Correlation of Paleostructure and Sediment Deposition in the Madison Limestone and Associated Rocks in Parts of Montana, North Dakota, South Dakota, Wyoming, and Nebraska

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1273-B

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By D. L. BROWN, R. K. BLANKENNAGEL, L. M. MACCARY, *and* J. A. PETERSON

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

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging In Publication Data
Main entry under title:

Correlation of paleostructure and sediment deposition in the Madison Limestone and associated rocks in parts of Montana, North Dakota, South Dakota, Wyoming, and Nebraska

(Geological Survey professional paper 1273–B)
Bibliography: 14 p.
Supt. of Docs. No.: I 19.16:1273–B
1. Limestone—Middle West. 2. Sedimentation and deposition. 3. Geology, Stratigraphic—Paleozoic. I. Brown, D. L. (Dennis L.) II. Series.
QE471.15.L5C67 1984 551.3′03 83–600277

For sale by the Branch of Distribution
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

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METRIC CONVERSION TABLE

Inch-pound units	Multiply by	To obtain metric units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

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

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

CORRELATION OF PALEOSTRUCTURE AND SEDIMENT DEPOSITION IN THE MADISON LIMESTONE AND ASSOCIATED ROCKS IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, WYOMING, AND NEBRASKA

D. L. BROWN, R. K. BLANKENNAGEL, L. M. MACCARY, and J. A. PETERSON

ABSTRACT

The present demand for large quantities of energy has created interest in the Fort Union coal region of the Northern Great Plains. Extensive development of this coal may increase the demand on the region's limited water resources. Water from Paleozoic rocks might supply a significant part of the required water. One area where ground-water supplies may be developed is in and near the Powder River basin and near the Black Hills.

Paleostructural elements have affected the thickness, rock facies, and distribution of porosity in all of the Paleozoic and Mesozoic rocks. Major structural elements, such as the Transcontinental arch, Alberta shelf, and Canadian Shield have affected sediment deposition and erosion continuously for long intervals of geologic time. Smaller elements, like the Lake Basin fault and Weldon-Brockton fault trends, have controlled sediment deposition and erosion intermittently for long intervals of time. Some paleostructural elements were of limited duration and may appear one time in the geologic record. Knowledge of the relation between paleostructures and sediment thickness, porosity, and facies is useful for predicting the location and water-bearing potential of aquifers in the study area.

INTRODUCTION

A major part of the United States coal reserves occur in the Fort Union coal region of the Northern Great Plains (fig. 1). Development of these coal resources may include onsite steam-power generation, gasification, liquification, and slurry-pipeline transport of the coal from the region. Development would place a significant demand on the region's limited water resources. Water from the Madison Limestone and underlying rocks might supply, at least on a temporary basis, a large part of the water required for coal development. These rock units underlie the Fort Union coal region and adjacent areas in Montana, North Dakota, South Dakota, Wyoming, and Nebraska. In order to address this problem, the Madison Limestone Project was established to determine the quantity and quality of water in rocks of Paleozoic age in an area of about 200,000 square miles in eastern Montana, western North Dakota and South Dakota, northeastern Wyoming, and a small part of northwestern Nebraska. One area where ground-water supplies may be developed is in and near the Powder River basin and the Black Hills uplift.

The overall objective of this report is to describe the relations between the Paleozoic sedimentary rocks and the inferred geologic processes that were responsible for their observed characteristics. Contemporaneous increments of sedimentary rocks were examined in order to reconstruct the geologic setting at the time of deposition. By mapping the rocks that occurred during limited intervals of time, one may be able to ascertain the mechanisms that have produced variations in facies and thickness. In other words, maps of rocks deposited during specific increments of time do not show deformations of later structural events and can be used to understand the sedimentary units at the time of their deposition. Some of the contemporaneous mechanisms affecting sediment deposition and erosion that may have been prevalent during Paleozoic time are eustatic sea-level fluctuations, biologic changes, subsidence of intracratonic basins, regional uplifting, activation of linear structural elements (faults and folds), and vertical adjustments on blocks of the Precambrian basement.

The specific objective of this report is to determine the location and frequency of occurrence of those paleostructures that are likely to have some effect on the occurrence of ground water. Once their azimuth, length, and periods of activity were determined, the paleostructures were used in a digital model (Downey, 1982) to help predict the occurrence and movement of ground water.

Paleozoic rocks comprise a complex system of aquifers and confining beds in the Northern Great Plains. The system is complex in many ways: (1) Rock types and gross facies within a particular rock type have great variability; (2) water quality ranges from fresh in the recharge area to dense brine in the deep basins; (3) ground-water temperatures range from the mean annual surface temperature, about 40°F, to greater than 300°F in the basins; (4) the altitude of some formations ranges from more than 8,000 feet above sea level in the mountainous areas to more than 10,000 feet below sea level in the deep basins; and (5) paleostructures have affected rock thickness, facies, directional

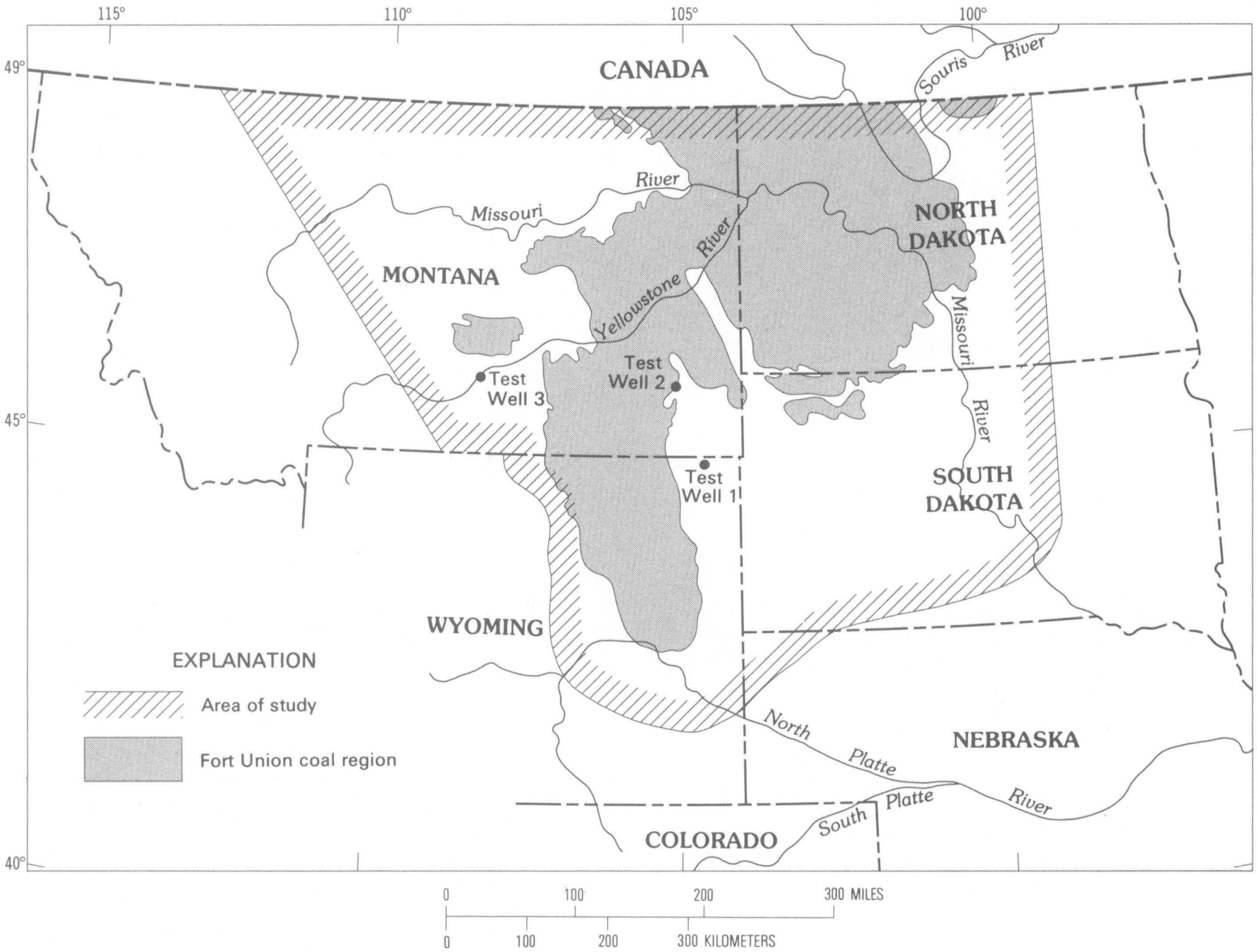

FIGURE 1.—Location of study area.

trends, and degree of vertical interconnection of potential aquifers.

The Madison Limestone is mapped as a single formational unit in parts of the project area and is mapped as the Madison Group where it is divided into formations in other parts of the area (table 1). For consistency, however, the term Madison Limestone is used in this report except where the Madison Group is specifically discussed. The Madison Limestone, in ascending order, generally consists of thin- to medium-bedded argillaceous to shaly or silty, in places cherty, limestone; thick- to massive-bedded fossiliferous to oölitic carbonate rock; and anhydrite and halite interbedded with carbonate rock and shale. These gross facies intertongue with each other, and the total section is made up of numerous cyclic, marker-defined units that incorporate variable proportions of the main rock facies. The Madison Limestone was subdivided into 13 units for the purposes of establishing a correlation framework (fig. 2). Each correlation unit is bounded by marker beds that consist of thin and widespread shaly carbonate or dark-shale intervals that are recognizable in the subsurface on gamma-ray neutron or gamma-ray sonic logs and are traceable throughout large parts of the project area. Similar marker beds characterize the Madison Limestone and its equivalents throughout most of the Rocky Mountain area. Log definition of marker beds is best expressed in the main part of the Williston basin; however, most of the beds can be traced with reasonable confidence in Montana, Wyoming, and South Dakota. The five marker beds that have proven to be the most useful for regional correlation purposes are shown in

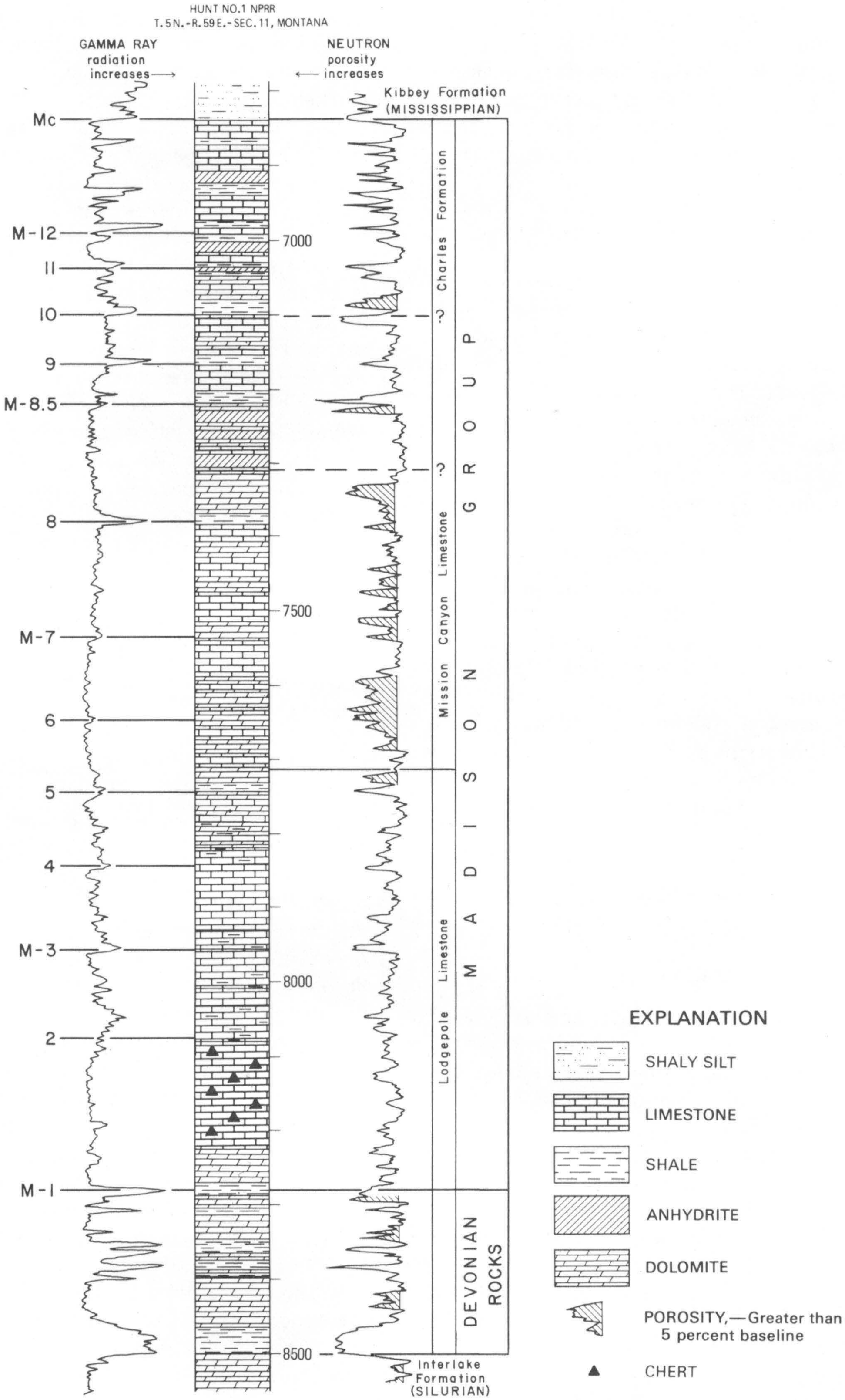

FIGURE 2.—Examples of well-log patterns and lithology of Madison Group marker units.

figure 2. Marker M–1 represents the base of the Madison Limestone; M–3 is near the Kinderhookian and Osagean boundary; M–7 and M–8.5 fall within the Osagean; and M–12 is near the Osagean and Meramecian boundary. Wherever a complete section is present, the top of the Madison Limestone is designated as the Mc marker.

ACKNOWLEDGMENTS

This study of the Madison Limestone and related rocks was conducted by personnel of the U.S. Geological Survey. Most of the maps in this report are modified from those originally constructed by Donald L. Brown (formerly with the U.S. Geological Survey). The original maps were designed for inclusion in one large volume that was to have described all aspects of the Madison study. However, owing to the cost of printing such a large volume, the results of the Madison study are published in several reports (Peterson, 1981; Thayer, 1981; MacCary, 1981). This report expresses the authors' synthesis of the structural history based largely on the interpretation of the thickness, rock type, and porosity maps. Some of the maps have been extensively modified from those originally prepared by Donald L. Brown.

The authors are grateful for the reviews of the earlier maps and manuscript by E. B. Ekren, U.S. Geological Survey; Sidney B. Anderson, North Dakota Geological Survey; and James L. Wilson, University of Michigan.

PALEOZOIC SUBSURFACE STRATIGRAPHY AND STRUCTURE

GENERAL CONSIDERATIONS

Both chronostratigraphic and lithostratigraphic units were used in the structural analysis of Paleozoic rocks. Five units of approximate chronostratigraphic age were determined for the Madison Group of Mississippian age. Although not specifically established as such, the lithologic units comprising the Big Snowy Group (Mississippian) were regarded as a chronostratigraphic unit (table 1). All other Paleozoic rocks plus the Triassic were mapped and analyzed as lithostratigraphic units. These are all bounded by unconformities, either at the base or the top, and all are time-transgressing units. Thickness maps of each chronostratigraphic and lithostratigraphic unit were drawn, and major rock-type and porosity maps were drawn for selected units.

Four factors control the thickening and thinning of sediments: (1) Differing rates of sedimentation; (2) differing rates of uplift or subsidence; (3) erosion and deposition; and (4) differential compaction. Items 1 and 4 are lithology dependent in part because some lithologies accumulate faster than others, and the same is true for the degree of compaction. By mapping time-marker beds, chronostratigraphic units can be determined that tend to be isolated from the effects of erosion and deposition. The effects of differential compaction are most important for those chronostratigraphic units containing marine shale, because shale compacts more than the other lithologies discussed in this report.

The two sediment-thickness factors most closely related are differing rates of uplift or subsidence and differing rates of erosion or deposition. The effects of erosion will be more or less evident in all the units studied. Farmer (1981) presents an excellent summary of the rationale used to relate the occurrence of thick and thin sediments to the structural events that may have affected their deposition and erosion.

All thickness maps were examined for significant occurrences of thick and thin sediments under the assumption that these features might indicate a tectonic effect on sedimentation. Thickness changes of regional extent might be caused by major tectonism on broad uplifts (Central Montana uplift, for example) or on intracratonic basins (Williston basin, for example). Some regional thickness changes may be due to eustatic sea-level changes produced by tectonism or by glaciation far removed from the study area; other changes may have been due to the development of organic deposits. When thick sediments tend to follow known structural features such as faults, folds, structural trends, and lineaments in the Precambrian basement, the effects of tectonism on sedimentation become more conclusive. Some structural axes of thick or thin sediments recur in successive mapped units, while others may appear only during one chronostratigraphic or lithostratigraphic interval. In some instances, the activity along the trend may be reversed during different intervals; in other words, a thin sediment in Ordovician time may be overlain by a thick sediment in Devonian time along the same structural feature. When gross sediment thickness for all mapped units is considered, it appears that all Paleozoic units from Cambrian through Mississippian thicken or thin in an east-west direction. The Pennsylvanian and Permian units and the Triassic have thinning and thickening axes generally trending northward.

In the depositional environment of clastic sediments, the expected result of tectonism is that thicker deposits will occur in the depressions, and thinner sediments will occur over elevated parts of the tectonic element. This relationship is true of the Cambrian, parts of the Devonian, the Big Snowy Group, Pennsylvanian and Permian units, and the Triassic. In the depositional environment of carbonate rocks, the effects of large-scale tectonism, such as subsiding basins, usually results in the accumulation of thick sediments. However, the effects of smaller scale tectonism is not clearly defined. Small tectonic elements that tend to elevate the sea floor may in fact cause a thickening of sediments due to reef or organic-mound development and to the greater current or wave energy in the shallower water. The mixed relations of tectonic activity to sediment thickness is most evident in the Ordovician, Silurian, some Devonian, and the Madison units because they are predominantly in the carbonate environment.

TECTONIC FRAMEWORK OF STUDY AREA

Much of the present-day structure in the study area is the result of Laramide deformation in Late Cretaceous and early Tertiary time. For the purposes of this study, only those structural elements known to be of Paleozoic or Precambrian age are considered in the analysis. The relation of the study area to the regional paleogeography and paleostructure is shown in figure 3. Because this map is generalized and of small scale, a more detailed paleostructural map was compiled on plate 1.

Many zones of weakness that existed prior to Laramide deformation were common avenues for the release of stress during Laramide, and thus have existed from very ancient times into the present. Northwest-, east- southeast-, and northeast-trending structural features of Paleozoic and Precambrian age occur throughout the Cordilleran shelf area. Many of these elements resulted from Precambrian shear zones and have since been zones of weakness. For example, the Colorado mineral belt south of the study area and

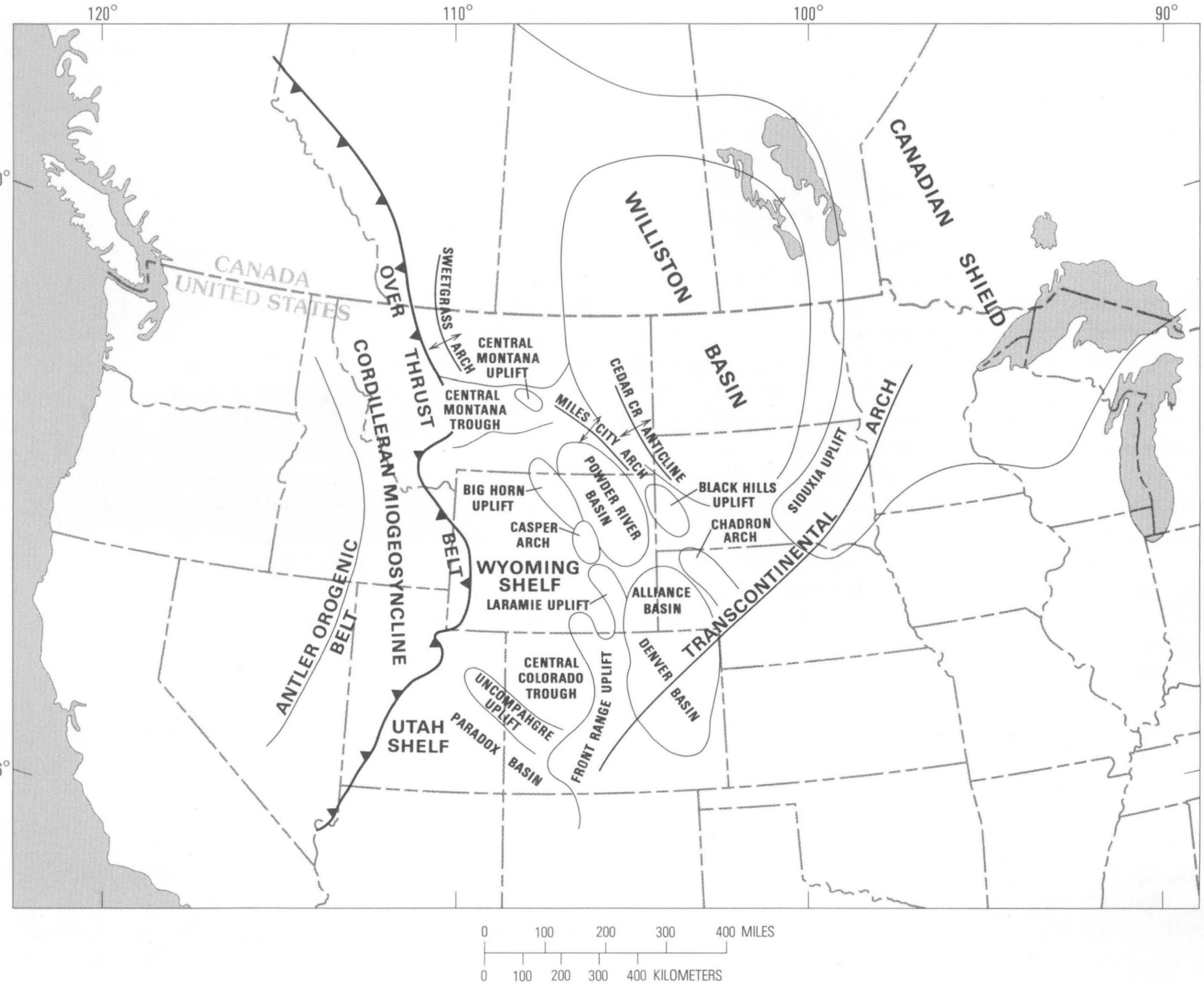

FIGURE 3.—Regional paleogeography and paleostructure during Paleozoic time, Western Interior, United States.

the Nashfork-Hartville fault trend in Wyoming and South Dakota (pl. 1) outline the limits of a regional Precambrian shear zone called the Colorado lineament (Warner, 1978). This shear zone, extends from Arizona to the Great Lakes and divides the Precambrian basement into provinces of two different ages, one of 2,400 million years north of the shear zone and one of 1,750 million years south of the shear zone.

Most of the paleostructural elements shown on plate 1 are classified as trends, even though their present-day structural configurations may be well documented. The Cedar Creek trend is now referred to as an anticline, but at different times in the geologic past it may have been a fault, a hinge line, a negative area, or remained quiescent. Structural elements of unknown or mixed genesis are classified as lineaments (O'Leary and others, 1976). Some lineaments are an alinement of recognized faults, folds, shears, or other structural features; others are deduced from tonal changes on satellite images or aerial photographs (O'Leary and others, 1976). Only those lineaments shown by tonal changes that are known or presumed to displace the Precambrian basement are shown on plate 1. Some paleostructures on plate 1 are assigned specific tectonic names (for example, Transcontinental arch) because they appear to have functioned in the same tectonic manner throughout their periods of activity.

The tectonic elements shown on plate 1 are those that are described in the literature as either being of a Precambrian origin or having been a control on Paleozoic sedimentation. Some are the combined elements of separate structures such as the Bottineau-Burleigh trend, which links the Bottineau anticline with the Burleigh high of Ballard (1963). Another of this type is the Nesson-Pierre trend which links the Nesson anticline and the Pierre arch. Major northeast-trending elements are the Transcontinental arch, Nashfork-Hartville fault trend, Rosebud arch, Weldon-Brockton fault trend, and the Hinsdale fault trend. Several minor faults and lineaments also trend northeast. Major northwest- or north-trending structural elements are the Sweet-grass arch, Cedar Creek anticline trend, Bighorn uplift, Nesson-Pierre trend, Bottineau-Burleigh trend, and the Black Hills uplift and its associated monoclines and anticlines. Major east-southeast-trending tectonic elements are the Central Montana uplift, Central Montana trough, and the Cat Creek, Willow Creek, Lake Basin, and the Nye-Bowler fault trends.

Smith (1965) suggests that the east-southeast-trending elements from the Cat Creek fault trend on the north to the Nye-Bowler fault trend on the south all lie within a broad, left-lateral Precambrian shear called the Lewis and Clark lineament. He postulates that this lineament extends from the Idaho batholith to eastern Wyoming. The movement on each element, the Cat Creek, Willow Creek, Lake Basin, and Nye-Bowler fault trends, is reported to be left lateral.

Recurrent movement on major northeast- and northwest-trending structural zones of Precambrian age were believed by Brown (1978) to have controlled Paleozoic deposition. The origin of the Precambrian shear zones in the Cordilleran shelf area is unknown, but the presence of left-lateral shears in a southeasterly direction, and right-lateral shears in a northeasterly direction may be indicative of wrench-fault tectonics. Wrench or transcurrent faults are described as high-angle faults with a large strike slip. They result from compression where both the maximum and minimum stresses occur in a horizontal plane. As originally described by Moody and Hill (1956), wrench-fault tectonics involved the boundaries of large tectonic plates of the Earth's crust; however, wrench faults may occur on a smaller scale when maximum and minimum compressive stresses occur in a plane parallel to the Earth's surface. The structural type and orientation of many features in the Rocky Mountain region have been described by Stone (1969) and Sales (1968) in terms of a wrench-fault tectonic model.

In attempts to fit the structural elements of the Rocky Mountain region into a simple wrench-fault model, some writers have: (1) Ignored evidence of vertical movement; (2) failed to consider all lineament directions; (3) confused fault separation and slip; (4) assumed that shear zones necessarily indicate horizontal movement; and (5) indicated that all lineaments of a given direction have the same degree of horizontal movement (Hoppin, 1974). Hoppin cites many examples where authors credit strike slip to lineaments even though there is no evidence for horizontal movement, and also credit azimuths for these lineaments that disagree with the actual measured azimuths. "Attempts * * * to reconcile other lineament directions into a single-stress system require complicated rotations and unique sequences of movements to make the aberrant lineaments fit the pattern expected by the theory" (Hoppin, 1974, p. 2270).

Geological literature describes large numbers of Precambrian shears and vertical faults that cut the basement underlying the study area (Wulf, 1963; Hoppin, 1974; Lisenbee, 1978; Smith, 1965; Thomas, 1974; Warner, 1978; Brown, 1978; Stone, 1969; Sales, 1968; Slack, 1981). Recurrent movement along Precambrian faults has resulted in vertical adjustments and attendant depositional draping over the positive element. Many of the monoclinal structures in the study area are thought to be of this origin. While vertical adjustments can be readily discerned, the horizontal components are obscure.

Many geologic mechanisms, in addition to regional and local tectonics, can be used to explain the observed sedimentation characteristics of the units studied. These characteristics include changes in water depth due to eustatic sea-level fluctuations, water-salinity changes, water-temperature variations, wave action and turbidity, biologic activity, and finally, the extensive, all pervasive diagenesis that has affected all Paleozoic rocks.

Accompanying the following sections of specific geologic units are maps with well control points. Each control well with its assigned county number is shown on plate 2. On completion of the Madison Limestone Project, well data will be retrievable from a computer file by using the county well number and State name.

PALEOSTRUCTURE AND SEDIMENTATION

CAMBRIAN SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

The marine sandstone, shale, and limestone of Cambrian age are the shoreward facies of a west-to-east Cambrian seaway that transgressed the western border of the North American Craton (Cordilleran shelf area). The lower part of the sequence in central Montana and Wyoming is Middle Cambrian age, but becomes younger to the east, and is of Late Cambrian and Early Ordovician age in the Powder River and Williston basins (Peterson, 1981). The Precambrian surface over which the Cambrian seas transgressed was irregular with a probable relief of 300 to 400 feet being common (Lochman-Balk, 1972). The Transcontinental and Sweetgrass arches both were orginally Precambrian structures, and although they may not have been uplifted during the Cambrian, they nevertheless helped to control Cambrian sedimentation. The eastward marine transgression periodically was interrupted by regression cycles and accompanying subaerial erosion (Lochman-Balk, 1972).

Some major tectonic events during the Cambrian were the initial slight downwarp of the incipient Williston basin, broad arching and uplift in the western shelf area, and development of an embayment across the Transcontinental arch. Geological evidence supports the hypothesis that major structural elements, as well as faults and folds associated with them, are the result of movement along fracture systems in the basement, many of which originated during Precambrian time. According to Pye (1958), "Zones of weakness in Precambrian basement rocks have been responsible to a considerable extent for the pattern of the present structures. In fact, areas of Precambrian weakness may still be areas of general weakness. However, later tectonic forces operating from different directions have broken further the Cambrian blocks." At least six structural-trend directions associated with deformations during Precambrian, Devonian, Pennsylvanian, Jurassic, Laramide, and later Tertiary time are recognized (Pye, 1958). Those of Precambrian age affect the thickness and facies distribution of the Cambrian rocks.

DEADWOOD FORMATION OR EQUIVALENT ROCKS (CAMBRIAN AND LOWERMOST ORDOVICIAN)

STRUCTURAL-THICKNESS RELATIONS

For the purpose of evaluating the Cambrian rocks in this report, the Deadwood Formation, as mapped, includes rocks of Middle Cambrian, Late Cambrian, and earliest Ordovician age (table 1). The thickness map (pl. 3) shows a general thinning of the Deadwood from west to east except along the Montana-North Dakota border where thick sediments occur in the incipient Williston basin. When the paleostructural map (pl. 1) and the thickness map (pl. 3) are compared, a few structural controls on the sediment thickness may be evident. A thick-sediment area extends from Wheatland County, Montana to Sheridan County, Wyoming. This arcuate lobe is partly bordered on the north by the Willow Creek fault trend, on the south by the Nye-Bowler fault trend, and on the west by the Big Horn uplift. A northwest-trending area of thin sediments in Fallon and Carter Counties, Montana, and Harding County, South Dakota, is bounded on the west by the Miles City arch and on the east by the Cedar Creek anticline trend. Two thin areas, one in Blaine and Fergus Counties, Montana, and the other extending from Musselshell to Powder River Counties, Montana, aline with the Bearpaw anticline and two parallel faults inferred from gravity data. Some thin areas may represent depositional draping over Cambrian structural highs or buried hills on the Precambrian surface. The scarcity of subsurface control precludes accurate location of these thin features and definitive interpretations as to their origin.

Three re-entrants along the southeast zero line (pl. 3) are related to spurs trending northwest from the Transcontinental arch. These spurs are an unnamed feature in Natrona and Carbon Counties, Wyoming, the Chadron arch in Nebraska and South Dakota, and the southern part of Nesson-Pierre trend in Tripp and Jones Counties, South Dakota. The latter spur is shifted southwest of the axis of the Nesson-Pierre trend and may be related to an unrecognized tectonic feature between the Nesson-Pierre and Cedar Creek anticline trends. An alternative explanation is that these features could be related in part or entirely to pre-Devonian erosion. Some Cambrian sediments may have been deposited over these spurs and then eroded during times of slight uplift. Another apparent structural control of sedimentation is the south-trending area of thin deposits in Williams and McKenzie Counties, North Dakota. This thin area also may be explained as a buried hill on the Precambrian surface. It lies adjacent to the Nesson-Pierre trend. Thick and thin sections trending eastward occur between the Bottineau-Burleigh trend on the west and the Canadian Shield on the east. These may be related to minor spurs projecting westward from the shield and may in part be related to pre-Middle Ordovician (Winnipeg Formation) erosion. The zero thickness line on the Towner anticline trend also may be a buried hill or Precambrian outlier from the Canadian Shield.

In the northwest, a prominent area of thin rocks with a zero thickness line occurs over the Sweetgrass arch from Toole to Cascade Counties, Montana. The Sweetgrass arch is postulated as an inherited Precambrian structure, although evidence for renewed activity in Cambrian time is reported by van Hees and North (1964).

STRUCTURAL ROCK-TYPE RELATIONS

The Cedar Creek anticline trend may have been affecting sedimentation during deposition of the Deadwood, and sediments near the Canadian border are locally thicker both west and east of the Cedar Creek anticline trend. The rock-type map (pl. 4), indicates that east of the Cedar Creek and south of the Kaycee structural trend, the dominant facies is sand with shale or carbonate. West of the Cedar Creek anticline trend and north of the Kaycee structural trend, the percentage of carbonates is large enough so that no major rock type is greater than 50 percent.

The sand source for the Deadwood and equivalent rocks in Wyoming and South Dakota was the Transcontinental arch. In eastern South Dakota and North Dakota, the source of sand was the west flank of the Precambrian Canadian Shield and perhaps the Transcontinental arch. A marine environment of carbonate, shaly carbonate, and sandy carbonate sedimentation occurred locally between the southern ends of the Cedar Creek anticline trend and Nesson-Pierre trend from Meade to Bennett Counties, South Dakota.

ORDOVICIAN SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

Sedimentation was continuous in most of the study area starting with the sand and shale sequence of Middle Ordovician age, continuing with thick carbonates of Middle and Late Ordovician age, and ending with carbonate and shale sequences of Late Ordovician age. The carbonates originally were more extensive than the lower sands and overlapped the Winnipeg Formation throughout much of the region. The Red River Formation is more than 700 feet thick in the central Williston basin (pl. 5) but is truncated by Devonian erosion around the borders of the basin, and in western Montana, northern Wyoming, and in eastern South Dakota and North Dakota. In the center of the Williston basin, the Red River consists of limestone with three evaporite cycles containing anhydrite. The formation grades outward from the basin to dolomitic limestone and ultimately to a broad belt of secondary dolomite.

RED RIVER FORMATION OR EQUIVALENT ROCKS (UPPER ORDOVICIAN)

STRUCTURAL-THICKNESS RELATIONS

The thickness map of the Red River Formation (pl. 5) shows that during this time, the Williston basin became a major center of deposition. To the southwest, the basin merges with a southwest-trending trough that is connected to another center of deposition located in Carbon, Yellowstone, and Big Horn Counties, Montana, and in Park, Big Horn, and Washakie Counties, Wyoming. The trough is bordered on the north by the Central Montana uplift and the Weldon-Brockton fault trend and on the south by the Tensleep and Thermopolis fault trends. The unnamed north-trending structural trend shown from Toole to Madison Counties, Montana (pl. 1) probably represents the western margin of the Paleozoic craton. Areal emergence along this margin resulted in thinning or absence of the Red River Formation, and the associated east-trending, thin and thick deposits east of the margin are the result of Devonian erosion. An east-trending thin area from Fergus to Garfield Counties, Montana is related to the Central Montana uplift. Northeast-trending thick and thin areas are parallel to the Hinsdale, Poplar, and Weldon-Brockton fault trends in Phillips, Valley, Roosevelt, McCone, and Garfield Counties, Montana.

The Cedar Creek anticline trend is the boundary between the uniform thickening in the Williston basin and the more chaotic thick and thin areas to the west. Deposition of the Red River may have been minimal over much of the Transcontinental arch; however, pre-Late Devonian erosion may explain many of the observed thickness changes in the Red River northwest of the arch. The formation is absent over the northwest-trending spurs projecting from the arch, such as the Chadron, and at the southern end of the Nesson-Pierre trend. The Williston basin axis or depocenter is shifted to the east of and is better defined than that during Cambrian time. The most active part of the Williston basin lies between the Cedar Creek anticline trend and the Bottineau-Burleigh trend; therefore, the subsidence may have been, in part, controlled by vertical adjustments along these tectonic elements. The principal mechanism that deepened the basin during Red River time most likely was subsidence within the craton.

Northeast-trending thin areas in Kidder, Eddy, and Foster Counties, North Dakota may have resulted from renewed uplift on the Canadian Shield. Similarly trending thin areas, present in the underlying Cambrian rocks, are thought to be of similar origin. The zero thickness line of the Red River Formation (pl. 5) resulted from widespread pre-Devonian erosion and truncation of the Ordovician rocks.

STRUCTURAL ROCK-TYPE RELATIONS

The large dolomite and dolomitic limestone areas in the western one-half of plate 6 were associated with a carbonate shelf on the western flanks of the Williston basin. Similarly, dolomite is the dominant rock type in the southern and southeastern parts of the study area. The Cedar Creek anticline trend may have affected the nature of various types of rocks. It appears to have been a moderately high area with local depressions on the west flank in which limestone accumulated. Along the axis of the structure, limy dolomite and dolomitic limestone are the dominant rock types, with dolomite predominant at the northwestern end of the anticline. East of the Cedar Creek anticline trend, limestone becomes the major rock type near the deeper parts of the Williston basin. The overall effect is one of a basin concentrically banded by facies of dolomite, limy dolomite, dolomitic limestone, and limestone at the center. This sequence is the usual basinal depositional order from shallow-water to deep-water facies in the carbonate environment.

In the extreme eastern part of the area mapped on plate 6, limestone is the major rock type. The Red River Formation was thinned by erosion in this area, and it is likely that the upper dolomitic limestone facies has been removed. The high that affects thickness lines in Kidder, Eddy, and Foster Counties, North Dakota also may be responsible for the crenulated boundary separating dolomitic limestone from limy dolomite in this area.

SILURIAN SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

The zero thickness line of Silurian rocks in the Northern Great Plains is erosional everywhere and not the result of nondeposition (Gibbs, 1972). The Silurian seas probably were very widespread and may have extended eastward across the Canadian Shield to include those Silurian marine rocks in the Hudson Bay area. Except for the Silurian section near Hudson Bay, all Silurian rocks have been removed from the shield, and the original shoreline is missing. A similar absence of Silurian rocks also exists to the west and the south. The Silurian section may have covered much of western Montana and connected with the Silurian facies in the geosynclinal region farther west. No Upper Silurian rocks are present in the study area.

INTERLAKE FORMATION
(UPPERMOST ORDOVICIAN AND SILURIAN)

STRUCTURAL-THICKNESS RELATIONS

Most of the thick and thin areas of the Interlake Formation on the flanks of the Williston basin are the result of extensive pre-Late Devonian erosion (pl. 7). Some of the northeast-trending thick sediments that were deposited across the Cedar Creek anticline trend may be stromatoporoid-coral reefs that developed along the Cedar Creek high during Silurian time, but part of them probably are caused by pre-Late Devonian erosion on the high. On the east side of the Williston basin, thin and thick areas are mostly east-trending across the direction of the Bottineau-Burleigh trend. These thickness changes also are most likely a result of post-Silurian erosion.

STRUCTURAL ROCK-TYPE RELATIONS

The most striking aspect of the Interlake rock-type map (pl. 8) is the preponderance of dolomite. A northeast area of limy dolomite occurs between the Nesson-Pierre trend and Bottineau-Burleigh trend. This facies is somewhat to the south of the Williston basin depocenter that occurred during Interlake time and may have been a sag or local depression near the center of the basin. Another similar area of limy dolomite partly surrounded by shaly and limy dolomite extends southward from Towner to Foster Counties, North Dakota. This area too may have been the result of a local sag related to the Towner anticline trend (pl. 1). Other scattered, small depressions filled with more limy sediments occur in Morton, Burleigh, Kidder, and Nelson Counties, North Dakota and in a northeast direction from Meade to Carson Counties, South Dakota.

DEVONIAN SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

Rocks of Devonian age overlap much of the entire area surrounding the Williston basin and extend onto the Canadian Shield to the east. Middle and Upper Devonian clastic rocks unconformably overlie the Interlake Formation in the Williston basin and overlie Ordovician and older rocks throughout most of the Cordilleran shelf (Peterson, 1981). The Devonian is a cyclic sequence of shallow marine carbonate and evaporite rocks including some halite in the center of the Williston basin. The Devonian carbonate section becomes more limy and less porous toward the center of the basin, and the rocks are more than one-half limestone in this area. A belt of dolomite extends northwestward across Montana following the general direction of the Black Hills uplift, Miles City arch, and Central Montana uplift. The paleostructural elements may have affected the dolomitization process during Late Devonian or Early Mississippian time.

There was a general withdrawal of the sea between Silurian and Devonian time, but there is only local evidence of much warping (Pye, 1958). The Middle Devonian seas transgressed old soil zones, and the minor recessions and transgressions engulfed later Devonian soils. The soil-derived beds in the Middle Devonian are named the "First and Second red beds" by subsurface geologists. Typical marine conditions prevailed where the seas were open to circulation; however, renewed uplift along tectonic elements, and the growth of reefs and shoals restricted circulation in the central Williston basin, resulting in the halite deposits in the Prairie Formation (table 1).

MIDDLE AND UPPER DEVONIAN ROCKS

STRUCTURAL-THICKNESS RELATIONS

The Middle and Upper Devonian section gradually thickens northward from its southern limit in Wyoming across the broad Wyoming shelf that occupied northern Wyoming and southern Montana, and thickens northwesterly from the flank of the Transcontinental arch. There are two areas where Devonian rocks are thin (less than 200 feet) or absent. One lies east-southeast from Judith Basin to Custer Counties, Montana (pl. 9). This zone is along the Central Montana uplift and ends in the vicinity of the Miles City arch. The other area is along the Cedar Creek anticline trend from Harding County, South Dakota to Dawson County, Montana. These ancestral tectonic elements that affected the deposition of Devonian rocks and their subsequent Early Mississippian erosion generally are close to and parallel with related Laramide structural features. Both the Central Montana uplift and the Cedar Creek anticline trend experienced structural growth during the Devonian; and along their axis both Devonian and Silurian rocks are absent locally owing to latest Devonian or Early Mississippian erosion.

A northwest-trending thin zone occurs along the Sweetgrass arch from Cascade to Toole County, Montana; to the west, a northwest-trending thin zone occurs from Flathead to Lewis and Clark Counties. Between these two thin zones is a thicker section that extends southward from Pondera to Cascade County, Montana. These thin and thick zones are good evidence for structural activity in this area and for probable activity along the unnamed north-trending structural trend that crosses the Sweetgrass arch and Scapegoat-Bannatyne anticline in Teton County, Montana. Poplar dome alines with a northwest-trending thin zone in Roosevelt and Daniels Counties, Montana.

The main area of subsidence of the Williston basin during Devonian time is between the Cedar Creek anticline trend on the west and the Bottineau-Burleigh trend on the east. Both of these paleostructures may have been hinge lines as the intracratonic basin slowly subsided. Many of the minor crenulations along the 200- and 400-foot thickness lines in the east and southeast probably are the result of Late Devonian or Early Mississippian erosion, especially along the Transcontinental arch. According to Sandberg and Mapel (1967), Devonian rocks are faulted along the west side of the Cedar Creek anticline trend; and they further show that thickness lines are disturbed in northeastern North Dakota along the Towner anticline trend.

Thickness lines are disturbed at the northern end of the Nesson-Pierre trend where a minor thin zone extends northward toward the Devonian depocenter. Although the northern part of the Nesson-Pierre trend is a Laramide structure, the thin zone in the Devonian supports the idea that the Nesson anticline proper was an ancestral tectonic element before the Laramide orogeny. The edges of the Transcontinental arch are difficult to determine during Devonian time. The arch was subjected to widespread erosion and removal of Devonian and older rocks.

MISSISSIPPIAN SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

The Mississippian deposition in the Northern Great Plains began with the transgressing seas that deposited dark organic shale and siltstone of the Bakken Formation. The system boundary between Devonian and Mississippian generally is placed within the Bakken. The Bakken is found only in the central Williston basin and in north-central and western Montana. Rocks of the Madison Group followed Bakken deposition and, in general, consist of a threefold division based on lithology. The lower unit, the Lodgepole Limestone, consists of argillaceous, shaly or silty, thin bedded limestone. The middle unit, the Mission Canyon Limestone, is a massive, fossiliferous oolitic and crinoidal limestone; and the upper unit, the Charles Formation, consists of anhydrite and halite with interbedded carbonate rock and shale. The three gross lithologic divisions intertongue with each other. Because these lithologies are sometimes indistinct, the Madison was subdivided into

13 units bounded by marker beds that can be distinguished on geophysical well logs (Peterson, 1981). Log definition of the shaly carbonate or dark shale markers is expressed best in the central Williston basin, but many can be traced throughout the study area. The five marker beds that have proven most useful for regional correlations of the Madison Group are shown in figure 2.

Overlying the Madison in the Central Montana trough and Williston basin is the Big Snowy Group of Mississippian age. The Big Snowy Group, more than 1,000 feet thick in the Central Montana trough and more than 600 feet thick in the Williston basin, is composed mostly of clastic rocks with minor quantities of argillaceous carbonate rock.

The most prominent structural features on the map of Madison Limestone thickness (pl. 10) are the Central Montana trough and the Williston basin (Craig, 1972). Rock-thickness lines indicate that these two structurally controlled elements were the sites of deposition of thick Madison sediments.

MADISON LIMESTONE

STRUCTURAL-THICKNESS RELATIONS

In the extreme northwest part of the study area, an area of thin sediments (pl. 10) occurs between the Pendroy fault and the Scapegoat-Bannatyne anticline. Parallel east-trending thickness lines north of the Central Montana uplift and east of the Sweetgrass arch probably are related to pre-Middle Jurassic erosion on the Alberta shelf where a decrease in thickness from 1,400 to 800 feet occurs. The Mississippian expression of the Central Montana trough is evident in areas where ancestral east-southeast-trending structures such as the Cat Creek fault trend, Central Montana uplift, Big Snowy lineament, Willow Creek fault trend, and Lake Basin fault trend provided zones of structural weakness along which the trough could subside. The Central Montana trough connected the Cordilleran geosyncline to the west with the Williston basin to the east. The thickest Madison section in the Central Montana trough is in the western part of the trough in Fergus, Petroleum, Musselshell, and Golden Valley Counties, Montana. The thick east-trending section then trends northeast and approximately parallels the Weldon-Brockton fault from Garfield to Roosevelt Counties, Montana and connects with the principal thickened area of the Williston basin. Secondary structures may have been superimposed on the principal elements of the trough resulting in northwest- and north-trending thin and thick deposits in this area.

Topographic highs northwest of the Transcontinental arch, such as the Chadron arch and the Nesson-Pierre trend, may have had a thin deposit of Mississippian sediments that later was removed by post-Madison erosion. The Hartville uplift and the Nashfork-Hartville fault trend resulted in north-trending thick and thin sediments in Niobrara and Goshen Counties, Wyoming, Fall River County, South Dakota, and Sioux County, Nebraska. These thick and thin areas probably are both depositional and erosional in origin.

Again the Cedar Creek anticline trend appears to have been a high area separating the Williston basin from the shelf area to the west. Thin and thick deposits along this structural element are evidence that the Cedar Creek anticline trend affected deposition and erosion from near the Weldon-Brockton fault trend in McCone County, Montana south to Shannon County, South Dakota. The most pronounced sedimentation effects are in Fallon County, Montana and Bowman County, North Dakota. The Cedar Creek anticline trend forms the western boundary of the Williston basin. The depocenter of the Williston basin is in McKenzie County, North Dakota. The eastern and southeastern limits of the Madison are truncated erosional surfaces on the Canadian Shield and along the northwest flank of the Transcontinental arch.

STRUCTURAL ROCK-TYPE RELATIONS

The relations of paleostructures to the rock types can be determined reasonably well for the total Madison section except along the edges of the basins where the relations are uncertain because the older Madison intervals are areally more extensive than younger ones. Dolomite is the predominant facies in the southern part of the area between the Transcontinental arch and the Nye-Bowler fault trend (pl. 11). A smaller area of dolomite occurs between the Nye-Bowler and Lake Basin fault trends in Carbon, Yellowstone, Big Horn, and Rosebud Counties, Montana. This dolomite area, as well as the larger one to the south, grades into limy and shaly dolomite.

Limestone is the principal rock type on the Alberta shelf north of the Central Montana trough and in the eastern part of the trough. The limestone facies continues across the northern part of the Cedar Creek anticline trend and is the predominant facies between the Cedar Creek and the eastern limit of the Williston basin. A large area of shaly and evaporitic limestone and dolomitic limestone occurs in the northern area between the Cedar Creek anticline trend and the Bottineau-Burleigh trend in an area approximately at the center of the Williston basin.

The Cedar Creek anticline trend from Dawson County, Montana, southeastward along its extension into South Dakota, apparently was a submerged high and was a hinge line between the Williston basin and the shelf area to the west. The complex facies distribution in the western area may be associated with the ancestral east-southeast-trending structures and the downwarping of the Central Montana uplift.

MADISON INTERVAL M–1 TO M–3

STRUCTURAL-THICKNESS RELATIONS

Madison interval M–1 to M–3 is from 200 to 300 feet thick throughout most of the study area, except in the center of the Williston basin where it is as much as 500 feet thick (pl. 12). The M–1 to M–3 interval is approximately equivalent to the lower one-half of the Lodgepole Limestone (fig. 2). The lower part of the interval contains the Waulsortian crinoid mounds on the west, southwest, and east flanks of the Williston basin (Peterson, 1981). These mounds, as much as 400 feet thick, account for many of the peripheral thick zones shown on the thickness map.

In the northwestern part of the study area, thin zones are associated with the Scapegoat-Bannatyne anticline and the Bearpaw anticline. At the south end of the Sweetgrass arch and east of the Bearpaw anticline in Blaine and Phillips Counties, Montana, thick zones probably are the result of crinoid-mound development along the southern perimeter of the Alberta shelf.

The east-trending thick zones in west-central Montana show the continued development of the Central Montana trough. The northeast continuation of this thick area is between the southwest extensions of the Hinsdale fault trend and the Weldon-Brockton fault trend in Phillips, Petroleum, and Garfield Counties, Montana. The western end of the trough is complex structurally, and local tectonic elements may account for the thick and thin sediments. South of the Central Montana trough are thick and thin sediments that may be associated with the Lake Basin fault trend, Nye-Bowler fault trend, and the Gardiner fault trend. In the southwest, several northwest-trending thick and thin zones lie between the Thermopolis fault and the Black Hills uplift. The thin deposits in this area may be related to spurs off the Transcontinental arch, and the thick deposits may be the result of oölite banks and crinoid mounding. Many of the thick deposits in South Dakota also may be the product of Waulsortian crinoid mounding.

A large, stable area of continuous deposition extends from the eastern end of the Central Montana trough, crosses the Miles City arch, and extends eastward across the northern tier of counties in South Dakota. Well control is sufficiently dense in this area to verify this belt of undisturbed deposition. The Cedar Creek anticline trend is less pronounced than in former times, but it apparently affected sediment accumulation along its central part in Dawson and Wibaux Counties, Montana and Harding County, South Dakota. Part of the thickness variation along this trend may be related to growth of crinoidal mounds or oölite banks.

Three minor thick sections occur between the northern ends of the Cedar Creek anticline trend and the Nesson-Pierre trend. These thick zones are in Richland County, Montana and McKenzie County, North Dakota. The depocenter of the Williston basin for Madison interval M–1 to M–3 time was between the Cedar Creek anticline trend and the Bottineau-Burleigh trend in North Dakota. South of this area, however, is a large, thinner sedimentary section located in Dunn County, North Dakota.

A northwest spur, the southern element of the Nesson-Pierre trend, forms a large indentation containing no sediments in Jones and adjacent counties in South Dakota. This paleostructural feature recurs at several times throughout the geologic record and may be related to the Siouxia uplift that extends southwest from the Canadian Shield. In the northeast part of the mapped area, thick and thin sections may be related to the Towner anticline trend, to an unnamed structural trend south of the Towner, and to crinoidal mounding.

Thick and thin sediment sections east and west of the Bottineau-Burleigh trend indicate that the structure was active in M–1 to M–3 time. Some of the thick zones near the Bottineau-Burleigh trend also may be due to crinoid-mound development.

STRUCTURAL ROCK-TYPE RELATIONS

Dolomite is the principal facies along the southern edge of the mapped area, and it extends to the northwest on the east side of the Horn structural trend and Bighorn uplift (pl. 13). Smaller patches of dolomite are associated with structures in the Central Montana trough in Golden Valley, Musselshell, Yellowstone, Fergus, and Rosebud Counties, Montana. The dolomite facies generally grade basinward into limy and shaly dolomite, and ultimately into dolomitic limestone.

Limestone is the predominant facies north of the Central Montana trough, in the western, deeper part of the trough, and in the eastern part of the trough. The central part of the trough, probably because of complex structural conditions that affected sedimentation, contains a heterogeneous agglomeration of facies. The limestone facies is prevalent from the Miles City arch eastward across the Cedar Creek anticline trend as far as the eastern truncated edge of the M–1 to M–3 interval.

The Cedar Creek anticline trend, although it affected sedimentation, was not as pronounced a structural element as it was in earlier geologic time. The map (pl. 13), indicates that the Cedar Creek anticline trend affected sedimentation in its north-central part in

Wibaux, Dawson, and Prairie Counties, Montana and Golden Valley County, North Dakota where dolomitic limestone, shaly limestone, and shale and limy shale extend eastward across the anticline. These rock types form an easterly band to the Nesson-Pierre trend and then become a wider band trending north-northeast to the northern part of the Bottineau-Burleigh trend. This north-northeast-trending facies of shale and limy shale is east and south of the deeper part of the Williston basin.

In the southeastern area the irregular northwest facies undulations probably resulted from extensions of the Transcontinental arch that aline with the southern continuations of the Cedar Creek anticline trend and the Nesson-Pierre trend. These spurs off the arch may have created ideal conditions for the development of crinoid Waulsortian mounds and oölite banks. The Cedar Creek anticline trend, although somewhat subdued, once again acted in conjunction with the Miles City arch, the Weldon-Brockton fault trend, and the Central Montana uplift as a barrier or hinge line controlling water depth in the eastern and northern mapped area.

In the northern and northwestern mapped area, significant facies changes occur between the Poplar and Hinsdale fault trends and in the area of the Bearpaw and Scapegoat-Bannatyne anticlines. The abrupt termination of rock types along the eastern margin of the mapped area indicates that extensive truncation by erosion has occurred since deposition of the M–1 to M–3 interval.

MADISON INTERVAL M–3 TO M–7

STRUCTURAL-THICKNESS RELATIONS

The aspect of the M–3 to M–7 thickness map (pl. 14), is one of gradual thickening of the interval from south to north toward the Williston basin center and the Central Montana trough. The downwarping and easterly definition of the Central Montana trough is displayed clearly on the map. The deepest part of the trough in the west is in Fergus and Petroleum Counties, Montana, and is alined along the Cat Creek fault and to a lesser extent alined with the Bearpaw anticline. A possible downwarping of the Sweetgrass arch resulted in the north-northwest-trending thick zones observed in Cascade, Teton, Pondera, Chouteau, and Toole Counties, Montana.

The thickness lines along the southern margin of the Central Montana trough are interrupted by a northwest-trending thin zone that alines with two parallel faults inferred from gravity data (Grose, 1972). The Lake Basin fault trend may have been responsible for some of the minor thick and thin sediment sections present along the southern edge of the Central Montana trough. As noted in the M–1 to M–3 Madison interval, the northeast part of the trough is parallel to the Weldon-Brockton fault trend during M–3 to M–7 time. Rejuvenation along the Weldon-Brockton and Poplar fault trends probably formed a graben between these structures. A thick zone occurs east of the Poplar dome and probably is a basin deep resulting from structural activity related to the dome and the northeast-trending fault trends that bound the zone. A northeast-trending thin zone occurs between the north end of the Cedar Creek anticline and the Weldon-Brockton fault trends.

In the southwest mapped area, thick and thin zones, trending northwest, occur along or parallel to the Horn structural trend and Bighorn uplift. Additional thick and thin zones striking northwest to north occur along the southern mapped area and are related to the Hartville uplift, Lusk embayment, Fannie Peak and Black Hills monoclines, Black Hills uplift, and Chadron arch. Irregular uplift along the Transcontinental arch may account, in part, for some of the thick and thin zones in this area.

Both the Miles City arch and the Cedar Creek anticline trend, while active in earlier times, were fairly stable during M–3 to M–7 time, although some bending of the thickness lines along the Cedar Creek anticline trend is observed. The Nesson-Pierre trend was one of the more active structural elements during this time interval. In the north, the trend defines a series of isolated thick sediments that may be organic mounds in Dunn, McKenzie, Williams, and Divide Counties, North Dakota. The effects of both sedimentation and erosion also are evident along the central and southern parts of the Nesson-Pierre trend. Structural activity at the southern extension of the Nesson-Pierre trend was responsible for the initial abrupt thickening basinward in Jones and Stanley Counties, South Dakota. The sudden thickness changes may indicate uplift and erosion due to faults associated with the Nesson-Pierre trend in this area. Structural activity, manifested by thickness changes and the zero line, has been noted in this area in several of the older geologic units.

The Bottineau-Burleigh trend, as in previous geologic times, was active and again appears to mark the eastern boundary of the basin depocenter. A northwest-trending, unnamed lineament and its northward extension is related to similarly oriented thick and thin zones between the Nesson-Pierre and the Bottineau-Burleigh trends.

STRUCTURAL ROCK-TYPE RELATIONS

Limestone is the predominant rock type covering most of the area from northern Montana, eastward across northern North Dakota (pl. 15). Minor, isolated areas of limestone occur in the southern part of the

Central Montana trough in the area of the northwest faults inferred from gravity data in Treasure, Yellowstone, and Musselshell Counties, Montana. The limestone lithology continues eastward across the northern part of the Cedar Creek anticline trend and covers most of the area east of the trend. Tongues of dolomitic limestone and shaly dolomite north of the Central Montana uplift trend northwest along the southern part of the Bearpaw anticline and east of the Bearpaw in Blaine, Phillips, Garfield, and Petroleum Counties, Montana. As in M–1 to M–3 time, the lithologies in the central part of the Central Montana trough are heterogeneous in M–3 to M–7 time, possibly due to complex structural effects.

Isolated areas of shaly limestone and evaporitic limestone occur between the Hinsdale and Poplar fault trends and in the northern part of the Poplar dome. Dolomite is the dominant rock type from the southwestern and southern area, north to the Central Montana trough, east to the Miles City arch, and east to the southern end of the Cedar Creek anticline trend. In the western mapped area, dolomite grades into deeper-water facies consisting of limy and shaly dolomite with en echelon tongues of the deeper-water facies occurring easterly along the Lake Basin and Nye-Bowler fault trends and along the Gardiner fault trend.

Deeper-water facies (limestone) occur across the Miles City arch and the Cedar Creek anticline trend beginning north of the northeastern part of the Kaycee structural trend. The Kaycee structural trend coincides approximately with the northern limit of the main belt of dolomite deposition in this general area. The Miles City arch and to a lesser extent, the Cedar Creek anticline trend were structurally active during M–3 to M–7 time in the area bounded by the two structures from Butte County, South Dakota to Wibaux County, Montana.

A northeast-trending graben may have developed between the Hartville uplift and the northeastern part of the Casper Mountain fault in Platt and Niobrara Counties, Wyoming. Deeper-water facies (limestone and dolomitic limestone) were deposited southwest of the Chadron arch and southeast of the Nashfork-Hartville fault trend. Occurrence of dolomite is minimal east of the Cedar Creek anticline trend, and it occupies an area southeast of the intersection of the Cedar Creek and the Kaycee structural trend to approximately the southern part of the Nesson-Pierre trend. The southern part of the Nesson-Pierre trend, from Stanley to Corson Counties, South Dakota was structurally active and had a significant effect on sedimentation and rock types, because evaporitic-dolomitic limestone occurs in this area. An unnamed northwest-trending lineament between the Nesson-Pierre and Bottineau-Burleigh trends in Corson, Walworth, Potter, and Sully Counties, South Dakota, may account for the facies distribution in the southeastern part of the mapped area. Activity along the southeastern end of the Bottineau-Burleigh trend is indicated by the facies distribution in Logan, Emmons, Burleigh, and Kidder Counties, North Dakota.

An arcuate area of shaly limestone and evaporitic-dolomitic limestone occurs near the southwestern part of the Towner anticline trend in Pierce County, North Dakota. The abrupt termination of facies at the eastern and southeastern limits of the M–3 to M–7 unit are the result of erosion and consequent removal of the M–7 marker bed east of the limit line.

MADISON INTERVAL M–7 TO M–8.5

STRUCTURAL-THICKNESS RELATIONS

The thickness map of M–7 to M–8.5 time (pl. 16) depicts a broad, stable, area of deposition with a gradual thickening to the north along the Canadian border in North Dakota. Several local tectonic events and pre-Middle Jurassic erosion disturbed this area, but not to the extent that occurred during earlier intervals of Madison time.

A northeast-trending thick zone occurs in a trough between the Pendroy fault and the Scapegoat-Bannatyne anticline in Pondera, Toole, and Liberty Counties, Montana. A minor thick zone, trending slightly east of north, crosses the Bearpaw anticline and may be related to this structure. Thick and thin zones are associated with a probable fault (from gravity data) that extends east-northeast in Blaine and Phillips Counties, Montana. Other minor thick and thin zones are associated with the northeast-trending Hinsdale, Poplar, and Weldon-Brockton fault trends. Many of the thin zones described may be in part the result of pre-Middle Jurassic erosion as well as the result of geologic structure.

The Central Montana trough is broader, more diffused, and less complex than in earlier intervals of Madison time, possibly because the area had been smoothed by deposition of the M–8.5 evaporites. Some scattered, localized thick zones occur in basinal deeps along east-southeast-trending structural elements. In the southwestern part of the trough, a thin zone occurs along the western part of the Lake Basin fault trend. Northwest-trending thick and thin zones occur near the intersection of the Lake Basin fault trend and two northwest-trending faults determined from gravity data. A west-northwest-trending thin zone in Park County, Wyoming, may be related to the Gardiner fault trend and the Nye-Bowler fault trend.

In the southeast, the north-northwest thickness variations may be extensions from the rejuvenated Transcontinental arch. Some, however, may be the result of carbonate-mound development or erosion. Renewed movement on the Horn structural trend, Bighorn uplift, Hartville uplift, Fannie Peak, and Black Hills monoclines, an unnamed anticlinal structure west of the Black Hills monocline, the Black Hills uplift, and the Miles City arch may account for some of the thickness changes.

Activity along the Cedar Creek anticline trend was very subdued, and the only significant depositional changes occur from Harding County southeastward to Pennington County, South Dakota. The Williston basin is diffuse and not as clearly defined as during earlier intervals. The depocenter of the basin was in Canada, north of the mapped area. Northwest-trending thick and thin zones occur along the Nesson-Pierre and Bottineau-Burleigh trends and along a lineament between the two trends.

In general, thin and thick deposits of sediment have a more consistent pattern east of the Cedar Creek anticline trend. In this area, the tendency is for trends to be oriented northwest and for sediments to thicken in this direction. The thickest section is in Canada, north of the North Dakota border. West of the Cedar Creek anticline trend, the dominant trends are easterly, with northerly directions becoming more common south of the Central Montana uplift. The section thins both to the northwest and to the south of the trough, in part because of postdepositional erosion.

STRUCTURAL ROCK-TYPE RELATIONS

Limestone is the dominant rock type in the northern mapped area extending east and southeast from Pondera County, Montana, into northwest North Dakota (pl. 17). In the northwest area, north of and paralleling the Cat Creek fault trend, the facies grades from limy and shaly dolomite to dolomitic limestone and limestone. Some control on facies is shown by the northeast-trending structural elements including the Pendroy fault, Scapegoat-Bannatyne anticline, and the probable fault that is indicated by gravity data east of the Bearpaw anticline in Blaine and Phillips Counties, Montana. A more subdued structural control of rock type can be seen along the southern ends of the Hinsdale, Poplar, and Weldon-Brockton fault trends.

A heterogeneous facies distribution again is found in the western part of the Central Montana trough, probably the result of structural adjustments between the Cat Creek and Lake Basin fault trends. Between these trends, in the western and central part of the trough, is an extensive east-trending band of evaporitic dolomite and limy and dolomitic evaporite. This band is interrupted locally by other facies ranging from limy and shaly dolomite to limestone and in some places by zones containing no rock types greater than 50 percent. Eastward, the evaporites grade into shaly limestone, evaporitic limestone, and into the evaporitic-dolomitic limestone that continues eastward across the Cedar Creek anticline trend into North Dakota. The evaporitic-dolomitic limestone, in addition to limestone, constitutes the predominant rock type between the Cedar Creek anticline trend and the Bottineau-Burleigh trend. The evaporitic rocks are bounded on the northeast by rock types where no rock type is greater than 50 percent.

Dolomite was less extensive in M–7 to M–8.5 time than in previous Madison intervals. In the west, dolomite begins south of the Lake Basin fault trend in Yellowstone County, Montana and continues southeastward until it grades into deeper-water facies east of the Cedar Creek anticline trend in Butte, Meade, Pennington, and Custer Counties, South Dakota. No dolomites were mapped east of the Cedar Creek anticline trend.

The western, southwestern, and southern limits of dolomite rocks are very irregular, and no dolomite was mapped in the area bounded by the Nye-Bowler fault trend, Bighorn uplift, and Tensleep fault trend. This area (the Bighorn basin), which contains the Gardiner fault trend, is characterized by deeper-water facies, notably dolomitic limestone and limestone. A large, basin-shaped area in Converse and adjoining Counties in Wyoming (possibly the incipient Powder River basin) shows a similar gradation from dolomite to deeper-water facies such as limy and shaly dolomite and limestone. This basin is bounded by the Horn structural trend and Bighorn uplift on the southwest, the Kaycee structural trend on the northwest, the Black Hills and Fannie Peak monoclines on the northeast, and the Hartville uplift on the southeast. Dolomites also grade into deeper-water limestone facies southeast of the Nashfork-Hartville fault trend. Dolomitic limestone and evaporites are the dominant rock type east of the Cedar Creek anticline trend and south of the evaporitic belt previously noted. Localized areas of limestone occur along both flanks of the southern part of the Nesson-Pierre trend.

MADISON INTERVAL M–8.5 TO M–12

STRUCTURAL-THICKNESS RELATIONS

The Cedar Creek anticline trend was the most prominent structural control as far north as McCone County, Montana, during this time interval because it separated the Central Montana trough area to the west from the Williston basin to the east (pl. 18). East of the Cedar

Creek there is a general thickening from south to north into the Williston basin. West of the Cedar Creek the sediments thicken into the Central Montana trough from both the north and the south. The thickest section in the Central Montana trough is in the western-most area in Judith Basin, Fergus, and Cascade Counties, Montana. This northward shift of sediment thickness within the Central Montana trough may mark the beginning of the Big Snowy trough. During earlier episodes of Madison deposition, the thickest sediments occupied a more southerly position. This thick zone lies between the western ends of the Cat Creek and Willow Creek fault trends. The less pronounced trough trends easterly between the Cat Creek and Lake Basin fault trends to the vicinity of the Miles City arch. An arm of the trough turns northeastward through Garfield, McCone, and Roosevelt Counties, Montana, and is parallel to the Poplar and Weldon-Brockton fault trends. These trends appear to affect the termination of the Cedar Creek anticline trend and provide the avenue by which the trough was able to cross the trend of the Cedar Creek anticline and merge with the Williston basin.

In the extreme northwest mapped area, the Pendroy fault and Scapegoat-Bannatyne anticline were active, resulting in a southwest-dipping half graben. Also in this northwest area uplift, possibly the effects of pre-Middle Jurassic erosion on the Alberta shelf resulted in thinning of the M–8.5 to M–12 interval of Madison rocks.

A local area of nondeposition or erosion occurs in the eastern end of the Lake Basin fault trend at the intersection with two northwest-striking faults indicated by the gravity data. Activity along these two northwest-trending structural elements was indicated during previous intervals, indicating that they had a significant effect during deposition of the Madison. For the interval M–8.5 to M–12 they probably have a greater extension to the northwest than is indicated on plate 1, because thickness lines are affected as far north as Petroleum County, Montana.

Other ancestral structures that appear to have affected deposition in the west and southwest include the Nye-Bowler fault trend, Bighorn uplift, and Rosebud arch. A northeast-trending zero thickness area begins near the intersection of the first three paleostructures and occurs along the Rosebud arch. In the south-central mapped area, the Black Hills monocline and Black Hills uplift affected sedimentation as indicated by the northwest-trending thin and thick regions. Throughout the southern area, undulations or spurs extended northwestward from the Transcontinental arch. The Williston basin again becomes more clearly defined during this interval, deepening to the north and bounded on either side by the Cedar Creek anticline trend and Bottineau-Burleigh trend.

STRUCTURAL ROCK-TYPE RELATIONS

The reactivation and significance of the Cedar Creek anticline trend during M–8.5 to M–12 time is clearly indicated by the difference in rock types east and west of the trend (pl. 19). West of the Cedar Creek, a complex and random pattern of rock types ranging from dolomite to limestone is predominant. East of the Cedar Creek, evaporitic rocks and heterogeneous rock types with no rock type greater than 50 percent predominate. The area east of the Cedar Creek anticline trend was more quiescent with restricted circulation of seawater, and a large area of evaporite occurs between the Nesson and Bottineau anticlines. Part of this may be due to previous development of carbonate bodies along the Cedar Creek anticline trend, thus creating an imperfect barrier to seawater entering the main basin.

West of the Cedar Creek anticline trend, deposits of limestone and dolomitic limestone are more common than dolomite, and the relation of rock types to ancestral structures is questionable. East, southeast, and northeast orientations of rock facies are common. An irregular, fairly extensive area of limestone occurs north of the Central Montana trough in the vicinity of the Cat Creek fault trend. More limestone occurs in the central and eastern parts of the trough.

MADISON INTERVAL M–12 TO MC

STRUCTURAL-THICKNESS RELATIONS

Two salient features of the thickness map (pl. 20) are the less extensive area of deposition during M–12 to Mc time and a more clearly defined Williston basin. The Cedar Creek anticline trend was less of a positive feature than formerly, but it was still well pronounced in the northern part in Dawson and McCone Counties, Montana, where it defined the western border of the depocenter.

The Central Montana trough contains a thinner section of sediments than in the previous intervals of time, partly because of postdepositional erosion of the interval. In the western and central parts of the trough, it is narrower than in earlier intervals, trending east-northeast through Park, Wheatland, Golden Valley, Musselshell, and Petroleum Counties, Montana. The thickest section in the trough is in the northeastern part of Wheatland County. In Garfield County, Montana, an arm of the Central Montana trough trends northeast in response to renewed activity along the Weldon-Brockton and Poplar fault trends. The northern end of the Cedar Creek anticline trend was active, as it interrupted the northeastern arm of the trough and formed the western margin of the Williston basin. The Cedar Creek anticline trend extended across the Weldon-Brockton, Poplar, and Hinsdale fault trends.

In the Alberta shelf area to the northwest, the absence of the M–12 to Mc unit is due to pre-Middle Jurassic erosion. In the southwestern mapped area, the Lake Basin fault trend at least partly was a controlling structural element at the southern border of the Central Montana trough. To the east and south, the two parallel northwest-trending faults (from gravity data) were active, as was the Rosebud arch that plunged to the northeast. The Kaycee structural trend may have created a northeast-trending thick zone from Campbell and Crook Counties, Wyoming, to the Cedar Creek anticline trend in Butte County, South Dakota. The M–12 to Mc interval is an imperfect chronostratigraphic unit, not nearly so useful for time-structural predictions as the previous intervals, because it has a widespread unconformity at the top in all areas except the Central Montana trough and the Williston basin.

The southern flank of the Williston basin is a broad, gently sloping shelf area. The northern border of the shelf approximately coincided with the southern edge of the Charles salt (informal subsurface usage). North of the shelf, the section rapidly thickens into the Williston basin depocenter. Some of the abrupt changes in thickness of the M–12 to Mc interval in the Williston basin may be the result of postdepositional solution of the bedded halite that makes up a large part of the Charles Formation in this area.

West of the Bottineau-Burleigh trend, significant thick and thin zones trend northwest in the shelf area described previously. These thickness undulations are related to postdepositional erosion and perhaps, to an unnamed northwest-trending lineament between the Nesson-Pierre and Bottineau-Burleigh trends.

STRUCTURAL ROCK-TYPE RELATIONS

The northern part of the Cedar Creek anticline trend, from approximately the southern boundary of Dawson County, Montana, to its probable extension northward across the Weldon-Brockton, Poplar, and Hinsdale fault trends, was the most significant structural element controlling facies to the east and to the west (pl. 21). East of this part of the Cedar Creek anticline trend to about the position of an unnamed lineament between the Nesson-Pierre and Bottineau-Burleigh trends, a vast area of evaporite and dominantly evaporitic rocks were deposited. The southern and southeastern margins of these deposits are arcuate, approximately congruent with the area where the dip of the shelf (see discussion of the structural-thickness relations) increases into the Williston basin.

Rock types east of the Cedar Creek anticline trend are quite different from those to the west and southwest. In general, carbonate rocks predominate to the west and evaporites to the east. Limestones and dolomitic limestones near the Cedar Creek anticline trend grade into shaly limestone and evaporitic limestone and dolomite that cover most of the gently dipping shelf area northeastward as far as the Bottineau-Burleigh trend. Evaporitic facies predominate in the basin center and along the southeastern margin of the basins.

In the western part of the Central Montana trough, the rock facies are mainly dolomitic limestone and limestone, although irregular areas of shaly limestone and evaporitic limestone and dolomite occur. Discontinuous patches of dolomite occur along both the northern and southern borders of the trough; however, the dolomitic areas certainly were more extensive prior to post-Mississippian uplift and erosion. The usual basinal depositional order from dolomite to limy and shaly dolomite and then to dolomitic limestone and limestone is not found in this area due to either the lack of detailed well-control points or to erosion of the sedimentary section. Because the sedimentary section is thin here, the presence of even a 10– or 20–foot-thick bed might alter the modifier of a rock type. Small, irregular areas of evaporitic rocks and areas where no rock types are greater than 50 percent are distributed randomly in the Central Montana trough and may be indicative of the lack of control, the thinness of the section, and the possibility of complex structural activity.

To the east, along the south flank of the Central Montana trough, the distribution of rock types is less complex, and the more usual depositional order from shallow- to deep-water facies prevails. A southeast-trending belt of dolomite extends from Treasure County, Montana to Meade County, South Dakota, and may be an erosional remnant of a once more extensive dolomite belt along the southern rim of the basin. Southwest-trending embayments containing dolomite coincide with the Rosebud arch and the Kaycee structural trend. Northward in Treasure County, Montana, dolomite grades to limy and shaly dolomite, dolomitic limestone and limestone. Between Powder River County, Montana and Meade County, South Dakota, the dolomite facies grades northeastward into dolomitic limestone and to limestone.

The limestone terminates in the east in Adams County, North Dakota, and except for isolated patches of this facies along the southeastern and northern mapped area, no important areas of limestone occur in the Williston basin area. Most of the rocks bordering the evaporites in the deeper part of the Williston basin are shown as having no constituent greater than 50 percent; however, evaporitic rock types are known to be present in this area.

BIG SNOWY GROUP

STRUCTURAL-STRATIGRAPHIC RELATIONS

The Big Snowy Group, now present only in the Central Montana trough and Williston basin, was more widespread than shown on plate 22. Post-Mississippian erosion or nondeposition in north and south-central Montana and around the periphery of the Williston basin reduced the areal distribution to the present boundaries (Peterson, 1981). These rocks, primarily clastic sediments containing minor quantities of fine-grained argillaceous carbonate rock, are primarily near-shore or restricted marine deposits.

STRUCTURAL-THICKNESS RELATIONS

The Central Montana trough was considerably narrower in Big Snowy time (pl. 22) than in the previously discussed Madison intervals. The trough extends eastward into the Williston basin, but the thickness of sediments in the trough is much greater than that in the basin. Much downwarping along east-southeast-trending structural elements, the Cat Creek fault trend, Central Montana uplift, Big Snowy lineament, and Willow Creek fault trend, accounts for the thicker sedimentary section and the development of two distinct basins in the western and central parts of the trough. These basins, containing in excess of 1,000 feet of sediments, occur mainly in Judith Basin and Petroleum County, Montana. The dips into these basinal areas from the margins of the Central Montana trough are steep, especially along the northern trough boundary. In Garfield and McCone Counties, Montana, the trough turns northeast, apparently controlled by activity along the Weldon-Brockton and Poplar fault trends.

The northern extension of the Cedar Creek anticline trend had little effect on the easterly trough into the Williston basin depocenter. The depocenter of the basin was in McKenzie and Dunn Counties, North Dakota where sediments in excess of 600 feet were deposited. Other localized basinal depressions with more than 600 feet of Big Snowy rocks occur to the north in Williams County, North Dakota and along the northern part of the Cedar Creek anticline in Wibaux and Dawson Counties, Montana.

The general shape of the Williston basin east of the Miles City arch is circular. Thick and thin zones in the mapped area between the Cedar Creek anticline trend and the Bottineau-Burleigh trend are oriented basinward from the southern, eastern, and northern present-day limits of Big Snowy rocks. The Bottineau-Burleigh trend appears to have limited the eastern border of the basin at this time. Many of these thick and thin sediments are due to post-Mississippian erosion, and many also may be caused by the dissolution of the underlying evaporite beds in the M–12 to Mc Madison interval.

STRUCTURAL ROCK-TYPE RELATIONS

Clastic rocks, mostly shale, sandy shale, and small areas of calcareous shale were deposited throughout the mapped area during Big Snowy time (pl. 23). In the areas of thick sediment accumulation in the Central Montana trough, calcareous shale is the predominant rock type. These calcareous rocks generally grade eastward into sandy shale and grade northeastward, along the Weldon-Brockton fault trend, into shale.

So much of the Big Snowy Group has been removed from the area by post-Mississippian uplift and erosion that it is difficult to relate facies changes to major tectonic elements. An example of the difficulty is demonstrated along the southern and southeastern margins of the mapped area, where an extensive band of shale grades basinward, in seemingly anomalous sequence, to calcareous shale and then to sandy shale. A more normal basinward sequence would be from sandy shale to shale to calcareous shale.

PENNSYLVANIAN AND PERMIAN SYSTEMS

STRUCTURAL-STRATIGRAPHIC RELATIONS

Pennsylvanian time marked the growth of many paleotectonic elements that affected most of the study area. Many older features were rejuvenated, and an unnamed structural trend in Powder River and Rosebud Counties, Montana appeared during this time. Major structural elements that affected Pennsylvanian and Permian sediments were the Wyoming shelf, Bighorn uplift, Williston and Powder River basins, Miles City and Chadron arches, Central Montana trough, Alberta shelf, and smaller, northwest-trending spurs off the Transcontinental arch.

Pennsylvanian rocks unconformably overlie Mississippian rocks in most of the study area; however, in the Central Montana trough and in the center of the Williston basin, the system boundary is difficult to pick, and the rocks may be conformable. The Pennsylvanian and Permian rocks are treated as a single unit in this report, because the boundary between them is within the Minnelusa Formation in the Williston and Powder River basins, and in western South Dakota. Permian rocks are truncated extenisvely by Triassic and younger rocks in central Montana and around the eastern and northern flanks of the Williston basin (Peterson, 1981).

STRUCTURAL-THICKNESS RELATIONS

The continued effect of the Cedar Creek anticline trend is shown prominently by the northwest alinement of thickness lines on plate 24. The trend again was a hinge line separating major depositional areas to the east and west, and it was an abrupt, western boundary of the central part of the Williston basin. The closeness of thickness lines in Dawson, Prairie, and Fallon Counties, Montana indicates a fault along the west side of the Cedar Creek anticline trend.

In central Montana, the Cat Creek fault trend, which was the northern limit of deposition in Big Snowy time, also was active in Pennsylvanian and Permian time and formed the northern depositional or perhaps truncation limit for these rocks. Beginning in Garfield County, Montana, the Weldon-Brockton fault trend again controlled a northeast-trending depositional environment. A probable half graben, between the Weldon-Brockton and Poplar fault trends, appears to deepen from McCone County northeastward into Roosevelt County, Montana.

The Central Montana trough is no longer a clearly defined structural element on thickness maps of the Pennsylvanian and Permian; however, the northern boundary of the trough occupies the same general position that it did during Big Snowy time, although thick and thin deposits indicate possible effects of the ancestral east-southeast-trending structures that occur between the Cat Creek fault trend and the Gardiner fault trend. Northwest-trending thick and thin sediments in the central mapped area probably resulted from deposition on the downdropped sides of minor faults. These north- and northwest-trending thick and thin sediments occupy the area between the two parallel faults (mapped from gravity data) and the Cedar Creek anticline trend. The major directions in this area are associated with a hitherto unmapped Pennsylvanian and Permian structural trend that parallels the Miles City arch, which also was structurally active at this time. Subsequent erosional episodes may have enhanced the contrast between the northwest-trending thick and thin sediments by stripping off more of the thin sediments on the elevated sides of the faults. Northerly trending thin sediments are prominent features that occur in the area west of the Horn structural trend and south of the Thermopolis fault in Wyoming.

The development of the ancestral Powder River basin is evidenced by southeasterly thickening of sediments between the Horn structural trend and the Black Hills uplift. Thickening increases rapidly from the Horn structural trend northeastward into a basinal deep in Niobrara County, Wyoming, where a 1,500–foot accumulation of Pennsylvanian and Permian rocks occurs. This depocenter is separated from a more regional thickening of sediments to the southeast by the Nashfork-Hartville fault trend. The fault appears to be associated with a low arch dividing the smaller, Niobrara County basinal deep from a larger deep centered in northwestern Nebraska. Between the Nashfork-Hartville fault trend and the Chadron arch, the Pennsylvanian and Permian rocks thicken rapidly southeastward from less than 1,400 to more than 2,200 feet in the northwestern Nebraska depocenter, which is probably the ancestral Julesburg basin.

A northwest-trending thin zone, centered in Bennett, Washabaugh, and Todd Counties, South Dakota, occurs between the southern extensions of the Cedar Creek anticline trend and the Nesson-Pierre trend. The northwestern limit of this thin area is bordered approximately by the Nashfork-Hartville fault trend. Pennsylvanian and Permian sediments have been removed from this apparent bedrock high by erosion. The abrupt thickness changes in this area are evidence that the southern extensions of the Cedar Creek anticline trend and the Nesson-Pierre trend were faults at this time.

The axis of the Williston basin trends approximately northward with a fairly slight thickening gradient from central South Dakota to southern North Dakota. The gradient steepens abruptly from southern North Dakota into the depocenter. In fact, steepening thickness gradients generally surround the Williston basin depocenter; again, the Bottineau-Burleigh trend may have been effective in limiting the eastern border of the basin.

STRUCTURAL ROCK-TYPE RELATIONS

Detailed facies analysis and the relation of rock types to major structural elements is depicted poorly for the Pennsylvanian and Permian rocks, because most of the mapped area on plate 25 is shown as rock types in which no major rock type is greater than 50 percent. This could result from the interval including too much section, because if three rock types were to occur in an area and no one of them was greater than 50 percent of the total thickness, then the vertical pattern would appear on the map. When rocks are divided into thinner units along chronostratigraphic boundaries, the chances of this pattern appearing are less likely because the time lines would follow the usual basinal depositional order. Shaly and sandy carbonates with minor areas of carbonates and calcareous or evaporitic shale are the dominant rock types in the western and northern mapped area. These facies, between the Cat Creek and Nye-Bowler fault trends in the west, continue northeastward where they are bordered by the Weldon-Brockton and Poplar fault trends. The eastern mapped area is bordered by calcareous shale and sandy, calcareous, or evaporitic shale.

TRIASSIC SYSTEM

STRUCTURAL-STRATIGRAPHIC RELATIONS

Triassic rocks overlie sediments of Permian age in south-central Montana, the Powder River basin, the Williston basin, and in western South Dakota. Triassic beds are truncated by pre-Middle Jurassic erosion along the south and east margins of the Alberta shelf and on the east side of the Williston basin.

STRUCTURAL-THICKNESS RELATIONS

In the western mapped area, plate 26, the northern limit of Triassic rocks is considerably south of the limits of the Pennsylvanian and Permian rocks due to erosional offlap. The dominant pattern of the Triassic thickness lines is one showing two basins separated by a broad, high area, which includes the Miles City arch and the Cedar Creek anticline trend. The southwest basin is distinct in outline and attains its greatest thickness in a southwesterly direction from Campbell to Natrona Counties, Wyoming. The northeast basin is less distinct, with discontinuous thick sections in southwestern and northwestern North Dakota, in part due to pre-Middle Jurassic erosion.

In the western mapped area, the Triassic rocks thicken from Stillwater County, Montana, southward to Hot Springs County, Wyoming where more than 1,100 feet of sediments were deposited. The greatest thickening occurs southwest of the Horn structural trend and west of the Bighorn uplift.

Lying between the Bighorn uplift and the Black Hills monocline is a northerly trending thick zone with more than 800 feet of Triassic rocks in Campbell County, Wyoming. North and southeast of this local thick section the rocks thin gradually toward the limits of the Triassic.

Triassic depositional patterns were affected by the Weldon-Brockton, Poplar, and Hinsdale fault trends and by the northwestern extension of the Cedar Creek anticline trend. The mapped limits of Triassic rocks changes from easterly to a more northerly direction from Rosebud County to the Canadian border. A northwestward-plunging embayment or graben between the Hinsdale and Weldon-Brockton fault trends terminates in a local deep containing more than 400 feet of sediments in Divide County, North Dakota. This thick zone is the maximum localized sediment deposit in the poorly defined Williston basin. Other localized deeps containing in excess of 300 feet of Triassic rocks are mapped along the east side of the Cedar Creek anticline trend in Bowman, Slope, and Golden Valley Counties, North Dakota, and southeast of the Weldon-Brockton fault trend in Richland County, Montana, and Williams County, North Dakota. A broad area containing more than 300 feet of sediments occurs in the northern mapped area at the north end of the Nesson-Pierre trend. The Nesson-Pierre was a negative structural element during Triassic time. Crenulations in the thickness lines in the eastern mapped area reflect the uplift along the Canadian Shield and subsequent pre-Middle Jurassic erosion.

STRUCTURAL ROCK-TYPE RELATIONS

The Triassic rock-type map, plate 27, indicates that ancestral structures had little effect on the facies distribution. Principal paleostructures, such as the Cedar Creek anticline trend, Bighorn uplift, and Williston basin generally are crossed by the facies trends with little regard for the position of the structures. Shale and sandy shale are the dominant types in the mapped area, with an east-trending band of shale from Powder River County, Montana to Corson County, South Dakota interrupted by north-trending prongs of sandy shale being the salient characteristic.

Shaly evaporites were deposited in a limited area in the poorly defined Williston basin. The evaporites are east of the Cedar Creek anticline trend in Billings, Slope, and Bowman Counties, North Dakota. Evaporitic shale and sandy shale grade into the evaporites in this area.

Shaly sandstones are distributed randomly to the north and south of the dominant east-west shale belt and become more pronounced in the Williston basin. Isolated sandstone deposits are more prevalent in the east and northeast mapped area, indicating the proximity to a source along the Canadian Shield.

POROSITY

GENERAL COMMENTS

Porosity in the Madison Limestone is discussed for each of the five chronostratigraphic units. The distribution of porosity in the lower three chronostratigraphic units generally follows the flanks of the Williston basin. Areas of porous rock are much smaller in the upper two chronostratigraphic units and in fact are restricted to minor, localized patches of porosity in the uppermost unit.

The main factors controlling porosity are: (1) The distribution of primary porosity in the various depositional facies; (2) the development of secondary porosity related to dolomitization or dissolution of calcium carbonate; and (3) the development of fracture porosity during post-depositional tectonism.

Some porosity development is related to structural elements, although it is not certain whether the porosity resulted from depositional directions contemporaneous with structural movement or from postdepositional structural activity. Porosity distributions that are related to structures can be seen in the various chronostratigraphic units along the Cedar Creek anticline trend, the Nesson-Pierre, and Bottineau-Burleigh trend, the Weldon-Brockton, Poplar, and Hinsdale fault trends, and along the Bighorn uplift. It is likely that much of the dissolution of calcium carbonate in Madison rocks, especially in the exposed areas, occurred during Cenozoic time.

The most dominant porosity pattern is an arcuate configuration that rims the Williston basin. The widest porosity belts occur in the east, south, and west parts of the mapped area. Some of the porosity is related to the extensive dolomitization that pervades Madison rocks in these areas, and some, no doubt, is related to postdepositional solution by ground water. Long-term exposure to erosion may result in areally distributed karst which overwhelms and obscures the smaller scale primary depositional and secondary solutional aspects of rock porosity. According to Sando (1974) the ancient karst surface developed on the Madison Limestone is a widespread feature. Karst features can be categorized as enlarged joints, sinkholes, caves, and two areally extensive solution zones. The upper solution zone of Sando correlates with the Madison interval M–12, and this lower solution zone correlates with the Madison interval M–8.5 of this report.

SPECIFIC CHRONOSTRATIGRAPHIC INTERVALS

MADISON INTERVAL M–1 TO M–3

Large areas of porous rocks in this chronostratigraphic unit are distributed widely along the eastern, southern, and western parts of the mapped area (pl. 28). Generally, the areas of greatest porosity development trend north and northwest.

Both primary and secondary porosity are associated with oölite banks and crinoid mounds along the eastern and southern flanks of the Williston basin. Ancestral structures that may have provided favorable environments for enhanced porosity include the Bottineau-Burleigh trend, the unnamed lineament between the Bottineau-Burleigh and Nesson-Pierre trends, and the southern part of the Nesson-Pierre trend. The wide porosity belt in the eastern mapped area continues northward into Canada.

Porosity appears to parallel the Cedar Creek anticline trend and the southwestern extension of the Weldon-Brockton fault trend. However, it needs to be pointed out that these do not necessarily indicate a relationship to paleostructural activity. Other porosity directions such as the northeasterly trend in McKenzie County, North Dakota and the northerly trend from Butte County, South Dakota to Billings County, North Dakota cannot be related to known ancestral structures. The porosity of carbonate rocks is determined by many factors ranging from the primary depositional aspects to secondary dolomitization and solutional effects, and it is, therefore, difficult to isolate geologic structure as a discrete mechanism. The large areas of porous rock in the west and southwest are associated with the Bighorn uplift and the complex of geologic structures to the north.

MADISON INTERVAL M–3 TO M–7

A wide band of porosity in the eastern mapped area extends northward to the Canadian border during the M–3 to M–7 interval (pl. 29). This porosity zone occupies somewhat the same area as a similar, but smaller zone during the previous interval of Madison time. Porosity development along the Cedar Creek anticline trend is more pronounced than in M–1 to M–3 interval, and a narrow band of porosity follows the structure from Meade County, South Dakota to McCone County, Montana. South and east of the Cedar Creek anticline trend a continuous, arcuate band of porosity extends to the area of the unnamed lineament between the Nesson-Pierre and Bottineau-Burleigh trends.

Porosity is developed in the vicinity of the Miles City arch in Powder River, Rosebud, and Carter Counties, Montana. A northwest-trending band of porosity begins at the north end of the Bighorn uplift and continues to the Canadian border. This band indiscriminately crosses all the east-southeast-trending structures from the Nye-Bowler fault trend on the south to the Cat Creek fault trend on the north. This lack of correspondence of porosity to known structures indicates the difficulty in attributing porosity to a single mechanism. Some areas of porous rock appear related to the Weldon-Brockton and Poplar fault trends because some trends of porous rock are clearly alined with these structures.

The overall porosity pattern for M–3 to M–7 is similar to that of M–1 to M–3 except that the areas with porosities of 15 percent or greater are larger. The north-trending area of porous rock in the western mapped area is more extensive, extending to the Canadian border.

MADISON INTERVAL M–7 TO M–8.5

Porosity distribution in the M–7 to M–8.5 interval is similar to that in the previous two intervals of the Madison except that the arcuate pattern around the Williston basin is very pronounced (pl. 30). The wide areas of porosity in the east and west mapped areas now are connected in the south by an east-trending band of porosity. This east-trending band of porosity has well developed northwest-trending spurs both to the east and west of the Miles City arch.

The Cedar Creek anticline trend appears to have had less effect on porosity in the M–7 to M–8.5 interval, because porosity associated with it is much less prominent than in the previous Madison units. North of the Central Montana trough, porosity bands appear to be related to the southwest extensions of the Hinsdale and Poplar fault trends. Within the trough, the porosity pattern is generally oriented in a northerly direction and bears little relation to the east-southeast-trending ancestral structures. Some of the trends of the porous rocks may be related to oölite facies (Peterson, 1981) with significant primary porosity that was not decreased by diagenesis.

MADISON INTERVAL M–8.5 TO M–12

Porosity distribution during the M–8.5 to M–12 interval was much less compared to the previous Madison intervals (pl. 31). Most of the porosity in the 10 percent range occurs in the eastern mapped area, between the Nesson-Pierre and Bottineau-Burleigh trends. The porosity band is narrow and does not extend east of the Bottineau-Burleigh trend.

A linear band of porosity occurs along or near the Cedar Creek anticline trend, continues to the south and east, and connects with the porosity band in the eastern mapped area. This whole complex of porosity forms an arcuate pattern that rims the Williston basin. Porosity west of the Cedar Creek anticline trend is more localized than in the previous intervals. A porosity area of significant size extends northwestward into the Central Montana trough from the Bighorn uplift, but does not extend entirely across the trough as was the case in earlier Madison intervals.

The smaller area of porous rock during M–8.5 to M–12 may be partly the result of depositional conditions prevailing during this interval. The seas were more saline in localized basins, and the precipitation of gypsum, anhydrite, and halite may have decreased porosity in the rocks. The M–8.5 to M–12 interval is truncated by erosion around the outer borders of the mapped area, and this may account for some of the smaller area of porosity shown on plate 31.

MADISON INTERVAL M–12 TO MC

Only minor porosity in the 10 percent range is shown in the M–12 to Mc interval (pl. 32). The orientations of these areas of porous rock are speculative because most are based on one or two well-control points. There is little correlation between porous rock and ancestral structures. The continued hypersaline condition of the sea precluded the development of porous marine rocks that usually are associated with marine organisms; also, what little primary porosity there may have been probably was sealed by evaporite minerals that precipitated in the more saline basins. The M–12 to Mc interval probably was more extensive but erosion has removed it in some areas such as north-central Montana.

DEPOCENTERS OF THE WILLISTON BASIN

The changing location and morphology of the depocenter of the Williston basin is shown on plate 33. An incipient basin began to form during the time of deposition of the Deadwood Formation. The basin depocenter was small and centered at the Montana-North Dakota border. The basin continued to enlarge and shift eastward during Red River time, until the depocenter was a large, nearly circular area in western North Dakota.

The depocenter migrated slightly west and north during the deposition of the Interlake Formation, with its northern limit occurring beyond the Canadian border. Continued northward migration of the depocenter occurred during Middle and Late Devonian time, and the actual basinal center was in Canada.

During deposition of the Madison Limestone, the depocenter moved southward until it occupied a position in eastern Montana and western North Dakota. The depocenter changed in shape and area throughout all the Madison chronostratigraphic units. The depocenter during M–1 to M–3 time is indefinite, possibly because of the difficulty in identifying the M–3 marker in the basin center. By the deposition of the M–3 to M–7 interval, the Williston basin once again was well defined, and the depocenter had a northwest trend. During deposition of the M–7 to M–8.5 interval, the depocenter migrated northward with much of it occurring in Canada. The area of the depocenter decreased considerably during M–8.5 to M–12 time and the basin again was centered in northwestern North Dakota. By M–12 to Mc time, the depocenter again was located mostly in eastern Montana and western North Dakota.

A radical departure in basin morphology occurred during Big Snowy time. The Williston basin proper was similar in outline to that during M–12 to Mc time but with the added westward-trending thick zones produced by the Central Montana trough. By Pennsylvanian and Permian time, the basin depocenter was elongated in a north-northeast direction. By Triassic time, the basin depocenter again was shifted northward and had a general easterly trend.

The depocenter map indicates an important fact to be considered in the study of intracratonic basins. These basins are not static through geologic time, but do change in size, shape, and position in response to tectonic forces, depositional rates, and erosional effects.

SUMMARY

The history of tectonic events that may have controlled depositon and erosion in the Madison Project study area are best summarized by plate 34. This plate is a synthesis of all thickness and facies changes that can be attributed, at least in part, to geologic structural events. The major tectonic elements that operated throughout most of the geologic units indicated on plate 34 are the Alberta shelf, Transcontinental arch, Canadian Shield, and Cedar Creek anticline trend.

The structural-element components in north-central Montana, the Cat Creek, Willow Creek, Lake Basin, and Nye-Bowler fault trends, the Central Montana uplift, and the Central Montana trough, for example, were significant structural controls on deposition and erosion for long periods of geologic time. Two northeast-trending elements, the Poplar and Weldon-Brockton fault trends, also were actively controlling the deposition and erosion of many geologic units.

Some smaller tectonic elements that affected intervals within the Madison Limestone may have negated any significant effect on the total Madison. For example, the Bearpaw anticline affected thickness in Madison intervals M–1 to M–3, M–3 to M–7, and M–7 to M–8.5, but no discernible effect is apparent in the total Madison Limestone column as summarized on plate 34. A few structures only appear briefly in the geologic record. The Rosebud arch affected sedimentation in only two Madison intervals, and the Lusk embayment appeared only once in the M–3 to M–7 interval. Similarly, a structural trend in Powder River and Rosebud Counties, Montana only affected the Pennsylvanian and Permian rocks.

The frequency of tectonic events appears greater in the Madison intervals than in earlier and later geologic units. This frequency is more apparent than real simply because the Madison was divided into the five chronostratigraphic intervals. Had other geologic units been divided into marker beds, a similarly significant sequence of events might have occurred.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1985—576-967