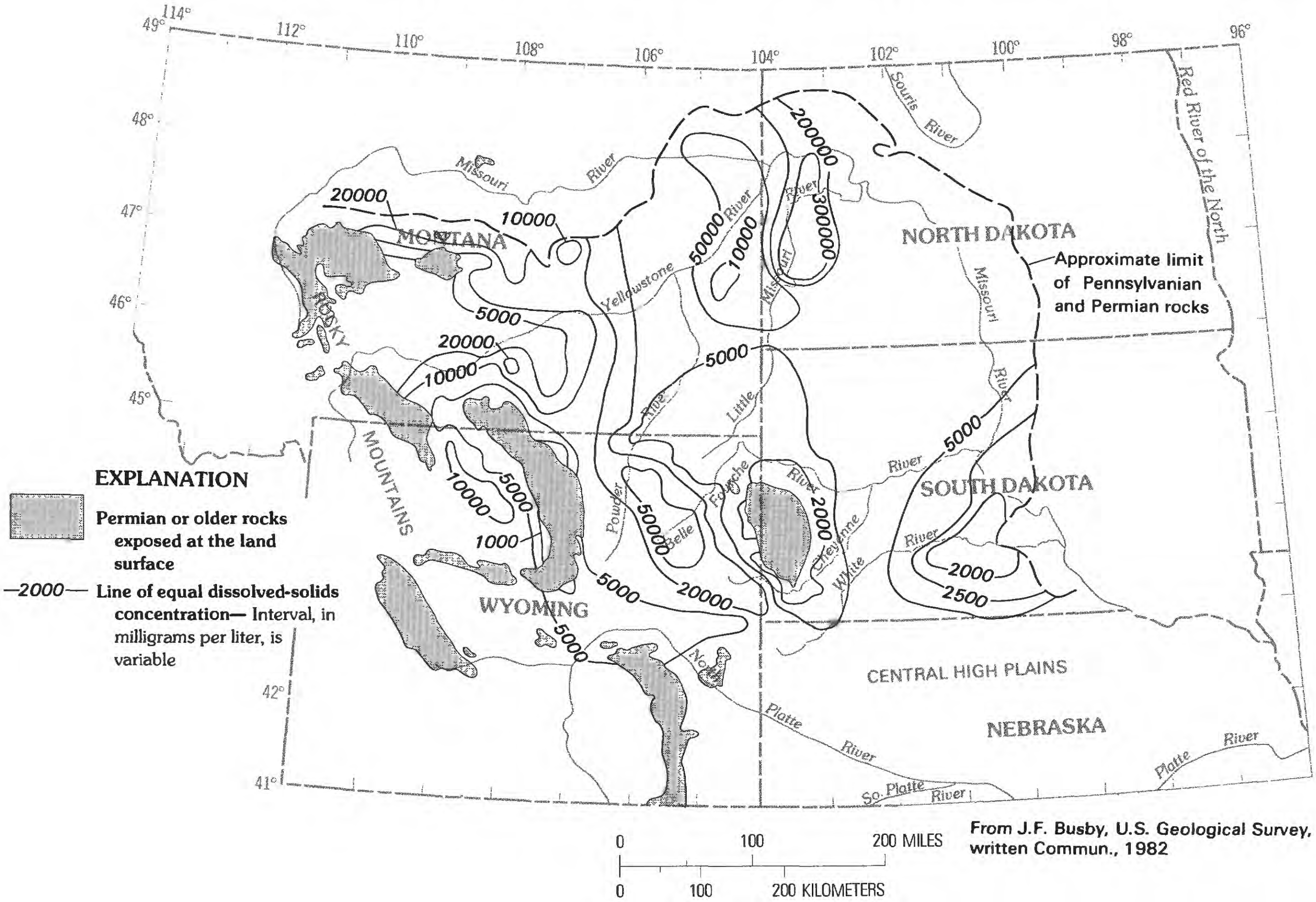

FIGURE 29.—Concentration of dissolved solids in water from the Pennsylvanian aquifer system.

discussion of these structural effects on ground-water movement.

SIMULATIONS

A calibrated digital simulation model such as the one developed for the northern Great Plains aquifer system can be used to evaluate the effects of planned development of the system provided the initial and boundary conditions, hydraulic parameters, and other needed hydrologic data can be specified. The accuracy of the evaluation depends primarily on the accuracy of the model input data. If a model is calibrated with accurate data—where the hydraulic head, transmissivity, leakage, and storage coefficient are accurately known, or where the error range of each parameter is known—then the evaluation by the model will be reliable within the range of acceptable error.

During the study of the northern Great Plains regional aquifer system, only hydraulic-head data were reasonably accurate. The other hydraulic parameters were estimated on the basis of field experience and were constrained by a reasonable range of each parameter; therefore, the digital simulation model is not considered to be fully calibrated. Nevertheless, the model was useful for understanding the aquifer systems and for estimating the effects of future development of the regional aquifer system.

To illustrate this potential, hypothetical simulations were made. Figures 45–47 indicate the effects on the Pennsylvanian and Cambrian-Ordovician aquifer systems if the Mississippian aquifer system is developed with a hypothetical pumping rate of 27.9 ft^3/s for continuous pumping of 5.9 years. The storage coefficient of the Mississippian aquifer system was assumed to be 2.0×10^{-6}. The effect on the Cambrian-Ordovician aquifer system is much greater than the effect on the Pennsylvanian aquifer system (figs. 48, 49). If the value of the storage coefficient of the Mississippian aquifer system is increased by two orders of magnitude from 2.0×10^{-6} to 2.0×10^{-4} with all other conditions kept the

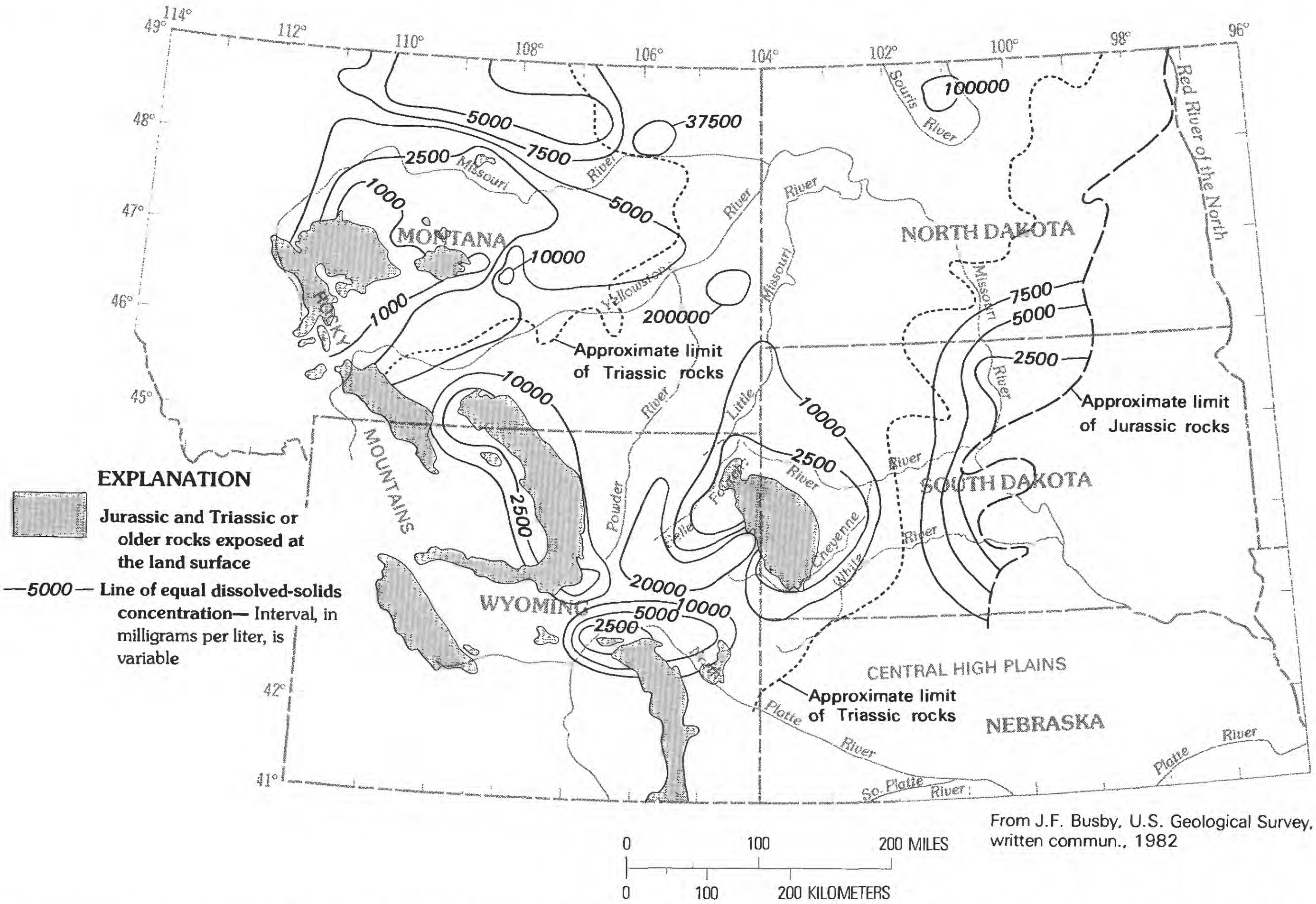

FIGURE 30.—Concentration of dissolved solids in water from the Triassic and Jurassic rocks (a major confining system or unit overlying the Pennsylvanian aquifer system).

same, the development effects on the Pennsylvanian aquifer system become negligible, and the effect on the Cambrian-Ordovician aquifer system is also reduced dramatically, as shown in figure 49. Even the drawdown in the Mississippian aquifer system is reduced significantly, as shown in figure 48, indicating that the value of the storage coefficient is important for using the model to evaluate the development effects. The reader should refer to Professional Paper 1402-E for a detailed discussion on model simulations.

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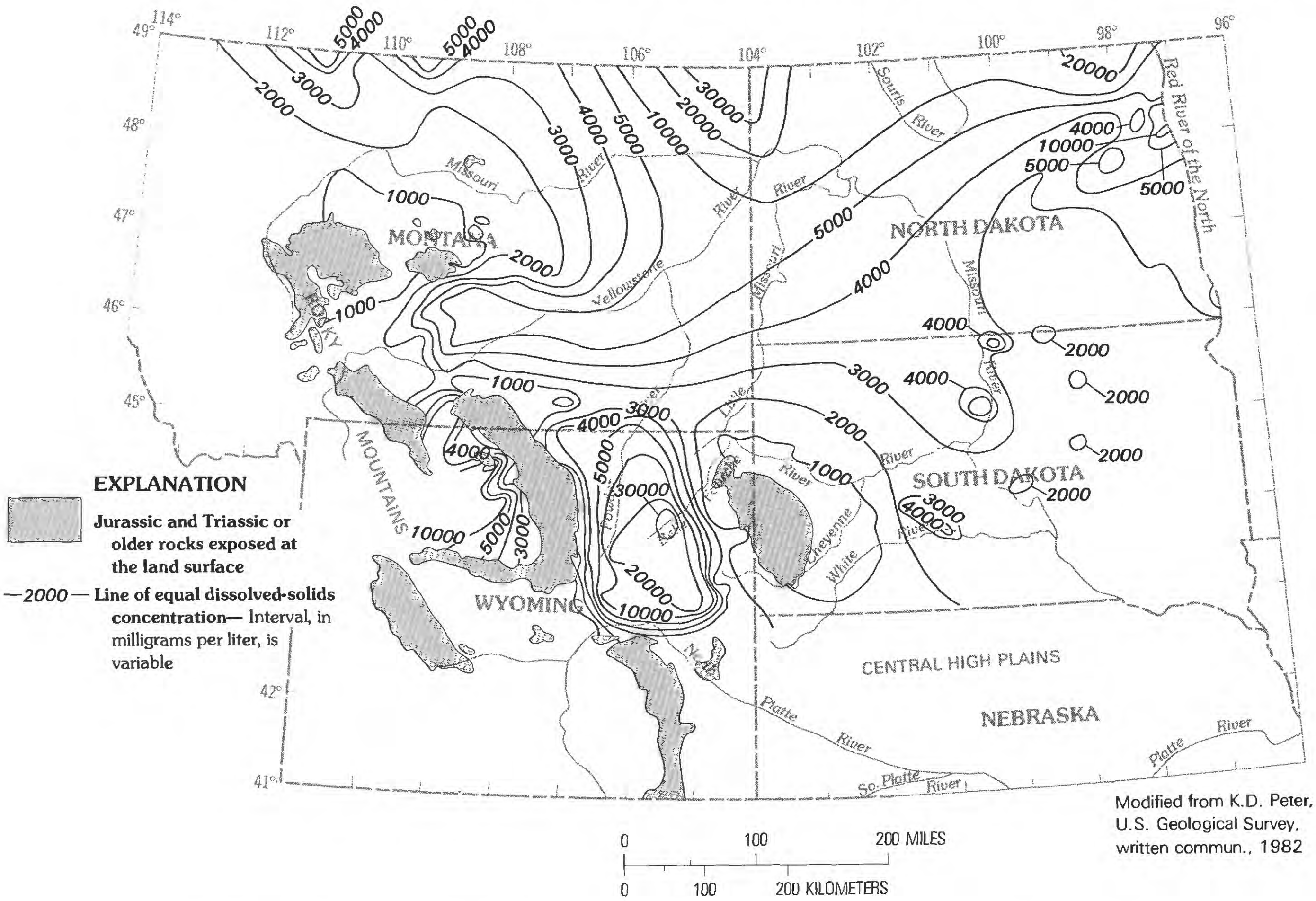

FIGURE 31.—Concentration of dissolved solids in water from the Lower Cretaceous aquifer system.

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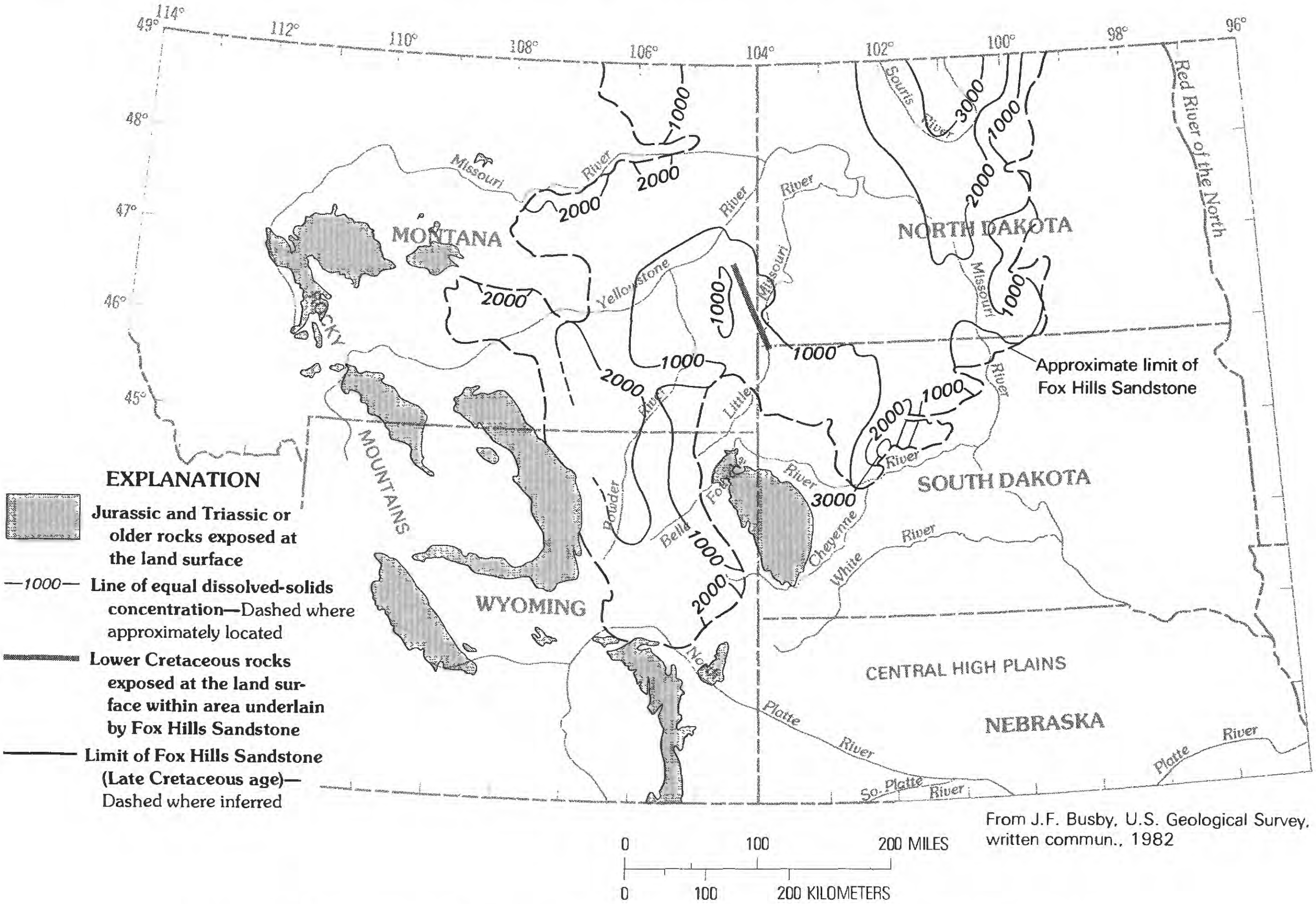

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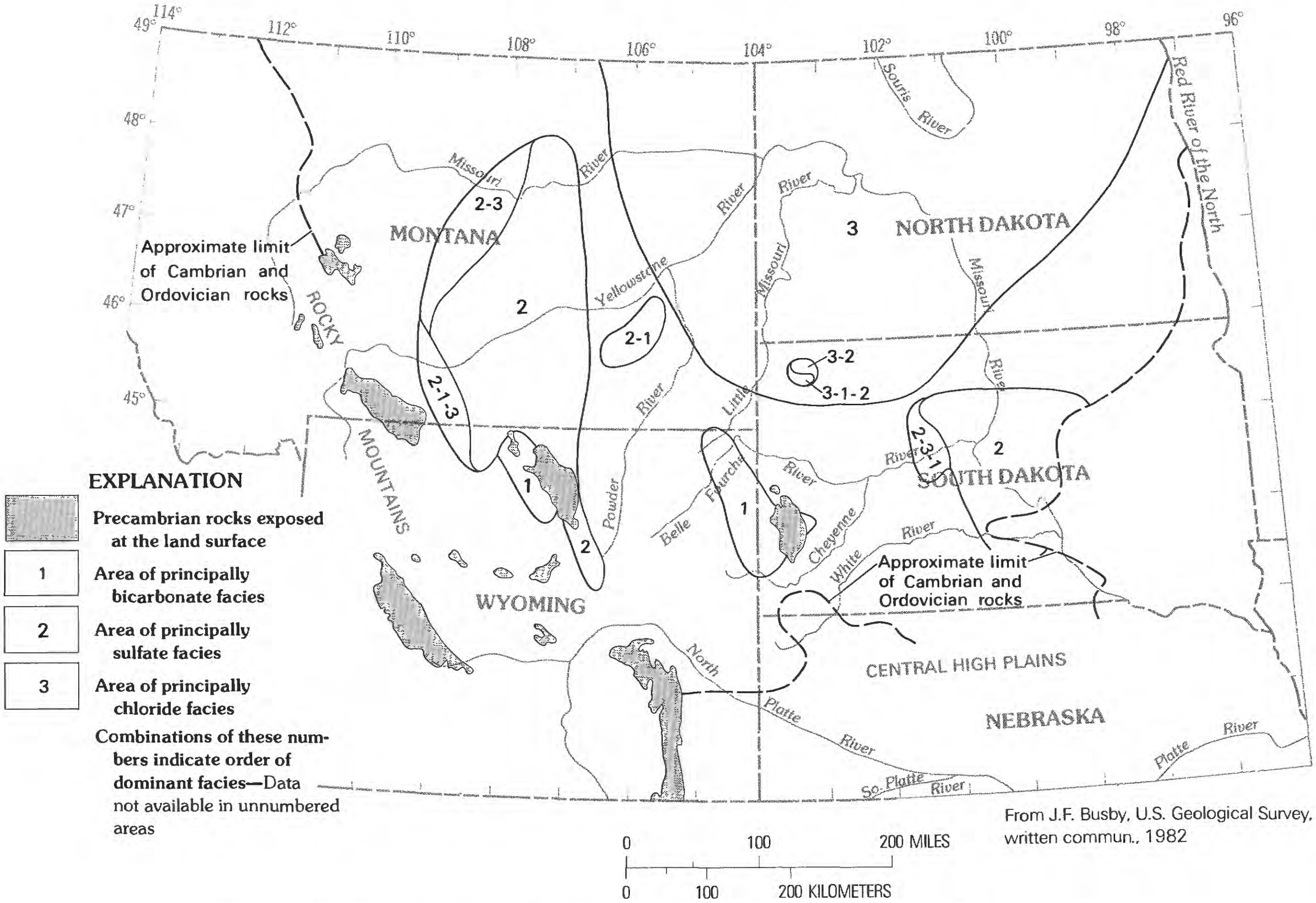

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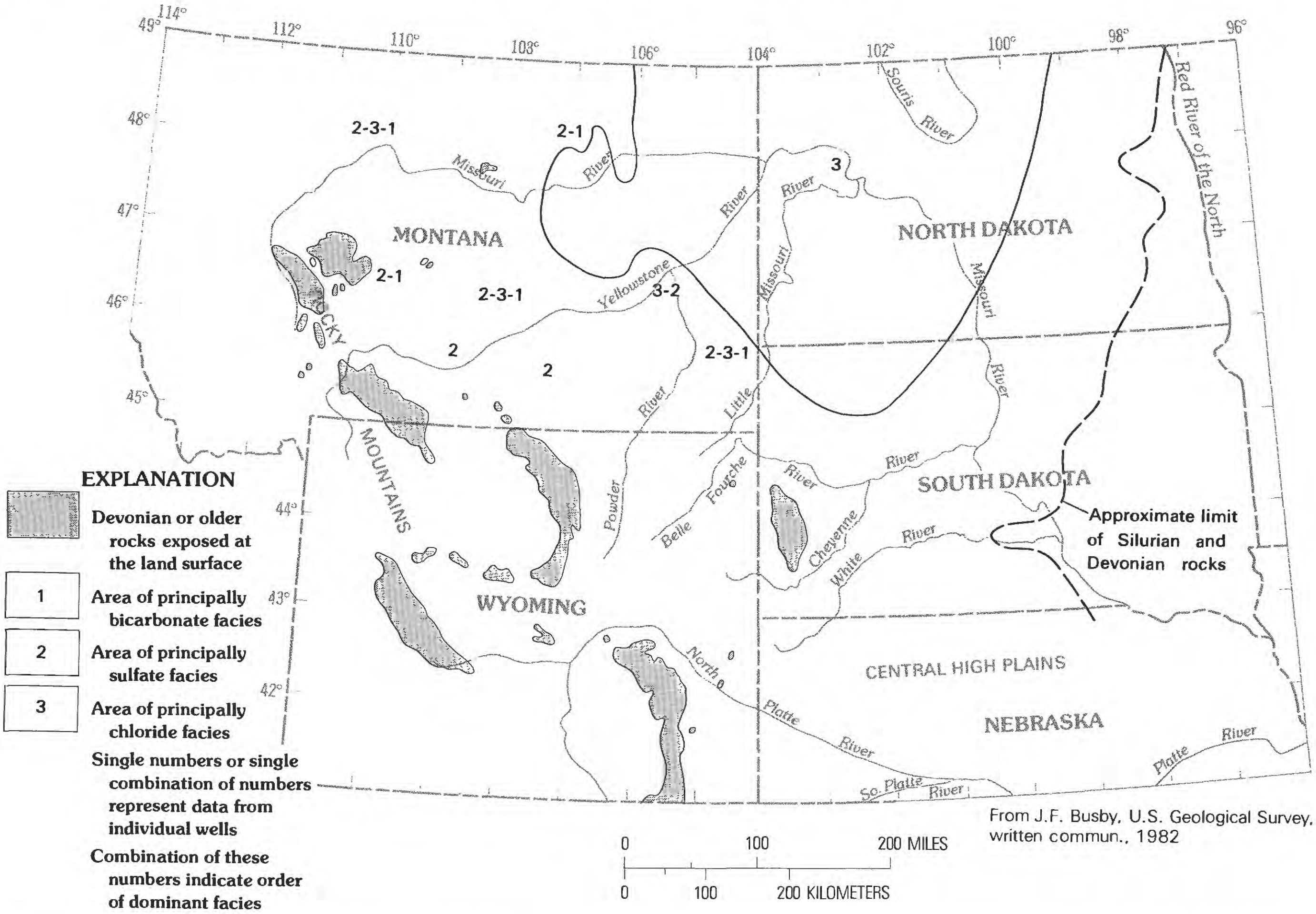

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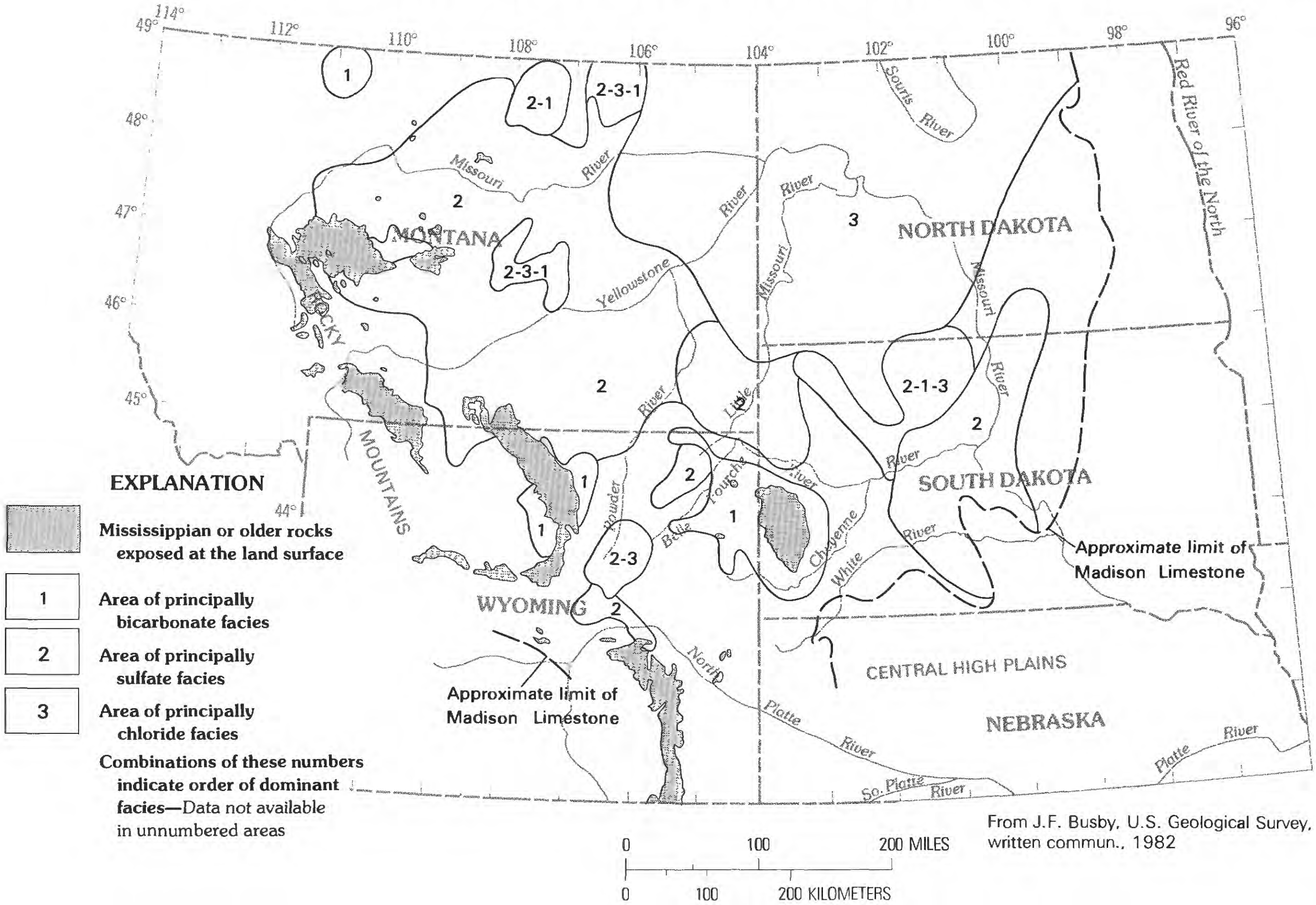

FIGURE 35.—Hydrochemical facies of water in the Mississippian aquifer system, including the Madison Limestone.

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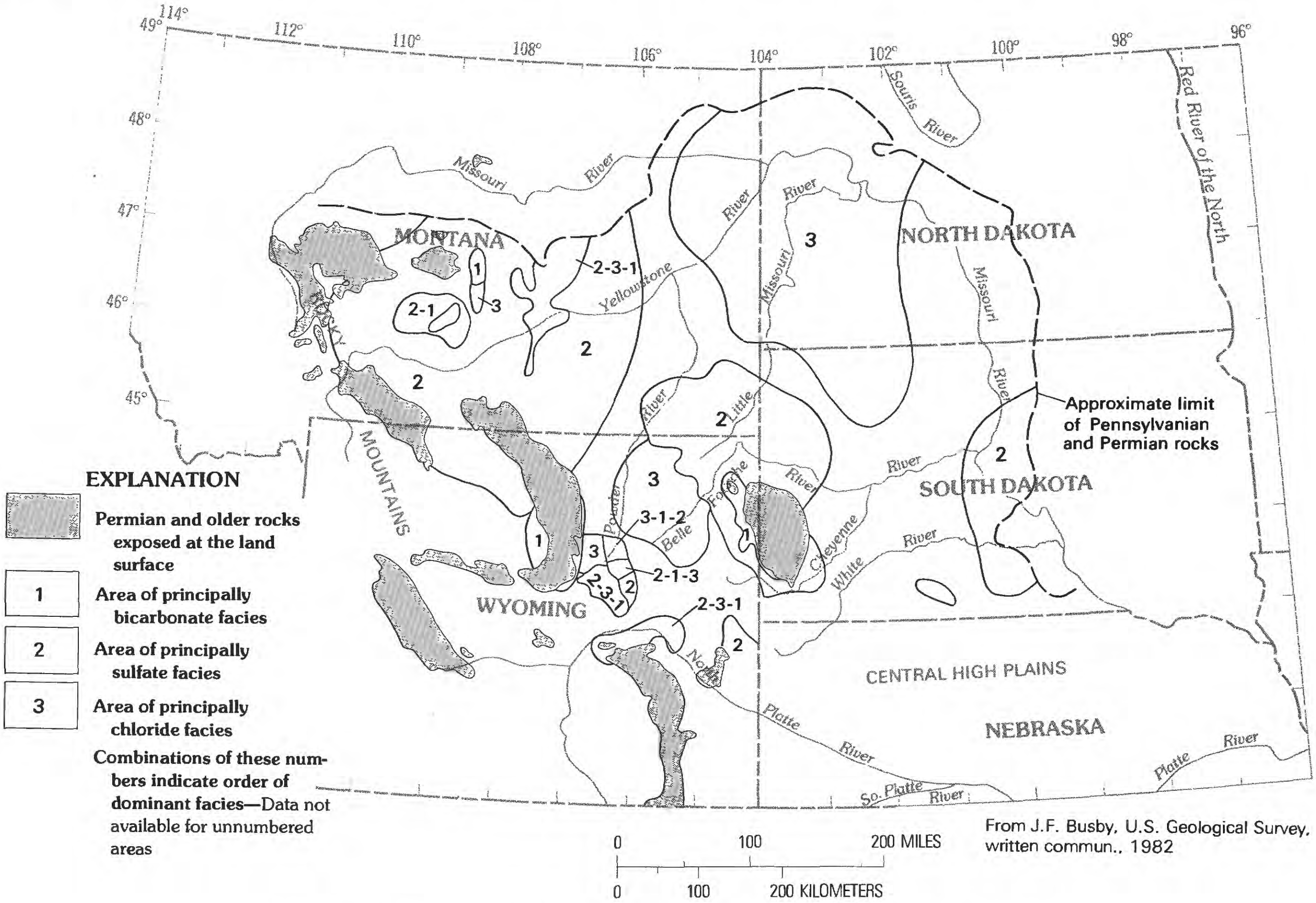

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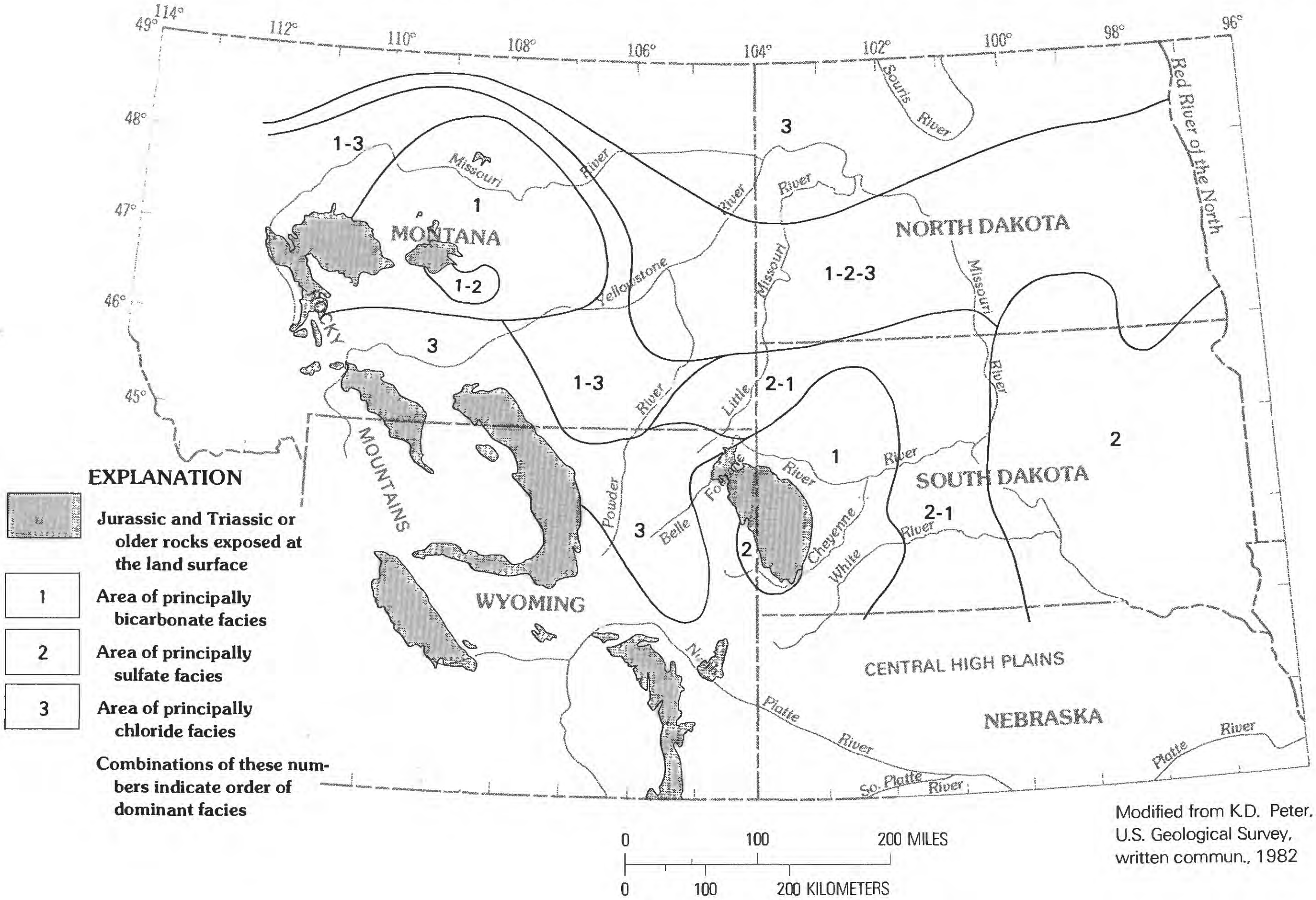

FIGURE 37.—Hydrochemical facies of water in the Lower Cretaceous aquifer system.

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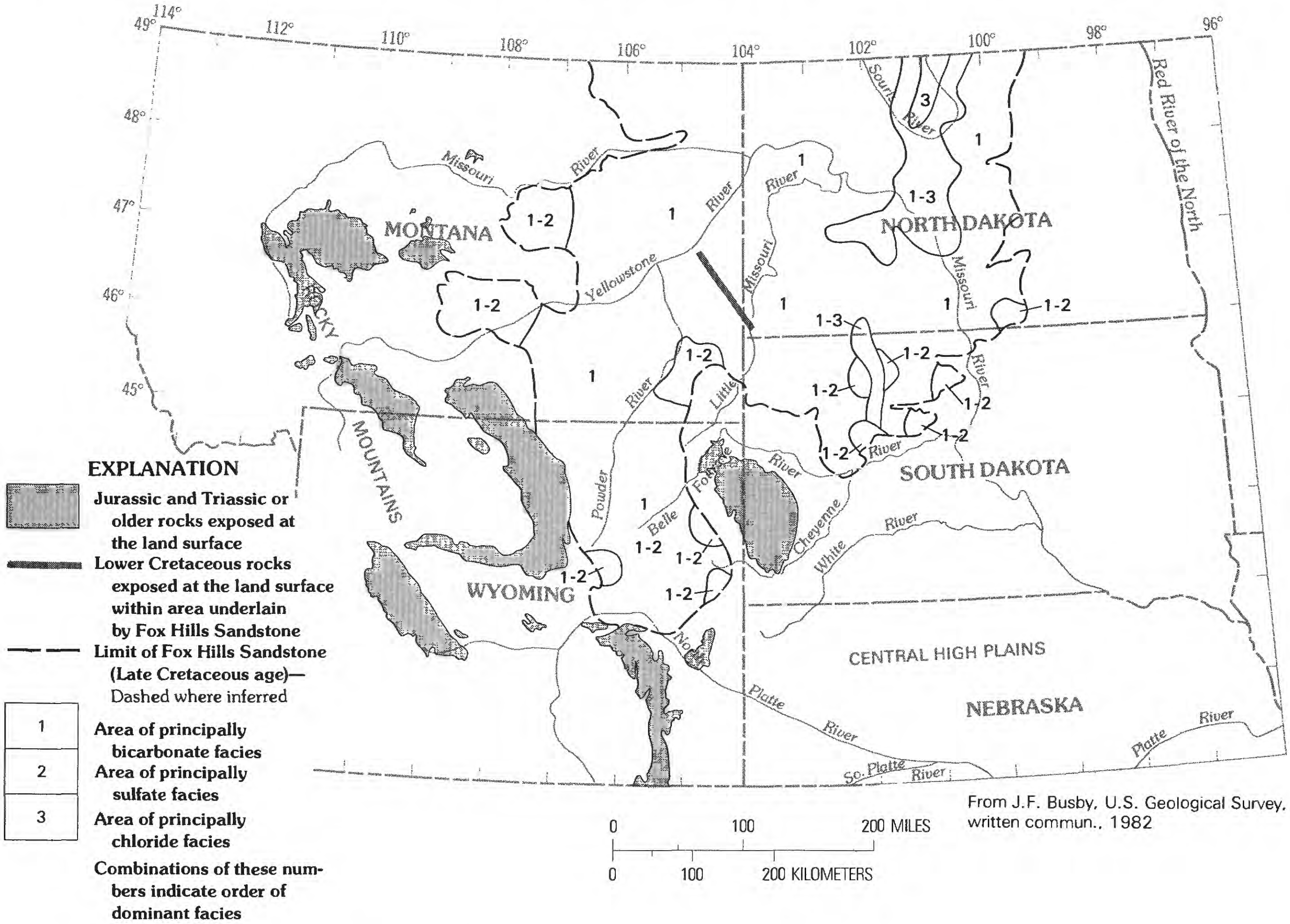

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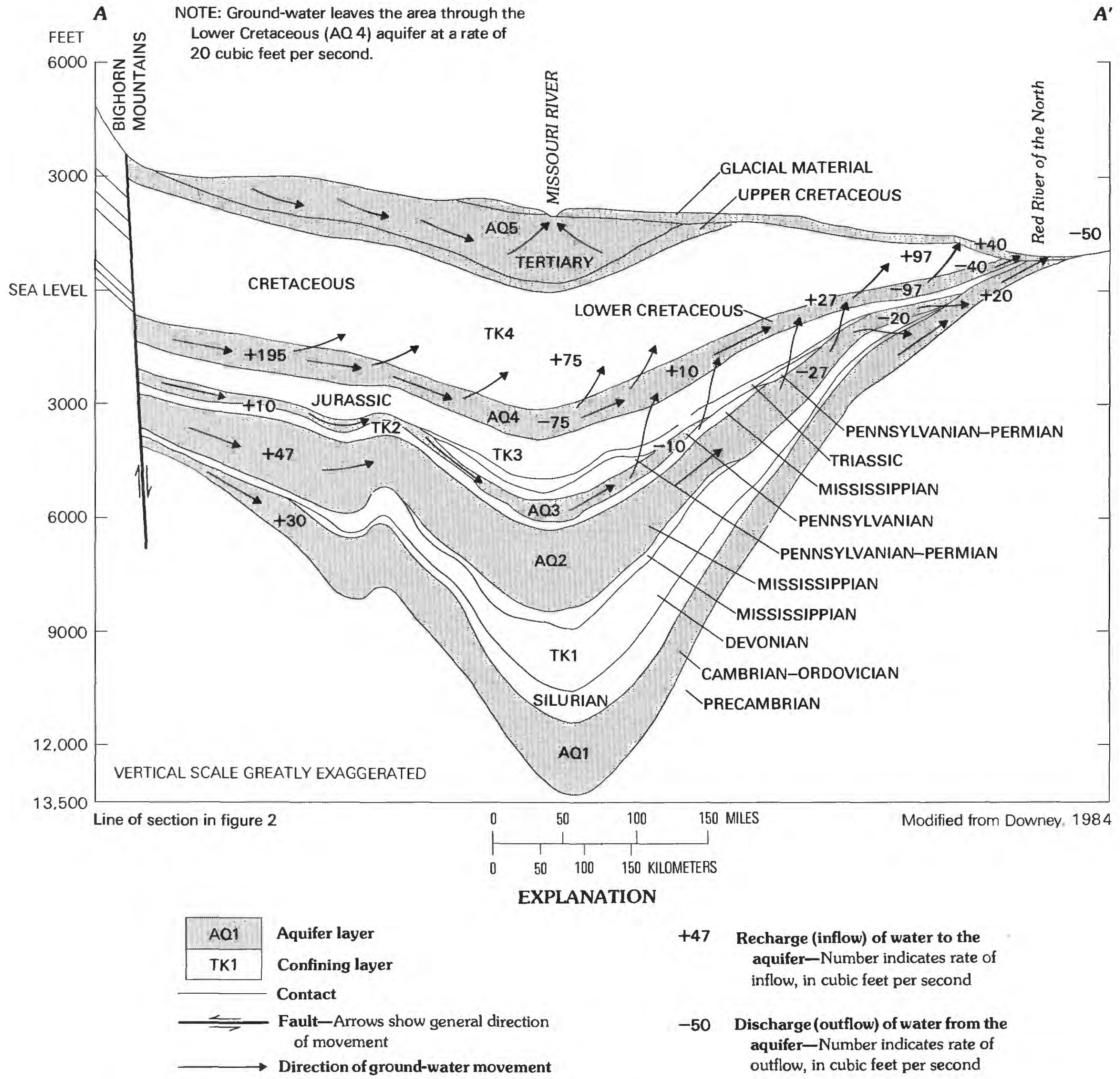

FIGURE 39.—Generalized geohydrologic section showing simulated rates of ground-water recharge, flow, leakage, and discharge from a ground-water recharge area in Montana to a discharge area in North Dakota.

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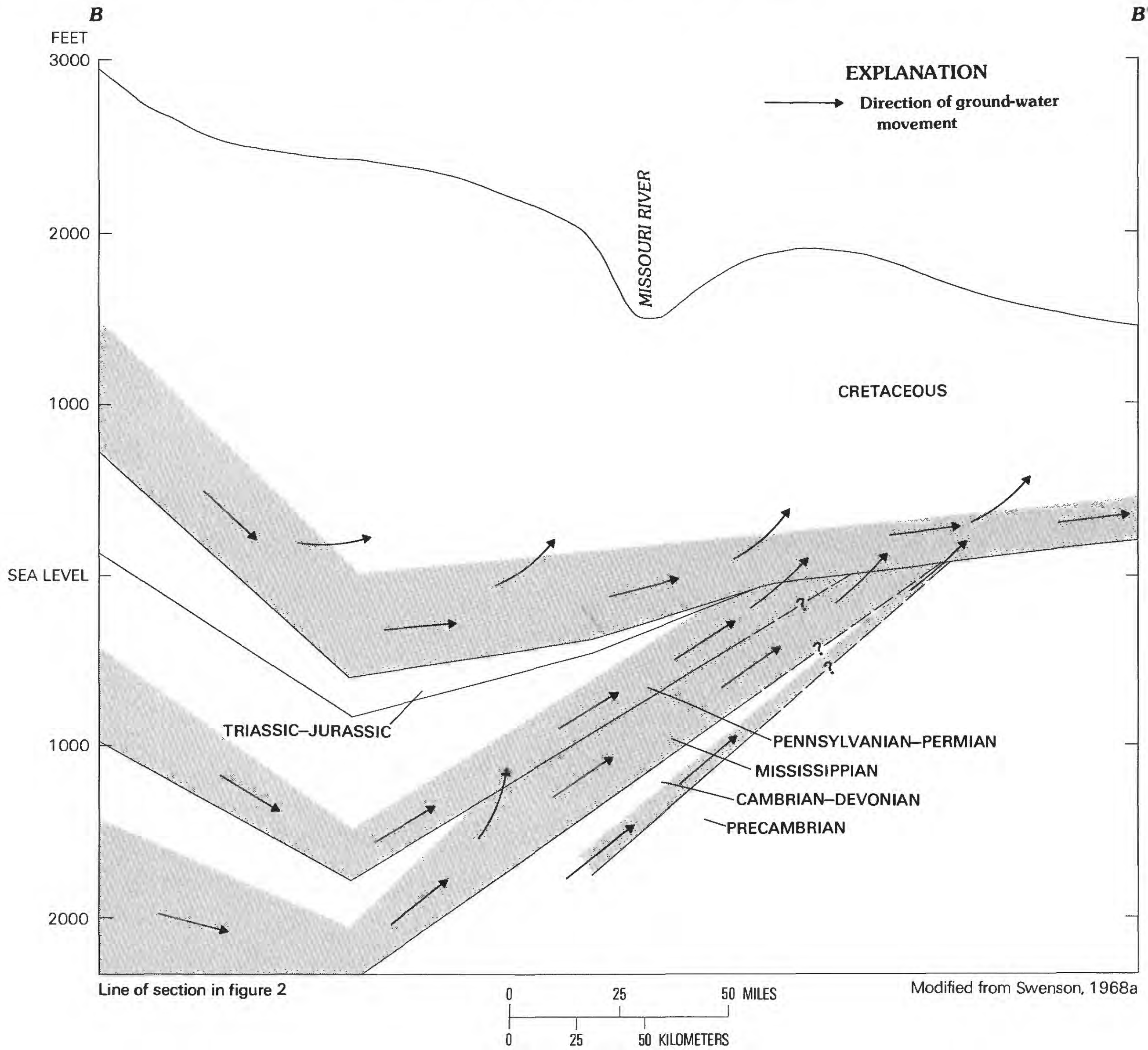

FIGURE 40.—Generalized geohydrologic section showing ground-water discharge from the aquifer systems consisting of rocks of Paleozoic age to the aquifer systems consisting rocks of Mesozoic age in central South Dakota.

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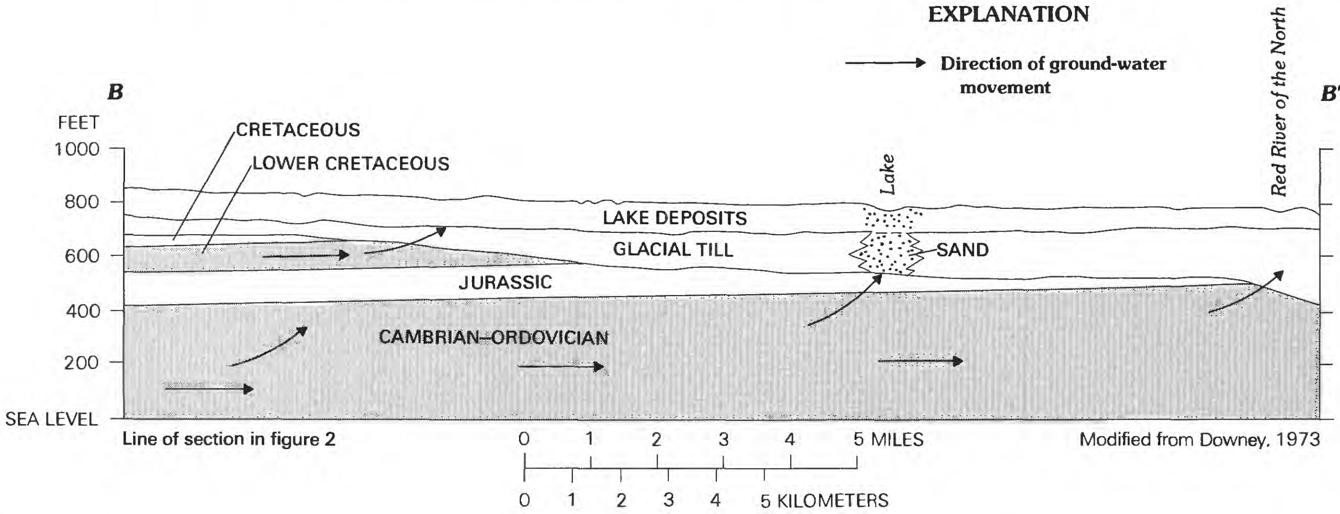

FIGURE 41.—Generalized geohydrologic section showing ground-water movement in the Cambrian-Ordovician aquifer system in northeastern North Dakota.

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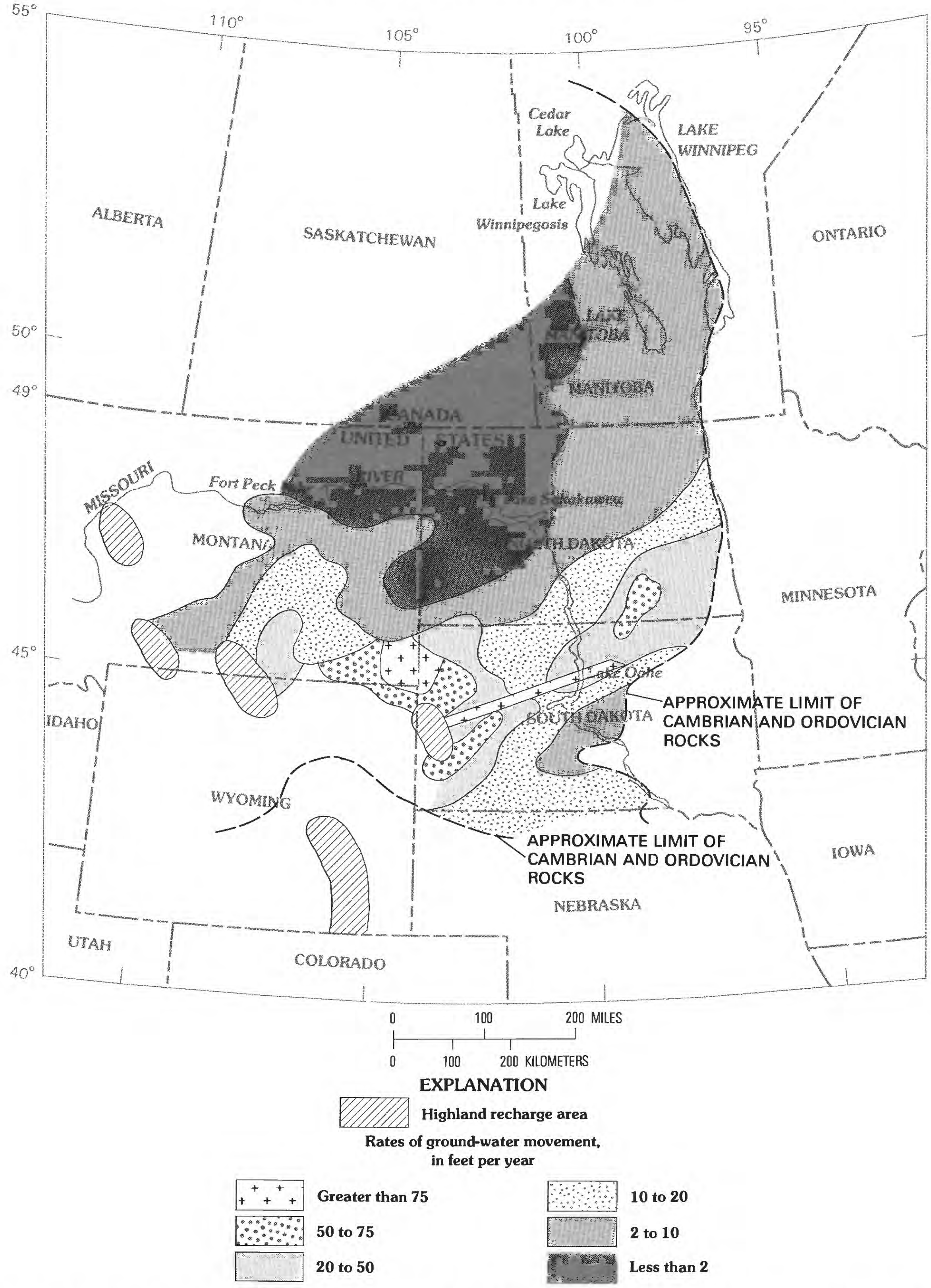

FIGURE 42.—Calculated rates of ground-water movement in the Cambrian-Ordovician aquifer system, study area and adjacent parts of Canada.

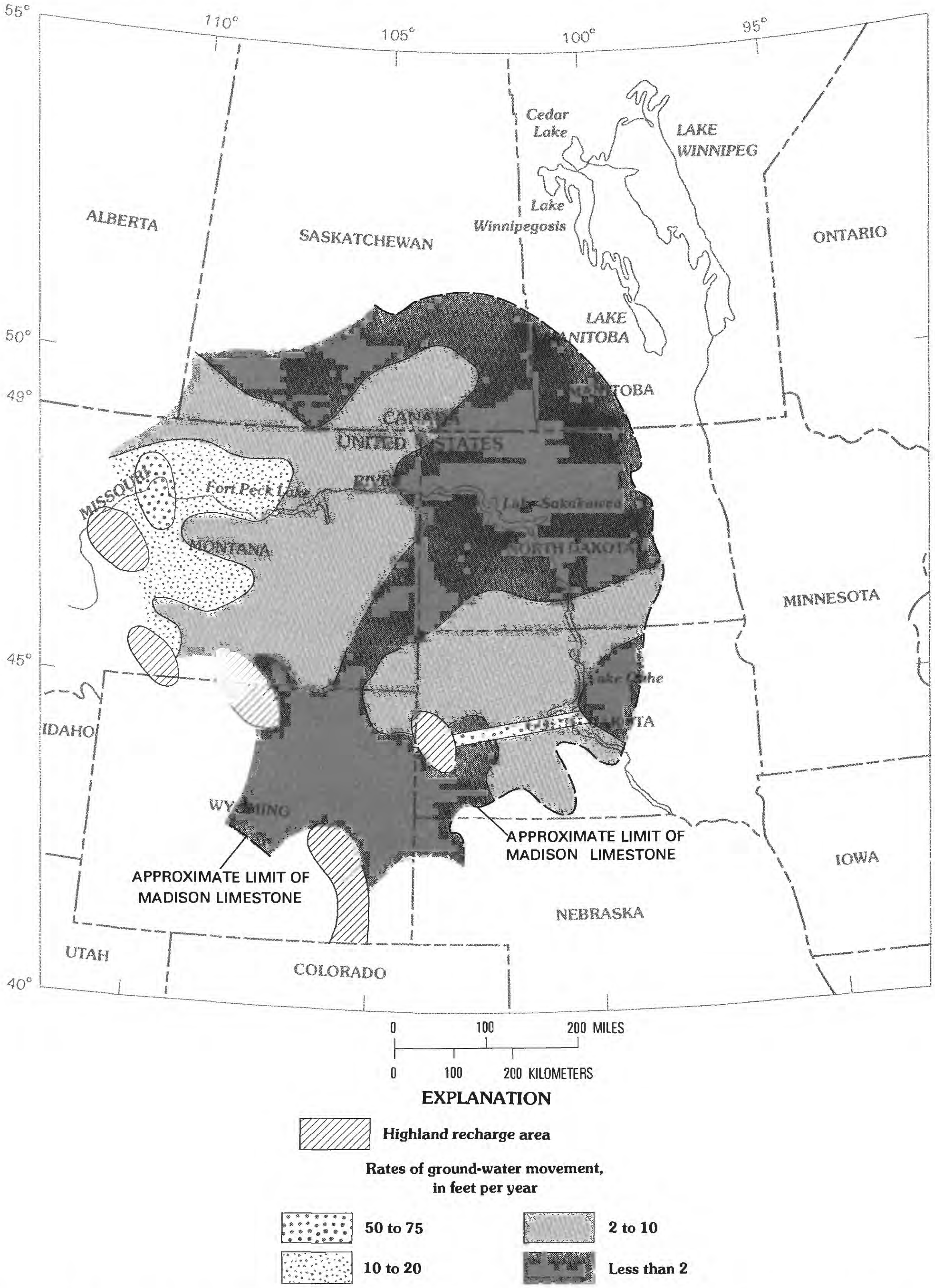

FIGURE 43.—Calculated rates of ground-water movement in the Mississippian aquifer system (including the Madison Limestone), study area and adjacent parts of Canada.

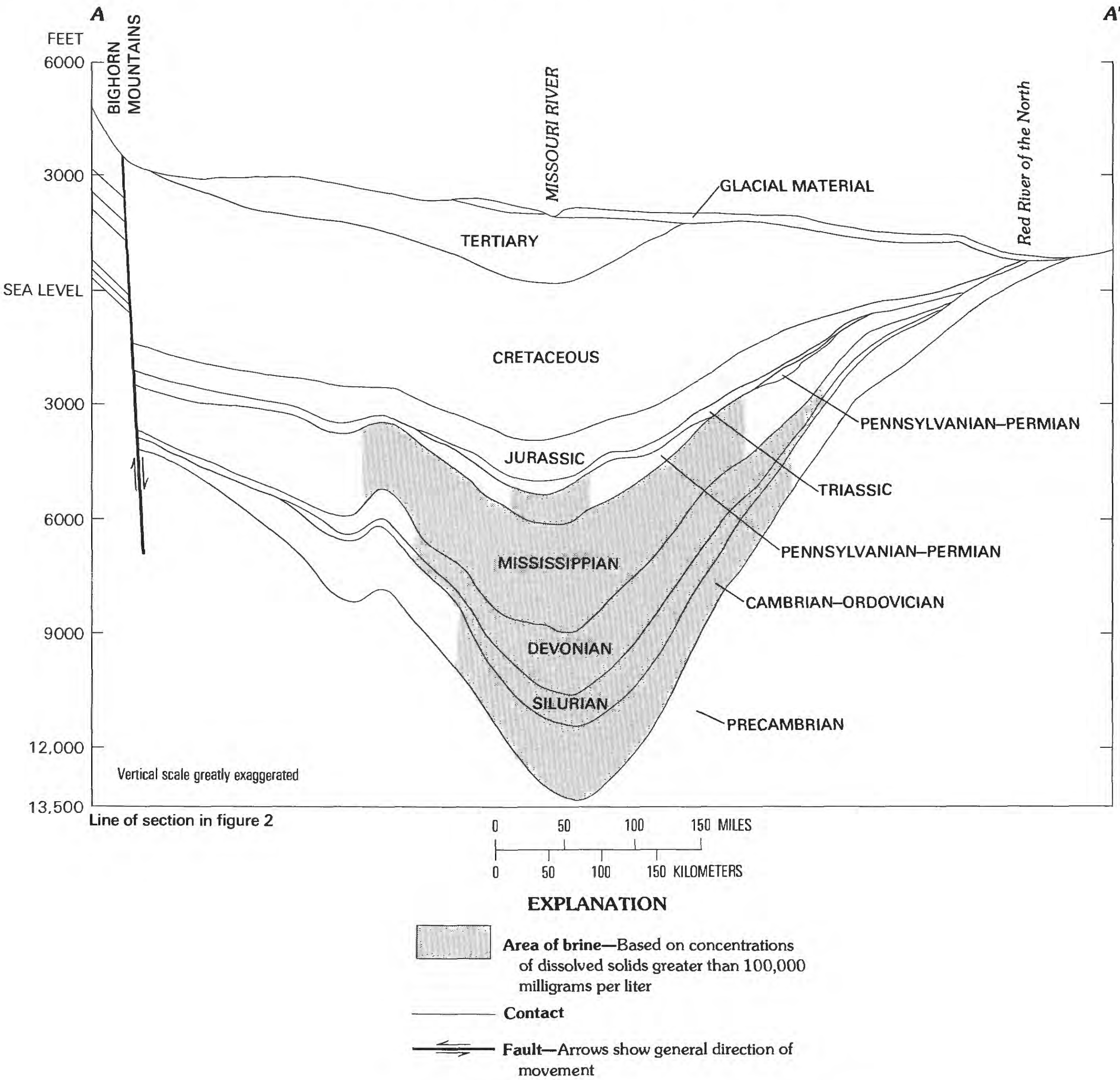

FIGURE 44.—Generalized geohydrologic section showing locations of brine in Williston basin.

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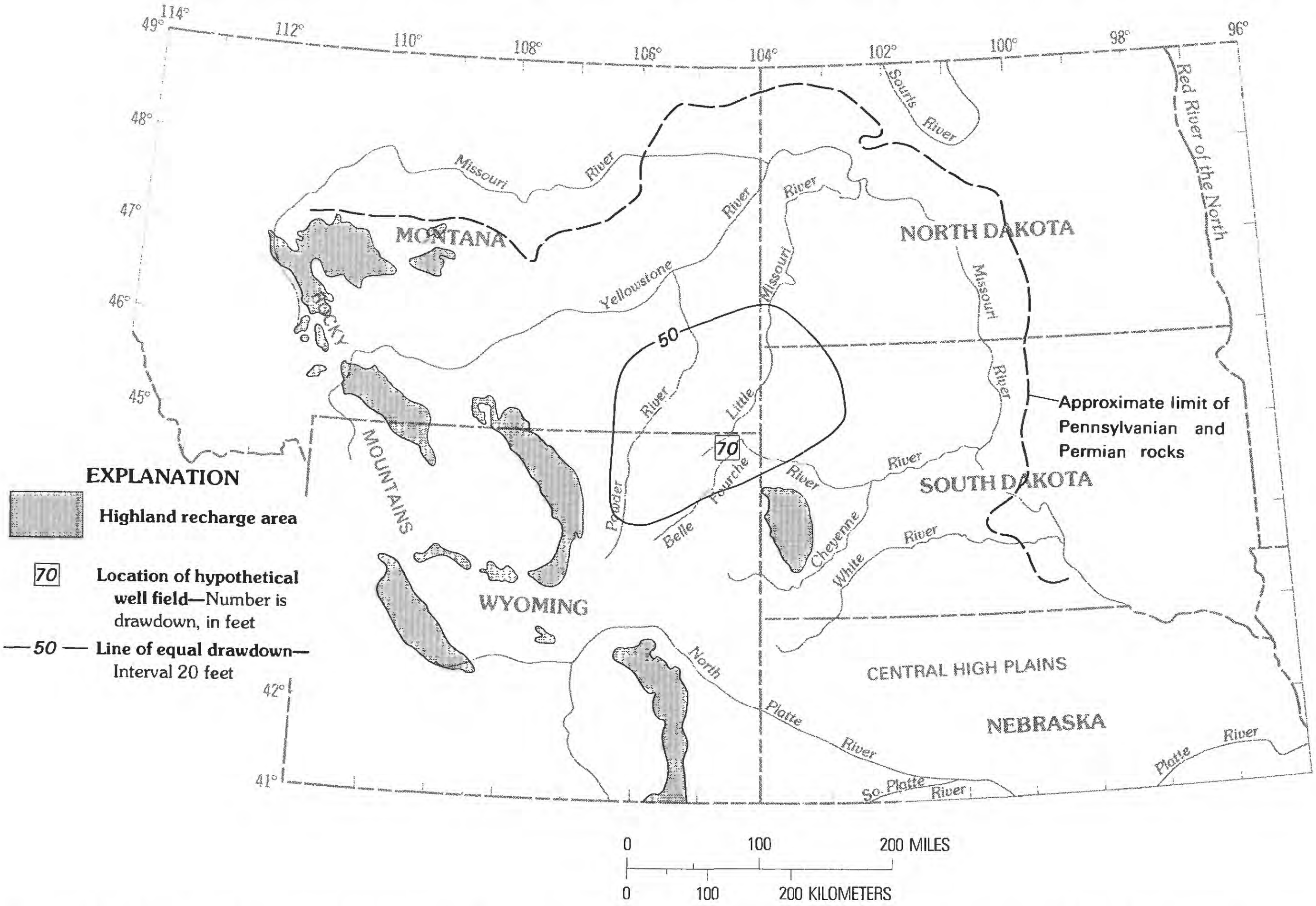

FIGURE 45.—Calculated drawdown in the Pennsylvanian aquifer system after 5.9 years of hypothetical pumping from the Mississippian aquifer system at a rate of 27.9 cubic feet per second and an assumed storage coefficient of 2.0×10^{-6}.

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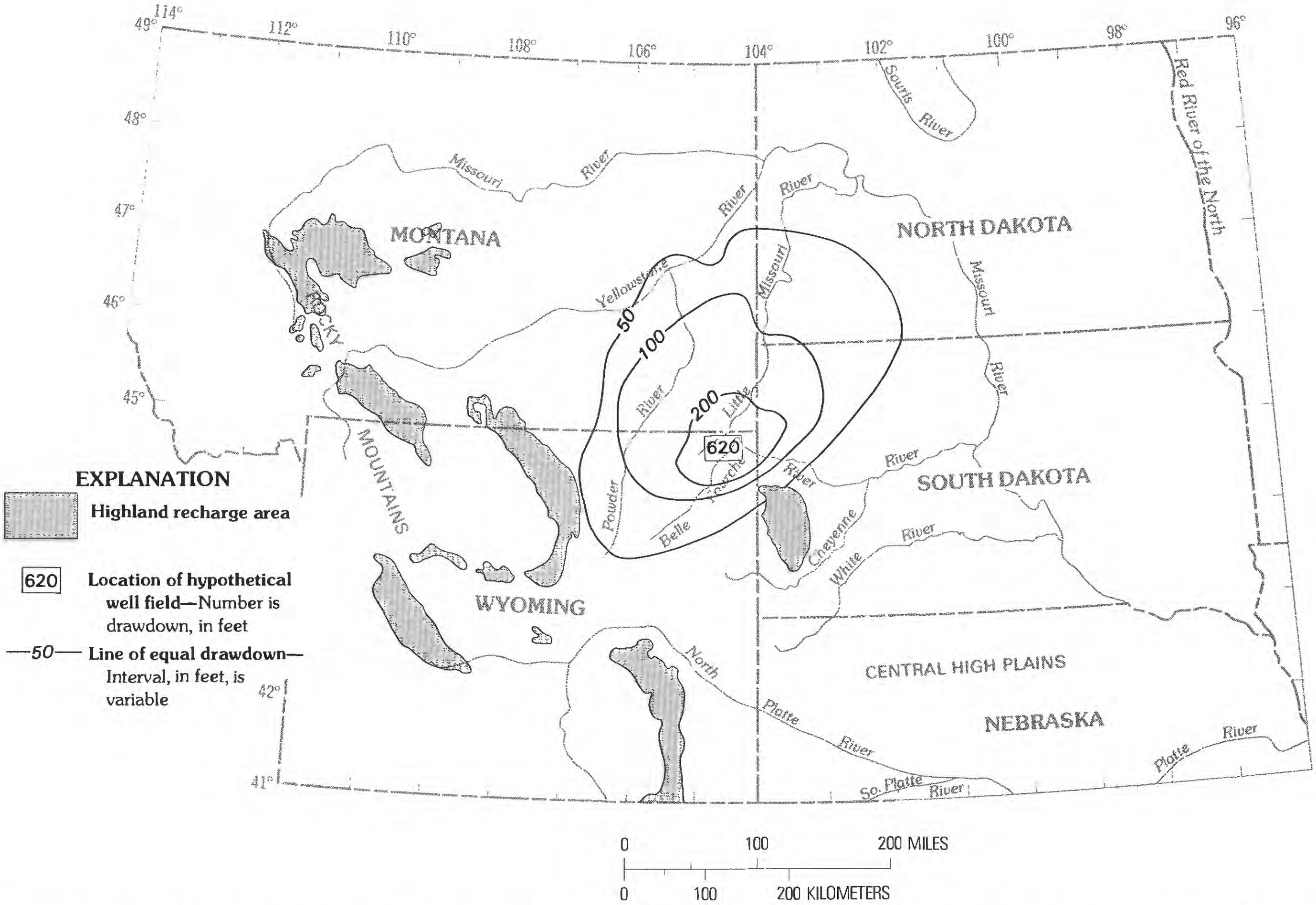

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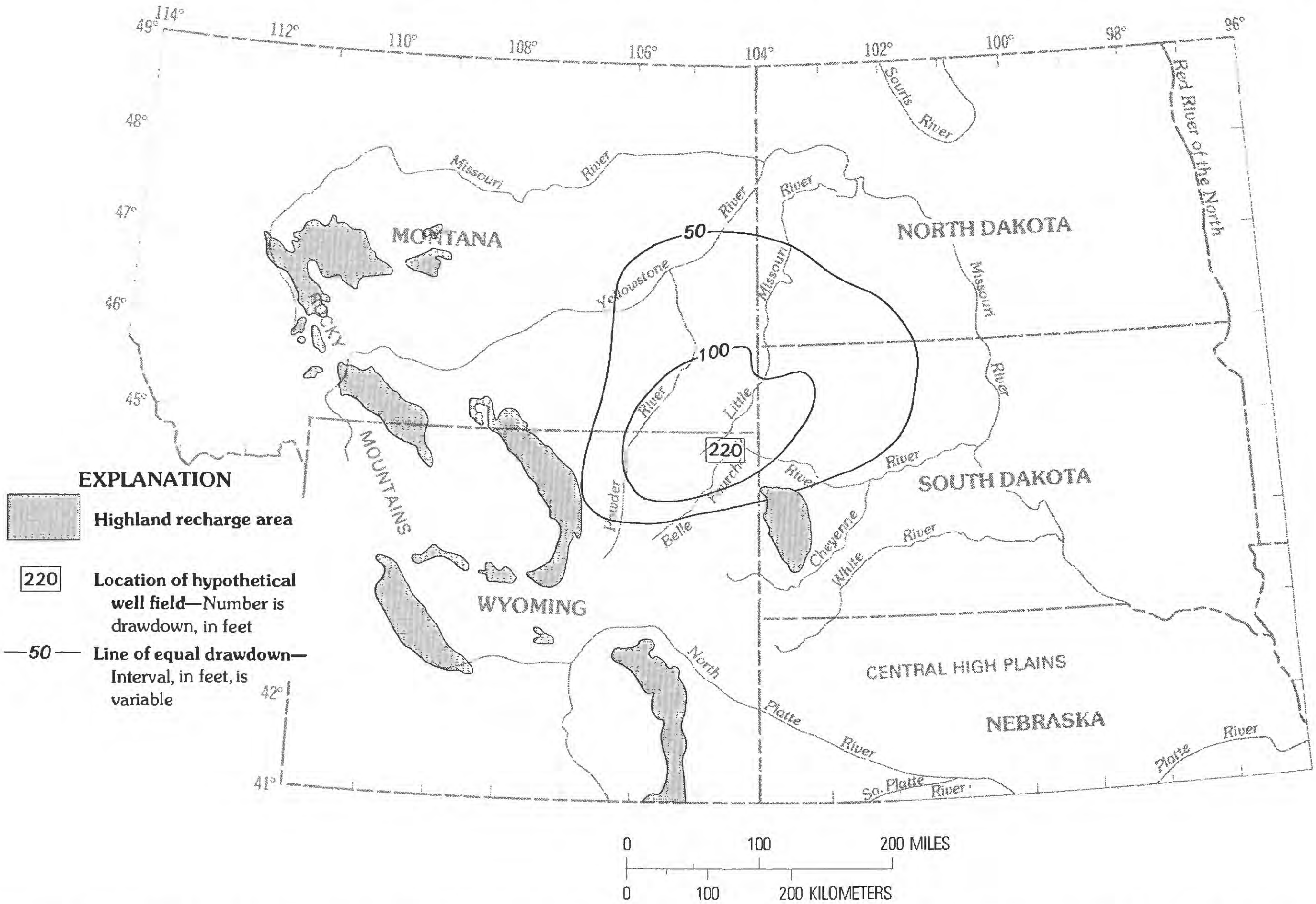

FIGURE 47.—Calculated drawdown in the Cambrian-Ordovician aquifer system after 5.9 years of hypothetical pumping from the Mississippian aquifer system at a rate of 27.9 cubic feet per second and an assumed storage coefficient of 2.0×10^{-6}.

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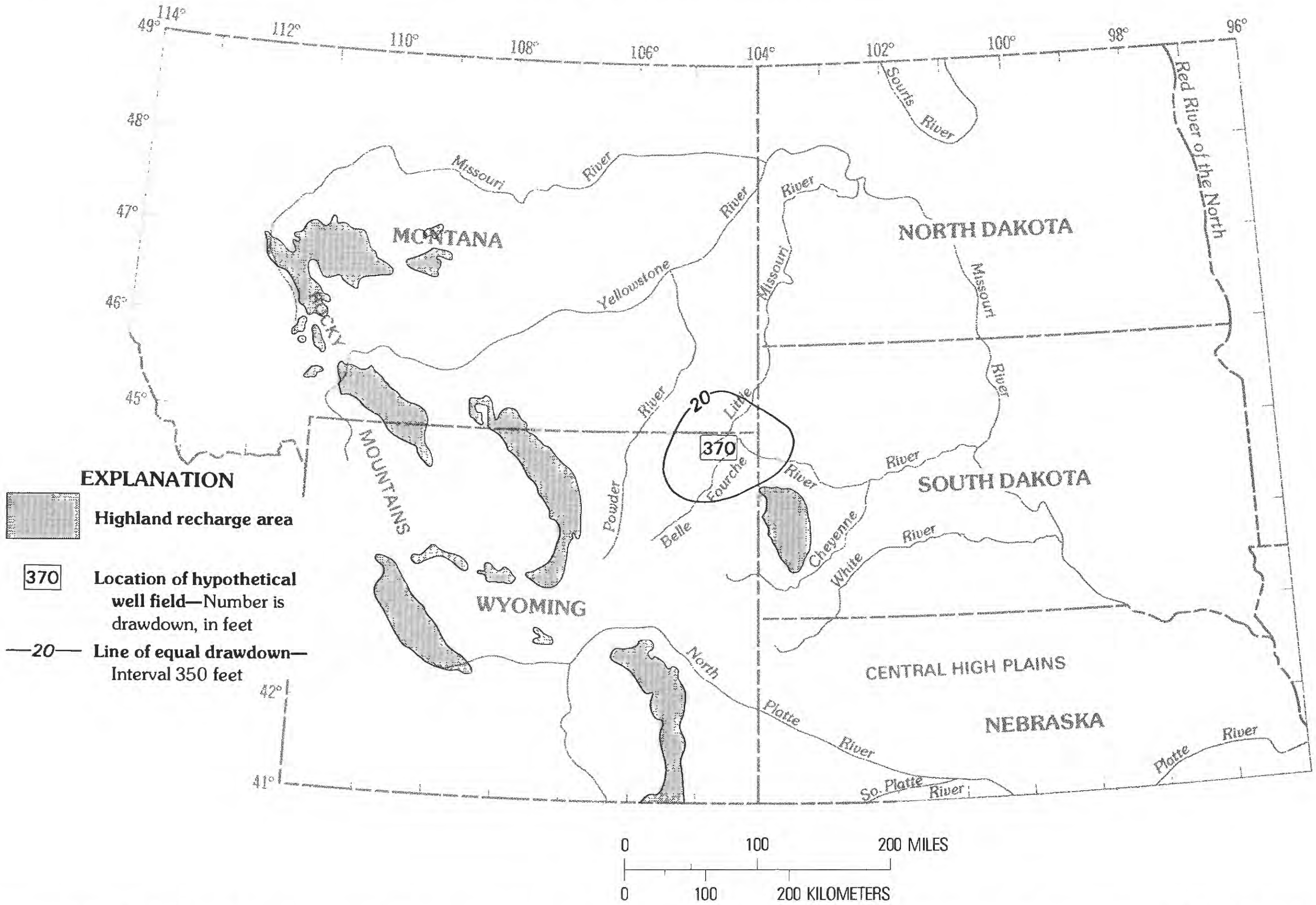

FIGURE 48.—Calculated drawdown in the Mississippian aquifer system after 5.9 years of hypothetical pumping at a rate of 27.9 cubic feet per second and an assumed storage coefficient of 2.0×10^{-4}.

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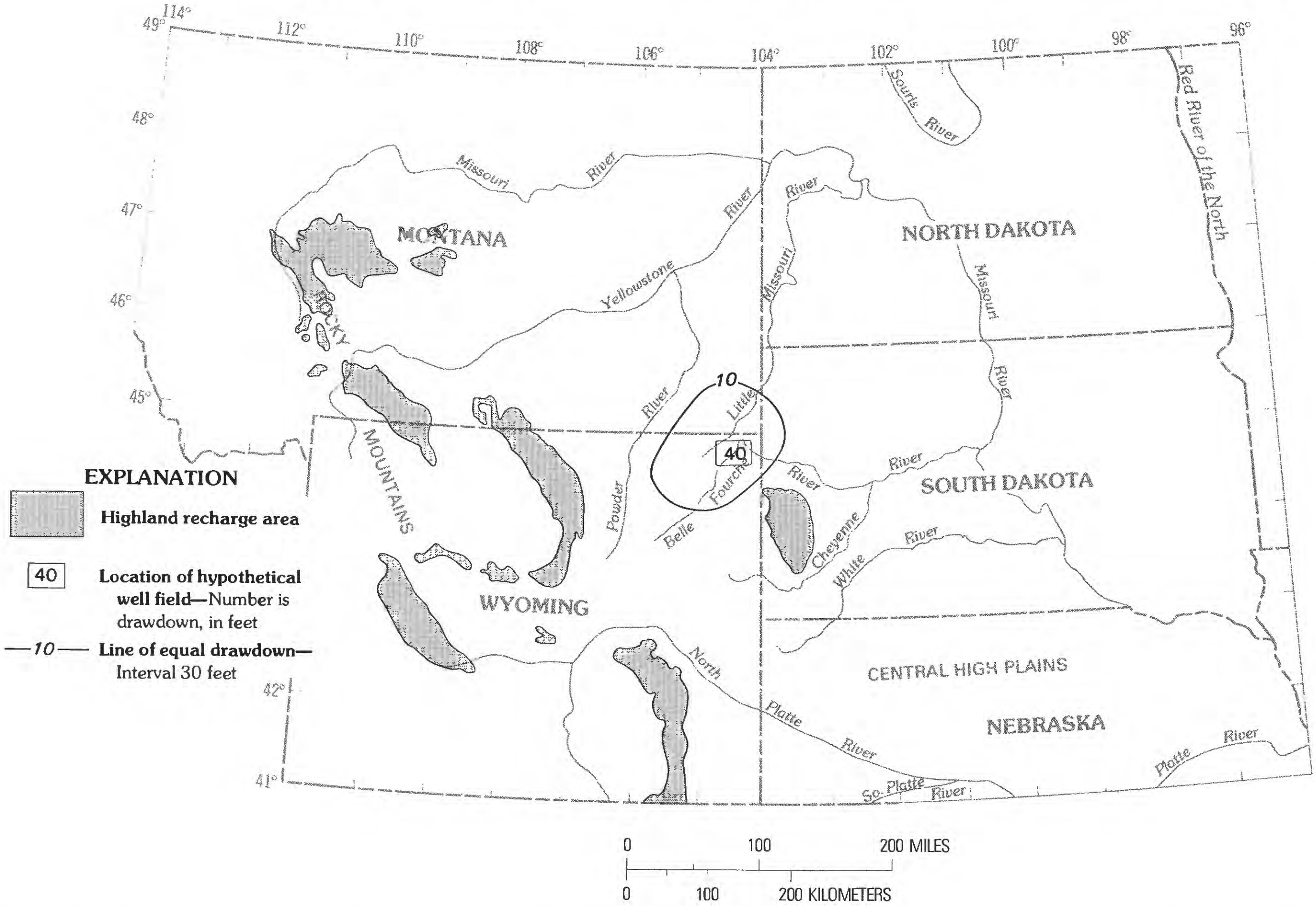

FIGURE 49.—Calculated drawdown in the Cambrian-Ordovician aquifer system after 5.9 years of hypothetical pumping from the Mississippian aquifer system at a rate of 27.9 cubic feet per second and an assumed storage coefficient of 2.0×10^{-4}.

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